The state and future of the cryosphere in Central Asia

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\section*{ABSTRACT}

Snow, glaciers and permafrost translate fluctuations of atmospheric conditions and highlight current environmental changes. Monitoring of these changes is one of the major objectives of the international climate observation strategy developed by the Global Climate Observing System (GCOS). Under ongoing climate change, the implication of altering meltwater released by snow, ice and permafrost will become increasingly relevant for the fragile mountain and lowland environments of Central Asia. These changes will affect the livelihood, particularly for mountain communities but also for the highly populated regions downstream. A degrading cryosphere may cause drastic ecological changes and endanger water, food and health security leading to pronounced political instabilities and changing socio-hydrological interactions. For successful mitigation, the adaptation capacity has to be enforced by first creating basic observational datasets in connection with climate scenario output. This information is a pre-condition to reduce on mid- to long-term the vulnerability of the local population.

So far, significant data gaps of in situ measurements in Central Asia, mainly from the mid-1990s to around 2010 impeded sound interpretations of long-term trends in the cryosphere. However, the progress made on glacier observation and capacity building in recent years, promises a future perspective for monitoring including snow and permafrost. This paper summarizes the current knowledge on the state of three essential climate variables (ECV) of the Central Asian cryosphere: snow, glaciers and permafrost in a context of future water security. It highlights the challenges for cryosphere assessments in the region and discusses ongoing monitoring efforts, future directions and emerging approaches, which might address current shortcomings of today’s monitoring network.

1. Relevance of the cryosphere for water availability

The changing cryosphere has become an icon for climate warming [1]. Changes of snow, glaciers and permafrost translate the fluctuations of atmospheric conditions and highlight current environmental changes [2]. During the past decades such changes have strongly affected the major Central Asian mountain ranges Tien Shan and Pamir [3]. These form the north-western margin of High Mountain Asia (HMA, Fig. 1) hosting 25,000 + glaciers. Maximum snow cover can exceed 80\% of the mountainous terrain and up to 32\% of the lowlands [4]. Permafrost contains highly variable amounts of ice depending on the substrate (e.g. rock glacier, bedrock, fine material, etc.). A rock glacier can contain ice contents between 10 and 90 vol\% whereas massive bedrock has in general very low ice contents. The different landforms of permafrost are found in the Central Asian highlands but have so far not been quantified.

Ice and snowmelt are principal water resources for the highly populated lowlands of Central Asia e.g. [5–7], and have a crucial role for mountain communities [8–10]. Especially where irrigation is a general practise, continuous socio-hydrological interactions establish [8]. Snow accumulation acts as a water reservoir mainly during winter months, controlling river runoff in spring and early summer. With increasing summer precipitation towards the East, summer snowfall is frequent [11,12]. Snow strongly influences the temperature regime in the ground, and therewith permafrost distribution [13–15]. Furthermore, fresh snow increases the albedo and hence provokes a significant reduction of glacier melt [16–18]. Glaciers and permafrost release most of their melt water during July to September. During dry and hot periods, glacier melt is a vital fresh water source [19,20]. So far, it is unknown how much permafrost melt contributes to the total river runoff.

Changes in the cryosphere have implications on the occurrence of natural hazards [21]. Hazards associated with glacier or permafrost degradation are expected to become more frequent and stronger in magnitude with the ongoing climate warming [22–24]. Associated processes could reach densely populated areas, might be transboundary and cause numerous victims (i.e. [25–27]). Increasing rates of glacier lake expansion from 0.8\% yr\textsuperscript{−1} [28] to >3\% yr\textsuperscript{−1} were observed for both the Tien Shan and Pamir [24,29]. However, no evidence of an increase in Glacier Lake Outburst Floods since 1970-ies could be observed [30].
but is expected for catchments with large high-altitude glaciers in the future [31–33]. The slow degradation of permafrost may lead to large rock falls. This creates the potential of strong cascading events, which include processes such as overtopping and lake dam breeches, provoking large debris flows [34,35].

Long-term monitoring of the cryosphere enables an improved understanding on the controlling processes driving its response to changing climate and on hazard potential [36–39]. In addition, it helps to better quantify the associated changes in meltwater release (e.g. [40]). Despite the significance and our current knowledge of the cryosphere at a global level, the heterogeneous response of snow, ice and permafrost in Central Asia remains poorly understood. Half a decade ago, the imminent need of improving the knowledge about spatio-temporal changes in the water cycle of Central Asian headwaters was highlighted [41–43]. In this study, we provide a review of recent research concerning the state, change and impact of the Central Asian cryosphere for the past decade.

2. The Central Asian cryosphere under a changing climate

The climate of Central Asia is formed at the boundary between temperate and subtropical climate zones and is characterised by an extreme continentality and strong topographical effects. Cold inflows of northerly and north-westerly direction and moist air masses from the Western Atlantic region are influencing the western and north-western flat plains of Central Asia. In the south and east, the mountain ranges of the Himalayan, Pamir, Hindukush and Tien Shan almost completely isolate Central Asia from moist air masses from the Indian Ocean [45]. Due to such barrier effects, arid and cold conditions dominate in the eastern part of both the Tien Shan [11] and Pamir [20,46,47] with precipitation maxima towards the summer [48]. A pronounced west to east gradient in seasonal precipitation distribution for the Tien Shan [11] and the Pamir [47] produces regionally variable snow cover, accumulation and ablation regimes, glacier mass balance gradients, and permafrost distribution.

For the Tien Shan, a consistent air temperature increase of about 0.1 to 0.2 °C per decade with more pronounced warming in the winter months was recorded during 1960–2007 [49–51]. This was accompanied by an increase of total annual precipitation, while the share of solid precipitation decreased due to warming [42,43,52]. These trends are still ongoing based on data from meteorological stations near Golubin glacier and near glacier No. 354, where significant May-September warming was observed until 2018. There are no significant trends in annual to seasonal precipitation changes. The changes are non-uniform across the region with a strong inter-annual variability [12,51,53].

For the Pamir, Pohl et al. [20] detected a temperature increase of 0.07 to 0.11 °C yr⁻¹ and likewise no precipitation trend during the last decades. Knoche et al. [54] highlighted the heterogeneity in solid precipitation evolution and found declining summer temperatures along with increasing annual precipitation amounts for the Northern Pamir. Unger-Shayesteh et al. [42] emphasized a shift in the timing of the onset of the melt season towards the earlier spring due to warmer spring temperatures. Aizen et al. [55] reported a reduction of the maximum snow thickness and snow-cover duration by 0.1 m and 9 days over the Tien Shan from 1940 to 1991. However, certain regions in the Eastern Tien Shan and Pamir tended to have increased average snow cover duration due to altered snow fall patterns and precipitation amounts that counterbalance the effect of air temperature increase [41,56]. This has been confirmed through recent monitoring of the meteorological variables and glacier mass balances at Abramov glacier [38].

3. Snow

Seasonal snow cover forms a major part of the annual water budget in Central Asia with estimates of snow water equivalent contribution of over 50% for the main basins [38]. Armstrong et al. [57] found seasonal snow contributions as high as 65–72% of mean annual runoff in the Amu Darya and Sry Darya basins using remote sensing and degree day melt modelling. This contrasts to 23% contribution of rainfall and 2–8% from glacier ice to the annual runoff [41,58]. Typically, annual glacier melt contribution is about 6% for Syr Daria and 20% for Amu Darya [35]. It is however much larger during the melting season and can reach up to 1.5 to 3 times the mean annual input [41]. In an earlier study, Aizen et al. [58] also found snowmelt to be a dominant contributor to annual runoff throughout the Tien Shan based on long-term hydrological records of the former USSR, albeit lower at around 30%.

Most studies on recent climate impacts on snow cover in Central Asia have focused on optical satellites to quantify snow cover extent (SCE). For example, Zhou et al. [59] used a combined AVHRR and MODIS...
dataset of SCE to assess changes in snow cover days and found significant decreases in number of snow on ground days for Central Asia from 1986 to 2008. However, results from a study covering the period 1986–2008 using passive microwave data Mankin et al. [60] showed reduced snow cover duration and maximum snow depths in Western and Eastern parts of the Tien Shan, whereas increased snow depth in Central Tien Shan, which was attributed to an increase in winter precipitation. Mankin et al. [60] investigated the sensitivity of global river basins to changes in snow supply under climate change projections. They found a high risk that snowmelt will no longer meet summer demand by mid-century in Central Asian basins. Increasing glacial runoff will possibly buffer decreasing snowpacks until mid-century when peak water is expected in many areas of Central Asia [40,61]. The second half of the century will then likely see decreasing runoff as both snow and glacial components will diminish.

The ability of black carbon (BC) and other aerosols to change the surface energy balance of snowpacks is of growing interest in the light of anthropogenic climate change. With many growing industrial centres close to the Tien Shan and Pamir, BC is increasingly being deposited in seasonal snowpacks [62]. Deposited BC reduces the surface albedo and therefore increase radiative forcing and can increase melt rates significantly [62,63]. The impacts of climate change on snow cover is driven by the interplay of accumulation (precipitation and its rain/snow partitioning) and ablation (air temperature, radiation). High elevation regions that are less sensitive to temperature increases and shifts in rain/snow partitioning will possibly see increased snowpacks (e.g.[64]), as for example has been attributed to the so called (and arguably misnamed cf.[65]) Karakoram anomaly, particularly over northern regions of Central Asia and north-eastern Tibetan Plateau, where precipitation increases are projected under CMIP5 simulations (e.g.[66,67]). However, projected temperature increases will likely change the seasonality of snowmelt and reduce lower elevation snow cover[67].

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 performance of models. During the Soviet Era field measurements of snow depth and density were routinely made

Fig. 2. Historical mean end-March snow depths from monthly Soviet era snow surveys 1960–1990 in main Tajik river basins. A linear fit line is added for visual interpretation only. Snow accumulations can be non-linear with significant snowpacks existing over 2000 m. Less coherent trends are likely due to microclimatic or topographical differences such as exposure to solar radiation or wind (Datasource NSIDC https://nsidc.org/data/g01092).
4. Glaciers

The Tien Shan hosts almost 15,000 glaciers, covering a surface area of around 12,300 km² [74]. The Pamir contains over 13,000 glaciers that cover an area of approximately 12,000 km² [75]. For the Pamir, median glacier elevation follows a gradient from West (~3800 m a.s.l.) to East (~5000 m a.s.l.). For the Tien Shan, median glacier elevations range from 3700 to 4200 m a.s.l. and are highest in the central part [74]. Most glaciers in both mountain ranges in Central Asia are so called polythermal glaciers. Polythermal glaciers contain cold ice but include also large volumes that are temperate (at the melting point). Most commonly, in dry and cold climates, small and non-dynamic glaciers have cold ice in the ablation area or at least in a surface layer with tens of meters of thickness at lower altitudes. In contrast, cold firn and ice in accumulation areas are only found at higher elevations (around > 5000 m a.s.l. [185,186]). These areas are going to play an important role in the near future, because the additional energy input from atmospheric warming is not transformed directly into increased and accelerated melting but rather into a rise in the firn and ice temperatures by the release of latent heat through refreezing. In general, the observations of firn and ice temperatures are very reliable climate indicators and the impacts of a change from cold to temperate firn/ice in the accumulation zones is directly reflected in an increase of mass loss for larger high-altitude glaciers [46]. Past and recent measurements on selected sites in Central Asia highlight the occurrence of both cold ice in the ablation and accumulation zones. Recent ice temperature measurements at the tongue of Batysh Sook glacier (a very small glacier < 2 km²) showed temperatures below zero degrees (approx. ranging from -5 °C to -7 °C at 10 to 16 m depth). From a 90 m deep borehole at the accumulation area of Gregoriev glacier, Thompson et al. [76] measured very low accumulation rates of around 0.3 m w.e. a⁻¹ during the period of 1961–1990 and negative temperatures throughout the whole borehole profile. The authors reported a minimum temperature of close to −4 °C at the bottom of the borehole. At the same site, Kronenberg et al. [77] confirmed similar accumulation rates for the period 1986–2017. However, the englacial temperature measurements in a depth of 15 m, corresponding to the zero annual amplitude (ZAA), had considerably increased from −8 °C [76] to −1.5 °C [77] from 1990 to 2018. However, Kronenberg et al. [78], found that for Abramov glacier at an altitude of around 4400 m a.s.l. in the Pamir-Alay, the accumulation sites were found to be temperate. They showed that the firm stratigraphy has however not changed importantly.

Farinotti et al. [79] calculated a total glacier ice volume of 3.27 ± 0.85 × 10⁶ km³ for Central Asia. The study showed that HMA, the area with one of the largest ice volumes outside the Polar Regions, hosts about 27% less glacier ice than previously suggested. Only a few measurements of individual glacier thicknesses are available for Central Asia, (e.g. [80–83]). However, data on glacier thickness distribution, internal ice and firm structure and their change remain sparse. In Central Asia, data on glacier covered area are still incomplete and heterogeneous [75]. More accurate glacier inventories appeared in the last years (e.g.[75,84]). Comparison with previous datasets is however not straightforward. Several studies using consistent data reported on heterogeneous area change (e.g. [85–89]). In four catchments in the Pamir-Alay, area reduction rates decreased from 0.46% yr⁻¹ in 1957–1980 to 0.27% yr⁻¹ in 1980–2001 [90]. For the Tien Shan, Narama et al. [91] reported an increase of area loss rates from 0.4% yr⁻¹ to 0.57% yr⁻¹ for At-Bashy (Central Tien Shan) and from 0.63% yr⁻¹ to 0.71% yr⁻¹ for Pskem (Western Tien Shan) but a decrease from 0.33% yr⁻¹ to 0% yr⁻¹ for the Fergana range from 1970 to 2000 to 2000–2007. For the Ak-Shyraqu massif (Central Tien Shan), area loss rates increased from 0.12% yr⁻¹ for 1943–1977 to 0.33% yr⁻¹ for 1977–2003 [92] and to 0.59 ± 0.34% yr⁻¹ for 2003–2013 [93]. These rates further accelerated up to 0.93 ± 0.61% yr⁻¹ from 2013 to 2018 with a significant negative correlation with glacier size.

During USSR most glacier mass balance monitoring sites were established in mid-1950’s [94,95]. The majority of the observation programmes stopped during the early 1990 s. Today, only one continuous series exist: Tyuysk Glacier, Kazakhstan. For Tyuysku, a mass balance of −0.4 m w.e. yr⁻¹ was reported from 1957 to 2018 [39]. Urumqi Glacier in the East Tien Shan has a relatively complete record since 1980 s with a reconstructed period back to the late 1950 s. A similar mass loss of −0.4 m w.e. yr⁻¹ was reported from 1957 to 2017 [39]. Efforts to re-establish in situ glacier observations have started since 2010 [38]. Such datasets, however, are limited to a few selected, well accessible glaciers but are of great importance to validate modelling studies and regional assessments. Current results, directions and monitoring strategies are further discussed in Section 7.
for Golubin, located in the Northern/Western Tien Shan indicated an increase of mass loss from −0.1 m w.e. yr\(^{-1}\) for 1927–1972 to −0.3 m w.e. yr\(^{-1}\) for 1972–2016 [113].

The aforementioned differences in literature might relate to (i) important methodological differences, (ii) different study periods and (iii) inconsistent region division. Inherent differences of the methodology individual studies relate to the uncertainty of each technique and were believed not to exceed the error bars provided by the individual studies. Inconsistent time periods make straightforward comparison difficult. Typically, studies including the early years of the 21st century revealed often less negative values [98–100] than studies focusing on periods after 2004 [101–103]. Using the annual time series, Barandun et al. [44] identified clearly less negative mass balances at the beginning of the study period (prior 2005). This might explain part of the tendency to provide more negative results when focusing on the period 2003 to 2009 (i.e. ICESat based). Inconsistent perimeter of the study regions can explain an additional fraction of the encountered differences in the results due to heterogeneous glacier responses within the individual sub-regions. Validation datasets from complete cryosphere-monitoring remain strongly under-represented in Central Asia. It is now a priority to develop and install monitoring schemes to characterise region-wide, past and present cryosphere changes coupled to high alpine meteorological observations at high temporal and spatial resolution for Central Asia.

Despite the differences in the published decadal mass losses, most of the studies highlight a complex and heterogeneous response through Central Asia (e.g. [44,99–101,103,114]). Brun et al. [115] showed that morphological variables explain only a limited fraction of the mass balance variability (8% for the Pamir, 20% for the Pamir-Alay and 36% for the Tien Shan). Many glaciers of the study area are heavily debris-covered in their ablation areas and debris thickness varies considerably [116]. The interaction with mass balance remains however poorly understood [115]. Furthermore, both the Tien Shan and Pamir are known to host numerous surge-type glaciers [117–119] biasing the glacier response to climate. Despite, Dehecq et al. [120] showed that the flow velocities of glaciers in Central Asia correlate well with the decadal glacier mass change for the period 2000–2016.

Pronounced variations of the meteorological settings throughout the region might principally be responsible for high local variability and distinct spatial patterns of glacier responses [20,47]. The variable climate conditions in Central Asia [121,122] are reflected in the heterogeneous accumulation and ablation regimes, mass balance gradients [11,47] and mass balance sensitivities [123]. Sakai and Fujita [124] showed that climatic settings represented by the three factors: summer temperature, temperature range, and summer precipitation ratio explain up to 60% of the spatially contrasting glacier response in High Mountain Asia. Despite the strong local differences in glacier response detailed assessments with a focus on Central Asia remain so far limited. The scarcity of reliable and appropriate glaciological datasets, as well as the heterogeneity of both their spatial and temporal extent for the Tien Shan and Pamir, hamper sound synthesis to a regional picture on annual to seasonal time scales [3,42,43]. Remote sensing has become very popular to shed light into unobserved, passed glacier changes. It is a powerful tool to study inaccessible glaciers from space, however mass change assessments are yet limited to intervals of 5 to 10 years. Geodetic surveys thus do not allow assessing glacier specific annual mass balance variability and detailed runoff contribution changes for the past decades. Furthermore, geodetic height-change measurements over accumulation areas relates to strong uncertainties due to the snow density assumptions needed to calculate mass change.

Thus, region-wide assessments cannot rely solely on geodetic surveys but also need to be combined with other techniques to investigate glacier mass changes at annual to seasonal scale.

Currently the potential to identify climatic and non-climatic drivers and the complex process chains and feedbacks interacting with the glacier mass change of the different subregions is limited. Observational datasets on climatic variables remain significantly unconstrained in Central Asia due to the scarcity of meteorological stations and their uneven distribution [72,125,126]. Gridree climate datasets based either on observations, reanalysis, or remote sensing show severe differences, and, due to the lack of validation data remain largely unconstrained in terms of precipitation intensities and seasonality [73,125–128].

Particularly important for future impact studies in Central Asia are subregional and local catchment-based estimates of water availability including sound assessments of glacier mass changes and their corresponding uncertainties by combining in situ observations with remote sensing and numerical models. This demands a solid base of observational, long-term data that is currently incomplete for Central Asia.

### 5. Permafrost

The Central Asian region encompasses the largest area of mountain permafrost in the world. It covers 3.5x10^6 km^2, amounting to 15% of the total areal extent of permafrost in the Northern Hemisphere. The regional pattern of permafrost distribution primarily depends on elevation, slope and aspect, which have a major influence on the energy balance at the ground surface. The mountain permafrost distribution depends on various additional parameters such as vegetation, debris and snow-cover, ground surface texture, winter air temperature inversion, surface- and groundwater presence as well as terrain movement (e.g. [129,130]).

Permafrost can be categorized into three zones: continuous, discontinuous and sporadic (Table 1) [131]. The altitudinal distribution of permafrost is controlled primarily by latitude, with approximately 140 m elevation increase of its lower limit per 1° south [131]. Because of the differences in surface energy balance (mainly higher insolation), the lower limit of permafrost on south-facing slopes is about 400–800 m higher than on north-oriented slopes [131,132].

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**Fig. 3.** Comparison of different mass balance assessments for (A) the Pamir/Pamir-Alay and (B) the Tien Shan. For the Pamir/Pamir-Alay, estimates are given for either the Pamir or both (Pamir and Pamir Alay). Only region-wide estimates and no subregion/catchment-wide studies were included in the comparison.
Permafrost temperature in the Tien Shan varied from –0.38 °C to –0.68 °C at depths of 14–25 m during 1974–1977, and has experienced a continuous warming since the 1950 s until present [133]. In accordance with interpolation of borehole temperature data, the active-layer thickness showed an increase from 3.2 to 3.4 m in the 1970 s to a maximum of 5.2 m in 1992 and 5.0 m in 2001 and 2004. The average active layer thickness for all measured sites increased by 23% in comparison to the early 1970 s [133]. Monitoring of permafrost temperatures in a network of boreholes at the Zhosalykezen pass in the Ili Alatau range since 1974 suggested a warming rate of about 0.01 °C yr⁻¹ at the depth of zero annual amplitude (ZAA = 13–17 m), while mean annual air temperature (MAAT) at the Tuyuksu meteorological station increased by 0.02 °C yr⁻¹ [124].

Warming of mountain slopes and permafrost has several important implications, which may affect communities many kilometers downstream [135,136]. Creep rates of rock glaciers are likely to increase [137,138], and increased thermally induced slope instabilities are expected, 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 (e.g. [31,129,139,140]). Furthermore, permafrost ground ice in the Central Asian mountains could also significantly contribute to the hydrological cycle of the region [40]. Rock glaciers, as a clearly visible permafrost landform, have been estimated to be especially valuable in terms of ground ice volumes and hydrological importance. They are currently the focus of research (e.g. [41,138,141–144]). With a relatively high ratio of rock glacier to surface ice in Central Asia [143,145], their role as a water reservoir may be of great importance. It has to be noted that current estimates for permafrost ground ice volumes only consider rock glaciers while ground ice within other permafrost terrain is neglected. This may lead to an underestimation of the real values [145,146]. Furthermore, permafrost responds more slowly to climate change due to the insulating effect of the overlaying active layer together with ventilation effects, which facilitate cooling of the ground [147,148]. Permafrost based water resources are therefore likely to be available on a longer time scale and may buffer water resource losses from surface ice [143,149]. However, it has to be stressed that permafrost distribution in Central Asia [15,129], and even more so, ground ice volumes contained in permafrost terrain are currently very uncertain. Thus, the estimates available today could change substantially once more data becomes available [144,146]. Moreover, assessing the contribution of permafrost ground ice to the hydrological cycle of a region remains challenging. Permafrost can influence the runoff regime in different ways. It may act as a water barrier during spring/summer snow melt and speed up the runoff process by providing surface and near surface flow paths above frozen and (partially-) impermeable frozen layers. Further, annually variable amounts of seasonally frozen water from the thawing active layer is released in summer. Finally, a largely unknown amount of water can be released by degradation of permafrost ground ice, especially in ice rich permafrost forms such as rock glaciers. Röger et al. [150] suggest that during degradation of permafrost in an alpine catchment, downstream runoff may be increased by up to 19%. However, the importance of rock glaciers to the total runoff is still object of discussion in the literature [141,146,151]. A better understanding of permafrost degradation processes has yet to be established and quantified at different spatial and temporal scales [150]. In CA in particular, baseline data and in-situ observations on permafrost is extremely scarce, and thus, very little progress has been made on quantifying changes of permafrost under climate change[3]. It is, however, crucial to improve our knowledge on permafrost distribution, thermal regime and its temporal evolution, as well as ground ice contents in order to improve model estimates for decision-making and implementation of disaster risk reduction and water resource management measures in Central Asia.

Table 1

<table>
<thead>
<tr>
<th>Part of the Tien Shan mountains</th>
<th>Continuous m a.s.l.</th>
<th>Discontinuous m a.s.l.</th>
<th>Sporadic m a.s.l.</th>
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<tr>
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<td>&gt; 3800</td>
<td>3800–3600</td>
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<tr>
<td>Northern and Eastern (42–43°N)</td>
<td>&gt; 3500</td>
<td>3500–3200</td>
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<tr>
<td>Inner (40°30’–42°N)</td>
<td>&gt; 3600</td>
<td>3600–3300</td>
<td>3300–2800</td>
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<tr>
<td>Permafrost Area (km²)</td>
<td>41,000</td>
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6. Implications of changes in the cryosphere on water security

As highlighted above, the Central Asian cryosphere is undergoing substantial changes, driven by atmospheric warming. This may have profound consequences on water availability for the region in near future, particularly under higher emission scenarios (Fig. 4). The dry summer months in Central Asia correspond to peak vegetation season and hence water demand. Snow and ice melt provide release of water resources during this time [143,145,149,152]. Particularly glacier melt becomes a vital buffer for fresh water during droughts [19,20,55,153]. Unlike seasonal snow cover that fluctuates annually, glaciers delay the passage of water through the hydrological system. Pritchard [153] showed that glaciers in Aral and Chu/Isyk-Kul basins produce melt-water net 7.5 ± 1.7 km³ on an average year which is equivalent to ten months of municipal and industrial demand for Afghanistan, Tajikistan, Turkmenistan, Uzbekistan and Kyrgyzstan, or the absolute-scarcity needs of 45 ± 10 million people—over half of the population—for four months.

A reduction of solid precipitation in future will influence mainly spring and early summer runoff. Changes in the seasonality of the snowpack, e.g. earlier melt-out, can have severe impacts on runoff regimes, particularly in unregulated watersheds [154]. Atmospheric warming will lead to higher glacier melt rates and will increase runoff until the so-called peak water is reached [155]. Beyond this point, melt water runoff will decrease as glacier mass diminishes beyond a certain threshold (Fig. 4). Glacier melt water contribution in Central Asia will reach its peak in the next few decades [156,157]. Huss and Hock [40] showed that changes in glacier melt contribution to total river runoff affects the major Central Asian river basins severely with an expected decrease of over 25% in the next century. Besides the reduced freshwater availability, the seasonality of river discharge will change [51,82,158–160]. Expected changes in the magnitude and seasonality can provoke water shortage and unexpectedly high meltwater releases leading to flooding (Fig. 4). However, to understand the full picture of the regional river runoff changes full hydrological modelling that includes processes related to i.e. ground water, precipitation, evaporation and permafrost is crucial. Such modelling, however, needs to rely on spatially and temporally high resolved monitoring of the main water storage bodies and meteorological variables in high alpine environments of Central Asia and hence is therefore often not straightforward.

The uncertainty of water availability in the context of a changing climate creates a major potential for political tensions and builds a complex set of future threats, affecting different domains such as water management, energy production and irrigation [161–164]. Currently, Central Asian countries are among the highest per capita users of water in the world and>90% of the region’s water is used for irrigation [164,165], while agricultural share of gross domestic product (GDP) in Central Asia has almost halved since the disintegration of the Soviet Union [166]. Changes in water supply in combination with rapidly growing and industrialising economies lead to an increased risk of water scarcity in the region. In addition, the complex geopolitical setting of transboundary water systems and energy flows provide increased potential for conflicts driven by reduced resources [167–169]. Complex allocation trade-offs exist in the region [168]. The energy-poor, yet water-rich upstream countries (Kyrgyzstan and Tajikistan), use water for hydropower production in the winter [162]. Conversely, the downstream states (Uzbekistan, Turkmenistan and Kazakhstan) have a high
water demand in the summer irrigation season [154,170,171]. In response to energy needs (and perceived future water shortages), upstream countries have been investing heavily in hydropower schemes (HPP) which generate power and balance water availability.

Reservoir construction will undoubtedly form a large part of regional climate change mitigation strategies [172] in order to address changes in future water availability. However, these projects need to be implemented in a coordinated fashion in order to avoid increased regional tensions [163]. On the other hand, the economic return on water is lower in Central Asia than anywhere else on the planet, therefore, it is evident that primary focus of the Central Asia countries should be on curbing excessive water demand and expanding other sectors of economy [164].

Detailed scientific knowledge on past and present changes, particularly at high temporal and spatial resolution, is vital to implement comprehensive adaptation and mitigation measures for sustainable water management. Currently, most of the water availability, forecasting schemes in Central Asia are based on extremely sparse datasets and do often not account for climate change. In the Soviet era, a threshold equal to runoff for the average dry year (e.g. 80% of the average annual runoff) for the water demand for irrigation was determined [173]. This scheme is still being enforced today. Poor water accounting and decay of infrastructure the system becomes even more inefficient. This is further exacerbated by changing runoff due to degrading cryosphere, especially after the peak water will be passed.

Yet, they are used as a basis for national and international allocation discussions (e.g. Interstate Commission for Water Coordination of Central Asia Interstate Commission for Water Coordination of Central Asia: http://www.icwc-aral.uz/icwc_bulletins.htm). Scarcity of reliable and appropriate meteorological and glaciological datasets hampers a sound synthesis of a regional picture [42]. Remote sensing techniques are suitable to study remote and unmeasured areas on a cost-effective basis, and can partly bridge the aforementioned deficit in data availability (e.g., [102,114,115,174]). However, the discrepancy and disagreement between region-wide surveys (e.g., [98,102,103]) as well as the coarse temporal resolution accentuate the indispensable need for (i) improved and extended ground measurements including deeper boreholes in permafrost areas, (ii) enhanced methods to observe glacier mass changes at regional scales on high spatio-temporal resolution and (iii) for more process-based research.

7. Future directions and initiatives to improve cryosphere monitoring in Central Asia

A new glacier monitoring network has been (re-)established since 2010 (Fig. 5) and helped to rebuild a scientific community focusing on cryosphere sciences as part of the international climate observation strategy developed by GCOS. Long-term mass balance time series for four glaciers in Kyrgyzstan were (re-)analysed and reconstructed as far back as to the last century (Fig. 5, [108,113,175,176]). Recent in situ data suggest a mean mass loss of $-0.3 \text{ m w.e. yr}^{-1}$ for Abramov from 2012 to 2018 and for Golubin from 2011 to 2018 (data averaged for hydrological year; [39]). These values are of the same order of magnitude as reconstructed mass balance time series for the past decades of $-0.26 \text{ m w.e. yr}^{-1}$ for Abramov (1998–2016) and $-0.4 \text{ m w.e. yr}^{-1}$ Golubin (2000–2016) [109]. Despite a sharp increase of mass loss for Golubin since the onset of the 20th century, the above summarised results show neither signs of an accelerating mass loss during the second half of the 20th century, nor clear positive trends in recent years for both Golubin and Abramov.

Additional long-term glacier monitoring programmes in the Tien Shan were (re)initiated for e.g. Barkrak Middle, Batysh Sook, No. 354 (Fig. 1). The modern glaciological measurements revealed mass losses ranging from $-0.3$ to $-0.6 \pm 0.2 \text{ m w.e. yr}^{-1}$ (2011–2018, data for hydrological year, [39] and for Barkrak Middle from 2017). Reconstructed mass balance time series for these glaciers confirmed the negative signal of $-0.3$ to $-0.4 \pm 0.3 \text{ m w.e. yr}^{-1}$ for the last decades [175,176]. For the Eastern and Western Pamir, barely any in-situ observations are available so far [38] and a first long-term monitoring programme for the Western Pamir was only just initiated at Zulmart and Yakarcha Glacier in 2018 and 2019, respectively [3]. Despite the successful re-establishment of glacier monitoring at selected sites (Figs. 1 and 5), complete cryosphere-monitoring, especially for snow and permafrost remains strongly under-represented in Central Asia.

Within the projects CAWa [177] and CATCOS/CICADA [38], meteorological variables and ground temperatures were measured at two high altitude automatic weather stations (AWS) in Kyrgyzstan since 2011/2013 [127] – both are located nearby a glacier (Abramov and Golubin) and part of the worldwide long-term monitoring network GTN-G (Global Terrestrial Network on Glaciers, [38]). At the Abramov station, the ground temperatures closely follow the air temperatures, even
during the winter months (Fig. 6). This indicates absent or thin snow cover at the sensor location, most likely due to strong winds. Precipitation is recorded mainly during spring and summer. Due to missing corrections of undercatch, measured values are substantially lower than annual precipitation sums in historical data recorded at a nearby location [178]. The observed ground temperature trend at 0.1 m depth correlates well with the air temperature trend of around 0.12 °C yr⁻¹ for 2011–2019. This is much higher than that estimated by Marchenko et al. [133], and may either be a result of the relatively short measuring period or an indication for stronger warming in recent years. For a sound comparison of different datasets and periods, long-term measurements are indispensable. The meteorological and ground measurements presented here, show a first step to such long-term time series that need to be connected to legacy measurements of the past.

The re-established monitoring networks in Central Asia provide a base for a first comparison and shows the importance of their continuation. We found an annual thermal offset between air temperature and ground temperature at 0.1 m depth ranges between 2.5 °C and 4.5 °C (not shown). These values are similar to observations made in the Swiss Alps [179]. The ground freezing (GFI) and thawing index (THI) (i.e. the sum of all daily negative, respectively positive, temperatures measured during one hydrological year) showed relatively low annual variabilities (Fig. 7). Compared to most of the sites included in PERMOS, the indices calculated for the Abramov site are considerably lower [179]. The permafrost thickness under current conditions using a simple approach according to Williams and Smith [130] is estimated to be 70–100 m.

Fig. 5. Measured and reconstructed mass balance time series for Central Asia. Data source: measured data series from WGMS [39]; reconstructed data series from [108,113,175,176].

Fig. 6. (a) The daily ground temperatures measured in different depths down to 1 m and the monthly measured precipitation (blue bars) from August 2011 to November 2019 at the AWS at Abramov. (b) Daily and monthly air temperature for the same period and location. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
However, permafrost temperatures most likely are not in equilibrium with the present-day climate and therefore, the actual permafrost thickness might be underestimated. However, to-date the time series are still short and other in-situ observations on permafrost are scarce. The continuation and expansion of these measurements are of high priority for the local communities that are potentially affected by the effects of permafrost degradation.

Uncertainties in quantifying snow based water resources may be addressed by emerging next generation methods that combine physically based models and data assimilation schemes to constrain prognostic variables such as SWE [180–182], which will likely help us to narrow down recent climate change impacts and therefore also debias climate models for improved climate impact projections (Fig. 8). Recent advances from the European Space Agency Sentinel missions have allowed the retrieval of snow depth at reasonably high resolution of 1 km in Mountains (Fig. 9, [183]). Airborne photogrammetric methods (e. g. [184]) can provide cm scale snow depth maps over large remote areas at reasonably cost and therefore likely an appropriate technology for mountains of Central Asia, particularly set within a data assimilation framework. In combination with improved earth-observation and modelling approaches, increased in situ observational networks are critical, particularly in poorly sampled high elevation regions where the bulk of snowpack mass balance is stored. Programmes such as the World Meteorological Organisation’s Global Cryosphere Watch aim to promote this effort particularly in harnessing science led observation and monitoring networks.

**8. Conclusion**

A new glacier monitoring network has been (re-)established since 2010. Strong efforts focused on the generation of new human capacities related to the corresponding research areas. Despite the successful re-establishment of glacier monitoring, complete cryosphere-monitoring remains strongly under-represented in Central Asia. Particularly, there is still a lack of in situ data of the other two cryospheric variables: snow and permafrost. Yet, conclusions on observed changes and their impacts on water availability remain subject of large uncertainties. It is now a priority to develop and install monitoring schemes to characterise

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**Fig. 7.** Ground freezing index (GFI) and ground thawing index (THI) of thermistor HM6 (0.1 m depth) and mean annual ground temperatures (MAGT) of all thermistors at Abramov during the measurement period (hydrological years 2011/12 to 2018/19).

**Fig. 8.** New snow reanalysis combine snow models with remote sensing data through a data assimilation scheme to improve our understanding of snow water content in remote areas. MODIS fractional snow cover (obs) is assimilated (A) for improved SWE estimates at basin level (B) with lower uncertainty (posterior) compared to deterministic simulations (open-loop) that are plagued by biases in the forcing. It is constrained by observed melt patterns which are highly correlated with absolute snowpack mass [181]. Such methods use global datasets and can be applied over large areas as in the example here in the headwaters of the Anzob catchment, Tajikistan, 2013–2014. Full methods description is presented in[181].
region-wide, past and present cryosphere processes and associated
runoff changes at high temporal and spatial resolution for Central Asia,
which can be used for improved water management. However, this
demands a universal strategy by combining in situ observations, nu-
merical modelling and remote sensing to reduce the currently existing
uncertainties. These actions should have highest priority and should be
combined with strong efforts in convincing the corresponding stake-
holders to support these monitoring systems by strengthening the cur-
rent fragile equilibrium between cooperation partners. Finally, this will
allow generating long-term and sustainable cryospheric networks.

CRediT authorship contribution statement

Martina Barandun: Conceptualization, Investigation, Methodology,
Formal analysis, Validation, Writing - original draft, Writing - review
and editing, Data curation. Joel Fiddes: Writing - original draft, Writing
- review and editing, Data curation. Martin Scherler: Writing - review
and editing, Data curation. Tamara Mathys: Writing - review and editing,
Data curation. Tomas Saks: Writing - original draft, Writing - review and editing.
Dmitry Petakov: Writing - review and editing, Data curation. Martin Hoelzle Writing - review and editing, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial
interests or personal relationships that could have appeared to influence
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Fig. 9. Mean March seasonal snow depth (m) 2017–2019 across Central Asia retrieved by ESA’s Sentinel 1 mission and processed by the recent snow depth algorithm
of [183]. This new product enables improved ability to monitor mountain snow cover depth at moderate resolutions (1 km). A 1 km glacier mask (light blue) derived
from the GLIMS database (http://glims.colorado.edu/glacierdata/) is used as it is not known how the product performs in glaciated areas. (For interpretation of the
references to colour in this figure legend, the reader is referred to the web version of this article.)


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