Temperature trend analysis: a case study of Kabul, Afghanistan

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Abstract

Climate change is one of the most important problems significantly affecting the exosphere, both directly and indirectly. The impacts of climate change can be disastrous not only for the environment but also for the lives, safety, and property of major populations, particularly in Afghanistan. This study assesses the variability of temperature trends in Kabul, Afghanistan. The predictands, i.e., the daily observed temperature data, were collected from local organizations, and the predictors were gleaned from the outputs of global climate models (GCM) based on the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). Two statistical downscaling models were used to simulate future climate conditions under three scenarios. Trend analysis was conducted by linear regression, and the performance of the two downscaling methods was checked by using measured indicators. The results revealed that temperature will increase from 2025 to 2100 relative to 1990-2020 under three model regional climate predictions (RCP). By 2100, the maximum temperature would increase by 1.8°C (7.7%), 2.5°C (10.3%), and 3.7°C (14.3%) according to RCP 2.6, RCP 4.5 and RCP 8.5, respectively. Moreover, the annual average temperature for the period of 2025-2100 was predicted to rise by 2.3°C (12.9%) under RCP 2.6, 2.6°C (14.3%) under RCP 4.5, and 3.6°C (18.8%) under RCP 8.5 relative to the reference period (1990-2020). Minimum temperatures also increase in the range of 2.2°C (19.9%) under RCP 2.6, 2.9°C (24.9%) under RCP 4.5 and 4.3°C (32.7%) under RCP 8.5. These temperature increases would affect ecosystems, crop production, human health, and many other sectors.

Keywords

Climate change, temperature trends, downscaling models, reference and projection periods, Kabul, Afghanistan.

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1. Introduction

Climate change is currently the most important topic globally. Many studies have determined the occurrence and effects of climate change worldwide (Saddique et al. 2019), but their impacts are not uniform across the globe: some regions are more susceptible to climate change (Munawar et al. 2022). It is widely accepted that human activities are major drivers of recent global climate change and global warming recorded since the pre-industrial era (Solomon et al. 2009). Changes in atmospheric properties impose a wide range of direct and indirect impacts on the environment, agriculture, food security, human health, and the hydrological cycle (Javadinejad et al. 2021). Meteorological properties change frequently, through significant changes in local distributional properties of temperature and precipitation, among other atmospheric variables (IPCC 2007a, 2007b, 2013). Changes in temperature variability can occur from diurnal to multi-decadal time scales and from the local to the global scale, potentially even displaying opposing signals in different seasons and at different spatial scales (IPCC 2022). According to the Intergovernmental Panel on Climate Change (IPCC) 6th assessment report, the projected average warming in Afghanistan will be about 1.4-6.0°C by the end of 2100.

In particular, the impacts of climate change are very serious for Afghanistan. Extreme events, including heat waves, floods, and droughts, are increasing, and they threaten the lives, safety, and property of major human populations (WBG 2021). The majority of Afghanistan's population relies on available natural resources directly or indirectly for their livelihoods (UNDP 2017). The increased frequency of extreme climatic events in Afghanistan has caused great economic losses (UNDP 2017) and threatens the foundations of the country's economy, stability, and food security. For example, the impacts of climate change have negative consequences for crop production; a reduction in crop yields reduces food security and damages the livelihoods of people. The country needs to promote and strengthen adaptation strategies to reduce the risks of climate change. It is important to know how trends, such as temperature trends, are changing.

Temperature trends were assessed by statistical downscaling models in this study. The observational data were acquired from local organizations such as the Ministry of Agriculture, Irrigation and Livestock (MAIL), the Ministry of Energy and Water (MEW), and the Meteorological Department of Afghanistan (MDA). The modeling study employed General Circulation Models (GCM) based on the Fifth Assessment Report (AR5) of the IPCC that is available in the Coupled Model Intercomparison Project Phase 5 (CMIP5). The GCMs support the assessment of potential climate change impacts on a global scale (Disasa, Haofang 2022). Predictors, in the statistical downscaling model (SDSM) for the relationship between the National Centers for Environmental Prediction (NCEP) predictors and local predictands (precipitation), were applied for screening purposes (Saddique et al. 2019; Munawar et al. 2022). The NCEP and National Center for Atmospheric Research (NCAR) data were acquired from the GCM (CanESM2) model.

The SDSM and the Long-Ashton research station weather generator (LARS-WG) are two well-known statistical downscaling models to downscale GCM outputs such as temperature, rainfall, and solar radiation (Saddique et al. 2019). Hence, many recent studies have focused on the evaluation and comparison of the two models in terms of their ability to simulate mean temperature and extreme temperature frequencies using a parametric distribution at a local scale (Hassan et al. 2014). The minimum temperature (T_{min}), maximum temperature (T_{max}), and average temperature (T_{ave}) were evaluated by using observed and generated climatic data under three representative concentration pathways (RCP) scenarios: RCP 2.6, RCP 4.5, and RCP 8.5. Future projections from the two models did not agree; the results of LARS-WG were close to the reference period, whereas SDSM projections differed significantly. Hassan et al. (2014) claimed that the different results arose from differences in downscaling strategies and basic concepts. Both models, however, can be adopted as downscaling tools for future periods (Hashmi et al. 2011; Hassan et al. 2014).

For Afghanistan, there are not many published papers on atmospheric trend analyses in recent years based on either of the two models. The main objective of this study is to assess atmospheric temperature change in the reference and future periods (1990-2100). The results will help to define the scale of change in temperature trends, thus supporting policies for adaptation and mitigation strategies to reduce climate change impacts.

2. Materials and methods

2.1. Study area

Afghanistan, located in the heart of south-central Asia between 33°56'2.54" N and 67°42'12.35" E (Sarwary et al. 2023), has a semi-arid climate (UNDP 2017; WBG 2021; Rasouli 2022). There is great variation in the climate, soil, topography, vegetation, and natural ecosystems of the country (Aich et al. 2017). Temperature varies greatly by season and altitude, with mountain regions ranging from <0 to >35°C. The average surface air temperature is 13.37°C with a range of 1.92°C, 13.74°C, 24.26°C and 13.41°C in December-February, March-May, June-August, and September-November, respectively. The average annual precipitation is 337.97 mm with a range of 134.35, 146.04, 22.03, and 35.05 mm in December-February, March-May, June-August, and September-November, respectively (WBG 2021).

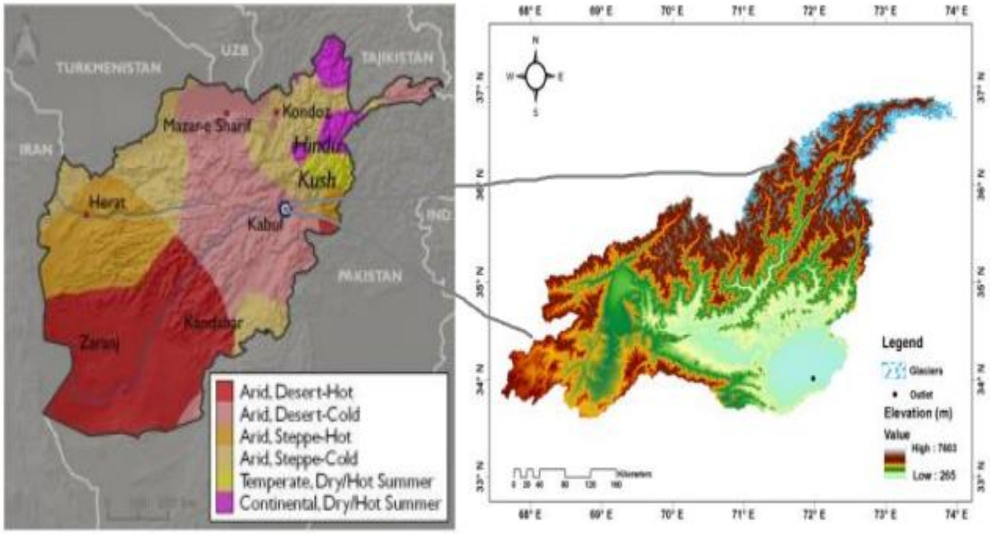

Fig. 1. The study area (USAID 2016; Bokhari et al. 2018).

This study was conducted in Kabul, the capital of Afghanistan, south of the Hindu-Kush mountain range. The climate of Kabul is affected by the climate of the Hindu-Kush mountains. This region has a continental, cold, semi-arid climate with rainfall concentrated in the winter and spring months. Winter (January-March) is a very cold season with snowfall, while spring is more humid with higher precipitation frequency. Summer has very low precipitation; it is the warmest season, with a longer sunshine period of about 356.8 hours per month in July and very low humidity (36% in June). Autumn has low rainfall of 3.7 mm, 18.6 mm, and 21.6 mm for October, November, and December, respectively, with warm afternoons and cool evenings. Kabul is situated at 34.45 N and 69.00 E at an elevation of 1805 m above mean sea level and covers a total area of 4655.25 km^2 (Table 1). The local steppe climate influences Kabul, which receives little yearly rainfall. The average annual temperature is 11.4°C, and the annual total precipitation is 362 mm. The driest month is June with about 1 mm of precipitation. Most rainfalls in March average 88 mm. July, with an average temperature of 23.2°C, is the warmest month. The lowest average temperature for the year is –2.9°C in January.

Table 1. Details of the meteorological stations in Kabul.

Station name	Lat (N)	Long (E)	Elevation (m)	Annual rainfall (mm)	Mean temperature (C)
Kabul – airport	34.55	69.21	1791	197	14.10

2.2. Data description

2.2.1. Site data

The daily observed maximum (T_{max}) and minimum temperature (T_{min}) were acquired from the meteorological stations collected by local organizations, including MDA, MAIL, and MEW, from 2003 to 2020 and online data sets. The thirty years of data (1990-2020) were used as the observed data period.

2.2.2. NCEP/NCAR reanalysis data

The daily reanalysis data for the baseline period were acquired from the NCEP/NCAR. NCEP predictors, in the SDSM model, for the relationship among the NCEP predictors and local predictands were applied for screening purposes (Saddique et al. 2019; Munawar et al. 2022). The NCEP/NCAR data were acquired from the GCM (CanESM2) model.

2.3. RCP Scenario Data

The Coupled Model Intercomparison Project Phase 5 (CMIP5) IPCC report that provides a wider picture of future climate change scenarios was used. Three future climate change scenarios, including a mitigation scenario (RCP 2.6), a medium stabilization scenario (RCP 4.5), and an extreme scenario (RCP 8.5) (Saddique et al. 2019) were selected for the periods of 1990-2100. RCPs describe different levels of greenhouse gases and other radiative forcing that might occur in the future. RCP 2.6 leads to a very low forcing level, RCP 4.5 leads to a medium forcing level, and RCP 8.5 leads to very high emission scenarios (Wayne 2013). Trend analysis was conducted by parametric methods such as regression.

2.4. Projection and downscaling

Downscaling of T_{min} and T_{max} was performed using two models, SDSM and LARS-WG. The available observed data were obtained from MAIL, AMD, and MEW and the missing data were derived from the open-source datasets for the period of 1990-2020.

LARS-WG is a stochastic weather generator that was applied for the simulation of weather data for reference and future climatic variable conditions. The observed climatic data (T_{max} and T_{min}) were used in LARS-WG to generate time series for future periods. The future climate scenarios were generated for the periods of 2025 - 2100 for selected RCPs (RCP 2.6, RCP 4.5, and RCP 8.5) based on the baseline parameters.

SDSM was used to develop the relationship between the predictands (T_{max} and T_{min}) and NCEP/NCAR predictors. NCEP predictors were used to simulate the time series data for the periods. The performance of the models to generate synthetic time series was calibrated and validated (Saddique et al. 2019; Javadinejad et al. 2021).

2.5. Model performance

Trend analysis was conducted by parametric methods such as linear regression as given by equation 1:

$$Y = a + bX \tag{1}$$

where: X is the explanatory variable; Y is the dependent variable; a is the intercept, b is the slope of the line.

The performances of the models were estimated by comparing the observed and generated T_{min} and T_{max} data by using statistical indicators. These indicators were computed by the equation 2-6 as follows:

$$R = \frac{\sum(X-\bar{x})(y-\overline{y})}{\sqrt{(x-\bar{x})^2-\sum(y-\overline{y})^2}} \tag{2}$$

$$R^2 = \text{Var-Exp by mod/ Total variance} \tag{3}$$

$$MAE = \frac{\sum_{i=1}^{n}[x_i-y_i]}{n} \tag{4}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}((Xi-Yi)2}{n}} \tag{5}$$

$$NRMSE = RMSE/Xi \tag{6}$$

Here: R is the correlation coefficient; R^2 is the determination coefficient; MAE is mean absolute error; $RMSE$ is root mean square error; $NRMSR$ is normalized root mean square error; X and Y are the values of variables; and $\bar{x}$ and $\bar{y}$ are the means of variables. Xi is the observed value of variables; Yi is the simulated value by the models; and n is the measured number (Ababaei et al. 2010; Delavar et al. 2016; Kounani et al. 2021; Munawar et al. 2022).

3. Results

3.1. Evaluation criteria

The results of the statistical measures proved both models were efficient over the validation period for the variables T_{min} and T_{max}. Table 2 illustrates measured indices of the statistical downscaling models. The models (SDSM and LARS-WG) were assessed (validated) by using statistical measures: R, R^2, MAE, $RMSE$, and

NRMSE (%) between observed and simulated data. The results of statistical measurements proved that both models are efficient for the estimation of T_{min} and T_{max}, as shown in Table 2.

Table 2. Performance indicators of maximum and minimum temperature

Variables	Models	*R*	R^2	*MAE*	*RMSE*	*NRMSE* (%)
T_{min}	LARS-WG	0.9996	0.9992	4.49	0.158	0.94
	SDSM	0.99	0.99	0.1121	0.159	0.85
T_{max}	LARS-WG	0.9989	0.9979	0.161	0.17	0.82
	SDSM	0.99	0.99	0.02	0.006	0.03

3.2. Temperature trend analysis for observation data

To analyze the variation of temperature variables for Kabul meteorological stations, daily observed data from local data sets (MAIL 2022; MDA 2022; MEW 2022) were used. The monthly and yearly averages of temperature are shown in Figure 2.

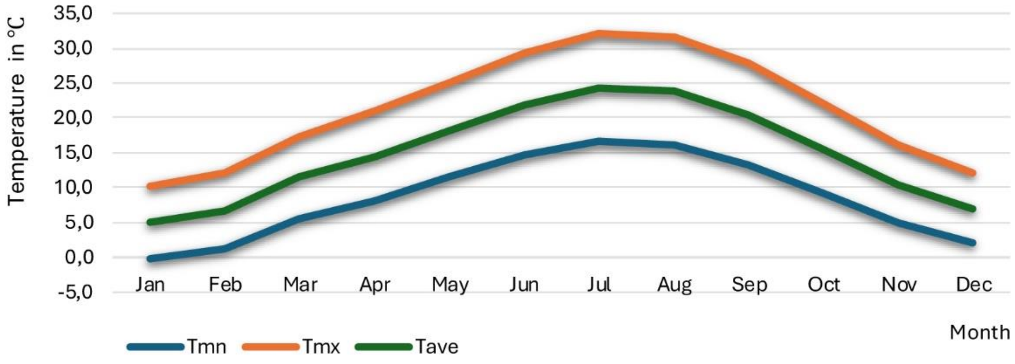

Fig. 2. The average monthly maximum (T_{max}), mean (T_{ave}), and minimum (T_{min}) temperatures during the reference period (1990-2020).

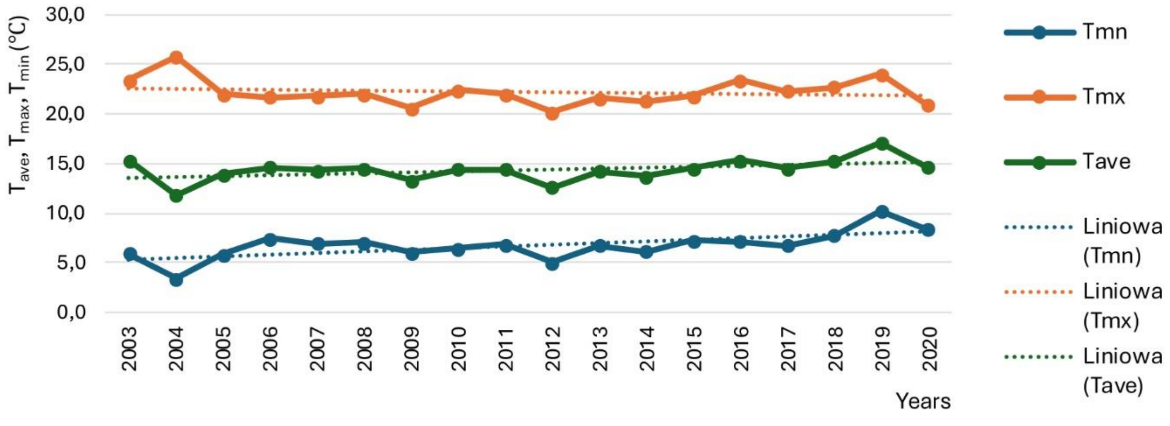

Fig. 3. Multi-year sequence (2003-2020) of the average annual maximum (T_{max}), annual mean (T_{ave}), and annual minimum (T_{min}) temperature.

Analysis of average monthly temperature trends indicates that January is the coldest month and July is the warmest month, with a range of –2 to 16.7°C in T_{min}, 5.0-24.3°C in average temperature, and 10.2-32.1°C in T_{max}.

3.3. Temperature trend analysis for the future

Annual changes were projected for maximum, average, and minimum temperatures under three RCPs for the future (2025-2100). Table 3 shows the projected average temperature during 2025-2100 based on the reference period (1990-2020) under RCP 2.6, RCP 4.5, and RCP 8.5. Moreover, Figure 3 shows the average temperature change compared to the future and baseline periods.

Table 3. Average annual average temperature during reference (1990-2020) and future (2025-2100) periods.

Annual average temperature (°C)				
	Ref.	RCP 2.6	RCP 4.5	RCP 8.5
1990	15.1			
1995	15.7			
2000	15.7			
2005	15.3			
2010	15.4			
2015	15.9			
2020	15.7			
2025		16.8	16.7	17.0
2030		16.8	17.0	17.3
2040		17.1	17.1	17.6
2050		17.7	18.0	18.8
2060		17.7	18.1	18.9
2070		17.7	19.0	20.7
2080		20.6	19.1	17.8
2090		17.8	19.2	21.9
2100		18.5	19.5	22.6
Average	15.6	17.8	18.2	19.2
Difference		2.3	2.6	3.6
Change (%)		12.9	14.3	18.8

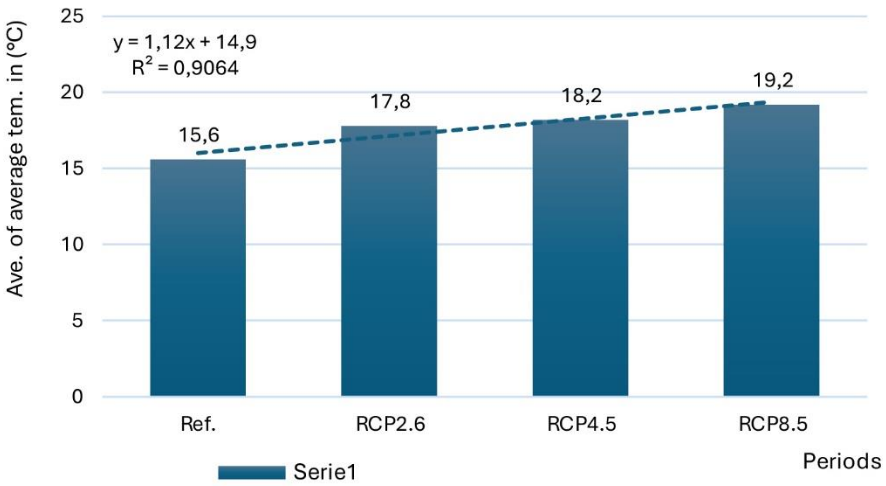

Fig. 4. The comparison of annual average temperature for the reference and future periods under different RCPs.

Average annual maximum temperature was shown in Table 4 and Figure 5 during reference and future periods.

Table 4. Average annual maximum temperature during reference (1990-2020) and future (2025-2100) periods.

Annual maximum temperature (°C)				
	Ref.	RCP2.6	RCP4.5	RCP8.5
1990	21.9			
1995	22.4			
2000	22.1			
2005	22.1			
2010	22.3			
2015	22.6			
2020	22.1			
2025		23.5	23.8	24.1
2030		23.6	23.5	23.7
2040		23.3	23.4	23.6
2050		24.2	24.6	25.3
2060		24.0	24.4	25.1
2070		24.4	25.7	27.1
2080		24.2	25.6	27.0
2090		24.5	25.8	28.5
2100		25.0	26.3	29.0
Average	22.2	24.1	24.8	25.9
Difference		1.8	2.5	3.7
Change (%)		7.7	10.3	14.3

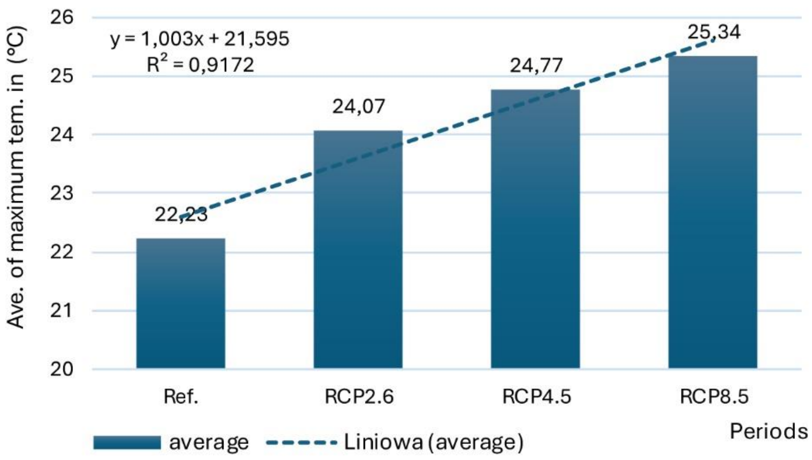

Fig. 5. The comparison of average maximum temperature for the reference (1990-2020) and future (2025-2100) periods under RCP 2.6, 4.5, and 8.5.

Table 5 and Figure 6 illustrated the average minimum temperature based on reference periods.

Table 5. Average annual minimum temperature during reference (1990-2020) and future (2025-2100) periods.

Annual minimum temperature (°C)				
	Ref.	RCP2.6	RCP4.5	RCP8.5
1990	8.3			
1995	9.0			
2000	9.2			
2005	8.5			
2010	8.5			
2015	9.2			
2020	9.3			
2025		10.1	10.6	11.0
2030		10.1	10.6	11.0
2040		10.9	10.9	11.4
2050		11.2	11.6	12.4
2060		11.5	11.9	12.8
2070		11.1	12.4	13.9
2080		11.5	12.7	14.3
2090		11.2	12.4	15.6
2100		12.1	13.3	16.3
Average	8.9	11.1	11.8	13.2
Difference		2.2	2.9	4.3
Change (%)		19.9	24.9	32.7

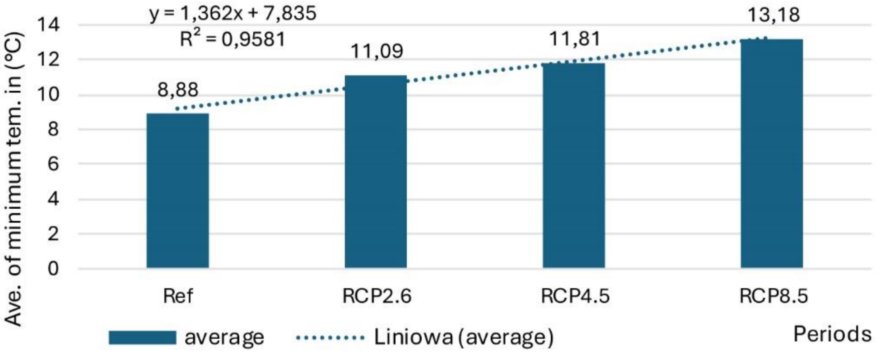

Fig. 6. The comparison of average minimum temperature for the reference (1990-2020) and future (2025-2100) periods under RCP 2.6, 4.5 and 8.5.

The annual change in temperature trends (average, maximum, and minimum temperature) is shown in Tables 6-8. Table 9 shows the monthly change in temperature trends. Table 9 shows the change in temperature trends by month (maximum, average, and minimum temperature) over the projection period (2025-2100)

The monthly projected T_{min} showed an increase ranging between 2.38°C, 3.20°C, and 4.61°C under RCP 2.6, RCP 4.5, and RCP 8.5, respectively. The monthly projected maximum temperature showed an increase ranging between 1.88°C, 2. ° C, and 3.92°C under RCP 2.6, RCP 4.5, and RCP 8.5, respectively. Also, the monthly projected average temperature showed an increase ranging between 2.13, 2.92, and 4.26°C under RCP 2.6, RCP 4.5, and RCP 8.5, respectively. The results showed a continuously increasing trend of projected temperature in future scenarios.

Table 6. Annual changes of maximum temperature during the projection period (2025-2100) under RCP 2.6, RCP 4.5, and RCP 8.5.

Annual change in maximum temperature (°C)			
	RCP2.6	RCP4.5	RCP8.5
2025	1.3	1.6	1.8
2030	1.4	1.2	1.5
2040	1.1	1.1	1.4
2050	2.0	2.4	3.1
2060	1.8	2.2	2.9
2070	2.1	3.5	4.9
2080	1.9	3.3	4.8
2090	2.2	3.6	6.3
2100	2.7	4.0	6.8
Avg.	1.8	2.5	3.7

Table 7. Annual change in average temperature during the projection period (2025-2100) under RCP2.6, RCP4.5 and RCP8.5.

Annual change in average temperature (°C)			
	RCP 2.6	RCP 4.5	RCP 8.5
2025	1.2	1.1	1.4
2030	1.2	1.4	1.7
2040	1.5	1.5	2.0
2050	2.1	2.4	3.2
2060	2.1	2.5	3.3
2070	2.1	3.4	5.1
2080	5.0	3.5	2.2
2090	2.2	3.6	6.3
2100	2.9	3.9	7.0
Ave.	2.2	2.6	3.6

Table 8. Annual change in minimum temperature during the projection period (2025-2100) under RCP 2.6, RCP 4.5 and RCP 8.5.

Annual change in minimum temperature (°C)			
	RCP 2.6	RCP 4.5	RCP 8.5
2025	1.23	1.7	2.14
2030	1.26	1.68	2.13
2040	2.03	2.06	2.5
2050	2.3	2.67	3.47
2060	2.64	3.06	3.89
2070	2.22	3.49	5.04
2080	2.61	3.83	5.42
2090	2.36	3.51	6.68
2100	3.21	4.38	7.44
Avg.	2.2	2.9	4.3

Table 9. Changes in temperature trends by month (T_{min}, T_{max}, and T_{avg}) under RCP 2.6, RCP 4.5, and RCP 8.5 over the period 2025-2100.

	T_{min}			T_{max}			T_{avg}		
	RCP 2.6	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5
Jan	2.56	3.57	5.11	2.06	3.14	4.08	2.31	3.35	4.60
Feb	3.64	4.88	6.28	2.85	3.96	4.92	3.24	4.42	5.60
Mar	3.86	4.76	6.27	2.66	3.42	4.76	3.26	4.09	5.52
Apr	3.96	4.65	6.07	3.70	4.58	6.06	3.83	4.62	6.07
May	3.07	3.54	4.75	2.95	3.81	5.10	3.01	3.68	4.93
Jun	2.34	2.84	3.99	2.66	3.47	4.64	2.50	3.16	4.32
Jul	1.79	2.55	3.73	1.22	1.78	2.96	1.50	2.16	3.35
Aug	1.33	2.28	3.58	1.33	1.74	3.05	1.33	2.01	3.32
Sep	1.05	2.04	3.53	0.63	1.14	2.79	0.84	1.59	3.16
Oct	1.67	2.57	4.12	0.61	1.16	2.81	1.14	1.86	3.46
Nov	1.74	2.52	4.06	0.79	1.52	2.82	1.26	2.02	3.44
Dec	1.71	2.37	3.94	1.23	2.09	3.12	1.47	2.23	3.53

4. Discussion and conclusion

This study was carried out to estimate temperature variables in the reference (1990-2020) and future (2025-2100) periods under RCP 2.6, RCP 4.5, and RCP 8.5 by using two statistical downscaling models (SDSM and LARS-WG). In general, according to the performance indicators, both models (SDSM and LARS-WG) are efficient for downscaling and projecting, but the LARS-WG model was approximately more suitable. The temperature trends (minimum, maximum, and average temperature) are shown to increase by a range of 0.28°C, 0.69°C, and 0.48°C, respectively the reference period (1990-2020).

The future temperature is predicted to increase from 2025 to 2100 at much higher rates compared to the reference period, under three RCPs. Average temperature showed an increase under RCP 2.6, RCP 4.5, and RCP 8.5 of 2.3°C, 2.6°C, and 3.6°C, respectively. Average temperature would increase by 12.9%, 14.3%, and 18.8% (Table 3, Fig. 4) by 2100 under RCP 2.6, RCP 4.5 and RCP 8.5, respectively. Maximum temperature would increase under RCP 2.6, RCP 4.5, and RCP 8.5 by 1.8°C, 2.5°C, and 3. ° C, respectively, for the future periods. Maximum temperature would increase by 7.7%, 10.3%, and 14.3% under RCP 2.6, RCP 4.5, and RCP 8.5, respectively, by 2100 compared to the reference period. Moreover, an increase in annual minimum temperature by 2100 was predicted at 2.2 C, 2.9 C, and 4.3 C under RCP 2.6, RCP 4.5, and RCP 8.5, respectively. The minimum temperature would increase at a rate of 19.9%, 24.9%, and 32.7% (Table 5, Fig. 6) under RCP 2.6, RCP 4.5, and RCP 8.5, respectively, during 2025-2100. Temperature increases with a range of values have been reported in many studies, such as Aich et al. (2017), Hassanyar et al. (2017), UNDP (2017), and WBG (2021). A 1°C increase from 1900-2017 was reported in WBG (2021). Annual temperatures have also been projected to increase by 3.50°C and 7.00°C (NEPA 2018), or 1.70°C and 2.30°C (Sarwary et al. 2023) by 2050; increases of 2.00°C and 6.50°C (FAO 2016) or 2.70°C and 5.50°C (WBG 2021) by 2100 under

RCP 4.5 and RCP 8.5, respectively, relative to the baseline period in Afghanistan. The temperature increase was projected to occur most rapidly during spring and summer at higher altitudes (central highlands and Hindu Kush) (NEPA 2018). Moreover, an increase in global mean temperature by 0.30-1.70°C under RCP 2.6, 1.10-2.60°C under RCP 4.5, and 2.60-4.80°C under RCP 8.5 has been projected by the end of the 21st century (2081-2100) relative to 1986-2005 (IPCC 2014). The global mean temperature is expected to increase by 1.40-5.80 C by 2100 (Sarwary et al. 2023).

This study revealed that temperature trends increase during reference and future periods. Climatic variation can affect many aspects of environmental systems. Although this study highlights temperature trends, additional climatic factors such as precipitation, wind speed, and solar radiation need further study. An increase in temperature would affect ecosystems, agricultural production, human health, and more environmental systems.

Afghanistan has faced a higher increasing temperature than the global average over the century, and it shows extreme vulnerability to hazards such as drought and flood. Findings revealed that an increase in temperatures (average temperature and maximum temperature) harms wheat production because of heat and drought stress, while the increase in minimum temperature has a positive effect on wheat production. This vulnerability is amplified by poverty, undernourishment, food insecurity, and inequality. These are the driving forces of negative impacts on agriculture, natural resources, natural ecosystems, forests, water resources, and society.

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