Diagnostic Analysis

of the Current State of the Cryosphere and its Impact on Water Availability in Central Asia

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CONTENTS

PREFACE

Climate-induced changes are dramatic in Central Asia, yet not well understood, despite the critical role of the Central Asian cryosphere in providing water to millions of downstream populations and ecosystems. The major mountain ranges of Central Asia, the Tien Shan and the Pamir, are unique in their hydroclimatic and cryospheric heterogeneity due to a diverse topographic and climatological setting resulting in complex flow regimes and geohazards. Its headwaters are crucial for water supply of the arid Central Asia, making the Tien Shan and Pamir one of the most important mountain water towers in the world. Seasonal snow cover, contributing over 50% to the yearly water balance exhibits changing patterns with downstream consequences. Glaciers serve as vital freshwater reservoirs during dry periods. Permafrost thawing, in turn, is associated with a variety of hazards, including the destabilization of rock walls, and debris flows, increased sediment loads in rivers, subsidence of the ground surface, and changes in subsurface hydrology.

Different studies have attempted to explain observed and modelled heterogeneity of the cryosphere response to climate change in Central Asia, but many processes and its consequences remain unexplained, in large part due to a drastic lack of direct measurements. There is an urgent need to better understand the region’s cryosphere and its interaction with the atmosphere and the hydrosphere. Predictions on future glacier response are associated with uncertainties related to incomplete knowledge of for example climatic and non-climatic drivers, glacier debris cover simulation, and understanding the surge-type glaciers. Snow cover prediction relate to unknown future distribution of the snow cover (rain instead of snow events). Unknown thickness of future snow cover also influences the accuracy of modelled permafrost temperature and representation of the predicted energy balance at the surface. Permafrost land surfaces will react particularly fast when permafrost is close to the freezing point render accurate predictions highly sensitive to accurate modelling of permafrost temperature.

Climate scenarios predict a sustained warming in the coming decades. However, uncertainties in this data remain large. Improving future climate forcing used to predict cryosphere changes is a priority, given discrepancies in past climate datasets across Central Asia. Sub-regional assessments of climate variables, combining in situ observation, proxy data from remote sensing and numerical models, are crucial for more accurate impact studies.

It is now time to aim for a comprehensive monitoring of the atmosphere-cryosphere-hydrosphere nexus to provide the baseline for future predictions of the major water tower of the region. The region, characterized by extreme climates and complex topography, heavily relies on the cryosphere, making it imperative to understand its dynamics for future water availability. Central Asian water resources, originating from the Pamir and Tien Shan mountains, play a critical role in socioeconomic development. Only based on sound scientific knowledge, sustainable adaptation strategies can be developed and implemented. As a recognized climate change hotspot, the region faces substantial challenges, particularly impacting vulnerable mountain communities engaged in subsistence farming and herding. Each Central Asian country faces distinctive water management challenges, requiring holistic approaches, international collaboration, and adaptive measures.

This report assembles current knowledge of observed and predicted climate change, its impact on the cryosphere in Central Asia's and on the crucial role of snow, glacier, and permafrost on water dynamics. Detailed analyses of climate and cryospheric changes in Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan reveal region-specific impacts on water resources, necessitating continuous monitoring, research, as well as cross-boundary collaboration efforts. With this report, we aim to identify current knowledge gaps and formulate strategies to improve the monitoring and research on the climate-cryosphere-water nexus.

The in-depth analysis presented in this report has significant implications for shaping policy discussions in the project countries of Central Asia. It lays a robust groundwork for creating nationally cohesive plans of action. Due to the diverse hydroclimatic and cryospheric characteristics, a nuanced comprehension of the region's cryospheric dynamics is essential to understand the varied impacts of climate change on countries. The Pamir and Tien Shan, with their distinct characteristics, show the importance of customized adaptation measures that address the challenges of each individual country. The analysis serves as a guide, highlighting the complexities of the cryosphere's reaction to climate change and providing the foundation for the formulation of harmonized adaptation strategies across the region.

CHAPTER 1: THE ROLE OF CRYOSPHERE OF CENTRAL ASIA FOR WATER AVAILABILITY

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Glaciers, emblematic indicators of climate warming, are critical reservoirs of freshwater for Central Asia. Despite their significance, a comprehensive understanding of their historical, contemporary, and future impacts on the region's water balance remains elusive (Giorgi et al., 2006). The responses of the cryosphere to climate change in Central Asia are characterized by diverse spatial and temporal patterns, resulting in varied meltwater contributions across catchments that significantly influence water availability dynamics for mountain communities, cascading downstream (Varis, 2014; Xenarios et al., 2019; Immerzeel et al., 2020; Nüsser, 2017; Nüsser et al., 2019). These communities are particularly vulnerable to interannual and abrupt fluctuations in water supply, adding to the elevated vulnerability of Central Asian nations to natural and anthropogenic hazards (Fay & Patel, 2008). With growing populations and an expanding water sector, the importance of reliable water supplies escalates, while simultaneous increases in water stress (Pohl et al., 2017) and competition for limited resources pose challenges to the adaptive capacity of rural communities (Garcia & Brown, 2009; Nüsser et al., 2019). It is crucial to note that these challenges are further complicated by the often-limited financial and institutional resources available to these communities (Manandhar et al., 2018).

Central Asia region exhibits a diverse range of hydrological regimes influenced by snowmelt, glacial meltwater, rainfall, and groundwater sources. Aizen et al. (1995) divided the Tien Shan into four hydrographic regimes, each of which has its own peculiarities of runoff formation:

1. Snowmelt rivers: The source of water for these rivers is mainly the gradual melting of the seasonal snow cover. The timing and extent of snowmelt play a significant role in shaping their hydrological regime.
2. Glacial meltwater rivers: Glacial meltwater is the main source of supply for these rivers. The proportion of glacial runoff varies with the size of glacial areas in the basin.
3. Rain-fed rivers: These rivers, located in regions with maximum precipitation in summer such as the Southern and Eastern Tien Shan, are fed mainly by direct precipitation in the form of rain. They are usually smaller in size and may reach into foothill valleys and beyond mountain ranges.
4. Groundwater-fed rivers: Groundwater sources contribute significantly to the flow of these rivers. The presence of groundwater plays a key role in determining their hydrological characteristics.

Flow formation and water availability in the Tien Shan region are closely related to the contribution of snow and glaciers. Snow cover is the most important source of water for many rivers in the Tien Shan (Aizen et al., 1995). The share of snowmelt in total runoff increases with altitude and reaches 40% at altitudes between 2000 and 3500 meters above sea level (m A.S.L.). Above these altitudes, the contribution of snow and glacial melt water increases rapidly and accounts for 55-60% of the total runoff in the Northern, Central and Eastern Tien Shan (Aizen et al., 1995).

At an altitude of 3800-4000 m A.S.L. in the Tien Shan, glacial meltwater becomes the dominant source of river feeding. In basins with extensive ice cover, glacial runoff can account for up to 45% of the total runoff. On average, glacial runoff accounts for 15-20% of the total river runoff in the entire Tien Shan region (Aizen et al., 1995). During the dry season from July to September, when the runoff in non-glacial basins decreases due to decreased precipitation and increased temperature, a constant water reserve is maintained in glacier-fed basins (Aizen et al., 1995; Sorg et al., 2012; Amstrong et al., 2019).

Central Asia is a mostly arid to semi-arid region (Barry, 1992) with high seasonal variability due to its continentality (Haag et al., 2019), and most anticyclones and cyclones are formed outside Central Asia (Ryazanceva, 1965). The meteorological conditions over Central Asia are influenced by the main direction of the large-scale circulation from west to east (westerlies). A deflection of these western trade winds to the north and south at the margin of the Tien Shan and Pamir leads to intense precipitation (Pohl et al., 2017) and under this barrier effect to increasingly dry conditions towards the center and east (Schienmann et al., 2008). In combination with the influence of the Indian summer monsoon in the south and Siberian anticyclonic activities from the north, this leads to pronounced contrasts in climatological settings within the Tien Shan and Pamir, which are reflected in heterogeneous cryospheric responses (Brun et al., 2019; Barandun et al., 2021; Barandun & Pohl, 2023). Thus, the interplay between large-scale atmospheric circulation and topographic effects plays a key role in the heterogeneous distribution of cryospheric components under a changing climate.

1.1 Snow: Seasonal Water Storage

Aizen et al. (1995) classified the Tien Shan into five distinct regions based on the interaction between the Siberian anticyclonic circulation and the westerly cyclonic activity to describe the formation of precipitation and humidity:

Western, southwestern Tien Shan and Pamir-Alay: This region includes the Fergana, Pskem, Chatkal, and Gissar (Pamir-Alay) mountain ranges. Large amounts of snowfall are recorded during the winter-spring period due to the interaction of the Siberian anticyclonic and southwest cyclonic circulations and a barrier effect at the western orographic margin (Aizen et al., 1995; Schienmann et al., 2008). The jet stream brings particularly warm and moist air masses as it moves from south to north in late winter, resulting in significant winter precipitation on the western margin, in contrast to other regions of the Tien Shan, where winters are dry. The continuous northward movement of the jet stream until late spring creates a north-south temperature contrast and intensifies cyclonic activity over entire Central Asia (Schienmann et al., 2008). As a consequence, the highest precipitation, characterized by heavy showers and thunderstorms, occurs in March and April. After this precipitation peak, precipitation decreases in August and September during the formation of the summer thermal minimum (Aizen et al., 1995), when the jet stream is typically located over northern Central Asia. A second peak in precipitation occurs in the fall, mainly in November (Aizen et al., 1995), when the jet stream starts to move southward again in the fall, causing instabilities (Schienmann et al., 2008).

Northern Tien Shan: This region, which includes the Talas, Kyrgyz, Kungei Alatoo, Zailiysky, and Dzungarian Alatau ranges, has a pronounced seasonal regime. In winter, the influence of the jet stream is weak in the Tien Shan (except for the western margin), and the Siberian highpressure system creates clear and calm winter weather, reducing winter precipitation in the north and east (Aizen et al., 1997). Thus, the lowest precipitation falls in January. Maxima is reached in the spring-summer period - from April (below 1000 m A.S.L.) to June (above 3000 m A.S.L.), with a northward moving jet stream in May (Aizen et al., 2001). These peaks are associated with frontal cyclonic circulation and the arrival of cold, moist air masses. At altitudes below 3000 m A.S.L., the second peak occurs in autumn when the northern jet stream shifts to higher latitudes (Aizen et al., 1995).

Central Tien Shan: Located south of the Terskey, Kyrgyz, and Talas Alatoo, with the Fergana Range to the west and the Kok-Shaal-Too and Meridional Ranges to the south and east, this region is characterized by strong orographic shielding and thus limited winter precipitation, especially in January and February, amounting to only 8-10% of the annual total. At the beginning of summer, cyclonic activity weakens and thermal lows begin to form (Aizen et al., 1997). During summer, the Siberian anticyclonic circulation brings cold and moist air masses to the northern, central and eastern Tien Shan, resulting in frequent spring or summer precipitation (Aizen et al., 1997). Increased condensation leads to increased precipitation at higher elevations. As a result of the development of convection and stratification of the atmosphere, summer precipitation peaks in June-July, caused exclusively by the arrival of cold, moist air masses from the west (Aizen et al., 1995).

South-Eastern and Eastern Tien Shan: This region includes the southern slopes of Kok-Shaal-Too, the eastern mountains of the Khan-Tengri glacial massif, and the adjacent Borokhoro and Bogdo ranges. Although the summer precipitation peak here is similar to that of the Central Tien Shan, the total amount of precipitation in this region is less. Strong cyclonic circulation from the south can lead to intense heavy precipitation (Zhang, 1987). During the winter period, precipitation falls mainly above 2000 m A.S.L. and is sparse. Maximum precipitation occurs in June-July (Aizen et al., 1995).

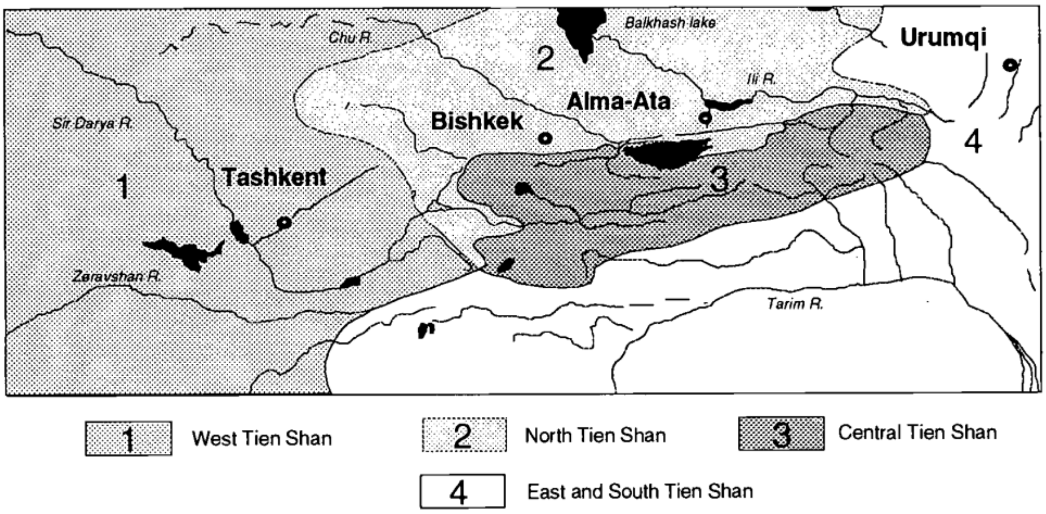

Figure 1.1.1. Classification of the Tian Shan by Precipitation Regime (Source: Aizen et al., 1995)

Based on the glacio-climatic regime and landscape of the Pamir, Aizen (2011) has divided the Pamir into five major regions: Pamir-Alay, Western Pamir, Central Pamir, Southeastern Pamir and Eastern Pamir. However, regional divisions vary substantially in literature and divisions are somewhat ambiguous (Barandun et al., 2021; Moelg et al., 2018; Brun et al., 2019).

Western Pamir: In Aizen (2011), the Western Pamir is the western margin of the Pamir where highest rates of total annual precipitation reach up to 2000 to 2500 mm. Similar to the Western Tien Shan, this region is affected by the northward movement of the jet stream but also to some extend by the Indian summer monsoon, both loaded with moist and warm air.

Central Pamir: The Central Pamir described in Aizen (2011) is often classified as part of Western Pamir in other literature (Mölg et al., 2018). This region hosts the highest glacier accumulation areas reaching up to 7400 m A.S.L. and the world largest alpine glacier outside of polar regions - Fedchenko glacier. The annual precipitation in Central Pamir varies between 800 and 1500 mm (Aizen, 2011) and remain influenced from the jet stream movement from south to north in late winter and spring as well as from north to south movement in autumn.

The high peaks of this region at its eastern margin serves as barrier for the warm and moist air masses of the westerlies, deflected south and north.

Eastern Pamir: Eastern Pamir in Aizen (2011) includes a large high elevation plateau extending over 4000 m A.S.L. occupying approximately 100 000 km^2. This region includes the Karakul region as well as territory of China. This region of Pamir, being shielded from the West and South has extremely arid climate with annual precipitation between only 50 and 150 mm. Extremely dry air and high solar radiation create ideal condition for moisture evaporation from snow and ice surface during the summer months (Aizen, 2011). The Tibetan anticyclone influence the local climate along the eastern margin (Archer & Fowler, 2004), that leads to frequent summer precipitation at its eastern margin. In other literature this region is often separated into the Chinese Pamir classified as Eastern Pamir and the eastern part of the Tajik Pamir is classified to belong to the Western Pamir.

South-Eastern Pamir: Overall, the southern parts of Pamir are lower than the Central and Eastern Pamir. Total annual precipitation in this part of the Pamir is low, varying between 93 mm^{yr-1} (Murgab meteorological station) and 182 mm^{yr-1} (Shaimak station) with a significant amount of precipitation received as snow (Pohl et al., 2015). The most dominant source of moisture at the southern margins of the Pamir is heavy precipitation provided by the Indian summer monsoon (Cadet, 1979). However, orographic shielding at the southern and southeastern margins of the Pamir greatly reduces the moisture supply and leads to very dry conditions towards the north, central and eastern part (Boos and Kuang, 2010; Haag et al., 2019).

Pamir-Alay: This region is very similar to the Western and South-Western Tien Shan with important winter precipitation, a first peak in spring and instabilities in autumn leading to as second precipitation peak in November (Aizen et al., 1995). The observation network at Abramov Glacier at 3837 m A.S.L. is one of the few long-term monitoring stations in the Pamir-Alay. Total annual precipitation at the station has been measured from 1968 to 1998 and is on average 750 mm yr^{-1} with the maximum occurring from March to May (Pertziger, 1996). The region has a strong vertical precipitation gradient of 1200 mm km^{-1} yr^{-1} (Kislov, 1982).

Seasonal snow cover constitutes a significant portion of the yearly water balance in Central Asia, contributing more than 50% to the snow water equivalent in the primary basins (Hoelzle et al., 2017). According to Armstrong et al. (2019), remote sensing and degree day melt modelling revealed that seasonal snow contributions can reach as high as 65–72% of the mean annual runoff in the Amu Darya and Syr Darya basins. This is in stark contrast to the 23% contribution from rainfall and the 2–8% contribution from glacier ice to the annual runoff (Sorg et al., 2012; Aizen et al., 1995).

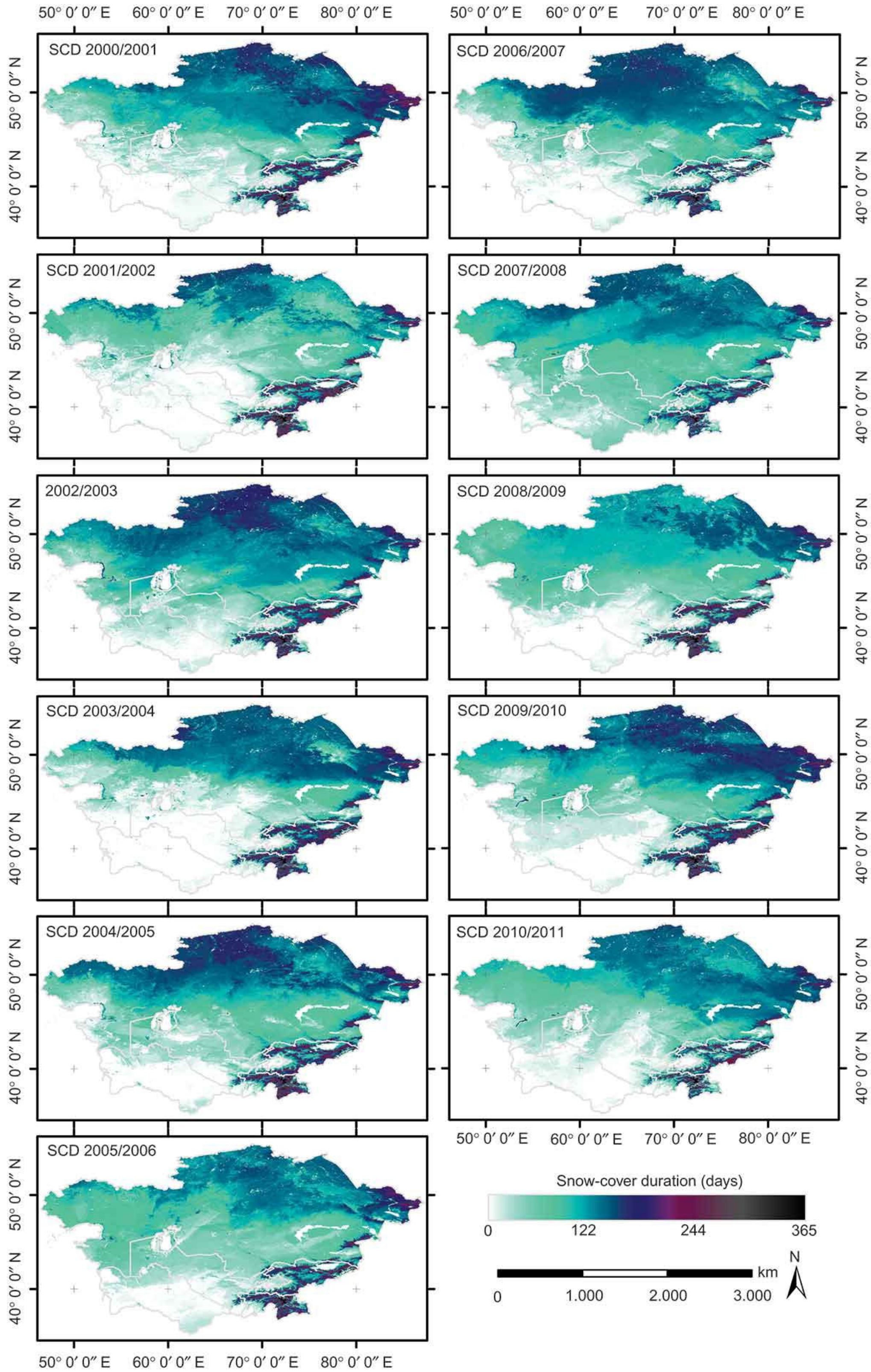

Figure 1.1.2. Snow Cover Day (days) for the hydrological years from 2000/2001 to 2010/2011 (Source: Dietz et al., 2013)

Changes in snow cover patterns have the potential to impact river dynamics, leading to diminished water flow during critical periods and heightened variability in water levels throughout the year. Recent findings derived from both remote sensing techniques (Adnan et al., 2017; Immerzeel et al., 2009; Peters et al., 2015) and in site measurements (Marty 2008; Serquet et al., 2013) have pointed to a seasonal reduction in the duration and extent of snow cover, particularly at lower altitudes. These observed changes carry significant implications for downstream ecosystems, agricultural practices, and water management approaches (Aizen et al., 1995; Sorg et al., 2012; Unger-Shayesteh et al., 2013). The urgency to implement comprehensive measures is underscored to effectively address the challenges posed by shifting snow cover patterns and their repercussions on water availability in Central Asia.

1.2 Glaciers: Frozen Reservoirs of Freshwater

Glaciers, ranging from small alpine glaciers to extensive ice sheets, exhibit a constant flow under gravity, shaping characteristic landscapes. Glacier formation begins with the accumulation of snow, which gradually compacts into firn, characterized by granular, compacted snow. Glaciers react to air temperature through melt and are thus a vital source of freshwater, particularly during seasonal melting, influencing regional hydrological dynamics.

Central Asia's Tien Shan and Pamir mountain ranges host over 25 000 of glaciers, totaling. The Tien Shan hosts almost 15 000 glaciers, covering a surface area of around 12 300 km^2 (Consortium, R., Randolph Glacier Inventory, 2017). The Pamir contains over 13 000 glaciers that cover an area of approximately 12 000 km^2 (Mölg, et al., 2018). The glaciers in this region exhibit diverse responses to climate change (Scherler et al., 2011; Kääb et al., 2012; Farinotti et al., 2015; Brun et al., 2017; Wang et al., 2017; Shean et al., 2020; Miles et al., 2021; Hugonnet et al., 2021; Barandun et al., 2020, 2021) that reflect the contrastic climatological and topographic setting described above (Fig. 1.2.1). Understanding these responses is crucial for assessing the future runoff of rivers and water resources in Central Asia. Historically, glacier mass balance monitoring began in the mid-1950s during the USSR era (Dyurgerov, 2002; Kuzmichenok, 2006), but the majority ceased in the early 1990s, leaving a data gap. Presently, only Tuyuksu Glacier in Kazakhstan provides continuous data, reporting a mass balance of -0.4 m w.e. yr^{-1} from 1957 to 2022 (WGMS, 2020). Efforts to re-establish glacier monitoring began in 2010 (Hoelzle et al., 2017), contributing to regional assessments despite limitations.

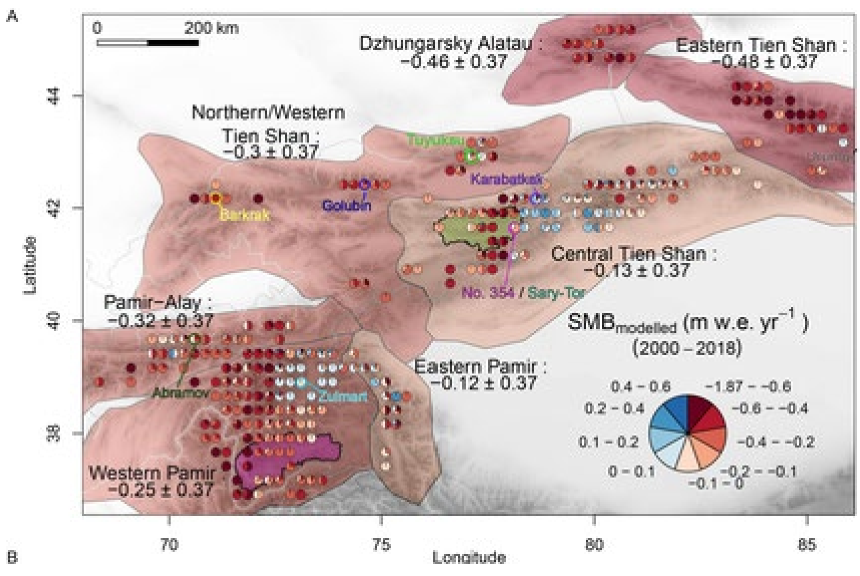

Figure 1.2.1. Heterogeneous glacier response for the Tien Shan and Pamir (Source: modified from Barandun et al., 2021)

Freshwater stored in glacial ice acts as a vital reservoir, releasing meltwater during dry and hot periods, especially in summer. Glacial meltwater significantly regulates river flow dynamics, impacting timing and volume, especially in major rivers like the Amu Darya and Syr Darya. On average, glacier melt constitutes approximately 6% for Syr Daria and 20% for the Amu Darya yearly (Worni et al., 2013). During the melting season, this contribution can be 1.5 to 3 times the mean annual input (Saks et al., 2022; Armstrong et al., 2018). Glacial melt ensures reliable water supply for agriculture, industry, and environmental conservation after seasonal snow has depleted.

Climate change poses a threat to glacial ice and water resources. Predictions suggest increased runoff in spring and summer, leading to glacial lake outburst floods, debris flows, and landslides causing damage to settlements and agriculture (Kaser et al., 2010; Huss and Hock, 2018; Bolch et al., 2011; Erokhin et al., 2018). Conversely, runoff during dry summer months may decrease steadily by the end of the century due to decreasing ice volume (Hagg et al., 2007; Hagg et al., 2013; Huss and Hock, 2018; Kure et al., 2013).

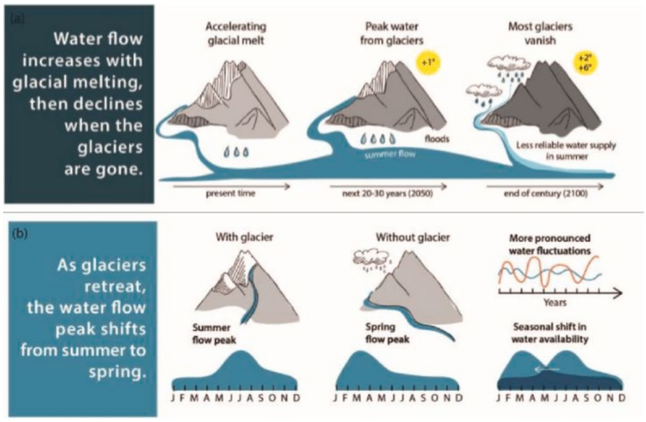

Figure 1.2.2. Schematic view of expected runoff changes under ongoing climate change: (a) affecting total glacier melt water contribution and (b) seasonality in water availability (Credits: Zoï Environment Network, Geneva).

These predictions underscore the need for effective water management and monitoring of glacier mass balance in the region. Ongoing efforts since 2010 aim to re-establish in situ glacier monitoring, contributing to validating modeling studies and regional assessments of glacier behavior and its impact on freshwater resources in Central Asia (Hoelzle et al., 2017, 2019; Schöne et al., 2013).

Central Asia's glaciers, a critical source of freshwater, face complex responses to climate change. Monitoring these glaciers are essential for understanding future water resource dynamics and mitigating the impact of climate change on the region.

1.3 Permafrost: The Frozen Foundation

Central Asia, characterized by its high mountains and continental climate, hosts extensive permafrost, particularly in the Pamir and Tian Shan Mountain ranges (Fig. 1.3.1). Permafrost, defined as ground remaining frozen for two or more years, is so far understudied.

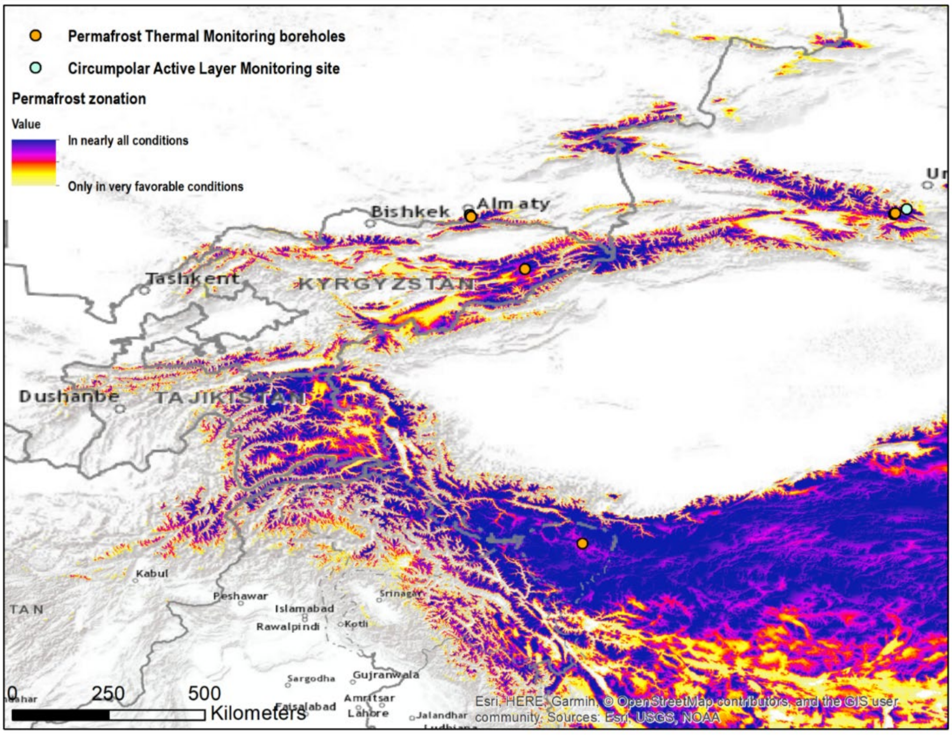

Figure 1.3.1. Overview of area where permafrost can be expected in High Mountain Asia (Source: Gruber, 2012)

Covering 15% of the Northern Hemisphere's permafrost, the permafrost of Central Asia and the Tibetan Plateau constitutes the largest permafrost area outside polar regions (Gruber, 2012). The distribution of permafrost is influenced by factors such as snow, temperature, solar radiation and local characteristics of surface and subsurface conditions. Permafrost, is soil or ground material, with temperature continuously remaining below 0°C (32°F) for two or more years. It varies in depth from a few meters to potentially several hundred meters (Gorbunov et al., 1996). It significantly shapes the hydrology of Central Asia by restricting water infiltration, influencing groundwater recharge, and altering river flow patterns in downstream regions.

The warming of mountain slopes and permafrost has broad consequences, impacting communities kilometers downstream (Huggel et al., 2005; Walter et al., 2020). Predicted outcomes include increased creep rates of rock glaciers (Delaloye et al., 2010; Sorg, 2015) and thermally induced slope instabilities, potentially causing debris flows, rock avalanches, or glacial lake outburst floods (Haeberli et al., 2017; Hoelzle et al., 2001; Gruber & Haeberli, 2007; Krautblatter et al., 2012). Moreover, it is still unknown if permafrost ground ice in the Central Asian mountains is expected to play a substantial role in the regional hydrological cycle (Huss & Hock, 2018). Analysis of ground temperature monitoring at the Abramov site by Pertziger (1996) in combination with recent observations at the Abramov meteorological station shows an increase in the mean temperature of the permafrost (Fig. 1.3.2).

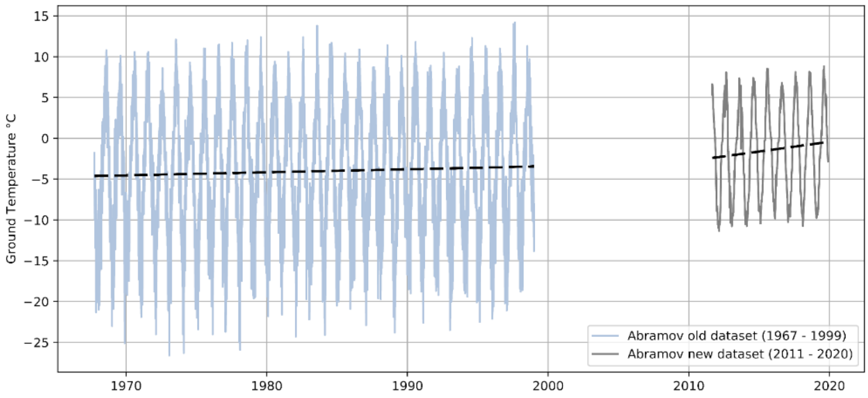

Figure 1.3.2. Observed ground temperature measurement at the Abramov site, Koksu valley, South Kyrgyzstan. Clear trends are visible at the old and new observation sites (Data source: Pertziger 1996 and Abramov Meteorological Station)

Despite the insulating effects of the active layer and ventilation, permafrost responds slowly to climate change, offering water resources on a longer time scale (Delaloye & Lambiel, 2005; Wicky & Hauck, 2017; Jones et al., 2018; Janke et al., 2017). There are substantial discussions, mainly from the Andes, if permafrost ground ice is an important contributor to the hydrological cycle or not (e.g. Arenson and Jakob, 2010; Arenson et al., 2022; Azocar & Brenning, 2010). However, uncertainties exist in permafrost distribution and ground ice volumes, underscoring the need for updated data (Kenner et al., 2019; Hoelzle et al., 2001; Halla et al., 2020; Arenson & Jakob, 2010).

Permafrost's impact on river flow regimes is multifaceted, influencing runoff dynamics during snowmelt and releasing water during active layer thawing in summer. Projections based on CMIP5 scenarios suggest ongoing permafrost degradation in Central Asia, with potential downstream runoff increases (Rogger et al., 2017). The vulnerability of permafrost to climate change poses a significant challenge. Rising temperatures accelerate degradation, impacting river basin hydrological patterns. Thawing permafrost releases greenhouse gases, contributing to the greenhouse effect (Koven et al., 2011). Historical data shows warming trends in the Tien Shan Mountains since the Little Ice Age, with projected increases persisting (Marchenko et al., 2007; Forsythe et al., 2017). Recent new measurements in a borehole in the Akshirak region showed a ground temperature increase at 20 m depth of around +1.9 °C from 1986 to 2022, which is actually higher than ground temperature series show at comparable sites in the European Alps (Cromo-Adapt project).

Understanding and addressing the vulnerabilities associated with permafrost degradation are crucial for sustainable water resource management in Central Asia. Monitoring ongoing changes and adapting strategies to evolving hydrological patterns are imperative for ecosystem health and effective disaster risk management in the region.

Conclusion

Central Asia stands at the intersection of dynamic climate patterns, high mountain ranges, and extensive cryospheric systems, including seasonal snow cover, glaciers, and permafrost. The intricate interplay of these elements profoundly influences the region's water availability, presenting both challenges and opportunities in the context of ongoing climate change.

The role of atmospheric circulation in shaping precipitation patterns across the Tien Shan and Pamir emphasizes the importance of understanding regional variations. Changes in seasonal snow cover, with its significant contribution to yearly water balance, necessitate a proactive approach to manage shifting water dynamics. The abundance of glaciers in the Tien Shan and Pamir underscores their crucial role as freshwater reservoirs. Diverse responses of glaciers to climate change require ongoing monitoring to assess their impact on future water resources in Central Asia. Extensive permafrost in the region shapes hydrology by influencing groundwater recharge and altering river flow patterns. The slow response of permafrost to climate change, coupled with uncertainties in distribution and ground ice volumes, highlights the need for continuous monitoring.

Predictions of increased runoff, potential hazards, and decreasing ice volumes highlights the urgency of effective water management strategies. Warming trends in the Tien Shan Mountains since the Little Ice Age emphasize the need for adaptive measures to address changing hydrological patterns. The complex dynamics of the cryosphere necessitate a holistic approach to water resource management in Central Asia. Ongoing efforts to monitor and understand cryospheric changes are vital for adapting to evolving hydrological patterns and mitigating the impact of climate change.

Continued research and monitoring are essential for refining predictions and addressing uncertainties related to cryospheric elements. Collaborative international efforts are crucial for developing comprehensive measures to safeguard water resources, ecosystems, and communities in Central Asia. The cryosphere plays a pivotal role in shaping the hydrology of Central Asia. As the region faces the challenges of climate change, understanding, adapting to, and mitigating the impacts on the cryosphere are imperative for ensuring sustainable water resource management and resilience in Central Asia.

CHAPTER 2: CENTRAL ASIAN WATER RESOURCES

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2.1 Overview of the Water Resources of Central Asia

Central Asia is highly dependent on freshwater resources for socioeconomic development (Abdullaev et al., 2019). Central Asian countries are interconnected by shared water resources, which are transboundary in nature. Water from a drainage basin generally collects into a river through surface runoff from precipitation, meltwater released from natural ice and snowpacks, and underground sources such as groundwater recharge and springs. About 6000 rivers originate in the mountains, including the great rivers, the Amu Darya River and the Syr Darya (Dukhovny et al., 2014). They are mostly fed by snow and glacier melt (70% to 80%) from the Pamir, Hindu Kush, and Tien Shan ranges (Djumaboev et al., 2019; Armstrong et al., 2019). Snow, glaciers and permafrost are the main components of the cryosphere. While snow and glacier meltwater production has received more attention, the role of permafrost as water resources is so fare not well understood. Permafrost occurs in continental areas at high latitudes defined by ground temperatures below 0°C. The majority of the mountain territory is in Kyrgyzstan and Tajikistan, which endowed with significant water resources - about 26% and 55%, respectively. The total volume of surface water resources in Central Asia is 120 km^3, of which the annual contribution of the Amu Darya and the Syr Darya accounted for 115.6 km^3 yr^{-1} (Safronova, 2009). Today, however, the total river flow of these two rivers is estimated to have decreased to only about 10%, due to strong water resource development in the upstream part of the Aral Sea basin (Djumaboev et al., 2019). The amount of meltwater varies from year to year, mainly depending on the amount of snow accumulation in the mountains during the winter months (Eshment, 2011; Armstrong et al., 2019). Apart from the importance of snow for the annual runoff, glacier melt contributes significantly during the summer months when snow is depleted and precipitation is sparse (Saks et al., 2022; Aizen et al., 1995). Glacial meltwater comes from a long-term reservoir built up over decades to centuries (Armstrong et al., 2019).

Table 2.1.1. Composition and volume of the main surface water resources of Central Asia (Safronova, 2009).

Country	Amu Darya basin km^3 yr^{-1}	Syr Darya basin km^3 yr^{-1}	Aral Sea basin km^3 yr^{-1}	%
Kazakhstan	-	4.50	4.50	3.9
Kyrgyzstan	1.90	27.4	29.30	25.3
Tajikistan	62.9	1.1	64.00	55.4
Turkmenistan	2.78	-	2.78	2.4
Uzbekistan	4.70	4.14	8.84	7.6
Afghanistan	6.18	-	6.18	5.4
Central Asia	78.46	37.14	115.6	100.0

The largest rivers in Central Asia are the Amu Darya and the Syr Darya. They are part of the Aral Sea Basin, of which the Amu Darya provides approximately 78 km^3 yr^{-1} and the Syr Darya approximately 37 km^3 yr^{-1} (Table 2.1.1, Safronova, 2009). Water resources are shared by all five Central Asian countries as well as Afghanistan and Iran (Table 2.1.1). The main contributor to the Amu Darya is Tajikistan with 63 km^3 yr^{-1}, while the Syr Darya is mainly fed by Kyrgyzstan with 27 km^3 yr^{-1}. All other countries account for less than 10% of Central Asia's total surface water resources and are heavily dependent on water supplies from upstream countries.

The Amu Darya rises at the confluence of the Pyanj and Vakhsh (formerly also Zerafshan). It flows downstream for 2540 km before terminating into the Aral Sea. The Syr Darya begins in Kyrgyzstan at the confluence of the Naryn and Kara Darya. It is 3019 km long and also flows into the Aral Sea. Two other major rivers in the basin are the Chu and Talas. They dry up before reaching the Syr Darya. Kazakhstan contributes 0.11 $km^3\ yr^{-1}$ (6.0%) and Kyrgyzstan 1.72 $km^3\ yr^{-1}$ (94%) to the mean annual flow of the Chu and Talas. The Karkara receives 0.23 $km^3\ yr^{-1}$ (38%) from Kazakhstan and 0.37 $km^3\ yr^{-1}$ (62%) from Kyrgyzstan (Tologonov, 2022). The average annual flow of rivers in the Tarim Basin, estimated within the borders of the Kyrgyzstan, is 6.99 $km^3\ yr^{-1}$ (Tologonov, 2022).

Kazakhstan: There are 85022 rivers and temporary watercourses in Kazakhstan (Tyumenev, 2008). The Irtysh is the world's longest tributary river. Its length within Kazakhstan is 1700 km (total length 4248 km). The second largest river is the Syr Darya, 1400 km long within the country (total 2219 km). There are the world's largest lakes - the Caspian Sea, and the Aral Sea situated in the country. The total volume of water in the lakes of Kazakhstan exceeds 190 km^3 (Tyumenev, 2008). Table 2.1.2 and Figure 2.1.1 show the surface water resources for all river basins of Kazakhstan and shows the share of water coming from local sources and from neighboring countries.

Table 2.1.2. Factual resources of the river runoff in Kazakhstan, $km^{3\ yr-1}$ (Source: Tursunova, 2022).

	local resources ($km^3\ yr^{-1}$)		external resources ($km^3\ yr^{-1}$)		local and external resources ($km^3\ yr^{-1}$)	
	total	including outflow outside Kazakhstan (returnable)	total	including formed of the territory of neighbouring countries	total	with anthropogenic changes in the main riverbed
Aral-Syr Darya	2.16	0.38	16.9	16.5	18.7	14.5
Balkash-Alakol	16.5	0.96	13.5	12.5	29.0	26.5
Ertis	26.5	1.36	8.32	6.96	33.4	29.4
Esil	2.68	-	-	-	2.68	2.68
Zhayik-Caspian	3.13	0.99	8.86	7.87	11.0	10.3
Nura-Sarysu	0.87	-	-	-	0.87	0.87
Tobul-Torgay	1.68	-	0.45	0.45	2.12	2.12
Shu-Talas	0.94	-	2.77	2.77	3.71	3.71
Total	**54.5**	**3.70**	**50.8**	**47.1**	**102**	**90.0**

Surface water is the largest water resource for Kazakhstan with a withdrawal rate of 90% (Karatayev et al., 2017a). Groundwater makes up 10-15% of surface water resources and accounts for 4.6% of total withdrawals (Karatayev et al., 2017b). Desalinated water is used to 4%, mainly in the central and northern part of the country where external water resources are scarce. Water availability in these large basins is unevenly distributed, with the three largest river basins, Aral-Syr Darya, Ertis (former Irtish), and Balkhash-Alakol, accounting for almost 75% of all water resources in the country (Karatayev et al., 2017b). Kazakhstan depends by up to 45% on external water resources (Table 2.1.2, Karatayev et al., 2017b). Apart from the natural distribution, water is disproportionate between urban and rural populations, both in terms of quantity and quality (O'Hara et al., 2008). The economy's water consumption is on average 32.5 $km^3\ yr^{-1}$. The largest water consumer is agriculture with up to 75%. Over 50% is used in the Aral-Syr Darya basin, where irrigated agriculture is traditionally developed. The largest industrial water consumption is registered for the industrially developed Ertis, Nura-Sarysu and Zhayik-Caspian basin ranging from 20% to almost 40%. The municipal-domestic sector uses only about 5% of water in Kazakhstan (Dostai, 2012; Medeu et al. 2020; Tursunova, 2022).

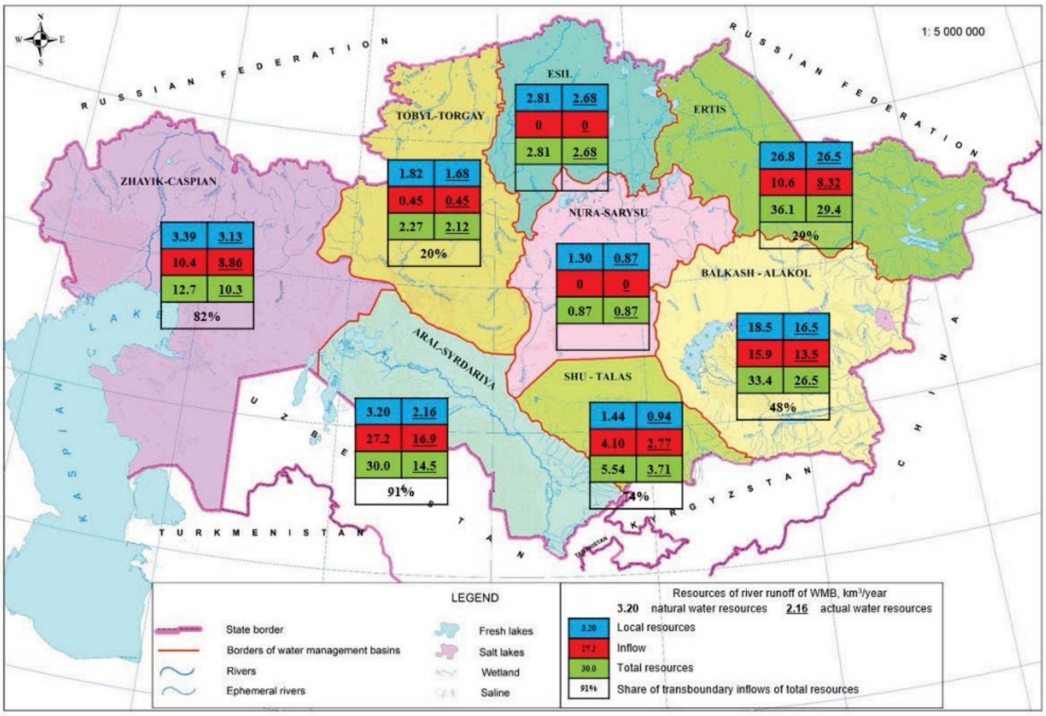


Figure 2.1.1. The river runoff resources for the different river basins in Kazakhstan (Source: Tursunova, 2022)

Kyrgyzstan: Kyrgyzstan has over 3500 rivers, of which 30 are large rivers. There are about 2000 lakes, where the largest and deepest lake is Issyk-Kul (Safronova, 2009). The largest rivers are the Naryn, Kara Darya, Tarim, Chu, Talas, and Chatkal rivers. The river Naryn significantly affects the economic activity of neighboring countries Uzbekistan, Kazakhstan and Tajikistan. The length of the river is 535 km, its basin area is 53 000 km^2, the river runoff fluctuates between 10-14 km^3 yr^{-1} merging outside of Kyrgyzstan with the river Kara Darya and forms the Syr Darya (State Water Resources Agency, 2023).

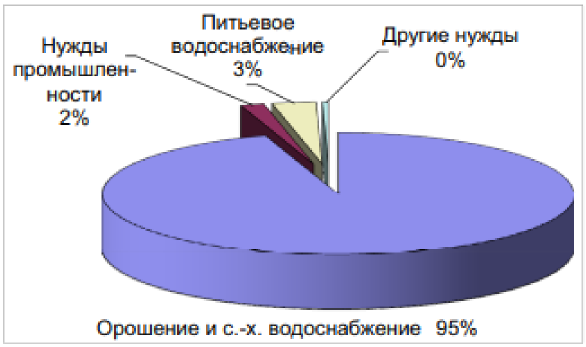


Figure 2.1.2. Types of water use in Kyrgyzstan (Source: Osmonbetova, 2021)

According to the distribution of river runoff per 1 km^2, the Naryn Oblast is the most abundant 299 000 m^3 km^{-2}, followed by the Issyk-Kul, Osh, Jalal-Abad and Chui Oblasts (Osmonbetova, 2021). The least water supplied regions are Batken Oblast (115 000 m^3 km^{-2}) and Talas Oblast (162 000 m^3 km^{-2}, Osmonbetova, 2021). The mean total annual river runoff in Kyrgyzstan is 47.2 km^3, with an average river runoff of 35 km^3 (74%) during the growing season and 12.2 km^3 (26%) during the autumn-winter and early spring periods (Osmonbetova, 2021; Malyshev, 1997). In Kyrgyzstan itself, 20-25% of the total reserves are used, the remaining water serves as important water resources for the neighboring countries. Fresh water in the country is spent on irrigation and other agricultural activities (almost 95%), industrial needs (1.6%), domestic and drinking water supply (more than 3%; Figure 2.1.2). Water for irrigation comes mainly from river discharge (80%) and partly from reservoirs (13%), while drinking water supply is mainly based on groundwater (FAO, 2016). Most of the surface and reacted groundwater is fed by the cryosphere (Hill et al., 2017).

Tajikistan: Tajikistan has rich water resources and occupies a key position as water tower in Central Asia. The basis of Tajikistan's water resources are glaciers. The number of glaciers reaches more than 14 509 with a total glaciated area of 11 146 km^2, which covers 8% of the country's territory (Gafforzoda et. al., 2023).

There are about 947 rivers flowing through the country, the total length exceeds 28 500 km, but the most important rivers are Syr Darya, Pyandzh, Vakhsh, Murghob, Kofarnihon, Surkhob, Oksu, Zerafshan. There are more than 1 300 lakes (Sarez is one of the largest). The lakes of Tajikistan contain more than 46.3 km^3 of water, of which 20 km^3 is fresh. The country has 10 reservoirs (Nurek, Kairakum, etc.) with a total volume of 15 km^3. The main users of water in Tajikistan are drinking water supply and sanitation, hydropower, irrigated agriculture, industry, fisheries, recreation, and the environment. Tajikistan uses only 17-20% of the water resources generated on its territory (Ministry of Energy and Water Resources of Tajikistan).

84% of the water in Tajikistan is used for agriculture, 8.5% of the consumption is accounted for drinking water and municipal services, 4.5% for industry and 3% for other users (Toderich, 2004). Tajikistan produces about 64 km^3 of water annually, about 55% of total amount of water in the Aral Sea basin (Toderich, 2004).

Turkmenistan: The main source of water for Turkmenistan is the Amu Darya River. Amu Darya is considered as international water resource and its use is controlled by multilateral agreements, which allocate 22 billion km^3 yr^{-1} of water per year to Turkmenistan. Water intake from Amu Darya amounts to almost 90% and is supplemented with surface runoff from three other rivers: Murgan, Tedjen, and Atrek, as well as minor quantities from small rivers of East and Central Kopetdag. The construction of the Karakum Canal in 1954, completed in 1988, transformed Turkmenistan's water landscape, supplying 13 km^3 of water annually from the Amu Darya River to the Karakum Desert. This canal, despite opening new agricultural tracts, particularly for cotton monoculture, results in significant water loss and widespread soil salinization (Glantz, 1999; Saiko and Zonn, 2000). There is practically no surface runoff originating on the territory of Turkmenistan and the countries water security relies strongly on water resources and their management of neighboring countries (Li et al., 2017; Malsy et al., 2012; Sorg et al., 2012). Some episodic runoff can occur only in some places formed by takyrs and takyr-like soils after rain fall (Orlovsky & Orlovsky, 2002). Turkmenistan's annual precipitation ranges from 100 mm to 400 mm (Orlovsky & Orlovsky, 2014). Ground water plays a marginal role in Turkmenistan's water resources. The total ground water reserves reach 3.4 km^3, of which only 1.3 km^3 is usable (Stanchin & Lerman, 2007).

Agriculture accounts for more than 90% of water consumption in Turkmenistan. Industry follows at 3%, the municipal sector at 2.7%, cattle breeding complexes and pasture irrigation at 0.6%, and fishery at 0.1% (Zonn, 2012). Water reaches the end user through a complex system of primary canals, which draw water from the rivers, secondary canals, which distribute water to large farming units across the country, and tertiary canals, which distribute water to farmers within the large units. The distribution of water to various uses (including system losses) is shown in Figure 2.1.3 (Stanchin & Lerman, 2007). Turkmenistan is confronted with significant challenges regarding water resources, utilization, and preservation, given the escalating anthropogenic impact on water bodies. The nation anticipates heightened water consumption in the future, driven by the accelerating pace of economic development and the expansion of production capacities in various sectors (Zonn, 2012). In the context of Turkmenistan, the nation's well-being and security hinge upon a dynamic interaction of internal and external factors, encompassing climate variability, institutional changes, regional land use transformations, and the broader processes of economic internationalization and globalization.

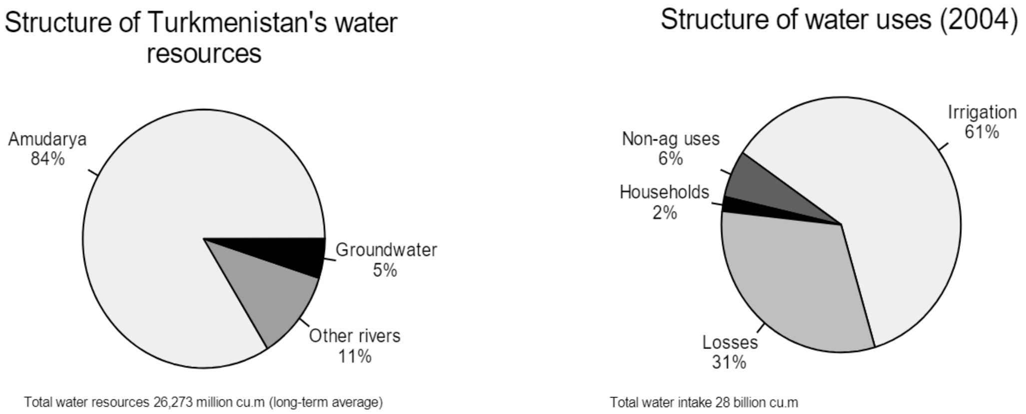


Figure 2.1.3. (left) Different water resources; (right) main water consumers of Turkmenistan's water resources (Source: Stanchin & Lerman, 2007)

The main water resources of Uzbekistan are Amu Darya and Syr Darya. Uzbekistan uses about 90% of its available water resources mainly during the growing season. During the off-season, freshwater is used for winter crop irrigation, moisture replenishment irrigation and washing of saline soils. There are 411 glaciers in the mountains, with a total glacier area of 190 km^2, which serve as long-term water reservoirs (Zhumayeva, 2021). The largest are Barkrak, Kalesnika and Pakhtakor. Groundwater and reuse of drainage water provide an additional but rather minor source of water (Table 2.1.3).

Table 2.1.3. Distribution of water resources by sources of water intake in 2014 (Source: State water cadastre of Uzbekistan, 2014)

River Basins	Water Intake by Source, km^3 yr^{-1}				
	Total	from main rivers	from small rivers	from groundwater	from drains
Amu Darya River	33.66	21.07	8.59	1.67	0.68
Syr Darya River	24.98	11.06	9.26	3.65	0.66
Total	56.64	32.13	17.85	5.32	1.34

Currently, Uzbekistan's available water resources consist on average of 11.5 km^3 yr^{-1} of surface runoff from internal rivers, 42.0 km^3 yr^{-1} from transboundary rivers, and 9.43 km^3 yr^{-1} from reuse and groundwater. From 1996 to 2013, the share of irrigation in total water consumption was 86%, the share of the energy sector was 8%, and the share of drinking and community/municipal water supply was about 4% (Figure 2.1.4).

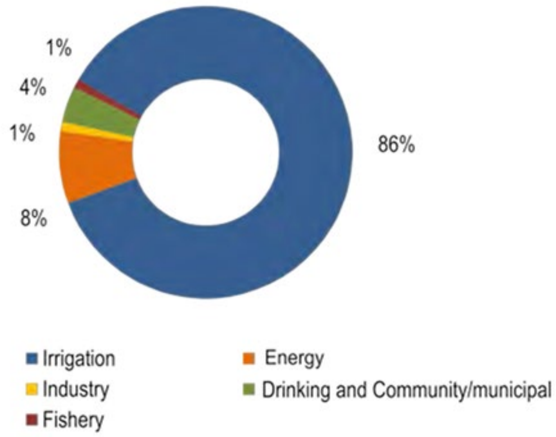


Figure 2.1.4. Share of water consumption in Uzbekistan from 2004 to 2013 (Source: State water cadastre of Uzbekistan, 2014)

2.2 Changing Water Resources under Climate Change

In Central Asia water withdrawal closely matches availability (IPCC AR6). Turkmenistan and Uzbekistan are the most water-stressed countries in the region (Karthe et al., 2017; Russell, 2018), with 88% of Turkmenistan's surface water originating from the Amu Darya, flowing inside Turkmenistan from Tajikistan and Afghanistan (Nationally Determined Contribution of Turkmenistan under the Paris Agreement, 2022; Duan et al., 2019). The cumulative effects of climate change will be profound and aggravate the pressure on water resource management. The climate of Central Asia is strongly continental. In the south and east, the mountain ranges of the Himalayas, Pamir, Hindu Kush and Tien Shan almost completely isolate Central Asia from humid air masses from the Indian Ocean. Because of these barrier effects, large part of the Tien Shan and Pamir are dominated by dry and cold conditions. For the Tien Shan, a steady increase in air temperature of about 0.1 to 0.2 °C per decade was recorded during 1960-2007, with more pronounced warming in the winter months. For the Pamir, the temperature increased from 0.07 to 0.11 °C yr^{-1} for the same period (Barandun et al., 2020).

Warming in Central Asia is expected to exceed the global average, with temperatures rising by an average of 5-6 °C by 2100 (Sara J. & Proskuryakova T., 2022). Ice and snowmelt are the main water resources for the densely populated lowlands of Central Asia (Konovalov & Shchetinnicov, 1994; Schaner et al., 2012; Chen et al., 2016) and play a crucial role for mountain communities (Figure 2.2.1; Nüsser, 2017; Nüsser et al., 2019; Sitara et al., 2015). Snow accumulation acts as a water reservoir, especially during the winter months, and controls streamflow in the spring and early summer. Glaciers and permafrost release most of their meltwater between July and September. Changes in snow, glaciers and permafrost due to an air temperature increase affect these water resources profoundly. Long-term monitoring of the components of the cryosphere is needed to better understand the climate response. It will help to better quantify the associated changes in meltwater runoff contribution (Barandun et al., 2020). Currently, the annual contribution of glacial meltwater from the Tien Shan Mountains to the upstream flow of the Syr Darya is 10% per year. The contribution of glacial meltwater to the Amu Darya is about 40% per year (Figure 2.2.1). However, for the dry summer months glacier meltwater contribution can drastically increase to up to up to 42% for Syr Darya and to 96% for Amu Darya (Huss & Hock, 2018). By 2050, surface runoff is projected to increase by 25% in the summer months for the Amu Darya due to increased glacier melt, and then decrease by about 28% until the end of the century. For

July and August, models predict a similar increase of runoff for Syr Darya. Future reductions in solid precipitation will primarily affect spring and early summer runoff.

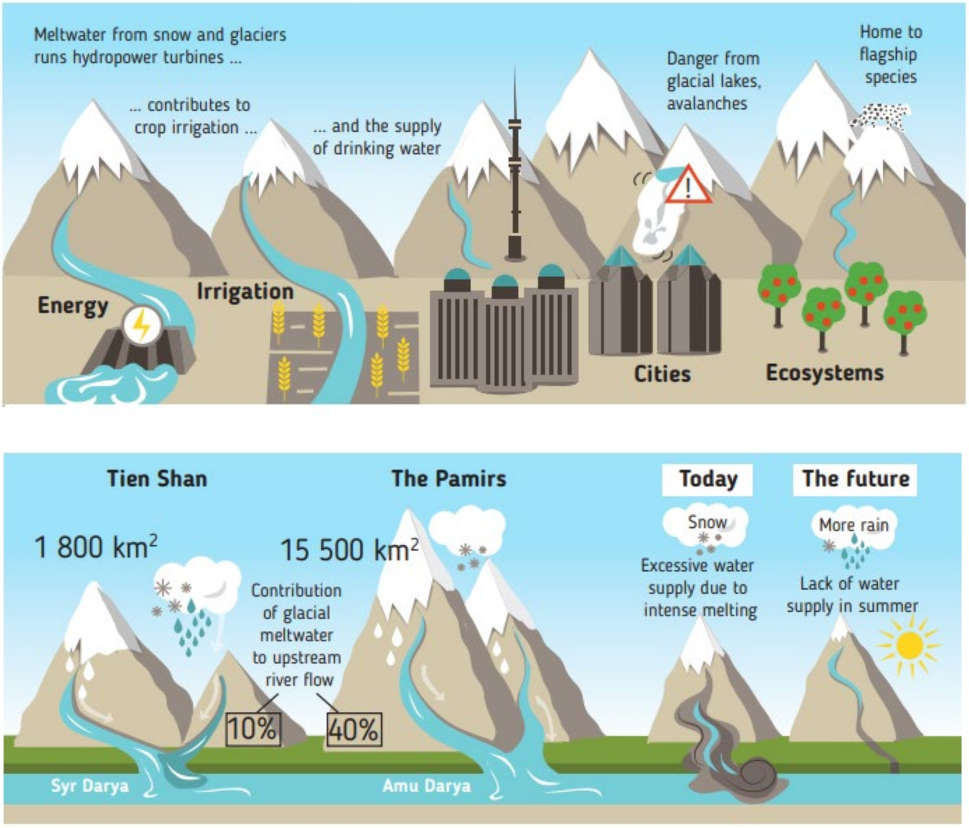
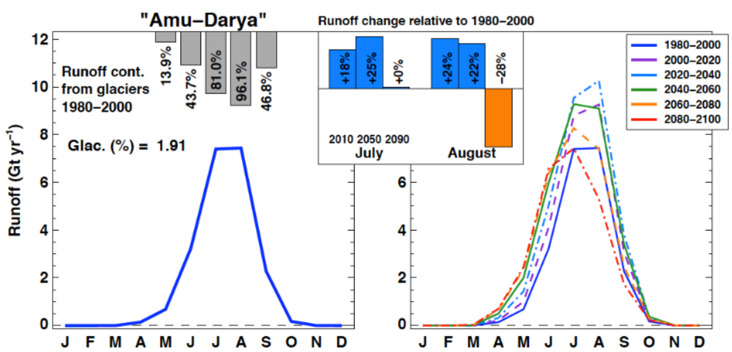


Figure 2.2.1. (Top) major water use depending on the cryosphere in Central Asia, and (bottom) water resources stored in the cryosphere of Central Asia today and expected changes in the future (Credits: Zoï Environment Network, Geneva)

Both extreme floods and extreme droughts will increase, as will overall water scarcity. Changes in the seasonality of the snowpack, resulting in earlier melting could lead to more spring and summer runoff in low snow years or droughts (Siegfried et al., 2012). This has the potential to trigger Glacier Outburst Floods (GLOFs) events, debris flows and landslides that can damage nearby settlements. As permafrost thaws in response to rising temperatures, it feeds back into the climate system by releasing trapped methane or carbon dioxide. The result is an increase in the greenhouse effect (Koven et al., 2011).



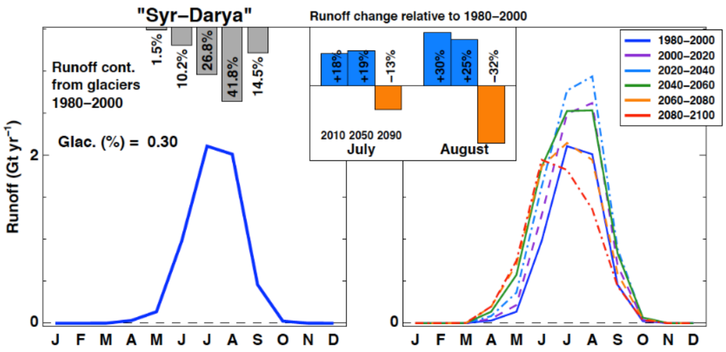


Figure 2.2.2. (Left) current and (right) future monthly glacier runoff for the two main rivers in Central Asia (Huss & Hock, 2018)

2.3 Water Resources Challenges

The cumulative effects of climate change will be profound. Warmer temperatures are already causing snow to melt earlier in the season, increasing water demand, and shortening the irrigation season. In combination with changes in the cryosphere meltwater contribution sever changes are to be expected. Both extreme floods and extreme droughts will increase, as will overall water scarcity (Sara & Proskuryakova, 2022). A potential threat to the region is the unregulated use of water, mainly for agricultural irrigation. In addition, water is the main source of electricity generated by hydropower plants (Schrader et al., 2019). The continuous supply of electricity to the population depends on the level of the reservoir, that show decreasing capacity with ongoing climate change.

All Central Asian countries are connected by shared water bodies and collectively face major water challenges. Rapid growth in population size and density has led to increased demand for water (Mankin et al., 2015). The transboundary aspect of water resources, uneven water distribution and withdrawing along river pose a challenge to regional water management (Munia et al., 2016; Krasznai et al., 2019). Competition and conflicts over water between different water users are also increasing. According Cassara et al. 2019 there are various water-related challenges in Central Asia especially regarding the water management systems. One issue is the fragmentation of water resource management across different ministries and agencies, with a large number of entities in charge. Another issue is the implementation of water reforms across Central Asia countries. Legal frameworks for water sector reform have been put in place and are regularly updated. However, implementation is a challenging task. Problems include gaps in national strategies, weak information systems and monitoring networks, lack of scientific and technical capacity among institutional staff, insufficient mobilization of public budgets, and poor coordination and information. Insufficient attention has been paid to environmental and health issues, resulting in reduced investment in infrastructure and maintenance, and deterioration of water and environmental monitoring networks (Cassara et al., 2019). Inappropriate use of fertilizers and pesticides has worsened surface and groundwater quality through increased soil salinization and chemical contamination, affecting human health, ecosystems and agricultural productivity (Cassara et al., 2019; Bekturganov et al. 2016). Until recent years, groundwater quality has received less attention than surface water quantity (Cassara et al., 2019). Significant water consumption by the population of Central Asia to irrigate moisture-loving crops such as cotton and rice has led to the depletion of the irrigation capacity of the Amu Darya and Syr Darya rivers. Uncontrolled use of river water resources has led to the environmental disaster of the drying up of the Aral Sea. In 2014, the eastern part of the South (Great) Aral Sea dried up completely.

Currently, Central Asian countries are among the highest per capita water users in the world (Dukhovny & Schutter, 2011). Most water is used for irrigation, while the share of agriculture in Central Asia's gross domestic product (GDP) has almost halved since the end of the Soviet Union (Hamidov et al., 2016). Changes in water supply, combined with rapidly growing and industrializing economies, are leading to an increased risk of water scarcity in the region. Most of the countries in the region are experiencing regular droughts. Lack of water affects arable lands, which leads to a decrease in the yield of wheat and other crops and contributes to the spread of pests and diseases. The human factor can also aggravate the situation with such negative impacts as unregulated grazing, deforestation, and inefficient farming. Together with climate change, this can significantly increase the processes of soil erosion and degradation. Hotter weather and an increase in the number of hot days will lead to increased desertification, decreased pasture productivity and a reduction in food supply. All these processes can affect food security (Idrisov, 2023).

Pollution of the waters of Central Asia occurs due to the development of industry, an increase in the number and density of the population, the use of cheap fertilizers and pesticides, the flow of pesticides into rivers from poorly equipped warehouses, and the presence of uranium mines and storage facilities. Biological pollutants are coming from domestic sewage and farm runoff, such as bacteria, helminths, viruses, as well as toxic metals in because of industrial activity (Safronova, 2009). An additional threat is posed by the largest tailings dump of toxic waste from a gold mining plant in the Tien Shan, where the rapidly melting Petrov glacier could destroy the dam and the contents would flow into the Ara-Bel and Naryn rivers, important water resources.

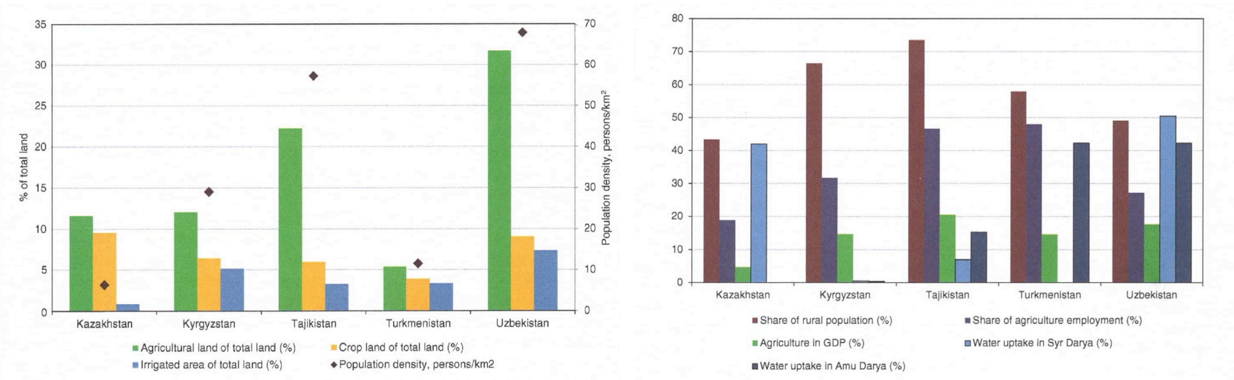


Figure 2.3.1. (Left) Importance of agricultural land in Central Asia, (right) proportional representation of agriculture land, crop land and irrigated land as well as the contribution to the GDP by agriculture for each Central Asian country (Murzakulova et al., 2019)

Extreme weather events caused by climate change impacts are currently major threats to the population. For example, emergency situations are caused by hail, mudflows, glacier outburst, drought, extremely high or low temperatures. Natural disasters destroy transport, energy and other infrastructure and damage agricultural land. In 2021, drought led to the death of several thousand animals in several regions of Kazakhstan, and the lack of water for irrigation sparked protests by farmers in the Chui region of Kyrgyzstan. In the spring of 2022, heavy rainfall in Tajikistan and Kyrgyzstan caused mudflows that caused significant damage in some areas of the countries (Idrisov, 2023). With ongoing climate change, such events will become more frequent.

Conclusion

Water plays a critical role in the socio-economic development of the Central Asian region. The arid zone of Central Asia constitutes a region confronted with a complex interplay of environmental, social, and economic challenges. The countries heavily rely on the shared water resources of the Amu Darya and Syr Darya river basins, the majority of which are fed by snow and glacier melt, making the cryosphere a crucial component of the region's water supply.

Climate change is having a cumulative effect on the region’s water resources, with rising temperatures and changing precipitation patterns. This poses risks such as increased water scarcity, changes in seasonality of snow cover, and the potential for extreme weather events. Existing challenges, such as fragmentation of water resource management, gaps in regulatory frameworks, and insufficient attention to environmental and health issues, place additional stress on the availability of water resources in the countries.

The socio-economic development of Central Asian countries is closely linked to the availability of water resources. The region faces escalating water demand due to population growth and economic development, leading to potential conflicts over water resources. Addressing these challenges requires not only effective policies, but also international cooperation to ensure sustainable and equitable water use.

Given the anticipated changes in water availability due to climate change, joint initiatives are needed to adapt and mitigate the impacts. This includes improved cryosphere monitoring along with better understanding of the dynamics of cryosphere in the past to better predict the future changes and its related effects on water.

CHAPTER 3: CLIMATE CHANGE IN CENTRAL ASIA

3.1 Climate Setting of Central Asia

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Located in the interior of the Eurasian continent and far from the ocean, Central Asia including five nations (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan) is characterized by arid to semi-arid climates with hot and dry summers and cold winters, sometimes severe with snowfall. The topography of the region is complex with elevation ranging from below 134 m A.S.L. in western Kazakhstan to more than 7000 m A.S.L. in the southeastern countries Kyrgyzstan and Tajikistan (Tien Shan and Pamir ranges). The average air temperature in January is moderate in the south with values of 0 °C and -17 °C in the north and can be well below -54 °C in the east of Kazakhstan[1] and -63 °C around the Bulunkul Lake in the Pamirs in Tajikistan[2] in extremely cold years. The mean air temperature in July varies from 25 °C in a greater part of the region to 30 °C in the south and desert areas, making it the hottest month of the year. The maximum values can reach up to 45 °C in the southern part of Central Asia with the record temperature of 50 °C in Termez and the Kyzylkum Desert (Chub, 2007).

The average annual precipitation distribution in Central Asia has a contrast between the plain dominated by steps, deserts, and semi-deserts in the large part of the region (>250 mm), foothills (250-500 mm), and mountain areas (up to 2000 mm in some windward slopes) in the east and southeastern of Central Asia (Chub, 2007). The western and north-western plains of the region are open to incoming northerly and north-westerly airflows and westerly moist air from the Atlantic, at the same time, the south-westerly moist air from the Mediterranean and the Arabic Sea reach the region when the jet-stream moves to the south of Central Asia (Schiemann et al., 2008).

Almost 80 million people in five Central Asian countries[3] depend on water originated in the region with the sky-scraping mountain ranges hosting more than 25 000 glaciers (Barandun et al., 2020). Glaciers significantly contribute to the mean annual and particularly to summer runoff of the two main transboundary rivers, the Amu Darya and Syr Darya, and they appear to be major indicators of climatic changes (Kriegel et al., 2013). However, mountains of Central Asia are sensitive to global warming due to enormous storage of water resources as glaciers and snow at high altitudes (Xenarios et al., 2019). According to the IPCC AR6[4], glaciers are likely to disappear by nearly 70% in Central and Western Asia where the annual runoff in large-scale glacierized catchments are projected to decline by over 10%, with the most significant reductions in Central Asia by the end of the 21st century.

Many studies have assessed the performance of Global Climate Models (GCMs) in simulating surface temperatures and precipitation characteristics as a significant impact on the hydrological cycle over the Central Asian region. For instance, the impact of climate change results on seasonal variability of precipitation and

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[1] www.kazhydromet.kz
[2] https://unfccc.int/sites/default/files/resource/4NC_TJK_eng_0.pdf
[3] https://www.worldometers.info/world-population/central-asia-population
[4] https://report.ipcc.ch/ar6/wg2/IPCC_AR6_WGII_FullReport.pdf

temperature over Central Asia under the framework of Coordinated Regional Climate Downscaling Experiment (CORDEX) shows relatively high warming trend in surface temperature (from 3 °C up to 11.4 °C on average) and a decrease in precipitation, particularly, in the south-eastern part of the region by the end of the century 2070-2100 (Ozturk et al., 2012, Ozturk et al., 2017). Downscaled emission scenario of high-resolution regional climate model indicates a warming of up to 7 °C in the northern part of Central Asia and mountain areas until the end of the twenty-first century (Mannig et al., 2013). However, climate change scenarios predict dryer summer conditions in a large area of Central Asia and wetter cold seasons over the northern part of the region. Huang et al. (2014) projected future change in the annual precipitation over Central Asia for the period 2011–2100 by applying CMIP5 under the different emission scenarios (RCP2.6, RCP4.5 and RCP8.5). The authors found increasing trends in annual precipitation (over 3-9 mm per decade) for the northern Central Asia, the Tian-Shan Mountains and northern Tibet by the end of 2100 in comparison with the previous investigations on climate change signals over Central Asia. The authors suggested that large-scale atmospheric water vapour fluxes and surface evaporation over the study region could be the possible mechanisms of the increasing changes in projected precipitation. Dike et al. (2022) investigated the spatial distribution and variability of precipitation across the SSPs in the CMIP6 GCMs and models projected a decrease in total spring wet-day precipitation amount over the south of Central Asia and a significant increase in the northern part of the region.

These studies aside, there have been relatively few investigations focusing on the projected changes in large scale atmospheric circulation as a main driver of precipitation extremes and as a source of water resources over Central Asia under global warming conditions. Zhao et al. (2018) simulated subtropical westerly jet (SWJ) stream and its effect on the projected precipitation over Central Asia for the summers of 2071–2100 by using of 25 CMIP5 models. By applying the empirical orthogonal function (EOF) method, these authors revealed the strength and position of SWJ over Central Asia in the future. According to the CMIP5 ensemble results, the SWJ axis shifting further south over Central Asia which will result in more summer rainfall in most of northern and north-eastern part of the region in the future, however, the authors found uncertainties regarding future precipitation changes in the rest of the Central Asia. Reyers et al. (2013) studied the link between weather system and precipitation frequency and its magnitude for the Aksu river basin in Central Asia and projected the changes in precipitation climatology over the Aksu basin until 2100. Outputs of statistical-dynamical approach show a decrease in annual precipitation over large parts of the Aksu river basin in Tien Shan and an opposite sign is defined to the southeast of the investigation area.

In some studies, the adverse effects of global warming to the Central Asian glacier zones and its negative consequences on water availability in the region have been evaluated (Barandun et al., 2020). Researchers have predicted a substantial glacier shrinkage due to the increase in air temperature over the Tien Shan and the Pamir, considered to be the water tower of Central Asia and its effects on the water availability until the end of the century (Sorg et al., 2015, Kure et al., 2013). Using the recent developments in the field of climate modelling, Malsy et al. (2012), White et al. (2014) and Radchenko et al. (2017), investigated the impact of climate change on water resources in Central Asia and defined the water scarcity might increase in the region. Moreover, the uncertainty of water availability in the context of a changing climate creates a major risk for agriculture, food and nutrition security, and the livelihoods of millions over Central Asia (Sommer et al., 2013; Bobojonov & Aw-Hassan, 2014; Hagg et al., 2013).

In summary, Central Asian region is severely impacted by global warming, as evidenced by the retreat of glaciers, water scarcity, and intensified desertification that can have substantial societal and ecosystem impacts. Nevertheless, anthropogenic climate change will contribute to the increased severity of cryospheric water resources, snow decline and thawing of permafrost that have threaten the downstream communities of Central Asia through changes in hydrological regimes and increases in the potential of landslides and glacier lake outburst floods. The capacity development and knowledge dissemination at various levels, generating long-term and sustainable cryospheric networks, improved water management and support a sustainable regional collaboration in the water sector can make climate risk management processes and outcomes more effective across the Central Asia.

3.2 Climate Change in Kazakhstan

by Zamira Usmanova[a], Vassiliy Kapitsa[a], Zarina Saidaliyeva[a], Martina Barandun[b]

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The climate of Kazakhstan, due to its great distance from the sea, is strongly continental, with long hot summers and cold winters, with large fluctuations in daily and annual air temperature. The maximum average precipitation in the territory falls in the period from April to July, the minimum - in August-September. Annual precipitation varies from less than 100 mm in some extreme south-western and southern regions of the desert zone to 1500 mm and more in foothills and mountainous areas (The 8th National Communication of Kazakhstan to the UNFCCC, 2022).

Historical Climate Change

According to the results of the assessment of changes in average monthly air temperature and monthly sums of precipitation, there is a widespread increase in both mean annual air temperature and average seasonal temperatures in Kazakhstan. Since the 1960s, each consecutive decade in Kazakhstan was warmer than the previous one. Since the mid-1970s, mostly positive anomalies of average annual and seasonal surface air temperature have been observed (Annual Bulletin, 2022; The 8th National Communication of Kazakhstan to the UNFCCC, 2022; Karatayev et al., 2022; Salnikov et al., 2015).

Comparison of the average multi-year air temperature values for two consecutive periods, 1961-1990 and 1991-2020, shows that the average annual temperature in Kazakhstan has increased by 0.9 °C on average (Figure 3.2.1). February and March have warmed the most - by 2.0 and 1.7 °C, respectively. The temperature in July and December did not change much. The average annual precipitation over the territory remained practically unchanged (Figure 3.2.1), but in some months it increased with a maximum in February (by 15.6 %), while in September and October precipitation decreased by 10.8 % and 14.8 %, respectively (The 8th National Communication of Kazakhstan to the UNFCCC, 2022).

The average annual precipitation on average for the territory of Kazakhstan decreased in the 1960s and 1970s. For the last 46 years period (1976-2021) no long-term trends were registered, however, there was an alternation of short periods with positive and negative precipitation anomalies (The 8th National Communication of Kazakhstan to the UNFCCC, 2022; Annual Bulletin, 2022; Karatayev et al., 2022; Salnikov et al., 2015).

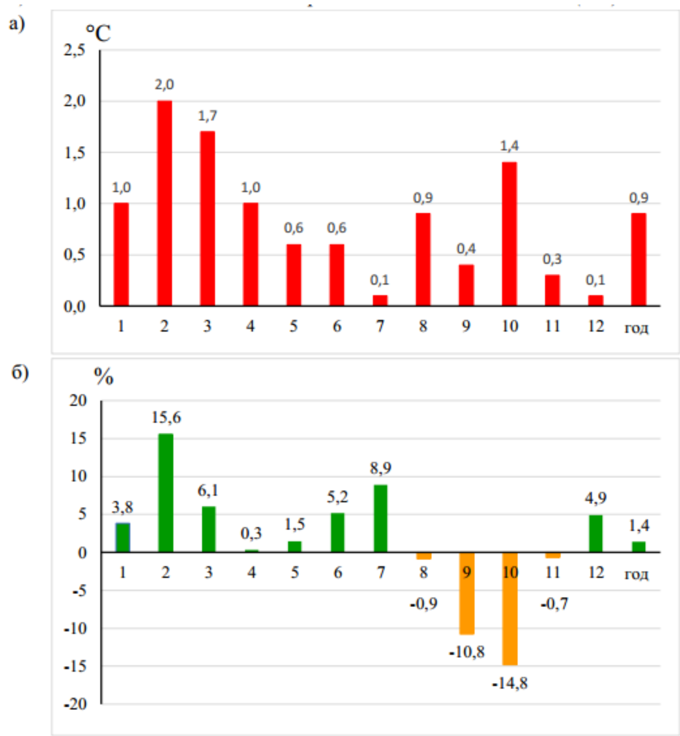

Figure 3.2.1 Anomalies in air temperature (a) and precipitation (b) averaged over the territory of Kazakhstan. Anomalies in temperature are calculated as the difference between long-term averages for the period 1991-2020 and for the period 1961-1990 (in °C), for precipitation - as the ratio of long-term averages (in %) (Source: The 8th National Communication of Kazakhstan to the UNFCCC, 2022)

Most of the research has been carried out in the plains and foothills of the country; the lack and absence of hydro-meteorological stations in mountainous and especially high-altitude areas make reliable assessment of climate change difficult (Piven, 2008, 2013). In the glacial-nival zone of Ile Alatau, an increase in average annual and seasonal air temperatures was observed according to data from the weather stations Tuyuksu-1, Mynzhylki, Big Almaty Lake (BAO) (Vilesov, 2007; Piven, 2008, 2013; Shahgedanova et al., 2018; Kapitsa et al., 2020) – the summer temperature increase rate was 0.03 °C yr^{-1} for the period 1957-2016. Shahgedanova et al (2018), Kapitsa et al (2020), Piven (2013), Vilesov & Uvarov (1997) reported that since the 1970s summer air temperatures have increased more intensively; there has been an increase in winter temperatures and an increase in the length of the warm period due to the increase in autumn season temperatures.

There are no high-altitude meteorological stations with a continuous series of observations in Zhetysu Alatau and Kazakh Altai (Kapitsa et al., 2017; Bolatova et al., 2023). However, significant positive air temperature trends for all seasons of the year, including the summer ablation season were found at different stations located in Zhetysu Alatau between 600 and 1700 m A.S.L. From 1960 to 2014, summer temperatures at regional stations in Zhetysu Alatau increased at a rate of 0.18 °C/10 years (Kapitsa et al., 2017). A similar increase in air temperatures was also found in the Kazakh Altai (Bolatova et al., 2023).

No long-term trends in either seasonal or annual precipitation were found in Ile Alatau, Zhetysu Alatau and Kazakh Altai; some (insignificant) increases in both seasonal and annual precipitation were found in recent decades (Piven, 2008, 2013; Shahgedanova et al., 2018; Kapitsa et al., 2017; Kapitsa et al., 2020; Bolatova et al., 2023); the observed negative anomaly of regional precipitation in the 1970s-1990s (Severskiy et al., 2006; Severskiy et al., 2016; Shahgedanova et al., 2018; Kapitsa et al., 2020) together with the increase in summer temperature affected the glacier mass balance across the Tien Shan (Farinotti et al. 2015), which was related to changes in atmospheric circulation (Cao, 1998; Shahgedanova et al., 2018). Similar climate variability trends are found for the entire Tien Shan (Aizen et al., 1996; Kutuzov & Shahgedanova, 2009; Narama et al., 2010; Wang et al., 2013; Unger-Shayesteh et al., 2013; Gan et al., 2015).

Future Climate Change

Surface air temperature is expected to continue to increase in all seasons, and while by mid-century the range of temperature increase is 2.3-2.6 °C according to the SSP2-4.5 scenario and 3.0-3.5 °C according to the SSP5-8.5 scenario, by the end of the century, this increase can even be greater (3.3-3.9 °C and 6.2-7.3 °C, respectively).

According to the highest emissions trajectory (SSP5-8.5), average annual temperature in Kazakhstan is forecasted to increase by more than 6 °C by the end of the century which is about 3 °C more than according to the lower emissions scenario (SSP2-4.5), indicating a large mitigation in warming across Kazakhstan that could be achieved by controlling global emissions. The rates of increase in average and seasonal annual temperature are not equal across Kazakhstan and greater warming is expected in the northern regions. The ensemble of models suggests that the probability of heat waves may increase significantly in the 21st century, especially under the high emission scenarios (SSP5-8.5) (The 8th National Communication of Kazakhstan to the UNFCCC, 2022).

Based on the 8th National Communication of Kazakhstan to the UNFCCC in 2022, most of the climate models forecast some increase in annual precipitation in Kazakhstan. By the middle of the current century this increase in precipitation will be 7-8 % on average for Kazakhstan depending on the scenario of greenhouse gas emissions. It could reach an increase of 11-14% by the end of the century. The change in annual precipitation amount is uneven across the country, the minimum increase of less than 10% is expected in the west of Kazakhstan. A maximum increase of slightly more than 20% is expected in the southeast. The greatest increase in average seasonal precipitation in Kazakhstan can be expected by the end of the century in the winter period by 20-35%, in spring by 13-16% and in autumn by about 7%. An unfavorable scenario is expected in the summer period that indicates a 12% decrease in precipitation on average for Kazakhstan. The intensity of extreme precipitation is likely to increase with increasing temperature. This conclusion is supported by data from different regions of Asia. However, this phenomenon strongly depends on local geographical conditions (The 8th National Communication of Kazakhstan to the UNFCCC, 2022).

Impact of Climate Change on Water Availability

Despite the observed reduction in glacier area, no significant reduction in streamflow has been observed in the northern Tien Shan and Zhetysu Alatau since the 1950s. Due to temperature increase, intra-annual changes (redistribution) of runoff have been observed: in autumn and winter the runoff increased in the northern Tien Shan due to increase in the duration of the melting season until early autumn; the increase in runoff of Zhetysu Alatau rivers in winter months is due to increase in the frequency of winter thaws (Shahgedanova et al., 2018; Issaldayeva et al., 2023).

Under current climate warming and insignificant changes in precipitation, glaciers are forecasted to lose half of their volume and a third of their area by the end of the XXI century, but will not disappear completely (Shahgedanova et al., 2018). The impact of forecasted climate change on the river runoff depends on the degree of glaciation in the catchment area. However, with current knowledge, uncertainties of climate scenarios and limited understanding of possible feedback mechanisms render predictions highly uncertain. The regions with a low degree (currently 2-4%) of glaciation (Turgen, Kaskelen catchments) will be vulnerable as summer discharge are expected to be reduced by 20–37%, especially under more pessimistic scenarios. In watersheds with a high degree of glaciation (Ulken Almaty, Talgar rivers) no statistically significant changes in summer runoff were found, while spring runoff increases under pessimistic scenarios (Shahgedanova et al., 2020). In watersheds with an average degree of glaciation (10–12%, Kishi Almaty), a reduction in summer runoff is predicted under less pessimistic scenarios, while by the most severe warming the more intense melting of glaciers and snow will provide water supply (Shahgedanova et al., 2020). After peak water, glacier melt contribution will decrease and snow melt will become the most dominant contributor (Kaser et al., 2010).

According to the results of forecasting of climatic parameters and river runoff of selected areas in the context of water management for different river basins, an increase in air temperature is expected, as well as an increase in precipitation amounts to varying degrees depending on the basin (The 8th National Communication of Kazakhstan to the UNFCCC, 2022). An increase in temperature has an impact to the melting of glaciers, which will lead to an increase in runoff of mountain rivers until the middle of the century and decrease until the end of the century as a result of the glacier retreat (The 8th National Communication of Kazakhstan to the UNFCCC, 2022). In particular, this trend in flow changes is typical for the following water basins: Aral-Syr Darya, Ertis, Shu-Talas. However, the Balkash-Alakol water basin is characterized by an increase in runoff towards the end of the century, which can be explained by possible longer lasting glaciation. All lowland water basins, in particular Nura-Sarysu, Yesil, Zhaik-Caspian and Tobol-Torgai, tend to reduce river discharge by the end of the century, which is associated with an increase in air temperature, high evaporation and a slight increase in precipitation (The 8th National Communication of Kazakhstan to the UNFCCC, 2022; Shahgedanova et al., 2020). According to Bolatova et al. (2023) estimates for two tributaries of the Ertis (former Irtysh) River in the Kazakh Altai, the average annual discharge of the Oba River is projected to increase by 5.7-8.1% under the RCP4.5 and RCP8.5 scenarios compared to the 1981-2010 baseline period. For the Ulba River Basin, projections show a slight increase by mid-century under both scenarios and in the far future under RCP4.5 (2-4%), and a slight decrease of 1% in the far future under RCP8.5, all compared to the baseline period.

Conclusion

The impacts of climate change are already being felt in Kazakhstan and will continue to increase under all climate scenarios. Not only average air temperature and precipitation levels are changing, but other characteristics are changing as well, including the frequency and intensity of weather and climate extremes. The effects of climate change in the future may be both negative and positive. As the existing infrastructure was generally built under the climatic conditions of past decades, climate change has mostly negative impacts, especially in arid regions, and often very significant ones. This is mainly due to the increased probability and intensity of heat waves and changes in the hydrological cycle (The 8th National Communication of Kazakhstan to the UNFCCC, 2022; Salnikov et al., 2023).

Climate change affects the conditions of river runoff formation in arid and mountainous areas of Kazakhstan. The runoff is predominantly determined by the proportion (degree) of glaciation and the influence of air temperature to all components of the mountain cryosphere: snow, glaciers and permafrost. The sparse network of hydrometeorological monitoring, especially in the foothills and mountainous areas, and the network of observations of the components of the cryosphere in Kazakhstan, create uncertainties in a clear assessment of climate change and its impact to glaciation and water resources. Future projections remain highly uncertain.

The improvement of hydro-meteorology and glaciology monitoring, and of the mechanisms for data acquisition, analysis and exchange among the institutions and agencies concerned, will contribute to better understanding of the changes that are occurring and to the accuracy of climate forecasts and, as a result, will improve early warning systems in case of emergencies and develop adaptation measures and solutions in the field of water resources management and adaptation to climate change.

3.3 Climate Change in Kyrgyzstan

by Erlan Azisov[a], Tomas Saks[b], Serikzhan Atanov[b], Martina Barandun[b]
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Introduction

The territory of Kyrgyzstan, located in Central Asia and the neighborhood of deserts, as well as at a considerable distance from the oceans and seas, is characterized by continental and arid climate. Climate conditions are defined with 4 landscape-climatic belts 1) valley - piedmont, 2) middle, 3) high, 4) nival. Kyrgyzstan is usually divided into four climatic areas: Northern and North-Western Kyrgyzstan, South-Western Kyrgyzstan, Issyk-Kul Basin and Inner Tien-Shan[5] (Podrezov, 2014). In general, climatic conditions are governed by the interaction between the southwestern branch of the Siberian anticyclonic circulation and cyclonic activity from the west (Aizen et al., 1995).

Historical Climate Change

Most studies focusing on Central Asia agree that the warming trend in mean annual temperatures is less pronounced in the high altitudes than in the lower elevation plains and protected inter mountain valleys (Unger-Shayesteh et al., 2013). For the winter months, a stronger warming trend can be detected at higher elevations of the Tien Shan (Kriegel et al., 2013; Mannig et al., 2013; Zhang et al., 2009).

For the whole territory of Kyrgyzstan, the average annual temperature increased by 1.6 °C in the 20th century considering a 100-year period. The largest change was observed in winter (2.6 °C), and the smallest in summer (1.2 °C). Moreover, for the Naryn Basin, warming in January reached up to 5.2 °C. For individual climatic regions, the increase in mean annual air temperature was different. Atmospheric precipitation was found to have no significant trend for entire Kyrgyzstan, however it slightly increased (by approximately 23 mm) in the Inner Tien Shan. Furthermore, both decrease and increase of mean annual precipitation were recorded in some subregions (Abdyrasuova et al., 2011). Precipitation changes in the country do not seem to suggest any significant trend.

Future Climate Change

Warming across the Central Asia land area is projected to be somewhat more than the global mean. The multi-model mean boreal summer warming in 2071–2099 is projected to about 2.5 °C and 6.5 °C above 1951–1980, in 2 °C and 4 °C world (Reyer et al., 2015). Future climate change in Kyrgyzstan is estimated by different climate scenarios and models in the First, Second and Third National Communications. On average for Kyrgyzstan in 2100 a temperature increase of 6.1 °C is expected under the medium scenario and 4.7 °C under the mild scenario. Under the pessimistic scenarios heat waves and other climate extremes will cause a severe threat to

[5] Third National Communication of the Kyrgyz Republic to the UN Framework Convention on Climate Change, 2016. Link : https://unfccc.int/sites/default/files/resource/NC3_Kyrgyzstan_Russian_24Jan2017.pdf

the ecosystem and threaten the livelihood in the affected regions considerably (Abdyrasuova et al., 2011). It has been estimated that heat waves will increase and 20-30% of summers will be significantly warmer in a 2 °C world while in a 4 °C world 50-80% of summers will be significantly hotter for the last quarter of the 21st Century (Reyer et al., 2015). Future projections on precipitation suggest that central and, especially, eastern Kyrgyzstan might become wetter (Reyer et al 2015). The changes in precipitation in a multi-model run are far more pronounced during the winter (DJF) than during summer (JJA) (Reyer et al 2015). Apart from changes in precipitation Kyrgyzstan will probably experience increased aridity in lower lying areas due to increased evapotranspiration as a result of rising temperatures.

Impact of Climate Change on Water Availability

Future climate change will bring changes in the streamflow seasonality, including a decreasing ratio between warm and cold season runoff volumes and the shift of warm season peak discharge towards boreal spring. The timing of peak water from glacier ablation are expected to be directly related to the magnitude of warming and the pace at which it occurs (Rounce et al., 2023). In some high-altitude catchments winter runoff increase has been observed (Saks et al., 2022). As well as the shift towards earlier snow cover onset and earlier snow cover melt has been detected (Dietz et al., 2014). Already now change from snow to rain precipitation has been observed in Central Asia, affecting streamflow (Li et al., 2020).

The rate of glacier area shrinkage is 0.2-1% per year, and their melting is not only becoming more intense, but also the duration of the ablation period from early spring to late autumn is increasing (Barandun et al., 2020). A longer melting period and more intense melt will result in an initial increase of runoff until peak water is reached. After peak water, meltwater contribution from glaciers is expected to decrease (Kaser et al., 2010; Huss & Hock, 2018; Barandun et al., 2020).

The degradation of glaciers will have a negative effect on agriculture, because as the number, area and volume of glaciers decreases on a long term, fresh water supply will especially become scarce during the growing season. Now, only about 7% of the land in Kyrgyzstan is suitable for irrigation and shift in the seasonal runoff pattern and the total amount of runoff under current climate change can crucially affect this. Retreating glaciers often leave behind glacier moraine dammed lakes, which potentially could lead to catastrophic flooding. For example, most glacial lakes in the northern Tien Shan mapped in 2000s developed mainly since the 1980s (Narama et al., 2009). A recent study (Dayrov et al 2022) suggests that there was a significant shift in the dynamics of 242 glacial lakes in Kyrgyz and Terskey mountain ranges, accounting for 30% in both areas. Forty-six new glacial lakes appeared between 2017 and 2019, while 18 glacial lakes disappeared.

Conclusion

Climate change in Kyrgyzstan impacts its cryosphere, causing significant changes in temperature and precipitation patterns. Throughout the 20th century, the country experienced an average temperature rise of 1.6 °C, with a more substantial warming of 2.6 °C in winter. These observed changes, combined with the uncertainties in precipitation trends, emphasize Kyrgyzstan's cryosphere's vulnerability to the effects of a changing climate (Abdyrasuova et al., 2011).

Climate change significantly affects river runoff formation in Kyrgyzstan, where the hydrological system is i closely linked to glaciation. Glacial meltwater is a significant contributor to river runoff, and changes in the timing and intensity of glacier ablation directly affect the seasonality of the runoff. Future projections suggest shifts in runoff volumes, peak discharge timing, and an increased risk of glacial lake outburst floods.

There are certain challenges and uncertainties in assessing the impact of climate change on glaciation and, subsequently, on water resources in Kyrgyzstan. Historical data show differences in precipitation trends, which impede a comprehensive understanding of the hydrological dynamics. The limitations in data and monitoring accentuate the requirement for better techniques to measure glacier area shrinkage, glacial lake dynamics, and runoff changes. These limitations may present risks to the accuracy of impact assessments and effective planning for future climate change scenarios (Abdyrasuova et al., 2011; Dayrov et al., 2022).

Enhancing monitoring of the Kyrgyzstan atmosphere, cryosphere and hydrosphere is essential given climate change challenges. Obtaining accurate data on temperature, precipitation, and glacial dynamics relies on robust and systematic monitoring systems. Expanding the monitoring network of the atmosphere, cryosphere and hydrosphere, alongside the implementation of advanced monitoring technologies and coordinated efforts between national and international agencies to establish standardized monitoring methodologies, will enable comprehension of both the direct impacts and lay the foundation for science-based decision-making and sustainable water management.

3.4 Climate Change in Tajikistan

by Hofiz Navruzshoev[a], Serikzhan Atanov[b], Martina Barandun[b]

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Introduction

In Central Asia, Tajikistan is known as a predominantly mountainous landscape. Mountains occupied nearly 93% of Tajikistan's territory (Xenarios et al., 2019; Gulahmadov et al., 2021). The impact of climate change in Tajikistan can be traced in many spheres of life. Between 1992 and 2016, natural disasters affected more than 80% of Tajikistan's population, resulting in economic losses of 1.8 billion USD. The effects of climate change are particularly hard on agriculture, with extreme weather events exacerbating the problems of villagers (Library of Congress, 2007). Changes in temperature and precipitation as a result of climate change may seriously affect hydrology and water resources and river basins in Tajikistan (Kure et al., 2013; Pohl et al., 2015).

Tajikistan is located in the subtropical zone and has a predominantly continental climate; however, the country has sharp differences in climatic conditions depending on altitude (Kobuliev et al., 2021). According to the popular Köppen-Geiger climate classification, the two most common types of climate in Tajikistan are cold semi-arid climate and Mediterranean climate with hot summers. The transition between the four main seasons is relatively abrupt. The subtropical lowlands in the southwest of the country, where the highest temperatures occur, have a particularly dry climate. The summer temperature range in these areas is typically between 27°C and 30 °C, with extremes as high as 50 °C. The winter temperature range is -1 °C to 3 °C. In the eastern Pamirs, summer temperatures range from 5 °C to 20 °C and winter temperatures range from -15 °C to -20 °C. In some regions (e.g., in the Murghab region bordering China), winter temperatures can drop to -45 °C; at high altitude, temperatures can reach the extreme value of -60 °C (Library of Congress, 2007; Climate Change Profile: Tajikistan, 2020).

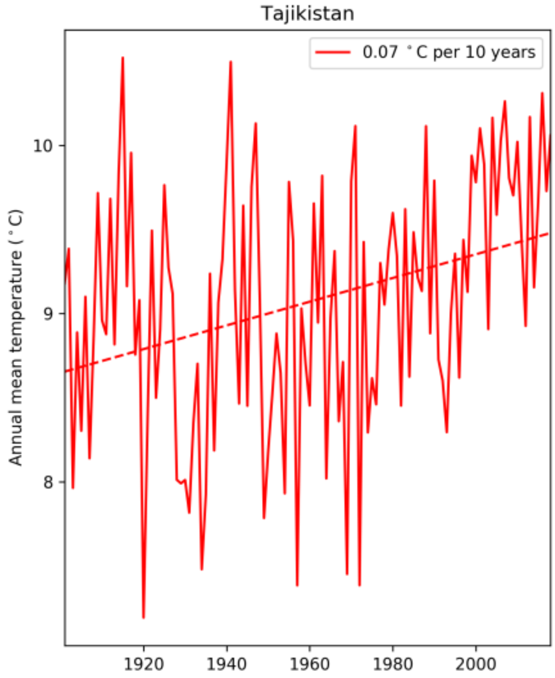

Figure 3.4.1. Past climatic trends for annual mean temperature from 1900 to 2016. Dotted lines represent the linear trend over time. The significant change per 10 years is noted in the upper right corner. (Source: Climate Change Profile: Tajikistan)

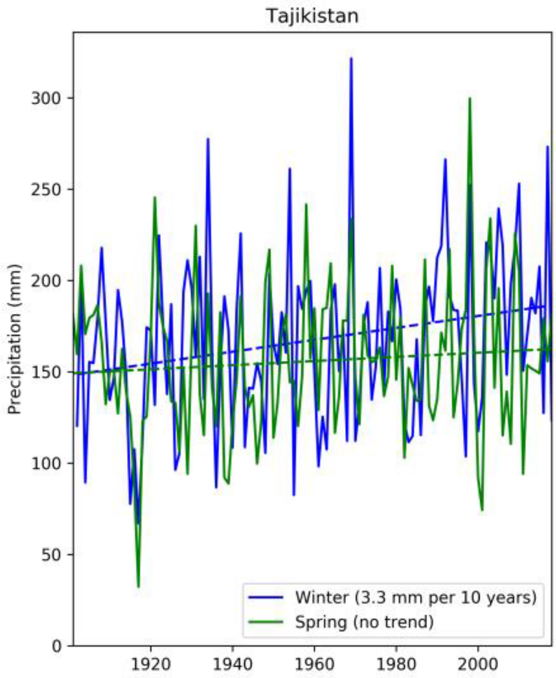

Figure 3.4.2. Past climatic trends for winter and spring precipitation from 1900 to 2016. Dotted lines represent the linear trend over time. The significant change per 10 years is noted in the lower right corner. (Source: Climate Change Profile: Tajikistan)

Historical Climate Change

Tajikistan's climate is strongly continental. As a result, there are large seasonal variations in temperature. Temperatures in Tajikistan are strictly controlled by altitude; the higher the location, the generally lower the temperature. Thus, consideration of altitude was considered important in explaining the spatial variation of temperature in Tajikistan, which is characterized by high temperatures for 5 months with mean annual variation of 12.9 °C at Murghab station (in the east) and 29.26 °C at Nizhniy Panj station (in the south) throughout the year (Figure 3.4.3, Gulahmadov, 2022). Depending on the altitude, the area and distribution of glaciers also vary, with glacier melt being much greater in the west and decreasing in the central and eastern parts of the country (Hoelzle et all., 2019; Barandun et al., 2020; Barandun & Pohl, 2023).

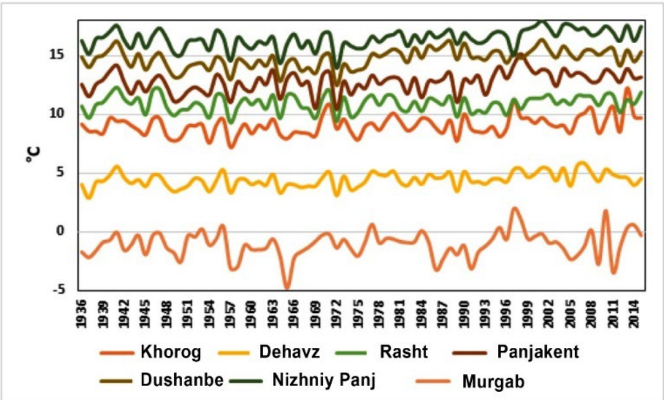

Figure 3.4.3. The mean annual temperature at the studied stations (°C) for the period 1936-2015 (Source: Gulakhmadov, 2022)

Between 1940 and 2017, Tajikistan experienced a temperature increase of 0.1 - 0.2 °C per decade. The number of days with temperatures of 40 °C and above is increasing (Figure 3.4.4). The largest temperature increases were observed in Dangara (1.2 °C) and Dushanbe (1.0 °C). Mountainous areas experienced an increase of 0.3 - 0.5 °C, while high alpine areas experienced an increase of 0.2 - 0.4 °C. Recent warming trends recorded between 2001 and 2010 show that the average temperature for each decade was 0.8 °C higher than the long-term average for areas within 1000 to 2500 m A.S.L. In high alpine zone, the observed increase was 0.2 °C above average for the same period. Temperatures were on average by 0.1 - 1.1 °C higher in winter and by 0.1 - 1.3 °C in spring. Autumn temperatures in all mountainous areas were 0.6 - 1.1°C above average [6, 7] (Mirzokhonova, 2022).

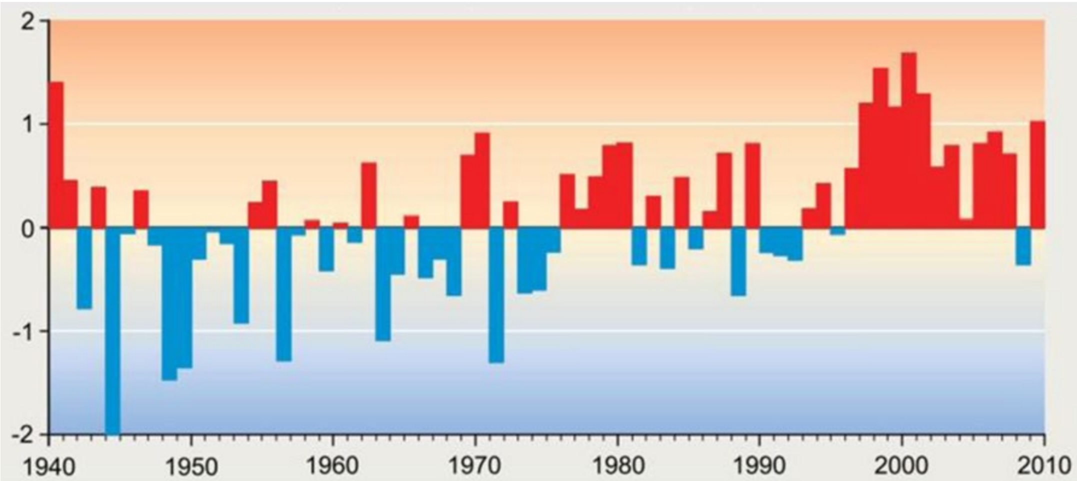

Figure 3.4.4. Annual air temperature anomalies from long-term average calculated from 1961 to 1990 (Source: National strategy of adaptation to climate change in the Republic of Tajikistan, 2019).

In Finaev et al. (2016), data from high-mountain meteorological stations in Tajikistan were analyzed. The data showed that the average air temperature has increased at many stations, while at some stations there has been a decrease in air temperature. In terms of precipitation, most stations have experienced an increase in the amount of precipitation.

Future Climate Change

The average annual temperature is projected to increase by 2 °C by 2050, especially between December and August (Climate Change Knowledge Portal WB, Climate Change Knowledge Portal). Time-series analyses over the past 59 years indicate that air temperatures have constantly increased with an average rate of 0.2 - 0.25 °C/decade for western part of Tajikistan (Brhane et al., 2023). The average temperature in Tajikistan is increasing uniformly in most areas, with a slight rise in the eastern region. From 2011-2041, no significant differences in warming between the different emission scenarios was found. However, starting from the mid-century (2041-2070), there will be a noticeable increase in temperature (inter-model range +1.1 to +2.8 °C at RCP8.5), and in the distant future (2071-2099), the temperature will rise significantly (inter-model range +4.8 to +6.6 °C at RCP8.5), with a broad range between +2.8 to +6.6 °C at RCP8.5. These changes in temperature will depend on emissions (Aalto et al., 2017).

[6] National strategy of adaptation to climate change in the Republic of Tajikistan, 2019. Link: https://faolex.fao.org/docs/pdf/taj190980.pdf

[7] Fourth National Communication of the Republic of Tajikistan, 2022. Link: https://unfccc.int/sites/default/files/resource/4NC_TJK_eng_0.pdf

The projected climate change signal for precipitation is weak, and the models have conflicting predictions about the direction of the change. On average, precipitation is expected to decrease in the western part of the country, while in the mountainous eastern part, it is expected to increase. However, since the eastern part of the country receives very little annual precipitation (usually less than 100 mm per year), the projected changes are also small. For instance, a +10% change would only translate to an increase of +5 mm or +10 mm yr^{-1}, which is not significant (Aalto et al., 2017).

Future climate warming will cause snowmelt to occur early in the spring months leading to frequent flood hazards (Xenarios et al., 2019). In areas where snow and glaciers are dominant, it is expected that the average annual river runoff will increase due to the rise in air temperature and the subsequent increase in snow and ice melt rate until approximately 2060. However, from around 2080, the average annual runoff is projected to decrease due to the disappearance of small glaciers in glacier-dominated regions (Kure et al., 2013).

Impact of Climate Change on Water Availability

Drought or water shortages can affect water quality, as reduced river flows during drought lead to a shortage for the removal of foul water and wastewater loads. This results in increased concentrations of pathogens, which can cause more infections. Increased summer temperatures lead to increased demand for drinking water, increased pressure on groundwater, and reduced groundwater recharge[8].

The main types of natural disasters are landslides, droughts, earthquakes, floods and epidemics. Under ongoing climate change this will intensify in the future. The worst drought in the country was in 2000, which affected about 3 million people. About 36% of Tajikistan's population is at risk of landslides and mudslides. In 2006, about 13,000 people were affected by floods and landslides[9]. In 2017, 157 houses, 604.4 ha of cropland, 16 bridges and about 1,200 km of roads were affected by 720 snow avalanches, 41 debris flows, 32 river level rise emergencies, 23 landslides, 33 earthquakes, 21 rockfalls and 13 strong winds. Total losses are estimated at 400-500 million USD (Khakimov et al., 2019, 2020). According to the UN Office for Coordination of Humanitarian Affairs, 85% of Tajikistan’s area is threatened by mudflows; some 50 000 landslides have been reported by Tajik Glavgeology during the 1990’s (Barbone et al., 2010). In the middle of the 20th century, around 6% of Tajikistan’s surface area was covered by glaciers. By the early 21st century this was believed to have declined to 5%. Simultaneously, the volume of ice mass found in Tajikistan’s glaciers is reported in its Third National Communication to the UNFCCC to have reduced by 30% over the same period. By the end of the century, Central Asian glaciers are projected to lose up to 50% of their mass, dependent on the emissions scenario. Glacial retreat will have a very significant impact on river runoff. An estimated 50% of the runoff of the Amu Darya is believed to origin from glacier melt, with similarly high dependence seen in most other Tajikistan’s rivers[10].

Conclusion

The impacts of climate change in Tajikistan are evident, particularly in the country’s cryosphere. Over the past decades, Tajikistan has experienced a significant increase in temperature, with observed trends indicating an increase of 0.1 - 0.2°C per decade between 1940 and 2017. The warming is more pronounced in certain regions,

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[8] Fourth National Communication of the Republic of Tajikistan, 2022. Link: https://unfccc.int/sites/default/files/resource/4NC_TJK_eng_0.pdf

[9] World Bank, Climate change knowledge portal. Retrieved from http://sdwebx.worldbank.org/climateportal/countryprofile

[10] World Bank, Climate change knowledge portal. Retrieved from http://sdwebx.worldbank.org/climateportal/countryprofile

such as Dangara and Dushanbe, where temperatures have increased by 1.2 °C and 1.0 °C, respectively (Gulakhmadov, 2022). Mountainous and alpine areas are also facing rising temperatures, threatening glaciers and snowmelt patterns. Increases in average winter and autumn temperatures and an increase in the number of days with temperatures above 40 °C highlight the vulnerability of Tajikistan's cryosphere to climate change (Mirzokhonova, 2022; National Strategy for Adaptation to Climate Change in the Republic of Tajikistan, 2019).

Climate change is significantly affecting the conditions that shape river runoff in Tajikistan, with glaciers playing a crucial role in this hydrological system. Based on the World Bank's Climate Change Knowledge Portal, approximately 50% of the runoff of the Amu Darya River, a vital water source, is primarily fed by glacier and snow melt. The expected increase in average annual river runoff until around 2060, due to rising air temperatures and enhanced snow and ice melt, illustrates the complex relationship between climate change and the hydrological cycle. After this runoff peak, glacier meltwater contribution will decrease and challenges arise from the projected decrease in runoff in the regions with glacier-dominated runoff feeding after 2080 (Kure et al., 2013; Xenarios et al., 2019).

There are many challenges and uncertainties in assessing the impacts of climate change on glaciation and water resources in Tajikistan. Historical data, as presented in the Climate Change Profile and the National Strategy of Adaptation to Climate Change, reflect the limitations of available information and hinder comprehensive assessments. These data gaps make it difficult to accurately predict the future trajectory of glaciers and water resources. In addition, the wide range of natural hazards, including landslides, droughts, and floods, complicates assessment and highlights the need for improved monitoring systems, data collection methods and capacities to enhance our understanding of these dynamic systems (Khakimov et al., 2019, 2020; Barbone et al., 2010).

Addressing the challenges posed by climate change in Tajikistan requires an urgent focus on improving monitoring systems and data exchange mechanisms. Enhancements in atmospheric, cryosphere and hydrological monitoring, with a particular emphasis on the spatial and temporal variations in temperature, precipitation, and glacier dynamics, are essential for accurate assessments and informed decision-making. Collaboration between national and international agencies, as well as the integration of advanced technologies, can facilitate the development of a robust monitoring framework. This improvement is not only essential for understanding the immediate impacts of climate change but is also crucial for predicting and adapting to future changes in the cryosphere and ensuring sustainable water resource management in Tajikistan (Aalto et al., 2017; Climate Change Knowledge Portal WB).

3.5 Climate Change in Turkmenistan

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Introduction

Turkmenistan has an extremely continental and arid climate, which is influenced by various factors. This climatic condition is attributed to its low latitude position, considerable distance from oceans, atmospheric circulation patterns, characteristics of the underlying surface, and the presence of mountain ranges in the southwest, south, and southeast (Orlovsky, 1994).

The aridity of the climate is characterized by minimal precipitation, low air humidity, sparse cloud cover, heightened evaporation rates, and frequent occurrences of droughts and dry winds. In Turkmenistan, ecological conditions support the flourishing of natural vegetation primarily during the colder months, benefiting from wet and humid winter-spring periods conducive to the growth of ephemers and ephemeroids. However, this vegetation undergoes desiccation during the hot and arid summer months. The cultivation of agricultural crops in Turkmenistan necessitates artificial irrigation, as natural conditions alone do not suffice for their growth. (Orlovsky, 1994)

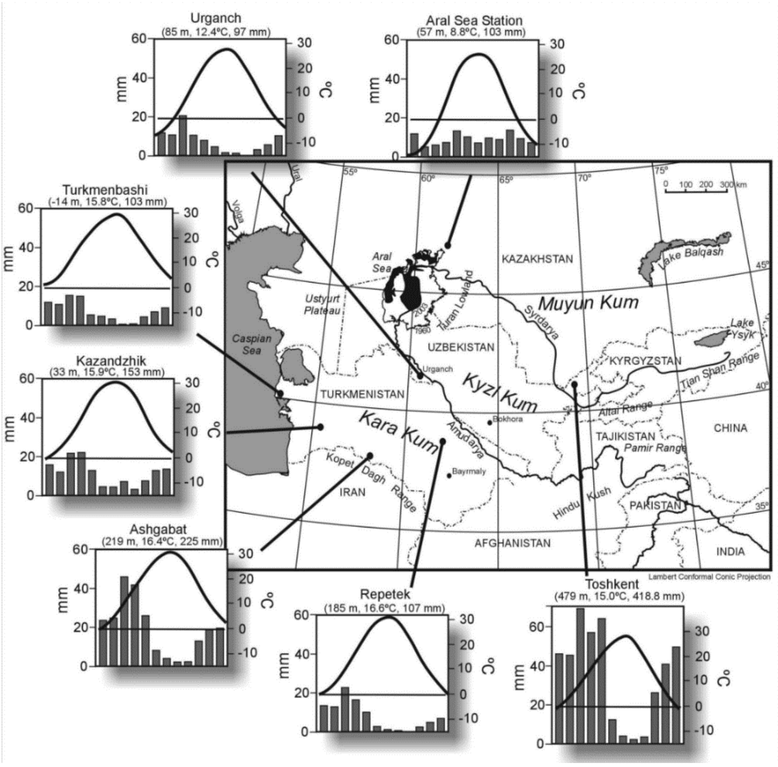

Figure 3.5.1. Overview and comparison of the monthly precipitation and air temperature distribution measured at different meteorological stations over Turkmenistan and other parts of Central Asia (Source: Lioubimtseva & Cole, 2006).

Deserts cover over 95% of Turkmenistan's total territory and more than half of the land in Uzbekistan and Kazakhstan (Lioubimtseva & Cole, 2006). The deserts and semi-deserts of Central Asia have a typical continental climate, which can be divided into two subregions—northern (mainly Kazakhstan) and southern or Irano-Turanian (Petrov, 1976; Lioubimtseva, 2002). In the southern Iranio-Turanian part of the region, winters are characterized by milder conditions, featuring a mean January temperature ranging between -10 °C and 0 °C, but average July temperatures hover around 32°C, reaching a maximum of 52°C in the eastern Kara Kum (Lioubimtseva & Cole, 2006). Precipitation in this subregion peaks in spring, aligning with the northward migration of the Iranian branch of the Polar front (Lioubimtseva & Cole, 2006).

Historical Climate Change

The historical climate changes in the territory of current Turkmenistan have been documented through various proxies, including biostratigraphic, geomorphological, and archaeological data. Based on Lioubimtseva & Cole, (2006) over time, the region has witnessed fluctuations, transitioning from hyper-arid deserts to subhumid shrub lands during the late Pleistocene (Kes et al., 1993; Varushchenko et al., 1987; Velichko et al., 1987; Tarasov, 1992; Tarasov et al., 1998). Notably, these environmental shifts, unlike tropical deserts, exhibited relatively small amplitudes in the Late Pleistocene and Holocene, marked by prolonged arid periods interspersed with brief humid intervals (Lioubimtseva & Cole, 2006). Evidence suggests that fluctuations in precipitation during these intervals did not surpass a total annual precipitation of 150 - 200 mm (Lioubimtseva & Cole, 2006).

The documented shifts from hyper-arid deserts to subhumid shrub lands, the severe arid phase of the Last Glacial Maximum (around 21 000 BP; Aubekerov et al., 1989; Tarasov, 1992), and the subsequent Holocene climatic optimum, known as the Lavliakan humid phase, influenced the development of subhumid steppes on the Ustyurt plateau (Doluhanov, 1985; Kes et al., 1993). Multiple smaller fluctuations in aridity occurred at finer temporal scales, with historical documents indicating slightly higher precipitation between the Caspian and Aral Sea from the 9th to 14th century AD (Varushchenko et al., 1987; Doluhanov, 1985). The shifting westerly cyclonic circulation, the position of the Siberian high, and the impact of the Caspian and Aral Seas played pivotal roles in controlling precipitation (Lioubimtseva & Cole, 2006). The impact of these climatic changes is evident in Turkmenistan's climate over time, emphasizing the inherent variability and the influence of various factors on precipitation patterns (Aubekerov et al., 1989; Tarasov, 1992; Doluhanov, 1985; Kes et al., 1993; Micklin, 1988; Varushchenko et al., 1987). While palaeodata offer insights into geomorphological and biological responses to climate change, caution is advised in predicting future trends based on paleoanalogs (Lioubimtseva & Cole, 2006).

Meteorological data reveal a steady increase in annual and winter temperatures since the past century, but the lack of long-term observations and reduced station functionality after the collapse of the USSR raises uncertainties (Lioubimtseva & Cole, 2006). The 2001 IPCC report on arid Central Asia notes an absence of discernible trends in annual precipitation for the region during 1900 - 1995. Despite the absence of a regional precipitation changes, spatial variability is observed at the landscape scale, exemplified by significant differences between trends in sandy deserts and neighboring irrigated lands in eastern Turkmenistan (Neronov, 1997).

Future Climate Change

Analyzing the trends of climate change in Turkmenistan, based on Lioubimtseva & Cole (2006) and other researchers, unveils a nuanced perspective marked by spatial variability and challenges in data interpretation. Based on palaeoanalogous scenarios, Central Asian deserts are predicted to become moister due to global warming, featuring a southward shift and probable intensification of westerly cyclones, akin to early Holocene conditions; however, palaeodata, despite their capacity to enhance our comprehension of climate change mechanisms over extended periods, generally fall short in capturing finer fluctuations in temperature and precipitation patterns (Lioubimtseva & Cole, 2006). Climate models predict temperature increases by 1 - 2 °C by 2030–2050, with variable precipitation projections, highlighting the extreme uncertainty in modeling arid zones (Lioubimtseva & Cole, 2006). The simulation of the REMO 0406 scenario by Duan et al. (2019), shows similarly a significant increasing trend in future temperature from 2016 to 2055 at 0.51 °C/decade, causing a decreasing trend in snow cover. The same simulation expects increased evaporation along the Karakum Canal and other conveyance infrastructure, leading to significant decreases in available water resources in Turkmenistan (Duan et al., 2019). The National Climate Change Strategy of Turkmenistan projects an insignificant increase in precipitation until 2020 but followed by a sharp decrease. The rate of reduction in precipitation will become more detectable after 2040, decreasing by 8-17% by 2100.

Climate records from the vicinity of the Aral Sea since the 1960s indicate a shift towards a more continental climate, with increased summer temperatures, decreased winter temperatures, reduced humidity, and altered precipitation seasonality (Middleton, 2002). The reduction of the Aral Sea's surface area has been linked to decreased precipitation and saline dust influencing rapid climate and vegetation changes (Glazovsky, 1995). While a likely air temperature increase is suggested for Central Asia, the aridity index shows no consistent trends for the entire region (IPCC, 2001). Remote sensing data, including the National Atmospheric and Oceanic Administration AVHRR temporal series, suggest a decrease in aridity in the northern part of the region and a southward shift of the desert zone (Zolotokrylin, 2003). Kharin et al. (1998), using the NOAA AVHRR series, also point to a possible decrease of aridity in this region during the past decades.

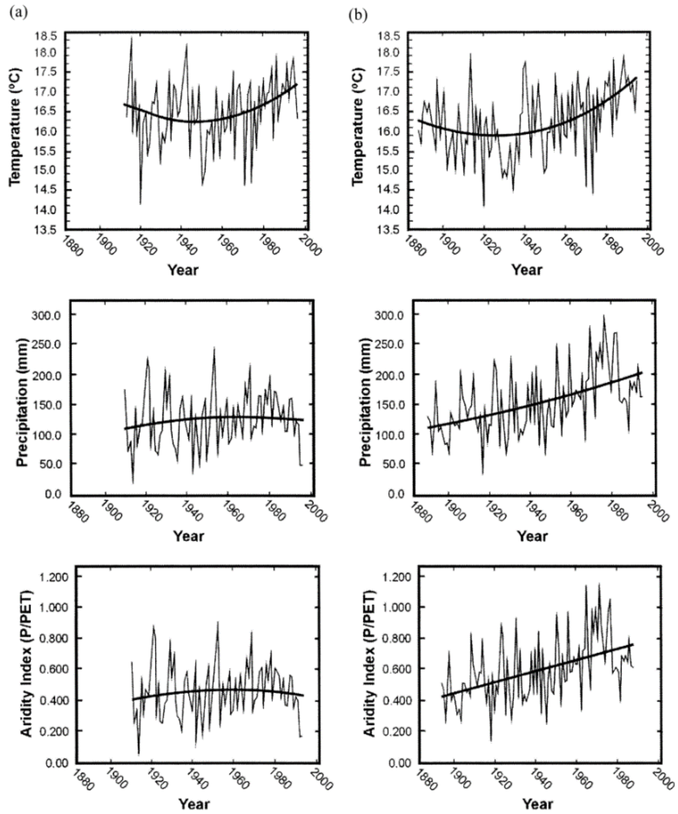

Figure 3.5.2. Precipitation, temperature, and aridity index (P/PET). (a) Repetek Station, Turkmenistan, 1910 to 1995. (b) Bayramaly Station, Turkmenistan, 1910 to 1995. (Source: Lioubimtseva & Cole, 2006)

The projections of climate change in Turkmenistan, rooted in a comprehensive analysis of historical data and scientific assessments, paint a complex picture of evolving environmental conditions. The interplay between global climate change and local anthropogenic processes such as the extensive redirection of water resources and the degradation of the Aral Sea remain unmeasured in current climate models but may significantly impact regional climate change. With an anticipated increase in temperature by 1–2 °C by 2030–2050 and variable precipitation projections, the region faces significant challenges concerning various sectors of the country's social and economic development, including water economy, agriculture, and public health. Projections suggest a noteworthy decrease in precipitation after 2040, posing substantial risks to water availability and potentially impacting sectors such as agriculture, public health, and the overall socio-economic landscape of Turkmenistan.

Impact of Climate Change on Water Availability

Projections for Turkmenistan indicate an anticipated trajectory towards increased warmth and probable aridity in the coming decades, with a heightened emphasis on aridity, particularly in the western part of the country. The foreseen rise in temperatures is expected to be most pronounced in summer and fall, with a more modest increase in winter. An especially noteworthy decline in precipitation is predicted during the summer and fall months, while winter months may experience either a slight increase or remain unchanged. These seasonal shifts are poised to have profound implications for agriculture, particularly in western Turkmenistan and Uzbekistan, where frequent droughts pose threats to crops such as cotton, cereals, and forage production. This, in turn, amplifies the already substantial water demands for irrigation, aggravating the existing water crisis and hastening human-induced desertification. The persisting series of severe droughts over the past decade, coupled with the continuous degradation of the Aral Sea and its tributaries—Amu Darya and Syr Darya—has fueled water disputes and escalated tensions among the Aral Sea basin states. The arid lowlands of both river basins are already witnessing the impacts of climate change through increased drought frequency and glacier recession (IPCC, 2007). The ongoing melting of glaciers and snowpacks, intensified by a warming climate (IPCC, 2007; Alamanov et al., 2006; Podrezov et al., 2001), is anticipated to temporarily boost water runoff in the coming decades, potentially promoting further expansion of unsustainable agricultural land use. Recognizing the likelihood of increased aridity and water stress, urgent measures involving new political and economic mechanisms are imperative to alleviate tensions in the future. The adaptation capacity of the western subregion of Central Asia is constrained by existing water stress, regional land degradation, and inefficient irrigation practices inherited from the Soviet era, posing significant challenges for sustainable development in the face of a hotter and drier climate (Lioubimtseva et al., 2012).

Based on Lioubimtseva et al. (2012), the escalating challenges posed by global climate change to human livelihoods increase susceptibility to ongoing desertification processes and natural climatic variations. In the case of desert nations such as Turkmenistan, the anticipated consequences of climate change include larger populations grappling with water scarcity, potential reductions in crop yields, and elevated risks of environmental migrations and political conflicts, all stemming from the depletion of essential resources vital for sustaining livelihoods (Barnet, 2007).

Conclusion

Turkmenistan faces a complex challenge shaped by its continental and arid climate, intertwined with historical changes and future projections. The complicated interplay of geographical factors, dominated by deserts, highlights the vulnerability of Turkmenistan and its dependence on artificial irrigation for agriculture. Historical climate changes, documented through various proxies, reveal the dynamic environmental transitions of the region. However, caution shall be exercised in directly applying historical analogs to predict future climate trends, given the unprecedented nature of contemporary human-induced climate change.

Future climate projections for Turkmenistan reveal spatial variability and uncertainties in modelling arid zones, including temperature increases and variable precipitation patterns. The impact of climate change on water availability is exacerbated by rising temperatures, reduced precipitation, and increased water demand for agriculture. The ongoing degradation of the Aral Sea and its river basins complicates the socio-economic landscape, requiring urgent action and adaptation strategies.

As Turkmenistan addresses these challenges, a holistic approach that integrates historical knowledge with contemporary climate science is critical for effective mitigation strategies. Adaptive strategies and policies will become important as projections unfold, recognizing the risks ahead and proactively building the country's resilience to a changing climate.

3.6 Climate Change in Uzbekistan

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Introduction

Devastating heatwaves, droughts, and floods have indicated that climate change and its impacts on the planet[11] have presented a significant risk across Central Asia, including Uzbekistan, over the past few years. According to the World Meteorological Organization (WMO), 2023 has a higher probability of an imminent El Nino event (large scale atmospheric circulation) and higher warming than in recent years, suggesting that climate change risks are likely to increase together with extreme weather events[12]. Preliminary estimates will make clear that adverse impacts pose threats to economic sectors[13], with risks becoming increasingly complex and management of the water stress difficult in the region (Unger-Shayesteh et al., 2013; Shahgedanova et al., 2020).

People living in developing and low-income countries like Uzbekistan are very vulnerable to natural hazards due to the socio-economic pressures imposed by geographic location and a limited welfare system, which will be further exacerbated by global warming (Xenarios et al., 2019). According to the United Nations Economic Commission for Europe (UNECE)[14] Uzbekistan has not fully adopted the climate action goals of the United Nations Sustainable Development Goals (SDGs) and is yet to develop its climate change strategy. While climate-related issues are cross-sectoral, an integrated framework of disaster risk research would enable the development of specific plans for hazard preparedness and response to extreme weather events in Uzbekistan.

Historical Climate Change

Uzbekistan lies in the central part of the Eurasian continent. The significant mountain ranges at the southern and eastern borders of the area are a major obstacle to rainfall from the nearby Indian Ocean which explains the aridity and extreme continentality of the country's climate (Schiemann et al., 2009). Large scale atmospheric circulations such as the El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO) and the Indian Summer Monsoon (ISM) have a positive impact on seasonal temperature and precipitation that can better explain the changes in climatic characteristics in Uzbekistan (Khaydarov and Gerlitz, 2019, Schiemann et al., 2007). Natural variability in the climate system of the region such as the changes in atmospheric circulation can be responsible in full or in part for extreme weather events observed in Uzbekistan (Gerlitz et al., 2018; Mamadjanova et al., 2018).

In general, Uzbekistan has three main climate zones: a zone of deserts and dry steppes occupying about 79% of the territory, the foothills or piedmont zone, and the area of high mountains extending over the remaining 21%, respectively (Chub, 2007). The mean air temperature in July varies from 26 °C in a greater part of the

[11] IPCC_AR6_WGII_FullReport.pdf
[12] El Niño expected to last at least until April 2024 (wmo.int)
[13] TNC of Uzbekistan under UNFCCC_english_n.pdf
[14] https://unece.org/fileadmin/DAM/env/epr/epr_studies/ECE.CEP.188.Eng.pdf

lowlands to 30 °C in the south and desert areas making it the hottest month of the year. The maximum values can reach up to 45 °C in the southern part of the country. The record temperature of 50 °C occurred in Termez and the Kyzylkum Desert. The coldest month is January when the mean air temperature drops to 0 °C in the south and can go below -8 °C in the north of the country. The minimum temperature can be well below -40 °C in the Ustyurt Plateau in extremely cold years.

The average precipitation distribution in Uzbekistan has a sharp contrast between the plain and mountain areas. Mean annual precipitation in major parts of the plains or deserts and dry steppes (Ustyurt Plateau, Kyzylkum Desert, Karshi, Dalverzin and Golodnaya steppes) is about 80 - 200 mm. However, precipitation can be significantly greater in foothills and the mountains, particularly in the northeast and the southeast of the country. In fact, precipitation in areas with an elevation between 600 - 1000 m A.S.L. or foothills (Tian Shan and Gissar-Alay mountain ranges) can reach up to 500 mm; above 1000 m A.S.L. the annual totals may exceed 500 mm. In some hillsides, especially the western slopes of Tian Shan, total annual precipitation may even be greater than 2000 mm (Chub, 2007).

Uzbekistan's average temperature and precipitation have changed in line with global warming for the last decades (Kuranboyeva et al., 2022, 2023). There has been a significant increase in temperature across the whole country since the 1990s, with downward though non-significant trends in precipitation in most parts of Uzbekistan (Figures 3.6.1 - 3.6.3). Annual average temperature was higher during the period 1991-2020 compared to 1961-1990, with 2016 being the warmest individual year (Figure 3.6.1). The recent warming in Uzbekistan has occurred since the 1980s, which is consistent with increasing anthropogenic emissions in the atmosphere.

The results from 82 meteorological stations show that the average annual air temperature for the period 1991-2020 increased by 0.8 °C relative to the average long-term meteorological data for 1961-1990 almost throughout the entire territory of Uzbekistan (Kuranboyeva et al., 2022). This number could reach up to 1.5 °C in stations located in central and desert areas of the country. There was a slight increase in precipitation in foothills and mountain areas by 20-48 mm; however, a decrease in precipitation amount (10-25 mm) was noted in the plain areas of Uzbekistan (Kuranboyeva et al., 2022).

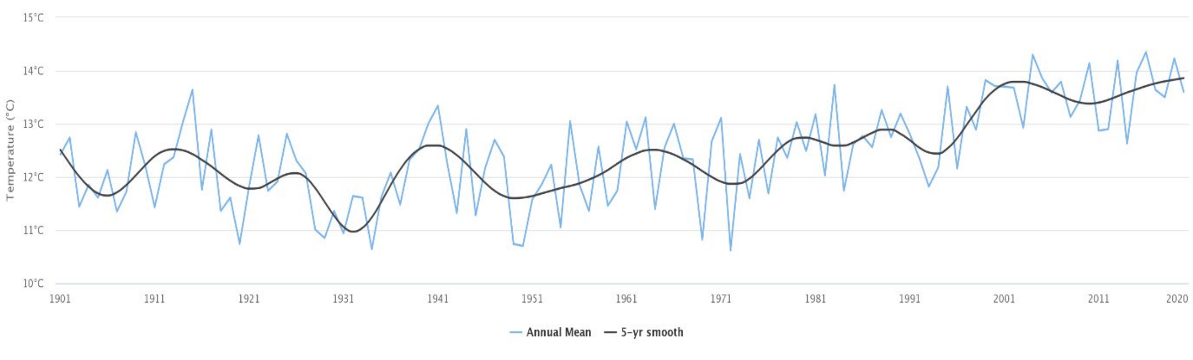

Figure 3.6.1. Plot shows the annual average temperature (blue line) from 1901 to 2020 with five years smooth (black line) for Uzbekistan. Source: Climate Research Unit (CRU), https://climateknowledgeportal.worldbank.org/

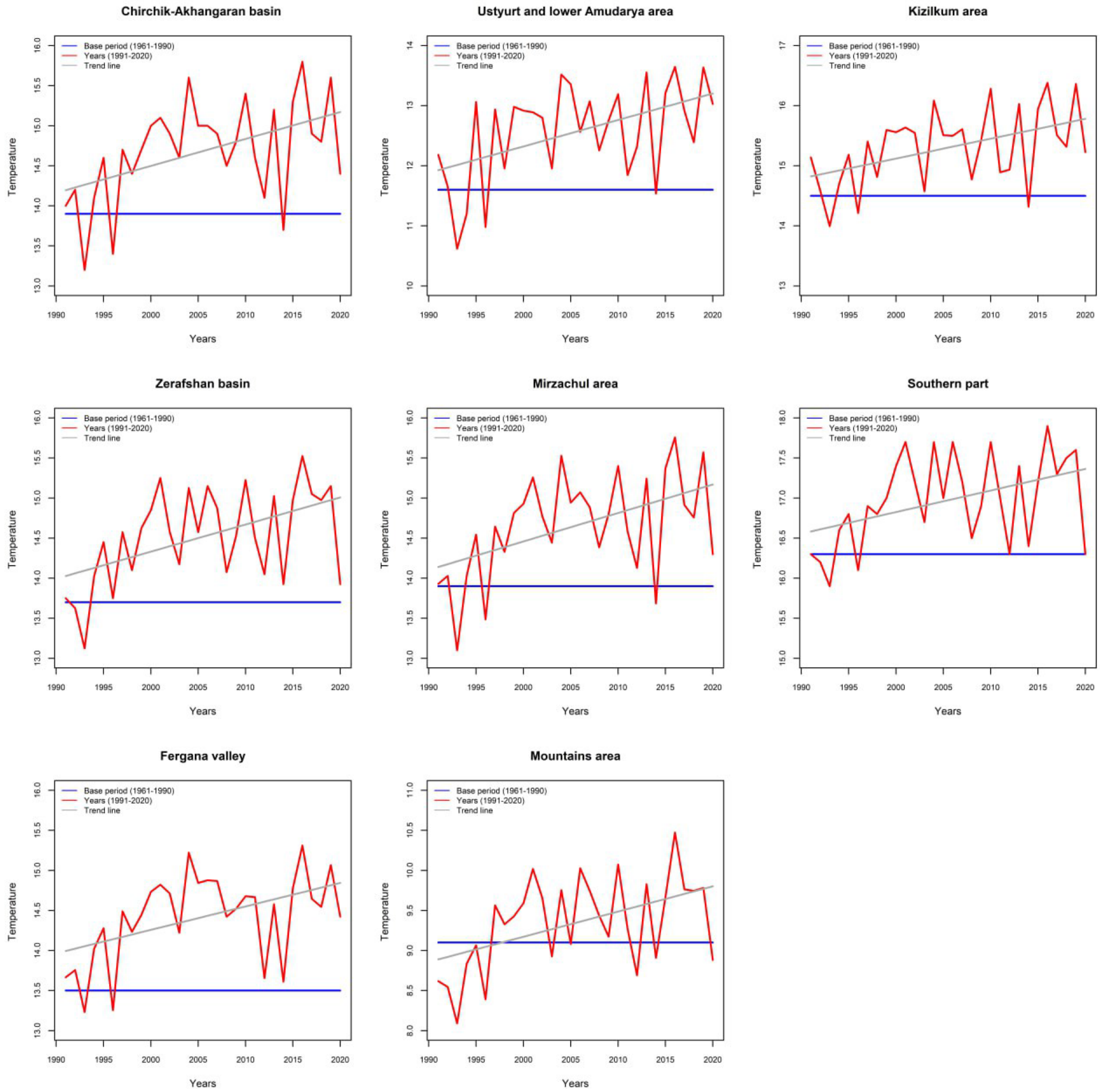

Figure 3.6.2. Annual average temperature for 1991-2020 (red lines) compared with the period of 1961-1990 long-term averages (blue lines) and trends in temperature (grey lines) observed in geographical areas of Uzbekistan. Data source: Uzhydromet

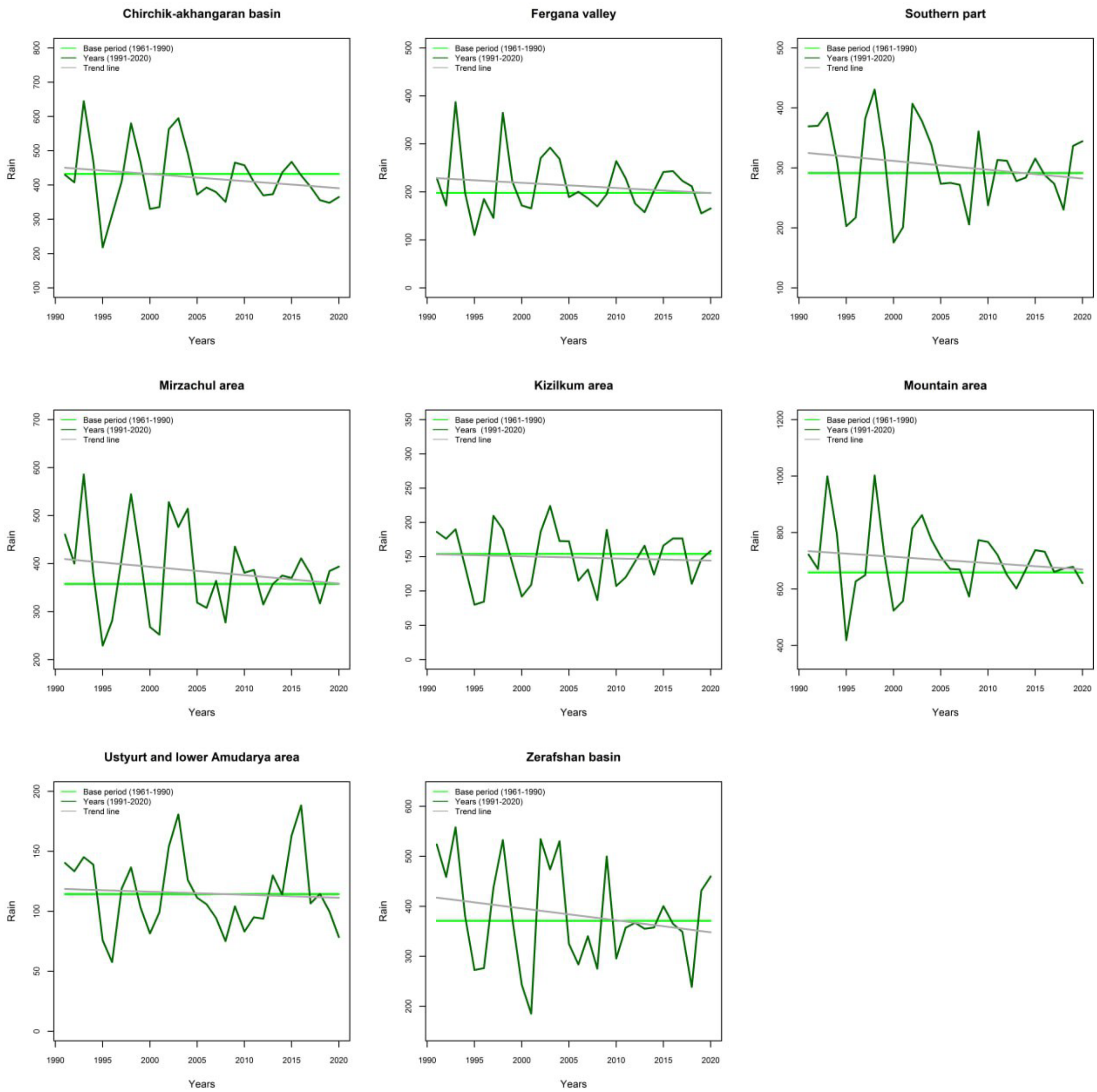

Figure 3.6.3. Annual average precipitation for 1991-2020 (dark green lines) compared with the period of 1961-1990 long-term averages (light green lines) and trends in precipitation (grey lines) observed in geographical areas of Uzbekistan. Data source: Uzhydromet.

Future Climate Change

For Uzbekistan, future projections of anthropogenic climate change have mainly been focused on surface temperature and precipitation characteristics over the region, which includes Uzbekistan. For instance, Ozturk et al. (2012) and Ozturk et al. (2017) investigated the impact of climate change results on seasonal variability of precipitation and temperature over Central Asia under the framework of Coordinated Regional Climate Downscaling Experiment (CORDEX) Region 8 by using RegCM4 and RegCM4.3.5. Results obtained from the regional RegCM4 model driven by the ECHAM5 A1B scenario for the future (2070-2100) climatology of Central Asia show relatively high warming trend in temperature (from 3 °C up to 11.4 °C on average) and a decrease in precipitation, particularly, in the southeastern part of the domain (Ozturk et al., 2012). IPCC's RCP4.5 and RCP8.5 scenario outputs for the HadGEM2-ES and the MPI-ESM-MR models downscaled by the RegCM4.3.5 climate projection for near future (2011-2040), mid-future (2041-2070) and far future (2071-2100) in (Ozturk et al., 2017) also show reasonably good agreement with the outputs in previous study (Ozturk et al., 2012).

The high-resolution regional climate model (RCM) REMO has been implemented over Central Asia by Mannig et al. (2013) in order to better understand the seasonal cycle of precipitation and temperature under the anthropogenic climate change. Huang et al. (2014) projected future change in the annual precipitation over Central Asia including Uzbekistan for the period 2011 - 2100 by applying CMIP5 GCMs under the different emission scenarios (RCP2.6, RCP4.5 and RCP8.5). Authors found increasing trends of the annual precipitation (over 3-9 mm per decade) in the north, the Tian-Shan Mountains by the end of 2100 when they compared with the previous investigations on climate change signals over the region. The authors suggested that large scale atmospheric water vapor fluxes and surface evaporation over the study region could be the 122 possible mechanisms of the increasing changes in projected precipitation. Malsy et al. (2012) and White et al. (2014) investigated the impact of climate change on water resources in Central Asia, including Uzbekistan. Malsy et al. (2012) found an increase in mean annual water availability in most river basins of Central Asia by applying the large-scale hydrology model WaterGAP3 driven by 3 GCMs ECHAM5, IPSL-CM4 and CNRM-CM3 under the two emission scenarios (IPCC-SRES A2 and B1) for the future climate (2071-2100). However, in White et al. (2014) the water discharge is projected to decline by 10-20% in the Amu Darya River basin by running the AMU-WEAP model under the high emission scenario (A2) of CMIP3 GCMs. A warming trend in summer temperatures up to 5 °C and seasonal shifts in precipitation cycle may lead to an increase in water demand of agriculture from the existing 10.6% to 16% for the Amu Darya basin by 2070-2099 (White et al., 2014). Thereafter, Radchenko et al. (2017) projected the potential changes of runoff in Syr Darya river basin in the Fergana Valley, by using dynamically downscaled A1B SRES scenario for the period 2071-2100. An increase in annual temperature from 3.7 °C up to 3.9 °C and increase in precipitation from 11% up to 13% (71-108 mm) was obtained for the future period 2071-2100 compared to the baseline period 1971-2000 for the 18 investigated river catchments of Syr Darya basin. The likely cause was attributed to evapotranspiration increase driven by changing trends in the temperature of the region (Radchenko et al., 2017). However, the authors of the study reported that the annual runoff in the Fergana Valley will likely reduce by 10%, even though an increase in runoff is estimated for non-glaciered river catchments in the future. At the same time, a seasonal shift in runoff to earlier phases was projected with an increase of winter-spring runoff between 44% and 107% and a decrease (12-42%) in summer runoff when irrigation water is paramount importance for success agriculture in the Fergana Valley. In many studies (Sorg et al., 2012a; Sorg et al., 2014; Sorg et al., 2015; Kure et al., 2013; Barandun et al., 2020) the adverse effects of global warming to the Central Asian glacier zones in the mountains including Uzbekistan have been evaluated. Based on glacio-hydrological Glacier Evolution Runoff Model (GERM) and application of downscaled atmospheric data from CMIP5 projection, (Sorg et al., 2014) predicted a substantial glacier shrinkage due to the increase of air temperature over the Tien Shan Mountains, considered to be the water tower of Central Asia (Sorg et al., 2012; Shahgedanova et al., 2020) and its effects on the water availability until the end of the century. Moreover, increased risks due to climate change and its negative consequences on farming and food productivity over Central Asia by application of SRES A1B and A2 greenhouse gas emission scenarios of Intergovernmental Panel on Climate Change (IPCC) have been recently investigated by Sommer et al. (2013) and Bobojonov and Aw-Hassan (2014). The existed literature on anthropogenic climate change impact in the region and adaptation measures considering temperature and precipitation projections for the region have been reviewed in some studies (Xenarios et al., 2019).

Conclusion

Changes in temperature and precipitation patterns, particularly the persistent increase in temperature since the 1990s, indicate an increased vulnerability to extreme weather events. These changes, in line with global warming patterns, increase the risks of heatwaves and droughts across Uzbekistan.

The impact of climate change on river runoff conditions in Uzbekistan is significant, with glaciation playing a crucial part in runoff formation. The reliance on glaciation complicates water resource dynamics as forecasts predict significant glacier shrinkage in the Tien Shan - a vital water source for the region (Sorg et al., 2012; Shahgedanova et al., 2020).

Even though multiple climate models provide valuable insights, challenges remain in evaluating the effects of climate change on the cryosphere and water resources. Limited data availability and monitoring infrastructure complicate a comprehensive understanding of current conditions and future trajectories. The lack of a fully adopted climate action plan along with water management related issues exacerbates challenges concerning the hazard resilience and ensuring sustainable water management.

Addressing these challenges requires an emphasis on improving a comprehensive climate, cryosphere and hydrosphere monitoring in Uzbekistan. Enhanced data collection, supported by advanced technologies and international collaboration, is crucial for accurately assessing and predicting climate change impacts.

CHAPTER 4: CRYOSPHERIC CHANGES IN CENTRAL ASIA

4.1 Cryospheric Changes in Kazakhstan

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Introduction

Current and prognosed assessments of climate change and its likely impacts to the environment, population and economy are among the most pressing issues for both Kazakhstan and the neighboring countries of Central Asia; an even more pressing issue, on which the well-being of the region's population and opportunities for sustainable economic development depend is the growing water deficit (Kotlyakov & Severskiy, 2006). Glaciers are known to be storages and regulators of water resources on different time scales, which is extremely important in the arid climate conditions of Central Asia. While the demand for water resources is increasing due to population and economic growth, water scarcity is likely to increase in the future, exacerbating water stress (Hoelzle et al., 2019; Xenarios et al., 2019; Pritchard, 2019; Kotlyakov & Severskiy, 2006). Projections include changes in snow cover and accelerated degradation of glaciers and permafrost in Central Asia, highlighting the importance of assessing the ongoing degradation of the cryosphere and its impact to the hydrological regime of rivers and other water resources such as groundwater in the region (Kotlyakov & Severskiy, 2006; Hoelzle et al., 2019; Barandun et al., 2020; Haeberli, 2017).

Past and Current Changes in Snow

Snow cover is one of the most important components of the cryosphere. In Kazakhstan, it largely determines the flow regime of rivers and the volume of seasonal freshwater resources. In the arid zone, the main part of the annual runoff (up to 90-95%) of the rivers Sarysu, Torgai, Yrgyz (Aral Sea basin), Zhem, Sagyz and Oyil (Caspian Sea basin) occurs in spring as a result of snowmelt (Water Cadaster, 2021). At the same time, the average annual runoff of the Amu Darya and Syr Darya reaches 72%, according to the estimates of Armstrong et al (2019) based on remote sensing methods and modelling. Snow affects the glacier mass balance, ground freezing and thawing regimes, and avalanche activity (Aizen et al., 1995; Severskiy et al., 2012) and transportation infrastructure (Bulletin, 2023; Information sheet #2 for ANEC, 2021). Particularly, snow hazards are important for Kazakhstan. In vast flat areas snowstorms occur for 8-12 hours and are annually counted at 40-50 days. This is of major relevance when the government has to design and operate transport systems. In Kazakhstan highways are more than 94 000 km long and railways cover around 16 000 km (Bulletin, 2023; Information sheet #2 for ANEC, 2021).

Snow as a type of atmospheric precipitation in solid form is an indicator of climatic changes. A number of studies contain data on changes in the amount of solid precipitation in the territory of Kazakhstan due to climate warming (Pimankina & Takibayev, 2023; Li et al., 2020a; Li et al., 2020b; Mashtayeva et al., 2016; Aizen et al., 1995). Observed changes are heterogeneous over space and time. For example, Zhou et al. (2017) observed decreasing duration of snow cover and snow depth in Altai, Tien Shan and Pamir. In contrast, Li et al. (2019) provides evidence that snow cover thickness increased in the Tien Shan between 1961 and 2014. According to ground observations by the Kazakh Hydrometeorological Service snow depth and snow water equivalent (SWE) in the Altai Mountains of Kazakhstan have increased at 72% at all observation points over the last 30 years (Pimankina & Takibayev, 2021).

According to the analysis of route observation data, in the Baldabrek River basin (Western Tien Shan), the average perennial water storage in the snowpack at the time of maximum snow accumulation (February) increased by 20% for the period 1991-2017, and the increase is even higher compared to the period 1955-1990 (Figure 4.1.1) (Pimankina & Takibayev, 2023).

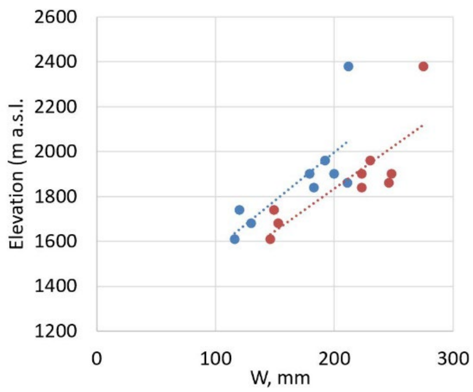

Figure 4.1.1. Variation of mean multi-year snow water storage (mm w.e.) by elevation in the Baldabrek River catchment. Blue dots are mean values for 1955-1990. Red dots are mean values for 1991-2017. (Source: modified by author Pimankina N.V., from Pimankina & Takibaev, 2023)

Currently, satellite data are widely used to study snow cover dynamics. For example, analyses of 28 years of MODIS and AVHRR radiometer data allowed Dietz et al. (2014) to identify a shift towards earlier snowmelt in the Pamir and Tien Shan mountains. Analyzing AVHRR data from 1986 to 2008, Zhou et al. (2017) concluded that the number of days with snow cover is both increasing and decreasing in different mountain areas. An analysis using the CRU grid archive to determine changes in precipitation and temperature since 1960 in combination with MODIS and GRACE data showed that the area of snow cover has decreased significantly in the Central Tien Shan and increased slightly in the Western Tien Shan (Chen et al., 2016).

Regular spatial monitoring of snow cover conditions has been carried out in Kazakhstan since 2000. Some results have been achieved in the field of seasonal and multy-year monitoring of snow cover using remote sensing data. In the study by Kauazov et al. (2023) it was found that in Kazakhstan there is a slight and statistically insignificant tendency for the snow cover area to decrease in March and April. A recent study undertaken by Terekhov & Abayev (2023) noted a decrease in snow cover area of East Kazakhstan with multiyear positive anomalies of snow-water equivalent in the snow cover.

Past and Current Changes in Glaciers

The modern glaciation of Kazakhstan covers the eastern and south-eastern part of the country and belongs to the Northern Tien Shan, Dzungaria (Zhetysu) and Altai Mountain ranges. All glacier systems are confined to transboundary basins (Ertis (former Irtysh), Balkhash-Alakol, Syr Darya, and Chu and Talas river basins) (Fig. 4.1.2).

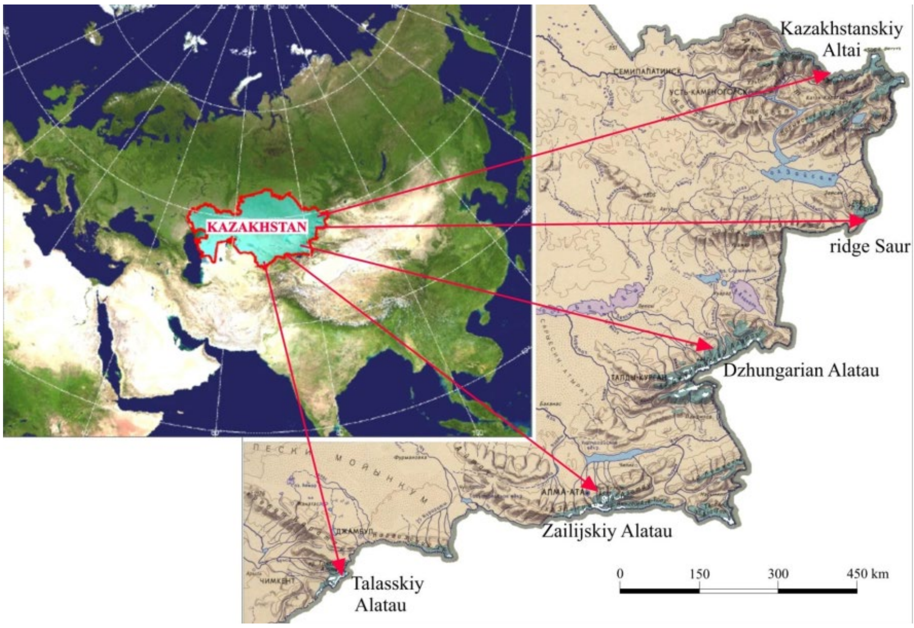

Figure 4.1.2. Glaciated regions in Kazakhstan (Source: modified by author Kokarev A.L., from Atlas of the Kazakh SSR, 1982)

In Kazakhstan there are 2054 glaciers with a total area of approx. 1032 km^2 (in 2013-2015). A significant part of glaciation is located in the Zhetysu (Dzungarian) Alatau (glacier area of 467 km^2), the smallest on the northern slope of the Saur Ridge (glacier area of 11 km^2) (Vilesov, 2016, 2018). The reduction of glacier area occurs in all mountainous regions of Kazakhstan, while the rate of degradation of glaciation of subregions is different. The glaciated area of Ile and Kungei Alatau decreased by 35% in the period 1955-2008, Zhetysu (Dzungarian) Alatau by 43% in the period 1956-2011 (Severskiy et al., 2016). The glaciation of the western part of the Zhetysu Alatau (Karatal River basin) decreased by ~45% in the period 1956-2011/12 (Usmanova & Kapitsa, 2015; Kaldybayev et al., 2016). Kaldybayev & Yaning (2022) estimated the reduction of the glacier area of the river basins of the northern part of Zhetysu Alatau by ~44% from 1956 to 2013. For Zhetysu Alatau, Nurakynov et al. (2023) showed a ~49% area decrease in glacier area between 1956 and 2016, which is close to the estimates obtained by Severskiy et al. (2016). Previous studies have also found glacier retreat, e.g. Bolch (2007) estimated a 32% area decrease in glaciers in the Ile and Kungai Alatau river basins between 1955 and 1999; Narama et al. (2006) showed a 12% area decrease in glacier area in the Ile and Kungai Alatau between ~1970 and 2000, and a 4% area decrease between 2000 and 2007.Glaciation of the Sharyn and Tekes river basins (Kazakh part) in the Terskey Alatau decreased their area by 28% in the period 1956-2013 (Usmanova, 2014; Usmanova et al., 2016). From 1950 to 2011, glaciation in the Kazakh part of the Altai decreased by 33.2 km^2 (46.5%) from 71.4 to 38.19 km^2, according to estimates by Vilesov, Severskiy & Morozova (2014). In southern Kazakhstan, glaciation is concentrated in the basins of Merke, Arys, Assa and Maidantal rivers. Due to the small size of the glaciers, the largest reduction in area is observed in the Merke and Assa river basins - 54% and 52%, from 8.9 to 4.1 km^2 and from 5.4 to 2.6 km^2, respectively, in the period 1955-2015 (Vilesov, 2016). In the Arys and Maidantal river basins, the glaciated area decreased in the same period from 35.3 to 21.6 km^2 and from 49.8 to 35.1 km^2, respectively (Vilesov, 2016). Mukanova et al. (2023, in review) estimated the change in the glaciated area by -140 km^2 or -49% at the northern slope of Ile Alatau from 1955 to 2022.

The founder of glaciological research in Kazakhstan is S.E. Dmitriev, who in 1896 studied the glaciers of Zhetysu (Dzungarian) Alatau, and in 1902-1908 made glaciological observations of the glaciers of Tuyuksu in the headwaters of the rivers Kishi Almaty (Malaya Almatinka) in Ile (Zailiyskiy) Alatau and Shelek (Chilik) Ile and Kungei Alatau. Targeted scientific research on glaciology problems was started in the post-war period since 1947 under the leadership of N.N. Palgov. Since the 1950s, glaciological studies of the regime and glaciers mass balance have been carried out under the programmes of the International Geophysical Year (IGY) 1957-1959 and the International Hydrological Decade (IHD) 1965-1974, then continued in the International Hydrological Programme (IHP), which is still in operation today under the auspices of UNESCO. During this period, glaciological studies were started on the glaciers of the northern and southern slopes of Ile Alatau (Northern Tien Shan), southern slope of Katun Ridge (Kazakh Altai), north-central ridge of Malobaskan spur (Northern Zhetysu Alatau) (Vilesov & Fedulov, 1968; Makarevich & Fedulov, 1968; Makarevich et al., 1969; Fedulov & Shultz, 1989; Makarevich, 1964a; Makarevich, 1964b; Makarevich & Shabanov, 1965; Tokmagambetov et al., 1977; Cherkasov, 2004; Ahmetova et al., 1998; Severskiy et al., 2008; Kotlyakov & Severskiy, 2006). In the early 1980s-1990s, for various reasons, the glacier observations were stopped, and unfortunately, the mass balance monitoring on the Shumskii Glacier was never resumed. With a mass balance time series of 24 years, it was, along with the Central Tuyuksu Glacier, one of the best monitored glaciers with particularly detailed observations in the 1960s-70s (Kotlyakov & Severskiy, 2006).

Currently, continuous mass balance measurements are only recorded for the reference glacier Central Tuyuksu (Tuyuksu), Kishi Almaty River basin, Ile Alatau. The Central Tuyuksu mass balance monitoring programme, which began in 1957, includes regular ablation measurements during the melt season and snow surveys at the end of the accumulation season using a network of ~100 stakes (Kapitsa et al., 2020). Annual values of accumulation, ablation and the resulting mass balance are provided to the World Glacier Monitoring Service (WGMS). Geodetic surveys are part of the monitoring programme and the glacier area has been mapped annually since 2006 (Kapitsa et al., 2020). This is the only comprehensive time series of the region and therefore of high importance and unique value to the international scientific community. The mass balance of Central Tuyuksu Glacier for the observation period 1958 - 2022 is mostly negative, except for a few certain years (Figure 4.1.3), confirming the continuing loss of mass and volume and the general negative trend of the Kazakhstan glaciers. Over the observation period 1958-2022, the mass balance of Central Tuyuksu Glacier was -28.0 m or -0.42 m w.e. yr^{-1} (Kapitsa et al., 2020; WGMS, 2023).

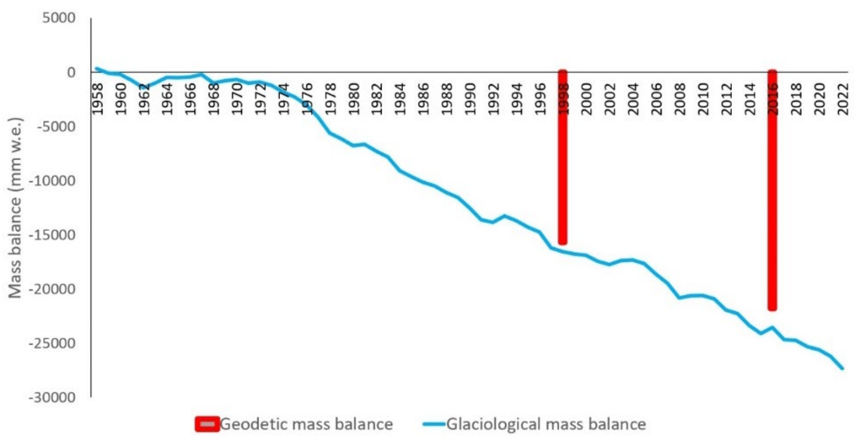

Figure 4.1.3. Cumulative glaciological and geodetic mass balances of the Central Tuyuksu glacier (mm w.e.) (Source: made by author, Kapitsa, V.P.)

The trends in area loss and surface retreat of the glaciers of the Tuyuksu group (Kishi Almaty River, Ile Alatau) were similar to those of the Central Tuyuksu (Kapitsa et al., 2020; Kokarev et al., 2022). As these glaciers are smaller than the Central Tuyuksu, the average area loss was higher, averaging 48% between 1958 and 2016. The average surface lowering of glaciers of the Tuyuksu group was 17.8 ±2.2 m; the geodetic balance for the period 1958-2016 was -20.28 ±2.32 m w.e. (-0.35 ±0.04 m w.e. yr^{-1}) (Kapitsa et al., 2020; Kokarev et al., 2022).

The results of regional mass balance estimates of Tien Shan glaciers over the last two decades are comparable (Brun et al., 2017; Farinotti et al., 2015; Gardner et al., 2013) with mass balance values ranging from -0.3 m w.e. yr^{-1} to -0.7 m w.e. yr^{-1}. Barandun et al (2021) estimated an area-weighted mean glacier mass balance of -0.23 ±0.37 m w.e. yr^{-1} from 1999/00 to 2017/18 for the Tien Shan and Pamir; mass balance rates for glaciers in the Northern/Western Tien Shan and Zhetysu (Dzungarian) Alatau were -0.3 ±0.37 and -0.46 ±0.37 m w.e. yr^{-1}, respectively. Shean et al (2020) estimated the geodetic mass balance of the Northern/Western Tien Shan and Zhetysu (Dzungarian) Alatau glaciers for the period 2000-2018 to be -0.27 ±0.09 and -0.49 ±0.16 m w.e. yr^{-1}, respectively. Despite the differences in published data on glacier mass loss, most studies highlight the complex and heterogeneous response of glaciers in Central Asia but agree with general mass loss for the Northern Tien Shan. Given the number of glaciers in Central Asia, regional detailed data on glacier mass balance dynamics with high temporal resolution are still rare (Hoelzle et al., 2019; Barandun et al., 2020).

Past and Current Changes in Permafrost

The study of processes and phenomena related to permafrost is important not only to make rational engineering decisions, but also to assess the contribution of permafrost to the total volume of water resources. In mountainous regions of Central Asia, where modern terrestrial glaciation is developed, permafrost is wide-spread. Under climate change in the mountains of Central Asia and significant glacier degradation, it is important to have factual information on the response of the high-mountain permafrost.

Permafrost in Kazakhstan is currently only found in high mountains (Severskiy et al., 2014). In the northern Tien Shan on the Ile Alatau ridge at absolute altitudes of 2400 - 3350 m A.S.L., the Kazakhstan High Mountain Geocryological Laboratory has been conducting geothermal monitoring of frozen grounds since 1974 (Gorbunov & Nemov, 1978). Thermistor sensors with an accuracy of up to 0.01 °C are used to measure soil temperature. In the first period of observations (1974) at the Zhosalykezen Pass, the temperature at the depth of zero annual amplitudes (13 - 17 m) in the boreholes varied from -0.4 to -0.8 °C. Furthermore, the temperature in all boreholes increased by 0.2 - 0.5 °C over the past 20-year period. The change of temperature regime of perennially frozen rocks in one borehole (borehole #1) for the period from 1995 to 2018 is shown in Figure 4.1.4 (Severskiy, 2019).

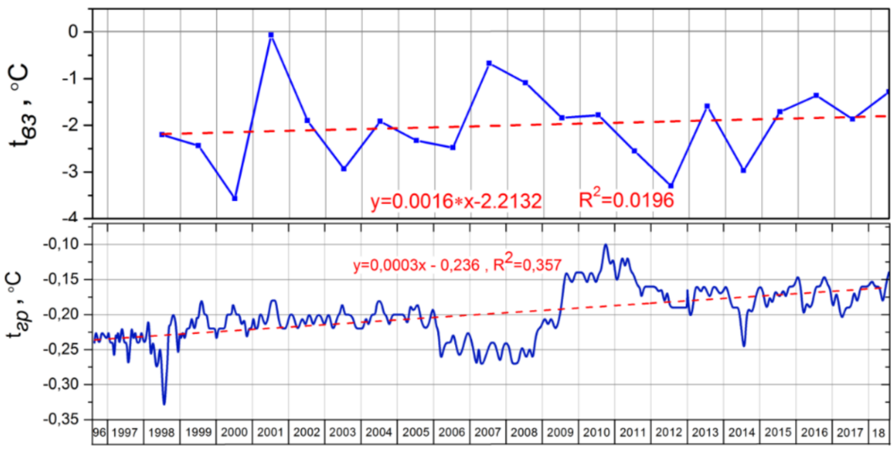

Figure 4.1.4. Top: change of the air temperature (tвз), bottom: subsurface temperature (trp) in one of the boreholes at a depth of 20 m (borehole #1) (Source: Severskiy, 2019).

From 1995 to 2010, the temperature of the permafrost at different depths (10, 15, 20, 25 m) was maintained in the range of -0.2 to -0.25 °C with insignificant fluctuations (up to 0.1 °C), but for the second period after 2011, the soil temperature increased to the range of -0.2 to -0.15 °C (Figure 4.1.5). In general, a weak warming (0.01 °C yr^{-1}) in the temperature regime of the permafrost is observed over the 44-years (Severskiy, 2019).

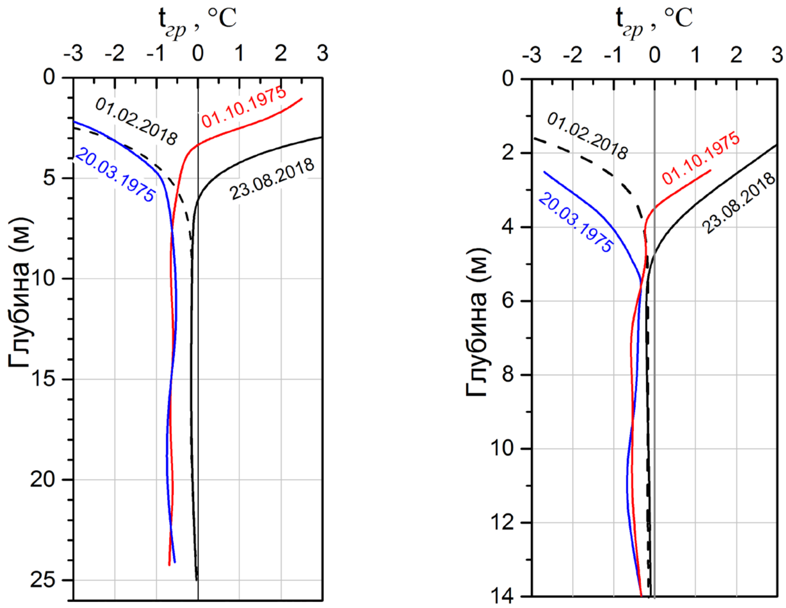

Figure 4.1.5. Ground temperature (trp) dynamics with depth (y-axes) in borehole #1 (left) and borehole #2 (right) at Zhosalykezen Pass. The active layer has increased in borehole 1 from around 3 m to 6 m and in borehole 2 from around 3.75 m to 4.4 m for the period of 1975 to 2018 (Source: Severskiy, 2019).

In 2013, geophysical surveys were carried out at the Zhosalykezen Pass in areas with natural conditions and in built-up areas. The results of these studies showed that when the slope exposure changes from north to south, there is a regular change in the type of frozen grounds strata distribution. The continuous frozen ground strata on the slope of the northern exposure are characterized by high (4500-11000 Ohm·m) values of specific electrical resistance (SER) and a thickness of about 100 m. On the southern slope, according to drilling data, the frozen grounds thickness is absent, which is confirmed by low resistivity values (780-1600 Ohm·m) (Severskiy, 2019; Severskiy et al., 2014). This allowed to reveal the influence of natural and anthropogenic local factors, slope exposure, tectonics, warming and cooling effect of building foundations to the structure of permafrost strata (Severskiy, 2019). Geophysical works carried out at the Zhosalykezen Pass using the sounding of field formation method in 2017 indicate the presence of permafrost at depths of 15 - 40 m, which is confirmed by thermometry data in a nearby borehole (Zheltenkova et al., 2020).

Permafrost and ground ice can contain large amounts of fresh water in solid form and might play a role in melt water contribution to total river runoff. The largest permafrost ice reserves in the region are contained in rock glaciers, moraines and rockfall layers. According to the results of Gorbunov et al. (2018), the underground ice reserves in the Northern Tien Shan are estimated at 56 km^3, which is 62% of the volume of the glaciers. It was found that the largest volumes of ground ice are contained in active rock glaciers. Mapping and remote monitoring, measuring of rock glacier velocities, their internal structure and the mapping of landscape features of rock glaciers are reflected in many works (e.g. Gorbunov, 1979; Gorbunov & Titkov, 1989; Kokarev et al., 1997; Bolch & Marchenko, 2009; Bolch & Gorbunov, 2014; Sorg et al., 2015; Kääb et al., 2021). However, a permafrost monitoring and permafrost research in the region have so far only gained little attention and more systematic studies are needed to 1) better quantify the ice content, 2) to map the internal structure of different permafrost landforms, 3) to understand the dynamic response of frozen ground to climate change, and 4) to understand the role of permafrost degradation in the hydrological cycle.

Conclusion

Ground observations have been instrumental in analyzing snow cover dynamics, and remote sensing data have enabled assessments of changes in Kazakhstan's overall snow regime. Over the past 65 years, mountain glaciation in Kazakhstan has shrunk by approximately 43% in terms of area and 65% in terms of volume. Glaciers in the Zailiyskiy Alatau have decreased by about 65-75% since the mid-19th century. Additionally, ground temperature monitoring in boreholes show a significant temperature increase in permafrost areas, with a notable 0.01 °C yr^{-1} trend from 1974-2018. This warming trend has also been observed in high-mountain meteorological data, with a 0.2 °C/10 years increase in mean annual air temperature. If these trends continue, it is expected that high-mountain permafrost will exhibit a nearly gradient-free thermal regime with near-zero temperatures in the next 20-30 years. Similarly, by 2050 glacier area may be reduced by one third relative to the current situation but will not disappear completely until the end of this century.

4.2 Cryospheric Changes in Kyrgyzstan

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Introduction

Kyrgyzstan is distinguished by its well-developed glaciation in Central Asia, being located inside the Eurasian continent, far from the oceans and in the zone of temperate latitudes it hosts a big part of the western component of the Tian Shan, and parts of the northern and eastern periphery of the Pamir-Alai. More than half of the territory of Kyrgyzstan (56.9%) is located at altitudes over 2500 m A.S.L. and almost a quarter (23.0%) above 3500 m A.S.L. (Usubaliev et al., 2021). Almost all mountain ranges of Kyrgyzstan, to a greater or lesser extent, are currently covered by glaciers. The glacial systems of the mountain ranges of Kyrgyzstan are not only an element of the alpine landscape, but they are also significant reservoirs of fresh water. Thus, glaciers play a crucial role in the process of river runoff formation. Their snow and ice resources are released during the warm seasons. Their role has increased, particularly in dry years glaciers become the only source of input for rivers, and thereby providing water resources to the lower valleys and plains (Usubaliev et al., 2021).

The complex orographic terrain of Kyrgyzstan has a great impact on the formation of permafrost, glaciers and the diverse distribution of snow cover.

Knowledge of the maximum water stored in the snow cover plays an extremely important role in solving many practical issues on the territory of Kyrgyzstan: predicting water availability for irrigated agriculture, assessing the possibility of the development of dangerous floods and mudflows during rapid snow melting in spring, determining snow loads on infrastructures, operating roads. Mountain permafrost can contain large parts of ice within the uppermost bedrock layers or large permafrost ice lenses are a considerably component of coarse debris covered zones such as rock glaciers or talus slopes. Permafrost can occur also on flat to gently sloping terrain. Thawing of permafrost is a major hazard and can have serious consequences for people and the environment. For example, when ice-filled permafrost thaws, it can turn into a muddy slurry that cannot support the weight of the soil and vegetation above it. Infrastructure such as roads, buildings could be damaged as the permafrost thaws.

Past and Current Changes in Snow

Kyrgyzstan is a Central Asian country with rich groundwater and surface water resources. Changes in the flow and distribution of its water sources, snow meltwater, glaciers and other tributaries, affect the availability of water in Kyrgyzstan. Runoff from snow meltwater is an important source of water of the Kyrgyzstan. Furthermore, especially in mountainous regions, floods caused by melting snow are often recorded, which pose a serious threat to natural and socio-economic systems. To reduce the tragedies and losses caused by floods, it is very important to analyze comprehensively snow melt patterns and potential flood processes implied.

Depending on the orographic conditions and the nature of the distribution of snow cover in the country, four zones are distinguished (Mamatkanov et al., 2006):

1. The zone of permanent snow cover is located within the high-mountain (nival) zone at altitudes from 3200 to 4800 m A.S.L. and above. The area of this zone is relatively small.
2. The zone of stable snow cover is located below the perennial snow line (from 3200 to 1500 m A.S.L.) and occupies a significant area. The duration of the snow cover is from 3 to 6 months, shortening with decreasing altitude.
3. The zone of unstable snow cover occupies heights from 600 to 1500 m A.S.L., including the foothills and adjacent valleys. This zone also includes some high-mountain areas (syrts), where there is very little winter precipitation.
4. Zone with no snow cover. This includes the Kochkor depression and the western part of the Issyk-Kul depression, where very little snow falls (Mamatkanov et al., 2006).

The distribution of snow cover over the territory, the duration of its occurrence, and the water reserves in the snow at the beginning of winter season are extremely uneven and influenced by climatic and orographic factors. In the mountains, favorable conditions are created for heavy precipitation, long-term preservation, and accumulation of snow, which has a huge impact on the dynamics of mountain glaciers, the permafrost temperature regime, and the formation of river flow.

Few studies exist on long-term trends and short-term variability of snow cover in Central Asia. Recent studies in the Central Asian region show changes in precipitation from snow to rain. Aizen et al (1997) analyzed snow data from 110 stations for the period from 1940 to 1991 and found a decrease of mean annual snow depth of 8 - 14 cm at elevations below 2000 m A.S.L. and of 6 - 19 cm at higher elevations. They also concluded that the number of days with snow cover decreased by 9 days during this period. Glazirin (2009) analyzed snow cover duration at the Oigaing and Tashkent stations from the 1930's and reported slight negative trends, which were, however, not statistically significant. Tsarev (2006) analyzed snow depth, precipitation and temperature data to estimate how climate change impacts the maximum snow storage in the mountains of Central Asia based on a temperature-precipitation approach. According to his results, scenarios of a temperature increase of 2 °C and a precipitation decrease by 30% would lead to about 30% less water storage in the snow pack in March when snow accumulation peaks.

Remote sensing products have become an important source of data for snow observations in recent years. Especially in remote areas such as the mountainous area of Central Asia, remotely observed snow cover area products have become available for the past three decades. Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Very High-Resolution Radiometer (AVHRR) data are among those widely used in Central Asia to assess water availability. Gafurov et al (2013) assessed the quality of MODIS snow cover data against manual observations from stations in Central Asia and reported about 93% accuracy. However, cloud cover prevents the efficient use of optical remote sensing in hydrological studies (Gafurov & Bàrdossy, 2009). A study by Peters et al (2015) indicated for the Tarim basin a snow cover reduction in lower elevations (< 3600 m A.S.L.) and found also evidences for an increase in snow cover duration at higher elevations (> 5000 m A.S.L.), which is also supported by some analysis of long-term accumulation measurements on Abramov glacier in the Pamir-Alay (Kronenberg et al., 2021). For regions with decreasing snow cover duration and a decrease in the proportion of snowfall, accumulation of snow on glaciers in winter will render their mass balance more negative. Moreover, changes in snow cover and significant shrinkage of glaciers are causing changes in the local water cycle, altering river runoff and groundwater supplies. Less precipitation in the form of snow leads to o earlier snowmelt, which could ultimately shift peak discharge and river runoff earlier in the year rather than in the summer when water demand is highest (Tomaszewska & Henebry, 2018).

Past and Current Changes in Glaciers

Glaciers in the mountains of Central Asia, as well as throughout the world, are severely degrading with varying rates of area reduction, depending on the region. The study and monitoring of glacial systems in the Central Asia under a prevailing arid climate in most of its territory and modern ongoing global warming has become more and more relevant.

Currently, due to ongoing global warming, glaciers are degrading, which manifests in a decrease in their area and volume. Over approximately a 70-year period, the area of glaciation in Kyrgyzstan decreased by an average of 16% (Usubaliev et al., 2021). The area of large glaciers decreased by 17%, and the area of small glaciers increased 2.5 times (245%). According to the Catalog of Glaciers of the USSR the glaciated area in 1960's was 8108 km^2 (glaciers <0.1 km^2). A recent glacier assessment reports an area of 6683.9 km^2 and estimates glacier volume at 530 km^3 as of 2016, suggesting an area and volume decrease of 18.5% (Usubaliev et al., 2021).

The most objective indicator of the state of glaciers and their evolution are long-term data on the mass balance of glaciers. During the Soviet time, in the 1950s and 1960s, a comprehensive system of cryospheric monitoring was initiated in the Tien Shan and Pamir. However, following the collapse of the USSR in the mid-1990s, most of these programs ceased abruptly (Barandun et al., 2019). Since 2010, a new glacier-monitoring network has been (re)established (Fig. 4.2.1) and initially four glaciers have been selected for long-term monitoring by a team of researchers from Kyrgyzstan, Germany and Switzerland as part of the Central Asian Water (CAWa), Capacity Building and Twinning for Climate Observing Systems (CATCOS), Cryospheric Climate Services for improved Adaptation (CICADA) and Cryospheric Observation and Modelling for improved Adaptation in Central Asia (CROMO-ADAPT). Since then, glaciological measurements have been carried out continuously. Currently, in Kyrgyzstan, mass balance monitoring of glaciers covers the glacial systems of the Northern, Inner, Central Tien Shan and the Issyk-Kul Basin. These includes the following glaciers: No. 354 located on the northwestern slope of the Ak-Shyirak mountain range; Batysh Sook located on the northern slope of the Zhetim-Bel ridge (Inner Tien Shan); Golubin (Ala-Archa river basin, northern slope of the Kyrgyz Ala-Too ridge); Abramov, located on the southern slope of the Alai Range; Glacier number 599 is situated on the southern side of the Kungey Ala-Too range, while Kara-Batkak and Turgen-Aku-Suu are positioned on the northern aspect of the Teskey Ala-Too range within the Issyk-Kul basin.

Various studies have generated ongoing mass balance data sets for specific glaciers through modelling. Azisov et al. (2022) conducted a study on the annual mass balance of Golubin spanning from 1900/1901 to 2020/2021 (Fig. 4.2.2). Their findings indicate a mass balance change of -0.16 ± 0.45 m w.e. yr^{-1} during this period.

Glacier mass balance analysis was carried out and continued on the Batysh Sook and No. 354 glaciers located in Inner Tien Shan (Figure 4.2.1) and results published in Kronenberg et al. (2016) and Kenzhebaev et al. (2017). The distributed accumulation and temperature index melt model (Hock, 1999; Huss et al., 2009) used to extrapolate point measurements from 2011 to 2021 was applied in order to reconstruct the mass balance from 2004 to 2010 (Figure 4.2.3). For Batysh Sook glacier an average annual mass balance of −0.61 m w.e. yr^{-1} was found for the period 2003/04 to 2020/21 and of −0.58 m w.e. yr^{-1} for glacier No. 354. Modern direct measurements have shown that the monitored glaciers in Kyrgyzstan experienced mass losses between −0.25 and −0.51 m w.e. yr^{-1} from 2011 to 2016. Reconstructed mass balances have confirmed this negative trend over the last few decades, indicating that the same glaciers lost between −0.30 and −0.43 m w.e. yr^{-1} from 2000 to 2014 (Hoelzle et al., 2019; Barandun et al., 2018; Barandun et al., 2015; Hoelzle et al., 2017; Kenzhebaev et al., 2017; Kronenberg et al., 2016; Azisov et al., 2022). As long term mass balance time series show there is a general negative mass balance trend for all monitored glaciers. This means that the ablation part of the glacier exceeds the glacier accumulation value. However, in some hydrological years a positive balance is also observed, which is associated primarily with favorable weather and climatic conditions and the location of a particular glacier in the mountain system. Despite the significant distance of the glaciers in question from each other on the territory of Kyrgyzstan and differences in topographic and climatic settings, synchronicity is observed in the long-term change of their mass balance. Glacier retreat intensifies but at varying rates, leading to a significant reduction in the size of glaciers but leaves a heterogeneous glacier response pattern (Barandun et al., 2021). The size of glaciers is rapidly decreasing not only in length and area, but also thinning of the surface of glaciers is occurring. In this case, not only the ablation zone, but also some parts of the accumulation zone are subject to reduction. The snow line has gone beyond the maximum elevations of the ridge in most recent years, with the exception of some of the highest levels (Usubaliev et al., 2021).

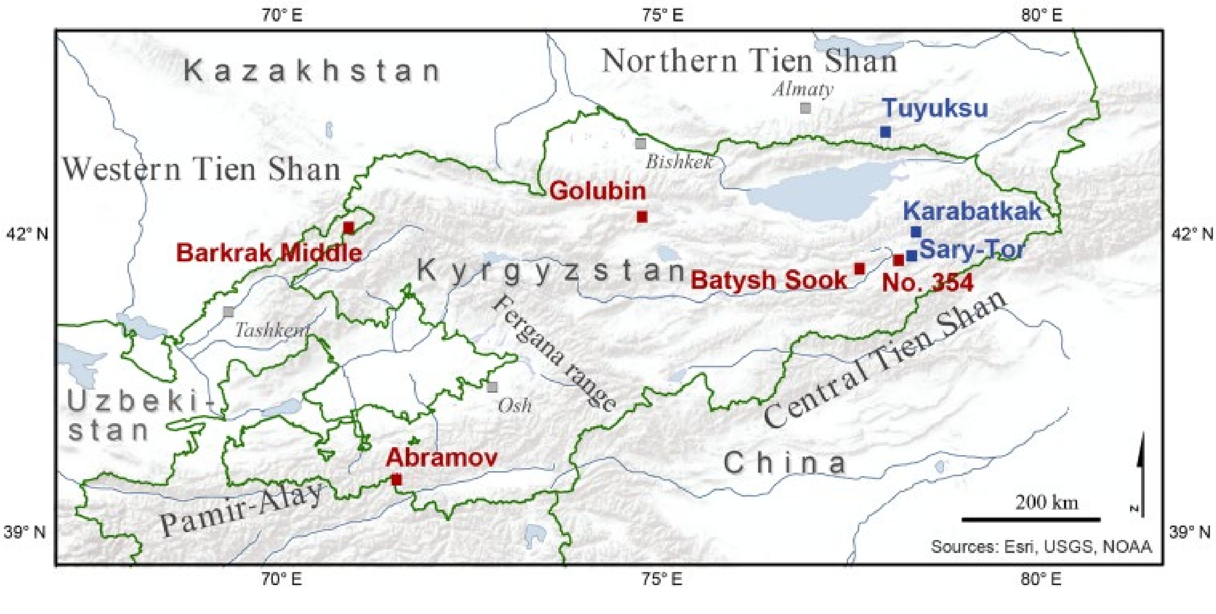


Figure 4.2.1. Map of glaciers in Kyrgyzstan, where the investigations were gradually re-established starting in 2010. Red symbols show glaciers investigated within the CATCOS, CICADA, CROMO-ADAPT and CAWa projects, and blue symbols show glaciers that are covered by other projects (Source: Hoelzle et al., 2017).

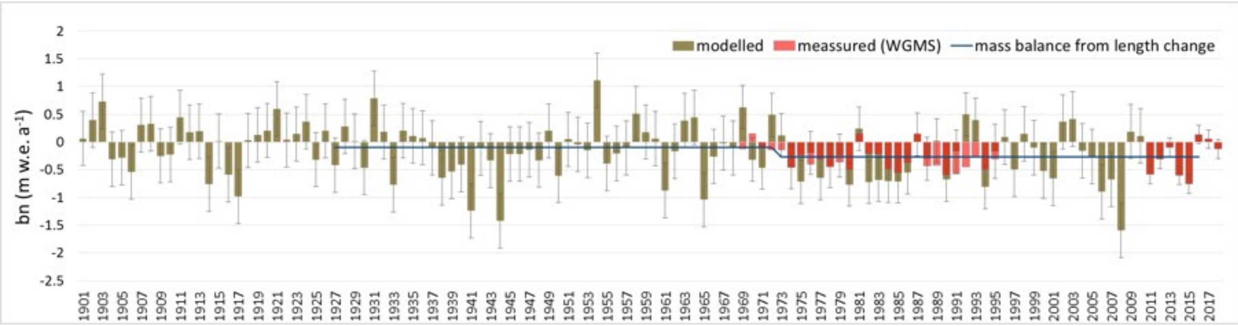
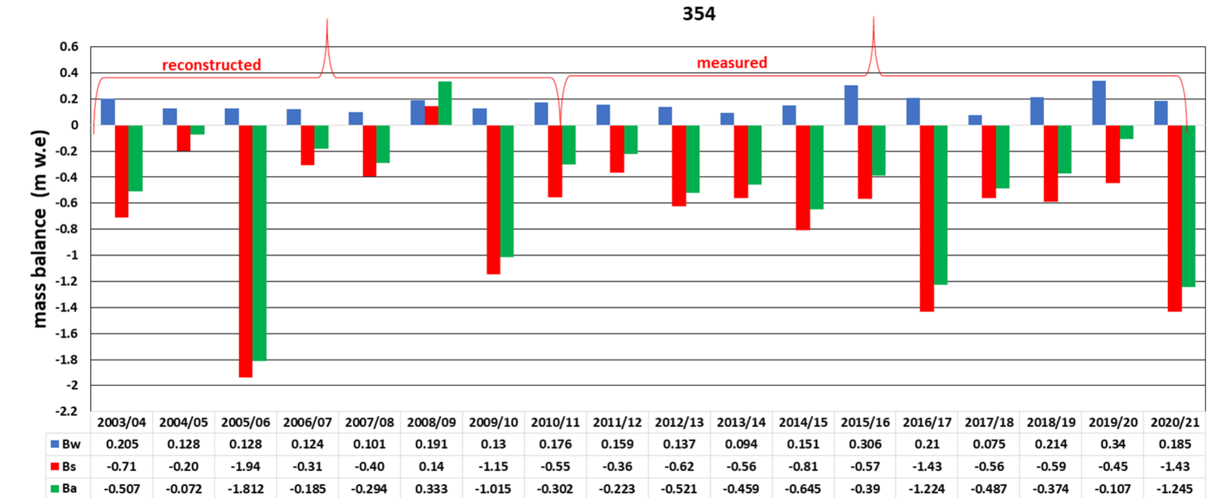


Figure 4.2.2. Modeled (green bars) and measured (red bars) mass balance time series with error bars describing the mass balance uncertainty. Blue line showing mass balance change derived from length change observations for two periods (1927 to 1972; 1972 to 2016) (Source: Azisov et al., 2022).



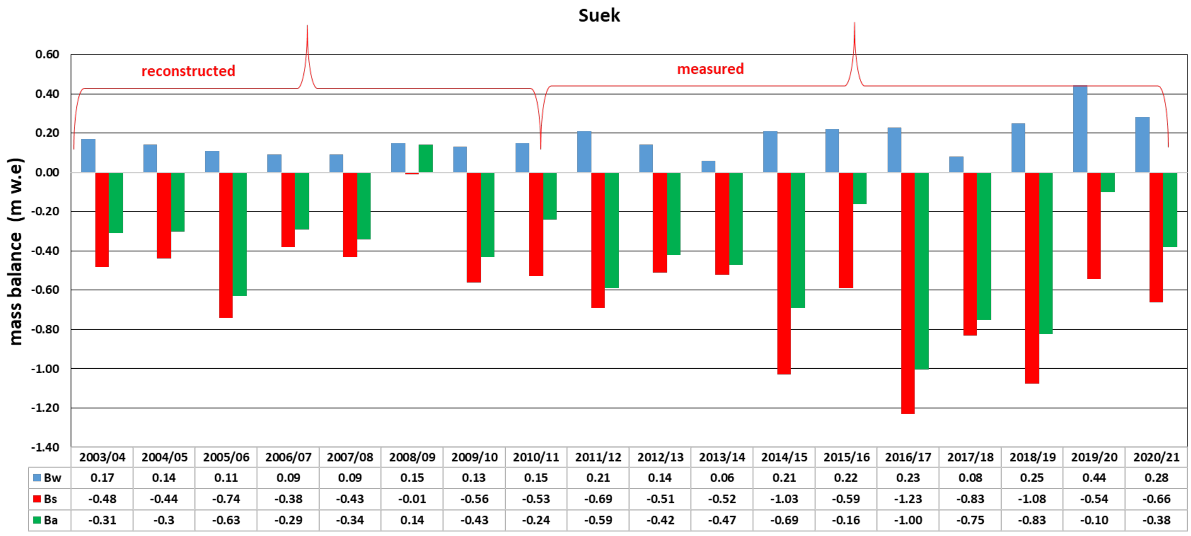


Figure 4.2.3. Reconstructed (2003/04-2009/10) and measured (2010/11-2020/21) summer balance (Bs, red), winter balance (Bw, blue) and annual mass balance (Ba, green). We used values from a distributed accumulation and simple energy balance approach based on Oerlemans, 2001.

Past and Current Changes in Permafrost

Permafrost is widespread in the highlands at altitudes above 3500-4000 m A.S.L. In general, the area of permafrost is estimated to be about 64 000 km^2, or 3.4% of Kyrgyzstan. Since the end of the Little Ice Age, permafrost in the Tien Shan has experienced continuous warming until present (Marchenko et al., 2007). Ground temperature measurements were carried out in 20 boreholes in the Akshiirak massif (42°N, between 4000 and 4200 m A.S.L.), and in more than 25 boreholes in the Kumtor valley (between 3560 and 3790 m A.S.L.). In the Akshiirak Mountain Range, at elevations of 4100 - 4200 m A.S.L. the lowest measured ground temperature was −5 °C in the bedrock (Paleozoic schist) and −6.7 °C in the ice-rich Late Pleistocene moraines. The corresponding thickness of permafrost was 350 - 370 m and 250 - 270 m, respectively (Ermolin et al., 1989; Gorbunov et al., 1996). The average active layer thickness for all measured sites increased by 23% in comparison to the early 1970s (Marchenko et al., 2007). As shown in Fig. 4.2.4, a new temperature logger was installed in Akshiirak, Kyrgyzstan in 2022. It shows that the permafrost temperature has increased in 20 m depth of about +0.9 °C since 1986.

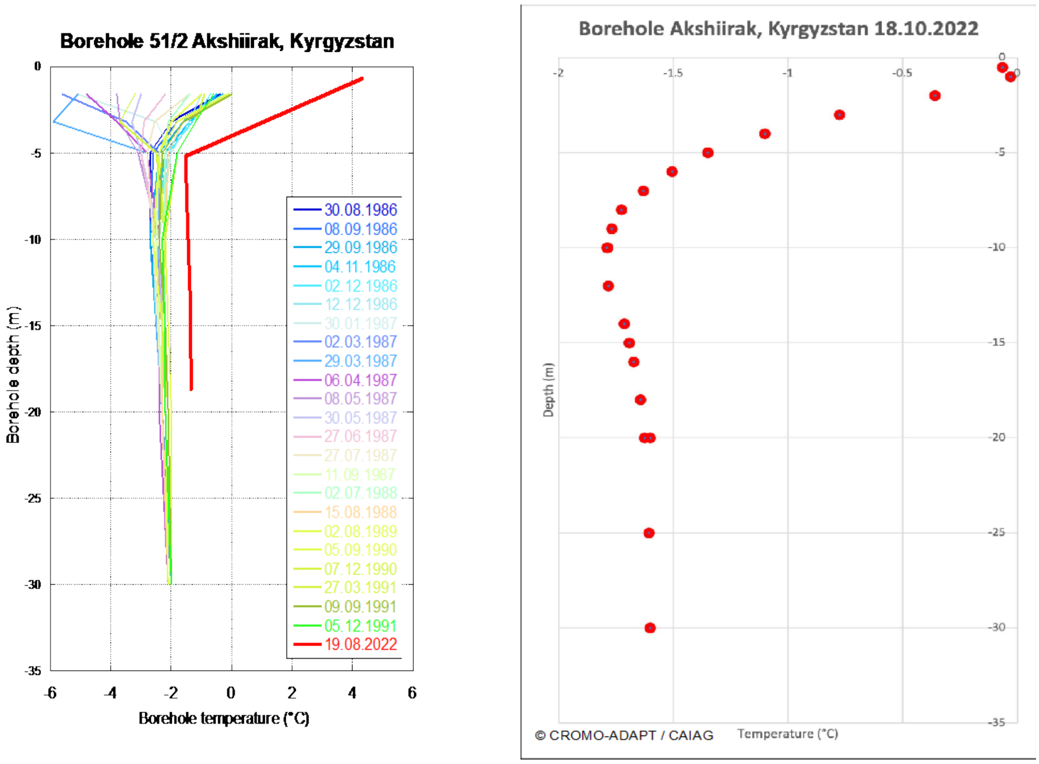


Figure 4.2.4: Borehole Temperature observations from 1986 to 1991 and again for 2022 in Akshiirak Kyrgyzstan show a clear subsurface warming (Credits: CROMO-ADAPT project, University of Fribourg).

Permafrost is of hydrological importance for Kyrgyzstan and has a significant impact on economic activity. The future degradation of permafrost is also a potential source of mountain hazards, exasperating the urgent need for continuous and sustainable mountain cryosphere monitoring. Warming of mountain slopes destabilizes permafrost, primarily through reduced mechanical strength, potentially leading to various types of mass movements such as debris flows, rock avalanches or in the case of ice-cored moraine dams, glacial lake outburst floods. Mass movements are complex phenomena and while climate induced permafrost degradation (observed at GTN-P sites in Tien Shan e.g. (Marchenko et al., 2007)) can be a key driver of such events, it is not straightforward to disentangle the climate signal from normal erosional processes in mountain regions. However, there is increasing evidence that increased incidence of thermally induced slope instabilities should be expected as high mountain regions are warming rapidly (Barandun et al., 2020). Due to the high potential energy inherent in steep environments and the possibility of compound events that entrain moisture sources (glacier ice, snow or water), the consequences of mass movements can be far reaching and affect communities many kilometers downstream.

Conclusion

Water resources in the arid continental regions of Central Asia are highly dependent on cryospheric components such as snow, glaciers and permafrost (Hoelzle et al., 2019). The Central Asian cryosphere is undergoing significant changes, driven by climate change. This may have a profound impact on water availability in the region in the near future, especially under higher emission scenarios. The dry summer months in Central Asia correspond to the peak of the vegetation season and thus of water demand. Snow and ice melt provide water resources during this period. Glacier melt in particular becomes an important freshwater buffer during droughts (Pohl et al., 2017; Pritchard, 2019; Barandun et al., 2020). The Tien Shan and Pamir in Kyrgyzstan act as water towers for Central Asia (Ibatullin & Ziganshina, 2019; Immerzeel et al., 2010; Kaser et al., 2010). The cryospheric components of these mountain systems store substantial volumes of water in solid form, which is crucial for the present and potential water availability and management under a changing climate.

4.3 Cryospheric Changes in Tajikistan

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Introduction

Tajikistan's cryosphere is a unique mountain resource that is highly vulnerable to future climatic and social changes (Immerzeel et al., 2020). The Pamir in Tajikistan is the main transboundary source of runoff for the Amu Darya, leading to regular conflicts over water allocation (De Stefano et al., 2017) and unsustainable water management (Micklin, 2010). While using only up to 20% of its own freshwater resources, Tajikistan's cryosphere provides a significant amount of water, mainly to Uzbekistan and Turkmenistan. Glaciers and perennial snowmelt are the main contributors of freshwater to the Aral Sea basin (Makhmadaliev et al., 2008). While snow melt provides up to 70% of the total annual runoff (Armostrong et al., 2019; Kraaijenbrink et al. 2021), the glaciers of High Mountain Asia release meltwater that meets the water needs of 250 million people during the dry summer season (Miles et al., 2021; Pohl et al., 2017; Pritchard et al., 2019). The Pamir are a major center of modern glaciation with unique temporal and spatial variability (Kraaijenbrink et al., 2017; Scherler et al., 2011; Shean et al., 2020; Wang et al., 2019; Barandun et al., 2021; Barandun & Pohl, 2023) due to a heterogeneous climate setting and sensitivity (Sakai and Fujita, 2017).

The earliest reports in Tajikistan on the cryosphere date back to the late nineteenth and early twentieth centuries, when various explorers visited the high mountain areas of Central Asia (Mergili et al., 2012). Full-scale studies began in 1946, and aerial photographs were taken with the aim of cataloging glaciers by visual inspection on helicopters, followed by interpretation of taken aerial photographs in 1971 (Catalogue of glaciers of the USSR, 1975). During Soviet period, systematic mapping of glaciers in Tajikistan was carried out in 1968 - 1973 as part of the Soviet Glacier Inventory (Kotlyakov, 1980). After the collapse of the USSR, starting in the

1990s, due to the inaccessibility of research sites and the high cost of field visits, glaciological research decreased sharply (Kayumov et al., 2022). Cryospheric research in Tajikistan is only slowly being revived (Lv et al., 2019; Hoelzle et al., 2019; Barandun et al., 2020).

Past and Current Changes in Snow

A permanent snow stake network was established in the 1960s and was surveyed annually until 1990 (monthly in some years; Bedford and Tsarev, 2001). Unfortunately, the monitoring activities were interrupted with the ending of the USSR and have only recently been resumed by national institutions (AKHA, TajikHydromet) (Bair et al., 2020). Gulahmadov et al. (2023) used the long-term historical data sets from the Varzob River Basin in Tajikistan to assess statistical trends and magnitude changes in temperature, precipitation, and snow cover in the Anzob (upstream), Maykhura (midstream), and Hushyori (downstream) regions of the Varzob River Basin. The results showed a decreasing trend in mean monthly air temperature at the Anzob station in the upstream region for all months except January, February, and December between 1960 to 2018 and 1991 to 2018. Seasonal precipitation showed a large increasing trend in January and February at Anzob station from 1960 to 2018, but a significant decreasing trend in April in the upstream, middle, and downstream regions between 1960 to 1990 and 1991 to 2018. Almost all stations showed a decreasing trend in annual precipitation between both periods, while the upstream region showed a non-significant increasing trend between 1960 to 1990. The monthly analysis of snow cover in the Varzob River Basin based on ground data showed that the maximum increase in snow cover occurred in April at Anzob station (178 cm) and in March at Maykhura (138 cm) and Hushyori (54 cm) stations. A Mann-Kendall test based on MODIS data revealed that the monthly snow cover in the Varzob River Basin increased in April and July, while a decrease was recorded in February, September, November and December from 2001 to 2022. A stable pattern and thus no trend was observed in March, May, August and October (Gulahmadov et al., 2023).

Smith and Bookhagen (2018) used 24 years (1987 to 2009) of satellite-based passive microwave snow water equivalent estimates to examine trends across High Mountain Asia, including the Amu Darya and Indus basins. Their estimates show most areas in the range of 50 - 100 mm of snow water equivalent for December to February, with a few over 100 mm in the Amu Darya basin. These values show little detail due to the coarse satellite resolution of 25 km (Bair et al., 2018, 2020). Thus, knowledge of the snowpack in Tajikistan remains poor. Thanks to a novel operational avalanche observation network, daily snow measurements are now available at several operational weather stations throughout the Pamir. Bair et al. (2020) combined these direct observations with downscaled reanalysis and remotely sensed measurements to improve snow water equivalent estimates. The study found a very heterogeneous distribution of snow properties across the region.

Precipitation data can provide an indication of snow cover patterns. There is considerable variability in the distribution of precipitation across Tajikistan (Aalato et al., 2017). Based on the interpolated station data, total mean annual precipitation ranges from less than 50 mm to more than 1000 mm. In addition, the analysis reveals three distinct regions with relatively high precipitation compared to other parts of the country (Figure 4.3.1). The driest areas of Tajikistan are the eastern Pamir and southwestern plains, which receive less than 200 mm of precipitation annually. The driest season is summer when rainfall only locally exceeds 100 mm. On the other hand, a significant proportion of annual precipitation occurs in spring, with the western regions of the country receiving more than 400 mm (Figure 4.3.1; Aalato et al., 2017). Total annual precipitation in the Gissary-Alai is high and characterized by a strong vertical gradient. Snow accumulation on Abramov Glacier located in the Alai have increased since the 1970’s (Kronenberg et al., 2021). In contrast, Niyazov et al. (2018) found a decrease in snow cover in the northeastern Alai range from 1940 to 2017. The area around the

Fedchenko glacier receives the highest amount of precipitation due to a strong barrier effect of westerly winds by the surrounding mountain peaks that shield the Eastern Pamir. Total precipitation for the cold season (October-April) for the Eastern Pamir showed a decrease of 25 mm or 25% at the Javshangoz weather station from 1940 to 2016 (Fig. 4.3.2; Niyazov et al., 2019). Similarly, at the Bulunkul weather station, a decrease in winter precipitation of 12 mm or 16% from the long-term mean was recorded for the period October to April (Fig. 4.3.2). At Khorog weather station, the amount of precipitation remained almost unchanged for the same period (Fig. 4.3.2).

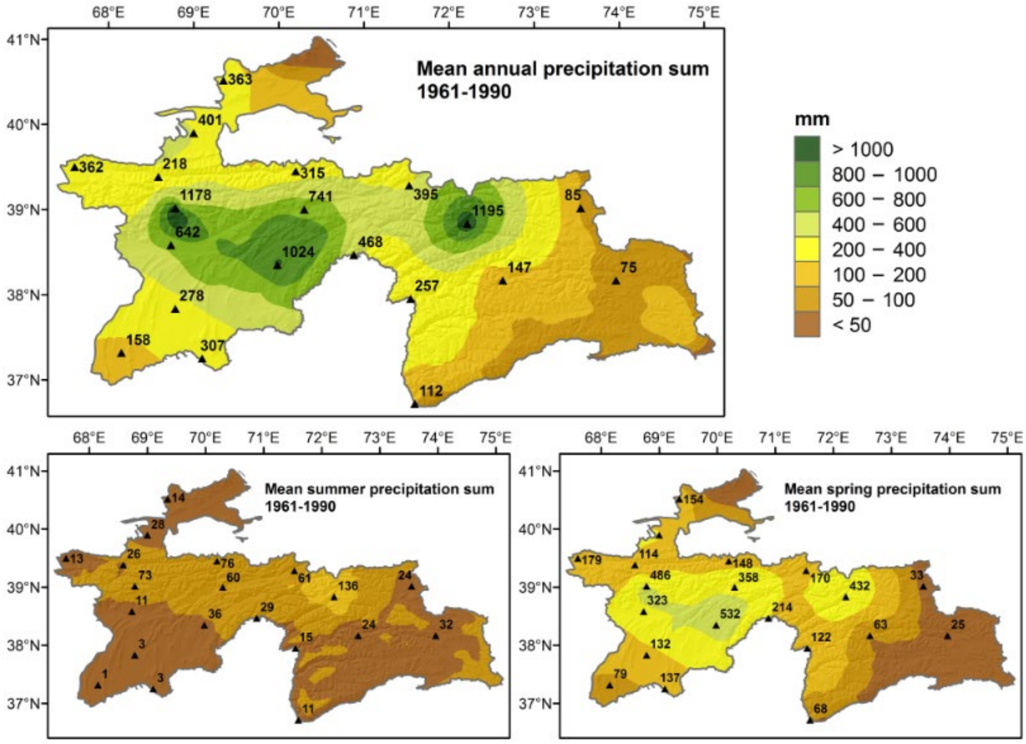

Figure 4.3.1. The interpolated mean annual (top), summer (June–August, the driest season, lower left) and spring (March–May, the wettest season, lower right) precipitation sum in Tajikistan based on 1961 - 1990 observations. The observed precipitation is presented only for a subset of the stations and measurements in high mountain areas are sparse and bias the result (Aalato et al., 2017).

Another good indicator on long-term snow cover changes is the regional end-of-summer snowline altitude over glacier area. The snowline altitude at the end of summer depends on the interplay of solid precipitation and air temperature and is also a good indicator for glacier mass balance. A remote observed mean snowline altitude on glaciers of 4355 ±134 m A.S.L. was reported for the Western Pamir and of 5050 ±35 m A.S.L. for the Eastern Pamir from 1998 to 2013 (Zhang & Kang, 2017). During the same period, the snowline increased by 0.3 m per year in the Western Pamir but decreased by 5.1 m per year in the Eastern Pamir (Zhang and Kang, 2017). This highlights the strong heterogeneity across the region from west to east and are consistent with the changing mass balance variability and trends from a first (2000 to 2011) to a second period (2007 to 2018) across the Pamir found in Barandun et al. (2021).

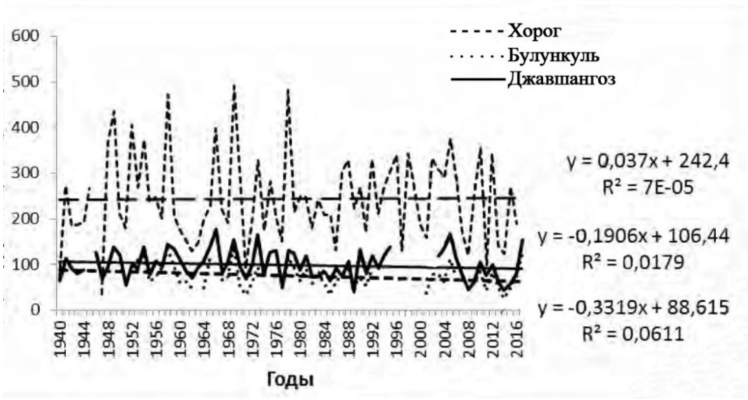

Figure 4.3.2. Total precipitation for the cold period (October-April) in mm from 1940 to 2016 (Niyazov et al., 2019).

Past and Current Changes in Glaciers

Mountain glaciers are an important indicator of climate change, and their dynamics, especially changes in surface mass balance, is an important climate variable. Tajikistan's glaciers cover an area of 8400 km^2, which is 6% of the country's territory. The largest glacier in Tajikistan, Fedchenko Glacier and its tributaries are one of the largest glacier systems outside the polar regions (Lambrecht et al., 2014). Fedchenko has experienced a large loss of thickness since the first scientific investigations in 1928 (Lambrecht et al., 2018). Lambrecht et al. (2018) found that thinning rates increased by a factor of 1.8 between 2000 and 2016 compared with 1928 to 2000. Even the highest accumulation basins above 5000 m A.S.L. were affected by glacier thinning, with change rates between -0.2 and -0.4 m yr^{-1} from 2009 to 2016. The estimated glacier-wide mass balance rates are -0.27 ± 0.05 m w.e. yr^{-1} for 2000 to 2011 and -0.51 ± 0.04 m w.e. yr^{-1} between 2011 and 2016 (Lambrecht et al., 2018). Despite increased mass loss, the accumulation pattern is persistent in the recent past (Lambrecht et al., 2020), in line with the findings of Kronenberg et al., (2021) and supporting the suggestion of Kääb et al. (2015) that the Pamir and Karakoram appear to be on the western edge of a mass gain anomaly (Pamir-Karakoram-Himalaya Anomaly) rather than its center.

Across the region, glacier regimes and their sensitivity are highly heterogeneous (Aizen et al., 2011; Sakai and Fujita, 2017), resulting in very different rates of glacier retreat across the Pamir (Dehecq et al., 2015, Barandun et al., 2021). The temporally and spatially heterogeneous glacier response suggests a more complex response of climate forcing to runoff and the importance of glacial meltwater variability for the region than previously thought (Barandun et al., 2021). In addition, the identification of 186 actively surging glaciers, mostly concentrated in the northern and western part of the Pamir (Goelich et al., 2020), further complicates an in-depth understanding of the current glacier-climate interactions (Wendt et al., 2017). Furthermore, surging glaciers can dam rivers, posing the threat of breaching and cause catastrophic floods (Dolgoushin et al., 1975; Kotlyakov et al., 2008).

Barandun et al. (2021) highlighted the large variation in glacier mass balance across the Pamir and suggested subregions with similar mass balances (Figure 4.3.3). Miles et al. (2021) found that 41% of glaciers accumulated mass over less than 20% of their area, and only 60% ±10% of regional annual ablation was compensated by accumulation. The authors suggest that without 21st century warming, 21% ±1% of ice volume will be lost by 2100 due to the current climate-geometric imbalance for High Mountain Asia, which translates into a 28% reduction in the meltwater contribution from glacier melt (Miles et al., 2021). Barandun and Pohl (2023) attempted to explain these heterogeneous responses in terms of climatic and morpho-topographic factors but were inconclusive due to the limited quality of the input data. The authors concluded that without a glaciological, meteorological, and hydrological in situ observing network providing data that allow direct calibration and validation of extensive data sets, neither our understanding of the changing climate and cryosphere at the regional scale for the Tien Shan and Pamir, nor the assessment of water availability for the region's growing population can be improved.

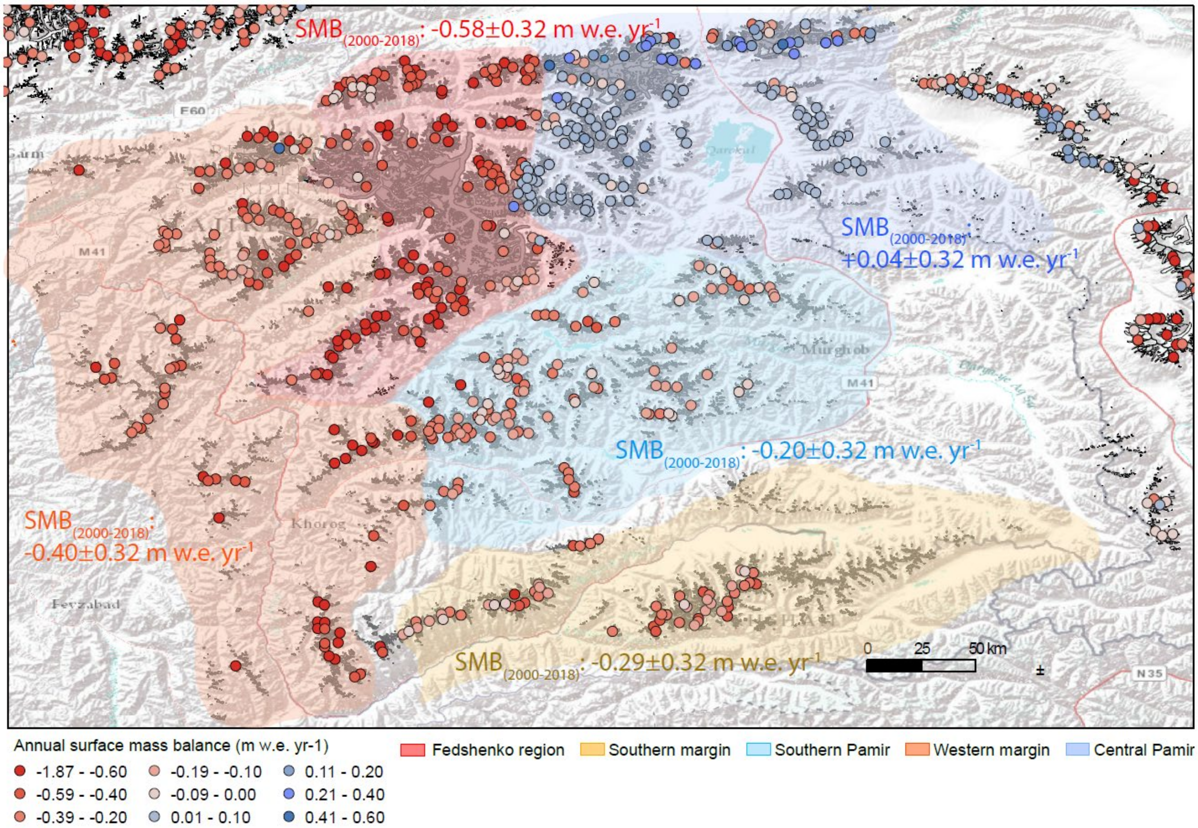

Figure 4.3.3: Annual surface mass balance for each glacier larger than 2 km^2 in the Pamir. Subregions with similar mass balance have been suggested in Barandun et al., (2021), highlighting the strong contrast in glacier regime, response, and climatic sensitivity (Source: Barandun et al., 2021).

The few existing observations tend to focus on changes in glacier area. A general loss of area has been observed in various catchments, such as for Fortambek, Sugran, Mushketova glaciers in Muksu, and glaciers in the upper reaches of Sauksay and Balyandkiik (Fig. 4.3.4) (Makhmadaliev et al., 2008). The Great Saukdara Glacier retreated by 2 km during the 20th century. In the Vanj, Gunt, Bartang and Shardara river basins, the area of glaciers has decreased by 25 - 30% in the last 50 years (Makhmadaliev et al., 2008). Glaciers in the Gissar-Alay are retreating heterogeneously. Kayumov et al. (2022) found a glacier retreat of 9% for the Sarygun catchment for the period 1977 - 2018. In the area of Lake Sarez, five small glaciers have completely disappeared. Glaciers in the Murghab region have melted by almost 30 - 40%. The glacier area of 7 km^2 in the Vuzhdara basin (Gunt) decreased in 1968 by 0.2 km^2 (4.9%; Navruzshoev et al., 2021). Glacier retreat in the Eastern Pamir is somewhat less pronounced than in the rest of the Pamir (Makhmadaliev et al., 2008).

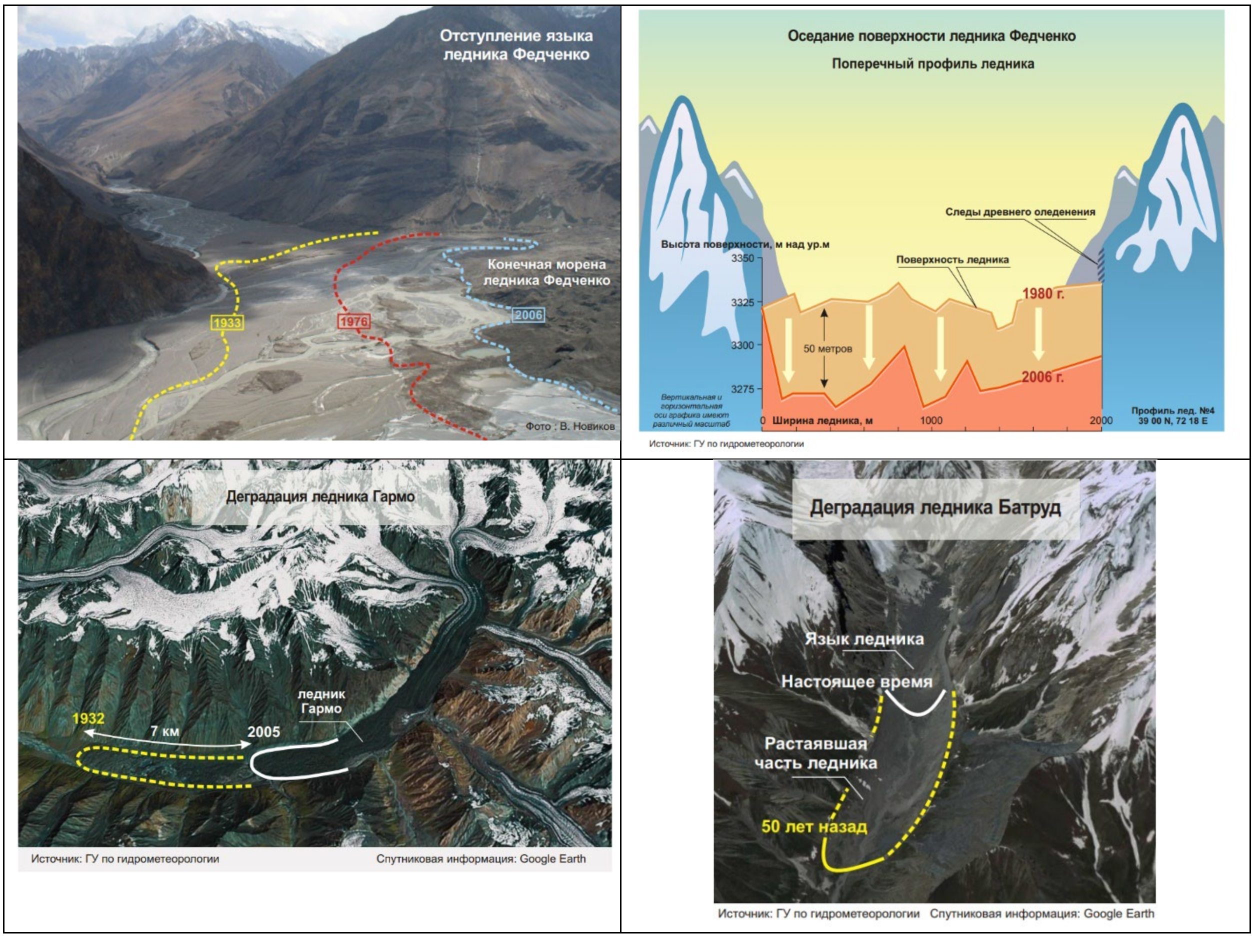

Figure 4.3.4: Top left) Retreat of Fedchenko glacier from 1933 to 2006, top right) Subsidence of the surface of the Fedchenko glacier from 1980 to 2006, bottom left) Retreat of the Garmo Glacier and bottom right) Retreat of the Batrud Glacier (Makhmadaliev et al., 2008).

Mass balance measurements in Tajikistan have only been resumed in the last years. Currently the mass balance of Yakartsha, GGP, Nissai (Sangvor), Zulmart and Glacier No. 457 are monitored. Measurement of mass balance at Zulmart Glacier (#139) were initiated in 2018. The vertical mass balance profile is shown in Fig. 4.3.5. The measurement results for the mass balance years from 2018/19 to 2021/22 showed that the mass balance of Zulmart Glacier (#139) is negative, with an average of -0.25 m.w.e yr^{-1}. The most negative annual mass balance (-0.31 mm w.e. yr^{-1}) occurred in the 2021/22.

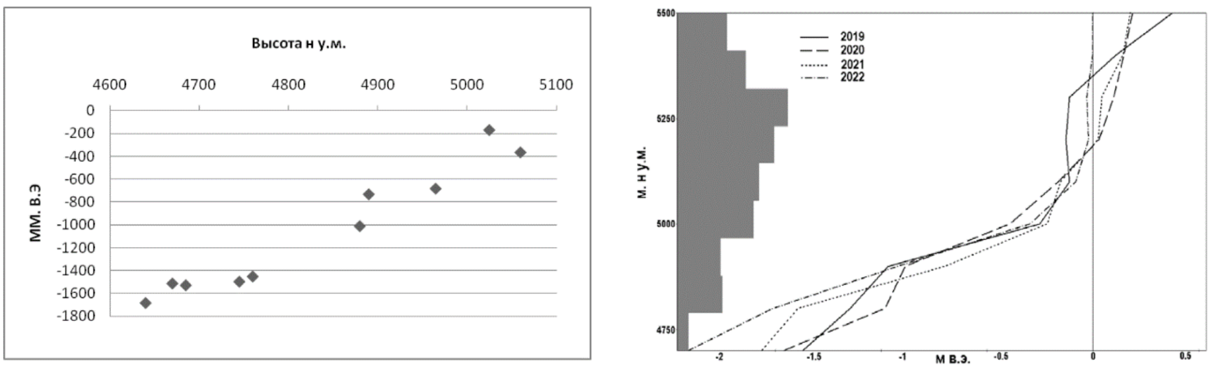

Figure 4.3.5. (left) Ablation stake readings of 4 years of measurements. (Right) Vertical mass balance gradient and hypsometry (grey bars) of Zulmart glacier (Kayumov et al., 2023).

Since 2020, the mass balance of glacier #457 is measured, using direct glaciological and modeling methods. The glacier is located in the upper Tokuzbulak River basin. The establishment of long-term monitoring in the Gunt River basin is an important step forward to improve glacier monitoring in the Eastern Pamir and to better understand the heterogeneous glacier response to climate change in the region. The glacier lost -0.3 m w.e. yr^{-1} of its mass for the balance year 2020/21, -1.0 m w.e. yr^{-1} in 2021/22 and -0.6 m w.e. yr^{-1} in 2022/23 (Fig. 4.3.6).

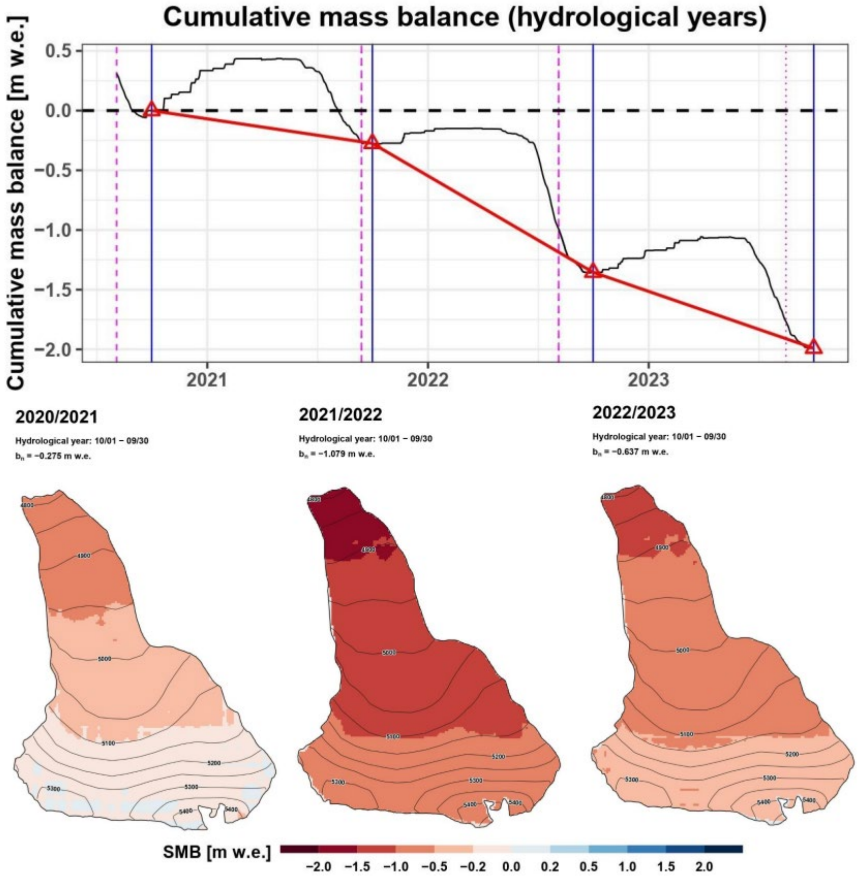

Figure 4.3.6: (top) Cumulative surface mass balance of glacier #457 from 2001 to 2023 as well as distributed mass balance maps for each hydrological year with measurements

Glacier mass balance time series in Tajikistan are still very short, however they are essential to better understand the ongoing heterogeneous response to climate change in the region. Thus, the sustainability, extension, and maintenance of the monitoring network in Tajikistan needs to be of greatest priority.

Past and Current Changes in Permafrost

In Tajikistan, particularly in the Pamirs, permafrost holds significant importance due to its extensive presence. Within mountain ranges, permafrost serves as a crucial water storage system, particularly valuable in arid regions. Additionally, it plays a pivotal role in influencing slope stability and associated natural hazards. Despite these implications, research on permafrost distribution, thermal conditions (including borehole temperature monitoring), and ground ice content in the region has been limited since the 1980s (Barandun et al., 2020).

Direct (in-situ) observations or data on permafrost in Tajikistan are scarce, and existing permafrost distribution maps are often based on simplified models that overlook key factors influencing permafrost occurrences (e.g. Gruber & Mergili, 2013; S. Gruber, 2012). In the Pamir, Mergili et al. (2012) identified about 84% of Gorno-Badakshan Autonomous Oblast as potential permafrost, covering approximately 54 000 km^2. Gorbunov (1978) suggested sporadic permafrost in the Pamir Alay starts at 3400 - 3800 m A.S.L., with continuous permafrost above 4000 m A.S.L.

Over the last sixty years, permafrost has been degrading and the volume of ground ice is expected to have strongly decreased. This trend is observed worldwide and most likely also persists in mountain regions of Central Asia (Biskaborn et al., 2019). This degradation can lead to widespread terrain instabilities, causing rock falls, mudflows, landslides, and reshaping the environmental landscape in mountainous areas (Allen et al., 2022). The development of dangerous and often catastrophic cryogenic geological processes is facilitated by the increased seismo-dynamic activity in the areas of high-mountain permafrost environments in Tajikistan. These factors need to be considered both when drafting projects for economic development of these areas and when taking measures to protect objects already built in the mountains (Frolov et al., 2022).

Furthermore, permafrost can also have an influence on Glacier Lake Outburst Flood (GLOF) hazards as many mountain lakes in Tajikistan are dammed by permafrost geomorphologies such as ice-cored moraines or rock glaciers (Allen et al., 2022; Zheng et al., 2021). Rock glaciers, a prevalent form of ice-rich permafrost, are especially abundant in the region, with Ma and Oguchi (2023) mapping over 600 rock glaciers in the Rushan range alone. Lakes dammed by rock glaciers (or any form of frozen sediments) can be prone to sudden drainage in case of degradation and subsequent loss of stability. In this context, rock glaciers are not only relevant as a store of potentially significant volumes of water (Jones et al., 2018), but also because of their hazard potential (Mergili et al., 2012).

Conclusion

The cryosphere in Tajikistan responds heterogeneously to climate change. This heterogeneity is unique. The observed changes in snow, glaciers and permafrost in Tajikistan not only affect water availability of a large part of Central Asia, but also provide a source for natural hazards. Despite its regional importance, direct observations in the region are extremely scarce and many monitoring sites have only been recently established. The lack of in situ observations hinders a profound understanding of the different responses and drivers across the Pamir. Large uncertainty in regional meteorological data remains a major obstacle to our understanding of the processes driving changes in the climate-glacier-discharge nexus. Continued monitoring efforts coupled with mass balance and runoff models are needed to understand the influence of climate induced cryosphere changes, and as a response, to develop policy responses to rapidly increasing water demand in Central Asia (Barandun et al., 2021). Tajikistan is experiencing significant changes in its cryosphere. International collaborations and projects, such as CROMO-ADAPT and PAMIR, demonstrate a commitment to enhancing monitoring capabilities and understanding the impact of climate change on the cryosphere. However most monitoring activities are just at its beginning. A major effort is needed to guarantee a long-term monitoring managed and executed by the national specialists in collaboration with regional scientific community.

4.4 Cryospheric Changes in Uzbekistan

by Gulomjon Umirzakov[a], Lidiya Karandaeva[b], Bibinur Gulmurzaeva[b], Tomas Saks[c], Serikzhan Atanov[c], Martina Barandun[c]

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Introduction

Central Asian countries are facing two primary challenges: water scarcity and the potential impacts of global warming. The growing water deficit in Uzbekistan is considered an urgent problem affecting the well-being of the population and the sustainable development of the economy (Lioubimtseva & Henebry, 2009). While snow melt provides more than 50% of the annual runoff, glaciers are the second most important water supplier (Schulz, 1965; Sorg et al., 2012). Glacier meltwater contribution becomes especially vital during the summer period when water demand is at its peak (e.g. Pohl et al., 2017; Pritchard, 2019; Barandun et al., 2020). Glaciers provide meltwater during these hot months, compensating for the depletion of seasonal snow reserves, and are particularly crucial in low water years when river runoff is deficient (Glazirin, 1985).

Since second part of 20th century, there has been a significant change of the cryosphere in Central Asia (Kudyshkin et al., 2014; Barandun et al., 2021; Aizen et al., 2007). The degradation of the cryosphere has strong implications for water availability, especially in the context of the ongoing global climate change. Researchers are alarmed by the continuing degradation of the cryosphere and emphasize the need for sustainable adaptation and mitigation measures addressing present and future water consumption challenges. Studies indicate that even a small change, such as 1 °C air temperature increase or 20% decrease in precipitation, can lead to a significant reduction in glacier area (Glazirin, 2009). In consideration of the high agrometeorological potential of Uzbekistan, this highlights the vulnerability of glacier-dependent regions to even slight changes in temperature and precipitation. This vulnerability has implications for water resource management and necessitates adaptive strategies in the face of global climate change. The transboundary nature of river systems of Central Asia emphasizes the need for international collaboration in addressing water-related challenges. Changes in glacier dynamics in one country can have cascading effects on downstream nations. For Uzbekistan, water resources from the cryosphere are crucial. However, the feeding zones of major rivers like Amu Darya, Zeravshan, and Syr Darya are located outside the country (Schulz, 1965).

Past and Current Changes in Snow

Snow cover serves as the dominant water source for the annual runoff of rivers in the Aral Sea basin (Aizen et al., 1995; Armstrong et al., 2019). However, estimating snow accumulation faces challenges due to the uneven distribution of snow across mountainous regions. The topography significantly influences the formation of snow cover in river basins, with elevation playing a crucial role. Estimated snow accumulation is thus unevenly distributed throughout mountainous territory. Relief impact on snow cover formation in river basins can vary substantially on small scale. The relationship between elevation and precipitation is locally influenced by factors such as mountainside orientation, terrain shielding from moisture air masses, and other variables (Dozier et al. 2016). Within mountainous river basins there is an observable precipitation gradient with elevation. This pronounced heterogeneity complicates monitoring and evaluating of snow resources, thereby introducing a substantial degree of uncertainty into snow resources assessments, especially for under-monitored high altitudes.

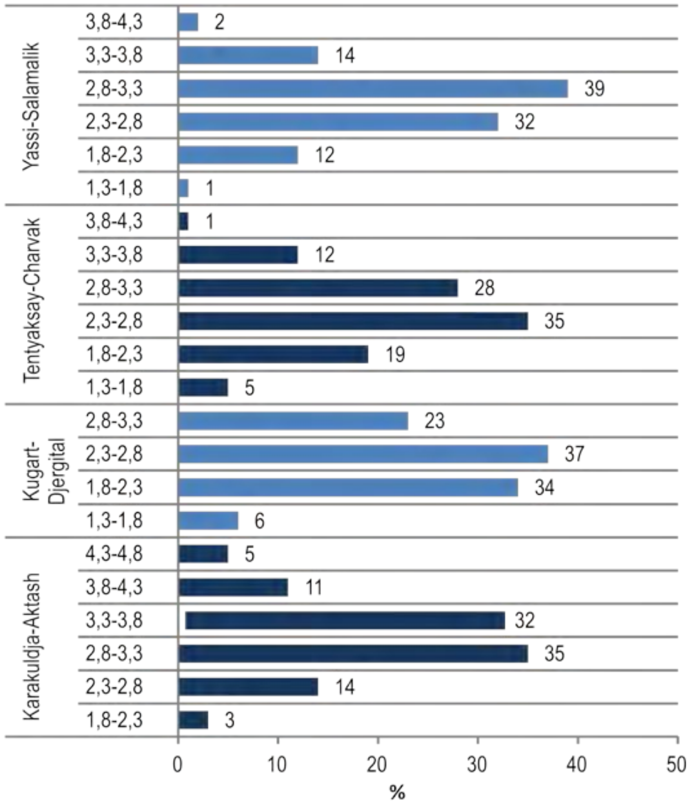

Figure 4.4.1. Distribution of the long-term mean annual accumulation of snow in % per elevation band (y-axes) at the end of March for mountainous rivers basins of Uzbekistan (TNC Uzbekistan, 2016)

The establishment of the snow monitoring in Uzbekistan is closely linked with development of hydrological research in Central Asia. First realizing that snow plays major role in runoff, Shultz (1965) classified Central Asian rivers according to their type of feeding. This prompted creation and expansion of the snow monitoring network in the 1940's: snow thickness and density monitoring in test polygons at the hydrometeorological stations in mountainous terrain; snow thickness monitoring along profiles in selected river basins; and starting from 1960's after helicopters were made widely available to hydrometeorological agencies, a snow stake network was developed. Monitoring of snow thickness was carried out 2 to 3 times a year. In the 1970 and 80-ies a lot of scientific attention was dedicated for quantifying snow resources, which started to be complemented by optical satellite data at the end of the 1980s. After the collapse of the Soviet Union, the snow monitoring network was greatly reduced. Starting from 21st century snow resources quantification more and more relies on remote sensing, but the snow water equivalent estimation remains challenging (Gafurov et al., 2013), mainly due to insufficient field observations.

The estimation of snow accumulations was based on an empirical scheme developed in NIGMI institute of UzHydromet, which covered several mountain catchments assessing snow resources for different elevation bands. This scheme is based on extensive snow observations carried out starting from 1960s up to late 1990s. As a result, snow volume estimation for various river basins and distribution curves of long-term average snow accumulation values per elevation bands were developed (Figure 4.4.1). For estimating snow cover in the upper watersheds of the Amu Darya and Syr Darya, Uzhydromet has developed a GIS-based system that processes satellite images to obtain information on snow cover in each considered river basin systematically (Fig. 4.4.2).

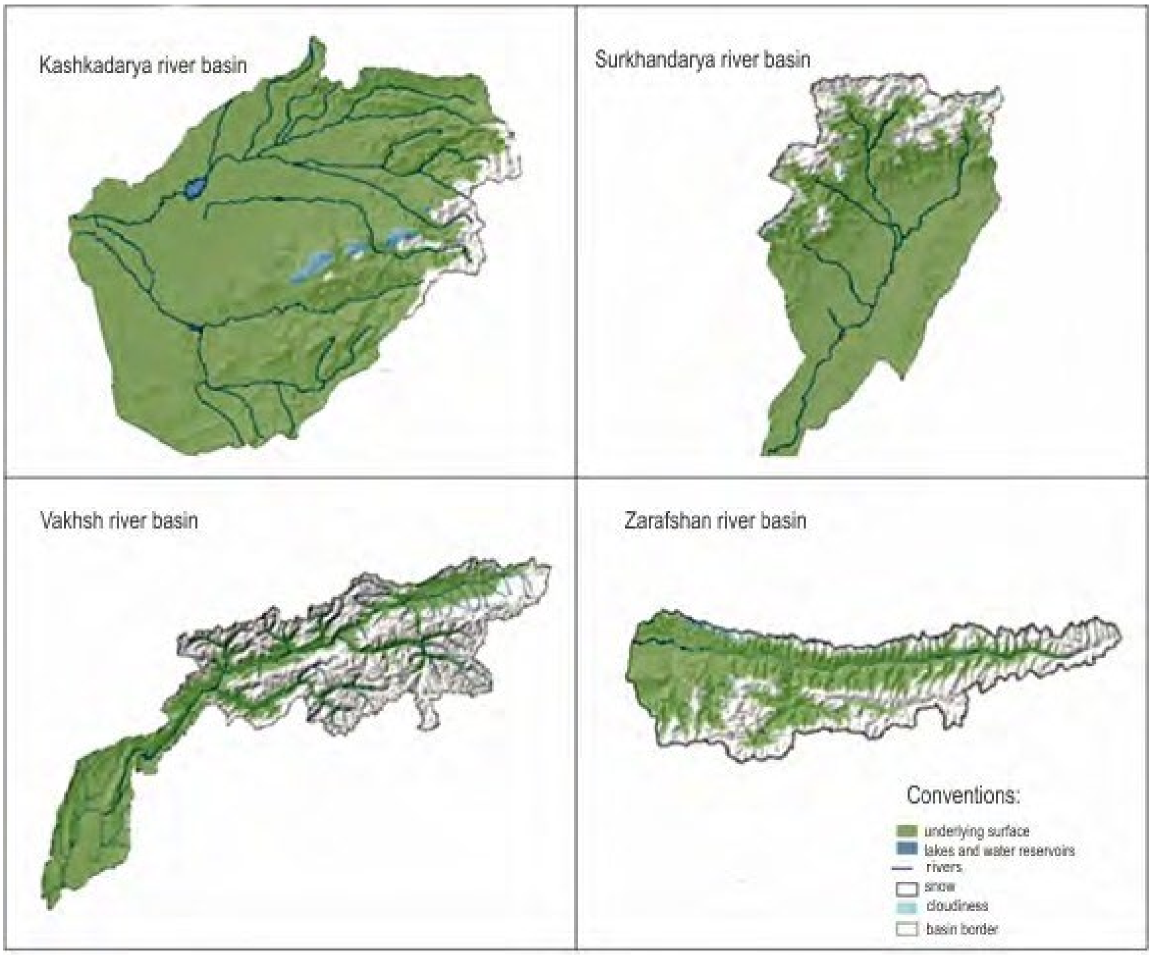

Figure 4.4.2 Maps of Snow Covers in River Basins Based on NOAA Data (as of 28.04.2015) (TNC Uzbekistan, 2016)

Numerous studies, based on remote sensing data show snow cover decline in the past decades. Young (2023) used two different statistical test to analyze MOD10C2 data for the period between 2000 and 2022/2023 to detect different seasonal trends in snow cover extent. Both applied methods produced similar results. These results were also supported by earlier studies of Zhou et al. (2017) using a combined SCE AVHRR and MODIS dataset for the period 1986 to 2008 and Mankin and Diffenbaugh (2015) showing a decrease in snow cover duration and maximum snow depth in the western Tien Shan.

Total annual precipitation amounts, averaged across different regions of Uzbekistan from 1950 to 2013, show a small decreasing trend (TNC Uzbekistan, 2016). Observations indicate a reduction in precipitation in mountain areas across all seasons, except for winter months in some parts of the Western Tien Shan. Modelled future changes in precipitation align with these historical trends according to climate change scenarios, indicating an overall decrease in water availability in Uzbekistan (Fig. 4.4.3) (TNC Uzbekistan, 2016). A significant reduction in snow cover area is expected in the river basins situated at the margin of the Western Tien Shan (such as the Ugam and Akhangaran rivers), as well as in river basins to the north of the Fergana Valley (like the Gavasay river) and the margins of the Gissar-Alay (covering the Kashkadarya and Surkhandarya rivers). The decrease in snow cover area is more pronounced in river watersheds with lower average elevations (TNC Uzbekistan, 2016).

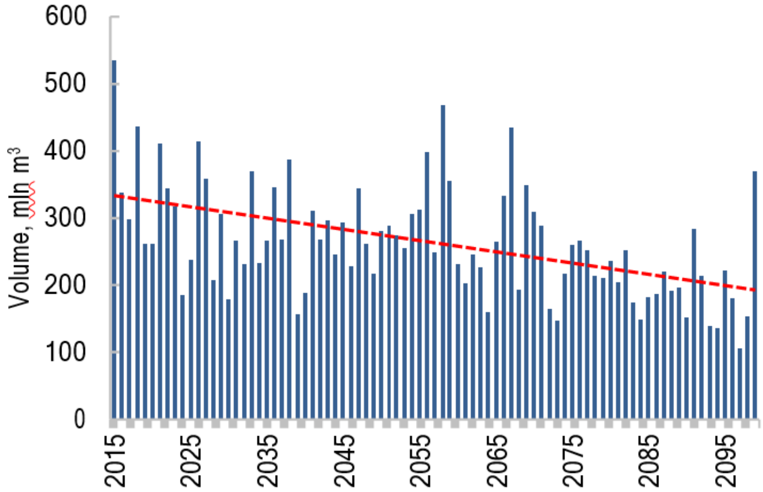

Figure 4.4.3. Estimation of snow accumulation for long-term perspective in Kashkadarya River Basin at the end of March (TNC Uzbekistan, 2016)

Past and Current Changes in Glaciers

Glaciers in Uzbekistan are situated in the Kashkadarya River basin (entirely), in the Pskem River basin (including tributaries of the Pskem River and the Oigaing River basin), and in the Surkhandarya River basin (including the Sangardak and Tupalang River basins, Kudyshkin set al., 2014). Glaciers within these basins are characterized by their relatively small size. As of 2010, the three regions hosted a total of 613 glaciers, covering an aggregate area of 158.19 km^2 (Table 4.4.1). Among these, 411 glaciers are situated within Uzbekistan, with a combined area of 99.69 km^2 (Kudyshkin et al., 2014).

Table 4.4.1. Total area and number of glaciers in river basins in different years of inventory (Kudyshkin et al., 2014)

River basin	Total area of glaciers, km^2			Number of glaciers		
	1957	1978	2010	1957	1978	2010
Pskem	119,80	106,13	102,52	211	260	262
Kashkadarya	18,14	15,51	7,85	68	65	61
Surkhandarya	70,37	59,20	47,82	289	285	290

Glacier research in Uzbekistan commenced in the early 1960s. Three comprehensive inventories of glaciers were conducted by the Uzbekistan State Hydrometeorological Service (Shchetinnikov & Podkopaeva, n.d.) and let for example to a first mapping of 140 glaciers covering an area of 128.8 km^2 in the Pskem River basin (Table 4.4.1; Kanaev, 1966).

Narama et al. (2010) highlighted that most dramatic glacier shrinkage has occurred in the outer ranges of the Tien Shan including the three above mentioned basins. According to Kudyshkin et al. (2014), the glacier area decreased by 17.28 km^2 for the Pskem River basin, by 10.29 km^2 for the Kashkadarya River basin, and by 22.55 km^2 for the Surkhandarya River basin, representing 14.4%, 56.7%, and 32.0% area reduction from 1957 to 2010, respectively, (Table 4.4.1). Whereas Semakova et al., (2016) reported an area decrease from 1960s to 2010s by 23% in the Pskem River basin (including the Maydantal), by 49% in the Kashkadarya and by 40% in the Surhandarya (including the Sangardak and the Tupalang) River basins (Fig. 4.4.4). The rate of glaciation reduction varies significantly among river basins located in different climatic and orographic settings and with different degree of glaciation. However, numbers in literature on glacier area also vary substantially, depending not only on the area change but also on the size of included glaciers, data source and the mapping techniques (e.g. Karandaeva, 2004; Tokmagambetov, 2010; Glazirin & Tadjibaeva, 2011; Finaev, 2013).

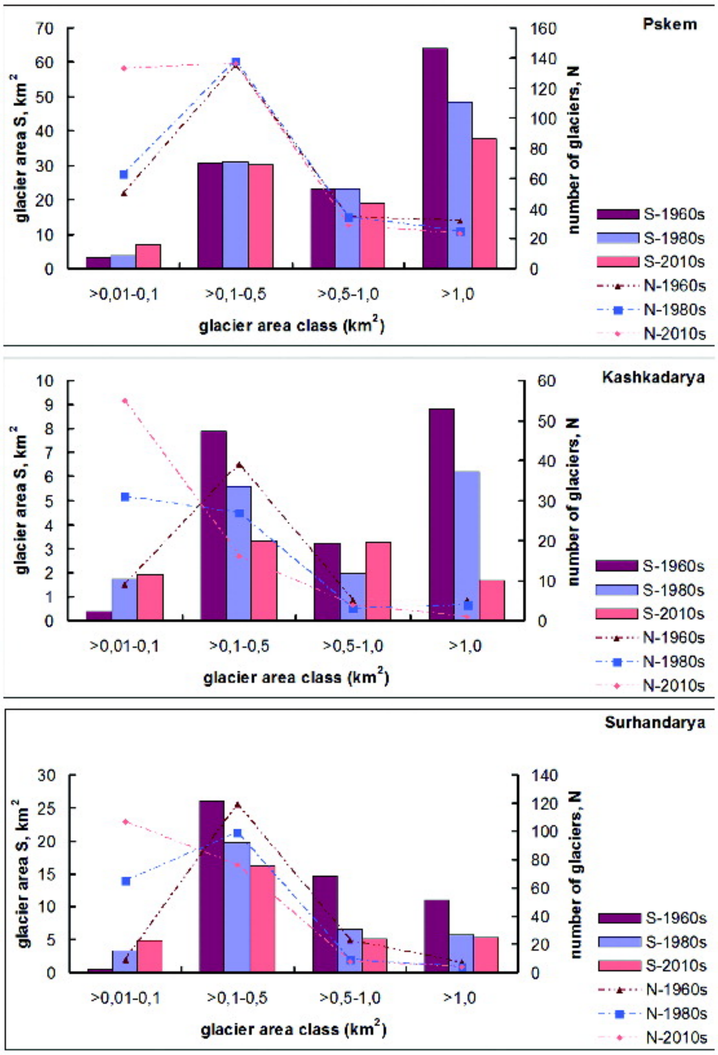

Figure 4.4.4: Number and area of glaciers in size classes for different periods from Semakova et al. (2016).

A large percentage of glaciers in Uzbekistan are small. Large glaciers have disintegrated to small glaciers and explain the increased numbers and area for small glaciers with recent years and the decreasing number and are of large glaciers.

Volume change estimate are rare for the region. According to the last inventory from 2010 covering the period 1957 to 2010, the ice volume has been reduced by 0.844 km^3 (or by 24.3%) in the Pskem river basin; by 0.261 km^3 (or by 67.4%) in the Kashkadarya river basin; and by 0.538 km^3 (or by 40.1%) in the Surkandarya river basin (data source: Hydrometeorological Institute (NIGMI) under the Uzbekistan Hydrometeorological Service (Uzhydromet)). Semakova & Semakov (2022) estimated a mean surface lowering rate of -0.68 ±3.91 m yr^{-1} from 2012 to 2014 and Semakova & Bühler (2017) calculated a geodetic mass balance in the ablation zone of the glaciers in the Pskem valley of −0.82 ±0.36 m w.e. yr^{-1} from 2000 to 2012. However, in both studies it is not clear how the accumulation area was treated. In comparison, results from direct glaciological monitoring at Barkrak glacier indicate somewhat less negative mass balances over the past 6 years with an accelerating mass loss trend for the past 3 years (Fig. 4.4.5). The most significant mass loss occurred in recent years, particularly for Barkrak Middle where mass loss has doubled (Fig. 4.4.6). The glacier area decreased over the years, from 2.39 km² to 1.84 km² for Barkrak Middle and from 0.56 km² to 0.42 km² for Barkrak Middle – East Branch.

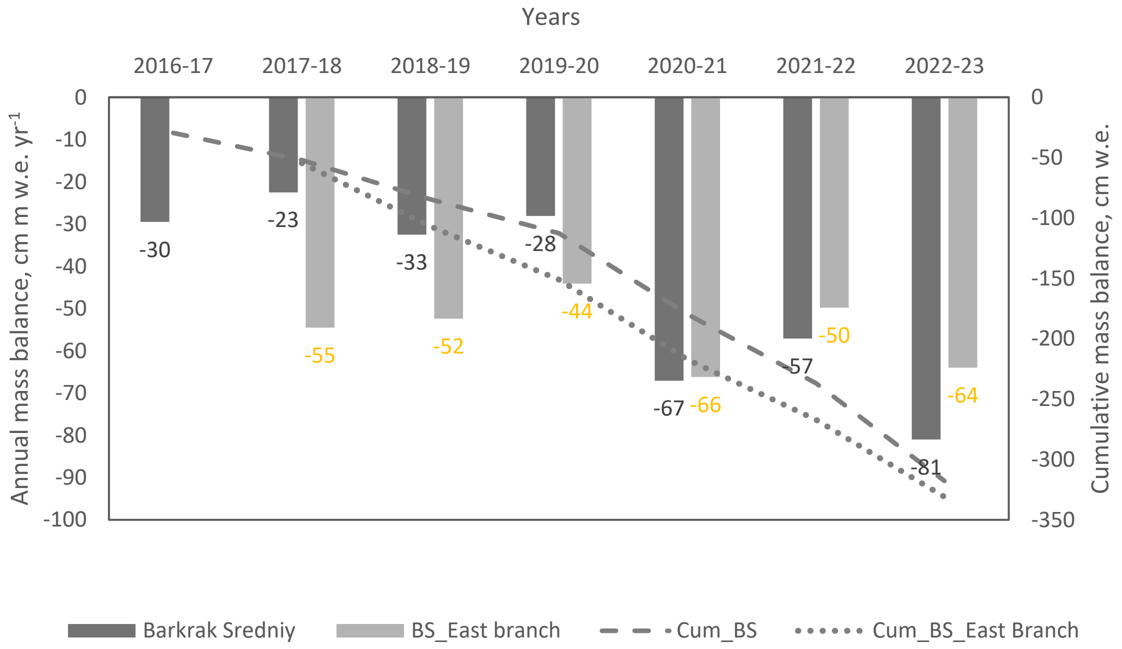

Figure 4.4.5 Annual and cumulative mass balance of Barkrak Middle and East branch of Barkrak Middle glaciers (Credits: CICADA project, University of Fribourg and ALM-202107010)

Currently Barkrak Middle is the only continuously monitored glacier in Uzbekistan. In the 1960s, the Institute of Mathematics of the Academy of Sciences of Uzbekistan and the Uzhydromet initiated the study of the regime of Pskem glaciers and conducted energy balance observations on two glaciers of the Barkrak group (Oigaing River basin) – Barkrak Middle and Barkrak Right – during the summers of 1961 and 1962. Studies on glacier dynamics and area changes intensified in the upcoming years and included for examples velocity measurements, meteorological observations, and mass balance observations (Vinogradov et al., 1966; Shchetinnikov & Podkopaeva, 1968; Shchetinnikov, 1976). In Uzbekistan, the CATCOS and CICADA projects have facilitated the re-establishment of a systematic glacier observations in 2017[15]. On Barkrak Middle Glacier, covering an area of 2.04 km², the mass balance has been regularly measured in situ since 2017 (Hoelzle et al., 2017) and data is submitted to the WGMS on a regular basis. The project included the installation of an automatic weather station and a camera on the glacier to monitor changes in the snowline elevation. The initiative aimed to enhance climate observation capabilities and contribute valuable data to global research efforts on cryosphere monitoring.

[15] CATCOS and CICADA projects - https://www.unifr.ch/geo/cryosphere/en/projects/glacier-monitoring-and-dynamics/cicada.html

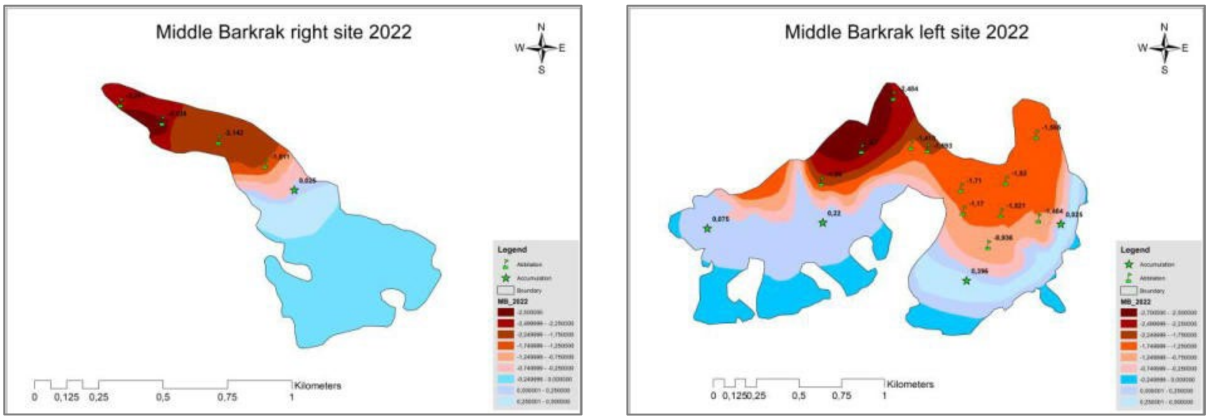

Figure 4.4.6. Surface mass balance distribution maps for Barkrak Middle for the hydrological years 2021-2022 (Credits: CICADA project, University of Fribourg and ALM-202107010[16]).

Past and Current Changes in Permafrost

The regional pattern of permafrost distribution primarily depends on elevation, slope, aspect and surface and subsurface characteristics which have a major influence on the energy balance at the surface and its transfer into the ground. Vegetation, debris and snow cover, ground texture and ice content, winter air temperature inversion, surface and groundwater presence and movements are also among the most important parameters that shape the mountain permafrost distribution. Generally, in northern Tien Shan continuous permafrost exists above 3600 m A.S.L. The discontinuous permafrost zone extends from 3200 to 3600 m A.S.L. while the sporadic permafrost zone is present from 2700 to 3200 m A.S.L. (Marchenko et al., 2007).

As of today, permafrost has not been intensively addressed by scientific community in Uzbekistan, therefore its distribution and occurrence can be judged just by regional permafrost estimates. According to Gruber (2012), permafrost distribution in Uzbekistan is limited to higher reaches of the Ugam, Pskem and Chatkal ranges.

Predictions for Future Climate Change

Glazyrin (2009) calculated possible responses of glaciation to various changes in annual precipitation sums and summer air temperatures. A complete deglaciation will occur by a climate scenario with a temperature increase of 3°C for the Oygaing River basin (station "Ustye"), which is the most glaciated basin in Uzbekistan (Glazyrin, 2009). Other study results based on future emission scenarios indicated an increased glacier shrinkage withing the next 30 - 50 years, leading to a complete disappearance of the glaciers located in the Kashkadarya and Surkhandarya river basins (WRE450, WRE750, A1FI). These modelling exercises also showed that after an initial increase of glacier melt, probably meltwater contribution will also strongly decrease, particularly in the dry summer season.

Glaciers function as natural reservoirs for fresh water. Glacial meltwater contribution to Amu Darya and Syr Darya during the summer month accounts for a substantial portion (35-55%) of the total river runoff (Armstrong et al., 2019). The passage underscores the critical dependence on glacial meltwater, especially during the high-demand summer months. The reduction in glacier sizes, in combination with decrease snow cover duration and snow depth, this poses a direct threat to water availability, particularly in dry years.

[16] ALM-202107010 - Development of Glacier Mass Balance Monitoring System in the Context of Global Climate Change and Technologies Predicting the Future State of Glaciers. Founded by Innovation Development Agency of the Republic of Uzbekistan

This situation will aggravate in the future with ongoing glacier retreat. Most significant changes have been observed at the western margin of the Tien Shan (Barandun et al., 2021; Narama et al., 2010). Glaciers in Uzbekistan are situated at a relatively low elevation and exposed to strong temperature increase effects that cannot be compensated by winter snow fall, causing a fragmentation of larger glaciers and a disappearance of smaller glaciers (Semakova et al., 2016). This trend is believed to accelerate in the upcoming years for the region. Small glaciers account for 80% of the total number of glaciers in Uzbekistan (Fig. 4.4.4). This underscores the vulnerability of the region to the prevailing climatic shifts (TNC Uzbekistan, 2016). Understanding the distribution and dynamics of the cryosphere at a regional level is essential for effective water resource planning.

Conclusion

The cryosphere in various river basins of Uzbekistan, such as Pskem, Chatkal, Kashkadarya, and Surkhandarya, have experienced a substantial degradation over the years. The decrease in glaciation area ranges from 24% to 56.7%, indicating a significant glacier area reduction. The mass balance of glaciers, such as Barkrak Middle Glacier, shows a consistent negative trend over the years. Changes in snow cover, essential for feeding rivers in the Aral Sea basin, are closely linked to variations in precipitation, temperature, and elevation. Uneven distribution of snow accumulation and changes in snow cover area contribute to uncertainties in so far sparse monitoring and forecasting activities. Permafrost remains strongly understudied in the region and not much is known about its presence, extent, and dynamics.

The degradation of the cryosphere in Uzbekistan is attributed to climate change, particularly the increase in average annual air temperatures. Predictive estimates suggest that, depending on different greenhouse gas emission scenarios, the trend of glacier shrinkage is likely to continue, with consequences for water resources. Changes in snow cover and glaciers have direct hydrological impacts, influencing river runoff during different seasons. Uzbekistan has undertaken systematic efforts, including the use of remote sensing technologies, to monitor and assess the state of glaciers and snow. International collaborations and projects, such as CATCOS and CICADA, demonstrate a commitment to enhancing monitoring capabilities and understanding the impact of climate change on the cryosphere.

In conclusion, Uzbekistan is experiencing significant changes in its cryosphere, with glaciers retreating, snow cover diminishing, and permafrost warming. This has implications for water resource management and hydrological systems. Ongoing monitoring, research, and collaboration with international organizations are crucial for better understanding and adapting to the expected changes.

4.5 Future perspectives on the cryosphere monitoring

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Over the rest of the 21st century glaciers in the mountain ranges of Central Asia are expected to continue the current, accelerating trend of mass losses (Hugonnet et al., 2021; Marzeion et al., 2012; Radić et al., 2014). Huss and Hock (2015) estimate the total ice volume lost by 2100 in the region at 54 to 88% of the 2010 total, depending on the climate scenario. Relative mass losses are projected to be highly heterogeneous: the smallest and lower-lying glaciers are predicted to effectively vanish well before 2100, even in the low-emission scenarios; by contrast, the thicker, higher-reaching ones would persist into the 22nd century even within the more pessimistic projections, albeit with volume losses of more than 50%.

Ongoing and future atmospheric warming will also affect the thermal regime of polythermal glaciers, which contain ice at sub-freezing temperatures and are a common feature across mountain ranges of Central Asia (Barandun et al., 2020). While the cold content of such glaciers will reduce the rate of mass loss, their transition towards temperate conditions could lead to an increase of potentially hazardous destabilization and collapse events (Gilbert et al., 2015).

Rapid glacier change will affect the hydrological regime of mountain catchments: as modeled by Huss and Hock (2018), annual runoff is expected to reach a maximum (due to increased melt), followed by a decrease as glaciers retreat. The timing of such "peak water" occurrence is controlled by the present-day amounts of ice (both in absolute terms and relative to the catchment area). While the peak is expected after year 2100 for the largest glacier complexes in the Pamirs, smaller catchments with more modest glacierization may already be past maximum runoff. Within the seasonal cycle, by 2100 runoff from glaciers is projected to strongly decrease in the late melt season (August to October), by more than 25% of the corresponding total basin runoff (Huss and Hock, 2018).

All predictions of future glacier change come with significant uncertainties, linked to the incomplete knowledge of the climatic and non-climatic drivers of glacier mass balance and the complex process chains and feedback effects driving glacier evolution in the different sub-regions (Barandun et al., 2020). Specific challenges include an accurate simulation of the evolving glacier debris cover (Compagno et al., 2022) and a better understanding of the future of unstable, surge type glaciers under a changing climate (Kääb et al., 2023). Better constraining the future climate forcing is also an important priority: currently, gridded datasets of even the past climate show severe discrepancies across Central Asia, and largely lack validation data in terms of precipitation intensities and seasonality (Schöne et al., 2019; Zandler et al., 2019). Particularly important for future impact studies are sub-regional and catchment scale assessments of glacier mass changes and their driving processes, as well as their corresponding uncertainties – by combining in situ observations with remote sensing and numerical models (Barandun et al., 2020).

CHAPTER 5: CRYOSPHERE MONITORING AND DATA

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The UN General Assembly agreed on 17 Sustainable Development Goals (SDGs) and related targets at the 21st Conference of the Parties to the UN Framework Convention on Climate Change (UNFCCC), which provide an overarching framework for the implementation of the Paris Agreement. However, major efforts are needed to achieve the SDGs and the 2°C (or 1.5°C) atmospheric warming target within a timeframe that avoids major disruptions for humanity. Therefore, monitoring and strategies to enforce climate resilience, mitigation, and adaptation must be based on sound baseline climate observation (Bojinski et al., 2014), and in particular the Essential Climate Variables (ECVs) defined by the Global Climate Observing System (GCOS) (GCOS, 2010). As noted by the World Meteorological Organization (WMO), there are currently large gaps in the global climate observing system, particularly in high mountain environments (WMO, 2019). Developing and emerging countries lack such baseline data, which is essential for planning and mitigating future developments. One region where climate change is predicted to have a major impact is Central Asia (SDC, 2012), and recent assessments by Brocard et al. (2021) as part of a MeteoSwiss evaluation of KGHydromet concluded that the current existence of "climate services" is rated at the lowest possible level, showing that these services within the Hydromet agencies in Central Asia need to be improved for all planned future activities. There is a need for long-term improvements in the understanding of cryosphere dynamics, particularly those related to snow, glaciers and permafrost, in the Central Asian mountains and related water availability in downstream Central Asian countries, as water quality and quantity problems become more acute, and the potential negative impacts of accelerated cryosphere degradation become a reality.

In around 2010, initial efforts were made to re-establish the glacier monitoring network in Central Asia, which was largely discontinued after the end of the USSR. Since 2010, these efforts have continued in collaboration between Central Asian and international scientists to (i) provide high-standard and modern scientific observation and (ii) to exchange knowledge and train young scientists and students. Today glacier observations in the region provide a sufficient dense network shared with the scientific community through open-access data centres. In the last 5 years, long-term monitoring efforts have been expanded to include snow and permafrost observations. Still relatively new, first systematic observations are carried out continuously and data reported to the international science community. These efforts are summarized in Table 5.1 and the monitoring network is shown in Figure 5.1. This chapter summarizes the current cryosphere monitoring strategy in Central Asia.

Table 5.1: Cryosphere monitoring network in Central Asia in 2023. In italics (AWS = Automatic Weather Station; SMB = Surface Mass Balance, ERT = electrical resistivity Tomography, RST = Refraction Seismic Tomography, BR = Borehole; GST = Ground Surface Temperature, Water level & discharge).

Site	$AWS_{off\ glacier}$	$AWS_{on\ glacier}$	Cameras	SMB	$SMB_{subseasonal}$	ice velocity in situ obs.	Water level & discharge	ERT	RST	BR	snow monitoring	on-glacier drone	GST
Abramov	since 2011	2018-2021	since 2011	1967-98, since 2011	since 2022	since 2022	since 2019	10	8	-	-	since 2022 (terminus only)	since 2011
Zulmart	since 2019	since 2023	since 2019	since 2018	since 2022	-	since 2022	3	2	-	-	since 2022	-
Golubin	since 2013	-	since 2013	1958-1994, since 2010	since 2023	-	since 2021	7	3	-	-	-	-
Yakarcha	since 2021	-	since 2021	since 2019	since 2023	-	since 2022	2	-	-	-	-	-
Barkrak	since 2016	-	since 2016	since 2016	-	-	since 2023	-	-	-	-	-	-
Batysh Sook	since 2023	since 2023	-	since 2010	since 2023	-	since 2021	7	3	-	-	-	-
#354	-	-	since 2014	since 2010	since 2023	-	since 2021	-	-	-	-	-	-
#457	since 2023	-	planned for 2024	since 2020	-	-	since 2022	2	1	-	-	since 2022	-
GGP	-	-	-	since 2020	-	-	-	-	-	-	-	-	-
Sangvor (Glacier catchment Nissai)	since 2021	-	2021 / 2023	since 2022	-	-	since 2021	-	-	-	since 2021	-	since 2021
Borehole KZ	planned for 2023	-	-	-	-	-	-	-	-	planned for 2023	-	-	-
Borehole TJ	planned for 2024	-	-	-	-	-	-	1	1	planned for 2024	-	-	-
Borehole KG (AK50/1_2022)	since 2022	-	-	-	-	-	-	3	3	since 2022	-	-	-
Turgen Aksuu	Since 1970	-	-	Since 2019	-	-	planned for 2024	-	-	-	Since 2019	-	-
Karabatkak	Since 1948	Since 2014?	-	1957-1998.	Since 2013	-	-	-	-	-	-	-	-
Sary Tor	Since 1930's (Tien Shan station)	-		1984-1989.	since 2014	-	-	-	-	-	-	-	-
Bordo	Since 1930 (Tien Shan station)	Since 2017	-	since 2015	since 2017	-	-	-	-	-	-	-	-
Tuyuksu	Since 1972	Since 2018	-	since 1958	since 1958	-	-	-	-	-	Since 1960	-	-
599	-	-	since 2019	since 2014	-	-	since 2021	1	-	-	-	-	-

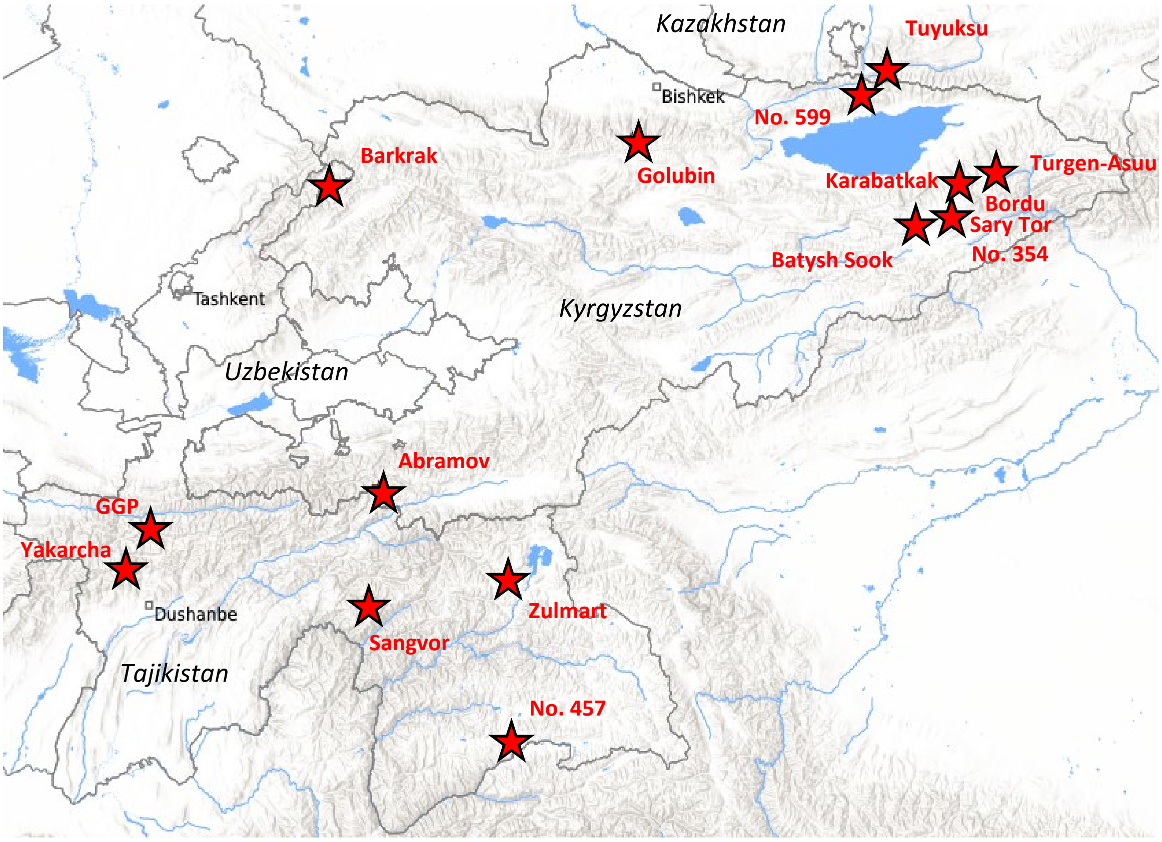

Figure 5.1. Cryosphere monitoring sites in Central Asia

5.1 Snow Monitoring Network in Central Asia

Many ground-based stations measuring snow were abandoned after the breakup of the Soviet Union in the early 1990s, and a new observational network is only slowly evolving in the region, especially in remote high-altitude regions. However, high altitude snow processes are likely to play a large role in annual water balances, yet such measurements are rare in the region. Efforts are currently underway to fill the observational gap to provide better estimates of the winter snowpack which is a critical determinant of seasonal runoff. A new spatio-temporal snow observation strategy has recently started to be implemented using snow depth maps at very local scale precision (Bühler et al. 2015). The snow depth maps are generated from Unmanned Autonomous Vehicle surveys (UAV) obtained at each monitoring site and across a range of elevations. All monitoring sites are in the source area of important rivers or particularly water-stressed catchments which are essential to the local and regional economy. The sampling strategy is to target climatic variability that exists between major basins and heterogeneity within basins due to elevation. These new data products will be used with more traditional observations from rehabilitated snow stake sites (ongoing) automatic stations and satellite data, together with multi-modal forecast models to produce spatio-temporally continuous estimates of the amount of water contained in the snowpack, or snow water equivalent (SWE), the most important snow parameter that water managers need to inform hydrological forecasting.

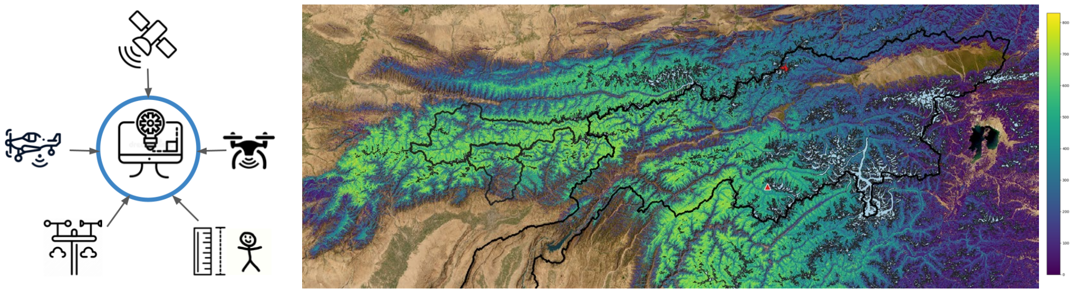

Figure 5.1.2. (a) The snow monitoring strategy currently employed in the CROMO-ADAPT project utilizes new and traditional observation data together with model based estimates of the snowpack to obtain (b) spatio-temporally continuous estimates of water resources contained in the seasonal snowpack

The SDC supported SAPPHIRE Central Asia Project (Smart & Precise Prognostic Hydrology in Central Asia) is an initiative developed to support the Central Asian National Services in utilizing modern automatic or remote monitoring technologies, e.g., processing and operationalizing high-frequency data from modern gauging stations. Within this project the CROMO-ADAPT snow team is implementing an operational basin scale snow tracker which compares real-time modelled snow water equivalent against climatic averages to identify anomalies over large areas (Fig. 5.1.2.) providing real-time analysis of snow water equivalent over the course of the snow season at basin scale in the region (Fig. 5.1.3, Fiddes et al. 2019). The important challenge this project addresses is how to integrate modern data streams and products into soviet era forecasting methods.

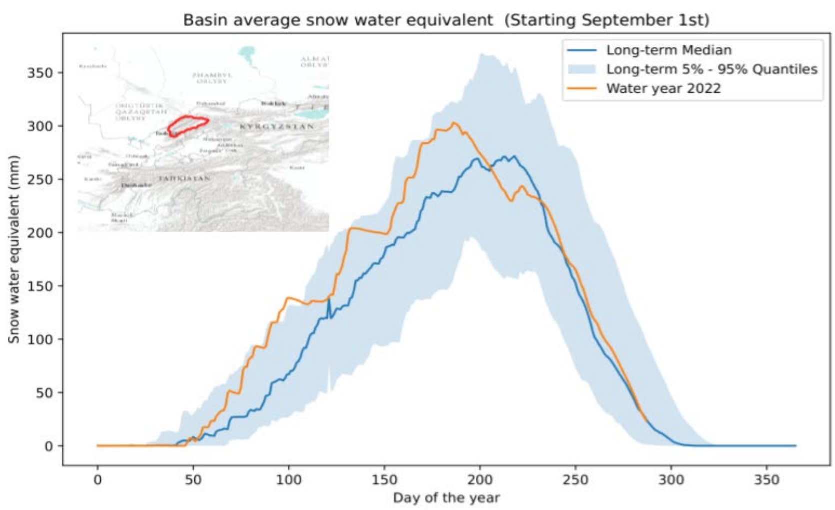

Figure 5.1.3: Snow trackers using a mixture of models and remote sensing to give real-time analysis of snow water equivalent anomalies at basin scale (Fiddes et al. 2019)

Apart from WRM, snow is of course relevant to DRR managers, primarily due to snow avalanches during winter and spring. Here the CROMO-ADAPT strategy is focused on key transport routes, infrastructure, and exposed settlements. We are upgrading AWS at existing snow avalanche stations of Kyrgyz Hydromet to be capable of running the SLF avalanche snow model SNOWPACK at these sites, we can then begin a process of assessing modern model-based hazard forecasting and how these can be utilized within existing soviet-era decision making schemes. A second important aspect of snow avalanche mitigation beyond forecasting is hazard zoning. KgHydromet has identified two at risk settlements where we will run the SLF snow avalanche dynamics model RAMMS to provide scenario-based hazard maps that detail coverage area, impact force and deposition depth due to potential avalanche events. These pilot sites will serve as demonstration of modern hazard zoning methods which can be scaled nationally once national level medium resolution DEM (<5m) is available.

5.2 Glacier Monitoring Network in Central Asia

In the 1950s, an extensive system of glacier monitoring was initiated under the auspices of the USSR Committee for the International Hydrological Decade, and measurements were intensified in the following decades (Dyurgerov et al., 2002; Kuzmichenok, 2009). Most of these in situ monitoring programs were discontinued with the collapse of the USSR. Data from monitoring activities are usually published in Russian. Most of the data are not digitally available, and access to archives is often restricted. Only on two glaciers in the Tien Shan monitoring activities were maintained after the collapse of the USSR in the mid-1990s: Tuyuksu Glacier, Kazakhstan and Urumqi Glacier, China. For these two glaciers, nearly continuous mass balance series exist since the mid-1950s (WGMS, 2020). Efforts to re-establish in situ glacier monitoring on other formerly monitored glaciers have been initiated since about 2010 (Hoelzle et al., 2017, 2019; Barandun et al., 2020). The monitoring strategy follows the international frameworks of the Global Terrestrial Network for Glaciers (GTN-G).

Today, the glacier monitoring network is active in Kazakhstan, Kyrgyzstan, Tajikistan, and Uzbekistan and primarily carried out by Central Asian research teams. Essential infrastructure has been established (Table 5.1) and is continuously maintained. Data is submitted to regional and international databases. Today the re-established network covers again most of the geographical and climatic zones, allowing a significant improvement in our understanding of the effects of climate change on glaciers in Central Asia and contributing to the improvement of estimates of changes in discharge and glacier-related hazards. However, many of these sites are still relatively new and their sustainability on a long-term basis is of highest priority.

Re-established long-term glacier monitoring provides the basis for accurate gap-filling and improved understanding of glacier response to ongoing climate change in the Tien Shan and Pamir (Fig. 5.2.1). With this basis of glacier monitoring in place today, it is possible to focus on improving the understanding of the processes driving the observed glacier response to ongoing climate change at high temporal and spatial resolution. Efforts are now underway to modernize the instrumentation and to complement the basic infrastructure with novel and more experimental set-ups for improved process understanding. These include GPS stations to monitor glacier dynamics, as well as in-situ monitoring of atmospheric variables at the glacier surface on sub-daily scales. This will help to better understand the current behaviour of glaciers, and ultimately their future response, and their meltwater contribution to total river discharge as a major summer freshwater resource in Central Asia and beyond.

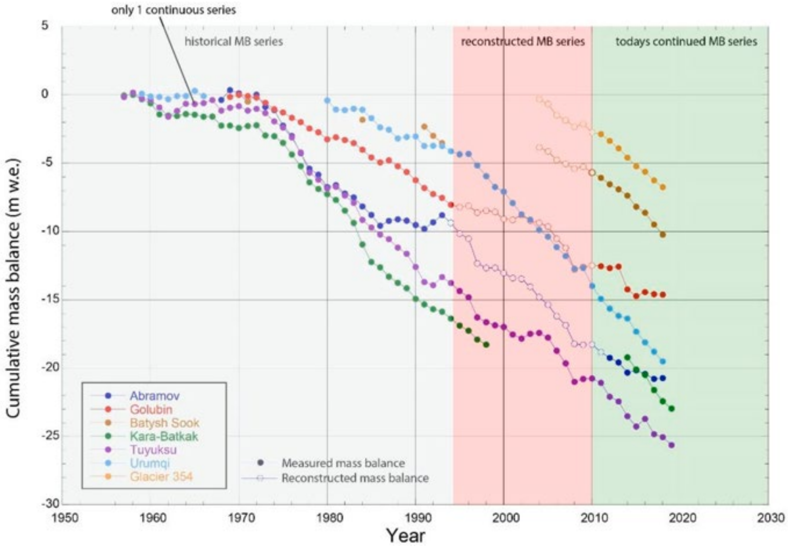

Figure 5.2.1. Re-established glacier mass balance observations in Central Asia (mod. after Barandun et al., 2020)

5.3 Permafrost Monitoring Network in Central Asia

Permafrost is recognized as an Essential Climate Variable (ECV) within the Global Climate Observing System (GCOS) of the World Meteorological Organization (WMO). The Global Terrestrial Network for Permafrost (GTN-P) is the primary international program dedicated to long-term monitoring of permafrost. The core mission of the GTN-P is to provide a sustained, comprehensive long-term monitoring network to provide consistent, representative, and high-quality long-term data series of indicator variables (ECV products) at globally distributed key sites and to assess the state and change of permafrost over time.

Research on high mountain permafrost only began in the late 20th century, but since then considerable progress has been made in understanding mountain permafrost processes (Gorbunov, 1978; Haeberli et al., 2010). As climate change continues, permafrost, defined as soil that remains at or below 0°C for two consecutive years, is warming in many regions of the world. The process of permafrost thawing is associated with a variety of hazards, including the destabilization of rock walls, increased sediment loads in rivers, subsidence of the ground surface, and changes in subsurface hydrology (Daanen et al., 2011; Haeberli et al., 2017; Ravanel et al., 2017). Thus, there is an urgent need to better understand the distribution of permafrost and ground ice volumes, and to assess the evolution of its thermal state with a changing climate. It has been shown that (mountain) permafrost is warming on a global scale (Biskaborn et al., 2019). Many permafrost regions that are relatively easily accessible are already very well monitored, such as the Mackenzie River region in Canada, northern Alaska, or the Swiss Alps (Fig. 5.3.1). The primary goal is to continue existing monitoring sites with long records and, where necessary and possible, to upgrade the instrumentation. It is also important to increase the number of sites in countries with small spatial coverage. These include the Tien Shan and the Pamir. Monitoring systems providing baseline data (such as ground temperatures from e.g. boreholes) for estimating future water availability and permafrost-related hazards of remote regions such as Central Asia (especially the Tien Shan or Pamir of Kyrgyzstan, Uzbekistan, Tajikistan) are still largely lacking (Hoelzle et al., 2019; Barandun et al., 2020).

Permafrost covers an area of about 3.5x10^6 km^2 in Central Asia and the Tibetan Plateau. This corresponds to about 15% of the total areal extent of permafrost in the Northern Hemisphere (Marchenko et al., 2007). Nevertheless, very little is known about the permafrost distribution, current thermal ground conditions, and ground ice contents in Central Asia. This is mostly due to the lack of in-situ baseline data sets (Barandun et al., 2020), as well as few remote or modelling studies that focus on Central Asian permafrost. The first systematic measurements of permafrost temperatures in the Northern Tien Shan began in 1973 (Gorbunov & Nemov, 1978). Initial geothermal observations (1974-1977) in boreholes in the Northern Tien Shan showed that permafrost temperatures in loose deposits and bedrock at 3300 m.A.S.L. varied from -0.3 °C to -0.8 °C (Gorbunov & Nemov, 1978). Marchenko et al. (2007) estimated from the analysis of 24 thermometric boreholes with depths ranging from 3 m to 300 m at varying altitudes, the authors have found an increase in permafrost temperatures from 0.3 °C to 0.6 °C in the Tien Shan Mountains, as well as an average increase of the active-layer of 23% compared to the early 1970s. Data on permafrost distribution and thermal state are even more scarce in the Pamir (Barandun et al., 2020). Here, permafrost occurrence has been described down to an altitude of 3800 m A.S.L. Projections for the extended Tibetan Plateau, which in most studies includes parts of the Pamir, suggest a reduction of near-surface permafrost of 39% by 2050 and up to 81% by 2100 (Guo et al., 2012; Bolch et al., 2019)

Recent efforts have helped to re-introduce permafrost monitoring in the New Cryosphere Network of Central Asia (Fig. 5.3.1). These efforts follow the international frameworks of the Global Terrestrial Network for Permafrost (GTN-P) and the WMO Global Cryosphere Watch (GCW) program. Expanding the network to include sites in regions with little or no data will fill critical data gaps and help improve our understanding and modeling capabilities of permafrost response to climate change. Especially for modeling purposes, the additional acquisition of complementary observations of active geomorphic surface processes (e.g., slope deformation and movement, thermokarst and lake development, coastal erosion, and terrain instability) is of high value.

Continuous monitoring needs focus on existing gaps in the understanding of permafrost dynamics. This will allow for a holistic understanding and harmonized monitoring approach of the cryosphere's contribution to regional water balances and risk profiles. The goal is to gradually establish new permafrost infrastructure for systematic observations of permafrost changes in the Tien Shan and Pamir (Fig. 5.3.2). Installations include boreholes, near-surface soil temperature loggers, and repeated geophysical surveys to establish a regional permafrost network. Permafrost monitoring is vital for communities living in Central Asian mountain ranges, primarily serving two critical purposes: firstly, permafrost degradation strongly impacts slope stability and has consequential impacts on infrastructure in the region as well as an increasing the risk for rockfalls and landslides; and secondly permafrost may act as a reservoir, storing water in the form of ground ice. As it thaws, it releases water, contributing to local hydrology. Therefore, understanding permafrost conditions better is crucial for managing water resources.

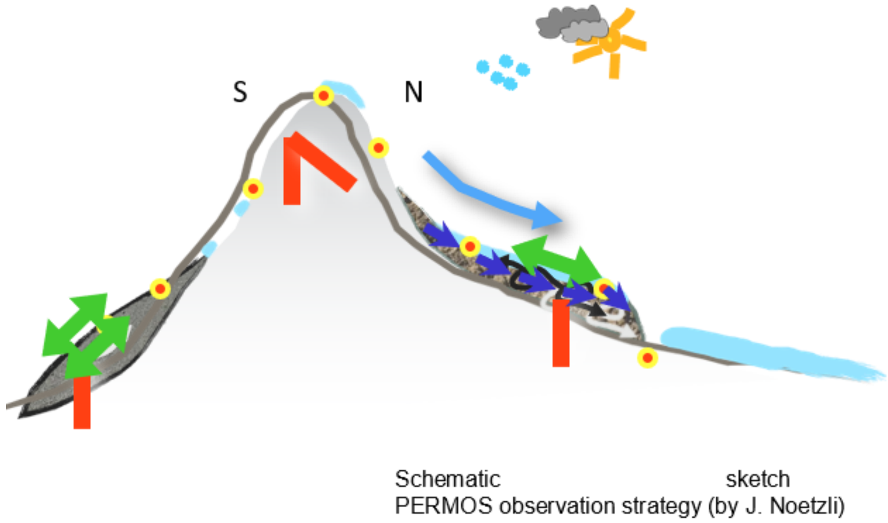

Figure 5.3.1. Permafrost monitoring strategy includes boreholes (red bars) to measure subsurface temperature, geophysical measurement (ERT and RST: green arrows), Ground surface temperature measurements (GST: yellow and red dotes) and permafrost kinematics (blue arrows).

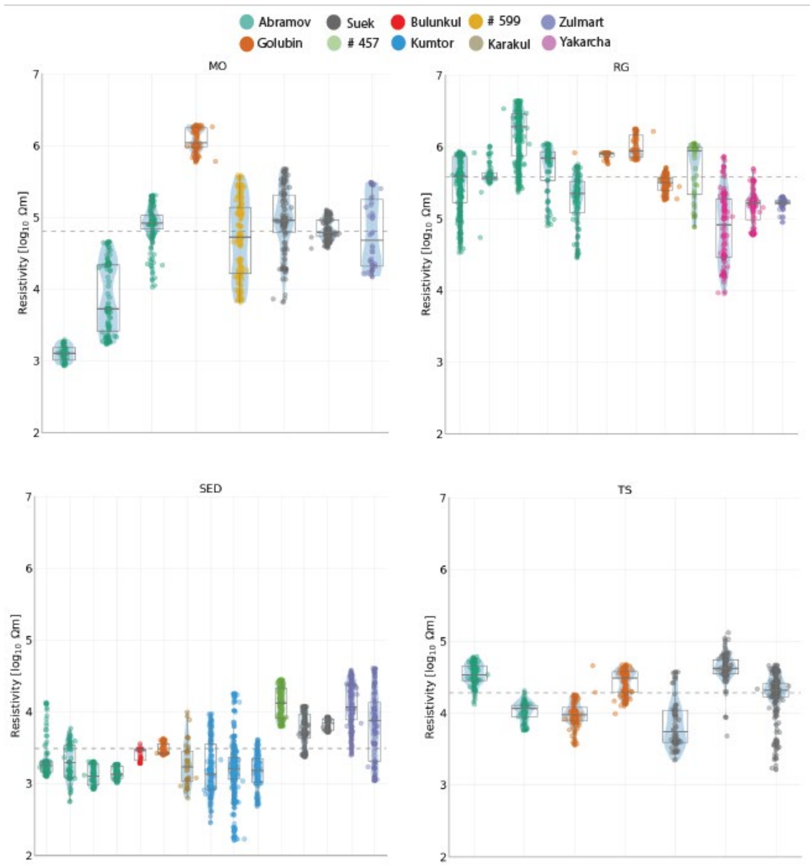

Figure 5.3.2. Resistivity distribution measured in different landforms (RG = rock glaciers, TS = talus slopes, SED = fine-grained sediment or vegetated sediments, MO = moraines) at the different study sites. Repeated resistivity measurements in the framework of a continuous monitoring network will reveal changes in resistivity which can be attributed to the loss of ice and/or gain of water in the ground (in case of decreasing resistivities).

5.4 Hydrological Monitoring Network in Central Asia

Hydrometeorological datasets in the different climate zones of Central Asia are sparse and have huge uncertainties, limiting our process understanding of the hydrology of these heterogeneous mountain landscapes. Differences in glacier response to climate change are apparent but an understanding of underlying processes in glacier dynamics and meltwater generation linked to meteorological forcing is limited. The severe lack of both hydrometeorological and glaciological data prevent robust modeling of relevant glacio-hydrological processes, and therefore, sound future predictions of water availability and glacier evolution.

The installation of a pro-glacial stream monitoring network aims at getting insights into glacier dynamics at high temporal resolution to pinpoint specific interactions between meteorological forcing and glacier response, in particular meltwater generation, in the different climate zones of Central Asia. The choice of locations follows the (re-)established trans-boundary network of glaciological measurement sites in Central Asia. This provides the benefit of having access to long-term glaciological and meteorological observations, existing field logistics, and expert knowledge from scientists in Central Asia. Currently, 8 glacier sites have been instrumented with hydrological monitoring stations consisting of water level gauges that are calibrated to discharge twice a year with multiple fluorescence dye tracer experiments per field season (Fig. 5.4.1).

The unprecedented comprehensiveness of the combined dataset of glacier mass balance, meteorological, and hydrological observations will ultimately allow improving and identifying glacio-hydrological models that are able to accurately represent the hydrological cycle in the different climate zones of Central Asia and its heterogenous glaciers (thermal regime, altitude, expositions, debris cover). These data will provide thus the basis to improve baseline knowledge on process representations, and their scalability and transferability, important for regional-scale water assessment studies, as well as a dataset for improving and validating large-scale remote sensing approaches.

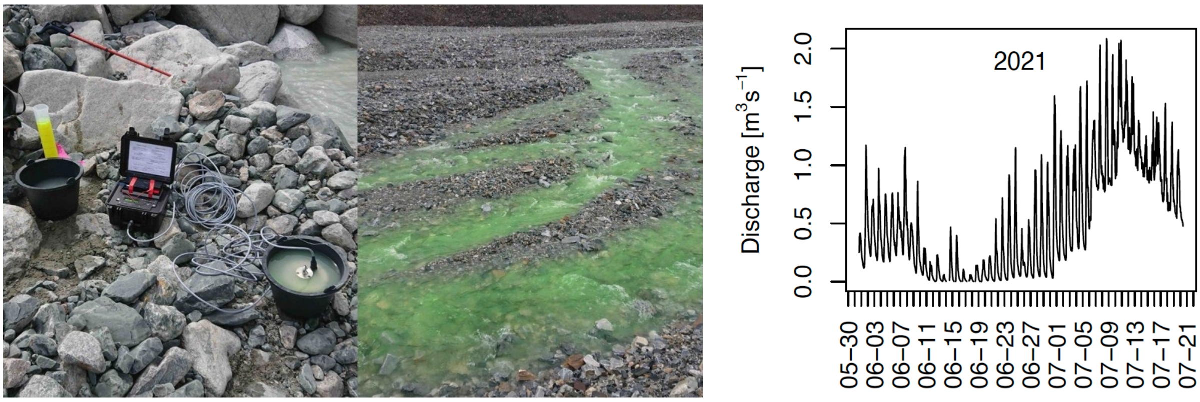

Figure 5.4.1. Discharge measurements using fluorescent dye tracer and a FL-30 fluorometer repeated at different water levels over the course of a day (top). Resulting discharge time series in hourly temporal resolution of calibrated water level (HOBO pressure transducers; not visible in the photograph).

5.5 Data Collection and Sharing

The collected data of the re-established cryosphere monitoring network is aimed to be entirely accessible in national as well as international data centres such as GTN-P, GTN-G (WGMS) or GCW. The current glacier monitoring data is already openly accessible by the international database structure. However, the establishment of an overall national cryospheric monitoring system with several comprehensive cryospheric sites is still not fully addressed and should be further developed (development of web-based access of data). Such systems are today available at other international monitoring sites such as GLAMOS and PERMOS in Switzerland, addressing the use to provide open access to high quality data to the national and international research community and stakeholders.

The collected high quality cryosphere data is used for improving water resource management and disaster risk reduction. For example, at the region of the Upper Naryn, glacier meltwater contribution to the Naryn river runoff was simulated. The obtained results will be further applied for improved parametrization of the Naryn river runoff modelling, the results of which are used by numerous stakeholders, thus contributing to the improvement of the Climate Services in the country.

CHAPTER 6: CONCLUDING REMARKS

The need to adapt to a changing climate, and ultimately to mitigate climate change requires more accurate information on the interaction between atmosphere, ocean and land, in order to improve our understanding of the major climate cycles of carbon, water and energy. A multitude of climate observing networks cover our entire planet. Together they form the Global Climate Observing System (GCOS), which monitors all relevant parameters to improve our understanding of the climate system, enhance climate services and better prepare for future changes.

The Global Terrestrial Network for Glaciers (GTN-G) and the Global Terrestrial Network for Permafrost (GTN-P) are two existing worldwide monitoring networks covering temporal and spatial information on states and changes from local to global scales with different levels of accuracies and uncertainties (WGMS, 2023; Streletskiy, 2021). These two networks and their strategies form the basis for the design of the Cryosphere Monitoring Network across Central Asia.

6.1 Snow Monitoring

Seasonal snow cover is a major component of the annual water budget in Central Asia, with snow water equivalent contributions estimated to be over 50% for major basins and as high as 65 - 72% for smaller basins (Armstrong et al. 2019). This contrasts with the 23% contribution of rainfall and 2-8% of glacier ice to annual runoff (Sorg et al., 2012, Aizen et al., 1995).

Most studies of recent climate impacts on snow cover in Central Asia have focused on optical satellites to quantify snow cover extent (Gafurov et al., 2016, Zhou et al., 2017). These studies, monitoring snow cover remotely, recognized a significant decrease in the number of days with snow on the ground for Central Asia from 1986 to 2008 based on SCE AVHRR and MODIS datasets. Results from a study covering the period 1986-2008 using passive microwave data by Mankin et al. (2015) showed a decrease in snow cover duration and maximum snow depth in the western and eastern parts of the Tien Shan, but an increase in snow depth in the Central Tien Shan, which was attributed to an increase in winter precipitation. They also found a high risk that snowmelt will no longer meet summer demand in Central Asian basins by mid-century. Increased glacial runoff may buffer declining snowpack until mid-century, when peak water is expected in many areas of Central Asia (Huss and Hock 2018, Rounce et al., 2020). In the second half of the century, runoff is then likely to decrease as both snow and glacier components decrease.

The ability of black and organic carbon and other light absorbing impurities to alter the surface energy balance of snowpacks is of growing interest in the context of anthropogenic climate change. With many growing industrial centres close to the Tien Shan and Pamir, light absorbing impurities are increasingly being deposited in seasonal snowpacks (Schmale et al., 2017).

Snow avalanches is another aspect of snow in Central Asia, which greatly affects people's lives. Just recently, a series of avalanches in Gorno-Badakshan Autonomous Oblast (GBAO region) in spring 2023 damaged several houses and killed 10 people[17]. During the Soviet era a network of avalanche monitoring stations were established along major mountain roads in Central Asia, responsible for early warning and post avalanche mitigation. During the past decades, due to insufficient funding and maintenance, many of these stations have

[17] https://www.reuters.com/world/asia-pacific/avalanches-kill-10-people-tajikistan-2023-02-15/

been closed, or their responsibilities reduced, leading to increase of avalanche hazards in the region, particularly in Tajikistan.

Our knowledge of snow cover magnitudes, dynamics and climate norms in the region is still very limited due to remote terrain, few in situ observations and often poor model performance. Field measurements of snow depth and density were routinely made during the Soviet era, but most recent studies have tended to focus on the snow cover extent parameter, which can be robustly observed by satellite sensors over large regions (e.g. Hock et al., 2019). Other key parameters are snow water equivalent (SWE) and the temporal behaviour of accumulation and melt. Estimating snow water equivalent remains one of the major challenges in snow hydrology (Gafurov et al., 2013), largely due to the challenge of quantifying (solid) precipitation, especially at high altitudes (Dozier et al. 2017; Gugerli et al. 2019, 2021, 2022). In general, the precipitation regime at high altitudes in Central Asia remains largely unconstrained (Immerzeel et al., 2015). In situ observations are scarce (and often highly uncertain due to undercatch), particularly at high altitudes, leading to high uncertainties in observation-based datasets.

The future strategy for snow monitoring in Central Asia should concentrate on re-establishing the once operational snow stake network, operated by national hydrometeorological services, and combine it with modern techniques and approaches, such as UAV surveys, remote sensing products, muonic or neutronic cosmic ray sensors, which together could be used to produce improved estimates of snow water equivalent. In parallel, avalanche hazard and early warning should be high on the agenda, including maintenance and re-establishment of the existing avalanche monitoring stations combined with new technologies for monitoring of avalanche hazards and early warning.

6.2 Glacier Monitoring

Glaciers in Central Asia play a crucial role during the dry season from July to September, when the runoff in non-glacial basins decreases due to decreased precipitation and increased temperature, runoff mainly depends on glacier meltwater contribution (Aizen et al., 1995; Amstrong et al., 2019). Glacier meltwater contribution during the growing season can increase up to more than 70% to 90% (Huss & Hock, 2019; Saks et al., 2021). Glacier response in Central Asia is heterogeneous in space and time; thus, changes in meltwater contribution vary from catchment to catchment, affecting water availability for mountain communities. Heterogeneous changes in the magnitude and seasonality of river runoff due to changing glacier melt regimes in combination with extreme events will make water resource management extremely challenging. Detailed quantitative knowledge, essential for effective risk management, is often lacking, particularly for remote communities. In Central Asia this involves (i) sparse direct observations of high alpine water resources, (ii) lack of tools for upscaling local observations to regional scale, and (iii) inadequate climate data input for future projections.

Glacier research in Central Asia has long legacy, with the first observations initiated already in the 19th century (Glazirin et al., 1988). The first mass balance measurements on glaciers were initiated in the 1950s in Kazakhstan and Kyrgyzstan. Decision-makers in the USSR realised that the abundant water resources of Kyrgyzstan and Tajikistan, together with a favourable topography, made these countries rich in water storage and hydropower potential. At the same time, the vast low-lying steppes in the middle and lower reaches of the Syr Darya and Amu Darya could be turned into centres of irrigated agricultural production (Dukhovny & Sokolov, 2003; Savoskul et al., 2003). Thus, the USSR began to develop large-scale irrigated agriculture, particularly cotton and wheat production, during the Stalinist period and under Khrushchev in the mid-1950s (Bernau & Sigfried 2012). These activities were greatly expanded during the International Hydrological Decade, a research programme on water problems that began on 1 January 1965, following a resolution of the United Nations Educational, Scientific and Cultural Organisation (UNESCO) in November 1964. After the collapse of the Soviet Union, scientific funding for glacier research was very limited, which led to a severe reduction in scientific research on the cryosphere, as well as the severe reduction or even cessation of several monitoring programmes. By the end of the 1990s, glacier monitoring was reduced to just one glacier: Tuyuksu. Efforts were made by the international community to resume glacier monitoring (Hoelzle et al., 2017) and later to establish new glacier monitoring sites, mainly in the Pamir (Barandun et al., 2020). Based on combining this valuable long-term monitoring sites with remote sensing and numerical modelling it has been shown that glacier mass balance variability is increasing in most mountainous regions of Central Asia (Barandun et al., 2021).

Currently, glacier mass balance monitoring is carried out in all mountainous Central Asian countries and the data are submitted annually to the WGMS (WGMS, 2023). The currently established glacier monitoring network is relatively well distributed throughout the different subregions of Central Asia, however gaps still prevail e.g. in the Dzungarstky Alatau (Barandun et al., 2021). The current monitoring is cost-effective for the national partners. Efforts are now needed to ensure the sustainability of the established monitoring network at both national and regional levels. In addition, current monitoring sites should be subject of specific scientific interventions, involving national and international scientists, to enhance detailed process understanding such as firn core observations (Kronenberg et al., 2021), englacial ice temperature or continuous ablation monitoring, glacier flow velocity monitoring or detailed albedo observation. This needs an update of current monitoring infrastructure with modern instruments and experimental measurement setups.

Remote sensing provides a powerful tool to study inaccessible glaciers from space, however mass change assessments are yet limited to intervals of 5 to 10 years (Kääb et al., 2015; Brun et al., 2017; Shean et al., 2020). Thus, geodetic surveys do not allow assessing glacier specific annual mass balance variability but provide a good overview of glacier mass changes on decadal to semi-decadal times scales (e.g. Denzinger et al., 2021; Kronenberg et al., 2016; Kapitsa et al., 2022). With improving sensor capability and better temporal and special resolution, remote sensing techniques advance fast and provide more and more suitable tools to observe systematically direct glacier changes as well as proxy parameters for glacier response to climate change. For example, remote sensing permits efficient and extensive snowline mapping. Different methods automatically discriminate snow over ice on high- to medium-resolution optical satellite images (e.g. Landsat; Naegeli et al., 2019; Rastner et al., 2019). Other studies rely on lower resolved optical imagery (e.g. Moderate Resolution Imaging Spectroradiometer (MODIS)) to produce regional maps of snow-cover (Notarnicola et., 2013). However, current methodologies using optical sensors still have important shortcomings, such as cloud-cover and cast shadows. Synthetic Aperture Radar (SAR) images have proofed suitable for transient snowline delineation (Winsvold et al., 2018). The combination of SAR and optical data in a complementary way shows a unique potential for a better monitoring of snow depletion. Callegari et al., 2016 retrieved snow-cover maps from SAR and optical images using self-learning Support Vector Machine (SVM). However, the work on multi-source image classification is still in an early phase and has not yet found established use in glaciology. Today a strategy is needed to directly integrate multi-source satellite image classification into applied glaciology. Furthermore, standardized tools for such remote sensing applications and trainings are need for a ready-to-use application for local scientists and stakeholders.

6.3 Permafrost Monitoring

Permafrost is thermally defined, with lithospheric soil temperatures below 0 °C for at least two consecutive years (van Everdingen, 1998). The potential impact of atmospheric warming on mountain permafrost and the influence on slope stability in alpine terrain was little recognised before the 1990s (Haeberli, 1992). With the expansion of tourism and the construction of infrastructure such as cable car stations and tourist facilities, global warming has influenced the awareness of permafrost distribution and its thermal regime in high mountain areas. There has been a demand for increased knowledge of (1) the distribution of mountain permafrost, (2) the thermal state and thickness of permafrost, and (3) how permafrost would respond to a changing climate. These questions led to European and Central Asian research initiatives (Harris et al., 2009; Marchenko, 2003; Marchenko & Gorbunov 2007). Main objectives were to monitor soil temperatures in a borehole transects, to develop methods for mapping and modelling mountain permafrost, and to assess hazards following potential permafrost degradation.

The Central Asian region is the largest area of mountain permafrost in the world, covering parts of southern Siberia, Mongolia, China, Kazakhstan, and neighbouring countries. It covers $3.5x10^6$ km^2, about 15% of the total areal extent of permafrost in the northern hemisphere. On the one hand, the northern Tien Shan has a long history of permafrost research, starting in the 1960s when the first soil temperature observations were initiated at the Zhosalykezen Pass in the Ili Alatau range, Kazakhstan (Marchenko & Gorbunov 1997; Marchenko 1999, 2001; Gorbunov et al., 2004). Observations there have been continuous since the installation of monitoring (Gorbunov, 1978; Marchenko, 2003; Seversky, 2017). On the other hand, studies of permafrost in the rest of the Tien Shan and Pamir are extremely limited. In the 1980s, permafrost was monitored in the Kumtor Valley, AkShiirak Massif, Kyrgyzstan, in several boreholes and later with some surface temperature measurements. For the rest of the Tien Shan and Pamir in Central Asia, there have only been some sporadic observations of the presence of permafrost (e.g. Gorbunov et al., 2000). Knowledge of the state, depth and distribution of permafrost is currently largely unknown, relying solely on modelling results (e.g. Gruber et al., 2011).

Changes in the permafrost thermal regime can have significant impacts on local hydrology, land surface energy and moisture balances, land-atmosphere carbon exchange, ecosystems and engineering infrastructure. Permafrost temperature observations at three sites during 1974 - 1977 and 1990 - 2009 indicate that the ground in the Kazakh part of the Tien Shan Mountains has warmed over the past 35 years. The increase from 1974 to 2009 varies between 0.38 °C and 0.68 °C at depths of 14 - 25 m. However, there is currently only one observation borehole in Central Asia, located in the northern Tien Shan. In the Pamir, permafrost studies are lacking, apart from some modelling studies and individual measurements.

Currently, the Cryospheric Observation and Modelling for Improved Adaptation in Central Asia (CROMO-ADAPT) project, funded by the Swiss Agency for Development and Cooperation (SDC), aims to (re-)establish permafrost monitoring networks in Kyrgyzstan, Tajikistan and Uzbekistan, and to improve monitoring activities in Kazakhstan. A borehole has already been installed in Kyrgyzstan and monitoring boreholes will soon be installed in Kazakhstan and Tajikistan. In addition, the project conducts annual permafrost field geophysical campaigns to characterise the ice content of the permafrost in Central Asia.

Except for the Northern Tien Shan in Kazakhstan, permafrost research is therefore still in its infancy. While current collaboration activities between Central Asian and Swiss scientists (CROMO-Adapt project) will greatly improve our understanding of the state and distribution of permafrost in the Tien Shan and Pamir, much more effort needs to be invested in capacity building of local researchers and national research institutions, as well as in raising awareness of the risks associated with permafrost degradation in Central Asian countries. One of the most pressing issues at present is the sustainability of permafrost research in Central Asian countries, since, apart from Kazakhstan, there are currently no trained scientists in Central Asian countries.

6.4 Cryosphere Meltwater Contribution to Total River Runoff

Due to the temporal and spatial limitation of cryosphere assessments and detailed runoff contribution changes from observations, region-wide assessments cannot rely solely on geodetic and in situ surveys but also need to be combined with other techniques to investigate cryosphere changes at annual to seasonal scale.

To calculate regional cryosphere response and meltwater release, simple models are suitable (e.g., Lutz et al., 2014; Immerzeel et al., 2015). Yet, these computationally efficient models suffer from insufficient representation of small-scale processes, using derived empirical or statistical relationships with fixed parameters (e.g., Rounce et al., 2020). Region-wide model applications often neglect relevant processes (e.g., sublimation, insulation effect of snow, ground porosity, refreezing of meltwater in firn) which can have a significant impact to snow, firn and ice layers (e.g. Kronenberg et al., 2021). More detailed models are useful to understand and quantify the role of individual processes linking atmosphere, cryosphere, and hydrosphere (e.g., Mölg et al., 2014).

Today developing the tools required for scalability and transferability of process-oriented cryosphere models by building cascading model workflows that assimilate multisource observational data, large-scale datasets, and small-scale process representations needs to move into the centre of the research on the regional cryosphere response to climate change. Alongside with the model development, training in model application, programming skills is essential to guarantee quality-ensured past, present and future simulations of regional cryosphere response to climate change.

6.5 Climate Time Series

While combined modelling and remote sensing studies have reconstructed region-wide cryosphere response to climate change for the past (e.g., Barandun et al., 2021; Gruber, 2012; Mankin & Diffenbaugh, 2015), future prediction remains incomplete due to lack of adequate models and their forcing or calibration data. A dominant source of uncertainty for cryosphere modelling regards meteorological forcing. Future projections of cryosphere changes rely on predictions of climate drivers from downscaled Global Climate Models (GCMs, Hock et al., 2019). The spatial resolution of GCMs (100-300km) can lead to considerable biases in modelled climate data for topographically complex areas where surface and subsurface conditions may vary strongly over short horizontal distances (Gubler et al., 2011). Some Regional Climate Models (RCMs) have been recently developed for Central Asia to derive regional climate fields at finer resolution of several tens of km (Ozturk et al., 2012; Russo et al., 2019). Unlike the understanding of the large-scale circulation system, assessment of regional- and local-scale climate conditions remains very difficult (Zandler et al., 2019). Continuous high-resolution (10-100m) climate fields are required to simulate local slope-scale processes. Uncertainties remain thus large, especially considering precipitation. In this context, reanalyses produced by atmospheric models, with spatial resolutions typically in the range of 10 – 50 km, represent an essential data source to fill the lack of current climate information and correct potential biases in future simulations (e.g., Pereira-Cardenal et al., 2011;

Maussion et al., 2014). Mostly, these require preliminary downscaling to increase representativeness of local scale patterns, using ground station data. The challenge is the lack of in situ meteorological data to assess the quality and biases of representative climate forcing, (Unger-Shayesteh et al., 2013).

It is now of priority to produce adequate climate time series for past, present, and future modelling. Inverse methods and proxy parameters such as snow cover (Molotch, 2010; Margulis et al., 2015; Aalstad et al., 2018) or glacier mass balance (Immerzeel et al., 2015) have the potential to improve debiasing (e.g., precipitation field). Ensemble-based data assimilation approaches have the advantage of directly quantifying uncertainties related to the forcing, samples, and models (Fiddes et al., 2019). These research lines need now to be pushed forward for Central Asia.

6.6 Transboundary Cooperation

The transboundary nature of water resources in Central Asia highlights the need for cohesive and coordinated efforts among the countries of the region. Each country faces unique challenges and relies on diverse water sources, making collaborative cryosphere monitoring and data sharing critical to understanding and addressing dynamic changes in the region's cryosphere.

Given the diverse water demand of Central Asian countries, a collaborative approach to cryosphere monitoring is essential. The establishment of a unified cryosphere monitoring network, building on existing strategies such as the Global Terrestrial Network for Glaciers and the Global Terrestrial Network for Permafrost, can facilitate the exchange of expertise and resources. Jointly managed observing stations across national boundaries would improve the accuracy and reliability of data and provide a comprehensive understanding of cryospheric dynamics across the region.

To ensure the effectiveness of transboundary cooperation, there must be a commitment to open data exchange and standardisation of measurement protocols. A centralised data repository accessible to all participating countries could streamline the exchange of information. Standardised measurement techniques and reporting formats will improve the comparability of data, enabling a more accurate assessment of regional trends and promoting a common understanding of the state of the cryosphere.

Recognising the heterogeneity of water-related challenges in each country, transboundary cooperation should include targeted initiatives to address specific issues. For example, Kazakhstan, characterised by large lakes and rivers, faces uneven water distribution and external dependencies (Karatayev et al., 2017). Kyrgyzstan relies heavily on cryospheric resources for irrigation (Hill et al., 2017; Saks et al., 2022; FAO, 2016), while Uzbekistan uses snow and glacier melt from the Pamir and Tien Shan mountains to almost 90% for irrigation (Zhumaeva, 2021). Turkmenistan faces water scarcity problems that are exacerbated by climate change, with a high dependence on the Amu Darya (Zonn, 2012). Tajikistan, a major contributor to the Amu Darya, is predominantly dependent on its extensive cryosphere (Dukhovny et al., 2014).

Transboundary cooperation is crucial for disaster preparedness, especially in regions prone to avalanches and other cryosphere-related hazards. Establishing and maintaining avalanche monitoring stations and incorporating modern technologies such as UAV surveys and remote sensing will strengthen early warning systems. This shared infrastructure would improve the coordination of disaster response, minimising the impact on communities across borders.

The interconnectedness of Central Asian countries through shared transboundary water resources requires a holistic approach to water security. Joint efforts can contribute to sustainable water management practices that ensure the conservation of ecosystems and biodiversity. This is particularly important for countries such as Tajikistan, which rely heavily on its extensive cryosphere for water resources, and to prevent further water quality degradation in shared river basins.

Effective management of Central Asia's water resources requires a unified approach that considers the specific challenges faced by each country. Transboundary cooperation is important to mitigate the impact of water-related challenges at the national level on agriculture, energy, industry and the overall well-being of the population, and to ensure water security and environmental sustainability in Central Asia.

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