Assessment of climate change projections in the Chenab River Basin, Western Himalaya

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General circulation models (GCMs) are vital to project potential changes in future climate under different emissions scenarios. Raw GCM output is not applicable at regional scale due to biases relative to observational data and coarse spatial scale for future climate predictions. Here, statistical downscaling method was employed to generate daily maximum temperature (Tmax), minimum temperature (Tmin) and precipitation of coarse spatial resolution of GCM (0.5 degree) which fall within the boundary of CRB. In this study, the fifth generation ECMWF atmospheric reanalysis (ERA5) data was used as observed data to downscale and bias-correct GFDL-ESM2M data under RCP4.5 and RCP8.5 emission scenarios for the near future (2020-2050), mid-century (2051-2080) and end of century (2081-2100) in the Chenab River Basin (CRB). The refined output from the GCM was further analyzed to depict climate changes in the CRB. It was found that a consistent increase in maximum temperature (Tmax) and minimum temperature (Tmin) was recorded under RCP4.5 and RCP8.5 in the future scenarios. In the CRB, the magnitude of increase in predicted Tmin was higher than Tmax. However, precipitation showed an increasing trend in near future while decreasing trend in the mid-century and end of century under RCP4.5.

Keywords: GCM; Climate change; Temperature; Precipitation; Chenab River Basin.

INTRODUCTION

A remarkable warming trend has been observed in almost all parts of the World since the 19th century [1] [2]. In the late 19th century, the Earth was approximately 0.8°C cooler than the early 21st century [3]. However, observed warming has not been constant during this period, which includes three periods of slowdown (1896-1910, 1941- 1975 and 1998-2013) and two periods of strong warming (1911-1940 and 1976-1997) in global mean surface temperature [4] and afterwards a reduction in the warming rate [5] [6]. There is a consensus that the changing climate will prompt changes in the intensity, extent and duration of extraordinary meteorological and climatic events [7].

The climate change impacts that could be averted by limiting global warming to 1.5 °C compared to 2 °C. For instance, a 10 cm lower sea level rise at 1.5 °C global warming compared to 2 °C [8]. The increase in Global Mean Surface Temperature (GMST) for the end of the 21st century relative to 1986-2005 is projected to increase in the range of 0.3 to 1.7 °C under RCP2.6, from 1.1 to 2.6°C under RCP4.5, from 1.4 to 3.1 °C under RCP6.0 and 2.6 °C to 4.8 °C under RCP8.5 derived from concentration-driven CMIP5 model simulations [9].The projected temperature is likely to increase around 1 °C to 3 °C by 2050s and 2 °C to 5 °C by the end of twenty first century, based on different emission scenarios [9].

Warming in the Himalayan region will likely be at least 0.3 °C to 0.7°C higher than global warming due to higher greenhouse gas emissions respectively, even if global warming is kept to 1.5°C [10]. Climate warming is leading to visible effects in the Himalayan region, with indications of changes in vegetation phenology and with reduced agricultural production in some of the major crops in some parts of the Himalaya, mainly due to changes in patterns of snowfall and monsoon rains [11]. The warming influence is much higher in the Eastern Himalayas compared with the Greater Himalayan region [12]. In the Upper Indus Basin (UIB) which includes the Chenab River Basin (CRB), there is also an increase in winter temperatures and a decrease in summer temperature for some regions [13] [14], suggesting that the rate and patterns of warming vary spatially. These variations in temperature could have a potential impact on water resources that supply water for irrigation to downstream areas, which are of major concern.

The frequency and intensity of extreme weather and climatic events have increased in the region which raised concerns over the impact of global climatic changes [15]. Precipitation fluctuations have a direct impact on floods, droughts, water resources and ecosystem services [16]. Precipitation changes may alter the hydrological cycle, which can affect both the environment and society [17]. This makes it imperative to study climate change projections from global climate models (GCMs) for accurate prediction of changes in climatic variables [18].

The performance of different GCMs varies greatly [19] [20]. Uncertainties in climate change impact assessments are characterized by large variations in GCM outputs of global and regional climate projections [21]. However, it is challenging to select a better performing GCM for South Asia, as none of the GCMs can reproduce all the salient features [22]. Climate models are persistent in the projected increase in precipitation in high latitudes and parts of tropics, and decrease in precipitation projections in some sub-tropical and lower mid-latitude regions [23] [24]. Apart from these areas of persistent increase and decrease in precipitation, there are areas of high uncertainty where climate models do not agree. For instance, climate model projections of precipitation averaged over the UIB are fairly large, ranging from -3.5 to +9.5% projected for 2050 and even larger for seasonal and individual basins [19]. The projected a decrease in precipitation over the UIB from GCMs. However, most GCMs agree on projections of temperature increase by 1.22 °C over the Hindukush Karakoram Himalaya (HKH) region for 2050 [19].

The present study is based on the outputs from GFDL-ESM2M and the fifth generation ECMWF atmospheric reanalysis (ERA5) gridded and reanalysis data as observed data to downscale and bias-correct the studied GCM. This study aims to evaluate the past and projected climate change over the CRB which is a transboundary sub-basin of the Upper Indus Basin (UIB). The river flow from the CRB is vital for irrigation of crops in Pakistan. In this context, the knowledge about the changing climate variables to ensure sustainable water supply to downstream people.

Material and Methods.

The Chenab River Basin (CRB) is a sub-basin of the Upper Indus Basin (UIB) lies in 73° 78' E and 32°-35° N (Figure 1). Most of the rainfall (about 75 %) in the Greater Himalaya (75 %), Middle Himalaya (65 %) and Outer Himalaya (64 %) ranges occurs during monsoon and remaining rainfall (15 %, 25 % and 24 % respectively) occurs during winter in the form of snow [43].

The Chenab river flows from the CRB is the second largest river in Pakistan which irrigate most of the Punjab province. The major area (about 65 %) of this transboundary basin lies in Indian administered Kashmir while the remaining area in Pakistan [42]. The upper half of the CRB lies in the Middle Himalayan range mainly receives precipitation during winter, while the lower reaches of the basin is a part of the Outer Himalaya which is predominantly under the influence of monsoon rainfall during summer (Grover et al., 2020). The elevation of the CRB ranges from <1500 to >6000 m. The CRB experience hot and moist tropical conditions at low elevations (<1500 m) while, the temperature becomes cooler and colder at higher elevations [44].

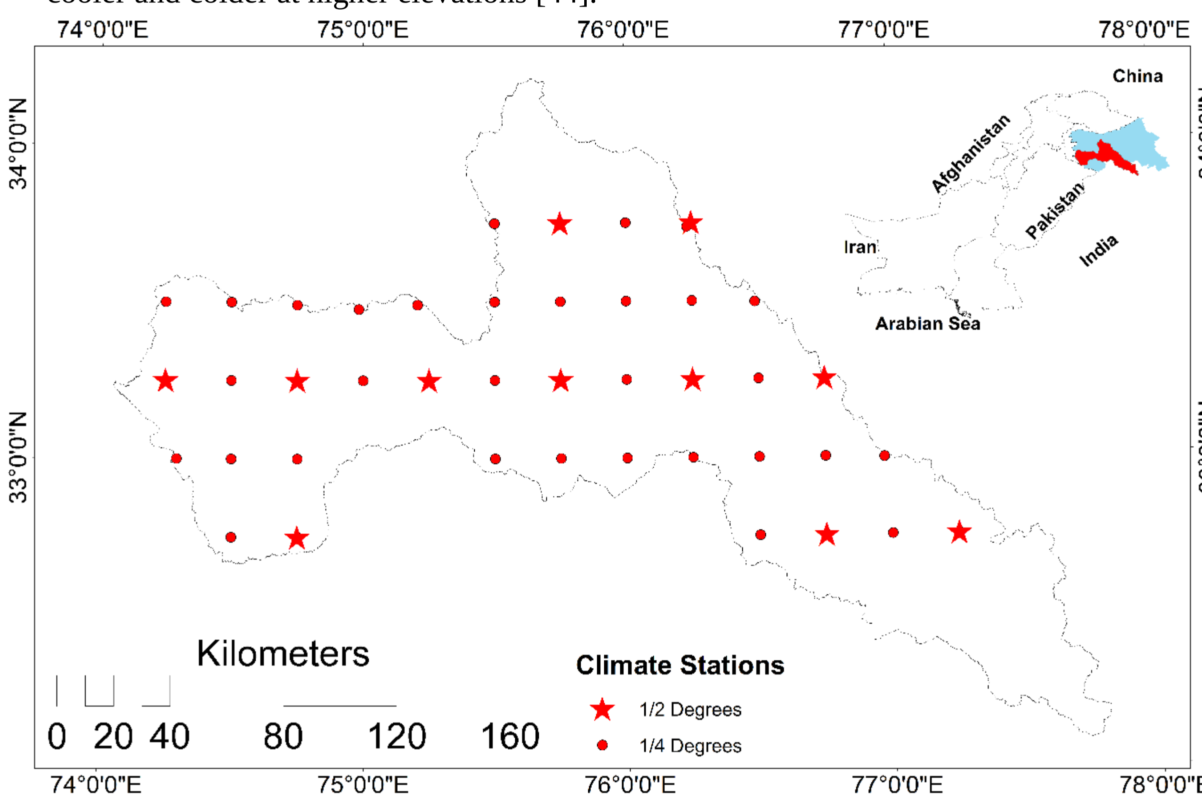

Figure 1 study are map of the Chenab River Basin (CRB) with climatic stations at a spatial resolution of ½ degree resolution which is interpolated to produce higher spatial resolution (1/4 degree).

Observed Data

The performance of the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA) 5-Land (ERA5) gridded product is considered the best among other recently released gridded and reanalysis products such as MERRA-2, JRA-5 and CFSR. ERA5 has finer resolution than its predecessor ERA-Interim [28]. Some studies documented the improved accuracy for various variables, areas and time scales [29] [30] [31]. ERA5 gridded and reanalysis dataset is employed to bias correct and downscale GCM data in the CRB. ERA5 is used for projecting temperature and precipitation in the CRB due to non-availability of the long-term time series observed data in the CRB. ERA5 data from twenty one grid points is extracted. The downscaled and bias-corrected data from the GFDL-ESM2M is interpolated to generate forty one regularly spaced grid points within the boundary of the CRB. In this study, the ERA-5 is used as observed data for downscaling and bias correction of GFDL-ESM2M climate model. GCM data is consisted of historical data (1950-2005 and future data (2006-2099) for RCP4.5 and RCP8.5 emission scenarios. The climatic variables such as maximum temperature (Tmax), minimum temperature (Tmin) and precipitation of GCM (i.e., GFDL-ESM2M) was bias corrected with ERA-5 data.

Global Climate Model

Global Climate Models (GCMs) are primary source of information for analyzing and assessing climate change and variability in future. GCMs are still unable to reproduce relevant climate processes accurately and precisely [31]. The temperature projections are more accurate and reliable from GCMs than precipitation projections [19]. A high degree of variations in outputs from GCMs lead to uncertain future predictions.

Many GCMs have been developed, with some reported to be more appropriate in certain geographic locations than others. For example, CMIP5 models performed better compared with the Providing Regional Climates for Impact Studies (PRECIS) for quantity and annual mean precipitation over the Indus River Basin [7] [32]. A large number of GCMs are available nowadays in the CMIP5 archive but identifying a set of representative climate models for a particular region is still a cumbersome task. The selection of climate models for climate change impact studies of a particular region is not a straightforward process [19]. In many studies, only a single GCM was used without a reasonable justification and often only based on the country of research. For example, the HADCM3 is commonly used by the UK, CGCM3.1 by Canadian researchers and CSIRO GCM in Australia [33].

This study is based on climate projections from GFDL-ESM2M out of several GCMs present in the CMIP5 repository due to its dominant ability to simulate climate over South Asia [34]. Many researchers used GFDL-ESM2M in previous studies due to its better performance to capture precipitation patterns over the Northern areas of Pakistan [35]. Moreover, the patterns of summer precipitation and westerlies are well presented by the GFDL-ESM2M over the South Asia [36]. GCMs can be employed to investigate climate change and variability in future over a particular region. The Intergovernmental Panel on Climate Change [9] advises that bias correction of GCMs is essential for long term reliability of observed data representing base climate data. In this study, Tmax, Tmin and precipitation was downscaled using observed data from 1990 to 2020.

The information of time series of precipitation, Tmin and Tmax from a specific location particularly at latitude and longitude from a global gridded dataset (ERA5) was extracted at grid points of GFDL-ESM2M which fall within the boundary of CRB (Figure 1). Furthermore, the extracted gridded data of ERA5 (observed data) employed to downscale and bias-correct GFDL-ESM2M model data in climate change toolkit (CCT). The downscaled and bias-corrected data of coarse spatial resolution (0.5 degree) was interpolated to generate grid points of finer spatial resolution (0.25 degree). The downscaled and bias-corrected data of historical period (1950-2005). The downscaled and bias-corrected data were used to generate future scenarios under RCP4.5 [scenario-1 (2020-2050), scenario-2 (2051-2080) scenario-3 (2081-2099)] and under RCP8.5 [scenario-4 (2007-2050), scenario-5 (2051-2080) and scenario-6 (2081-2099)] and historical period (2050-2006). The CRB averaged data was calculated using the inverse distance weighting approach [37] from interpolated grid points (i.e., 41 stations).

The climate change toolkit (CCT) to handle big data for climate change analysis at large scale and long time periods [38]. The CCT can be used for recognition of extreme events in historical data and projection into the future. CCT performs multiple tasks in one package such as to extract, downscale, bias correct and interpolate data from the GCM. The bias correction method is used to eliminate biases in the modeled simulated data. CCT provides the most common and simplest additive and multiplicative bias correction factor for bias correction to the temperature and precipitation variables respectively. This method was applied on twenty one meteorological stations to downscale GCM data using ERA5 as observed data. Furthermore, spatial interpolation is applied to climate data of 0.5˚grid point to obtain finer resolution (0.25˚grid point) in the CCT.

Result and discussion.

Future precipitation trends

The future predicted increase in precipitation in the CRB indicate no uniform trend for various time spans in coming days with respect to baseline period. Figure 2 shows the results of change in precipitation under emission and future scenarios. The predicted precipitation shows an increase in annual rainfall under RCP8.5 in near future (2020-2050) and mid- century (2051-2080) while decrease in annual rainfall towards the end of the century (2081-2099). However, the predicted annual precipitation under RCP4.5 shows opposite trends.

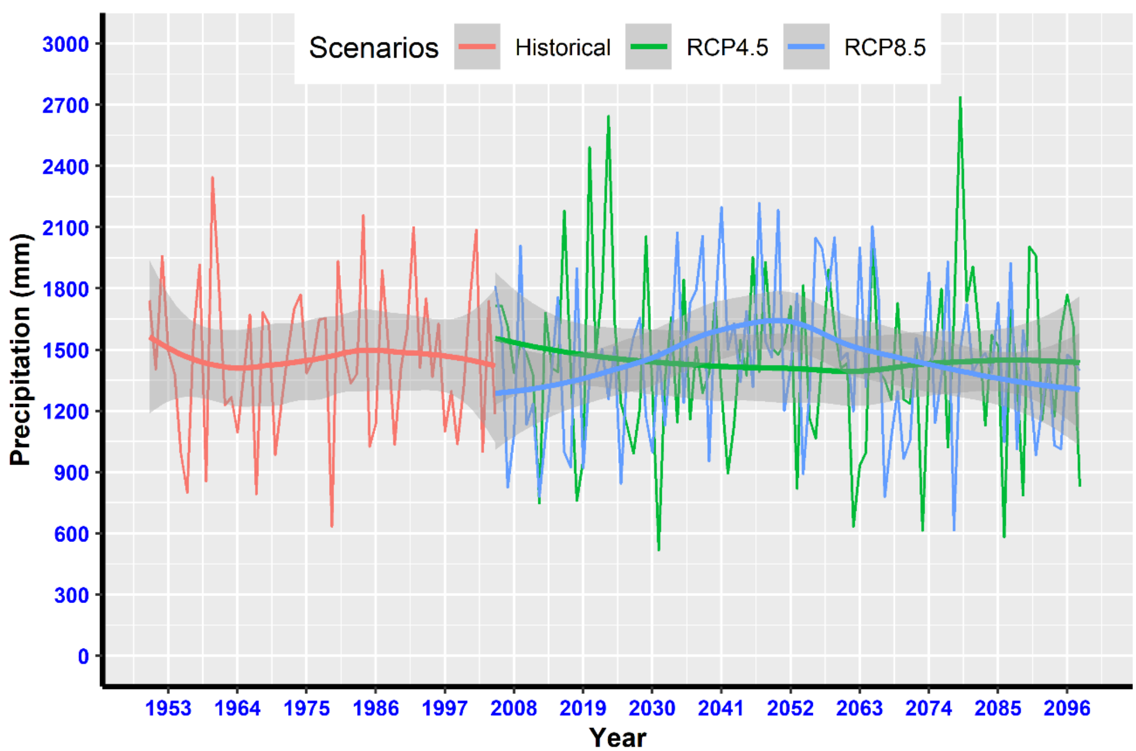

Figure 2 Average annual precipitation of historical (1950-2005) and future (2006-2100) scenarios which include the studied period in near future (2020-2050), mid-century (2051-2080) and end of century (2081-2100) under RCP4.5 and RCP8.5 from GFDL-ESM2 global climate model.

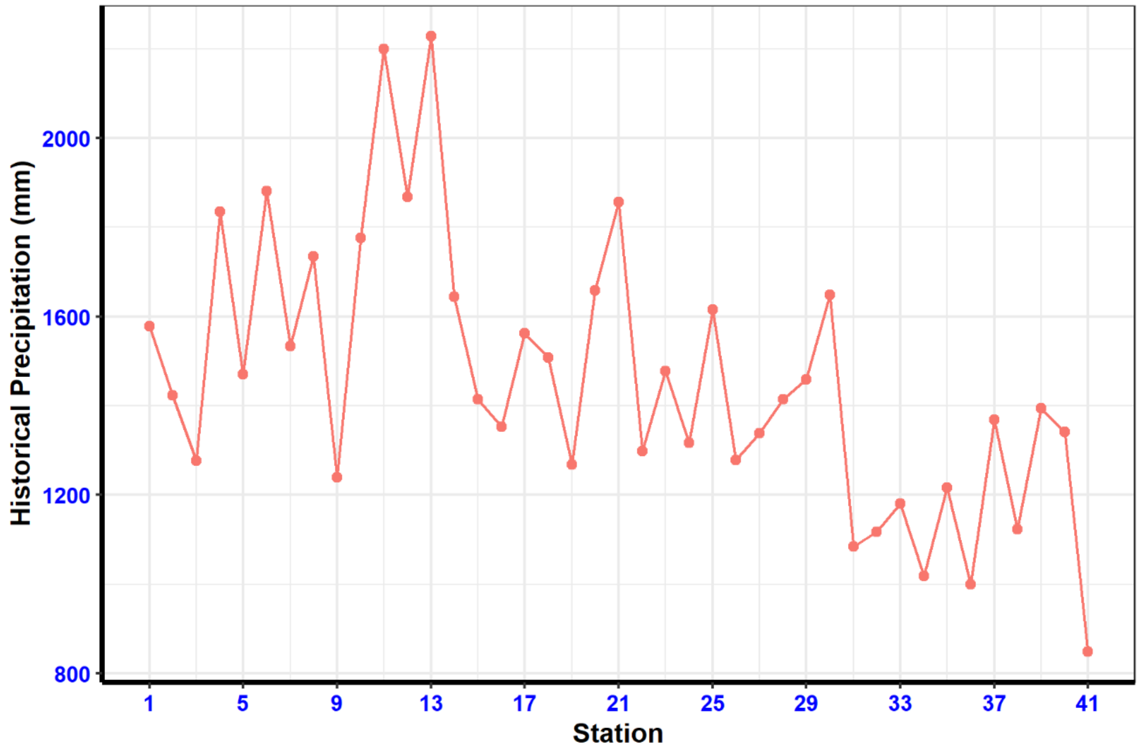

Figure 3 Average annual precipitation of historical period (1950-2005) from each climate station in the CRB.

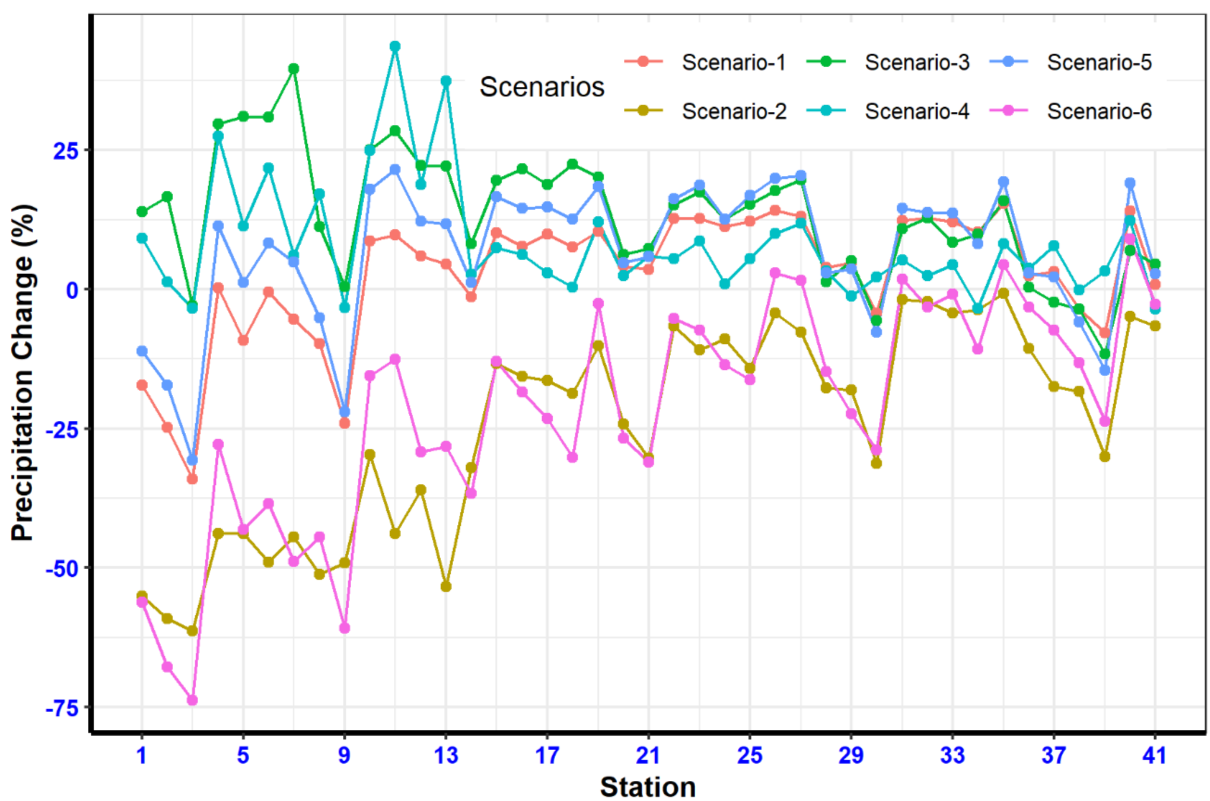

Figure 4 Percentage change in projected precipitation with respect to historical period (1950-2006) at each climate station in the CRB under studied scenarios such as scenario-1 (2020-

2050rcp4.5), scenario-2 (2050-2080rcp4.5), scenario-3 (2081-2099rcp4.5), scenario-4 (2020-2050rcp8.5), scenario-5 (2050-2080rcp8.5), scenario-6 (2081-2099rcp4.5).

Figure 3 shows the average precipitation in the CRB at each climate station for historical period (1950-2006) and Figure 4 shows an annual change in annual precipitation with respect to baseline period at each climatic station in the CRB for the projected scenarios. The climatic stations from 1 to 15, 16 to 30 and 31 to 41 are mostly located in the western, central and eastern part of the CRB respectively. The highest decrease in precipitation was projected by scenario-2 and scenario-6 in climatic stations mostly located in the western part of the CRB. The percentage change in future precipitation under scenario-2 and scenario-6 with respect to baseline period decreases on climatic stations from west to east of the CRB. Overall, the smallest percentage change with respect to baseline period in annual precipitation occurs on climatic stations located in central and eastern part of the CRB.

Future temperature trends

Figures 5 and 6 show the historical and projected Tmax and Tmin under RCP4.5 and RCP8.5 respectively. Both historical Tmin and Tmax show a decreasing trend in the first two decades (1950 to 1970) while increasing trends afterwards (1970-2006). Both Tmax and Tmin indicate rapid increase in near future (2020-2050) while slows down towards the mid-century and end of the century under RCP4.5. Steep trends in projected Tmin compared to Tmax were depicted under RCP8.5 in mid-century and end of the century.

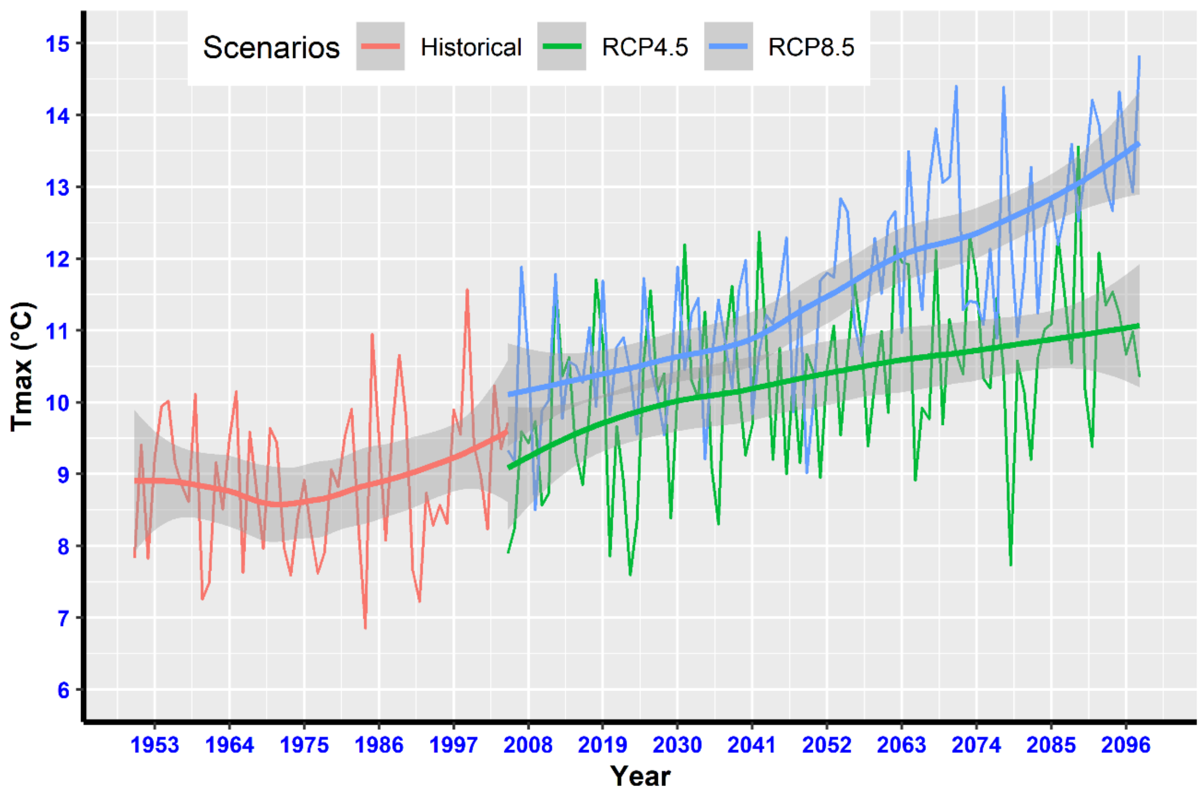

Figure 5 Average annual temperature maximum (Tmax) of historical (1950-2005) and future (2006-2100) scenarios which include the studied period in near future (2020-2050), mid-century (2051-2080) and end of century (2081-2100) under RCP4.5 and RCP8.5 from GFDL-ESM2 global climate model.

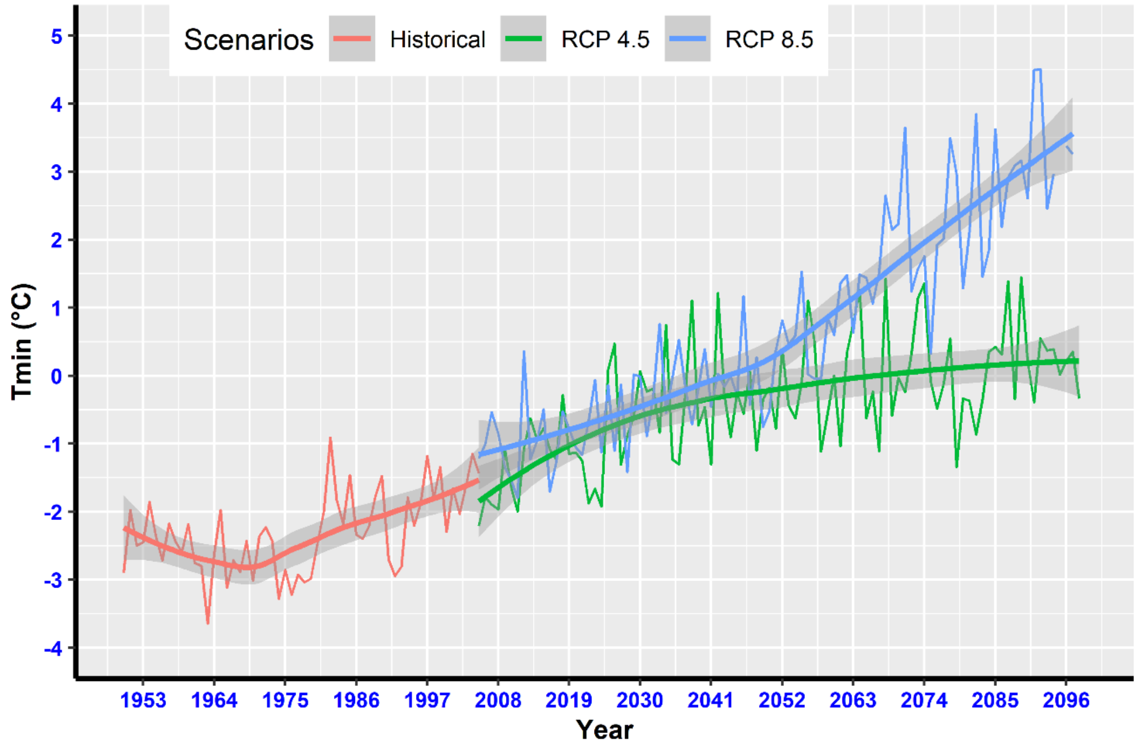

Figure 6 Average annual precipitation of historical (1950-2005) and future (2006-2100) scenarios which include the studied period in near future (2020-2050), mid-century (2051-2080) and end of century (2081-2100) under RCP4.5 and RCP8.5 from GFDL-ESM2 global climate model.

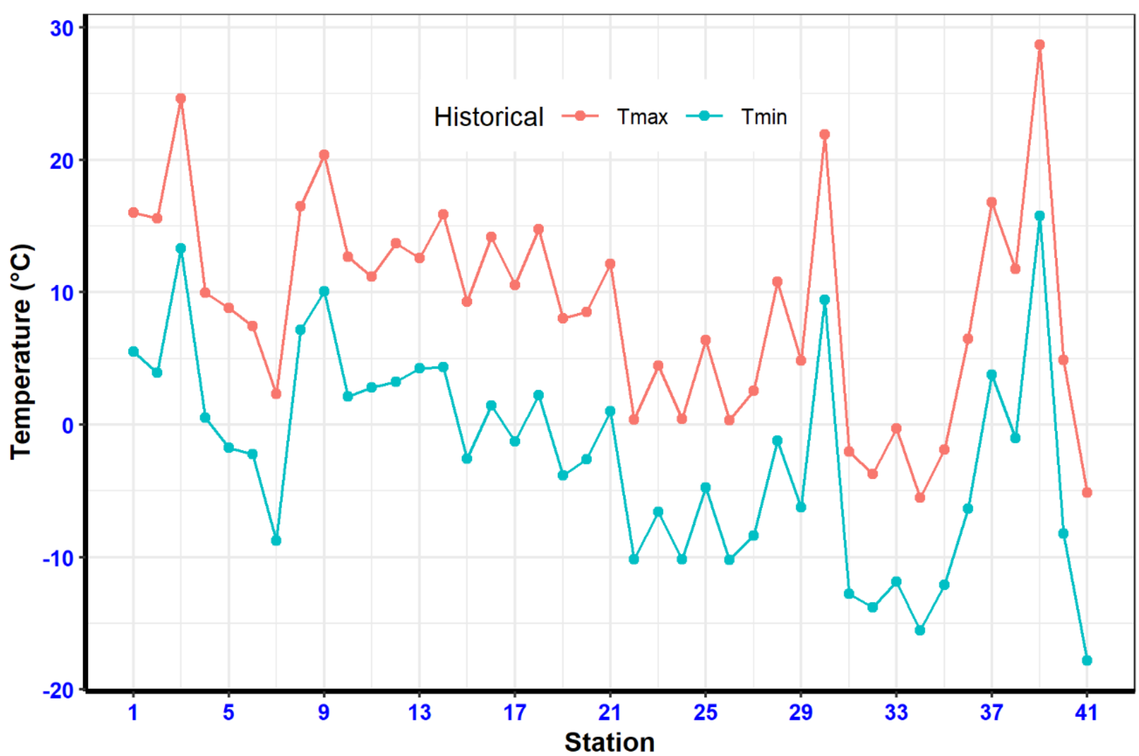

Figure 7 Average annual temperature maximum (Tmax) and temperature minimum (Tmin) of historical period (1950-2005) from each climate station in the CRB.

Figure 6 shows the spatial distribution of historical maximum temperature (Tmax) and minimum temperature (Tmin) at forty one climate stations in the CRB. Average annual Tmax was recorded above zero Celsius while Tmin was recorded below zero Celsius at most of the climate stations in the CRB. Comparatively higher temperatures were recorded in the western part while lower temperature was observed in the central part. Only some stations showed Tmax around or below zero Celsius located in the central and eastern part of the CRB. However, Tmin was recorded below zero Celsius at majority of stations in the central and eastern part of the CRB.

The predicted Tmax and Tmin indicate increase in temperature in coming years (Figure 8 and 9). Tmax and Tmin was projected to increase under all scenarios including the highest increase in scenario-6 and the lowest increase in scenario-1. The projected increase in Tmax was the highest in the western part while decreases towards the cenral part under scenario-6 in the CRB. All remaining scenarios (from scenario-1 to scenario-5) showed a continuous decrease in Tmax towards the eastern part of the CRB. However, the highest increase in projected Tmin was recorded to decrease towards the eastern part of the CRB. Tmin indicate a significant rise with respect to historical period under RCP8.5 for mid-century (above 3 °C) and end of the century (above 5 °C).

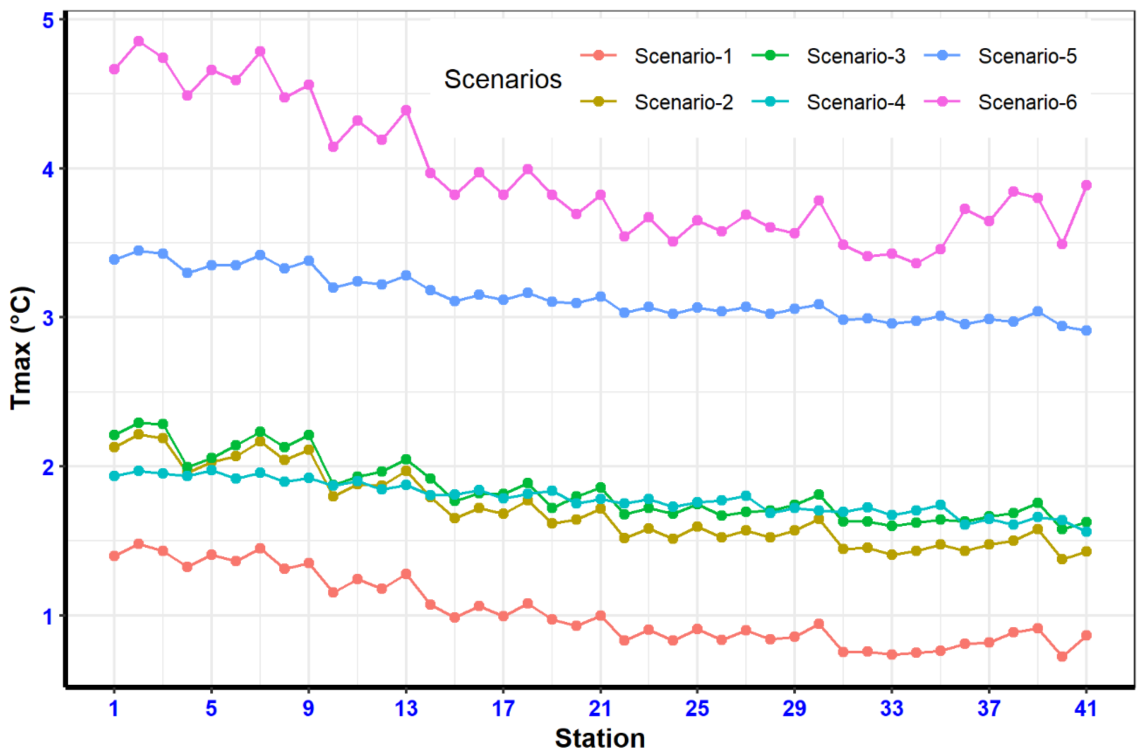

Figure 8 Temperature maximum (Tmax) projected with respect to historical period (1950-2006) at each climate station in the CRB under studied scenarios such as scenario-1 (2020-2050rcp4.5), scenario-2 (2050-2080rcp4.5), scenario-3 (2081-2099rcp4.5), scenario-4 (2020-2050rcp8.5), scenario-5 (2050-2080rcp8.5), scenario-6 (2081-2099rcp4.5).

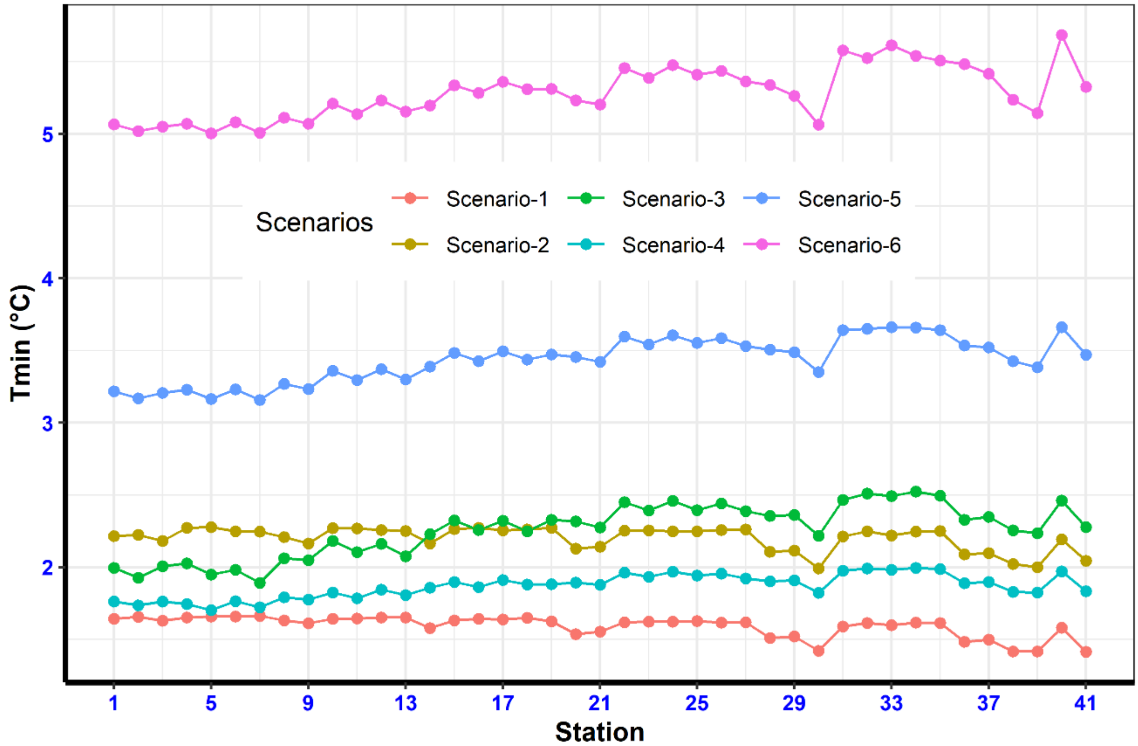

Figure 9 Temperature minimum (Tmin) projected with respect to historical period (1950-2006) at each climate station in the CRB under studied scenarios such as scenario-1 (2020-2050rcp4.5), scenario-2 (2050-2080rcp4.5), scenario-3 (2081-2099rcp4.5), scenario-4 (2020-2050rcp8.5), scenario-5 (2050-2080rcp8.5), scenario-6 (2081-2099rcp4.5).

Discussion

In the CRB, precipitation projections show various trends of increase and decrease while overall no specific trends were found in the future projected precipitation under studied scenarios. Rajbhandari et al. [32] found non-uniform trends in overall projected precipitation in the western Himalaya. However, Lutz et al. [19] projected a marginal increase in precipitation over the Upper Indus Basin (UIB). A study on Jhelum basin which is adjacent to the CRB reported a decrease in precipitation under RCP4.5 while slight increase under RCP8.5 [45]. In another study over the Himalaya Karakoram Hindukush (HKH) region, projected precipitation from eight GCMs is expected to decline [46]. The future projections of precipitation in the sub-basins of the UIB show wide variations [31] [19] [39]. Similarly, results of projected precipitation trends are not uniform in the CRB. Palazzi et al., (2015) projected large variations in precipitation projections and trends from 32 CMIP5 GCMs in the Himalaya region. The climate and topography of the Himalaya and its sub-basins such as CRB is very complex which could be one of the major factors in large variations in results in precipitation projections. The projected change in precipitation with respect to baseline ranges from 75 % decrease to 35 % increase at various stations in the CRB. However, the range of annual precipitation varies greatly (800 to 220 mm) in the CRB which could be another major factor to higher variations in the projected precipitation in the CRB.

In the UIB, the rate of increase in temperature is projected to be higher than global average warming [32] [47]. Similarly, the increase in temperature projected in the CRB is higher than other parts of the world. The projected increase in Tmin is much higher than Tmax in the CRB. For instance, the increase in Tmax in the CRB ranges from 2.29 to 4.85 °C while the increase in Tmin ranges from 2.52 to 5.68 °C under RCP4.5 and RCP8.5 respectively by the end of the century. The average annual increase in global average temperature was 1.8 to

4.4 °C under the RCP4.5 and RCP8.5 by the end of the century [23]. This increase in temperature may lead to decrease in snow accumulation during winter in the CRB. The seasonal flow during spring which is dependent on the snowmelt may be severely affected by rising temperature in the CRB.

The results of projected temperature and precipitation in the CRB indicate a massive rise in future temperature while no specific increase in precipitation. This will raise the concerns about water availability in the CRB. A higher increase in temperature will lead to increasing evaporative losses. It will be a serious threat to future water supply from this sub-basin to agriculture and industrial sectors. The major crops of this region are irrigated by water from the CRB. The demand for domestic and agriculture water will increase in coming years in this region which could be a potential area of research especially to study its impact on agriculture.

Conclusion.

This study evaluates the future projected temperature and precipitation in the CRB for future scenarios [near future (2020-2050), mid-century (2051-2080) and end of the century (2081-2100)] under RCP4.5 and RCP8.5. The temperature and precipitation data of GFDL-ESM2M was downscaled and bias-corrected using gridded and reanalysis data (ERA5). In the data scarce CRB, ERA5 employed for the assessment of long-term time series of climatic variables. The results revealed a significant increase in Tmin and Tmax while varying degree of variations in precipitation. A significant increase in precipitation was recorded in near future while decreasing trend in precipitation in the mid-century and end of century under RCP8.5. The increase in Tmin and Tmax is consistent throughout 21st century under both emission scenarios. The highest increase in temperature was observed under RCP8.5 towards the end of century. Tmin shows a rapid increase in near future while its increasing tendency slows down towards the end of century under RCP4.5. However, the increase in Tmin was much higher than increase in Tmax in the CRB. Both Tmin and Tmax shows a steep upward trend towards the end of century under RCP8.5.

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