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PROJECTED CLIMATE CHANGE AND HYDROCLIMATIC EXTREMES BASED ON THE CMIP6 MULTI-MODEL ENSEMBLE: A CASE STUDY OF THE ARAL-SYR DARYA BASIN

The Aral-Syr Darya Basin, a complex mountain-plain river system, is already experiencing strong climatic and anthropogenic stress affecting water security. This study analyzes observed climatic changes and provides a multi-model ensemble-based assessment of future climate conditions and associated uncertainties in the region. The analysis is based on climate projections under the SSP3-7.0 and SSP5-8.5 scenarios from the CMIP6 multi-model ensemble relative to the 1981–2010 baseline period. Changes in mean temperature, precipitation intensity (RX1day), maximum duration of dry periods (CDD), and the number of extremely hot days (TX35) were examined. The results indicate substantial warming by the end of the 21st century, reaching +6.0–6.8 °C. The number of extremely hot days is projected to exceed 61 days per year. Total precipitation may increase by 17–20%, accompanied by greater irregularity with stronger rainfall events and longer dry intervals. A shift in peak precipitation from summer to the winter-spring period was revealed, leading to a “wet year–dry summer” dissociation. These projected atmospheric changes increase potential risks for regional hydrobiology and water availability, particularly in arid lowlands, intensifying summer water scarcity and desertification processes. The findings highlight the urgent need to strengthen transboundary water management cooperation within the Syr Darya Basin to support regional climate adaptation.

Keywords: climate indices, CMIP6, droughts, extreme precipitation events, IPCC AR6 Interactive Atlas.

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CMIP6 көпмодельді ансамблі негізінде климаттың болжамды өзгерістері мен гидроклиматтық экстремалды құбылыстарды бағалау: Арал-Сырдария өзені алабы мысалында

Арал-Сырдария алабы – су қауіпсіздігіне әсер ететін климаттық және антропогендік қысым-ға ұшыраған күрделі таулы-жазықтық өзен жүйесі. Бұл зерттеуде өңірдегі байқалған климаттық өзгерістер талданып, болашақ климаттық жағдайларға ықтималдық тұрғысынан баға берілді. Талдау 1981–2010 жылдардағы базалық кезеңмен салыстырылып, CMIP6 көпмодельді ансамблінің SSP3-7.0 және SSP5-8.5 сценарийлері бойынша алынған климаттық болжамдар негізінде жүргізілді. Орташа ауа температурасының, жауын-шашынның тәуліктік ең жоғары мөлшерінің (RX1day), құрғақ кезеңдердің ең ұзақ ұзақтығының (CDD) және өте ыстық күндер санының (TX35) өзгерістері қарастырылды. Зерттеу нәтижелері ХХІ ғасырдың соңына қарай ауа температурасының айтарлықтай артып, +6,0–6,8 °C-қа дейін жететінін көрсетті. Өте ыстық күндердің саны жылына 61 күннен асуы мүмкін. Жылдық жауын-шашын мөлшерінің 17–20%-ға артуы болжанымымен, оның кеңістіктік-уақыттық біркелкілігі төмендеп, нөсерлі жауын-шашын оқиғаларының күшеюі және құрғақ кезеңдердің ұзаруы күтіледі. Сонымен қатар жауын-шашынның ең жоғары мөлшері жаз мезгілінен қыс-көктем кезеңіне ауысатыны анықталды, бұл «ылғалды жыл – құрғақ жаз» құбылысының қалыптасуына әкеледі. Аталған өзгерістер, әсіресе, алаптың қуаң жазық өңірлерінде су тапшылығы қаупін күшейтіп, шөлейттену үдерістерін жеделдетуі мүмкін. Алынған нәтижелер климаттың өзгеруіне бейімделуді қамтамасыз ету мақсатында Сырдария алабындағы трансшекаралық су ресурстарын бірлесіп басқару тетіктерін жетілдірудің өзектілігін көрсетеді.

Түйін сөздер: климаттық индекстер, CMIP6, құрғақшылық, экстремалды жауын-шашын құбылыстары, IPCC AR6 интерактивті атласы.

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Прогнозируемое изменение климата и экстремальные гидроклиматические явления на основе многомодельного ансамбля CMIP6: на примере бассейна реки Арал-Сырдарья

Бассейн Арал-Сырдарья, представляющий собой сложную горно-равнинную речную систему, уже испытывает сильную климатическую и антропогенную нагрузку, влияющую на водную безопасность. В этом исследовании анализируются наблюдаемые климатические изменения и дается ансамблевая оценка будущих климатических условий в регионе. Анализ основан на климатических прогнозах в соответствии со сценариями SSP3-7.0 и SSP5-8.5 из многомодельного ансамбля CMIP6 относительно базового периода 1981–2010 годов. Были изучены изменения средней температуры, интенсивности осадков (RX1 день), максимальной продолжительности засушливых периодов (CDD) и количества чрезвычайно жарких дней (TX35). Результаты указывают на существенное потепление к концу 21-го века, которое достигнет +6,0–6,8 °C. По прогнозам, количество чрезвычайно жарких дней превысит 61 день в году. Общее количество осадков может увеличиться на 17–20%, что будет сопровождаться большей неравномерностью, более сильными осадками и более длительными периодами засухи. Было выявлено смещение пика осадков с летнего на зимне-весенний период, что привело к разделению «влажный год – сухое лето». Ожидается, что эти изменения усилят риски нехватки воды, особенно в засушливых низменностях, и ускорят процессы опустынивания. Полученные результаты подчеркивают настоятельную необходимость укрепления трансграничного сотрудничества в области управления водными ресурсами в бассейне реки Сырдарья для поддержки региональной адаптации к изменению климата.

Ключевые слова: климатические индексы, CMIP6, засухи, экстремальные осадки, интерактивный атлас IPCC AR6.

Introduction

Climate change has become a major driver of water resource transformation in arid and semi-arid regions, where even relatively small shifts in temperature and precipitation seasonality can have significant consequences for agriculture, water supply, and ecosystem functioning [1]. This issue is particularly relevant for Central Asia. Regional assessments emphasize [2] that droughts have long-term negative impacts on the agricultural sector and livestock production [3] and pose a serious threat to water security [4]. At the same time, these processes are accompanied by an increase in the frequency and intensity of temperature extremes [5,6].

In this context, the Aral–Syr Darya Basin (ASB) represents one of the most climate-sensitive and socioeconomically important river basins in Central Asia. The Syr Darya is a transboundary river [7] whose runoff is generated primarily in the Tien Shan Mountains of Kyrgyzstan, Uzbekistan, and Tajikistan, whereas its lower reaches in Kazakhstan are used predominantly for irrigation purposes [8,9]. The pronounced mountain–lowland structure of the basin makes it vulnerable to two interrelated processes: changes in temperature and snow-glacier

regimes in the upper reaches and increasing aridity and water demand in the lower reaches. International assessments indicate [10–12] that in the Syr Darya and Amu Darya basins competition between different water-use sectors may intensify in the 21st century under conditions of potentially declining runoff, which further complicates transboundary water resources management.

Current climate change increases both rapid (“fast”) and gradual (“slow”) risks associated with hydrological processes in the major river basins of Central Asia. In arid regions, not only mean climatic conditions but also extreme events and the intra-seasonal distribution of precipitation are crucial, as they determine moisture deficits in agriculture and the likelihood of flood-related erosion.

Under conditions of high climatic and hydrological uncertainty, ensemble-based characterizations of future climate change are becoming increasingly important. In modern climate research, this approach is implemented through scenario-based projections using multi-model ensembles of global climate models, where the results are interpreted in terms of ranges of possible changes and a comparison between different emission pathways [13]. At the regional level, this approach is particularly

important [14], because even when a robust warming signal is evident, uncertainty in estimates of precipitation, drought, and extreme events may remain significant. At the same time, practical decisions in irrigation management, runoff regulation, and agricultural adaptation require understanding not only the expected change but also its range of model uncertainty.

Observed climate changes within the ASB are examined in detail in a number of regional studies [6,9,10,15], based on the analysis of long-term meteorological observations. These studies demonstrate a statistically significant increase in air temperature, as well as the presence of turning points in the regional climate regime in the second half of the 20th century [15,16]. In contrast to temperature characteristics, precipitation changes exhibit pronounced spatial heterogeneity and less consistent trends across different parts of the basin. These results are consistent with broader assessments for Central Asia, where rising temperatures and more frequent heat extremes represent a persistent climate signal, while changes in precipitation and aridity indicators depend strongly on season, orographic conditions, and the internal climate variability [13,16].

A number of studies [6,3,10,17] have emphasized the close relationship between climate change and water resource transformation in Central Asian River basins. Rising air temperatures increase evaporation and alter the seasonal distribution of river runoff, including shift towards earlier periods of the year [18]. This effect is particularly significant for the ASB, where the majority of water consumption occurs during the summer season, when climate-induced reductions in water availability may intensify water shortages in the lower reaches of the river.

The role of snow and glacier feed in the formation of river runoff in the Tien Shan has received considerable attention in the latest publications. Previous studies demonstrate that reductions in glacier area and volume in Central Asia under warming conditions may initially increase the share of meltwater in river discharge, followed by a long-term decline in water resources as glacial reserves become depleted [19-21]. This transition is considered one of the key risks to the sustainability of water supply and the irrigation systems in large transboundary basins in the region, including the ASB.

Another important research direction concerns water resource management and distribution of transboundary river flow in the ASB. Modeling studies of water use scenarios indicate that climate

change may exacerbate existing tensions between economic sectors and basin countries, particularly under conditions of increasing irrigation demand and uncertainty of future flow [22-25]. In this context, climatic factors are increasingly viewed as amplifying existing water management risks.

A specific regional factor influencing the climate system is the transformation of the underlying surface in the Aral Sea region associated with the Aral Sea crisis. Studies of regional climate responses to desiccation of the sea indicate that the reduction of the water surface area and the formation of vast dry-bottom areas lead to changes in local thermal and moisture contrasts, increased summer heating, and modification of the microclimate of adjacent territories [26,27]. Review papers emphasize that these mesoclimatic effects interact with global climate trends and are accompanied by intensified dust processes and landuse changes, which significantly complicate the assessment of risks to human health, agriculture, and aquatic ecosystems in the region [28,29]. Endorheic lakes of arid regions are highly sensitive to both climate change and anthropogenic regulation of inflow, making the Aral Sea basin an important indicator of regional hydroclimatic transformations [30]. In recent years, climate reanalysis datasets and multi-model ensembles of global climate models have been increasingly used to analyze climate change and associated hydrological risks. The ERA5 reanalysis and its derivatives are considered reliable sources of spatially consistent climate data for regions with limited observation networks, including Central Asia [31]. Climate projections from CMIP6, in turn, allow multi-model ensemble-based assessment of future changes in temperature, precipitation, and extreme climate events under various socioeconomic development scenarios [13,14].

Taken together, the results of previous studies confirm the high climatic sensitivity of the ASB to climate change, while also highlight remaining scientific gaps. In particular, there is a lack of studies that combine analysis of observed historical trends with multi-model scenario projections within a unified basin-scale risk assessment framework. Moreover, relatively few studies consider extreme climate indices alongside mean characteristics. These gaps underline the importance of comprehensive climate assessments aimed at reducing the uncertainties in climate and water management risks in the region. The specific features of the Aral Sea region remain insufficiently integrated into interpretation of climate-related risks.

Furthermore, within Kazakhstan, the ASB is characterized by persistent water resource shortages caused by a combination of climatic aridization, interannual runoff variability, and increasing transboundary anthropogenic influences [32]. Existing water management practices and infrastructure do not fully meet the demands of growing water consumption, which poses potential threats to the sustainable development of the region, agricultural production, the resilience of the Syr Darya Delta ecosystems, and, finally, the Northern Aral Sea [30]. Over the past decade, total water consumption by economic sectors and the population throughout the ASB has averaged approximately 40 km³ (including water reuse). The largest water consumers are the Uzbekistan (24.2 km³, or about 60% of total basin withdrawal) and Kazakhstan (9.0 km³, or about 23%) [7,24].

Despite numerous regional studies, integrated analyses combining observed historical trends with multi-model CMIP6 ensemble projections at the basin scale remain limited. Moreover, existing studies often focus on changes in mean climatic conditions, while the response of climate extremes may be substantially nonlinear and spatially heterogeneous. To address these gaps, this study provides one of the first comprehensive assessments of observed climatic changes and CMIP6 climate projections specifically tailored for the ASB. The analysis combines historical meteorological observations with CMIP6 multi-model projections under the SSP3-7.0 and SSP5-8.5 scenarios using data from 35 meteorological stations distributed across the basin. Particular attention is given to the spatial variability of climate change impacts and the identification of climatic hotspots within the Aral Sea region. The results also highlight the combined influence of climate warming and land-surface degradation associated with the desiccation of the Aral Sea. The results reveal a shift toward a “wet year–dry summer” regime, characterized by increasing annual precipitation accompanied by enhanced summer aridity. In addition, climate projections are evaluated alongside potential hydroclimatic implications and long-term water-use pathways in Kazakhstan, including business-as-usual, water-saving, and innovative development scenarios, as well as potential transboundary influences associated with the Kambar-Ata-1 hydropower project. The findings provide a robust scientific basis for improving transboundary water management and supporting climate adaptation strategies aimed at strengthening regional water security.

Materials and methods

2.1 Methods for Analyzing Future Climate Change

This study presents a basin-scale synthesis combining CMIP6 ensemble projections, ETCCDI extreme indices, and observations from 35 meteorological stations across the entire ASB. The assessment of future climate change in the ASB was conducted using data from the IPCC AR6 Interactive Atlas [33], developed as part of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (AR6 Working Group I, [13]). The Interactive Atlas provides spatially consistent climate fields and indices calculated using multi-model ensembles of global climate models from CMIP6 project, ensuring comparability of results and proper consideration of inter-model uncertainty. The climate projections presented in the Interactive Atlas are based on the outputs of multi-model climate model ensembles, including:

- CMIP5 (Coupled Model Intercomparison Project Phase 5) – global atmosphere-ocean general circulation models (GCMs) simulated under four emissions scenarios (RCP2.6, RCP4.5, RCP6.0, RCP8.5) for both historical and future periods.
- CMIP6 (Coupled Model Intercomparison Project Phase 6) – an updated and expanded set of global climate models using new Shared Socioeconomic Pathways (SSP) scenarios, including SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, which incorporate improved representations of recent climate processes and climate change trends.
- CORDEX (Coordinated Regional Climate Downscaling Experiment) — regional climate models (RCMs) that provide higher spatial resolution than global models, which is especially important for assessing regional changes and extreme events.

The models included in the analysis were selected based on data availability for key variables and scenarios. They cover the historical period and at least two future scenarios, ensuring comparability between CMIP5 and CMIP6. In the Interactive Atlas, various models are interpolated onto a common spatial grid (2° for CMIP5, 1° for CMIP6, 0.5° or finer for CORDEX) and combined to facilitate the comparison of climate indices and changes under different global warming scenarios (e.g., 1.5°C, 2°C, 3°C). The results are presented in the Interactive Atlas in form of global maps, regional aggregated time series, warming stripes, seasonal maps, and other visual representations that support

multi-model ensemble analysis. The analysis was conducted for a region corresponding to the spatial extent of the ASB within the IPCC reference regional framework, allowing the results to be interpreted within the broader context of Central Asia.

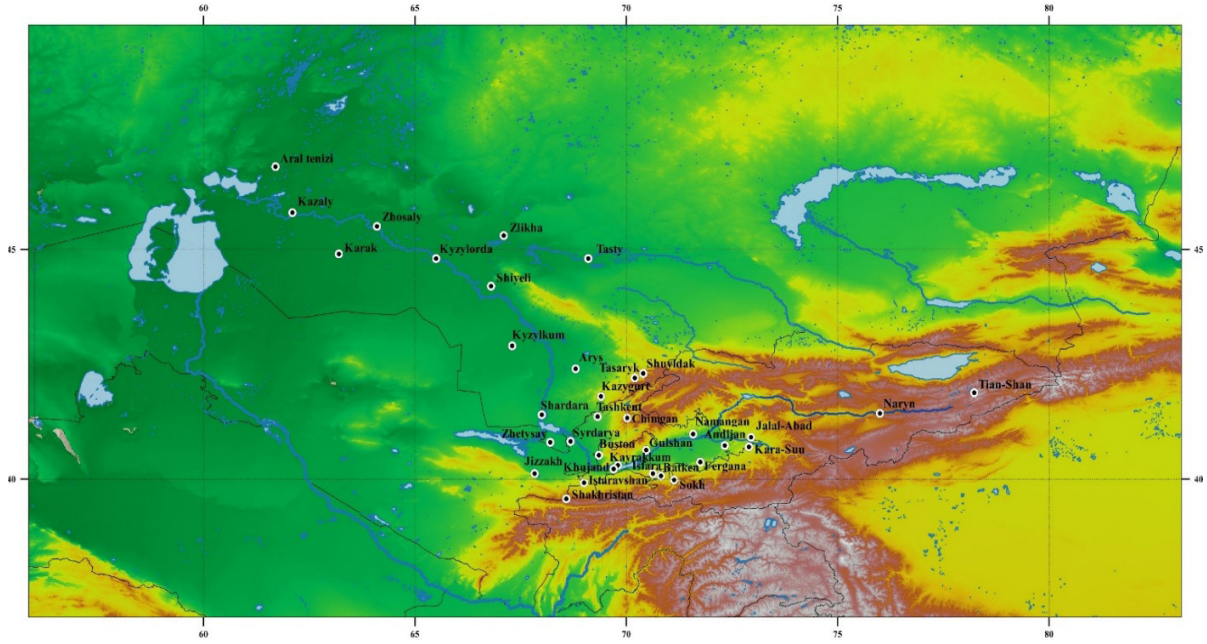
Additionally, observational data from key meteorological stations within the basin or in its immediate vicinity in Kazakhstan, Uzbekistan, Tajikistan, and Kyrgyzstan were used in the analysis (Table 1, Figure 1).

Table 1

List of meteorological stations in Central Asian countries used in the study

№	Meteorological station	Country	Coordinates		Elevation, m
			Latitude	Longitude	
1	Batken	Kyrgyzstan	40.07	70.82	1060
2	Jalal-Abad		40.91	72.95	764
3	Kara-Suu		40.70	72.90	867
4	Naryn		41.43	76.00	2039
5	Tian-Shan		41.88	78.23	3336
6	Andijan	Uzbekistan	40.73	72.33	477
7	Jizzakh		40.12	67.83	345
8	Namangan		40.98	71.58	474
9	Sokh		39.98	71.13	762
10	Tashkent		41.36	69.32	489
11	Fergana		40.37	71.75	584
12	Chimgan		41.33	70.02	1670
13	Syrdarya	Tajikistan	40.82	68.68	264
14	Buston		40.52	69.35	1983
15	Gulshan		40.63	70.47	556
16	Istaravshan		39.92	69.00	1004
17	Isfara		40.12	70.63	874
18	Kayrakkum		40.30	69.80	347
19	Khujand		40.22	69.70	428
20	Shakhristan	Kazakhstan	39.57	68.58	3143
21	Aral Tenizi		46.78	61.65	62
22	Shardara		41.25	67.97	271
23	Shiyeli		44.18	66.73	152
24	Zhosaly		45.51	64.20	101
25	Kyzylorda		44.82	65.53	128
26	Kazygurt		41.75	69.38	575
27	Arys		42.43	68.79	238
28	Shuyldak		42.30	70.43	1947
29	Tasty		44.80	69.16	191
30	Tasaryk		42.23	70.16	1128
31	Kazaly		45.76	62.11	66
32	Zlikha		45.22	66.88	138
33	Karak		45.22	66.88	144
34	Kyzylkum		44.87	67.27	184
35	Zhetysay		40.81	68.18	255

Note: Compiled by the authors

Figure 1*Location of study area spatial distribution of meteorological stations within the ASB**Note: Compiled by the authors*

The following metrics were used to evaluate model performance:

R – Pearson's correlation coefficient between modelled and observed monthly mean air temperatures;

RMSE – root mean square error;

MAE – mean absolute error;

NMAE – normalised mean absolute error (relative to the mean absolute value of observations);

Bias – systematic error of the model, defined as the difference between the mean observed and modeled values over the historical period.

To reduce systematic model errors, the Linear Scaling (Delta) Method was used. For temperature, monthly bias was calculated additively:

$$\text{Bias}_T(m) = \bar{T}_{\text{obs}}(m) - \bar{T}_{\text{model,hist}}(m) \quad (1),$$

where $\bar{T}_{\text{obs}}(m)$ is the average temperature at the weather station for month m over the baseline period; $\bar{T}_{\text{model,hist}}(m)$ is the corresponding average temperature from the raw model data at the nearest grid cell.

The bias-corrected daily mean temperature was calculated as:

$$T_{\text{corrected}}(d) = T_{\text{model}}(d) + \text{Bias}_T(\text{month}(d)) \quad (2).$$

The calculated correction factors for the 35 meteorological stations were spatialized across the grid using cubic spline interpolation. The method assumes that the systematic error of the model remains constant over time; consequently, the corrections calculated for the historical period were applied to future CMIP6 projections while preserving daily variability.

Bias correction via the linear scaling method was applied exclusively to daily temperature series, as temperature shows strong systematic regional biases across high-altitude and arid terrain. Daily precipitation values were kept in their raw GCM-simulated form without multiplicative scaling. This approach was chosen to preserve the internal physical consistency of simulated precipitation frequency and threshold-based indices, avoiding artificial distortions in non-normal precipitation distributions. Model validation for precipitation was therefore performed by evaluating raw ensemble performance directly against historical station observations.

To maintain transparency, data processing in this study was divided into two distinct streams:

Regional climate anomalies, broad spatial trends, and multi-model consensus figures for mean surface temperature and precipitation were extract-

ed directly from the IPCC AR6 Interactive Atlas for the Aral-Syr Darya region.

Localized climate extremes, threshold-based index calculations, and station-specific future projections were calculated directly by the authors from daily CMIP6 model outputs. The list of individual CMIP6 models, their grid resolutions, and tabulated numerical projection results are compiled in Appendix A, while the spatial maps of calculated indices are presented in Appendix B.

All climate indices used in this study were calculated in accordance with the IPCC AR6 methodology and the recommendations of the Expert Team on Climate Change Detection and Indices (ETCCDI). This methodology is based on internationally recognized approaches for describing extreme climate events and their temporal variability, as documented in the IPCC and ETCCDI technical guidelines and assessment documents. The calculations rely on a standardized set of climate indices of extremes developed by ETCCDI, which includes temperature and precipitation indicators applicable to both observational data and climate model outputs (CMIP5/CMIP6 and CORDEX). The methodology follows ETCCDI recommendations and the technical guidelines of the World Meteorological Organization, including the Guidelines on the Analysis of Extremes in a Changing Climate [34], as well as on standardized definitions of 27 core indices, widely described in the climatological literature [35–40]. These approaches are incorporated into the calculation modules of the IPCC AR6 Interactive Atlas [33], which provides regional estimates of the climate indices under both observed and projected conditions, ensuring compatibility with widely accepted scientific assessments of climate change and extreme events at regional and global scales. Future climate conditions were analyzed for two socioeconomic development scenarios: SSP3-7.0, representing a pathway characterized by regional fragmentation and relatively high greenhouse gas emissions, and SSP5-8.5, representing a fossil-fuel-intensive development pathway associated with very high emissions. Projected changes were evaluated for three-time horizons: 2021–2040 (near-term), 2041–2060 (mid-century), and 2081–2100 (long-term).

Climate changes were analyzed as anomalies relative to the 1981–2010 baseline period, which is adopted in IPCC AR6 as representative of the present-day climate. The CMIP6 multi-model ensemble was used for all analyzed parameters, with a primary focus on the ensemble median, which is considered the most robust estimate of the climate signal. Inter-model uncertainty was assessed through analysis of

the ensemble spread, allowing for a more reliable interpretation of the range of possible climate changes in the ASB. Among the methodological limitations, it should be noted that the spatial resolution of the Interactive Atlas corresponds to that of global climate models and are therefore does not allow for detailed local-scale analysis. Nevertheless, these datasets provide a reliable basis for identifying regional climate trends and assessing potential changes in extreme climate conditions at the river basin scale.

2.2 Current situation in the ASB

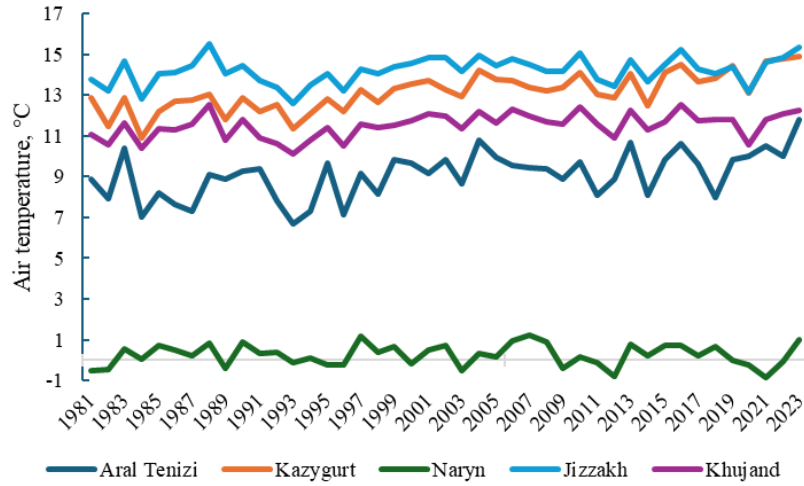
The climate of the ASB is strongly continental and is influenced by Arctic, temperate, and tropical air masses. During the cold season, the western spur of the Siberian anticyclone plays a significant role, contributing to the formation of persistent cold and low-snow conditions. In the warm season, the influence of continental air masses from temperate and tropical latitudes, originating over Central Asia and Iran, increases. Overall, the ASB is characterized by hot, dry summers and relatively mild winters in the lowland areas, while the foothill and mountainous regions experience cooler and wetter climatic conditions [41]. In the Uzbekistan-Tajikistan part of the basin, located mainly within the Fergana Valley and adjacent mountainous areas, average July temperatures reach +32 to +36 °C. In January, temperatures in the lowland areas are around 0 to –6 °C and decrease significantly at higher elevations [42] (Figure 2).

To illustrate the observed climatic changes across the basin, representative meteorological stations were selected from different physiographic zones, ranging from the lowland desert areas of the lower ASB (Aral-Teniz) to the mountainous regions of the Tien Shan (Naryn). Analysis of the observational records reveals a consistent increase in mean annual air temperature at all stations (Figure 2a), although the magnitude of warming varies depending on local geographical conditions. The seasonal distribution of temperature changes is particularly noteworthy. The most pronounced warming has occurred during the cold season and early spring, especially in February and March. January temperatures (Figure 2b) have increased markedly since 2010, with mean monthly values rising by approximately 0.8–1.0 °C at lowland stations, compared to less than 0.5 °C in the mountainous regions. This pattern indicates strong winter warming over a short period of time. Summer temperatures have also increased, particularly during July (Figure 2c) and August. In addition, the duration of periods with air temperatures exceeding 35 °C has expanded in the desert regions.

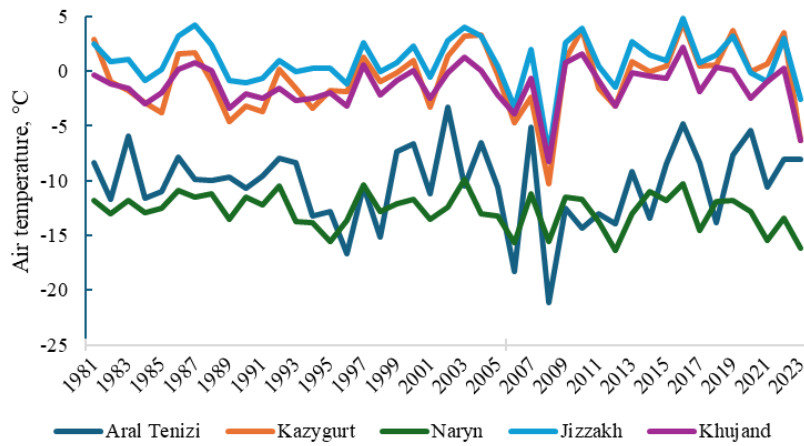
Figure 2

Air temperature at representative meteorological stations across different parts of the ASB during 1981–2023: a) mean annual air temperature; b) mean air temperature of the coldest month (January); c) mean air temperature of the warmest month (July).

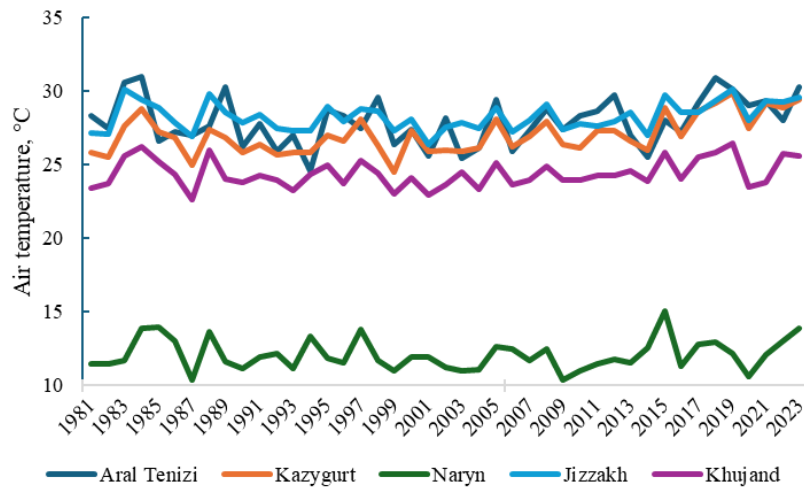
a)



b)



c)



Note: Compiled by the authors

An analysis of long-term observations indicates a pronounced warming trend throughout the ASB. In southern Kazakhstan, the increase in mean annual air temperature over recent decades has been approximately 1.3–1.6 °C, with a linear trend coefficient of approximately 0.44 °C per decade [41]. In Kyrgyzstan, the increase in mean annual temperature during the period from 1981 to 2020 is estimated at 0.28 °C per decade, with the most pronounced warming in spring. Similar trends are observed in the Uzbekistan-Tajikistan part of the basin, where the mean annual temperature has increased from approximately 10.1 °C in the early 1980s to approximately 11.6–11.9 °C in recent years, corresponding to an overall increase of 1.5–2.0 °C [42]. In contrast to temperature trends, changes in the precipitation regime are less consistent and are characterized by significant interannual variability. In the lowland areas of the ASB in southern Kazakhstan, a slight increase in winter precipitation is observed, accompanied by a tendency toward decreasing summer precipitation. At several stations, summer precipitation sums have dropped to 35–50 mm per season. Mean annual precipitation in this region remains relatively low, amounting to 130–140 mm in the Kyzylorda region and 240–280 mm in the Turkestan region, while in the foothill areas it can reach 400–500 mm. In Kyrgyzstan, a slight increase in annual precipitation within the ASB was observed during 1981–2020 period, reaching up to 6.4 mm per decade, primarily due to increases in winter and spring precipitation. Overall, precipitation changes across the basin are less pronounced than temperature trends and remain spatially heterogeneous.

Results

Using the IPCC Interactive Atlas [33], tabular data were obtained for six critical climate indices reflecting both mean climate conditions (mean annual air temperature and mean annual precipitation) and changes in the frequency and intensity of extreme climate events:

- Mean annual air temperature (MAAT, in °C);
- Mean annual precipitation (MAP, in %);
- Number of days with maximum daily air temperature above 35 °C, characterizing extreme heat stress (TX35, in days);

- Maximum 1-day precipitation amount, reflecting the intensity of extreme precipitation (RX1day, in %);

- Maximum number of consecutive dry days, used as an indicator of aridity (CDD, in days);

- Standardized Precipitation Index for a 6-month accumulation period, used to assess medium-term meteorological drought.

The tabulated results are presented in Appendix A, while the spatial distribution of the indices is shown in the form of maps in Appendix B.

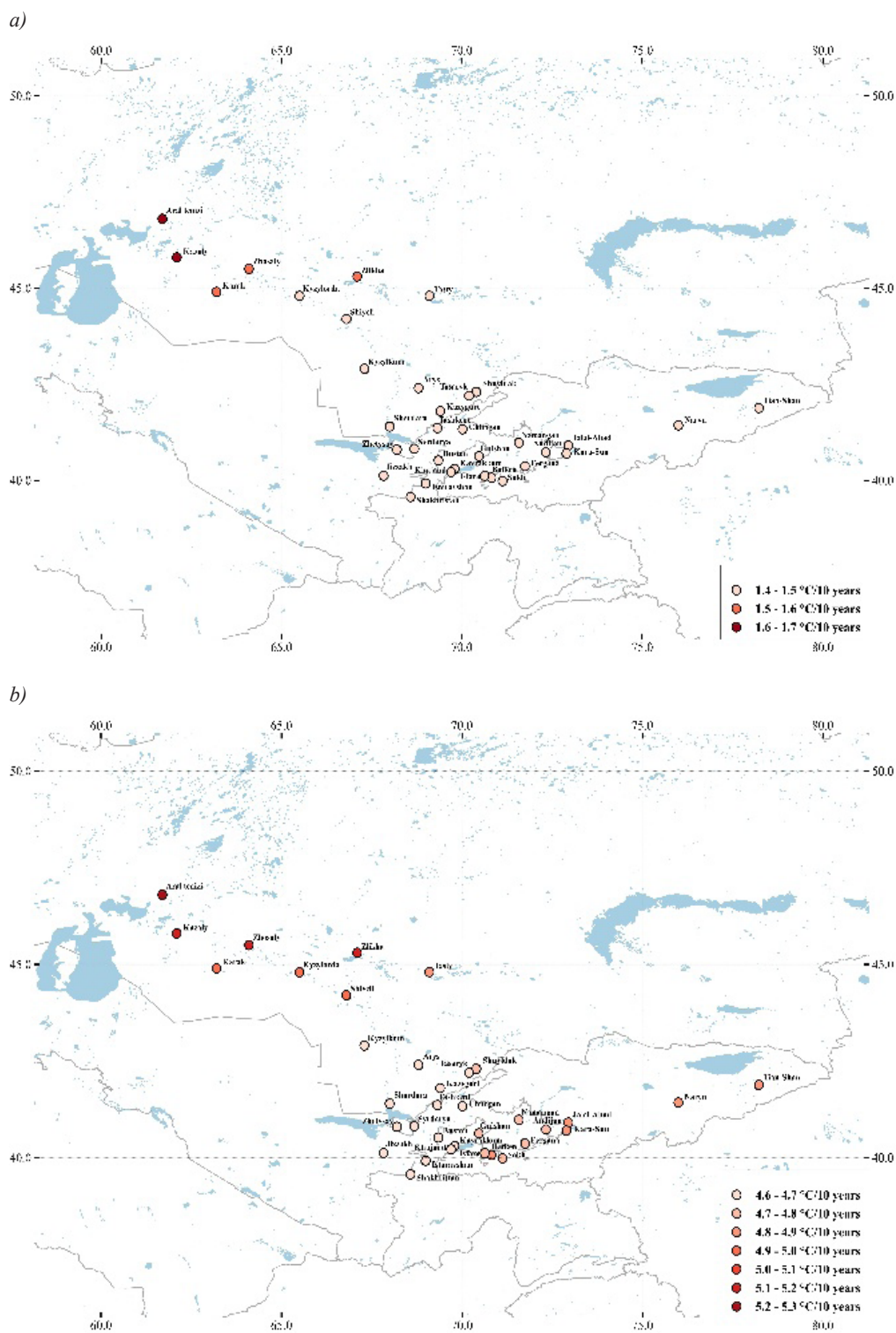
3.1 Projected of changes in mean annual air temperature

This study intentionally focuses on moderate-to-high emission pathways (SSP3-7.0 and SSP5-8.5) to capture a range of plausible risk trajectories under continued global socio-economic development and limited decarbonization efforts. Low-emission scenarios (such as SSP1-2.6) were excluded because current global emission trends and regional climate trajectories in Central Asia align more closely with intermediate and high radiative forcing pathways, making high-impact scenarios particularly critical for long-term water resources planning.

The root mean square error (RMSE) of the models ranges from 0.8 to 10.2 °C, while the mean absolute error (MAE) varies between 0.6 and 10.2 °C. The highest errors (5–10 °C) are associated with mountain stations, where complex topography introduces substantial uncertainty into climate simulations. Climate models generally reproduce temperature conditions more accurately over relatively flat terrain. Accordingly, when only lowland stations are considered, RMSE values range from 1.87 to 3.96 °C and MAE values from 1.72 to 3.90 °C. The normalized mean absolute error (NMAE) does not exceed 4.6 for the full station dataset and remains below 1.0 for lowland stations, indicating an acceptable representation of the relative amplitude of temperature variability. Model bias ranges from –10.2 to 5.7 °C for all stations and from –3.2 to 3.9 °C for lowland stations. These results indicate the presence of systematic model errors, particularly in mountainous areas. Bias correction was therefore applied individually to each model and calendar month. Overall, the validation results demonstrate that all CMIP6 models reproduce regional temperature conditions with satisfactory accuracy and are suitable for subsequent analyses.

Figure 3

Spatial distribution of projected temperature changes over the basin under the SSP3-7.0 scenario (2081–2100 relative to 1981–2010). (a) Spatial pattern of mean temperature anomalies ($^{\circ}\text{C}$); (b) Decadal warming trends ($^{\circ}\text{C}/10$ years).



Note: Compiled by the authors

However, in the medium term (2041–2060) and especially in the long term (2081–2100), a substantial divergence of the projected trajectories becomes evident. Under the SSP3-7.0 scenario, average regional warming in the period 2081–2100 is up to +4.7 °C (ranging from +4.6 to +5.3 °C). In contrast, the SSP5-8.5 scenario shows significantly stronger warming, reaching +6.0 to +6.8 °C. The difference between the scenarios by the end of the century exceeds 1.5 °C (Table 2), highlighting the high sensitivity of the regional climate system to global emissions pathways.

Table 2

Changes in mean annual air temperature for selected meteorological stations (2081–2100)

Meteorological station	SSP3-7.0, °C	SSP5-8.5, °C
Aral Tenizi	5.3	6.8
Kazaly	5.2	6.6
Zhosaly	5.2	6.7
Naryn	4.9	6.3
Fergana	4.8	6.3
Jizzakh	4.6	6.0

Note: Compiled by the authors

For the SSP5-8.5 scenario, the increase in air temperature displays a pronounced nonlinear pattern. In spite of warming reaching approximately +3.0 °C by 2060, it nearly doubles over the subsequent four decades, exceeding +6.0 °C by 2100. This acceleration after mid-century indicates that adaptation strategies based solely on linear extrapolations of current trends may be ineffective and underestimate the magnitude of future climate change, requiring radical transformations across economic and planning sectors.

An analysis of the spatial distribution of warming reveals local amplification of the climate signal. Stations located in the Aral Sea region and adjacent arid areas, including Aral Tenizi, Kazaly, and Zhosaly, show the highest warming rates. In the SSP5-8.5 scenario, warming at the Aral Tenizi station may reach +6.8 °C by the end of

the century, while Kazaly is projected to experience warming of approximately +6.6 °C. These are maximum values for the entire analyzed region, significantly exceeding the average warming rates even in this extreme scenario. A likely physical explanation for this amplification is the loss of the moderating influence of the Aral Sea, which previously provided regional cooling and thermal inertia. The continued reduction of the water surface and expansion of dry bottom areas contribute to enhanced surface heating and increased continentality of the regional climate. The observed significant warming in the Aral Sea region confirms that this territory is becoming a climatic hotspot, where global warming is reinforced by regional land-surface changes.

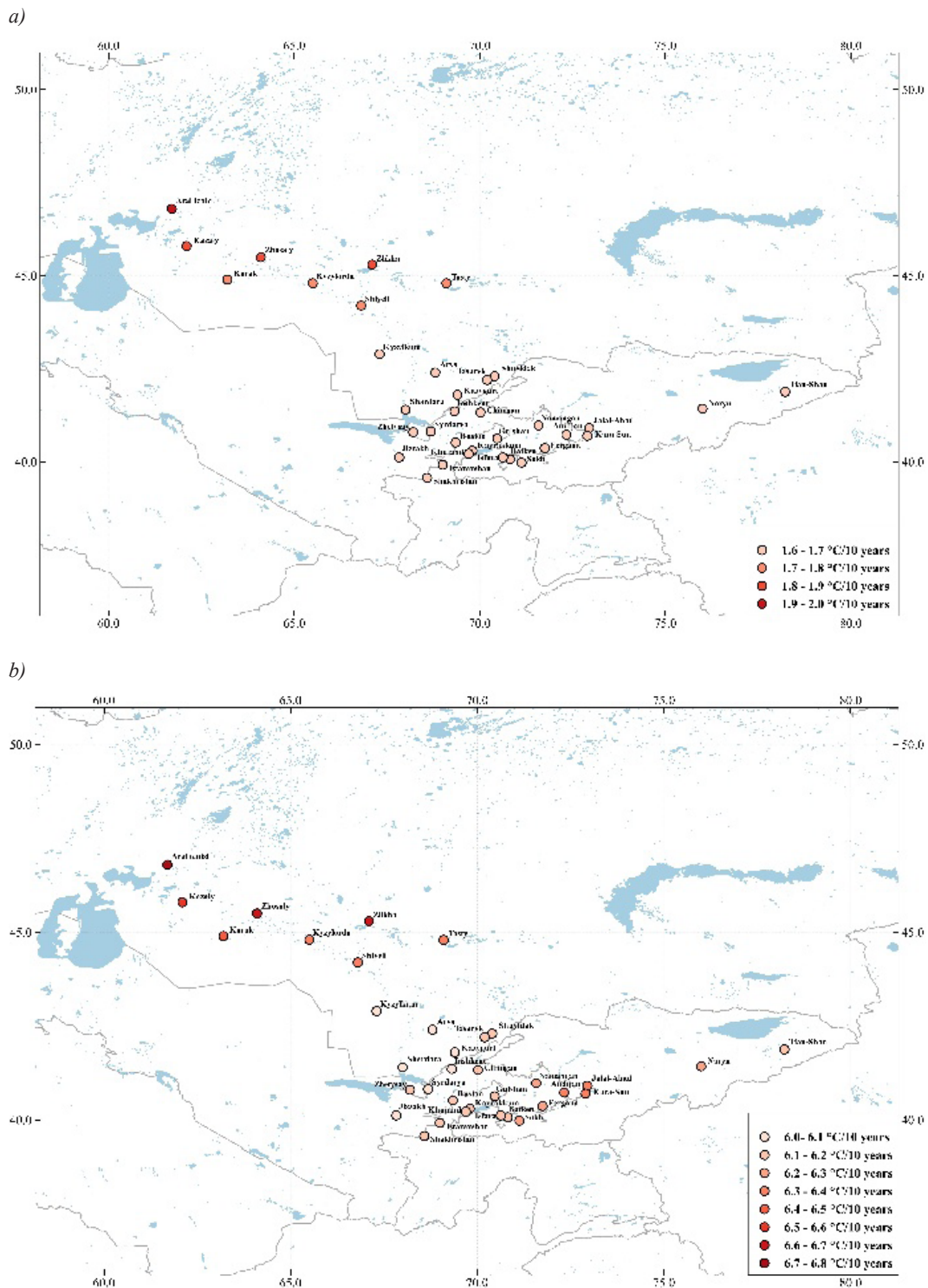
Meanwhile, mountainous areas also demonstrate substantial warming. For example, Naryn station is projected to warm by approximately +6.3 °C in SSP5-8.5. Although slightly lower than values observed in the Aral Sea region, this increase remains extremely large and may have significant consequences for glacier dynamics and runoff formation in the headwaters of the Syr Darya.

Rising average annual temperatures represent only one aspect of regional climate change. A more significant threat to ecosystems, human health, and the economy is the frequency and duration of extreme temperature events, expressed by the TX35 index (number of days with maximum temperature above 35 °C).

The selection of extreme climate indices from the Expert Team on Climate Change Detection and Indices (ETCCDI) was based on three considerations. First, indices such as RX1day, CDD, and TX35 are internationally standardized and widely used in climate-change studies, allowing direct comparison of the results obtained for the Aral–Syr Darya Basin with those reported in the IPCC AR6 assessment. Second, these indices reflect key hydroclimatic hazards in the basin: TX35 characterizes extreme heat events, CDD represents the duration of dry spells affecting water resources and agriculture, and RX1day captures intense precipitation events associated with flash flooding. Third, the selected threshold- and percentile-based indices can be consistently calculated from both daily station observations and CMIP6 model outputs, ensuring methodological compatibility between the observational and projected datasets.

Figure 4

Spatial distribution of projected temperature changes over the basin under the SSP5-8.5 scenario (2081–2100 relative to 1981–2010). (a) Spatial pattern of mean temperature anomalies ($^{\circ}\text{C}$); (b) Decadal warming trends ($^{\circ}\text{C}/10$ years).



Note: Compiled by the authors

Model projections clearly demonstrate that the increase in the number of extreme heat days is non-linear and considerably outpaces the increase in air temperature. Under the SSP5-8.5 scenario, by 2081–2100 the number of days with temperatures above 35 °C increases by approximately 3.5 times compared with the 2021–2040 period (Table 3). This phenomenon can be explained by a shift in the statistical distribution of air temperature. Even a moderate increase in the mean temperature significantly raises the frequency of events in the upper tail of the distribution. This results in a disproportionate increase in extreme heat events. For example, in Jizzakh, the projected increase in TX35 rises from +29.5 days in 2041–2060 to +61.8 days in 2081–2100, indicating a sharp acceleration in the occurrence of extreme heat events.

Table 3

Projected change in the number of days with $T > 35^{\circ}\text{C}$ (SSP5-8.5) for selected meteorological stations

Meteorological station	TX35 (2021-2040, days)	TX35 (2081-2100, days)
Jizzakh	17.5	61.8
Tasty	19.1	62.0
Syrdarya	14.4	60.2
Tashkent	12.4	55.5
Fergana	5.1	30.2
Naryn	0.5	5.2

Note: Compiled by the authors

3.2 Projected changes in the average annual amount of precipitation

The analysis of water resources in Central Asia requires consideration of two key, often contradictory, trends: changes in the total annual precipitation amount and its intensity (RX1day), as well as the dynamics of dry periods (CDD), and overall moisture conditions (SPI-6).

Prospective precipitation changes demonstrate a predominantly positive trend across the region. By the end of the 21st century (2081–2100), the SSP5-8.5 scenario indicates an increase in average annual precipitation of approximately 17–20%. The largest

increases are projected in southern Kazakhstan and in the areas adjacent to the Syr Darya River (Shardara +20.7%, Arys +20.9%).

It is important to emphasize that a positive trend in total precipitation does not necessarily imply an increase in moisture conditions. Analysis of monthly precipitation patterns reveals a precipitation deficit during the warm half of the year.

However, within this general trend, a significant local anomaly is observed. The Jizzakh station, which also exhibits the highest projected heat stress (TX35 up to +61.8 days), shows the smallest projected increase in precipitation, only +2.0% by 2100 according to SSP5-8.5 (Table 4). The combination of extremely high evaporation caused by rising temperatures the almost complete absence of compensating precipitation growth makes the Jizzakh region a critical zone of maximum projected moisture deficit (P-E index, precipitation minus evaporation). This situation threatens the sustainability of local agricultural systems and may accelerate desertification processes.

The RX1day index (maximum precipitation in one day) reflects the intensity and associated flood risk. The analysis shows that the increase in precipitation intensity significantly exceeds the growth in average annual precipitation. Under the SSP5-8.5 scenario, RX1day is projected to increase by 25%–35% on average by the end of the century. The largest increase is expected in the area of Kyzylkum station (RX1day increases by 34.7%), while in Chimgan, a foothill area, RX1day increases by approximately 28.7%.

Two indices are used to assess drought risk: SPI-6 (standardized precipitation index for 6 months period, reflecting overall moisture conditions) and CDD (the maximum duration of consecutive dry days, reflecting the continuity of moisture supply). The SPI-6 index shows a strong positive trend across the region under both scenarios. This confirms that the hydrological cycle in Central Asia is generally intensifying, with an increase of the total volume of atmospheric moisture. This trend is particularly pronounced in the mountainous regions, where increases reach +72.1% in Naryn, and +70.7% in Tien Shan under the SSP5-8.5 scenario. A positive shift in SPI-6 indicates increased medium-term meteorological wetness relative to the baseline distribution and should not be interpreted as a direct measure of atmospheric moisture.

Figure 5

Projected changes in mean annual precipitation under the SSP5-8.5 scenario for a) 2021–2040, b) 2081–2100

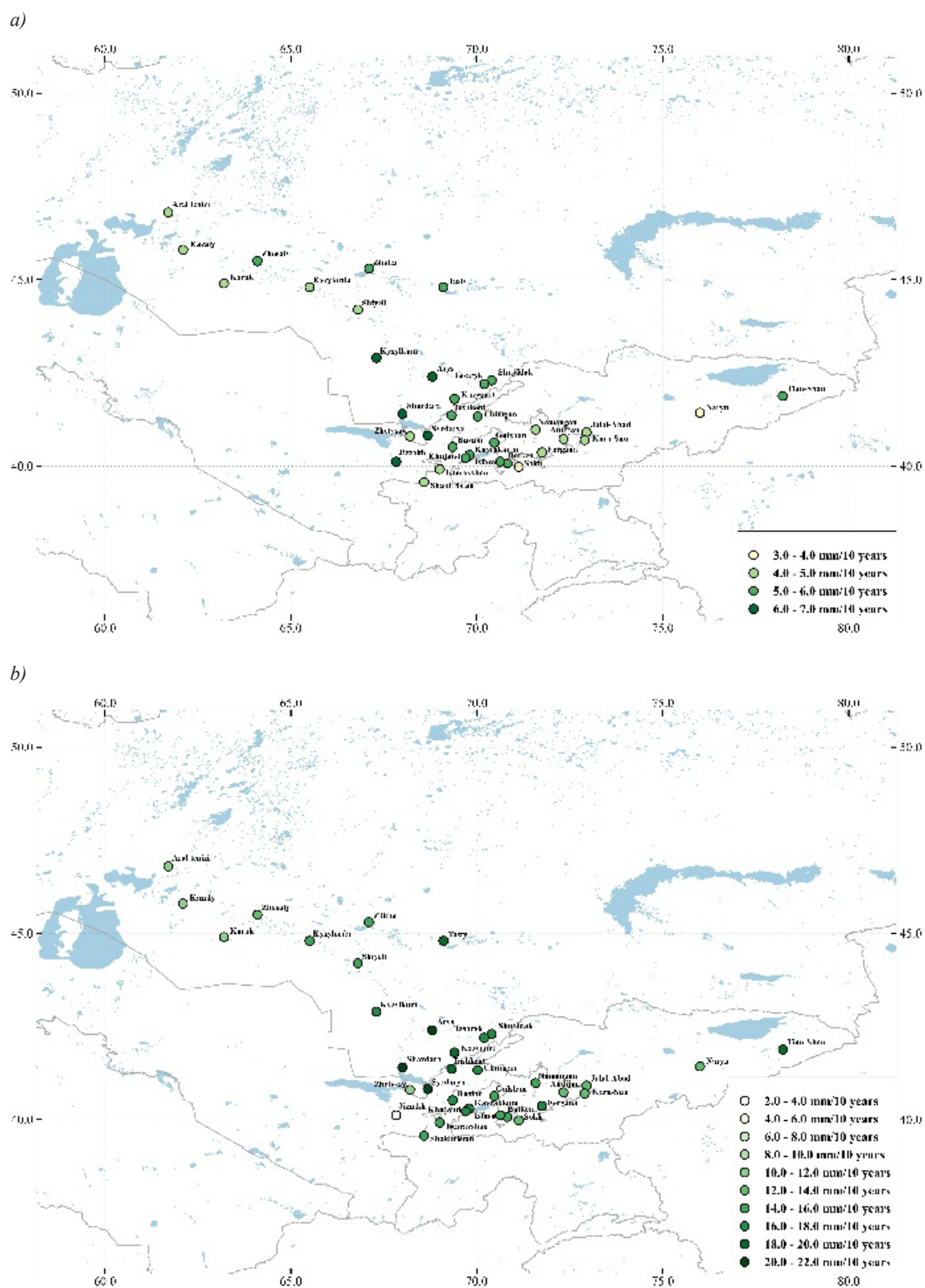


Table 4*Summary assessment of hydroclimatic instability for selected meteorological stations (2081–2100, Scenario SSP5-8.5)*

Meteorological station	MAP (%)	RX1day (%)	CDD (days)	6-month precipitation change (%)
Kazaly	11.2	29.1	+11.2	35.3
Aral Tenizi	11.0	25.2	+9.7	32.1
Jizzakh	2.0	33.6	0.0	39.5
Naryn	12.8	16.5	+4.0	72.1
Kyzylkum	17.9	34.7	-1.2	40.5

Note: Precipitation changes for the 6-month accumulation period (SPI-6 timeframe) are given as percentage changes (%) relative to the 1985–2014 baseline.

In contrast, CDD trends are more heterogeneous. Most inland and foothill stations show either a reduction or stabilization in the duration of dry periods. However, a concerning opposite trend is observed in key arid regions. For example, in the Aral Sea area, at the Kazaly station, CDD is projected to increase by +11.2 days by the end of the century under the SSP5-8.5 scenario, while the Aral Tenizi station shows an increase of +9.7 days.

Discussion

4.1 Discussion of climate trends and risks

The identified discrepancy between the moderately linear average temperature increase and the exponential rise in the TX35 index indicates that the actual impact of climate change on human health and the economy – particularly labor productivity and energy demand for cooling – will be significantly more severe than estimates based solely on mean temperature trends. Extreme heat stress is likely to become the dominant climate risk factor in the region. Geographical analysis highlights areas expected to experience catastrophic levels of heat stress, primarily concentrated in arid lowland and oasis zones. Lowland steppe areas are considered to be at highest risk. For example, at the Jizzakh, Tasty, Syrdarya, and Arys stations, TX35 is projected to reach 60.2–62.0 days per year by 2100 under the SSP5-8.5 scenario. In Jizzakh, the projected increase reaches +61.8 days, equivalent to more than two additional months annually with temperatures exceeding the dangerous threshold of 35 °C. Such conditions are similar to those currently observed in extremely arid regions of the Middle East [43]. This scale of heat stress will require substantial revisions of labor regulations, particularly in the agricultural sector, and will likely lead to a significant decline

in overall labor productivity unless extensive heat protection measures are implemented.

Large urban centers, particularly those located in foothill zones, may also experience severe heat stress. In Tashkent, TX35 is projected to increase by +55.5 days by 2100 (SSP5-8.5), while in the densely populated Fergana Valley (Fergana and Namangan stations) the increase may reach +30.2 days. When combined with the urban heat island effect – which is not fully captured by meteorological station data – these changes could significantly amplify public health risks. Even in high-altitude regions, where absolute TX35 values remain low (Naryn: +5.2 days for SSP5-8.5), the mere occurrence and growth of extreme heat events indicate the upward expansion of heat stress into mountain environments, posing risks to unique alpine ecosystems.

In lowland regions, an important climatic phenomenon is emerging that can be described as “wet year–dry summer” dissociation. Under this regime, the region may exhibit relatively high overall moisture availability (high SPI-6 values) due to rare but intense rainfalls (high RX1day), while the intervals between precipitation events become longer (high CDD). For arid ecosystems and rainfed agriculture, the critical factor is not the annual precipitation amount, but the continuity and regularity of moisture supply. Rising CDD values in arid zones imply an increased likelihood of frequent, intense, but short-lived droughts (“flash droughts”), interspersed with destructive flooding events. The combined analysis of temperature trends and hydroclimatic indices allows for assessment of risks for key sectors and ecosystems across Central Asia. Mountain systems such as the Tien Shan and Pamir-Alai are the region’s primary “water towers”, critically important for generating runoff for major rivers Amu Darya and Syr Darya. These regions are projected

to experience some of the highest absolute temperature increases (e.g., Naryn: +6.3 °C under SSP5-8.5) together with the highest increase in overall moisture (Naryn and Tien Shan: SPI-6 increases up to +72.1% by 2100).

According to previous studies [7, 10, 22, 32, 42, 44] of mountain hydrology in Central Asia, increasing temperatures may accelerate glacier and snowmelt processes and alter the seasonal distribution of runoff. Consequently, higher annual precipitation does not necessarily translate into increased summer water availability for irrigation. As a result, snow cover, which traditionally acts as a natural long-term regulator of runoff, melts earlier, shifting peak runoff to spring, when irrigation water demand is minimal. During the summer, when agricultural water demand reaches its maximum, runoff volumes are likely to decline despite increases in total annual precipitation. These processes may pose additional challenges for water security in Central Asia, particularly for irrigation-dependent regions, hydropower production, and drinking water supply.

Regions surrounding the Aral Sea, near Kazaly and Aral Tenizi stations, are the most vulnerable. Three adverse factors converge in these areas:

1. Maximum projected warming
2. Increased duration of dry periods (CDD)
3. Relatively small increases in overall moisture (SPI-6)

The interaction of these factors is expected to increase atmospheric moisture deficit and intensify soil drying. These changes may contribute to land degradation, increasing the vulnerability of regional ecosystems and placing additional pressure on local socioeconomic systems. Furthermore, regions with relatively small projected increases in precipitation, such as Jizzakh, may face similar, although more localized, risks to agricultural productivity due to the combined effects of heat stress and water scarcity.

Densely populated and agricultural areas, such as the Fergana Valley (Fergana, Namangan, and Khujand stations), are likely to experience dual climatic stress. The first component is direct heat stress (TX35 reaching up to +30.2 days in Fergana under the SSP5-8.5 scenario), which may create additional risks for agricultural productivity and necessitate either a switch toward more drought-resistant crop varieties or the implementation of advanced protective technologies. The second component is the increased risk of flooding and inundation (RX1day increases of +23.7% in Fergana and +28.0% in Khujand), potentially damaging infrastructure and caus-

ing agricultural losses during sowing or harvesting periods.

Climate conditions characterized by temperature increases approaching 6 °C and prolonged periods exceeding 35 °C represent the emergence of a fundamentally new climatic regime. Such climatic conditions would require substantial adaptation measures in agriculture and water management.

4.2 Water management implications under projected climate change

In this study, we did not perform hydrological modeling, as such analyses fall beyond the scope of the present research. Instead, we discuss previously published water-management scenarios as literature-based pathways that help place the projected climate changes into a broader regional context. To address water supply issues in the ASB, three scenarios for the future development of water use in the region have been proposed and assessed using criteria of water availability for natural and socioeconomic systems [44]:

1. The business-as-usual scenario assumes the continuation of water use trends that have developed in the basin over recent decades. According to this scenario, domestic water consumption is likely to grow by approximately 15% every decade. Demand is suggested to grow primarily due to increased water consumption by economic sectors, while environmental water requirements remain unchanged. Under this trajectory, the development of water use would be associated with a high risk of severe freshwater shortages, potentially leading to severe economic losses and environmental degradation. In this scenario, the ASB would remain at a “crisis” level of water availability, estimated at -0.6.

2. The water-saving scenario involves the comprehensive reconstruction and modernization of irrigation and collector–drainage networks as well as hydraulic infrastructure. It includes establishing an optimal drainage regime, improving the technical condition of irrigation and drainage systems, and increasing their efficiency to 0.75. Additional measures include the introduction of automated systems for water accounting, distribution, and irrigation. As a result, total domestic water consumption, together with environmental and mandatory runoff requirements, is suggested to stabilize in the long term. With the adoption of advanced technologies, domestic water consumption could subsequently decrease by approximately 10%. However, this scenario does not exclude the possibility of a freshwater shortage in the long term, which may require the implementation of territorial water redistribution programs. Un-

der this pathway, the ASB would remain at a “critical” level of water availability, estimated at 0.7.

3. The innovative scenario assumes the implementation of a strategy aimed at the transformation of the water sector mainly in the Republic of Kazakhstan based on the principles of sustainable development. A key element of this strategy is the formation of a Unified Water Supply System at the national level. The development of water-intensive industries would be accompanied by intensified water-use efficiency, while the expected reduction in available water resources would be partially compensated through transboundary and interbasin water transfers. Under this development scenario, it is possible to avoid “crisis” and “critical” levels of water availability. However, the ASB would still remain within the “tight” water availability category with an index value close to 1.0.

Within the framework of these water-use development scenarios for the ASB, the Kambar-Ata-1 hydropower project on the Naryn River (Kyrgyzstan) can be considered a significant factor influencing their implementation, particularly in terms of flow regulation and transboundary interaction [45]. Under the business-as-usual scenario, the commissioning of such a large hydroelectric complex without coordinated flow management mechanisms could aggravate existing imbalances. Increased water consumption combined with insufficient coordination with upstream countries could intensify water shortages downstream, particularly in the irrigated areas of Kazakhstan and Uzbekistan.

In contrast, the water-saving and, especially, innovative scenarios provide greater opportunities for positive integration of this project into regional water management systems. The Kambar-Ata-1 reservoir could function as a seasonal regulator of river flow, storing water during high-water periods and ensuring more stable summer releases that are essential for irrigation in downstream areas. Such an approach is consistent with the concept of a unified water supply system and coordinated interstate resource redistribution. However, the effectiveness of this strategy directly depends on governance transparency, the existence of clear international agreements, and the consideration of environmental constraints. Otherwise, the project may increase transboundary tensions and environmental risks, potentially offsetting the expected benefits even under the innovative scenario.

Water scarcity, driven by climate change, inefficient water use, and deteriorating infrastructure, represents a major challenge to socioeconomic de-

velopment in Central Asia, particularly in southern Kazakhstan. Over the past 50 years, regional glaciers have lost approximately 30% of their area [46], altering hydrological regimes and reducing river discharge while water demand continues to increase. Addressing this challenge requires substantial investments in water-saving technologies, improvements in infrastructure, and institutional modernization [25]. For downstream countries, these measures should be complemented by effective transboundary cooperation aimed at ensuring equitable water allocation within the basin. If current trends persist, increasing competition for water resources and growing supply instability in the ASB may hinder the maintenance of environmental flow requirements for the Northern Aral Sea ($3.63 \text{ km}^3 \text{ year}^{-1}$) and the lower Syr Darya lake systems ($1.7 \text{ km}^3 \text{ year}^{-1}$) [7]. Strengthening regional water security will therefore require coordinated basin-wide management and effective mechanisms for transboundary water governance.

Conclusions

The analysis of projected climate data for the SSP3-7.0 and SSP5-8.5 scenarios relative to the baseline period of 1981–2010 indicates that Central Asia is moving toward a trajectory of critical climate risk, particularly under the high-forcing SSP5-8.5 scenario. In the long-term perspective (2081–2100), regional warming in Central Asia may reach $+6.0$ to $+6.8^\circ\text{C}$ under the SSP5-8.5 scenario, significantly exceeding the global average. This warming is further amplified by regional factors, creating climatic “hotspots”, particularly in the Aral Sea region. The greatest threat to the region is not the gradual increase in mean air temperature itself, but the exponential growth in the number of days with maximum daily air temperature above 35°C (TX35). In arid lowland areas such as Jizzakh and Tasty, this indicator may exceed 60 days per year, making traditional forms of economic activity during the summer period extremely difficult. At the same time, the region is expected to experience increasing hydroclimatic contrasts. This will manifest as a rise in the rainfall intensity (RX1day up to $+34.7\%$) and a simultaneous increase in the number of consecutive dry days (CDD up to $+11.2$ days in Kazaly). Such disproportion reflects a fundamental instability in the regional water regime, characterized by alternating intense flash floods and prolonged, but relatively short-lived, drought periods.

The impact of global warming on water resources is of particular concern. Despite an overall

increase in moisture availability, rising temperatures in the mountainous regions (Naryn, Tien Shan stations) will lead to earlier snowmelt. As a result, peak river discharge is expected to occur earlier in spring, while in summer – the period of maximum irrigation demand – water availability may decrease. This creates additional risks to water security in the countries of the ASB. Under these conditions, the development of a comprehensive climate adaptation system is essential. Priority should be given to modernizing water resource management systems to account for the increasing instability of the hydrological cycle. Particular attention should be paid to the development of infrastructure for the accumulation and regulation of floodwaters originated from intense precipitation events, which could partially compensate for summer runoff deficits. In the Aral Sea region, where longer dry periods are expected, adaptation measures should include the implementation of soil-moisture conservation technologies, modernization of irrigation infrastructure, and the introduction of water-saving agricultural practices. Adaptation to increasing heat stress is equally important. The rapid growth in the number of days with temperatures above 35°C requires the development of national population protection programs, including revising building standards to improve passive cooling of buildings, mitigation of the urban heat island effect, and introduction of regulations limiting outdoor work during periods of extreme heat. In agriculture, a gradual transformation of production system is necessary. The most vulnerable regions, such as the Jizzakh, require a transition to drought-resistant crops, a change in cropping patterns, and an implementation of precision farming technologies to maximize the efficiency of limited water resources.

Overall, the projections indicate that maintaining a global climate trajectory closer to SSP3-7.0 is critical for preventing unsustainable levels of heat stress and desertification in Central Asia by the end

of the 21st century. The difference of approximately 1.5 °C between the scenarios by 2100 (SSP3-7.0: +4.8 °C vs. SSP5-8.5: +6.3 °C) may determine whether the region faces manageable adaptation challenges or risks escalating environmental and socio-economic crises.

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Data Availability Statement: The datasets generated and/or analysed during the current study are not publicly available due to institutional and legal restrictions under the legislation of the Republic of Kazakhstan but are available from the corresponding author on reasonable request.

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Author Contributions

Conceptualization, Zh. Naurozbayeva; methodology, Zh. Naurozbayeva, G. Monkayeva and M. Zhunissova; software, N. Rakhmatulla; validation, Zh. Naurozbayeva and Ye. Beldeubayev; formal analysis, Ye. Beldeubayev; investigation, Zh. Naurozbayeva, Ye. Beldeubayev, S. Maznev, G. Monkayeva and M. Zhunissova; resources, N. Rakhmatulla; data curation, Zh. Naurozbayeva; writing-original draft preparation, Ye. Beldeubayev and S. Maznev; writing-review and editing, Zh. Naurozbayeva and S. Maznev; visualization, Ye. Beldeubayev; supervision, Zh. Naurozbayeva, S. Maznev; project administration, Zh. Naurozbayeva; funding acquisition, Zh. Naurozbayeva. All authors have read and agreed to the published version of the manuscript.

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