Projection of climate change scenarios in the Kabul River Basin, Afghanistan

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This study was conducted to examine the changes in future temperature and precipitation of the Kabul River Basin in Afghanistan by using the outputs of three general circulation models (GCMs) under two representative concentration pathway (RCP 4.5 and RCP 8.5) scenarios. Future climate data for temperature and precipitation obtained from climate models were bias corrected using the delta change approach. Maximum and minimum temperatures and precipitation were projected for three future periods: 2020s, 2050s and 2080s against the baseline period of 1961–1980. The mean annual temperature in the basin is projected to increase by 1.8°C, 3.5°C and 4.8°C by the 2020s, 2050s and 2080s respectively. The mean annual precipitation is projected to increase whereas monthly precipitation is expected to increase and decrease according to the months for the whole river basin, under both scenarios, by 2100.

Keywords: Climate change, Kabul River Basin, RCPs, temperature, precipitation.

AN increase in CO_2 as a result of industrialization and urbanization along with population growth has caused global warming. As a result, increased temperatures and changing rainfall intensity have been reported. Basins dominated by glaciers and snow are highly vulnerable to climate change as alterations in temperature and precipitation inevitably affect the hydrology cycle, snowmelt and water resources[1,2].

Global surface temperature has increased by 0.74°C in the last century with the warming trend accelerating in the last 50 years[3]. There was a rise in temperature of 0.39°C in central Asia from 1979 to 2011 but with significant local heterogeneity[4,5]. According to Cruz *et al.*[6], global temperature increased by about 1–2°C in the last century. This has caused rapid melting of glaciers and snow, resulting in more frequent floods. Changes in temperature and precipitation in the future may affect public health as well as irrigation, industry, ecosystems and public water demand[7]. The increase in temperature may cause decreasing snowpacks in mountainous areas, increasing the potential for evapotranspiration. Besides, if the climate gets warmer and drier, the sensitivity of the hydrological cycle will increase[8]. Due to these changes, the stream flow will be severely affected, especially in arid and semi-arid regions, where there are significant fresh water sources of snow and ice.

As a consequence of climate change, water management has become a serious issue and has been identified as a global societal challenge. Several studies related to climate change forecasting have been conducted on a global scale with reference to the General Circulation Models (GCMs). However, considerable uncertainties are involved in impact analysis[9]. Climate prediction is highly uncertain since the system is very sensitive to changing green house gas (GHG) concentrations and difficult to quantify[10]. Uncertainties are introduced while defining GHG emission scenarios for GCMs and their development. The structural uncertainty within these models causes them to project different climates under various GHG emissions[11]. The uncertainty introduced by GCMs and emission scenarios can be addressed by using statistical methods to establish an empirical relationship among GCM outputs, climate variables and local climate[12,13]. Another way of reducing uncertainty is to use multiple GCMs. The ensemble projections of climate change aim to address uncertainty in the impact analysis[9] using various methods, of which arithmetic ensemble is one.

Since 1960, the mean annual temperature in Afghanistan has increased by 0.6°C at an average rate of around 0.13°C per decade[14], whereas changes in the precipitation regime vary more between regions. The mean annual rainfall of Afghanistan decreased slightly at an average of 2% per decade since 1960. Additionally, in Afghanistan, drought during the period 1993–2003 is considered to provide major physical evidence of climate change[15]. Floods are also specific complex and risky phenomena, occurring several times in different provinces of Afghanistan. Wi *et al.*[16] studied climate change and its implications on stream flow in the Kabul River Basin, Afghanistan, for the future period of the 2050s under RCP 4.5 and 8.5 using GCMs. According to his results, the mean annual temperature at this basin will increase by 2.2°C and 2.8°C under RCP 4.5 and RCP 8.5 respectively, whereas the precipitation does not show a clear trend.

There are five river basins in Afghanistan and the Kabul River Basin (hereafter KRB) was selected for this study. The water resource of KRB is divided between Afghanistan and Pakistan[17]. This is the most important and populated river basin in Afghanistan and the population has increased at a rate of approximately 4% per year from 2002 to 2007 (ref. 18). Moreover, the high rate of population growth in this basin is expected to continue. Based on the projections of the United Nations, the population of KRB will more than double and reach nine million by 2057. So far no studies have been conducted to predict the future climate of KRB using RCP scenarios. Therefore, the main objective of this study is to estimate the changes in future precipitation and temperature and to

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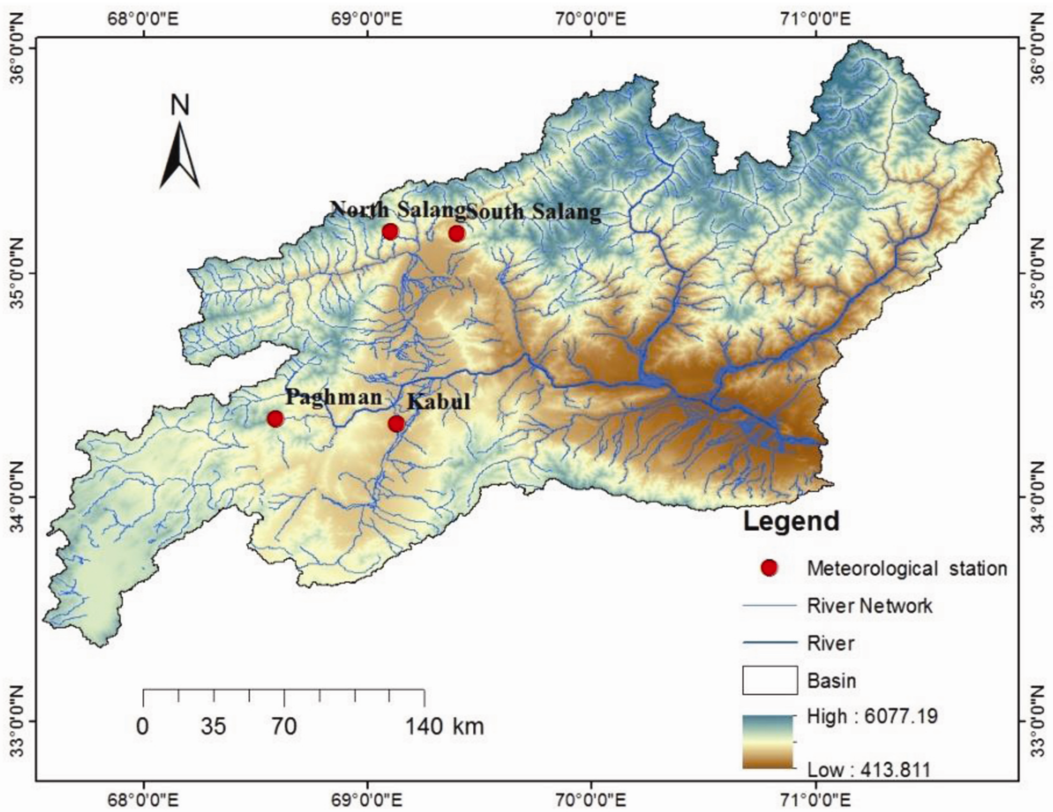

Figure 1. Location map of the Kabul River Basin with the meteorological stations used in the study.

quantify the uncertainties under climate change scenarios from three GCMs in the Coupled Model Intercomparison Project Phase 5 (CMIP5).

KRB extends from 33°29′ to 36°6′N in geographical width and from 67°43′ to 71°40′E in geographical length on the coordinates of Afghanistan[19] (Figure 1). The basin is 700 km long, of which 560 km flows inside Afghanistan with a total drainage area of 67,370 sq. km (ref. 16). Originating from the Paghman mountains on the west and Kohe Safi mountains on the east[20], the river flows west to east and can be counted as a main source of fresh water[17]. KRB represents 26% of the total water resources in Afghanistan with a mean annual stream flow of 24 billion cubic metres. It covers 12% of the total area of Afghanistan and is regarded as the most important river basin in the country[21]. The total population of KRB stands at 7,184,974 with a density of 93 per sq. km, containing 35% of the country's total population[19]. The climate of KRB is categorized by cold winters with extreme precipitation for seven months (November–May), and hot summers with less or no precipitation and stream flow, except in those rivers and streams fed by melting snow or glaciers. Due to the variation of elevation, precipitation varies considerably throughout the basin. Moreover, 72% of the total runoff is created by the melting of permanent snow. Eventually, KRB joins the Indus River Basin in Pakistan[15].

Historical monthly baseline data for maximum and minimum temperatures and precipitation were collected from the Department of Meteorology and Hydrology of Afghanistan. The period from 1961 to 1980 was taken as the baseline for four meteorological stations inside KRB (Figure 1). Table 1 illustrates the brief characteristics of four meteorological stations in KRB for the period 1961–1980.

The temperature in KRB varies according to elevation and season. The maximum temperature for the basin occurs in June–August with a mean temperature of 19°C. The mean maximum temperature in the basin showed an increase of 2% for the period 1961–1990 compared to recent years. Additionally, the mean minimum temperature for KRB is 5°C, with the Panjshir sub-basin being the coldest. The coldest months for KRB are November–February when the temperature drops below zero. Similarly, analysis of this data showed that the hottest year with respect to maximum and minimum temperatures for all stations occurred in 1979, with a peak mean monthly maximum temperature of 34°C and a mean monthly minimum temperature of 16.4°C in July for the Kabul station. Furthermore, time series data proved that the coldest year for minimum and maximum temperatures was 1968 with a lowest mean monthly maximum temperatures of 2.5°C and a mean monthly minimum temperature of –5°C at the North Salang station.

Table 1. Characteristics of the climate stations used in this study

Stations	Mean annual precipitation (mm)	Mean maximum temperature (°C)	Mean minimum temperature (°C)	T_{mean} (°C)	Lat.-N (°)	Long.-E (°)	Elevation (masl)
North Salang	990.11	4.23	2.82	0.70	35.19	69.1	3366
South Salang	1035.55	6.47	0.11	3.17	35.18	69.4	3172
Paghman	436.82	17.25	3.1	10.17	34.35	68.59	2114
Kabul	298.85	19.74	4.6	12.18	34.33	69.13	1791

Analysis of the precipitation data for the 20 years from 1961 to 1980 showed April to be the wettest month for the whole river basin while June–September were the driest months. Furthermore, analysis of time series data showed that the highest mean annual precipitation of 956 mm occurred in 1972 for the whole basin. In addition, 1970 was the driest in the 20-year period, with a maximum precipitation of 700 mm in the south Salang station, while Kabul station had the lowest record of 180 mm in the populated area.

Among the 39 GCMs built in the Coupled Model Intercomparison Project Phase 5 (CMIP5), 3 have been selected in this study. As they cover better resolutions varying from 0.40° × 0.40° to 2.8° × 2.8° with vintages later than 2010. Similarly, these GCMs have been widely used in climate change impact assessment studies in this region. For this study, two kinds of scenarios from RCP 4.5 (stabilizes radiative forcing at 4.5 W/m^2 in 2100 without ever exceeding that value) and RCP 8.5 (rising radiative forcing pathway leading to 8.5 W/m^2 by 2100) were considered to forecast future climate data (2010–2099) with respect to the baseline (1961–1980). Four RCPs (RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5) comprise the scenario set, based on their radiating forces. These four RCPs consist of a range of greenhouse emission scenarios with or without climate policies. The RCP 2.6 is the low emission scenario which leads to very low forcing level. It is possible to achieve RCP 2.6 pathway, only if proper mitigation policies and efforts are made to reduce greenhouse emission. RCP 4.5 and RCP 6 are the intermediate stabilization scenarios which can only be achieved if proper adaptation strategies are implemented. RCP 8.5 pathway arises when very little or no effort is taken to reduce greenhouse gas emissions[22]. Even if strong mitigation measures are taken in the future, climate would be changing. Under such circumstances, either adaptation strategies will be formulated and implemented to reduce impact of climate change or no effort will be taken to reduce greenhouse emissions in the future. Therefore, to study the impact of climate change with and without adaptation strategies in future, RCP 4.5 and RCP 8.5 were selected for the study.

Meteorological data for the future period was downloaded from the earth system grid federation (ESGF) website and used for climate change projection. The output data (temperature and precipitation) of the models were downscaled using the delta change approach. This is the most preferable method for transformation since it can reliably simulate climatic parameter changes in relative rather than absolute values[23]. The delta change method uses differences between simulated current and future climate conditions from GCMs added to observed (baseline) time series of climate variables.

$$T_f = T\,(\text{GCM simulated})_f - T\,(\text{GCM simulated})_p, \quad (1)$$

$$P_f = \text{PPT (GCM simulated)}_f/\text{PPT (GCM simulated)}_p, \quad (2)$$

where p is used for the present and f is used for the future time period. The future scenarios are then generated using eqs (3) and (4).

$$F_s\,(T) = T\,(\text{baseline}) + T_f, \quad (3)$$

$$F_s(\text{PPT}) = \text{PPT (baseline)} \times P_f, \quad (4)$$

where $F_s(T)$ is for future temperature, $F_s\,(\text{PPT})$ is for future precipitation and PPT is for precipitation.

The GCM models for KRB were selected using statistical analysis. As statistical indicators, the coefficient of determination (R^2) and root mean square error (RMSE) offer the simplest and easiest method for mathematical calculation[24]. This study uses three GCMs to project the future global data (2010–2099) in the four meteorological stations and the future mean changes of meteorological parameters corresponding to the baseline period (1961–1980). Therefore, the mean monthly values of R^2 and RMSE are developed among the meteorological parameters (maximum temperature, minimum temperature and precipitation) of the GCMs and the baseline data for the period 1971–1980. These are then compared with the bias-corrected values of maximum and minimum temperatures and precipitation for the same period, based on the general rule that R^2 is greater and RMSE is lower after bias correction. Thus, the three GCMs; CCSM4, MIROC5 and BCC-CSM1.1 can be used effectively in KRB. The comparison results of R^2 and RMSE values are satisfactory after bias correction. Table 2 shows the mean values of R^2 and RMSE for precipitation and maximum and minimum temperatures in all three GCMs at each of the four stations in KRB.

To understand the future changes in maximum and minimum temperatures and precipitation, their projected

Table 2. Summary of the statistics for baseline and simulated temperatures, and precipitation at four meteorological stations in the Kabul River Basin for the baseline period 1961–1980 before and after bias correction

Station	Meteorological data	Before bias correction	After bias correction
North Salang (3366 masl)	Precipitation	$R^2 = 0.07$	$R^2 = 0.40$
		RMSE = 9.36 mm	RMSE = 9.24 mm
	Maximum temperature	$R^2 = 0.58$	$R^2 = 0.72$
		RMSE = 12.3°C	RMSE = 3.4°C
	Minimum temperature	$R^2 = 0.58$	$R^2 = 0.73$
		RMSE = 8.07°C	RMSE = 3.58°C
South Salang (3172 masl)	Precipitation	$R^2 = 0.076$	$R^2 = 0.31$
		RMSE = 11.03 mm	RMSE = 10.2 mm
	Maximum temperature	$R^2 = 0.66$	$R^2 = 0.89$
		RMSE = 9.84°C	RMSE = 2.47°C
	Minimum temperature	$R^2 = 0.64$	$R^2 = 0.90$
		RMSE = 5.99°C	RMSE = 2.22°C
Kabul (1791 masl)	Precipitation	$R^2 = 0.01$	$R^2 = 0.2$
		RMSE = 4.64 mm	RMSE = 3.65 mm
	Maximum temperature	$R^2 = 0.69$	$R^2 = 0.92$
		RMSE = 6.54°C	RMSE = 2.84°C
	Minimum temperature	$R^2 = 0.81$	$R^2 = 0.89$
		RMSE = 3.7°C	RMSE = 2.61°C
Paghman (2114 masl)	Precipitation	$R^2 = 0.11$	$R^2 = 0.19$
		RMSE = 6.9 mm	RMSE = 6.7 mm
	Maximum temperature	$R^2 = 0.65$	$R^2 = 0.92$
		RMSE = 7.54°C	RMSE = 2.61°C
	Minimum temperature	$R^2 = 0.69$	$R^2 = 0.91$
		RMSE = 5.61°C	RMSE = 2.17°C

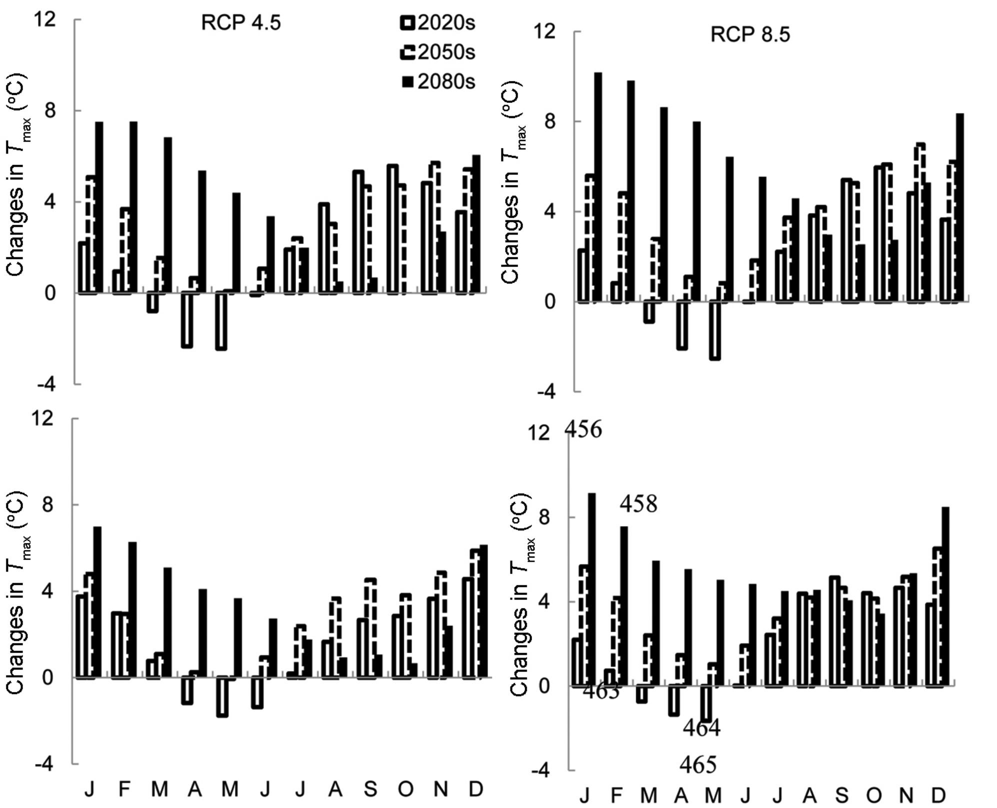

Figure 2. Future mean monthly changes in T_{max} and T_{min} relative to the baseline period (1961–1980) under RCP 4.5 and RCP 8.5 in the Kabul River Basin.

Table 3. Future mean seasonal and annual changes in maximum and minimum temperatures (°C) relative to the baseline period (1961–1980) under RCP 4.5 and RCP 8.5 scenarios in the Kabul River Basin

Period	RCPs	Annul		Spring		Summer		Fall		Winter	
		T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}
2020s	RCP 4.5	1.8	1.5	–1.6	–1.4	3.7	1.5	4.6	3.6	0.7	2.4
	RCP 8.5	1.9	2.0	–1.5	–0.9	3.8	3.9	4.8	4.3	0.7	0.7
2050s	RCP 4.5	3.1	2.9	0.6	0.3	3.3	3.5	5.2	4.8	3.4	2.9
	RCP 8.5	4.1	3.7	1.2	1.4	4.3	4.0	6.4	5.2	4.3	4.0
2080s	RCP 4.5	3.9	3.4	4.3	3.4	1.0	1.2	2.9	3.0	7.2	6.1
	RCP 8.5	6.2	5.7	6.6	5.1	3.3	4.3	5.4	5.7	9.5	7.5

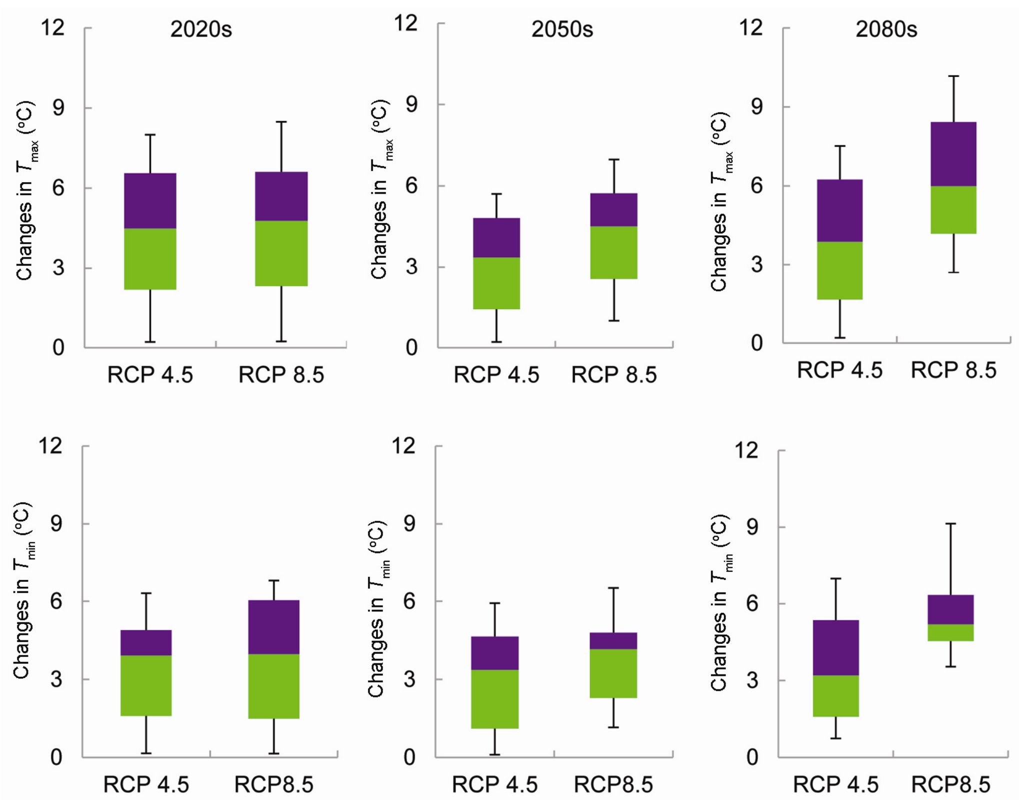

Figure 3. Changes in annual mean T_{max} and T_{min} for the 2020s, 2050s and 2080s relative to the baseline period of 1961–1980 under RCP 4.5 and 8.5 scenarios in the Kabul River Basin.

values were considered in three future periods: the 2020s (2010–2039), 2050s (2040–2069), and 2080s (2070–2099) relative to the baseline period (1961–1980) under two emission scenarios (RCP 4.5 and RCP 8.5). The changes in mean monthly maximum and minimum temperatures projected by three GCMs under RCP 4.5 and RCP 8.5 scenarios relative to the baseline period are shown in Figure 2. The projected values of all GCMs under the two emission scenarios show that the maximum temperature increases for all months in all three periods except March, April and May of the 2020s under both scenarios. Comparisons between baseline and projected values show that the maximum temperature will rise by 6.2°C in the 2080s under RCP 8.5 and 3.9°C under RCP 4.5 relative to the baseline period (1961–1980) at the four stations in the Kabul River Basin. The hottest month at all stations is July, but in August the mean temperature is 20°C in the whole basin. The coldest month in the historical period is January (–5.3°C) and this month is also the simulated coldest in the future, followed by February. The mean temperature is expected to increase by 1.7°C, 3°C and 3.7°C under RCP 4.5 and 2°C, 3.9°C and 6°C for RCP 8.5 in the 2020s, 2050s and 2080s respectively.

Mean monthly changes in minimum temperature projected by the GCMs under both RCPs also show an increasing tendency. Figure 2 shows that the minimum temperature increases for all months except March, April and May of the 2020s. The months of December and

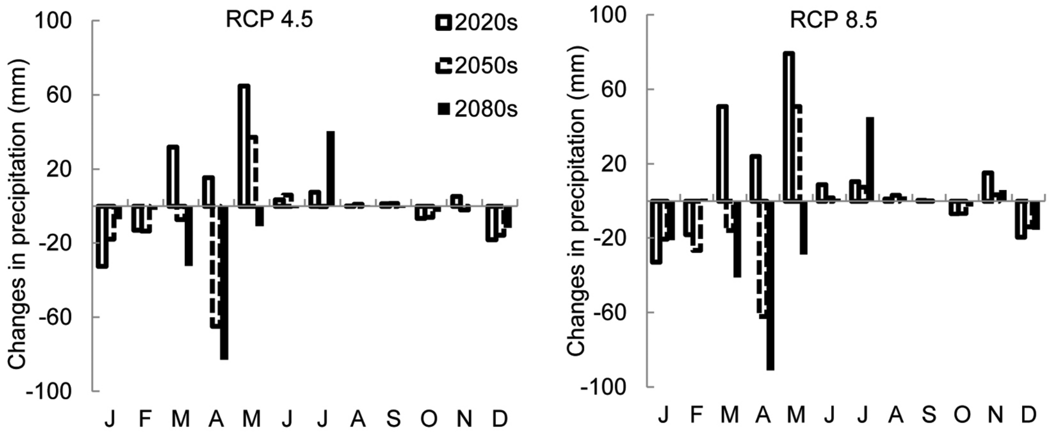

Figure 4. Future mean monthly changes in precipitation relative to the baseline period (1961–1980) under RCP 4.5 and 8.5 scenarios in the Kabul River Basin.

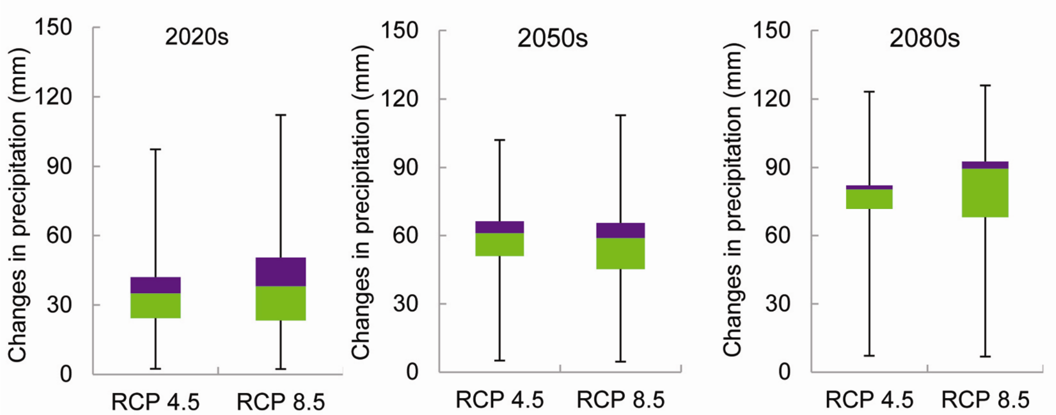

Figure 5. Changes in mean annual precipitation for the 2020s, 2050s and 2080s relative to the baseline period of 1961–1980 under RCP 4.5 and 8.5 scenarios in the Kabul River Basin.

January are more affected by changes in minimum temperature. Comparison of the baseline and projected values shows that the minimum temperature will rise by 3.4°C under RCP 4.5 and 5.7°C under RCP 8.5 by the 2080s.

Table 3 presents the annual and seasonal mean changes in maximum and minimum temperatures for the entire Kabul River Basin relative to the baseline period. Afghanistan has four seasons, namely spring, summer, autumn and winter. This section compares annual and seasonal changes throughout the whole basin. The results show that all seasonal changes are increasing under both scenarios except spring in the 2020s. The winter season is the most affected, with maximum temperatures reaching 9.5°C and minimum temperatures 7.5°C under RCP 8.5 scenario in the 2080s. Annual changes in maximum temperature will be 1.9°C in the 2020s, 3.6°C in the 2050s, and 5.1°C in the 2080s under both scenarios and minimum temperatures 1.8°C, 3.3°C, and 4.6°C respectively.

This section presents the highest continuous annual changes in maximum and minimum temperatures for the future periods. The box plots with whiskers in Figure 3 show the highest projection of maximum and minimum temperatures relative to the baseline period. The bar represents the median value and the upper limits of the box plots show the highest projection. By checking the upper ends of the whiskers, the projection values under RCP 8.5 are always greater than RCP 4.5 for both maximum and minimum temperatures, indicating 0.5°C in the 2020s, 1.1°C in the 2050s, and 2°C in the 2080s for the maximum temperature, and 0.3°C, 0.6°C, and 2.6°C for the minimum temperature respectively. As a result of the upper ends of the box plots, a maximum temperature of approximately 8.5°C and a minimum temperature of 7°C can be reached in the future periods of 2010–2099. This indicates that the mean temperature is expected to increase by almost 8°C in the future, especially under the RCP 8.5 scenario.

The changes in monthly precipitation over the Kabul River Basin under RCP 4.5 and 8.5 scenarios are shown in Figure 4. The wettest month has shifted from April to March. Besides, under both scenarios, the decreasing change is seen in January, February, March, April, October and December. The precipitation peaks change in

May for only the 2020s, approaching 80 mm under the RCP 8.5 scenario. Based on the historical period 1961–1980, the wettest month is in April with 173 mm of precipitation, and there are also rapidly decreasing changes during this month. These results show that the majority of months can be under drought, causing water stress over the whole area in the future.

Figure 5 shows the expected changes in annual precipitation in 2020s, 2050s and 2080s. In the box plots, the median values are represented by the mid vertical bars of the box and the maximum and minimum values of projections by the upper and lower limits of the whiskers. The upper ends of the whiskers show the highest increase in projections, with 100 mm in the 2020s, 110 mm in the 2050s, and 125 mm in the 2080s under RCP 4.5, and 120 mm, 115 mm and 130 mm under RCP 8.5 for the mean annual precipitation changes. On the other hand, the lower ends show a lowest amount of increase in precipitation of 30 mm, 50 mm and 70 mm in 2020s, 2050s and 2080s respectively relative to the baseline climate conditions.

The main objective of this study was to assess the changes in future precipitation and temperature of the Kabul River Basin under RCPs. It is projected that the mean annual maximum and minimum temperatures are expected to increase in the whole basin under both RCP scenarios for all three future periods. The highest increase of mean annual temperature is projected for the winter and spring seasons under both RCPs. The mean maximum temperature is expected to increase by 2.9–4°C and the minimum temperature by 2.7–3.7°C for 2010–2099 under both scenarios. In contrast, the mean annual precipitation is expected to increase with monthly variations (both increase and decrease) by 2100 compared to the baseline period. The findings of this study can help water managers, planners and policy makers to manage the impact of climate change on future water availability, floods and droughts in the basin.

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