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ANALYSIS OF FUTURE CLIMATE SCENARIOS AND ITS IMPACTS ON WATER RESOURCES OVER THE MIGHTY MOUNTAIN RANGES (HIMALAYA, KARAKORAM AND HINDUKUSH) OF GILGIT-BALTISTAN, PAKISTAN

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Abstract
Gilgit-Baltistan (GB) is a meeting point of three mighty mountain ranges, the Himalayas, the Karakoram and the Hindu Kush. As this region feeds the Indus River and fulfills the water requirements of Pakistan, so, there is a dire need to foresee the future climate changes in this region. The aim of this study is to project the temperature and precipitation changes over the HKH region according to two sets of Representative Concentration Pathways (RCPs 4.5 and 8.5). Both RCPs (4.5 & 8.5) projected an increase in average monthly, seasonal as well as annual temperature for both the near future and midcentury periods with a rate of 0.2°C and 0.6°C per decade simultaneously. For RCP 4.5 an increasing precipitation of 0.54 mm per year and for RCP 8.5 a decreasing precipitation of -0.70 mm per year was projected for the 21st century. Both RCPs projected the highest change in winter temperature during the near and the midcentury period. Both RCPs show a slight seasonal shift in precipitation, however, more precipitation is projected for the season March to May (MAM) and less for the season September to November (SON). These changes ultimately affect the water flow in the mighty Indus River and its tributaries.

1. Introduction

For our world, climate change is not a new miracle, it has been changed since the beginning of this glob (Ahmed and Shaukat 2012). Over different time scales, climate of the globe varies due to natural causes, but these causes are not majorly accountable for significant changes in climate. Solar & volcanic events just produce a small fluctuation in the climatic pattern. Land, Ocean and Atmospheric interactions cause normal cyclic changes in the weather, therefore, the weather conditions all over the world. Other factors that attribute the climate pattern are the Earth's trajectory about the Sun and its changes every 1000,000 years (Imbrie and Imbrie 1980), the axis of rotation every 400,000 years (Bourlière 1982), and disparity in the spin on the axis changes after 260,000 years (Members 1976). Glaciers around the world are also expanding due to changes in orbit a million years later (Hays, Imbrie et al. 1976, Barron 1985, Rind and Peteet 1985). The movement of tectonic plates is also a factor which changes the geography of the earth (Eddy, Gilliland et al. 1982). The sudden shift in the Ocean current repeatedly released GHGs from ice in and above sea, which warm our planet (Bourlière 1982). The climate of the planet is also cool due to the sudden disruption in Oceans (Cook and Jacoby 1983). Other factors identified are southern oscillations, El Nino southern oscillations (ENSO) effects, El Nino (hot water) and La Nina (cold water) (Cook and Jacoby 1983, Rasul 2012).

Humanitarian accomplishments are the main cause of global warming and climate change.

Anthropogenic causes are controllable but now they dominate natural activities. This has upset the atmospheric heat budget balance, and has trapped more amounts of heat in the biosphere than the normal need for discipline in the process of life (Khan 2017).

Compare with other regions of Pakistan, limited studies are available dealing with climate change in Gilgit-Baltistan (GB). Poor accessibility and low populations are the reasons for less meteorological stations in the region, so data records are few. However, on small-scale some researchers tried to apprehend the spatial & temporal variations in temperature and precipitation. Rasul et al. (2011) investigated that in the northern mountainous region of Pakistan, the temperature rose twice as high as in the lowlands. Their results also indicated that the climate of northern mountains remained warm at 1.3ºC during 2001 - 2010, which hosts glaciers in the HKH mountain range. Khan et al. (2015) identified a warming trend in UIB for the period 1961 to 2011. Between 1961 and 2010, with increased elevation at higher mountain catchments, maximum temperature and mean temperature have increased while precipitation and minimum temperature have decreased. Qamar (2017) identified that in the previous century the mountain regions of Pakistan faced a rise of 0.6ºC to 1.0ºC in average temperature. And, the northern part, which is outside of the monsoon region, suffered from aridity. The minimum temperature in summer over the extreme northern part of Pakistan shown a slight cooling trend. Rainfall in the Upper Indus Basin is projected to increase, and a decreasing trend is projected for the lower basin. As GB is the host of Asian Water Towers, there is a dire need to investigate the climatic condition of this region and also give some future projections with fine resolution. Although, it is very difficult to predict climatic conditions for up to a year or more with sufficient accuracy, planners and policymakers need to know the future picture of climate for adaptation measures. Scientists from different disciplines have struggled to develop climate models for projection of future climate based upon emissions, economic, population growth, and technological trends. Based upon these data sets, different scenarios emerged, and Global Climate Models (GCMs) were developed, incorporating Physio-Mathematical concepts of internal atmospheric dynamics and external forcing. Downscaling of the GCM's output with the help of the Regional Climate Models (RCMs), provide the finer resolution climate change scenarios. Generally, the temperature and precipitation scenarios are required by almost all the members of the user community who provide the by-products further(Zain 2010).

Statistical and dynamical downscaling is normally used in climate research. Statistical downscaling is based on the statistical relationships between global-scale features from GCMs and the fine local scale climate of a particular location which requires fewer computing resources. While dynamical downscaling involves nesting a regional Climate Model (RCM) into a GCM, it simulates local feedback features which may not be captured by statistical methods and require strong computing resources. This study employed Linear Interpolation and Bias Correction (LIBC) to examine the future scenarios over Gilgit-Baltistan which is composed of three mighty mountain ranges HKH in near (2021-2050) and mid-century (2051-2080). This research guided two questions (i) What are the projected temperature and precipitation for Gilgit-Baltistan, under two representative concentration pathways RCP 4.5 and RCP 8.5 for the 21st century? (ii) How do these projections change annual, seasonal, and decadal scale in the same area for the same period?

2. Materials and Methods

2.1. Study area

The meeting place of three mighty mountain ranges of the world (the Karakoram, the Himalaya and the Hindukush) is Gilgit-Baltistan (GB). It has a unique geographical composition on the globe. It covers an area of 72971 km^2, located in the north of Pakistan (75º 08′ 48.12″ E & 37º 00′ 47.33″ N to 77º 41′ 11.82″ E & 35º 27′ 26.06″ N). It is bordered by

China to the east, Khyber Pakhtunkhwa (KPK) to the west, Wakhan Corridor of Afghanistan to the north, and India to the south-east. Administratively, the region is divided into ten districts (Astor, Diamer, Gilgit, Ghanche, Ghezer, Hunza, Kharamang, Nagar, Shigar and Skardu). GB has an estimated population of 1,441,523 and is headquartered in Gilgit (Perkin 2003, Raza, Hussain et al. 2016).

Gilgit-Baltistan is a major catchment of the River Indus, which is the lifeline of Pakistan's irrigation, agriculture and hydropower. It contains the world's second highest peak, K-2 or Chogori (8611m) (Immerzeel, Droogers et al. 2009), along with 101 peaks whose heights are more than 7,000m (Rajbhandari, Shrestha et al. 2015). The GB Digital Elevation Model (DEM) is shown in Figure 01.

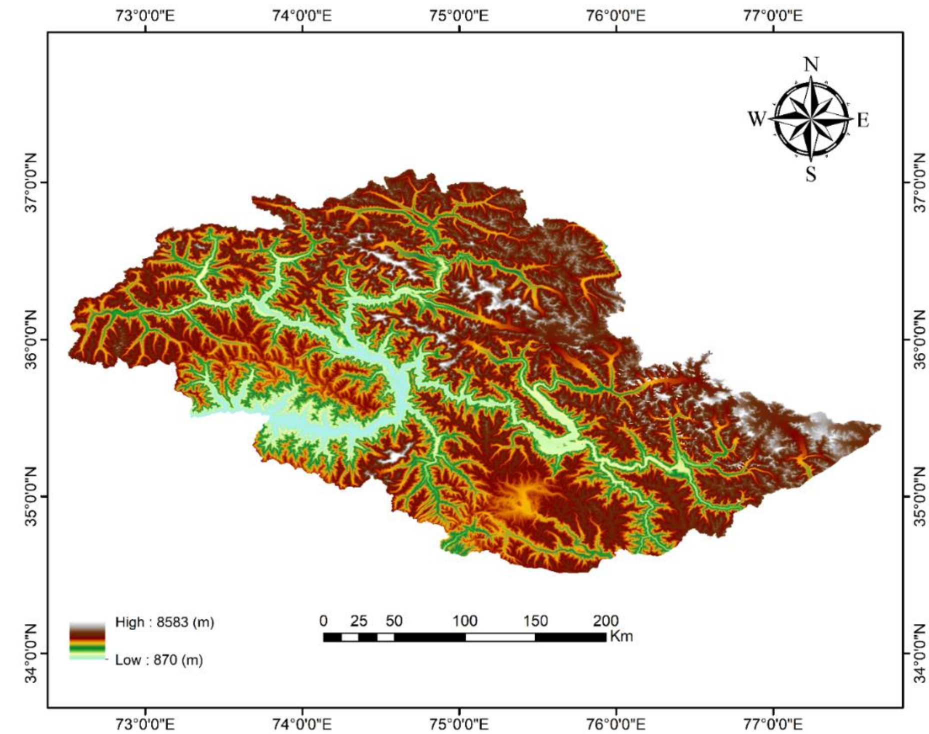


Figure 1. Study area map of Gilgit-Baltistan (GB).

2.2. Data

The Asian Precipitation Highly Resolved Observational Data Integration toward Evaluation of Water Resources (APHRODITE) has long-term daily gridded precipitation and temperature datasets for Asia including the study area i.e. GB. APHRODITE has been chosen for this purpose based upon its fine spatial and temporal resolution i.e. 0.25° and daily, respectively. The gridded historical product based on APHRODITE data was linearly interpolated at 1 km. It was found in previous studies that runoff was higher than the observed precipitation even without accounting of losses due to evapotranspiration, sublimation and percolation to the groundwater (Tahir, Chevallier et al. 2011). That led to the conclusion that APHRODITE precipitation was underestimated at high altitudes, likely due to the valley-bottom location of precipitation observations and due to limitation of data availability (Immerzeel, Van Beek et al. 2012).

2.3 Methodology

Bias corrections for precipitation and temperature were applied to the APHRODITE data. Temperature lapse rates from Tahir et al., were incorporated to correct the APHRODITE temperature data for the historical period at 1 km horizontal resolution. Precipitation gradients for the GB were calculated by using a proxy method that uses glacier mass balance data (Tahir, Chevallier et al. 2011). The proxy method uses three estimates of precipitation gradient (here we used precipitation gradient = 0, 0.3, 0.6 [%/m]) to calculate the regional glacier mass balance (Kääb, Berthier et al. 2012). For every guess, a unique value of mass balance was obtained. These mass balances were then compared with the observed mass balances for each zone of the glaciers in the GB. The comparison of observed and model calculated mass balance was then used to forecast the optimum value of the precipitation gradient for each glacier. These values of the precipitation gradient give reliable values of the mass balance. Then the optimum precipitation gradient values were checked for the significance, leaving the 10th and 90th percentile values. These significant values were interpolated into the whole GB. This interpolated precipitation gradient is then incorporated into each and every map for the daily precipitation data of the APHRODITE. The gradients were applied using the model of Hewitt (Hewitt 2007), which says that the precipitation increases up to the altitude of 5500 m and decreases afterwards.

In this study, RCP 4.5 and RCP8.5, both medium and high-end scenarios are used to investigate the impact of subsequent radiative forcing on the climate of the region. RCP4.5 is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshooting the long run radiative forcing target level (Wood, Leung et al. 2004, Riahi, Grübler et al. 2007, Wise, Calvin et al. 2009). While on the high-end i.e., RCP 8.5, the 8.5 Wm-2 case, carbon dioxide levels rise above a massive 1,300 parts per million by the end of the century and are still rising fast (Fowler, Blenkinsop et al. 2007). The choice of two particular scenarios among a set of four RCPs has been made in a fashion to find the impacts on regional climate in both cases, i.e., extreme climate change scenario and relatively intermediate pathway. The scenarios have been made use to obtain future projections corrected under the methodology of Linear Interpolation and Bias Correction (LIBC). LIBC is a merger of two techniques, Spatial Linear Interpolation (SLI) in comparison with Bias Correction and Spatial Disaggregation technique (BCSD)) and correction factor technique to adjust the biases within the GCMs.

Four GCMs have been selected based on the criteria: (i) they have a good correlation (greater than or equal to 0.88) with baseline APHRODITE time-series, (ii) their normalized root mean square error is less than or equal to 0.15 and (iii) their normalized standard deviations lie within ±0.4 to that of normalized standard deviation of APHRODITE dataset. The selected GCMs along with their default spatial resolutions and standardized output statistics are mentioned in Table 1.

Temperature and precipitation monthly datasets for the GCM baseline period (1975 -2005) and future period (2010 – 2100) were downloaded through multiple Earth System Grid Federation (ESGF) gateways. For observations, APHRODITE's daily temperature and precipitation datasets were obtained through the latest V1204R1 and V1101R2 APHRODITE's databases respectively. Pertaining to the objective of this study, the final ensemble product of selected GCMs is made at a gridded horizontal resolution of 0.1 degree or roughly 10 km for the period 2010 - 2100.

Table 1. Selected model output statistics for GB, averages under RCP4.5 and RCP8.5. 'T' for Temperature, P' for precipitation.

Model	Center	Resolution	RMSE(T)	RMSE(P)	SD(T)	SD(P)	r(T)	r(P)
CCSM4	National Center for Atmospheric Research	1.25 x 0.94	0.05	0.15	0.31	0.28	0.89	0.99
CanESM2	Canadian Center for Climate Modelling and Analysis	2.81x 2.81	0.05	0.11	0.31	0.28	0.99	0.94
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory	2.5 x 2.01	0.05	0.15	0.31	0.25	0.99	0.86
HadGEM2-ES	Met Office Hadley Centre	1.87x1.25	0.04	0.11	0.30	0.24	0.99	0.92

3. Results

3.1. Projected Trends of annual Temperatures

Fig. 2 depicts the projected annual temperature on the basis of representative concentration pathways RCP 4.5 and RCP 8.5. Both pathways are given coherent changes in annual mean temperatures to 2050, after that, the projection of RCP8.5 showed a sharp increasing trend, while RCP 4.5 showed a comparatively smooth increasing trend. On the basis of RCP 4.5 the annual temperature of the 21st century over GB will change at the rate of 0. 2°C per decade, while RCP 8.5 given an increasing rate of 0.6°C per decade for the 21st century. The projected annual temperature simultaneously on the basis RCP 4.5 & RCP 8.5 declared that the last decade of this century will be the warmest decade on record.

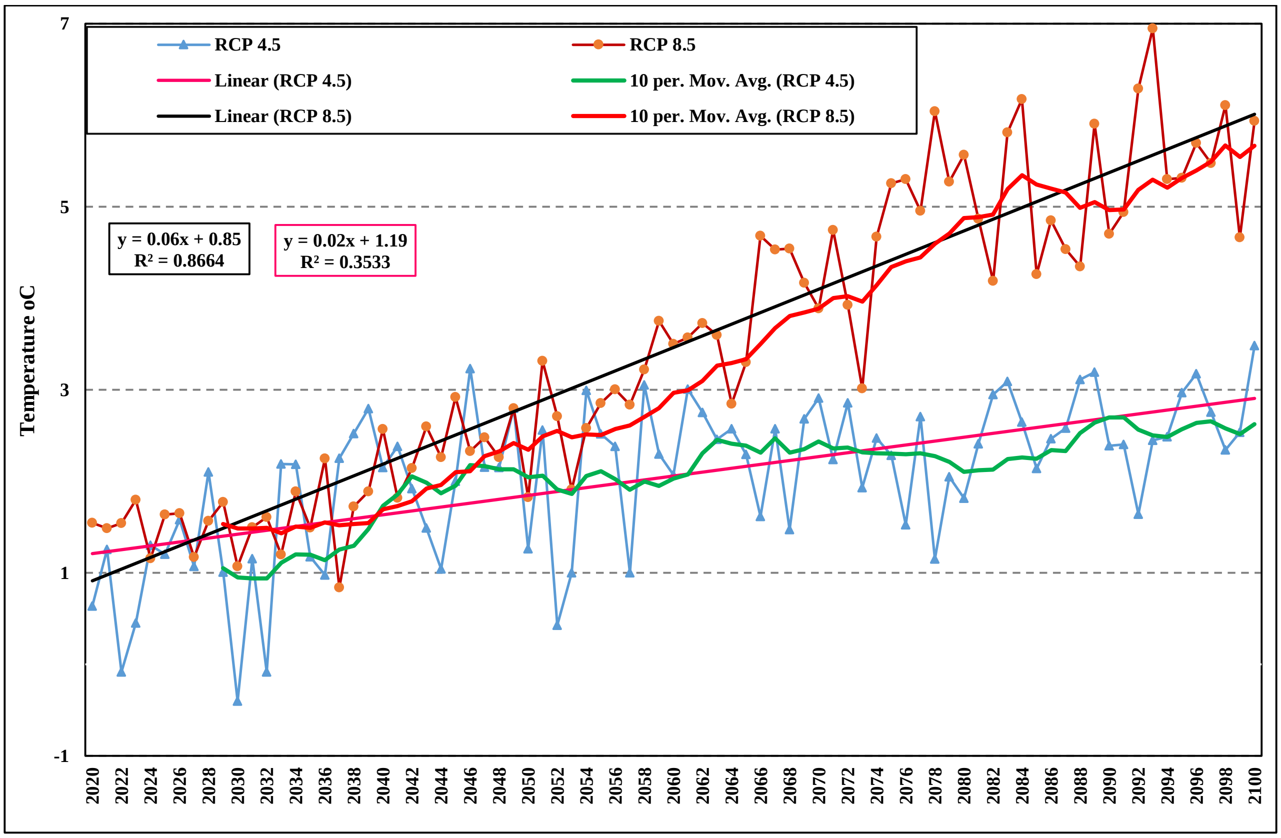


Figure 2. Projections of annual temperatures on the basis of RCP 4.5 and RCP 8.5.

3.2 Projected Trends of annual Precipitations

Figure 3 depicts the projected annual precipitation over GB for the 21st century. Together RCP 4.5 & RCP 8.5 projected somehow synchronize precipitation while the trend of precipitation projected for RCP 8.5 has decreasing trend. The highest annual precipitation projected under RCP 4.5 and RCP 8.5 were simultaneously for year 2078 and 2027. Ten years moving averages identified that the decadal average of RCP 8.5 will greater than that of RCP 4.5 up to 2072 after that the projected decadal average for RCP 4.5 is greater than that of RCP 8.5. Both RCPs project that the last decade of the 21st century will be the driest decade of the recent century.

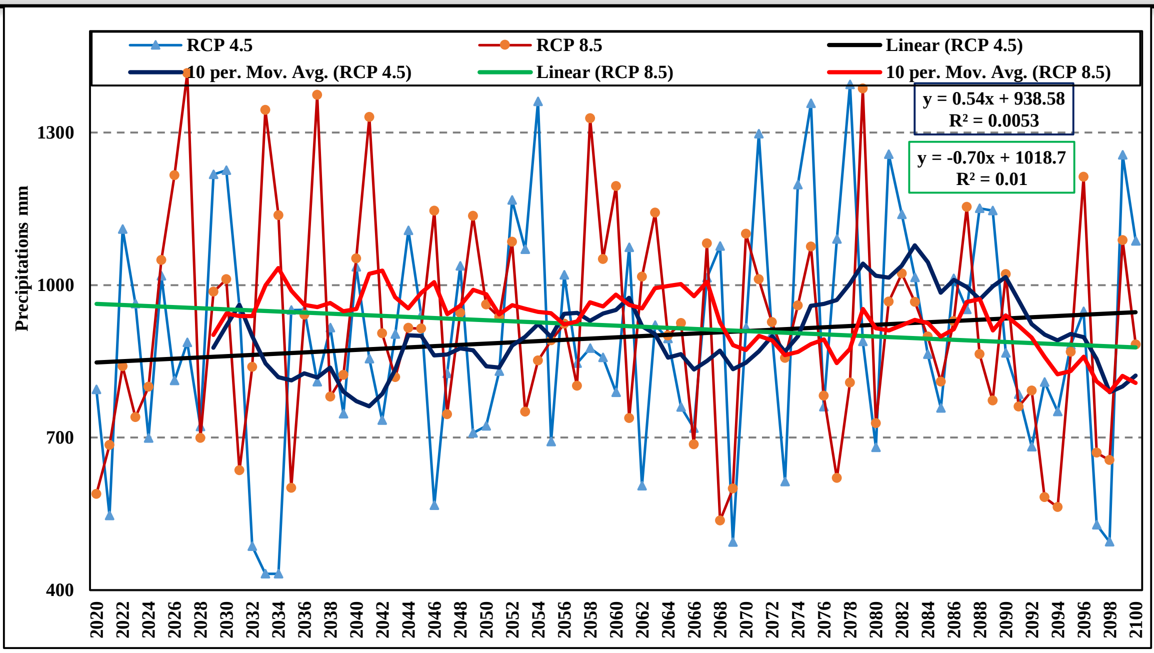
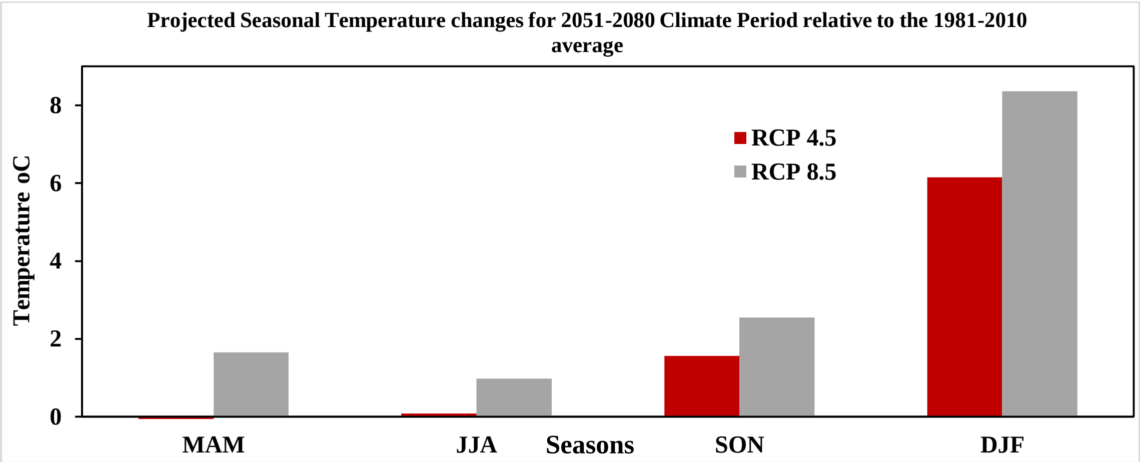


Figure 3. Projections of annual precipitations on the basis of RCP 4.5 and RCP 8.5.

3.3 Projected Changes in Seasonal Temperatures and Precipitations



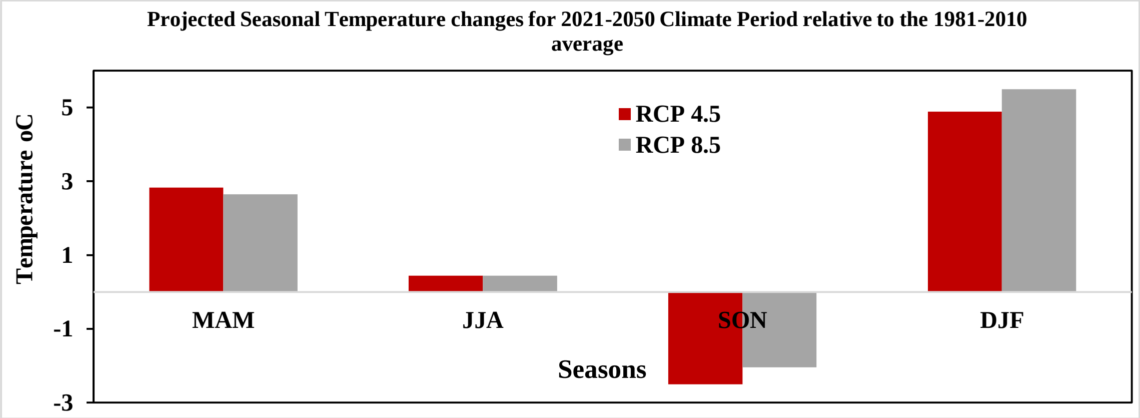
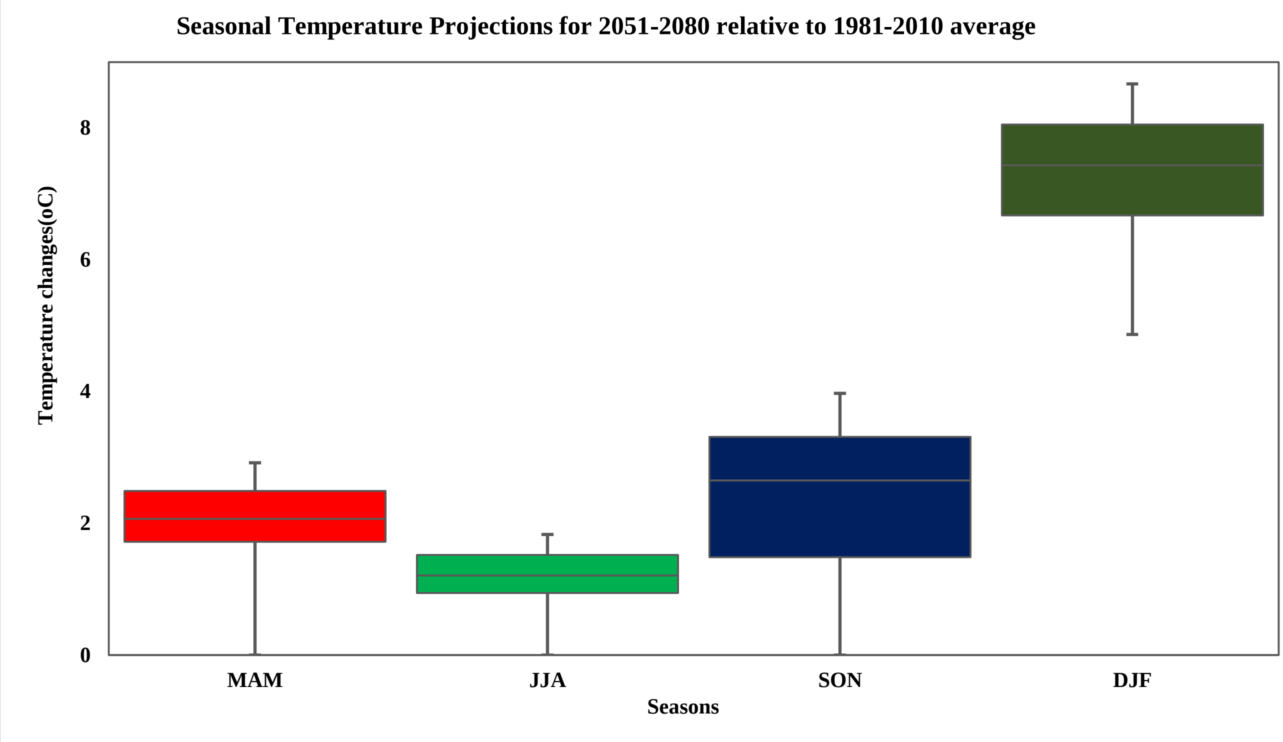


Figure 4. Comparative graphs for Seasonal temperature projections changes under RCP 4.5 and RCP 8.5 for the near future (Top) and midcentury (below) relative to the 1981-2010 climate period.

Figure 04 gives the relative changes of projected seasonal temperatures from 1981 - 2010 average, for the near and far future. For both periods, RCP 4.5 and RCP 8.5 projected the largest changes during DJF. For the near future, both RCPs projected a negative change in seasonal temperature for SON season. RCP 4.5 projected smallest changes in seasonal temperatures of MAM and JJA for the midcentury period. For both the near and far future, RCP 8.5 projected the smallest changes in seasonal temperature of 0.97°C and 0.45°C respectively during JJA. Except for MAM in near future RCP 8.5 projected larger changes in seasonal temperature for all seasons compared to RCP 4.5, for which RCP 4.5 projected larger change.

The box plot of projected seasonal temperature for the near and far future relative to 1981 - 2010 average is shown in Figure. 5. Which showed that the projected relative maximum and minimum temperatures simultaneously 4.4°C & 1°C with a mean value of 2.7°C for MAM in the near future, while that of 2.9°C and 0°C with a mean value of 2°C for MAM in the far future. The projected relative temperatures of maximum value 1.5°C and minimum value 0°C with a mean value 0.8°C were given for JJA in the near future, and that of values 1.9°C, 0°C and 1.2°C were simultaneously projected for the far future. For SON, the projected relative maximum, minimum and mean temperatures were given 4.6°C, 0°C and 1.8°C simultaneously in the near future, while in the far future these values were given 4°C, 0°C and 2°C respectively. Projected values of relative temperatures maximum, minimum and mean for DJF were 6.5°C, 3°C and 5.2°C in the near future and in the far future these values were given simultaneously 8.7°C, 4.9°C and 7.4°C.

The box plot of projected seasonal precipitations for the near and far future is shown in Fig. 6. Which showed that the projected maximum and minimum precipitation simultaneously 370mm & 170mm with a mean value of 290mm for MAM in the near future, while that of 410mm and 140mm with mean value of 325mm for MAM in the far future. The projected precipitation of a maximum value of 378mm and a minimum value of 135mm with a mean value of 236mm were given for JJA in the near future, and that of values 355mm, 110mm and 245mm were simultaneously projected for the far future. For SON, the projected maximum, minimum and mean precipitations were given178mm, 65mm and 110mm simultaneously in the near future while in the far future these values were given 185mm, 85mm and 150mm respectively. Projected values of precipitations (maximum, minimum and mean) for DJF were 290mm, 130mm and 235mm in the near future and in the far future these values were given simultaneously 315mm, 110mm and 200mm.



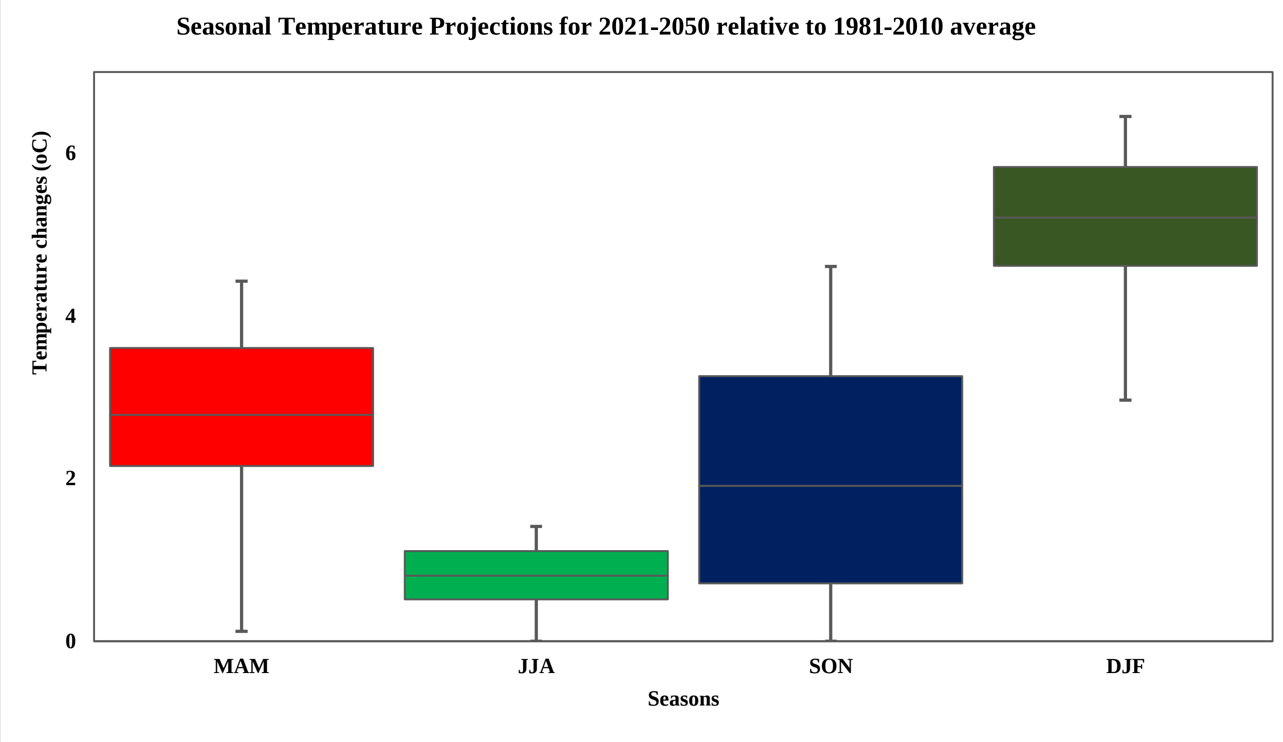
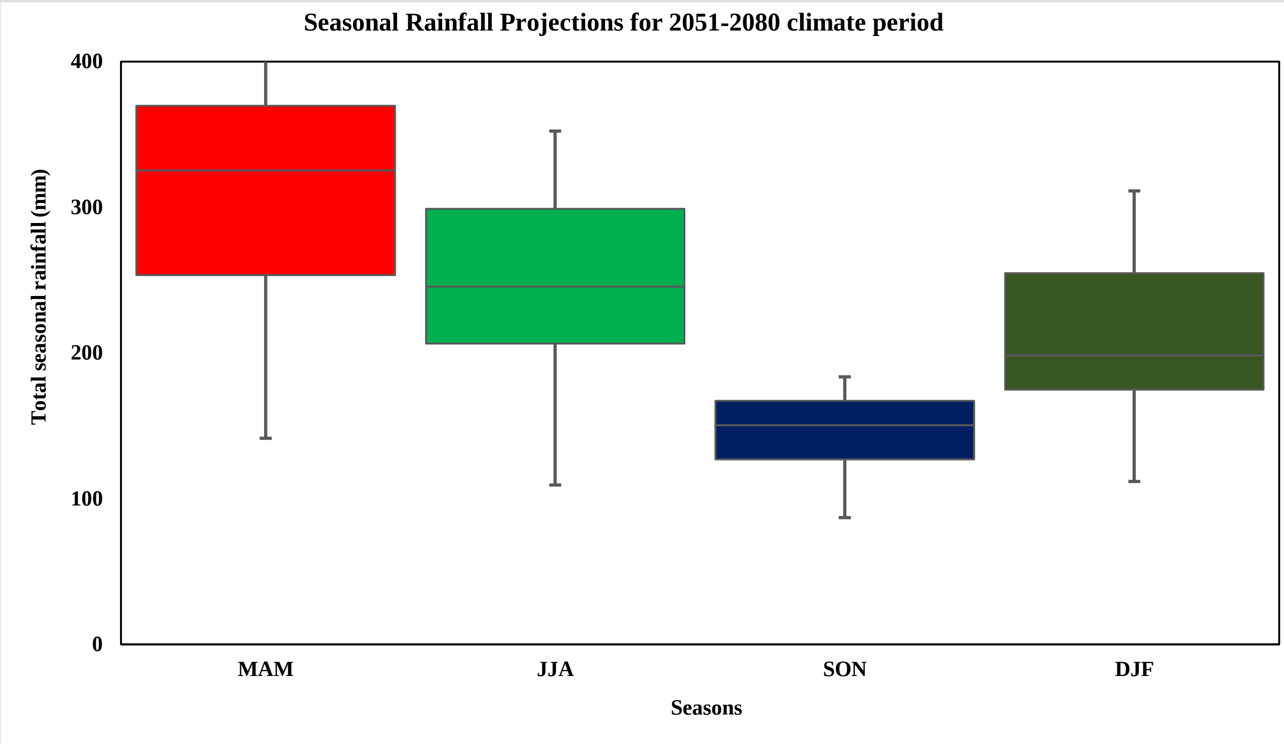


Figure 5. Mean seasonal temperature projections change for both RCPs in the near future (top) and midcentury (bottom).



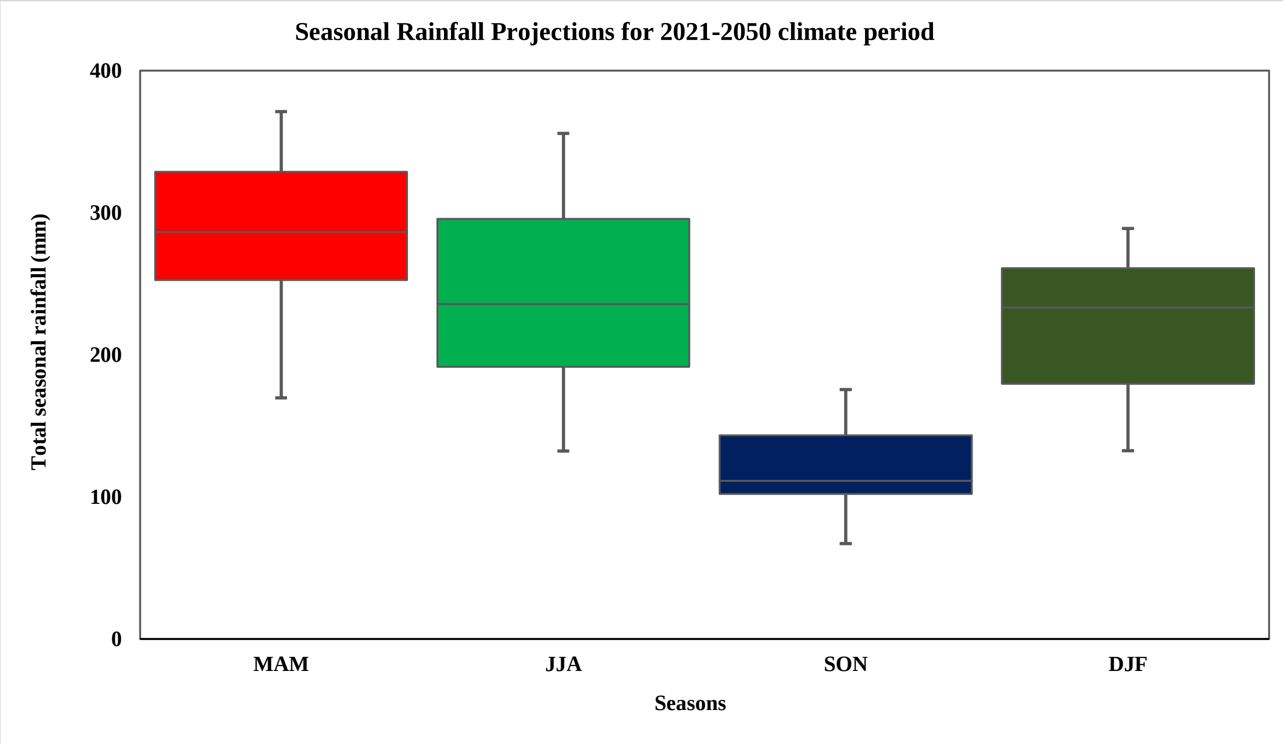


Figure 6. Projected seasonal precipitation for both RCPs in the near future (top) and midcentury (bottom).

4. Discussion

Studies are not available related to future climate change in HKH region of Pakistan. Though a small number of studies somehow reported its past and future trends along with the rest parts of Pakistan. Our study projected an increase of average monthly, seasonal, annual as well as decadal temperatures for both the near future and midcentury periods for RCPs 4.5 and RCP 8.5. RCPs projected changes in summer, and winter mean temperatures are simultaneously 1.9°C and 7.4°C for midcentury relative to the 1981-2010 average. Both RCPs projected the largest change in winter temperatures in the region. The results are somehow consistent with other studies in the region such as Munir et al. (Salathé Jr. 2005), reported the average annual, summer and winter temperature for the northern part of Pakistan would increase 4.67°C, 4.56°C and 4.72°C simultaneously by the year 2080, for A2 scenario base on the ensembles of 13 GCMs. Qamar et al. (Chaudhary, Mahmood et al. 2009), also projected a change in average annual temperature at the rate of 0.76°C per decade to the year 2050. This temperature increase projected that, the study area is likely to increase water stress, shrinking of the HKH glaciers and hence change the pattern of water availability for agricultural purposes in the Indus River (Salathé Jr. 2005).

The projected precipitation for RCP 8.5 shows a slight decrease in midcentury compared to the near future, while RCP 4.5 shows a slightly increasing trend in the midcentury compared to the near future. RCP 8.5 rainfall projection is slightly more than that of RCP 4.5 projection for the near future, but it is slightly less for the midcentury climate period. On average, total annual rainfall in the study area is expected to remain the same, and variation in seasonal rainfall is expected in the current climate period. Both RCPs (4.5 & 8.5) projected more rainfall for the main season, March to May (MAM) as compared to all other seasons during the near future and midcentury climate periods. These results are coherent to the results of Munir et al. (2011), who also reported an increase in average summer rainfall and that of a decrease in winter precipitation for the Northern part of Pakistan in 2080, however, in general, they reported no significant increase in annual precipitation for the Northern part of Pakistan tile the end of recent century(Sheikh, Iqbal et al. 2011).

5. Conclusion

On the basis of RCP 4.5 the annual temperature of 21st century over the whole GB will change at the rate of 0.2°C per decade, while that of RCP 8.5 is given an increasing rate of 0.6°C per decade. For the near future, RCP 4.5 & RCP 8.5 project the monthly mean minimum temperature for January (-8.2°C & -7.1°C) and that of maximum average monthly temperature for June and July (10.9°C & 11°C). For the far future, both scenarios project the minimum monthly average temperature for January (- 6°C & -3.5°C) and that of the maximum average monthly temperature for August (11.4°C & 12.5°C). Both scenarios projected a significant and maximum variation in precipitation over the northern part of GB. The rate of change of annual total precipitation for the 21st century on the basis of RCP 4.5 and RCP 8.5 are simultaneously 0.54 mm / year and -70 mm / year. The box plot of projected seasonal temperature for the near and the far future relative to the 1981-2010 average is shown in Fig. 07. Which showed that the projected relative maximum and minimum temperatures simultaneously 4.4°C & 1°C with a mean value of 2.7°C for MAM in the near future, while that of 2.9°C and 0°C with a mean value of 2°C for MAM in far future.

There is a dire need to assess the impact of climate change in the HKH region of Pakistan. And there is also a prime need to develop an integrated adaptation strategy to cope with adverse effects and to reap the positive impact of climate change. For mitigating the negative impacts, for example, glacier lac outburst, landslides etc., early warning systems need to be developed to closely monitor and take some remedial measures. Efficient water management systems also needed to be introduced, to limit the adverse effect of climate change on agricultural land and forested areas of the region.

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