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Impacts of Climate Change on Temperature and Precipitation in Nepal: Projections and Bias Correction

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Abstract: Climate change is likely to have a significant impact on Nepal, affecting its infrastructure, agriculture, and water resources. This study created day-to-day bias-corrected data of precipitation (ppt), maximum temperature (t_{max}) and minimum temperature (t_{min}) at 0.25° spatial resolution for Nepal using 7 CMIP6-GCMs under two shared socioeconomic pathways, SSP245 and SSP585. The bias-corrected datasets were produced using an empirical robust quantile mapping method for ppt and quantile mapping with linear transformation function method for t_{max} and t_{min}. The bias-corrected dataset was evaluated by comparing it against observed data for the mean values of ppt, t_{max} and t_{min}. Our bias-corrected projections reveal a warming of 4-6°C and an increase in ppt of 40-60% by the end of the 21st century. These changes will have a significant impact on Nepal's climate, environment, and people. The bias-corrected projections can be used to assess the impact of climate change in Nepal and to develop adaptation strategies.

Keywords: *Climate change, Bias-Correction, CMIP6, Global Climate Model, Nepal*

Conflicts of interest: None
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1. Introduction

Climate change is a result of the air's ozone harming substance groupings of CO2 and other ozone harming substances increasing exponentially (Malla, 2008). It poses a critical global challenge, affecting ecosystems, economies, and the livelihoods of millions. In this context, understanding the impacts of climate change at regional levels becomes paramount. This study explores the specific case of Nepal, a nation with unique geographical diversity and a pronounced vulnerability to climate change. As per projections, climate change will influence the quality and quantity of water in the future (Pandey et al., 2020). Lately climate change in Nepal has brought a quick rise in temperature, an unpredictable pattern of ppt, a more limited winter, and more frequent and prolonged droughts (Palazzoli et al., 2015). So, accurate projections for this region are essential for informed decision-making and mitigation efforts.

Nepal's geography is diverse, ranging from lowlands in the south to towering Himalayan peaks in the north (Shrestha et al., 2016). It is also a country with a high level of biodiversity and one of the nations that are acutely responsive and exposed to the consequences of climate change. As a result of global warming, Nepal has seen an increase in hydrometeorological extremes, a shift in the pattern of ppt, and a rapid rise in temperature (Talchabhadel and Karki, 2019). Nepalese environmental change research predicts that temperature is supposed to rise steadily all throughout the 21st century (Shrestha et al., 2016). The average annual temperature in Nepal is expected to ascend by 1.2°C, 1.7°C, and 3°C from the benchmark time of 1961–1990 in 2030, 2050, and 2100, respectively, as per research by the Organization for Economic Cooperation and Development (OECD). Comparative projections for annual precipitation for the same time periods incorporate increments of 5, 7, and 12% (Khadka and Pathak, 2016). Such changes affect diverse sectors, including agriculture, public health, and the sustainability of mountain ecosystems (Malla, 2008).

To understand the complex interplay of climate factors in Nepal, we rely on General Circulation Models (GCMs), which are mathematical models that simulate the circulation of the Earth's atmosphere, providing insights into past, present, and future climate trends (Christensen et al., 2008; Y. Mishra et al., 2018; Mishra et al., 2020). However, these models often work at spatial resolutions that are insufficient for precise regional assessments, and they may contain biases in temperature and precipitation (Christensen et al., 2008; Mishra et al., 2018; Mishra et al., 2020; Timilsina et al., 2021). Thus, to produce reliable assessments of climate change and its impacts, the application of bias correction techniques becomes imperative (Christensen et al., 2008; Mishra et al., 2020).

The primary objective of this study is to generate accurate projections of daily ppt, tmax and tmin for Nepal. Using information from seven different CMIP6-GCMs, we employ advanced bias correction techniques (quantile mapping with a linear transformation function and empirical robust quantile mapping) to refine these projections. By evaluating historical data and examining future scenarios (SSP245 and SSP585), our research seeks to shed light on Nepal's climate change projections across its varied landscapes, spanning the near future (NF) (2023-2048), mid future (MF) (2049-2074), and far future (FF) (2075-2100). These findings are vital not only for policymakers, but also for stakeholders engaged in crafting strategies to address Nepal's evolving climate and precipitation patterns.

2. Materials and methods

2.1. Study area

Our study focuses on Nepal, a landlocked country located in South Asia, covering a total area of 147,516 square kilometers. Nepal's geographic coordinates extend from approximately 26°22' to 36°27' latitude and 80°4' to 88°12' longitude (Devkota et al., 2006). Nepal's topography is characterized by remarkable variation, primarily categorized into three distinct regions: the Terai region, which comprises the lowlands and lies at elevations below 610 meters; the Hilly region, characterized by elevations ranging from 610 meters to 4,877 meters; and the Himalayan region, which includes the towering peaks of Nepal, reaching elevations from 4,877 meters to the country's highest point at 8,848 meters above sea level (Devkota et al., 2006). The nation is primarily drained by three major river basins: the Koshi, Narayani, and Karnali. These river basins, in turn, contribute to the larger Ganges River basin (Devkota et al., 2006). The map of the study area is shown in figure below.

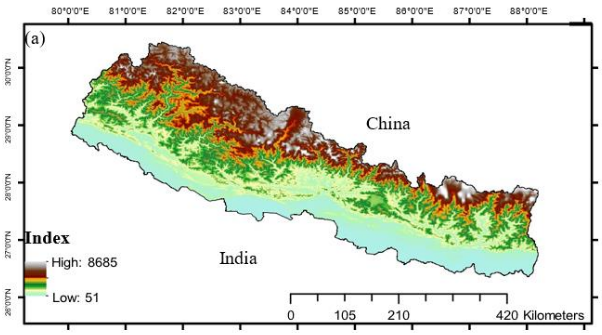


Figure 1: Topographical relief map for bias-corrected CMIP6 projections. (a) Nepal political map with topographical color scale in the background.

2.2. Data sources

Temperature and precipitation Data

To ensure the reliability of our historical temperature data, we gathered observed daily ppt, tmax and tmin records from a network of 216 weather stations spanning Nepal. These observations cover the period from 1980 to 2014 and were originally compiled by Sheffield et al. in 2006 (Sheffield et al., 2006). Additionally, we acquired data for 18 specific stations located within the Narayani River basin from the Department of Hydrology and Meteorology (DHM). We also gathered data from 18 specific weather stations situated within the Narayani River basin. To make sure this data was reliable, we carefully compared it to Sheffield's dataset. We found that the two datasets matched quite closely. Further, another study by (Shah et al., 2016) also confirmed that Sheffield's dataset aligns well with weather station data across South Asia. Considering the sparse distribution of weather stations, particularly within the challenging terrain of the Himalayan region, and recognizing gaps in observational data, we concluded that employing the dataset from (Sheffield et al., 2006) as our observational reference was the most prudent choice for this research.

GCMs (CMIP6) data

This study used historical (1980-2014) data and future (2015-2100) projections of CMIP6 GCMs for all three variables: ppt, tmax and tmin. The temperatures and precipitation variables are established based on two scenarios i.e, SSP245 and SSP585. The scenarios used in the CMIP6 combine Share Socioeconomic Pathway (SSP) and aim for a specific level of radioactive forcing by the end of the 21st century. SSP245 is based on the socioeconomic pathway (SSP-2) with the target radioactive level of 4.5 W/m² (Gidden et al., 2019) and SSP585 is based on emission scenarios SSP-5 and radioactive level of 8.5 W/m² (Gidden et al., 2019; V. Mishra et al., 2020). The CMIP6 projections exhibit improved accuracy for ppt and temperature uncertainties compared to CMIP5 (Hamed et al., 2022). We chose 7 CMIP6-GCMs to obtain raw daily ppt, t_{max} and t_{min} from https://nex-gddp-cmip6.s3.us-west-2.amazonaws.com/. Incorporating multiple GCMs helps to mitigate the inherent biases present in the GCMs.

The overall methodology of this study is shown in Figure 2. The major activities involved are:

Acquisition of data: The observed data and GCMs data set were acquired. The observed data consisted of daily ppt, tmax and tmin of 216 stations all across Nepal at the spatial resolution of 0.25° for the period of 1980 to 2014. The GCMs data consisted of historical (1980-2014) and future (2015-2100) projections of temperature and precipitation for seven CMIP6-GCMs.

Selection of stations: The stations for the observed data were selected based on their availability and representativeness of the different climatic zones in Nepal.

Selection of GCMs: The GCMs were selected based on their availability of all three variables (ppt, tmax and tmin) for both SSP245 and SSP585 scenarios.

Bias correction: The GCMs data was bias-corrected using the quantile mapping method.

Projection of future climate: The bias-corrected GCMs data was used to project future climate change in Nepal for the three future periods: Near Future (NF, 2023-2048), Mid Future (MF, 2049-2074), and Far Future (FF, 2076-2100).

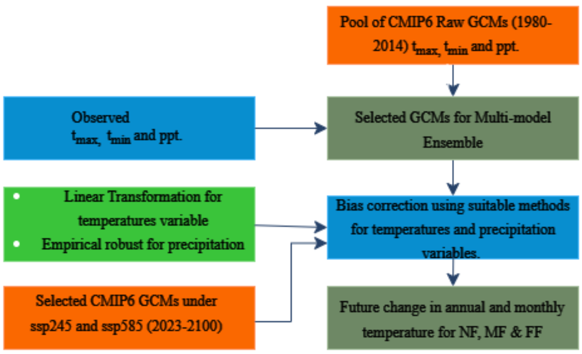


Figure 2: Methodological flowchart of the study

GCMs Selection

We chose seven CMIP6 General Circulation Models (GCMs) for ppt, tmax and tmin. Multiple GCMs helps us reduce uncertainties that can be inherent in these models. Seven GCMs were deemed sufficient to start with. Our selection of these seven GCMs was based on their ability to provide daily tmax, tmin and ppt data for historical periods as well as two future scenarios, SSP245 and SSP585 under r1i1p1f1 initial conditions. They have also been widely used in climate change studies for the South Asian region (V. Mishra et al., 2020). To assess how well these GCMs performed, we used historical observed monthly mean tmax, tmin and ppt data from the period 1980 to 2014 as a reference. This allowed us to evaluate the accuracy of the GCMs in representing real-world climate conditions. Here's a table showing which different CMIP6 models we used in our study:

Table 1. CMIP6-GCMs used for bias correction

S.N.	Model Name	Country	Latitude (°)	Longitude (°)	Research Centre
1	ACCESS-CM2	Australia	0.25	0.25	Australian Community Climate and Earth System Simulator (ACCESS)
2	ACCESS-ESM1-5	Australia	0.25	0.25	Australian Community Climate and Earth System Simulator (ACCESS)
3	INM-CM5-0	Russia	0.25	0.25	Institute of Numerical Mathematics (INM)
4	MPI-ESM1-HR	Germany	0.25	0.25	Max Planck Institute of Meteorology
5	MPI-ESM1-LR	Germany	0.25	0.25	Max Planck Institute of Meteorology
6	NESM3	China	0.25	0.25	NUIST Earth System Model
7	NorESM2-LM	Norway	0.25	0.25	Norwegian Climate Centre

SSP selection

In our research, we specifically chose to focus on two climate scenarios, SSP245 and SSP585, because they represent contrasting pathways for our planet's future. SSP245, resembling a more cautious approach, targets a moderate environmental impact with a radiative forcing goal of 4.5 W/m² by the century's end (Gidden et al., 2019). On the other hand, SSP585 represents a less cautious scenario with a higher radiative forcing target of 8.5 W/m² by the end of the century (Gidden et al., 2019; Mishra et al., 2020). By studying these two scenarios, we aim to understand and compare the potential climate outcomes for Nepal under different levels of environmental concern and action.

Bias correction methods

Uncertainties in the climate model make it challenging to predict future climate accurately, so to address this issue, bias correction is employed (Muerth et al., 2013). For modifying RCM output, bias correction processes use a transformation algorithm. The primary objective is to identify any biases between observed and simulated climatic variables. These corrected output will serve as the foundation for both control and scenario RCM runs (Teutschbein and Seibert, 2012). Several bias correction methods have been developed for precipitation and temperature (Gudmundsson et al., 2012; Luo et al., 2018; Timilsina et al., 2021). Precipitation correction methods includes Daily Bias Correction (DBC), Quantile Mapping, Local Intensity Scaling (LOCI), Distribution Mapping (DM), LS and PT. Similarly, DM, DT, EQM, LS, quantile mapping (QM), multiple regression and gamma-gamma transformation are used for temperature correction (Gudmundsson et al., 2012; Luo et al., 2018). For this study, we used quantile mapping tools. Numerous researches identify the quantile mapping tools are the most effective tools in removing biases. (Teutschbein and Seibert, 2012; Zollo et al., 2014; V. Mishra et al., 2020). We implement Empirical Robust Quantile mapping technique for bias correction of historical (1980-2014) for precipitation using data by Sheffield et al. This approach extends the empirical quantile mapping method by using non-linear local linear least square (NLLS) regression to establish a quantile-quantile link between historical observed and modelled time series data. The quantile mapping method provides robust framework for correcting biases and enhancing the reliability of climate projection. The estimation of a flexible quantile mapping function g() such that $F-1(\tau)=g[F-1(\tau)]$ is done using NLLS based on the ten closest data points indicated in the quantile-quantile plot for each quantile level $\tau = 0, 0.01, 0.02, \ldots$, 0.99, 1.0. The future projection at time 't' is then derived through the expression:

$\hat{x}(t)=\bar{g}[x(t)]$ (Qian and Chang, 2021).

For temperature bias correction, the Linear transformation function is employed. According to (Timilsina et al., 2021) linear transformation function shows better performance than other methods, so we choose it as a best performing bias correction method for temperature. The Linear QM framework assumes a linear connection between quantile functions of observed values and the model over the historical period. Mathematically, this relationship us expressed as,

$F-1(\tau) = a + b*F-1(\tau)$,

Where coefficients 'a' and 'b' are derived through a linear least square regression. Consequently, bias corrected future projections at time 't' are calculated as,

$\hat{x}(t) = a + b*x(t)$.

Challenges

Obtaining accurate and reliable historical climate data for bias correction across Nepal posed a considerable challenge, particularly in remote and higher Himalayan regions. In particular, we encountered gaps in the daily data from the Department of Hydrology and Meteorology (DHM) for the Narayani River basin for the years spanning from 1980 to 2014. To address these gaps, we used average data of each month over the long period. Additionally, to ensure data accuracy, we meticulously cross-verified Sheffield's dataset with DHM's data. This was done to guarantee the reliability and consistency of the climate data we used for our research. Furthermore, managing extensive datasets and handling complex computations throughout the research process presented significant hurdles. These challenges are inherent in climate research, but require careful attention and resources to navigate effectively.

3. Results

We began by examining how ppt, tmax and tmin might change in the future. We used data from seven different climate models (CMIP6-GCMs) to make these predictions. We looked at two different scenarios, SSP245 and SSP585, and divided the future into three timeframes: NF, MF and FF. We compared these future projections to the past, specifically from 1989 to 2014. The combined results from all the models suggest that annual ppt in Nepal could increase by about 40-60% in the later part of the 21st century, especially under the SSP585 scenario. How much the rain increases, along with how hot it gets, depends on the scenario. For example, in the Far Future, under SSP245, tmin might go up by around 2°C. However, under SSP585, the increase could be as much as 4°C. Similarly, tmax could rise by about 2-4°C by the end of the 21st century. Figure 3 below shows the change in more detail.

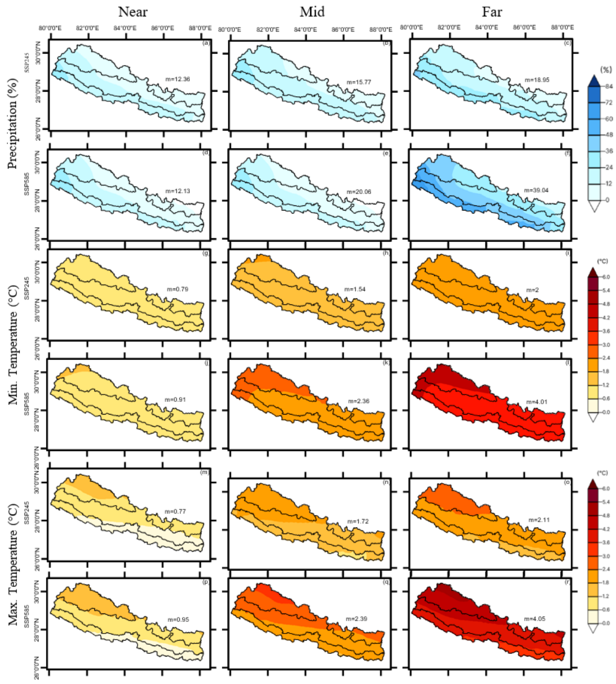


Figure 3: Projections of ppt tmax and tmin for the NF, MF and FF using raw output from CMIP6-GCMs. (a-f) Multi-model ensemble (MME) mean projected change in mean ppt for the NF, MF and FF with respect to the historical period (1989-2014), (g-l) same as (a-f) but for mean annual t¬¬¬¬¬min, (m-r) same as (a-f) but for the mean annual tmax. Median of all three variables is shown in each panel.

We started with raw climate data for ppt, tmax, and tmin. This data was essential for understanding how Nepal's climate might change in different future scenarios. However, this raw data has some inaccuracies, so we needed to remove inherent biases. Bias correction helps make the data more accurate, especially at the local level. We did this correction for both the past (1980-2014) and the future (2015-2100) under two different scenarios: SSP245 and SSP585. After correcting the data, we estimated the multi-model ensemble mean bias in ppt, tmax and tmin from all 7 CMIP6-GCMs (Fig. 4). The bias was compared against observed data from Sheffield et al. (2006). Before the correction, we noticed that the raw data tended to overestimate ppt in most of Nepal (Fig. 4a). On the other hand, it underestimated both tmax and tmin in many areas (Fig. 4c, f). After applying bias-correction methods, the bias was eliminated to some extent in all three variables (mean annual ppt, tmax and tmin) (Fig. 4b, d, f).

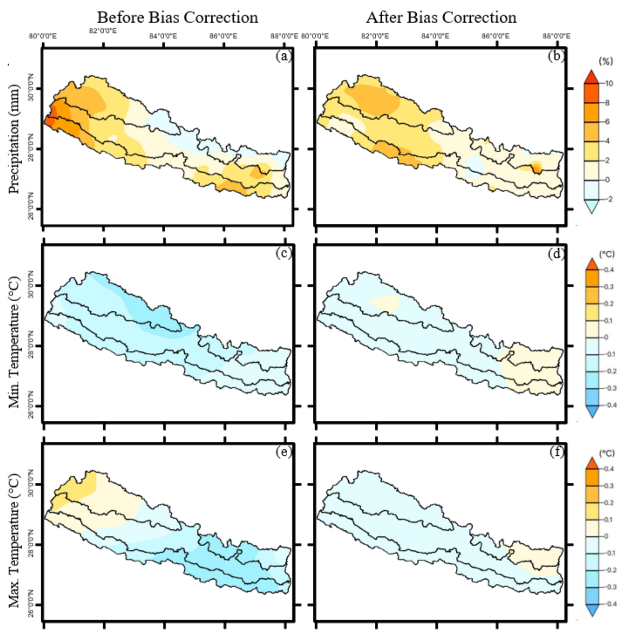


Figure 4: MME mean bias in ppt, tmax and tmin in 7 CMIP6-GCMs. (a-b) Bias (%) in mean annual ppt for the historical period (1985-2014) before and after the bias correction, (c,d) Bias (°C) in mean annual tmin before and after bias correction, and (e,f) bias (°C) in mean annual tmax before and after bias correction.

After that, when we corrected the ppt data for three aforementioned future time period, we found that it still showed similar patterns to the raw data from the climate models (Fig. 3). This means that both the raw and corrected data indicate that southwestern Nepal will likely see a significant increase in annual ppt, with the Terai region being the most affected. Under SSP585, the increase in ppt is even more pronounced compared to SSP245 (Fig. 5a-f). For temperature, we found that annual mean tmin is expected to rise by about 2.84°C under SSP245 and 5.42°C under SSP585 (Fig. 5g-l). Similarly, annual mean tmax is expected to increase significantly, with SSP585 predicting a median increase of more than 4.8°C across Nepal (Fig. 5m-r).

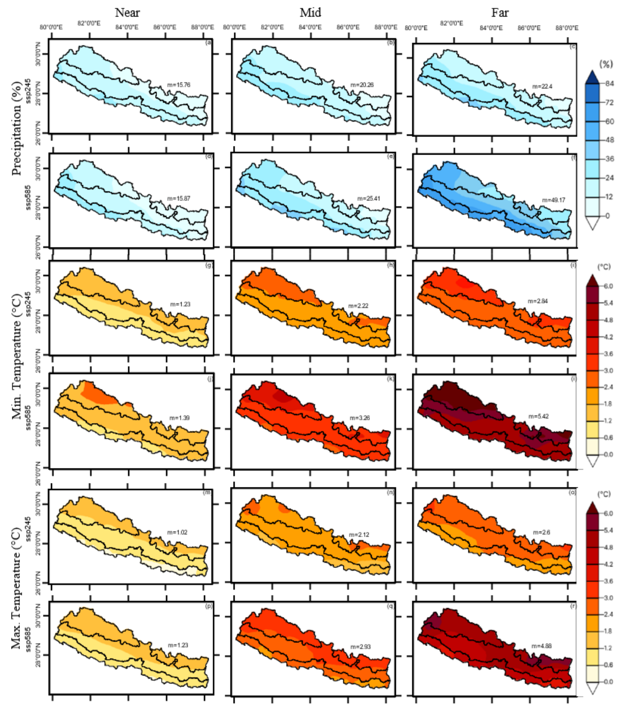
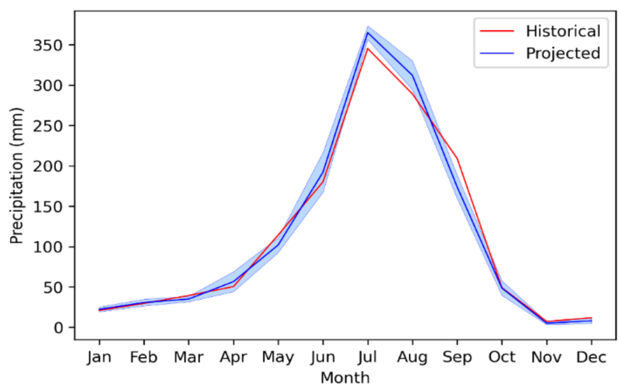


Figure 5: Projections of ppt, t_{max} and t_{min} for the NF, MF and FF using bias corrected output from CMIP6-GCMs. (a-f) MME mean projected change in mean annual ppt for the near, mid and far future with respect to the historical period (1989-2014), (g-l) same as (a-f) but for mean annual t_{min}, (m-r) same as (a-f) but for the mean annual t_{max}. Median of the MME mean ppt, t_{max} and t_{min} are shown in each panel. Projected changes were estimated for the two scenarios (SSP245 and SSP585) against the historical period.

We calculated month-wise multi-model ensemble mean of bias-corrected ppt, tmax and tmin from the CMIP6-GCMs for the period of 1985-2014. Then, we compared these corrected values ppt, tmax and tmin with observations from the same time period. What we found is that the patterns of monthly ppt, tmax and exhibit similar patterns to the observed dataset (Fig. 6).



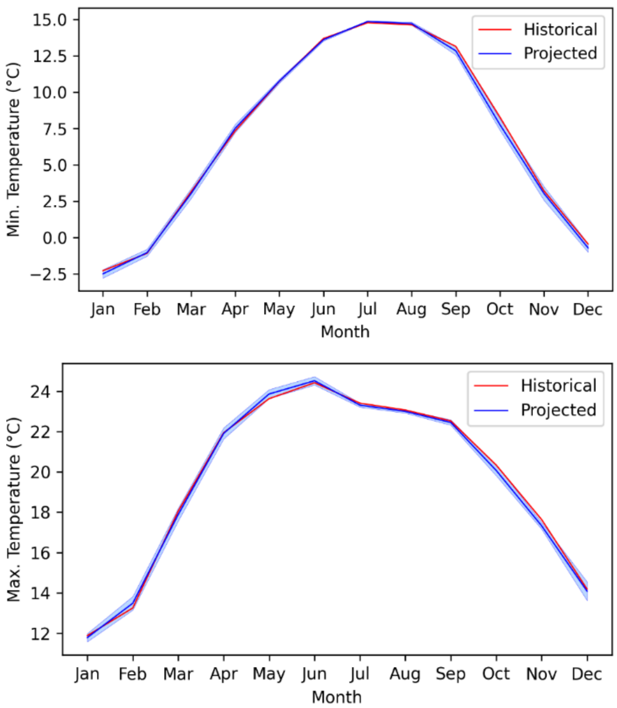


Figure 5: Month-wise cycle of bias-corrected ppt, tmax and tmin. Comparison of the MME (blue) mean month-wise cycle of bias-corrected (a) ppt, (b) tmax, and (c) tmin against the observations for the 1985-2014 period (red). The shaded area represents the level of uncertainty, which has been estimated using one standard deviation, based on 7 CMIP6-GCMs.

For further analysis, we used a 30-year window to analyze data for different parts of the country. We focused on the most concerning scenario, SSP585, which represents the worst-case situation. We looked at each 30-year period, starting from 1986-2015 and continuing through to 2100, comparing it to the reference period of 1985-2014. This allowed us to estimate how things might change over time. Our findings indicate that across all regions of Nepal, we can expect an increase in average annual ppt in the future. By the end of the 21st century, this increase could be substantial, ranging from 40-60%. However, it's important to note that there is more uncertainty in the projections for the Terai region compared to other parts of Nepal. On the other hand, the uncertainty in projections for tmax and tmin is much lower than that of ppt. We anticipate that both tmax and tmin could rise significantly, by around 4-6°C, in the far future. These changes in temperature and ppt have important implications for Nepal's climate and environment.

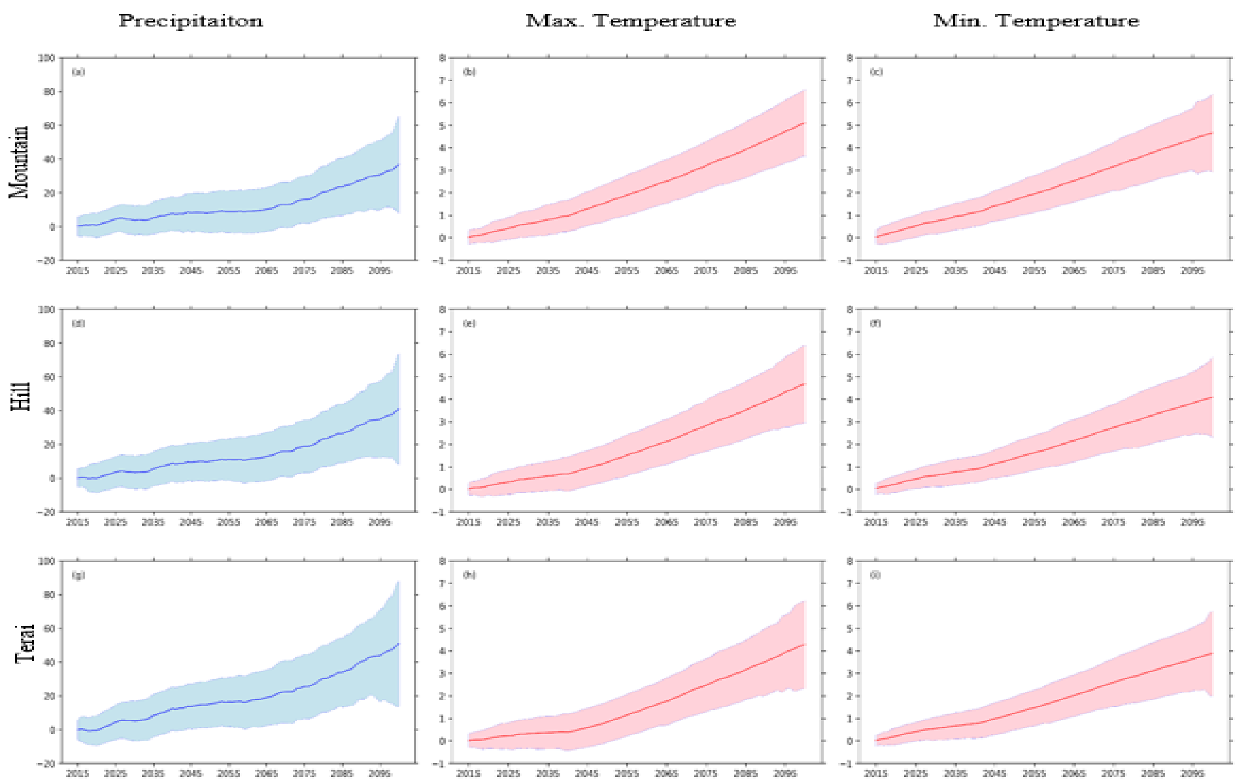


Figure 6: MME mean change in ppt, tmax and tmin in Nepal. Region-wise changes in the MME mean annual ppt (%), tmax (°C), and tmin (°C) estimated using a 30-year moving window against the historical reference period of 1985-2014. The shaded area represents the level of uncertainty, estimated using one standard deviation, based on 7 CMIP6-GCMs.

We looked at how three important climate factors - ppt, tmax and tmin - are expected to change in different regions of Nepal over time. We compared these future projections with the past to understand the changes better. In the NF, under the SSP245 scenario, we expect an increase in annual ppt of about 10-21%. The Terai region will see the most significant increase, while the Mountain region will have the smallest rise. In the FF, ppt is projected to increase significantly in all regions of Nepal, by around 40-60% (Table 2). When it comes to temperature, we anticipate a noticeable difference between the NF and FF. In the NF, under SSP245, tmax may rise by 0.62-1.27°C (Table 3), while tmin could go up by 1.05-1.47°C (Table 4). However, in the FF under SSP585, the increase in tmax could be as high as 4.4-5.21°C, and minimum tmin may rise by 5.15-6.16°C. We also calculated the standard deviation to understand the level of uncertainty in these projections for each region and time period under both scenarios.

Table 2: Region wise MME mean projected change in mean annual ppt (%) against historical mean (1985-2014) with uncertainty (one standard deviation) based upon corrected data from 7 CMIP6-GCMs.

Region		Mountain	Hill	Terai
Historic(mm)		998.37	1480.21	1521.44
ssp245	**NF**	11.44±25.32	15.09±28.69	20.49±32.16
	MF	15.45±24.75	18.76±27.31	22.8±31.74
	FF	17.45±26.61	22.58±30.13	30.36±35.08
ssp585	**NF**	10.72±24.35	14.33±26.2	20.71±29.86
	MF	19.39±23.64	23.96±26.59	32.12±31.31
	FF	40.45±31.62	47.48±35.32	59.97±43.30

Table 3: Region wise MME mean projected change in mean annual tmax (°C) against historical mean (1989-2014) with uncertainty (one standard deviation) based upon corrected data from 7 CMIP6-GCMs.

Region		**Mountain**	**Hill**	**Terai**
Historic(°C)		9.77	22.37	30.56
ssp245	**NF**	1.27±0.64	0.96±0.63	0.62±0.63
	MF	2.32±0.76	2.05±0.77	1.8±0.76
	FF	2.81±0.82	2.53±0.87	2.29±0.93
ssp585	**NF**	1.52±0.67	1.15±0.7	0.77±0.76
	MF	3.21±0.88	2.85±0.93	2.5±0.98
	FF	5.21±1.24	4.79±1.32	4.4±1.42

Table 4: Same as Table 3 but for mean annual tmin.

Region		Mountain	Hill	Terai
Historic(°C)		-3.28	10.36	18.75
ssp245	**NF**	1.47±0.65	1.19±0.58	1.05±0.56
	MF	2.55±0.83	2.19±0.76	2.06±0.75
	FF	3.22±0.89	2.81±0.84	2.65±0.86
ssp585	**NF**	1.73±0.60	1.4±0.55	1.24±0.58
	MF	3.74±0.88	3.25±0.85	3.08±0.87
	FF	6.16±1.25	5.39±1.24	5.15±1.28

4. Discussion

The results obtained from 7 CMIP6-GCMs provide valuable information about the projected changes in ppt, tmax and tmin in Nepal under different scenarios (SSP245, SSP585) and different time periods (NF, MF and FF). Based on bias corrected ppt projection, the Terai region is expected to have highest increase in ppt, while the Mountain region has the smallest increase in ppt (Table 2). Under SSP585 scenario across all the regions of Nepal, there will be substantial (40-60%) increase in ppt in late 21st century, whereas in the case SSP245 scenario, there will be less increase in ppt. This finding shows a line with global change pattern, which indicates a shift towards wetter condition in different geographical regions of Nepal in the 21¬-st century. In the case of tmax and tmin, this study showed increasing trend in temperature in Nepal throughout the 21st century (Figure 4). The bias corrected MME annual tmax and tmin are projected to rise by 4-6°C the end of 21st century (Figure 6). This indicates that there will be hotter climatic condition in future in Nepal.

Implications

The projected alterations in precipitation and temperature are poised to have far-reaching consequences across numerous sectors in Nepal, including agriculture, water resources, and infrastructure. The anticipated increase in ppt is a double-edged sword. On one hand, it can be beneficial for agriculture by providing more water for crops. However, it also elevates the risk of floods, landslides, and soil erosion, which could harm both agricultural activities and infrastructure (Karki et al., 2012). The rise in temperature, on the other hand, presents challenges for agriculture. It's expected to bring about increased evaporation rates, greater water stress, and alterations in crop growth patterns. These negative effects are likely to be most pronounced in the mountainous and hilly regions of Nepal, where agriculture plays a crucial role in livelihoods.

Additionally, the projected increase in ppt has implications for Nepal's water resources. It could lead to higher runoff, potentially causing flooding in certain areas. Conversely, the increased evaporation rates might result in water shortages in other regions. These changes could significantly affect access to water for various purposes, including drinking, irrigation, and hydropower generation. Furthermore, the heightened risk of flooding and landslides poses a threat to infrastructure elements such as roads, bridges, and related constructions. These challenges underscore the importance of proactive planning and adaptation measures to address the potential impacts on these critical sectors.

Policy and adaptation implications

The findings of this study carry significant implications for policy formulation and adaptation strategies in Nepal, especially in the context of climate change. As noted by Timilsina et al. (2021), even modest increases in temperature can usher in substantial shifts in climate patterns. Consequently, this study underscores the urgent need for timely policy development and proactive adaptation measures to mitigate the potentially severe impacts of evolving climatic conditions.

Nepal's government stands at a critical stage where it must proactively address the challenges posed by climate change. Policymakers are urged to prioritize the development of comprehensive policies and strategies designed to alleviate the adverse effects of climate change on key sectors such as agriculture, water resources, and infrastructure. These policies should be rooted in a holistic approach, encompassing both mitigation and adaptation measures.

Effective policies should prioritize the enhancement of sectoral resilience to climate change impacts. For agriculture, this could entail investments in improved irrigation infrastructure, sustainable farming practices, and diversification of crops to adapt to changing conditions. Likewise, measures to conserve water resources and manage them more efficiently will be crucial for ensuring continued access to water for various purposes, including drinking and irrigation.

In light of the increased risk of flooding and landslides, the establishment of robust early warning systems is imperative. These systems should be region-specific and capable of delivering timely alerts to vulnerable communities. Adequate preparedness and response mechanisms must also be in place to minimize casualties and damages.

In summary, the study's findings accentuate the urgency for Nepal to take proactive steps in aligning its policies and adaptive strategies with the evolving climate. Timely and well-informed action can help mitigate the potential adverse consequences on agriculture, water resources, and infrastructure, ultimately contributing to the resilience and sustainable development of the nation in the face of a changing climate.

Comparative analysis

Our study shows a significant increase in mean annual ppt, particularly in the Karnali (Western Region). This aligns with the findings of Chapagain et al. (2021), which also projected higher yearly ppt in the Karnali region. This consistency in results suggests a similar trend in different studies, emphasizing the reliability of our findings. Karki et al. (2012) previously reported that climate change would lead to higher temperatures in Nepal. Our study's projections also confirm this trend. Moreover, when comparing the SSP585 scenario with the SSP245 scenario, our research reveals that the annual increase in tmax and tmin is projected to nearly double in all geographical regions of Nepal by the end of the 21st century (see Table 3 and Table 4). This highlights the increasing challenges related to rising temperatures.

Addressing uncertainties

It's essential to acknowledge that uncertainties still exist, as is common in climate research. While our bias correction method enhances the reliability of our projections, the inherent uncertainties in General Circulation Models (GCMs) persist (Moghim et al., 2017). We mitigated some uncertainties by using multiple models, but there may still be some associated with the specific models we selected (Tebaldi and Knutti, 2007). Additionally, the coarse resolution of GCMs limits their ability to provide detailed spatial information. Nepal's diverse topography demands higher-resolution data to accurately capture local climate variations.

5. Conclusion

The projected climate data obtained by using 7 CMIP6-GCMs predict warmer and wetter climatic conditions in Nepal for two emission scenarios i.e., SSP245 and SSP585, adopting quantile mapping (QM) for bias correction. Ppt, tmax and tmin data were projected based on different time periods (NF, MF and FF) under two scenarios. The findings suggest that there is significant increase in ppt by 40-60% and warming trend of temperature with projected rise 4-60C at the end of 21st century. Across three geographical regions of Nepal, Terai region is projected to have higher ppt than other regions. In both raw and bias-corrected dataset, there was a significant rise in mean annual ppt in the southwestern parts of Nepal. Under SSP585 scenario, it is predicted that the ensemble mean tmax is going to upsurge remarkably all over Nepal. Rising temperature and increase in ppt will affect the water resources availability. Projected dataset of ppt, t¬¬max and t¬min have notable implication for infrastructure planning, resource management and livelihood of the people in Nepal. Bias-corrected projection provide better understanding for the lawmakers to understand the potential impacts of climate change and to formulate mitigating strategies to reduce possible effects.

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