Projection of Hot and Cold Extremes in the Amu River Basin of Central Asia using GCMs CMIP6

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Abstract

The extreme temperature has become more frequent and intense due to global warming, particularly in dry regions, causing devastating impacts on humans and ecosystems. The transboundary Amu river basin (ARB) is the most vulnerable region in Central Asia (CA) to extreme weather linked to climate change. This study aimed to project warm and cold extremes in ARB for three Shared Socioeconomic Pathways (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) and two time-horizons, 2020–2059 and 2060–2099, using daily maximum ($T_{\max}$) and minimum temperature ($T_{\min}$) simulations of global climate models (GCMs) of Coupled Model Inter-comparison Project phase six (CMIP6). Results revealed that the basin's west experiences more hot extremes and the east more cold extremes. Climate change would cause a significant increase in the annual mean of $T_{\max}$ and $T_{\min}$. However, the increase in mean $T_{\min}$ would be much higher (5.0°C) than the mean $T_{\max}$ (4.6°C). It would cause an increase in the hot extremes and a decrease in the cold extremes in the basin. The higher increase in the hot extremes would be in the west, while the higher decrease in the cold extreme in the basin's east. The number of days above 40°C would increase from 45 to 60 days in the basin's west and northwest compared to the historical period. The number of days below -20°C would decrease up to 45 days in the basin's east. Overall, the decrease in cold extremes would be much faster than the increase in hot extremes.

1. Introduction

Global warming-induced climate change caused a change in temperature extremes' recurrence, intensity, duration, timing, and geographical variability (Hadi Pour et al., 2019; Pérez et al., 2021). The changes in temperature extremes significantly affected human health, agricultural yield, economic activities, social conflicts, biophysical environment (Shahid et al., 2017; Li et al., 2019; Pour et al., 2020a; Pérez et al., 2021; Zhao et al., 2021a). Natural hazards like the frequency and severity of heat waves, cold spells, aridity and forest fires have also been exacerbated by increasing temperature extremes (Ahmed et al., 2018; Ajjur and Al-Ghamdi, 2021; Khan et al., 2019). The recurrence, duration and severity of temperature extremes have also increased in CA like many other regions (Feng et al., 2018; Peng et al., 2020; Pour et al., 2020b; Zhang et al., 2019b). Global warming would be further intensified in the forthcoming years even if the carbon emission reduction is possible according to the Paris agreement (Du et al., 2021; Hamed et al., 2022c; Zhao et al., 2021a). Dry regions like CA are more vulnerable to temperature extremes for their friable ecosystem (Khan et al., 2019a; Salman et al., 2017). Evaluation of possible changes in temperature extremes is vital for such regions for adaptation and mitigation planning.

Global climate models (GCMs) of CMIP5 and earlier versions have been widely used for the projection of climatic extremes in many regions of the globe (Ajjur and Al-Ghamdi, 2021; Li et al., 2019; Seong et al., 2021; Sharafati et al., 2020; Ying et al., 2020; Zhao et al., 2021b). CMIP6 is the latest generation of CMIPs that integrated radiative concentration pathways with shared socioeconomic pathways for climate change projections. The CMIP6 GCMs have some advantages, including enhancement in model structure, spatial resolution, uncertainty, and representing synoptic progressions (Eyring et al., 2016; Hamed et al., 2022c; Kamal et al., 2021; Su et al., 2021a). This emphasizes reassessing the changes in temperature

extremes for new scenarios using CMIP6 to update the knowledge of climate change implications on temperature extremes and rationalize the adaptation strategies planned based on CMIP5 projections.

Uncertainties associated with GCMs hinder the reliable projection of extreme temperature (Pour et al., 2018; Shiru et al., 2020; Shiru et al., 2019). Generally, projection uncertainties are minimized using GCMs ensemble, selected according to their ability to replicate the observed climate (Ahmed et al., 2020; Hamed et al., 2022a; Hassan et al., 2020; Lutz et al., 2016; Salman et al., 2018). Different methods, including statistical metrics, multi-objective linear programming and machine learning methods, have been used to assess GCMs' past performance and create an ensemble using best performing GCMs (Hamed et al., 2022b; Nashwan and Shahid, 2020; Noor et al., 2019; Shiru et al., 2020; Srivastava et al., 2020).

The extreme indices are commonly used to assess the changes in climatic extremes. The Expert Team on Climate Change Detection and Indices (ETCCDI) proposed 27 extreme climate indices, including 16 temperature extremes (Ying et al., 2020). These extremes are based on days with temperatures above or below specific physically-based thresholds or quantiles (Zhang et al., 2011; Khan et al., 2019b). Therefore, they can provide different characteristics of both hot and cold extremes related to social impacts. This has made them widely used for assessing temperature extremes across the globe.

Amu river, the largest transboundary river and the primary source of CA's freshwater, flows within five riparian's countries (Dilshod et al., 2021). The livelihoods and economy of approximately 80 million people from these countries depend on water supplies by ADR (Hu et al., 2021; Saidmamatov et al., 2020). About 6 million hectares (ha) of lands in Uzbekistan in Turkmenistan, Afghanistan, Tajikistan and Kirgizstan are irrigated by the Amu river (Ahmad and Wasiq, 2004). The basin's hydrology has undergone tremendous change in the recent past due to human intervention in river flow (Khaydar et al., 2021). The increased temperature in the basin has worsened this situation and imposed further stresses on water resources and public health (Hoell et al., 2020; Hu et al., 2021; Su et al., 2021b). Xu et al. (2021) projected that increased temperature in the Amu river basin (ARB) would decrease river flow by 78.8–98.7% during 2021–2050. The faster glacier melting under a warmer climate would shift the peak flow from summer to spring. Su et al. (2021b) projected to decline in the glacier extent in ARB by 71.9% for RCP8.5 over 2021–2100. This decline of the glacier would reduce future runoff and water availability especially for irrigation in summer in crop season the downstream of the river. Increased temperature extremes would worsened the situation. Studies related to changes in temperature extremes in CA is very limited (Table 1). Focus of none of the previous studies was ARB.

The present study aimed to assess the change in temperature extremes in ARB. Daily $T_{\max}$ and $T_{\min}$ simulations of four CMIP6 GCMs for four SSPs were used to project the changes in twelve temperature extremes over ARB. Maps were prepared to show the geographical distribution for the changes for different scenarios and future horizons, which could be used for growing public awareness and devising adaptations.

Table 1
Existing temperature extreme studies in CA's regions

Author	Major Findings
Feng et al. (2018)	Rise in both $T_{\max}$ and $T_{\min}$, but it was faster for $T_{\max}$. Warm indices showed a substantial increase from Turkmenistan to China.
Hu et al. (2016)	Increasing trend in $T_{\min}$ and $T_{\max}$ at annual and seasonal scales, except in winter $T_{\max}$. Increase in warm nights and days and decrease in the cold nights and days
Peng et al. (2020)	Increase in annual maximum of $T_{\max}$ and minimum of $T_{\min}$ for all RCPs
Zhang et al. (2019a)	Increase in $T_{\max}$ and $T_{\min}$ and extremes related to $T_{\min}$.
Zhu et al. (2020)	Increase in $T_{\max}$ and $T_{\min}$ and days having $T_{\min} > 25^{\circ}\text{C}$, while decrease in days having $T_{\min} < 0^{\circ}\text{C}$ for all RCPs.
Liu et al. (2020)	Increase in mean temperature in CA by 1.48°C for 1.5°C warming scenario. Increase in hot days and growing season length.
<i>RCP= Representative concentration pathways.</i>	

2. Study Area And Data

2.1 Amu river basin

The ADR is the main water resource in CA and a major feeder of the Aral Sea (average discharge $78.5 \text{ km}^3/\text{year}$). It flows 2,540 km within riparian countries, including Tajikistan, Kyrgyzstan, Afghanistan, Turkmenistan, Uzbekistan, and ends at the Aral sea (Gao et al., 2021; Hu et al., 2021). It mostly recharges by glaciers and snow melted water, especially by Vakhsh and Pyandj tributaries as headwaters in the high mountain of the Pamir, Tien Shan and Hindukush in Tajikistan and Afghanis, which contribute 85% of river flow (Kattakulov et al., 2021; Schlüter et al., 2013). The topography of the basin (Figure 1) is complex, with 7,750 m elevation in the high upstream mountains to 200 m in the plains. The climate of the ARB is continental, with a yearly average temperature of 13.1°C and total precipitation of 1015 mm in the upstream mountains and 100 mm in the low lands deserts (Gao et al., 2021; Salehie et al., 2021b). The annual evaporation in ARB is nearly 2000 mm (Wang et al., 2021).

2.2 Datasets

Daily $T_{\max}$ and $T_{\min}$ of four GCMs CMIP6 were used to project temperature extremes in ARB (Table 2). Salehie et al. (2021a) evaluated the skill of 19 GCM-CMIP6 for the ARB and found these four GCMs as the best in simulating the observed climate of the basin. Therefore, these four GCMs were selected. The first

models run (r1i1p1f1) was applied for a fair comparison. GCMs' simulations were obtained from: <https://esgf-node.llnl.gov/search/cmip6/>.

Table 2
General circulation models (GCMs) used in this study.

No	Model name	Institution	Country	Resolution
1	AWI-CM-1-1-MR	Alfred Wegener Institute Climate Model	Germany	0.9°×0.9°
2	CMCC-ESM2	Fondazione Euro-Mediterranean Center on Climate Change	Italy	0.9°×0.9°
3	INM-CM4-8	Institute for Numerical Mathematics	Russia	1.5°×2.0°
4	MPI-ESM1-2-LR	Max Planck Institute Earth System Model	Germany	1.875°×1.86°

3. Methods

The present study evaluated twelve temperature extremes, as described in Table 2. The threshold-based extremes were estimated, considering 1975-2014 as the base period. These indices were calculated using the matrixStats package of R software. The GCMs were interpolated to 1°×1° resolution, nearly to the mean resolution of all GCMs, using the bilinear interpolation method discussed in Hamed et al. (2021) to avoid inconsistency due to spatial resolutions (Nashwan and Shahid, 2020). The hot and cold extreme indices were assessed using T_{max} and T_{min} of CMIP6 for the historical and the two future periods at 73 grids over the ARB, and the changes were presented using maps.

Table 2
Definition of the hot and cold temperature indices used in this study

Index	Definition	Unit
MxT_{max}	Annual highest maximum temperature	°C
$MeanT_{max}$	Annual mean maximum temperature	°C
$p95T_{max}$	Temperature above 95-th percentile during the base years	°C
$p99T_{max}$	Temperature above 99-th percentile during the base years	°C
$D40T_{max}$	Days with temperature more than 40 °C	Days
$D45T_{max}$	Days with temperature more than 45 °C	Days
MnT_{min}	Annual lowest minimum temperature	°C
$MeanT_{min}$	Annual mean minimum temperature	°C
$p05T_{min}$	Temperature below 5-th percentile during the base years	°C
$p01T_{min}$	Temperature below 1-th percentile during the base years	°C
$D20T_{min}$	Days with temperature less than -20 °C	Days
$D30T_{min}$	Days with temperature less than -30 °C	Days

4. Results

This study evaluated six hot extremes: MxT_{max} , $MeanT_{max}$, $p95T_{max}$, $p99T_{max}$, $D45T_{max}$, $p99T_{max}$ and six cold extremes, MnT_{min} , $MeanT_{min}$, $p05T_{min}$, $p01T_{min}$, $D20T_{min}$ and $D30T_{min}$. The spatial distribution of the indices for the reference or base period (1975-2014) and their projected changes in the near (2020-2059) and far (2060-2099) futures for four SSPs are presented in the following sections.

4.1 Hot Extreme

Figure 2 shows the spatial variability of MxT_{max} for the reference period and its changes in two future time horizons for four SSPs. The figure indicates that the annual maximum of T_{max} is highest (47°C) in the west and northwest of the basin. It gradually decreases towards the center (32 to 44°C) and reaches a minimum, 23°C in the basin's east. The geographical variability of projected change in the MxT_{max} was almost similar for all SSPs. SSP1-2.6 showed a similar increasing pattern in MxT_{max} in the two future periods, while SSP2-4.5 showed a greater increase in MxT_{max} during 2020-2059 than during 2060-2099. The highest increase in MxT_{max} (3–6°C) was projected in the far future for higher SSPs. The lowest rise in MxT_{max} was projected in the basin's center and north for all SSPs. However, the projected highest rise

in MxT_{max} was different for different SSPs. For higher SSPs, a greater increase in MxT_{max} was projected in the east and central northwest of the basin.

The spatial distributions of $MeanT_{max}$ for the reference 1975-2014 period and its change in two future time horizons are shown in Figure 3. The highest $MeanT_{max}$ for the reference period (22.5°C) was in the west and northwest of the basin. It gradually decreases towards the center ($7.5\text{--}20^{\circ}\text{C}$) and reaches in the range of $0\text{--}2.5^{\circ}\text{C}$ in the basin's east. The $MeanT_{max}$ was projected to increase more for higher SSPs. For example, SSP1-2.6 projected an increase in $MeanT_{max}$ by 1.8°C , while SSP5-8.5 by 2.2°C in the near future. Greater changes were also projected in the late period. For example, the increases were between 2.2 and 2.6°C in the near future for different SSPs, while those were between 4.2 and 4.6°C in the far future.

Figure 4 presents the results obtained for T_{max} above 95-th percentile ($p95T_{max}$) in the ARB. The highest value of $p95T_{max}$ (40°C) was observed in the basin's west and northwest and the lowest in the east (15°C). The $p95T_{max}$ was projected to increase gradually from lower to higher scenarios and from the early to the later period. The increase would be 1.5°C in the near future for SSP1-2.6, and between 1.5 and 2.5°C for SSP5-8.5. For the far future, it would be $1.5\text{--}3^{\circ}\text{C}$ for SSP1-2.6 and 5.5°C for SSP5-8.5. Overall, a greater change in $p95T_{max}$ over the whole basin was projected for SSP-7.0 (between 4 and 5°C) followed by SSP2-4.5 (up to 3.5°C).

Figure 5 showed the changes in T_{max} above 99-th percentile ($p99T_{max}$) in the ARB for two future periods and four SSPs. Different parts of the basin showed different patterns in $p99T_{max}$. The highest $p99T_{max}$ during the reference period was 45°C in a small patch in the west. It was between 20 and 40°C in the center, north, south and northwest, and only 15°C in the basin's east. The projected change showed a steady rise in $p99T_{max}$ with time. SSP1-2.6 showed changes between 1.0 and 1.5°C in the early and 2°C in the late periods. The projected increase for SSP5-8.5 was between 1.5 and 2.5°C in the near and 4.5 and 5°C in the far future. The result revealed that the rise in $p99T_{max}$ from the early to the late period was faster for higher SSPs than the lower SSPs. The geographical variability of the projected changes revealed the largest increase in the west, northwest and a small part in the centre of the basin.

The spatial pattern of increase in $D40T_{max}$ is presented in Figure 6. The geographical distribution of hot days for the historical and future periods was more or less similar. The $D40T_{max}$ varies from $25\text{--}50$ days in the west and northwest to 5 days in the basin's center and east for the reference period. An increase in $D40T_{max}$ was projected by 5 to 60 days for different SSPs and futures. All the scenarios projected the increase in $D40T_{max}$ only in the basin's north and northwest and no change in the east. A gradual expansion in the area of increased $D40T_{max}$ was noticed with time. The results increase more hot days in the region where hot days are already very high.

A similar increase in the days with a temperature higher than 45°C ($D45T_{max}$) was also noticed (Figure 7). In other parts of the basin, it may seldomly reach above 45°C . The spatial distribution of $D45T_{max}$ for

the reference period showed that it only occurs for up to 7 days in the basin's west. The projection of D45 showed a possible increase by 5 to 45 days. But the increases would be concentrated only in the basin's northwest. The increase will be much faster in the later period for all SSPs than in the earlier period. The projected increase in $D45T_{max}$ for SSP1-2.6 was 10 to 15 days for the far future. It indicates a nearly 100% increase in extremely hot days in the northwest of the basin, even if the global temperature can be restricted to below 2°C according to the Paris agreement.

4.2 Cold Extreme

The spatial pattern of annual minimum temperature (MnT_{min}) for the base period and the projected changes in MnT_{min} in ARB for two future time horizons for four SSPs are presented in Figure 8. The basin experiences the lowest MnT_{min} (-40°C) in the east. It varies between -20 and -35°C in the rest of the basin. This means all the basin experiences frosting temperatures during winter. The changes in MnT_{min} were like other indices, greater changes in the later period than the early period and a higher increase for higher SSPs than lower SSPs. The highest increase in MnT_{min} (13°C) was projected in a small portion in the northwest for SSP5-8.5, followed by SSP3-7.0 (12°C), SSP2-4.5 (10°C) and SSP1-2.6 (8°C). However, the change in MnT_{min} across the whole basin was between 0 and 10°C for SSP1-2.6 and SSP2-4.5, and between 2 and 13°C for SSP3-7.0 and SSP5-8.5 in the far future. Overall, the results revealed a higher increase in MnT_{min} compared to MxT_{max} . It indicates the extreme cold temperature is decreased faster than the increase in extremely hot temperature.

The spatial distribution of $MeanT_{min}$ and its projections are present in Figure 8. The lowest $MeanT_{min}$ (-12°C) was noticed in the basin's east and the highest (12°C) in the west and northwest. The $MeanT_{min}$ in the north, south and center of the basin was between 0 and 9°C. The projected change in $MeanT_{min}$ showed a gradual increase from lower to higher SSPs and from the near to the far future. In the early period, the projected increase in $MeanT_{min}$ was between 1.4 and 1.8°C for SSP1-2.6 and SSP5-8.5, respectively, while it was between 1.8 and 5°C in the far future for the same SSPs. The highest increase in $MeanT_{min}$ was noticed in a narrow path in the basin's north, south, east and northwest for the far future. In contrast, the spatial distribution of projected change in $MeanT_{min}$ was different for different SSPs in the near future. However, the projected increase was higher in the south for most SSPs.

The geographical distribution of $p05T_{min}$ and its projected changes are shown in Figure 10. The basin's east experiences the lower $p05T_{min}$ (-20 to -30°C) than the other parts (-5 to -10°C). Besides, a small patch in the basin's south also experiences a relatively high $p05T_{min}$ (-15 and -20°C). The geographical variability in $p05T_{min}$ projection was similar for all SSPs in the near future (1 to 3°C). It was projected to rise between 2.5 and 7.5°C for the far future for all SSPs. The highest increase (7 to 7.5°C) was in the north, south and smaller area in the center and northwest for SSP5-8.5. Overall, a higher increase in $p05T_{min}$ in the basin's north and south was noticed.

Figure 11 shows the spatial distribution of $p01T_{min}$ and its projections for two future periods in ARB. The lowest $p01T_{min}$ (-35°C) was observed in the basin's east and the highest (-10°C) in the rest of the basin. The $p01T_{min}$ was projected to increase from the early to the late period. The geographical distribution of the change in $p01T_{min}$ was similar for all SSPs in the near future. They showed an increase in $p01T_{min}$ in the range of 1 to 4°C . However, the spatial pattern of the increase was different for the far future. A large increase in $p01T_{min}$ (up to 8.5°C) was projected for higher SSPs than only in the range of 1 to 5°C for low SSPs. This indicates a very fast rate of increase in $p01T_{min}$ in the later period for higher SSPs.

Figure 12 shows the spatial distribution of $d20T_{min}$ for the reference period. The changes in $d20T_{min}$ for two future periods and four SSPs are also presented. The $d20T_{min}$ varies from 100 days in the river upstream of the basin to 10 days in the west. The $d20T_{min}$ was projected to decrease for the whole basin. However, the decrease would be more (25 to 45 days) in the cold regions (river upstream) than in the other parts (5 days). The results indicate cold days would decrease more where it is more frequent and less where it is less experienced. This would make the geographical variability of cold days more homogeneous over the basin.

The spatial distribution of $d30T_{min}$ for the reference period was similar to $d20T_{min}$ (Figure 13). The $d20T_{min}$ was only noticed in the eastern mountainous cold region. It seldomly occurs in other parts of the basin. The projected changes in $d20T_{min}$ showed decreases in its occurrence in the range of 5 to 25 days for different SSPs. The decrease would be much higher in the far future for higher SSPs. However, there would be a more or less similar decrease in $d20T_{min}$ for all scenarios in the near future. There would also not be a significant difference in the projected changes in $d20T_{min}$ between the near and far future for SSP1-2.6. The results indicate a decrease in freezing days by 5 to 10 days in the near future, even for the mildest climate change scenario (SSP1-2.6)

5. Discussion

The changes in hot and cold extremes in the ARB for two future periods under four SSPs have been evaluated in this study. The results indicate that the frequency, intensity, spatial extent, and temporal variations in temperature extremes have increased in CA's arid and semi-arid regions. Overall, the study revealed that increases in hot extremes and decreases in cold extremes in the basin. However, decreases in cold extremes would be much faster than increases in hot extremes. No study previously assessed the changes in temperature extremes in ARB using CMIP6 models and SSPs. However, the study's findings collaborate with those obtained using CMIP5 models and RCP scenarios. Zhu et al. (2020) reported a temperature rise between 2.0°C and 5.0°C and the consequent decrease in the annual freezing days over CA for RCP4.5 and 8.5. Hu et al. (2016) also showed that the warmer days would increase and cold days would decrease over CA.

The present study revealed greater changes in temperature extremes for higher SSPs and the far future. However, some indices showed similar changes for all SSPs in the near future. For example, the

geographical variability of projected change in the MxT_{max} was almost similar for all SSPs in the near future. However, a large change was noticed between the near and far future for most indices for higher SSPs. For example, a decrease in $MeanT_{min}$ for SSP5-8.5 was projected between 1.4 and 2.2°C in the early period, while it was projected in the range of 4.2 to 5.0°C in the far future for the same SSP. Similar large shifts were also noticed for almost all hot and cold extremes. This indicates a sharp change in some temperature extreme in the latter part of the century for higher SSPs in the ARB.

Some of the temperature extremes were noticed to increase significantly even for the mildest climate change scenario (SSP1-2.6). For example, the days with a temperature higher than 45°C ($d45T_{max}$) is nearly 0-7 days in the basin for the reference period. It was projected to increase by 5 to 10 days in the early period and 5 to 15 days in the late period for SSP1-2.6. This indicates a two-fold increase in $d45T_{max}$ in the early period and nearly three folds in the far future. Similarly, $d40T_{max}$ was projected to increase two-fold in the late period for SSP1-2.6. This indicates a sharp rise in hot days in ARB, even if the global temperature can be restricted to 2°C, according to the Paris agreement.

Overall, the minimum temperatures were projected to increase more than the maximum temperature. For example, MnT_{min} was projected to increase up to 13°C while MxT_{max} by nearly 7°C. The $MeanT_{max}$ was projected to rise up to 4.6°C while the $MeanT_{min}$ was more than 5.0°C. This indicates higher effects of climate change on cold extremes than the hot extremes in the basin. Global mean surface air temperature has been projected to rise by 2.6~4.8°C in the late period for RCP8.5 (Olsson et al., 2014). In contrast, global warming would increase the mean temperature of the basin by up to 6.5°C by 2100 (Reyer et al., 2017). This indicates higher impacts of global warming in ARB. The present study also indicates that increased mean temperature would intensify the extreme temperature events in ARB (Guo et al., 2018; Yu et al., 2020).

The ARB flows through several CA's arid and semi-arid countries, having a fragile ecosystem that is susceptible to global warming-induced climate change (Hu et al., 2021; Luo et al., 2020). The basin would experience a large increase in temperature extremes even the temperature rise could be limited to below 2°C by 2100. Increased temperature extreme might cause severe implications in the basin, including reduction of vegetation cover, agricultural irrigation demand, declination of glacier extent, increase in surface runoff and a shift in water available period (Luo et al., 2020; Su et al., 2021b; Wegerich, 2002). Water stress, land degradation and insufficient environmental management capability have made CA highly vulnerable to many natural hazards (Luo et al., 2020; Reyher et al., 2017; Yu et al., 2020; Zhang et al., 2019a). Increased temperature extremes will certainly aggravate the situation if vulnerability reduction measures are not adopted.

6. Conclusion

This study attempted to assess characteristics of hot and cold extremes over ARB using twelve indices. Results revealed that the number of hot days would increase especially in the far future. In contrast, the number of cold days would likely decrease. The increase in the number of hot extremes would be higher

in the basin's west to northwest, while the decrease in cold extremes would be only in the east, which generally experiences a long cold period. These extreme temperature changes reflect a noticeable impact of climate change in the ARB. The information generated in this study can be useful for researchers. It can also serve as a good base for developing mitigation strategies and decision-making planning. The maps and data generated in this research can be used for other climate applications. Future work should consider other indices like heat and cold waves. In addition, a comparative study using CMIP5 and CMIP6 models can be conducted to quantify the changes needed in adaptation planning that was derived using CMIP5 models.

Declarations

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Conflict of interest

The authors declare no conflict of interest.

Availability of data:

All the data are available in the public domain at the links provided in the texts

Availability of code

The codes used for the processing of data can be provided on request to the corresponding author.

Authors contribution

All the authors contributed to conceptualizing and designing the study. Obaidullah Salehie and Tarmizi bin Ismail gathered data; the programming code was written by Shamsuddin Shahid and Mohammed Magdy Hamed; the initial draft of the paper was prepared by Obaidullah Salehie and Mohd Khairul Idlan Muhammad; the article was repeatedly revised to generate the final version by Tarmizi bin Ismail and Shamsuddin Shahid.

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Figures

Figure 1

Topography of the Amu river basin and its location in Central Asia.

Figure 2

Spatial distribution of the annual maximum of $T_{\max}$ ($MxT_{\max}$) for the reference period and the projected changes in $MxT_{\max}$ in the near and far futures for four SSPs.

Figure 3

Same as Figure 2, but for the annual mean of $T_{\max}$

Figure 4

Same as Figure 2, but for $T_{\max}$ above 95-th percentile.

Figure 5

Same as Figure 2, but for $T_{\max}$ above 99-th percentile.

Figure 6

Spatial distribution of the days with a temperature higher than 40°C ($D40T_{\max}$) and the projected changes in $D40T_{\max}$ in the near and far futures for four SSPs.

Figure 7

Same as Figure 6, but the days with a temperature higher than 45°C

Figure 8

Spatial distribution of the annual minimum of $T_{\min}$ ($MnT_{\min}$) for the reference period and the projected changes in $MnT_{\min}$ in the near and far futures for four SSPs.

Figure 9

Same as Figure 8, but for the annual mean of $T_{\min}$.

Figure 10

Same as Figure 8, but for $T_{\min}$ below 5-th percentile

Figure 11

Same as Figure 8, but for $T_{\min}$ below 1-th percentile

Figure 12

Spatial distribution of the days with a minimum temperature of less than -20°C ($D20T_{\min}$) and the projected changes in $D20T_{\min}$ in the near and far futures for four SSPs.

Figure 13

Same as Figure 12, the days with a minimum temperature of less than -30°C ($D30T_{\min}$)