



Inferring the impacts of climate extreme in the Kabul River Basin

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Abstract

The increasing temperature and variability in precipitation, in terms of both frequency and intensity, are affecting different sectors in the Himalayan region. This study aims to quantify the future scenario and related extremes in the Kabul River Basin (KRB) of the western Himalaya using high-resolution climate datasets. We selected four representative General Circulation Model (GCM) runs from Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios, based on future projections, climatic extremes and their abilities to represent the historical climate cycle (1981–2010) of KRB. The seasonal analysis of precipitation shows decreasing pattern during the winter and pre-monsoon seasons and annual mean temperature will increase consistently by 3 to 5 °C in RCP4.5 and 8.5 scenarios. Ten indices were selected to study climatic extremes pertaining to the health, agriculture and water resources sectors. The extremes, like consecutive summer days, warm days and heatwaves, will increase, whereas the frost days, cold nights, cold waves and extreme precipitation days will decrease towards the end of this century. Besides, the extremes are not homogenous in time and space. Based on the results of this study, there is a need for prompt climate actions in order to increase the adaptive capacity against these extreme changes and to build resilient livelihoods in the KRB.

Keywords Western Himalaya · Afghanistan · Increasing temperature · Warm days · Climate change impact

Introduction

Stressful climatological conditions, usually in the form of increased frequency and intensity of weather and climatic extremes, can affect the natural environment and the human system (Easterling et al. 2000). Climatic trends have been changing significantly in the Himalayan region (Dimri et al. 2021; Latif et al. 2021), thereby influencing the availability of water (Barnett et al. 2005; Lutz et al. 2014), agriculture

productivity (IPCC 2014; Meresa et al. 2017) and human health (Dhimal et al. 2021; Seneviratne et al. 2012). This is likely to continue in the future affecting the Himalayan ecosystem and its functions (Huss & Hock 2018; IPCC 2014; Parmesan et al. 2000).

The term climate extreme refers to weather and climate variables exceeding a threshold near the upper and lower range of observed values usually seen in the form of unusual and severe weather events (Seneviratne et al. 2012). The variations and trends in these extreme climate events have received much attention, due to loss of lives and economic damages (Bouwer & Bouwer 2019). According to the World Health Organization (WHO), nearly 150,000 deaths occur each year in low-income countries primarily due to the adverse effects of climate change (Kumaresan & Sathiakumar 2010). There is a high association between increased temperature and malaria cases in the southwestern highland region of China (Liu et al. 2021), the increased incidence of dengue in the Himalayan region (Dhimal et al. 2021), diarrheal events in Bhutan (Wangdi & Clements 2017) and heat-related mortality in Europe (Ballester et al. 2023). The change in precipitation influences photosynthetic activity (Teng et al. 2022), development and productivity of crops

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(Motha 2011), soil quality and the menace of pests influencing pollination (Rosenzweig et al. 2001), threatening national and regional food security (Nelson et al. 2009) in the Himalayan region (Rasul et al. 2019).

Compared with the 78 global watersheds, the Upper Indus Basin is the most important and vulnerable water tower to climate change (Immerzeel et al. 2020). Few studies have been conducted on water availability in the Kabul River Basin (KRB), the westernmost tributary of the Indus River (Hassanyar et al. 2017; Mack et al. 2010b; Tünnermeier et al. 2005). Recent studies in KRB (Bokhari et al. 2018; Sidiqi et al. 2018; Wi et al. 2015) and nearby mountain range of the Himalayan region (Krishnan et al. 2019; Palazzi et al. 2013) have indicated the increase in temperature trends and climatic extremes (Khan et al. 2022; Sidiqi et al. 2018). The worsening climatic conditions in the region will cause even more stress for vulnerable groups of Afghanistan (Savage et al. 2009).

Climate change impacts have widespread impacts on various sectors, including agriculture, human health and water resources which are the focus of this study. Among them, agriculture is particularly vulnerable to climate change due to changes in precipitation and temperature patterns (Rezaei et al. 2023). Health sector is highly susceptible to the impacts of climate change. That includes a rise in heat-related incidences, spread of infectious diseases, water and vector-borne diseases and poor health conditions aftermath of disasters (Dhimal et al. 2021). Water sector is highly vulnerable to changes in precipitation patterns which can result in too much and too little water. In addition, extreme events such as increased frequency and intensity of floods and droughts will affect both quantity and quality (Khanal et al. 2021; Pokhrel et al. 2021).

In this study, we have selected the General Circulation Model (GCM) runs based on their abilities to represent the historical climate cycle of the KRB. The study not only presents the future changes in the average precipitation and temperature patterns of the region but also looks at the changes in extremes events in the basin and discusses its potential implications for health, agriculture and water resources. The novelty of this study lies in its use of high-resolution (10 km) downscaled GCMs to calculate the climatic extremes and discuss by being based on the sectoral implications for the KRB.

The results are discussed in terms of the potential sectoral implications of climatic extremes indices. While at present, most studies are studying individual sectors, our study has attempted to bring together the sectors and potential implications, enriching the improved exchange between sectors and understanding in the holistic approach. Quantitative assessments of the impact of climatic extremes on sectors provide crucial information for sector-specific resource management and a better understanding of the water-food-health

nexus, leading to better policy formulation. This will also help in a broad understanding of the societal risk related to the extreme events and eventually support appropriate action planning towards achieving the Sustainable Development Goals 6 (water), 13 (climate), 3 (health) and 2 (food security).

Methodological approach

This section describes the methodological approach that was taken for the selection of the GCM runs specific to the KRB and outlines the sector-specific indices that were used for the analysis.

Kabul River Basin

The KRB is one of the main tributaries of the Indus River (Fig. 1). The Kabul River originates from the Sanglakh Range of the Hindu Kush mountains in Afghanistan and sustains the livelihoods of millions of people in both Afghanistan and Pakistan (Hassanyar et al. 2017). The KRB covers 69,312 km² and has an elevation range of 430–7350 masl, with 3% of the area being above 5000 m asl. The basin is dominated by 47% grassland, while forests constitute 8%, the cultivable land is 7% while the unused land is 37% (Najmuddin et al. 2017). The basin, where agriculture is the main source of livelihood, accounts for about 20% of the total irrigated land in Afghanistan (Lashkaripour & Hussaini 2008).

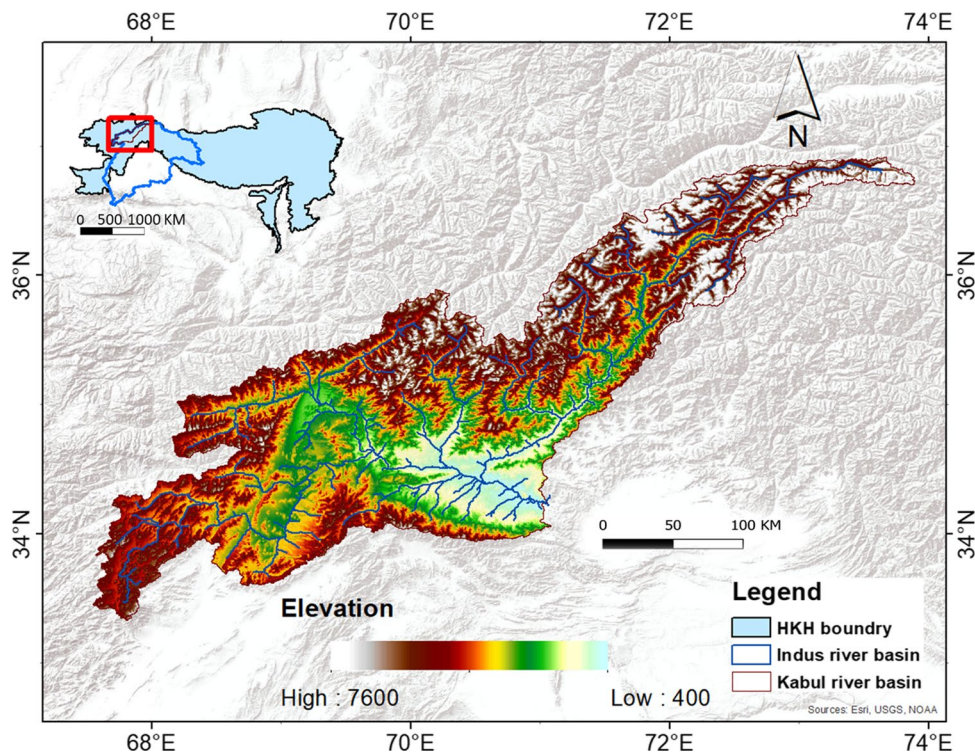
The KRB is also the most populated area in Afghanistan. The northern part of the basin has mostly high mountains while the central and south-eastern parts are low agricultural lands (Lashkaripour & Hussaini 2008). The basin has 1364 km² of glaciers (2% of the total area) and the region is mostly fed by snow and glacier melts. Water resources and the hydrological cycle act as an important component in the sustainable development of the region (Sidiqi et al. 2018).

The climatic conditions for the reference period

This study considered the regional dataset prepared by Lutz et al. (2014) as a reference dataset. This dataset is developed based on the Watch Forcing Data ERA-Interim (WFDEI) dataset (Weedon et al. 2014). WFDEI dataset has been used in the nearby sub-basins of sub-basins of Upper Indus Basin (Ali et al. 2022; Azmat et al. 2020). The precipitation dataset is further corrected using the Global Precipitation Climatology Centre (GPCC) dataset (Schneider & Homewood 2013) and observed glacier mass balance data. The air temperature data is bias corrected with data from observed stations from the region.

The average annual precipitation and mean temperature is shown in Fig. 2. The average annual precipitation sum of

Fig. 1 The Kabul River Basin. In the inset, the Hindu Kush Himalaya (HKH) (the blue shaded area) and the Indus River Basin (black boundary)



the basin is ~722 mm (1981–2010), with February, March and April being the months with the highest precipitation rates. The pre-monsoon season records the highest precipitation of 311 mm (43% of the total), while the post-monsoon season, with 92 mm (12.8% of the total), records the lowest level of precipitation. The precipitation amount,

frequency and intensity vary spatially and influences the local weather. The spatial graph (Fig. 2) shows that the precipitation level ranges from 200 mm/year (central and north-eastern parts) to 1600 mm/year (northern part) and is more (> 1000 mm/year) in the northern part of the basin (especially in the 35°N–36°N latitude). The precipitation

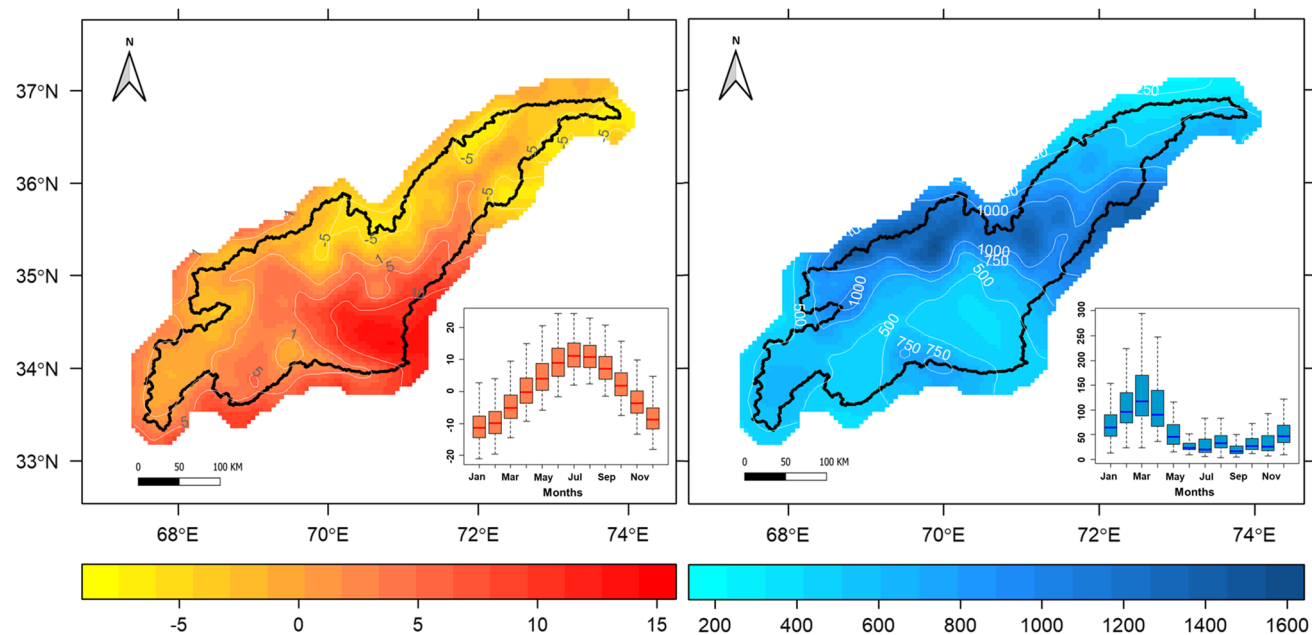


Fig. 2 Spatial variations in average annual mean temperature (left) and average annual precipitation (right) in the Kabul River Basin. Boxplot of monthly average is shown in the inset

levels vary highly in the winter months, with the highest variability being in March.

The average annual mean temperature of the basin is ~ 1 °C; however, the average monthly mean temperature drops to -10 °C in December and January, while it increases to as high as 15 °C in July and August. Spatially, the temperature is higher (> 5 °C/year) in the southern valley of Kabul River (below 35°N) of the basin (Fig. 2). The average monthly temperature shows similar variability throughout the year.

Selection and downscaling of the General Circulation Model runs

The Coupled Model Intercomparison Project (CMIP) allows to study and make intercomparison of multi-model simulations of present-day and future climates. IPCC Fifth Assessment Report (AR5) has prompted rapid model development, encouraging the use of the climate model simulations for analysis (Meehl et al. 2005). AR5 suggests different Representative Concentration Pathway (RCP) scenarios. In this study, we looked into two different climate change scenarios, RCP4.5 and RCP8.5, in order to understand the future climate scenario of the KRB.

There is great variability in the projections of precipitation and temperature made by different GCM runs. A total of 105 GCM runs for RCP4.5 and 77 for RCP8.5 from the Coupled Model Intercomparison Project (CMIP5) experimental design were considered for this study. Each GCM run and ensembles has represented atmospheric circulation and regional climate differently, based on their physics, realization and initialization (Bader et al. 2008). To select the GCM runs that represent the study area, a three-step selection procedure integrating the envelope-based and past-performance approaches were used, as suggested by Lutz et al. (2016). This approach was also used for the National Adaptation Plan (MoFE 2019) as well as to understand future climate scenarios of Koshi River basin (Kaini et al. 2019). The following were the three steps:

1. In the first step, the changes in the annual mean temperature (ΔT) and annual precipitation sum (ΔP) between 1981–2010 and 2071–2100 were calculated over the area of interest of all GCM runs. The distribution of change values provided four different spectra of possible climatic conditions: warm–dry, warm–wet, cold–dry and cold–wet. Five models from each corner (from 20 GCM runs) were selected based on projections of temperature and precipitation change for both RCPs. Here, only those models that had data available at a daily time step were selected.

2. In the second step, the 20 model runs obtained from the first step were reduced to eight models, based on their projected changes in climatic extremes for both RCPs. Here, two climate change indices for both air temperature and precipitation were used. For temperature, the Warm Spell Duration Index (WSDI) and the Cold Spell Duration Index (CSDI) were analysed as proxy for warm and cold conditions, while for precipitation, the number of extremely wet days (R95pTOT) and Consecutive Dry Days (CDD) were considered as proxy for wet and dry conditions. The percentage changes in the indices were calculated for 2071–2100 using the reference period of 1981–2010.

3. In the third step, the final selection of four GCM runs for each scenario was based on the skill of these models representing the historical climate cycle (from 1981 to 2010) using reference data sets. Summer, winter and annual biases were calculated against the reference dataset for both precipitation and temperature. Winter precipitation was specifically considered as the study area gets the majority of its precipitation during this season as snow.

The downscaling process involved correcting the bias in the eight selected GCMs. These GCMs were obtained from the Earth System Grid Federation (ESGF) infrastructure through the Climate4impact webpage, and then, the quantile mapping (QM) method was used to adjust the biases in climate variables derived from the models relative to that of the reference climate dataset (10 km). QM has been successfully used in the Himalayan region with complex topography (Kaini et al. 2019; MoFE 2019).

The GCMs were downscaled from a coarse resolution of approximately 100–250 km to a finer resolution of 10×10 km. The average monthly graph of raw GCM and bias-corrected GCMs (Supplementary Fig. 1) shows some divergence from the reference datasets. Bilinear interpolation in R programming was done to align coarse-resolution GCMs with the spatial resolution of the reference dataset. The downscaling process involved the conversion of the GCMs from their original coarse resolution to the 10-km finer resolution, generation of empirical cumulative distribution functions for each month using daily data from both the GCM and reference grid, and finally application of the correction function on a daily basis for each grid cell at the finer resolution. As the quantile mapping method matches the quantiles of the GCM dataset with reference dataset during the reference period at monthly scale, the monthly graphs of the bias-corrected GCMs, overlaps with the reference dataset for both precipitation and temperature (Fig. 2, Supplementary Fig. 1). This integrated approach facilitated both bias correction and downscaling approach.

For the analysis, we chose the time period of mid-century (2036–2065) and end-century (2071–2100). These values are compared to the reference period (1981–2010). Since the mid-century is about 30 years away from the present time, these studies can provide crucial information about the changes in climatic indices which could be useful for developing adaptation strategies.

Sector-specific climatic indices

The sectors which were climate sensitive in KRB were selected for this study, i.e. health, agriculture and water resources. Ten extreme indices defined by the ET-SCI (Expert Team on Sector-Specific Climate Indices) were chosen for analysing the implications of climate change in these sectors. Some indices applied to more than one sector (Supplementary Table 1). For our analysis, we selected six indices for water resources (include the cryosphere), nine for agriculture and nine for the health sector.

In the “Result” section, the two opposite extremes indices are presented together for efficient visualization and understanding. Likewise, to understand the uncertainty, during the analysis of extremes and future scenarios, the standard deviation range from the selected models is provided for all the indices.

Consecutive summer days (CSU) and consecutive frost days (CFD) reflect the heat and cold indices of the area. CSU is counted as the maximum number of consecutive days when the maximum temperature is greater than the average daily maximum temperature, 6.2 °C for the KRB. Similarly, CFD is the maximum number of consecutive days with a daily minimum temperature of less than 0 °C.

The heatwave duration index (HWDI) and cold wave duration index (CWDI) with respect to the mean of the reference period reflect excessive heat days or excessive cold days. The HWDI shows the number of consecutive days when the daily maximum temperature (TX) is greater than the mean (a 5-day window centred on each calendar day) of the daily maximum temperature of the reference period (TXnorm) and the temperature offset (T) (i.e. $HWDI = TX > TX_{norm} + T$). More than 6 consecutive days are considered, and the offset temperature is taken as 5 °C. Likewise, the CWDI indicates the number of days when: $TN < TN_{norm} - T$. Here, TN is the daily minimum temperature, TNnorm is the mean of the minimum temperatures of a given climate reference period (i.e. 1981–2010).

Warm days with respect to the 90th percentile of the reference period (TG90P) and cold nights with respect to the 10th percentile of the reference period (TN10P) help in understanding the sensitivity of the day and night-time temperatures in the KRB. To calculate the warm days, the percentage of warm days with respect to the 90th percentile of the daily mean temperatures of a five-day window centred

on each calendar day of the reference period (1981–2010) was calculated. Likewise, for calculating the cold nights, the percentage of cold days with respect to the 10th percentile of the daily minimum temperatures of a 5-day window centred on each calendar day of the reference period (1981–2010) was calculated. The percentage was then converted to the number of days per year by multiplying by 3.65.

Consecutive dry days (CDD) and consecutive wet days (CWD) reflect the dryness and wetness of an area. CDD is the maximum number of consecutive precipitation days with less than 1 mm during a year. Likewise, CWD is the maximum number of consecutive precipitation days greater than 1 mm during a year. In the visualization, the annual change is presented spatially to show the projected changes in the different areas of the basin. These two indices indicate whether there will be more dryness or wetness in the future.

Very high precipitation (RGT90P) and very low precipitation (RLT10P) reflect the extremes of precipitation. RGT90P is the number of days when the daily precipitation amount is more than the 90th percentile of the daily average precipitation. For this, at first, the 90th percentile precipitation was calculated (5 mm for KRB); then, this value was used to calculate the number of days with precipitation of at least more than 5 mm for the annual time series of the daily precipitation. Likewise, for very low precipitation, the threshold of the 10th percentile of precipitation (1 mm) was used. Based on this value, the number of days with a maximum of 1 mm of precipitation was counted.

Results

Selection of the General Circulation Models

Figure 3 shows the projected changes in temperature and precipitation from the reference period (1981–2010) to the end-century (2071–2100). The figure shows that the temperature would rise in the range of 3–10 °C and the precipitation would increase in the range of 0–50%. From this first step of the selection process of the GCMs, five GCM runs were selected from each corner, and altogether, 20 GCMs were selected. This corner represents four probable future climates: warm–dry, warm–wet, cold–wet and cold–dry.

The selected 20 model runs that were selected from step 1 (Supplementary Table 2), and from step 2, 12 model runs in RCP4.5 and eight in RCP8.5 were further selected based on the highest change in extreme values by the end-century. Likewise, the seasonal and annual biases of temperature and precipitation were applied in the third step. The temperature and precipitation biases of summer and winter were calculated—to reflect the seasonal dynamics. The lowest bias models, i.e. models that better represent the historical cycles, were selected as the final models at each corner of each RCP.

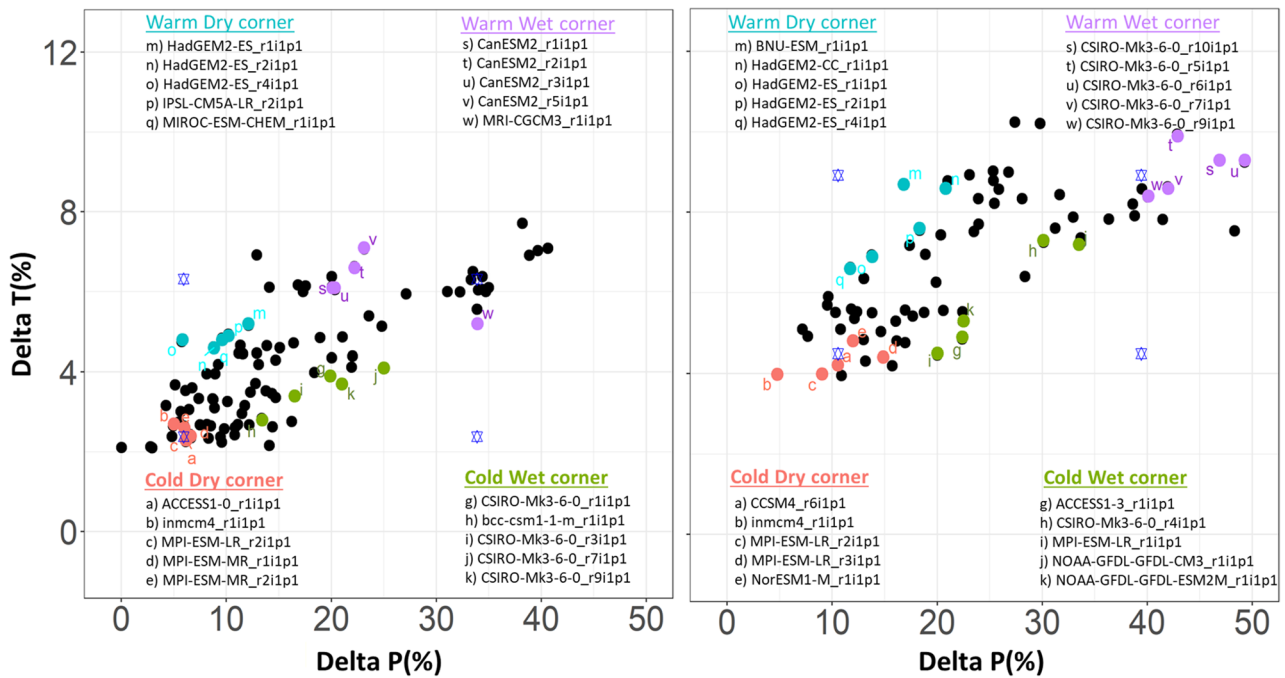


Fig. 3 Delta precipitation (P) and delta temperature (T) changes between 1981–2010 and 2017–2100 for Representative Concentration Pathway (RCP) 4.5 (left) and RCP8.5 (right) climate scenarios

The details of the selected models are presented in Supplementary Table 3.

The future scenario of temperature and precipitation in the basin

The temperature of the KRB is projected to increase by 2.7 °C in RCP4.5 and by 5.1 °C in RCP8.5 scenarios, and the precipitation is projected to increase by 4.5% in RCP4.5 and by 12.4% in RCP8.5 compared to the reference period (Fig. 4).

Supplementary Table 4 shows that all the eight models signify increasing temperature in both scenarios. The standard deviation among the models in terms of temperature change is low (1.4 °C) with a coefficient of variation of 37%. However, there is higher variability in future precipitation scenarios in the basin. On an average, while the precipitation pattern indicates an increase, some models show a decreasing scenario in RCP4.5. Therefore, there is comparatively higher standard deviation (16.8%) and a coefficient of variation (201%) in precipitation than in temperature.

The seasonal projection shows that the temperature of the basin will increase more in the winter and post-monsoon seasons, followed by monsoon (Table 1). There will be less precipitation in December–February (winter) during RCP4.5, while in RCP8.5, it will decrease

in December–May (both in the winter and pre-monsoon seasons).

Extreme indices in the basin and its sectoral implication

Table 2 presents the values of extreme indices during the reference period (1981–2010), mid-century (2036–2065) and by the end-century (2071–2100). Here, warm days and the HWDI are projected to increase more pronounced; 157 (± 17.8) warm days are projected in RCP4.5 and 259 (± 17.8) in RCP8.5; however, during the reference period, it is 35 warm days. As for heatwaves, they will occur for 79 (± 12.4) days in RCP4.5 and for 176 (± 12.4) days in RCP8.5. A detailed assessment and visualization of the extreme indices are presented below.

Consecutive summer days and consecutive frost days

Summer days will increase, and the frost days will decrease in the basin. On average, the summer days (reference period: 142 days) are projected to increase to 199 (± 15) in RCP 8.5 and to 165 (± 17) days in RCP 4.5 by the end of the century. However, frost days would decrease to 177 (± 12) days in RCP 8.5 scenario (reference period: 243 days). In Fig. 5, the percent of change

Fig. 4 Multi-model ensemble of temperature and precipitation under Representative Concentration Pathway (RCP) 4.5 (blue) and RCP 8.5 (red) for the period of 1981 to 2100. The coloured band represents the standard deviation resulting from the selected General Circulation Models. The black line represents the reference period (1981–2010). Mid-century period is 2036–2065 and the end-century is 2071–2100

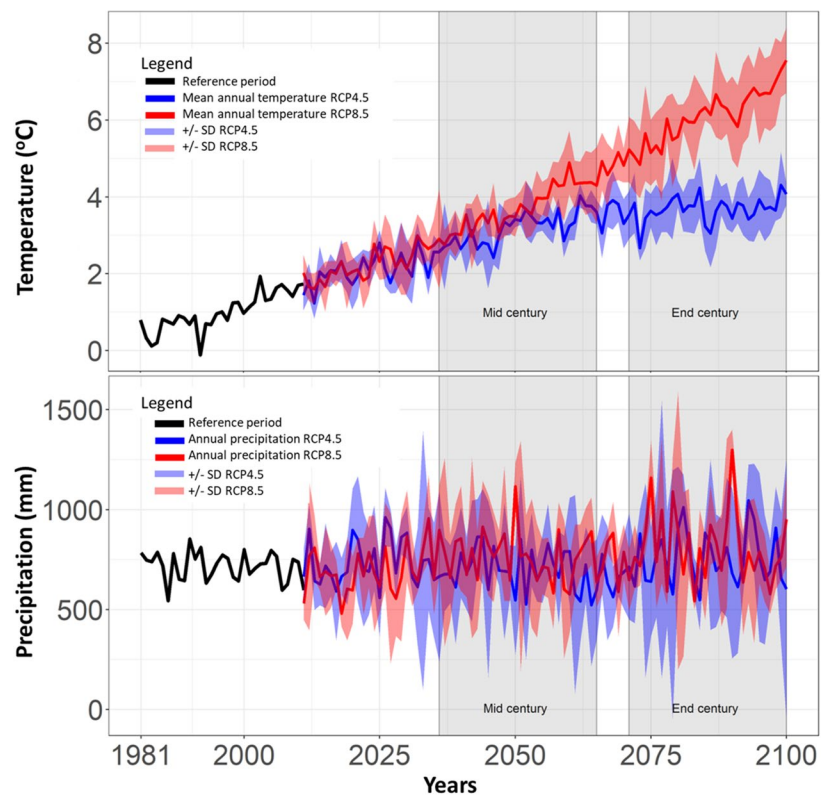


Table 1 Seasonal changes in precipitation and temperature, of the selected models for mid-century (2036–2065) and end-century (2071–2100) under Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios

| Seasons | Average temperature (1981–2010) (°C) | Change in temperature (°C) (standard deviation) | | | |
|------------------------|--------------------------------------|---|-------------|--------------|-------------|
| | | RCP4.5 | | RCP8.5 | |
| | | 2036–2065 | 2071–2100 | 2036–2065 | 2071–2100 |
| Winter (Dec–Feb) | –9.33 | 2.69 (0.42) | 3.34 (0.78) | 3.3 (0.46) | 5.88 (0.51) |
| Pre-monsoon (Mar–May) | –0.42 | 1.86 (1.09) | 1.8 (1.71) | 1.1 (1.66) | 2.88 (2.16) |
| Monsoon (Jun–Aug) | 10.42 | 1.87 (0.67) | 2.32 (1.37) | 2.28 (1.02) | 4.38 (1.75) |
| Post-monsoon (Sep–Nov) | 3.08 | 2.21 (1.52) | 3.17 (2.1) | 4.16 (1.6) | 7.3 (2.62) |
| Annual average | 1.00 | 2.16 (0.93) | 2.66 (1.49) | 2.71 (1.185) | 5.11 (1.76) |

| Seasons | Precipitation (1981–2010) (percent of annual total) | Change in precipitation (%) (standard deviation) | | | |
|------------------------|---|--|----------------|---------------|----------------|
| | | RCP4.5 | | RCP8.5 | |
| | | 2036–2065 | 2071–2100 | 2036–2065 | 2071–2100 |
| Winter (Dec–Feb) | 219.63 (30.39) | –17.06 (17.3) | –12.76 (14.71) | 3.95 (16.15) | 16.65 (41.3) |
| Pre-monsoon (Mar–May) | 311.37 (43.08) | –9.86 (21.63) | 0.07 (15.24) | –4.77 (5.1) | –12.55 (13.92) |
| Monsoon (Jun–Aug) | 99.30 (13.74) | 28.40 (57.59) | 45.89 (46.58) | 31.60 (35.7) | 62.69 (75.26) |
| Post-monsoon (Sep–Nov) | 92.48 (12.8) | 15.39 (9.23) | 12.64 (18.44) | 22.02 (22.96) | 29.47 (53.06) |
| Annual average | 722.78 | 4.22 (26.44) | 11.46 (23.74) | 13.2 (19.98) | 24.07 (45.89) |

from the base period (1981–2010) is shown. The summer days will be more in the north-eastern part and the decrease in the frost days will be more in the south-eastern part of the basin, though similar changes will be observed throughout the basin. The north-eastern

part of the basin is mostly at a higher altitude, while the south-eastern part is flat-land area, with human settlement. This means that there will be more summer in the upstream area, while the settlement area will have fewer frost days.

Table 2 Extreme indices during the mid-century and by the end-century. The values in parentheses represent the ensemble standard deviation

| Indices | Reference days (1981–2010) | RCP4.5 | | RCP8.5 | |
|---------|----------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| | | 2036–2065 (mid-century) | 2071–2100 (end-century) | 2036–2065 (mid-century) | 2071–2100 (end-century) |
| CSU | 142 | 161 (17) | 165 (17) | 174 (15) | 199 (15) |
| CFD | 243 | 211.3 (10) | 204.8 (12) | 205.1 (10) | 177.2 (12) |
| HWDI | 15 | 59.2(14.3) | 79.1 (12.4) | 83.6 (23.2) | 176.2 (12.4) |
| CWDI | 7 | 3.4 (2.5) | 2.9 (2.2) | 4.6 (2.9) | 1.9 (2.0) |
| TG90P | 35 | 131.8 (24.2) | 157.2 (17.8) | 175.2 (27.8) | 259.0 (17.8) |
| TN10P | 36 | 11.9 (3.5) | 11.5 (4.0) | 11.6 (4.0) | 5.8 (2.5) |
| CDD | 54 | 48 (12) | 47 (13) | 55 (13) | 56 (14) |
| CWD | 9 | 9 (3) | 10 (3) | 10 (3) | 9 (3) |
| RGT90P | 37 | 35 (4.6) | 37 (5.6) | 36 (5.1) | 35 (5.8) |
| RLT10P | 278 | 281 (7.8) | 278 (8.5) | 281 (8.4) | 285 (9.1) |

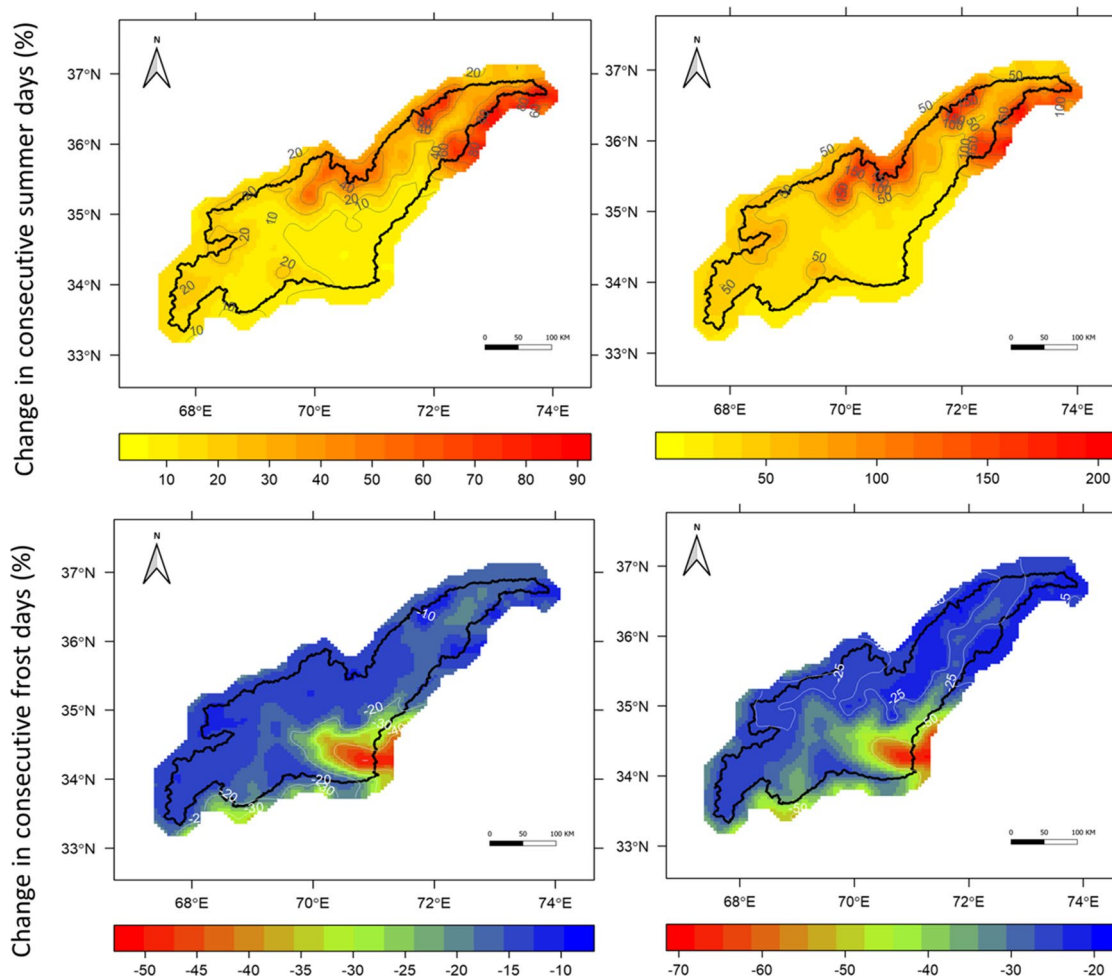


Fig. 5 The percentage change in consecutive summer days (top) and frost days (bottom) during 2071–2100 is shown for Representative Concentration Pathway (RCP) 4.5 (left) and RCP 8.5 (right) scenarios, relative to the reference period (1981–2010)

Heatwave duration index and cold wave duration index with respect to the mean of the reference period

Figure 6 shows the annual values of the HWDI and the CWDI. Here, the projections are of a continuous increase in heatwave and a decrease in cold wave. The HWDI will increase to an average of 79 (± 12.4) days in RCP 4.5 and 176 (± 12.4) days in RCP 8.5 by the end-century. The CWDI will decrease to 2.9 (± 2.2) days in RCP 4.5 and 1.9 (± 2) days in RCP 8.5. Thus, there is a higher possibility of uncomfortably hot and unusually humid weather in the future in the KRB.

Warm days and cold nights with respect to the 90th and 10th percentiles, respectively, of the reference period

The number of warm days will continually increase, while the number of cold nights will decrease in the future scenario (Supplementary Fig. 2). The average of 35.5 days of warm days will rise to between 157 (± 17.8) (RCP 4.5) and 259 (± 17.8) days (RCP 8.5) by the end-century. However, the average 36 days of cold days will decrease between 11.5 (± 4) (RCP 4.5) and 5.8 (± 2.5) days (RCP 8.5) by the

end-century. The trend of increasing warm days in RCP 8.5 is rather alarming.

Consecutive dry days and consecutive wet days

Both CDD and CWD are likely to increase, but not in a distinct pattern. Figure 7 shows that during the reference period (1981–2010), the average number of CDD was 54 days; this will change to 47 (± 13) days in RCP 4.5 and to 56 (± 14) days in RCP 8.5 during 2071–2100. Further, while the number of CWD will remain almost the same during the base period, in the future, in both scenarios, it will nominally fluctuate. Spatially, CDD will increase prominently mostly in the west and CWD in the east part of the basin.

Very high precipitation and very low precipitation days

Figure 8 shows that the pattern of extreme precipitation will vary in the future scenario. The 10-year moving average shows that the number of days greater than the 90th percentile is likely to decrease, but with some variability. There is no clear trend, but the end of the century will see an average of 35 wet days, with a standard deviation of 6 days (reference

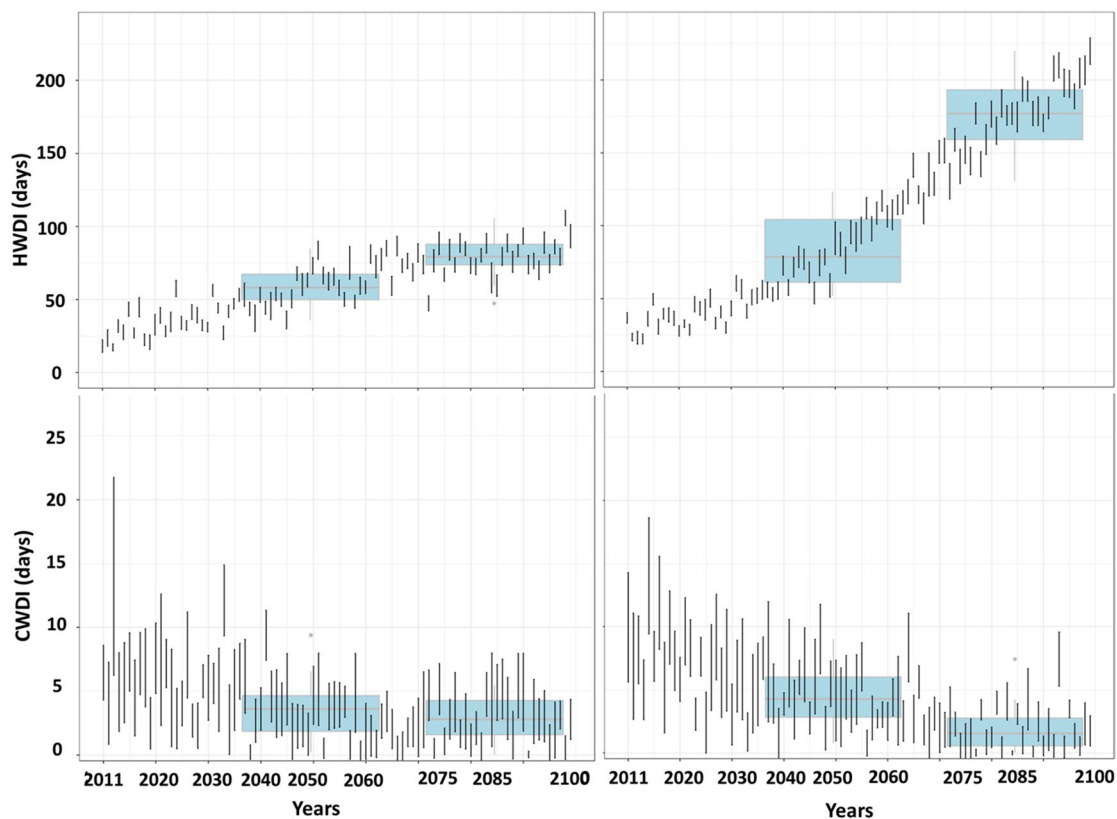
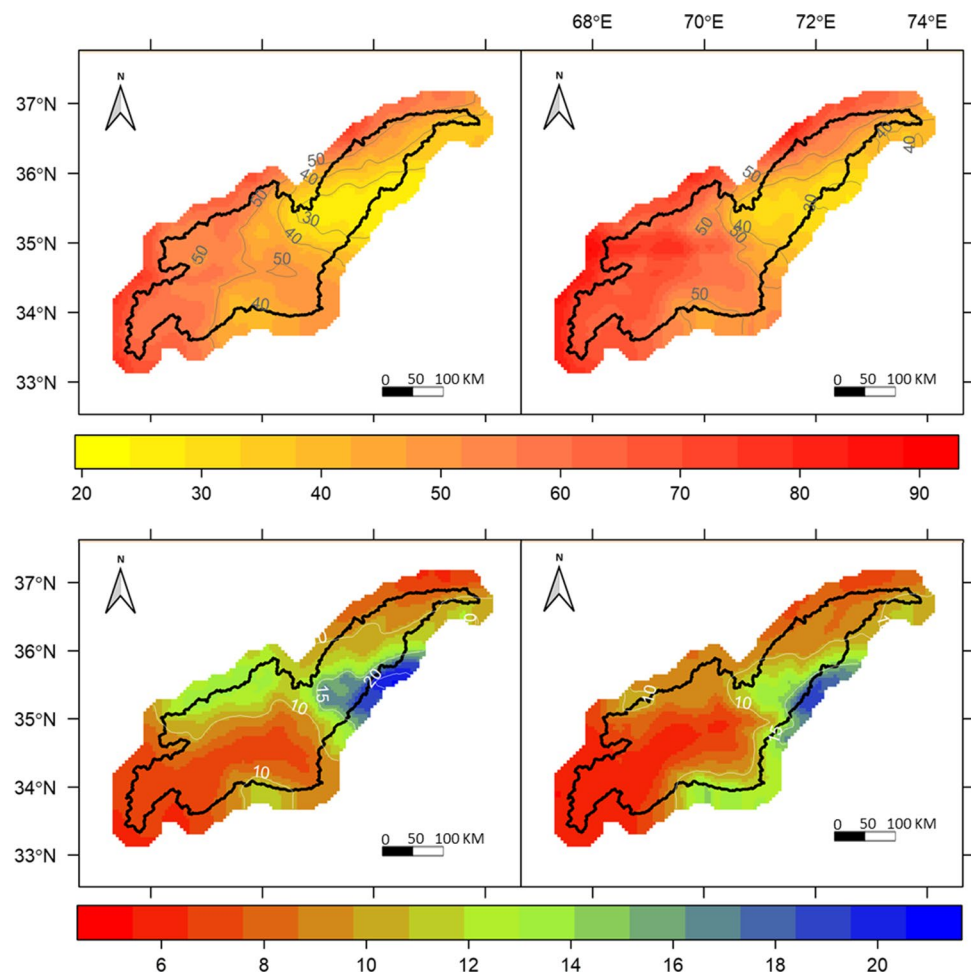


Fig. 6 The annual averages of heatwave days (upper panel) and cold wave (lower panel) in the Kabul River Basin are shown for Representative Concentration Pathway (RCP) 4.5 (left) and RCP 8.5 (right)

scenarios. Each line plot displays the range of values for individual years, while the box plot represents the mean and standard deviations for the mid-century (2036–2065) and end-century (2071–2100)

Fig. 7 The annual consecutive dry days (upper panel) and consecutive wet days (lower panel) during end-century are shown for in Representative Concentration Pathway (RCP) 4.5 (left) and RCP 8.5 (right) scenarios, in comparison to the reference period (1981–2010)



period: 37 days). In the case of days with very low precipitation, they are likely to increase to 285 days (reference period: 278 days), with a standard deviation of nine days.

Discussion

Our study in the KRB indicates an increase in temperature trends and seasonal fluctuation of precipitation patterns. Similar results can be seen in other studies conducted on temperature (Bokhari et al. 2018; Ghulami 2017; R. Hashmi et al. 2020) and precipitation (Mack et al. 2010a; NEPA, UNEP., 2015) in the basin. Under the RCP4.5, there is evidence of decrease in precipitation by up to 50% in the winter season (December to March) by using the NASA Earth Exchange Global Daily Downscaled Projections (Bokhari et al. 2018). Nearly 20% decrease in monsoon precipitation in Pakistan and southeastern Afghanistan is forecast by the end of the century (Shroder & Ahmadzai 2016).

Inferences of impact due to the climate extreme

Agriculture Cereals such as wheat, corn, barley, sorghum, rice and potatoes, and other entities such as cotton, fruits, nuts and grapes are the major agricultural products in the KRB (Muradi & Boz 2018). The increase in the extreme indices such as HWDI (Supplementary Fig. 3), CWDI (Supplementary Fig. 4), consecutive frost days and very low precipitation days is most likely to increase the irrigation water demand (Lutz et al. 2022; Shroder & Ahmadzai 2016), influencing the cropping system (Iizumi & Ramanakutty 2015), vegetative growth, fruiting and grain production across species (Hatfield & Prueger 2015; Mbow et al. 2019). The yield of crops including wheat, barley decreased due to the extreme cold winter and warm summer (Karimzadeh Soureshjani et al. 2019). However, in semi-arid regions, crops such as maize have shown water saving potential (Zou et al. 2021). Studies in India (Lobell et al. 2012) found accelerated wheat senescence due to extreme heat, while

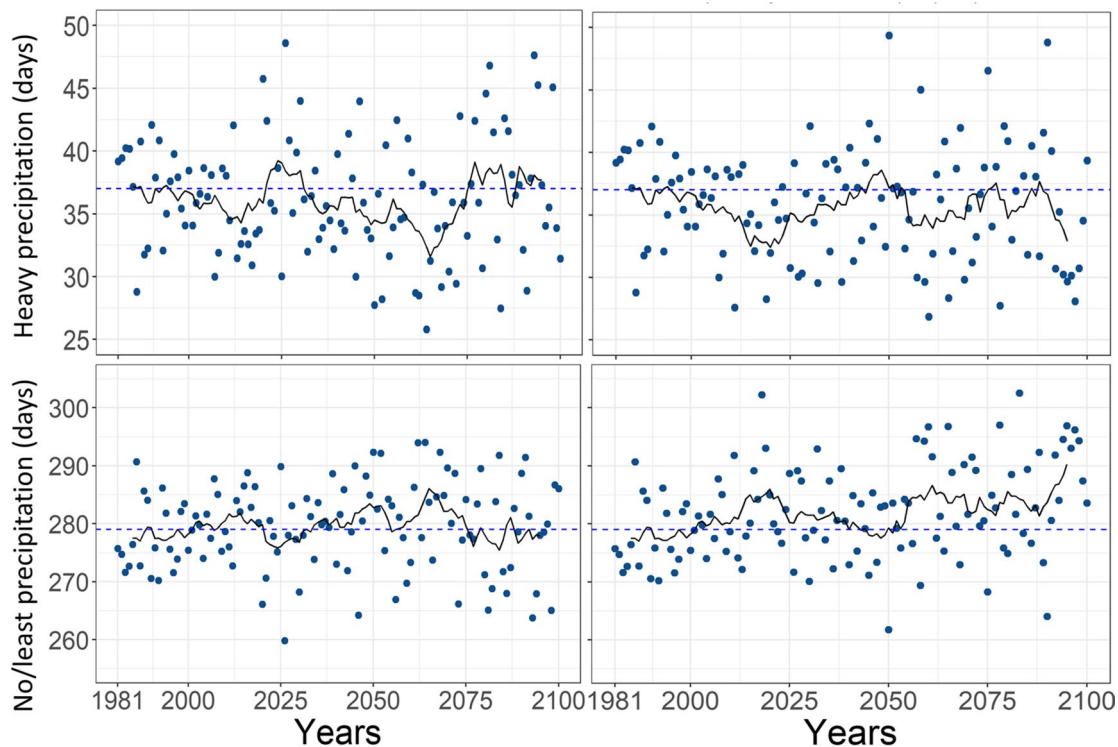


Fig. 8 The number of very high (upper panel) and very low (lower panel) precipitation days from 1981 to 2100 is shown for both Representative Concentration Pathway (RCP) 4.5 (left) and RCP8.5 (right)

scenarios. Each blue dot represents the value for an individual year. The black line indicates the 10-year moving average, while the blue dotted line represents the average of the reference period

research in the Indus basin (Y. Zou et al. 2021) showed climate change-induced alterations in wheat phenology, affecting anthesis stage, maturity and growing length. Moreover, supplementary Table 5 have highlighted various risks and uncertainties associated with crop production and food security.

Human health The KRB basin accounts for 35% of Afghanistan's population and has the fastest population growth rate compared to other parts of Afghanistan (MEW & World Bank 2013). Based on the study in Afghanistan, the temperature rise has a higher health risk in the mountains of the Himalayan region (Anwar et al. 2019). There is growing evidence of increased health risks under future climate change projections (Patz et al. 2005). The increasing extremes in KRB such as consecutive summer days, cold nights (Supplementary Fig. 5), warm days (Supplementary Fig. 6) is likely to have both direct (in the form of escalating vector-borne diseases, illness and death) and indirect (in the form of pathogenic activities and proliferation of bacteria) impacts on human health (Bowles et al. 2014). Death due to heatwave in France in 2003 (Fouillet et al. 2006); India and Pakistan in 2019 (Khan et al. 2019) and surge in waterborne disease

in the States (Curriero et al. 2001) (Supplementary Table 5) are exemplary to be cautious.

Water resources Around 70% of the total runoff in the KRB is contributed by the seasonal snowmelt (Kraaijenbrink et al. 2021; Sidiqi et al. 2018). The increasing temperature and heat-related indices such as consecutive summer days, HWDI and extreme precipitation are most likely to cause a change in the intra-annual flow pattern and seasonal shifting (Lutz et al. 2022) with more frequent and heavier flooding events (R. Hashmi et al. 2020). The snowpack in the Indus basin will most likely decrease by about 50% by the end of the century under RCP8.5 (Kraaijenbrink et al. 2021). The impact in variability and river flow in the area is shown by Shroder and Ahmadzi (2016); snow and glaciers melt by Zaman and Khan (2020); hydrological regime by Dahri et al. (2021); water resource availability by Savage et al. (2009); elevation-dependent warming by Hashmi et al. (2020); probability of drought by Tabari (2020) and flood frequency and intensity by Iqbal et al. (2018). Supplementary Table 5 has shown that with the temperature rise, the solid form of precipitation is likely to shift to the liquid form Hock et al. (2019) and likely to affect the landscape of the basin and

influencing the frequency of cryospheric hazards such as erosion, landslides, avalanches, flash floods and GLOF.

Uncertainty and limitations

In this study, we have attempted to look into the potential implications and impacts of climatic extremes on three sectors. As these three sectors are not stand-alone and linear, due to the interaction between these sectors and feedback loop among the different spheres, the impact is likely to occur in complex combinations, often shaped by physical processes and societal decisions (Raymond et al. 2020). Both precipitation-based extremes and temperature-based extremes can potentially occur simultaneously in the same location. The simultaneous presence of two or more types of extremes emphasizes the intricate interplay of climatic factors. The current study does not delve into the investigation of concurrent events by intersecting these indices. Examining the convergence of these extremes can provide valuable insights into their interconnectedness and potential impacts, warranting a detailed assessment of affected sectors.

In this study, it is assumed that the same physical and societal conditions will prevail in the future; however, it is important to acknowledge that along with the relative value of change in any hydro-meteorological characteristics of a location; the spatial extent, location's climatology, the adaptive capacity of the human and natural system also plays a crucial role in determining the impact of the change in that location (Meehl et al. 2000), and non-climatic factors often play a key role in risk management and adaptation (CCSP 2008).

We only considered precipitation and temperature data for future projections. However, other variables like relative humidity, solar radiation and evapotranspiration may also change. There are also uncertainties in emission scenarios, GCMs, understanding of atmospheric processes, socio-economic development and policy responses. Analysing these uncertainties is beyond the scope of this study, and further research is needed.

Policy responses

The improved understanding of the potential impacts of climate change on health, water and agriculture is vital for designing effective adaptation strategies at the local level. Incorporating projected changes in policy formulation sectoral planning improves our understanding of the water-energy-food-health nexus for sustainable living. The integrated approach would better predict the associated risks and hazards arising from changing climate (Rising et al. 2022).

The Afghan government has made efforts to combat climate change, including the establishment of the National

Climate Change Committee (NCCC), implementation of the Afghanistan's Climate Change Strategy and Action Plan (ACCSAP) and the formulation of the National Adaptation Programme of Action and Nationally Determined Contribution (NDC). These initiatives demonstrate Afghanistan's commitment to low-emission development strategies and the need for financial, technological and capacity support for adaptation (NEPA 2017). The Ministry of Agriculture Irrigation and Livestock (MAIL) is also actively engaged in addressing climate change impacts and aligning with the Sustainable Development Goals (SDGs) (MAIL 2019). Our study on extreme climate events highlights the importance of considering their implications on key sectors for effective implementation of national and local adaptation plans as directed by the UNFCCC. Furthermore, improving monitoring efforts across the basin would provide valuable insights into the current status and help address challenges posed by projected climate change.

Conclusion

This study analysed future climate change scenarios and extreme events in the Kabul River Basin by downscaling the four GCM runs for RCP 4.5 and 8.5, based on their skill to represent the historical climate cycle. According to these selected GCM, the KRB is projected to experience an increase in the average annual temperature (by 2.6–5.1 °C) and precipitation (by 4.5–12.2%) with pre-monsoon (which accounts for 43% of the total precipitation) and winter precipitation decreasing by the end-century, thereby escalating climatic vulnerability. Further, the analysis of the extreme events in the basin brought forth some noteworthy points: warm days, consecutive summer days, consecutive dry days and the duration of heatwaves will increase; at the same time, the number of cold nights, consecutive frost days and the duration of cold waves will decrease.

The discussion section insights into how extreme may impact health, agriculture and water resources. These environmental challenges necessitate immediate actions, including the inclusion of the climate information across multiple sectors. A comprehensive evaluation of hydro-climatic variables and their impact on different sectors, combined with the development of the adaptation measures and policy responses will better equip the region for future climate-related challenges. It is crucial to emphasize the importance of a robust and effective climate information system at the sub-basin and regional levels, and an urgent need for policy responses to address climate change adaptation.

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Author contribution Kabi Raj Khatiwada conceptualized, designed and lead the overall analysis of the manuscript. Saurav Pradhanaga and Santosh Nepal helped in the methodology, analysis, interpretation, visualization of the results and finalizing the manuscript.

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Data availability The global data were downloaded from the climate4impact.eu portal and downscaled data can be shared on request to the corresponding author.

Code availability The codes for sectorial analysis can be shared on request to the corresponding author.

Declarations

Competing interests The authors declare no competing interests.

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