WMO/GCW Technical Report 1

Status of the Monitoring of the Cryosphere in Central Asia (2024)

Afghanistan, Tajikistan, Kyrgyzstan, Uzbekistan and Kazakhstan

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FOREWORD

The Global Cryosphere Watch (GCW) of the World Meteorological Organization (WMO) is coordinated today through its Advisory Group under the remit of the Commission for Observations, Infrastructure and Information Systems (INFCOM). For over a decade, now, GCW has been an effective engagement mechanism between research, academia and the WMO operational community. These engagements have led to a dedicated focus on the cryosphere in the WMO's Integrated Global Observing System (WIGOS), the Information System (WIS), and the Integrated Processing and Prediction System (WIPPS), as well as more broadly, in the core programmes of WMO. Through GCW, Members have gained advanced knowledge and tools to support their decisions and actions on the sustainability of observations, data exchange and access, improved monitoring and supporting prediction of changes in the cryosphere and their impacts.

The cryosphere, a critical component of the Earth system, is highly sensitive to global warning. The changes in the cryosphere can lead to significant hazards to human society, although the full extent of these hazards is still not fully understood.

The snow and ice are a vital reservoir of freshwater for over two billion people on Earth. The melting of the ice sheets of Antarctica and Greenland contributes significantly to sea level rise. Permafrost degradation poses a significant threat to infrastructure in polar and high-altitude regions, resulting in economic losses. Furthermore, the permafrost is estimated to hold twice as much carbon as currently exists in the Earth's atmosphere and its thawing, in the long term, would lead to increases in the carbon emissions. The loss of sea ice in the Arctic and around Antarctica has significant consequences on ocean and atmospheric circulation, the polar ecosystems and on the Indigenous Peoples.

The GCW Technical Report series started with this report, aims to disseminate technical and scientific assessments and guidance to Members. As the responsibilities for monitoring and predicting changes in the environments where the cryosphere is present span multiple organizations at national levels, we need to leverage the insights and data available and enhance our predictive capabilities. These are paramount to developing more effective strategies and for informing decisions addressing impacts, whether on water availability, sea level rise, or emerging hazards.

These reports are part of the contribution of WMO, through GCW, to the observance of the UN International Year of Glaciers' Preservation, in 2025.

I wish to extend my gratitude to the GCW experts for the preparation of these reports. This collective effort underscores the importance of international cooperation through WMO on the sharing of knowledge and resources to address the complex challenges posed by the cryosphere. I am confident that the GCW Technical Reports will serve as an essential resource for all stakeholders involved in cryosphere research and monitoring.

Michel Jean

President, Commission for Observations, Infrastructure and Information Systems (INFCOM)

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Cover page image: Zarafshan glacier, Tajikistan in 2020 (credit J. Boenisch)

1. BACKGROUND

Central Asia, a region characterized by its vast mountain ranges and diverse climatic conditions, is home to a substantial portion of the world's cryosphere. This includes extensive glaciers, widespread snow cover, and significant areas of permafrost. The cryosphere in this region is of paramount importance as it directly influences water resources, natural hazards, and ecosystems, all of which are vital to the livelihoods and health of millions of people. Understanding and monitoring the cryosphere in Central Asia are crucial for assessing the impacts of climate change, which is increasingly disrupting the delicate balance of these environments.

Cryosphere monitoring involves the systematic measurement of various parameters, such as the mass of snow and ice, the extent and duration of snow and ice cover, the reflectivity (albedo) of snow and ice surfaces, and the temperature and thickness of permafrost layers. These measurements are essential for tracking changes over time and predicting future trends, helping to inform water management strategies, disaster risk reduction efforts, and environmental conservation initiatives. Monitoring techniques employed in the region range from remote sensing technologies, such as satellite imagery, to ground-based observations and sophisticated modelling approaches. Together, these methods provide a comprehensive understanding of how the cryosphere is responding to changing climatic conditions.

The primary goal of this report is to summarize existing mountain observation and data sources related to the cryosphere in Central Asia. This includes data from in situ observations, remote sensing platforms, and numerical weather prediction models, all of which contribute to a broader understanding of snow, glaciers, permafrost, and related hydrological processes. The focus is on the Hindu Kush, Pamir and Tien Shan Mountain ranges, which span the countries of Afghanistan, Tajikistan, Kyrgyzstan, Uzbekistan, and Kazakhstan (Figure 1). These ranges are critical to the region's cryosphere and play a significant role in the water cycle, feeding major rivers that are lifelines for agriculture, energy production, and drinking water.

The report provides an overview of cryosphere monitoring in Central Asia, offering insights into its historical development, current state-of-the-art practices, and potential future directions. However, the report is not exhaustive. Some omissions are inevitable, but the document should nonetheless serve as a valuable resource for understanding the landscape of cryosphere monitoring in the region and it should be updated as new information becomes available.

Geographically, the report emphasizes the key Central Asian countries that share a common scientific and operational history, particularly under the influence of the former Soviet Union. This shared history has shaped the development of cryosphere monitoring in these countries, leading to a relatively cohesive approach across the region. Afghanistan, however, presents a unique case. Despite having a similar climate and topography to neighbouring Tajikistan, Afghanistan's history of conflict and instability has resulted in the absence of dedicated cryosphere monitoring programmes. As a result, the report includes references to Afghanistan where possible, but the primary focus remains on the core Central Asian bloc of Tajikistan, Kyrgyzstan, Uzbekistan, and Kazakhstan, where more substantial monitoring efforts have been established.

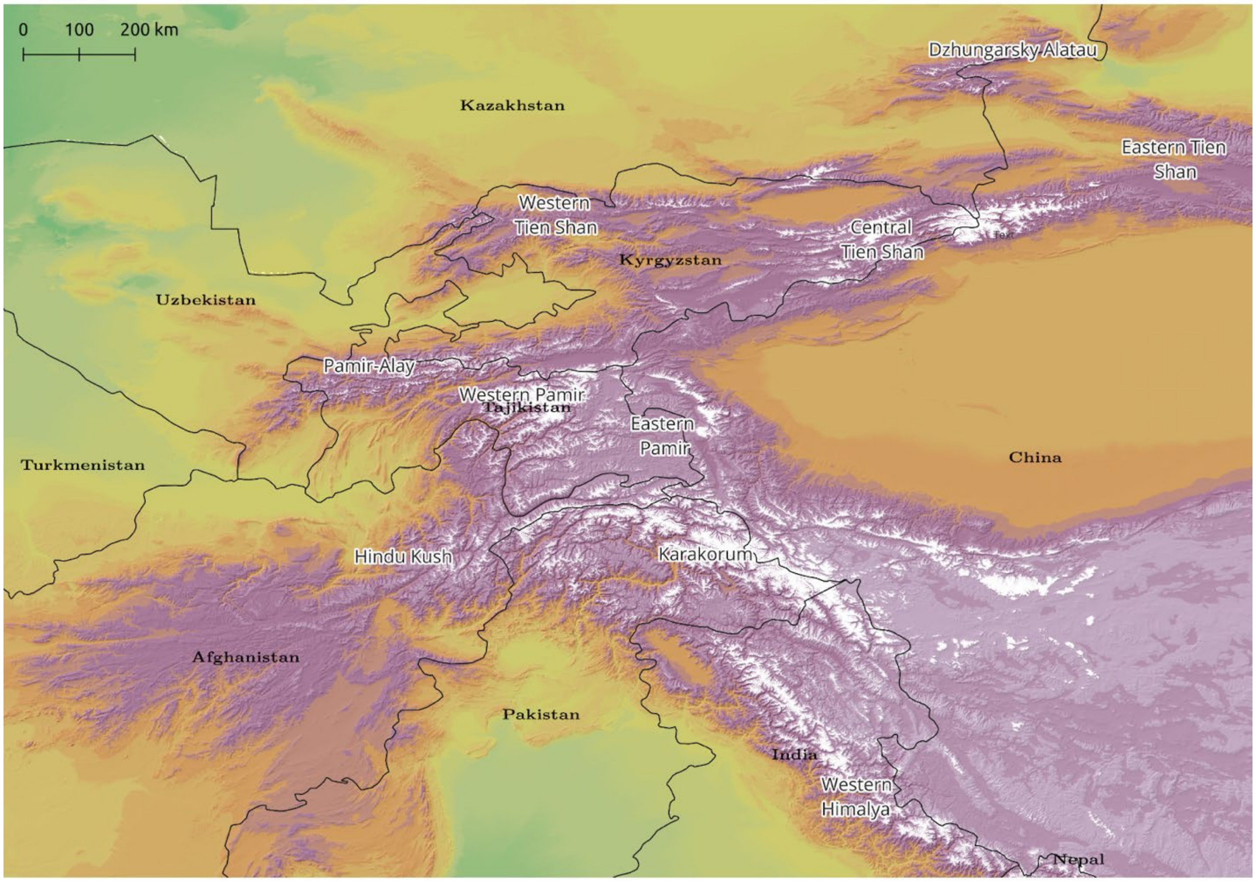

Figure 1. Overview map of the region with the main mountain ranges indicated.

2. STATUS OF IN SITU OBSERVATION OF THE CRYOSPHERE

In this chapter, an overview is presented of in situ observations pertaining to the cryosphere within the region, with a primary focus on the national agencies. Figure 2 provides a detailed depiction of the spatial distribution and extent of the principal components of the cryosphere across Central Asia. This figure, alongside Figure 3, highlights a critical issue: the scarcity of in situ observational data at higher elevations. This limitation poses significant challenges for accurately monitoring and understanding cryospheric processes in these mountainous areas.

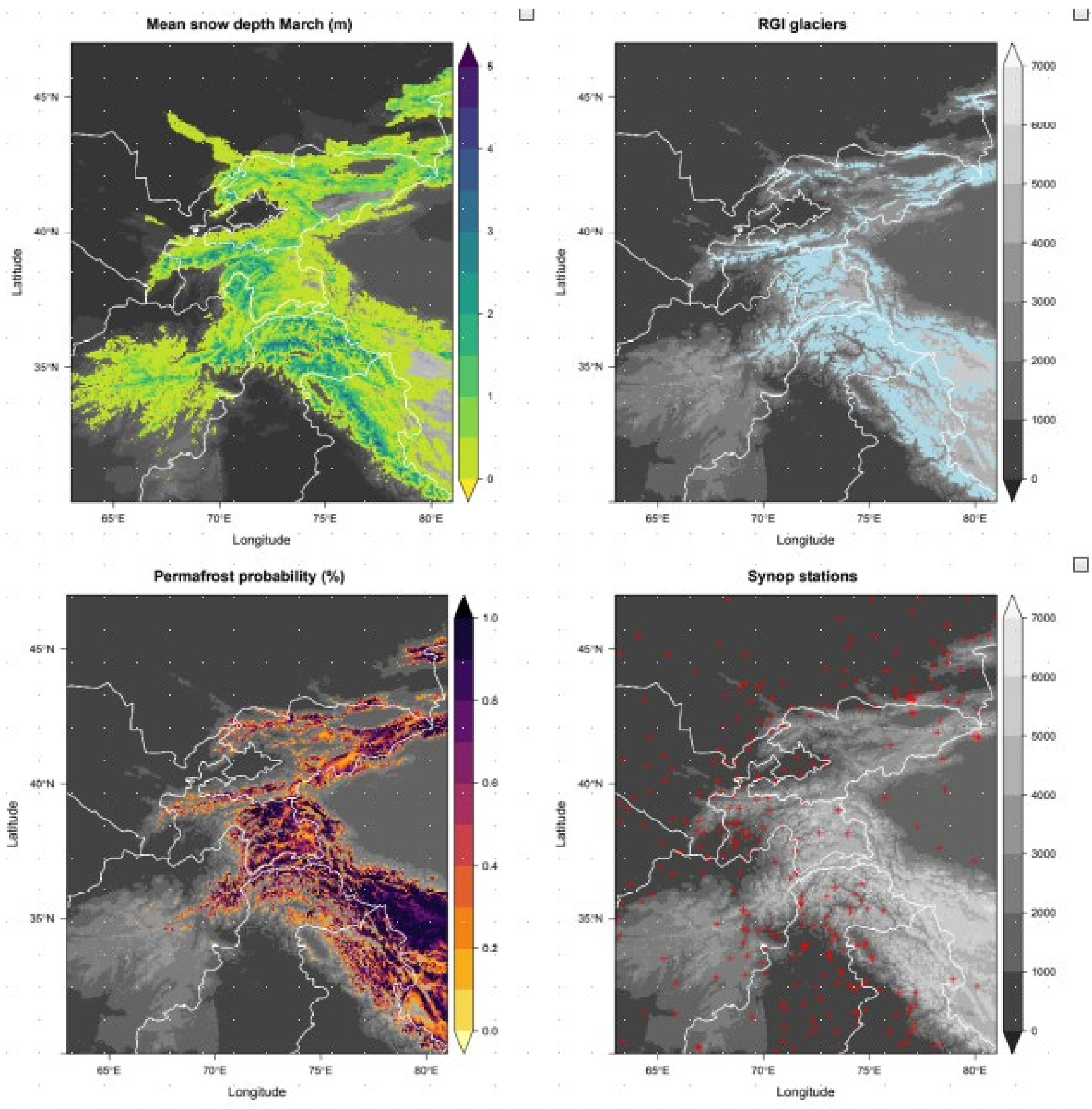

Figure 2. The cryosphere of Central Asia: (A) Mean March snow depth 2017–2019 computed from Sentinel-1 radar (Lievens et al. 2019) (B) Glacier outlines from the Randolph Glacier Inventory (C) modelled Permafrost probability (Gruber 2012) and (D) WMO Synop.

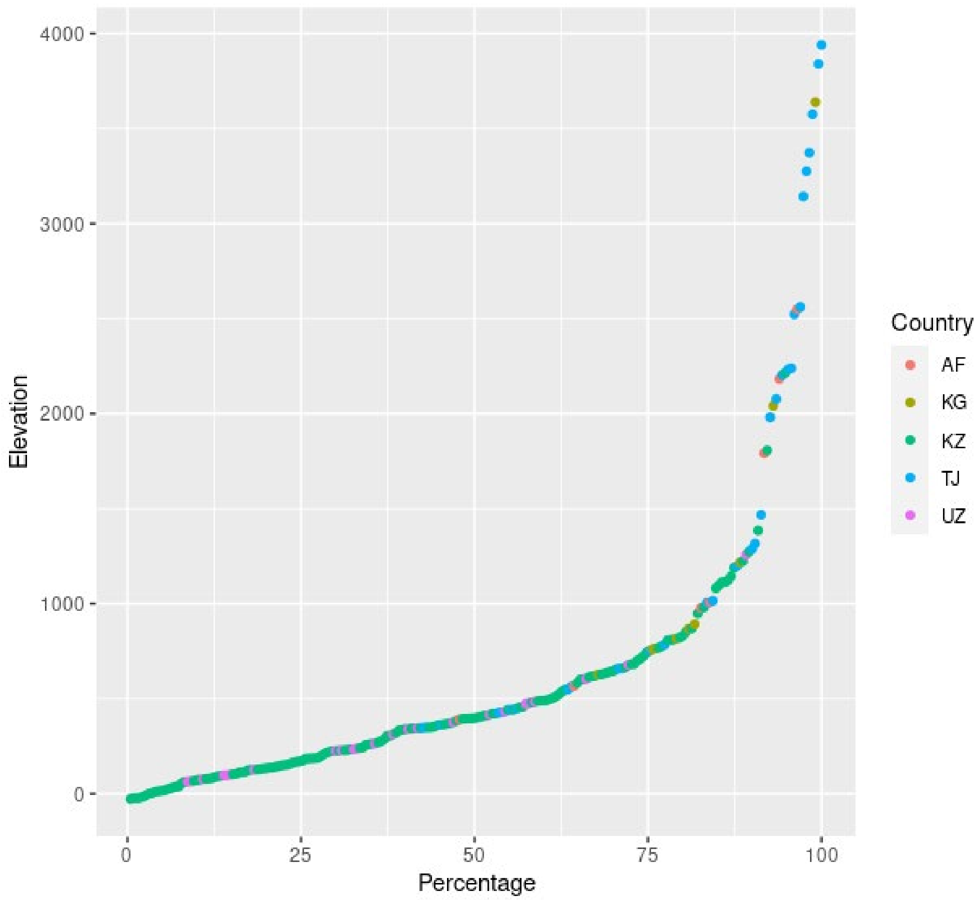

Figure 3. Cumulative plot of elevation of Synop stations in the region. Only 3% of stations can be considered high altitude at elevations over 3000 m, mainly in Tajikistan (one from Kyrgyzstan). The high mountain zone is under-represented by surface meteorological observations.

Snow observations

The Central Asian snow monitoring network has a long and rich history and was at its greatest extent during the Soviet Union era (Figure 4). At this time monthly campaigns were conducted during which snow depth and density (to compute the water equivalent of the snowpack) were systematically collected across the region by helicopter-based surveys of snow stakes (Figures 5, 6). An exception is Afghanistan, which while nominally administered by the Soviet Union has little history of snow monitoring besides data collected at WMO Synop stations.

During the 2000s World Bank financed efforts were underway in Afghanistan to modernize the hydrometeorological network and as part of this effort, snow observation stations. During the decade 2010–2020 similar efforts have been underway in Central Asia to update the monitoring network with automatic weather stations, some of which report snow depth (Figures 7, 8). Helicopter based snow-surveys continue in several countries, albeit at a reduced intensity due to budgetary constraints. For example, Tajikistan conducts annual snow monitoring campaigns in spring at the expected time of peak – SWE, or the maximum accumulation of the snowpack and its water resources. However, these are primarily targeted at strategic regions in upstream catchments of the main Nurek and Rogun dam cascades in the Vakhsh basin.

Prior to 1990ties, the hydrometeorological agencies of the various Soviet republics were responsible for snow monitoring activities and this responsibility has been inherited by the Hydromet agencies of the current independent states (Figures 9, 10). Although complex transboundary issues have transpired due to the formation of national borders and sovereign states which was not envisaged by the Soviet era water management architecture. For example, the Zarafshan basin was historically monitored by the Uzbek Hydromet Agency as this water was primarily used by the large downstream irrigated regions of Samarkand and Bukhara. While tensions existed under the previous Uzbek Government of Karimov, these have thawed since 2016 and now there is strong cooperation on water and energy infrastructure investments (e.g. planning of Zarafshan hydropower cascade).

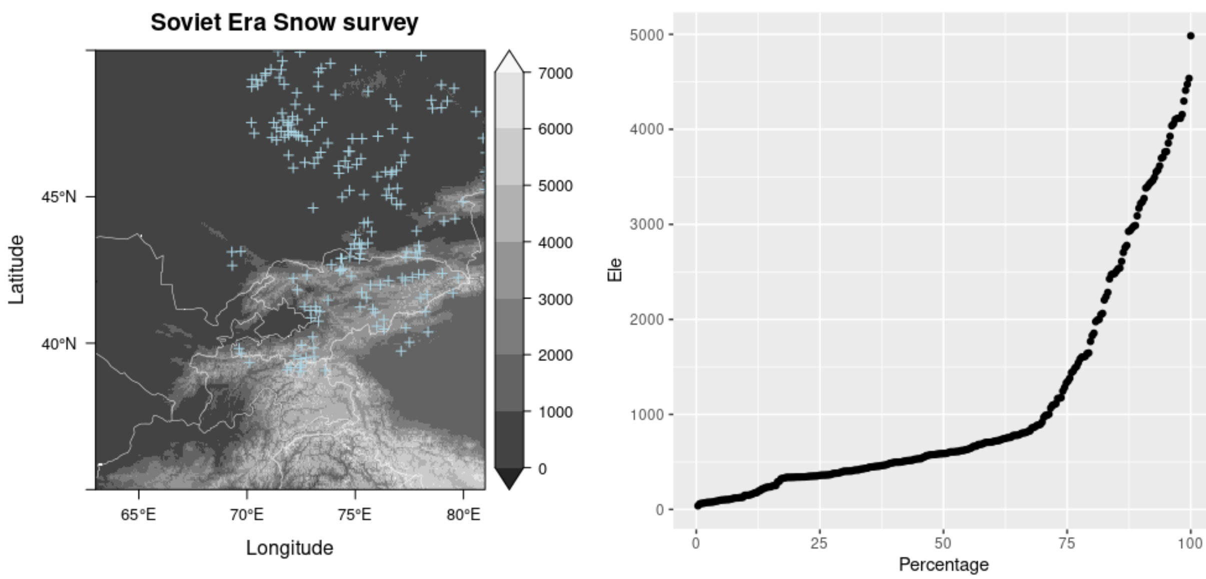

Figure 4. (A) Location of Soviet era snow sampling sites (B) Cumulative elevation profile, showing under-representation of high mountain snow survey sites.

Figure 5. Installation of snow stake in Tajikistan (courtesy of Tajik Hydromet).

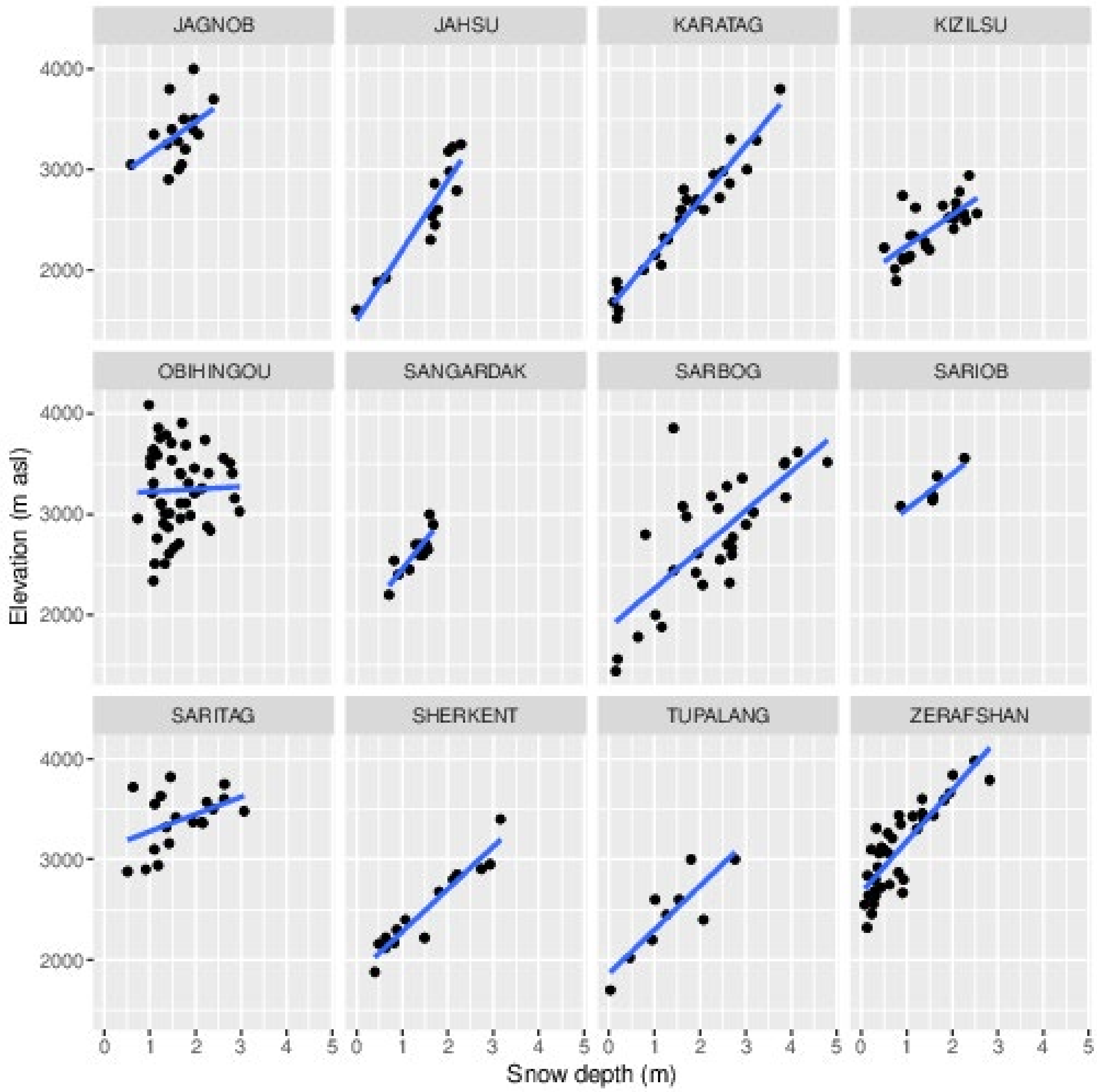

Figure 6. A selection of average snow depth variation with elevation from 1980–1990 from several catchments in Tajikistan

Barandun et al. 2020

Figure 7. Modern automatic Snow station (left) in Tajikistan under the World Bank financed the Central Asia Hydrometeorology Modernization Project (CAHMP) project, equipped with modern snow depth laser (Lufft), together with a pluviometer (right) and snow measurement stake (centre).

Figure 8. Snow observation station Too-Ashuu in Kyrgyzstan equipped with an automatic measurement station from the World Bank financed CAHMP project (S. Belekov).

Figure 9. Manual snow measurements of snow height and water equivalent are made at many SYNOP stations in the region, but this data is not transmitted in real time via the WMO Information System (WIS. Soviet era equipment and protocols are still used, as seen here with the snow water equivalent sampler (Tajik Hydromet Station Iskanderkul).

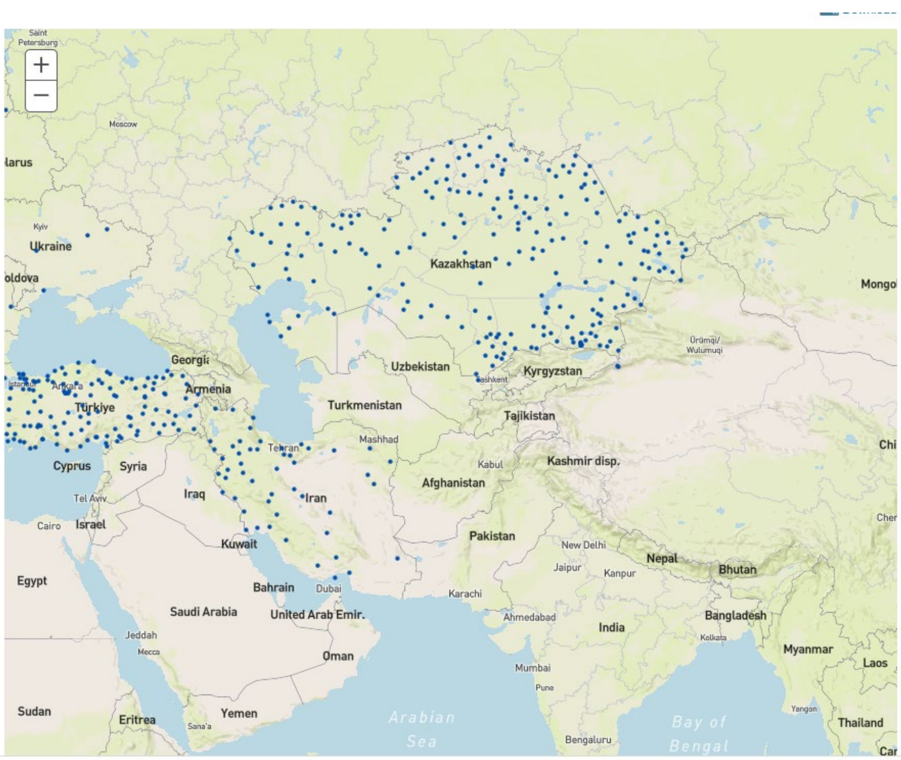

Figure 10. Most SYNOP stations in the region are collecting snow data – especially in mountain areas. These are mainly manual observations made by observers. However, few are reporting in real time via WIS, and previously via the Global Telecommunication System (GTS) except for Kazakhstan, shown here from the WMO OSCAR/Surface.

It should be noted that snow monitoring has two distinct objectives with different monitoring requirements:

(i) Water resources that require assessment of peak snow accumulation and the snow water equivalent stored for spring/ summer discharge;

(ii) Real-time monitoring of snow precipitation events (or other weather events such as rapid warming, or rain-on-snow events) that can lead to hazardous avalanche conditions (Figure 11).

Soviet era protocols still exist for both tasks and are still in use by the Hydromet agencies in the region, however, key protocols require updating so that data from new automatic weather stations (AWS), remote sensing systems, or Numerical Weather Prediction (NWP) outputs can be accessed by decision makers responsible for hazard or water management.

In the region, the accessibility of the road network is the priority from a hazard perspective with several important pass roads such as the Anzob Pass (Tajikistan) or Too-Ashuu (Kyrgyzstan) routinely threatened by avalanches. However, with the increase in the popularity of backcountry skiing activities in parts of Kyrgyzstan, this focus is starting to prove inadequate and improved forecast products are needed.

Figure 11. Freshly fallen snow avalanches killed seven people on 30 January 2017 Anzob Pass tunnels, Tajikistan

Figure 12. Wet snow avalanche in Yagnob, Zerafshan May 2018 – destroyed farm buildings and other infrastructure plus made agriculture land unavailable for early seeding.

Glacier observations

Glacier monitoring in Central Asia started in the mid-1950s during the Soviet era. At that time, several glaciological monitoring programmes were established in the mountain ranges of Central Asia (Dyurgerov, 2002, K, 2006). The majority of the observation programmes stopped during the early 1990s. Today, only one continuous series exists, on the Tuyuksu Glacier, Kazakhstan. Urumqi Glacier in the eastern Tien Shan has a relatively complete record since 1980s with a reconstructed period back to the late 1950s. Efforts to re-establish in situ glacier observations have started since 2010 (Hoelzle et al. 2017) and now at least one more glacier is annually monitored in each major range (Figures 12, 13).

A thorough inventory of past glacier measurements in the region that have been archived at World Glacier Monitoring Services (WGMS) is given by Hoelzle et al. 2017. Table 2, of that publication summarizes the total number of past glacier observations. Historical mass balance measurements exist with mean observation period lengths close to 20 years. Thickness change measurements for nine glaciers and repeated front variation measurements for glaciers with measurement periods from nine to 20 years are also available. Most of the mass balance measurements were initiated between 1960 and 1970 and were discontinued in the 1990s after the collapse of the USSR. These historical measurements are now complemented by the new monitoring programme and gaps have been reconstructed using mass balance models (Figure 14).

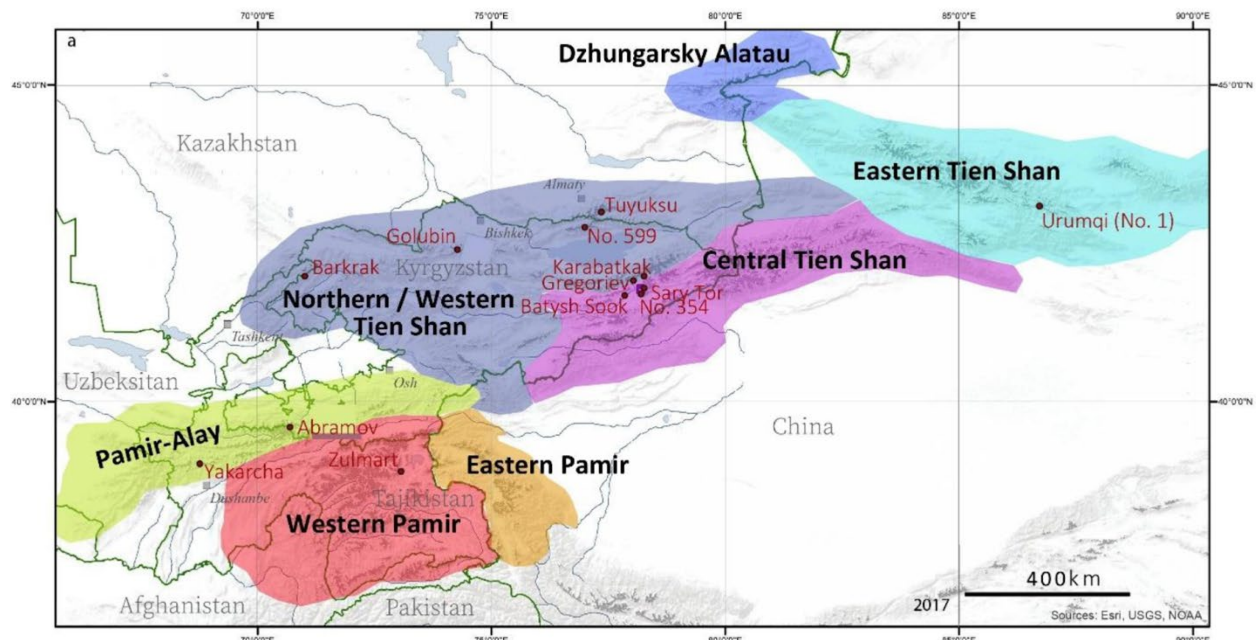

Figure 13. Main mountain ranges of Central Asia: Tien Shan and Pamir are shown divided into subregions. In red, the glaciers that have been selected for long-term monitoring by the Swiss Development Cooperation (SDC) / University of Fribourg (UNIFR) projects CATCOS, CICADA, CROMO-ADAPT (Table 2 of this report). Apart from No. 354, 599 and Zulmart, glaciological observations are available for all sites since the mid-20th century.

Barandun et al 2020

Figure 14. Resumption of glacier monitoring activities have been supported largely by SDC/UNIFR over the last 15 years. Drilling mass balance stakes in the Nissai Range Western Pamir, Tajikistan (CGR/CROMO-ADAPT, see Table 2 of this report).

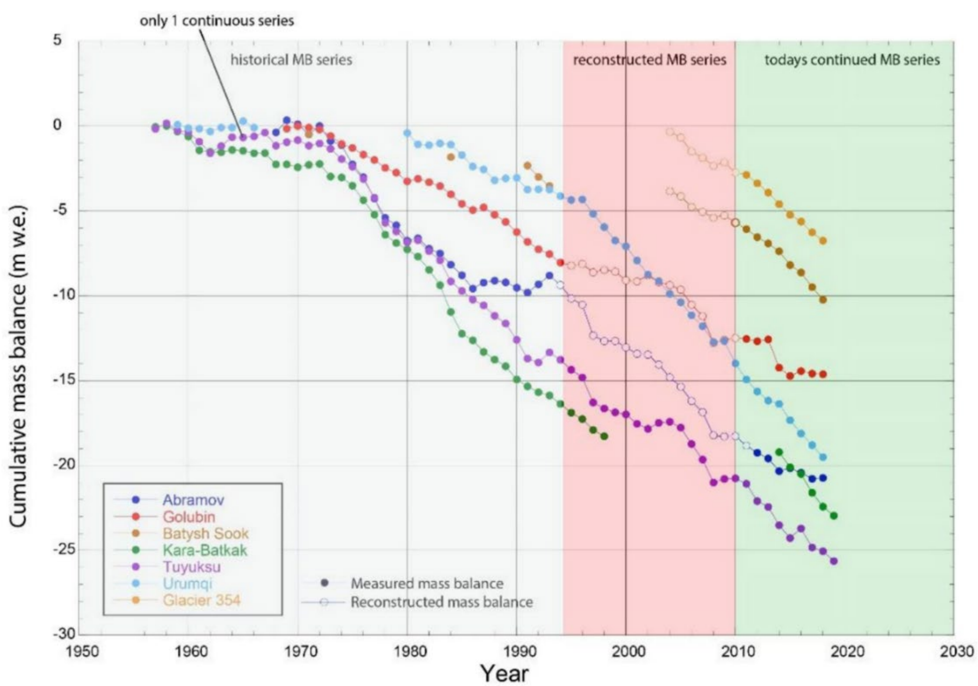

Figure 15. Measured and reconstructed glacier mass balance in Central Asia. *Data source*: measured data series from WGMS; reconstructed data series from supporting studies. Barundun et al. 2020

Permafrost observations

The Central Asian region encompasses the largest area of mountain permafrost in the world (Barandun et al. 2020). It covers 3.5 x 106 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 has a major influence on the energy balance at the ground surface. Mountain permafrost distribution also depends on various additional factors such as vegetation, debris and snow cover (Barandun et al 2020).

Two permafrost boreholes are available in the Global Terrestrial Network for Permafrost (GTNP) database for Central Asia, one in Kazakhstan, one in Kyrgyzstan. These were installed by S. Marchenko (Marchenko et al. 2007) but are no longer active. The CROMO-ADAPT project has included support for permafrost monitoring in Central Asia and has re-equipped the Kygyz borehole in October 2022 and a new borehole in Tajikistan.

There is extensive knowledge in Central Asia on permafrost although it tends to stem from the Soviet era syllabus of "Geocryology" which focused on Arctic permafrost and less so on mountain permafrost which is more relevant to the mountainous regions of Tien Shan and Pamir. While the Soviet syllabus focused on engineering issues in tundra landscapes the current focus of mountain permafrost investigations is related to mountain hazards due to destabilizing slopes with climatic change and also a growing interest in ice rich landforms (such as rock glaciers) as a potential water resource in absence of surface ice that is rapidly depleting, particularly in relatively dry catchments such as those found in eastern Pamir, Tajikistan. The permafrost monitoring strategy currently supported by the CROMO-ADAPT project is based on international best practice and extensive experience in monitoring mountain permafrost in Switzerland from PERMOS (Swiss National Permafrost Monitoring Network) e.g. Noetzli et al. 2021 and the WMO Best Practices for Permafrost , *Guide to Instruments and Methods of Observation, Vol II – Measurement of Cryosphere Variables* (WMO-No. 8)

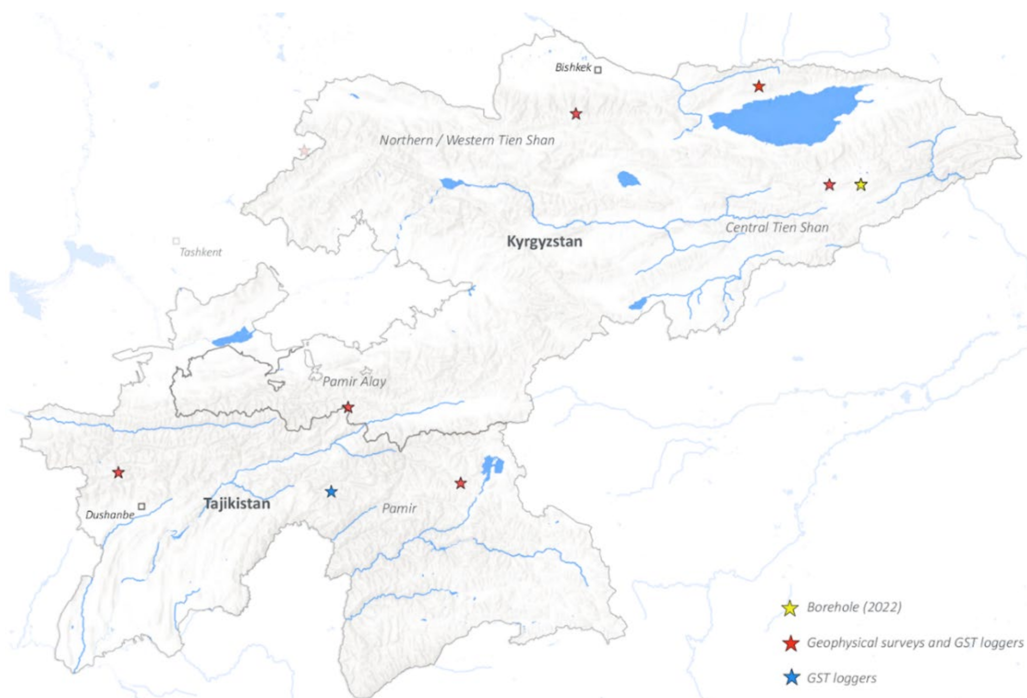

Figure 16. Map of Permafrost investigation sites under the CROMO-ADPT project which supports permafrost monitoring in the region

Source: T. Mathys, UNIFR

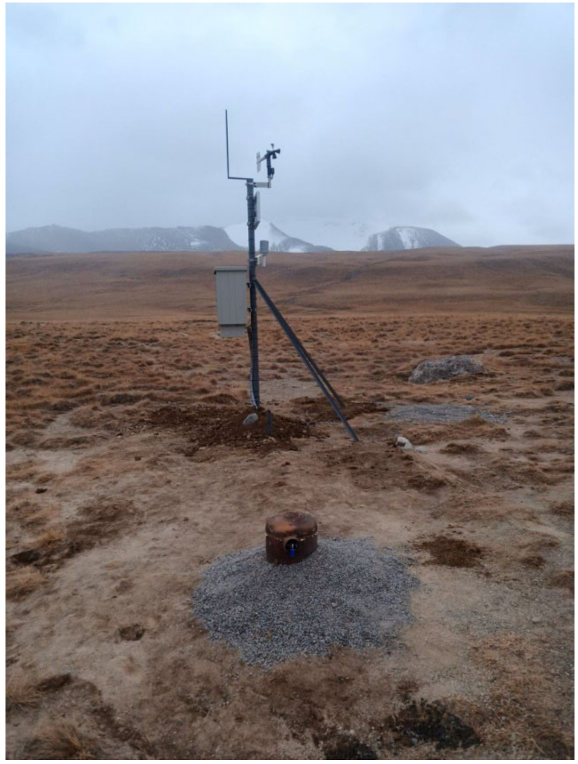

Figure 17. New permafrost borehole in the Arabel valley (close to Kumtor mine) in the Central Tien Shan

Source: E. Mattea, UNIFR

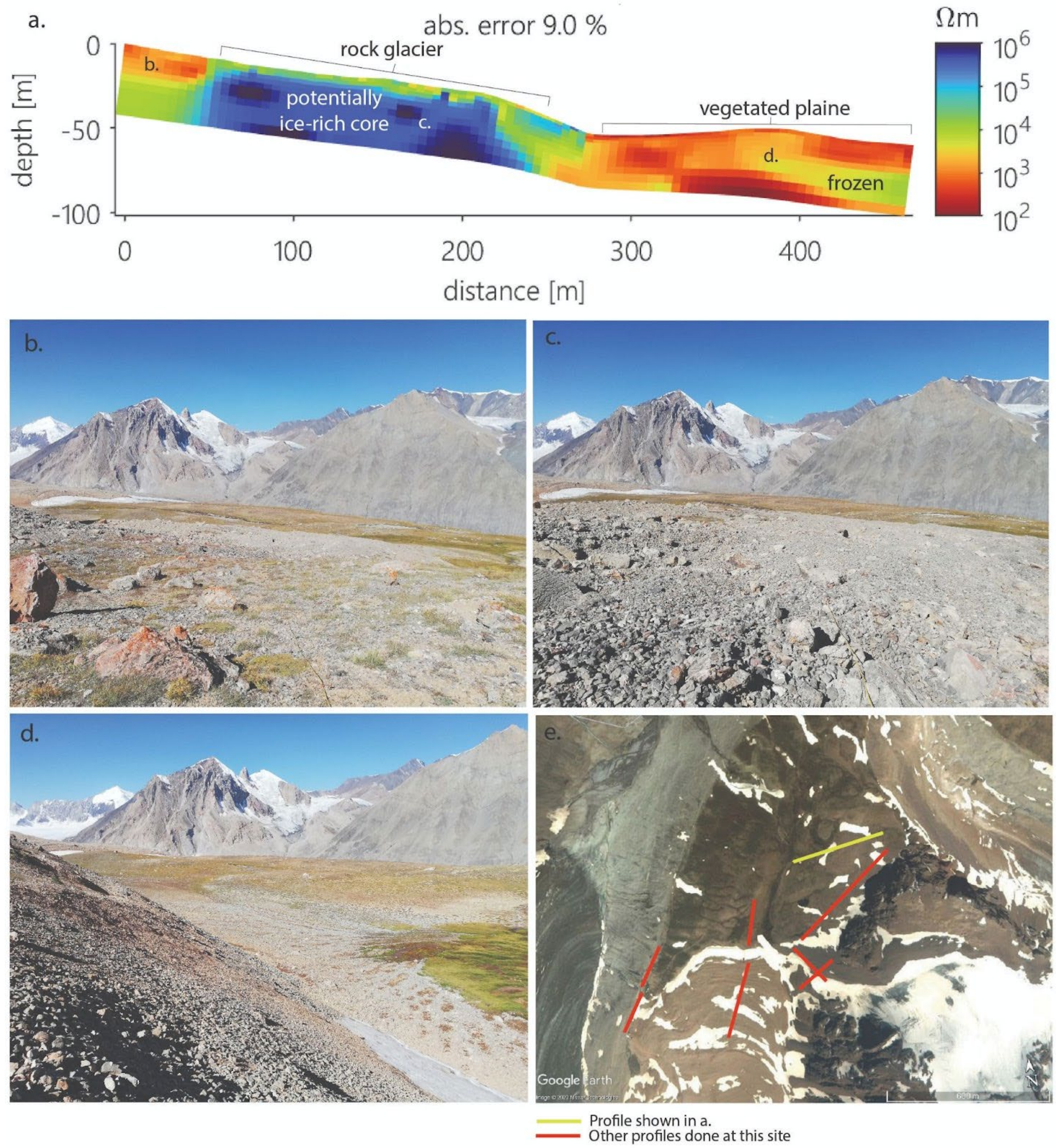

Figure 18. Geophysical Permafrost investigations near Abramov glacier in the Pamir Alay

Stockton et al. 2021: IPA report Kyrgyzstan, T. Mathys UNIFR

3. STATUS OF HISTORICAL RECORDS AND RECOMMENDATIONS FOR DATA RESCUE

There exists an extensive archive of glacio-hydrological records from the region. During the Soviet era, the hydrometeorological data records were archived in duplicate at both Uzbek Hydromet in Tashkent (regional centre) and Moscow as well as at the source state Hydromets (Figure 18). These physical backup archives are effective and important, so the task in question is not so much data rescue (data is generally well archived), but data digitization, so data are accessible. Some examples of successful efforts are noted below. The challenge is that hydrological data is usually completely unavailable digitally and it should be the focus of data rescue efforts.

A first successful example is the EU funded Zarafshan Integrated Basin Programme (ZIBP) when the Tajik Ministry of Energy and Water staff reconstructed a historical time series of meteorological and hydrological data, going back to the 1930s (Figure 19). Where data-gaps existed, research visits to Tashkent and even Moscow were organized to retrieve copies of missing data. The challenge is that these are paper-based archives and extensive digitization efforts are required to make these data usable. Some stations that have reported to GTS are archived and accessible via NOAAs Global Surface Summary of the Day (GSOD) archive as daily data, only.

Another notable data rescue effort was conducted in the early 2000s by Daniel Bedford (Department of Geography Middlebury College, USA) and Boris Tsarev, State Hydrometeorological Service (Russian acronym SANIGMI) in Tashkent, Uzbekistan. The resulting dataset provides observations of monthly snow depth, snow density, and snow water equivalent from three river basins in Central Asia: Amu Darya, Sir Darya, and Naryn. Temporal coverage varies for each snow point, with the longest station record extending from 1932 to 1990 (Bedford, D. and B. Tsarev. 2001, Figures 4–6).

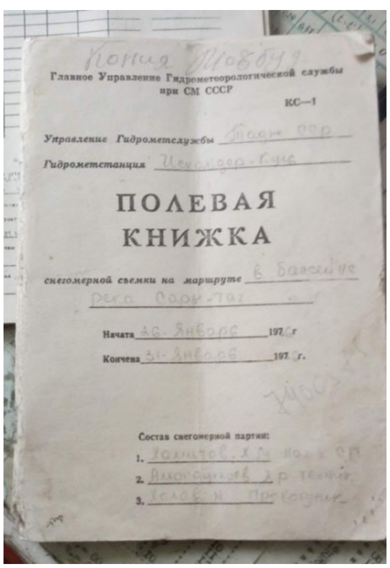

Figure 19. During the time of the USSR, cryosphere data were archived at multiple levels from the Soviet state, regional, to the Moscow level and even onsite such as this report of snow survey near Iskanderkul 26–31 January 1976 seen at the Tajik Hydromet station Iskanderkul (Left) or the Soviet era glaciological reports archived at Tajik Hydromet (Right).

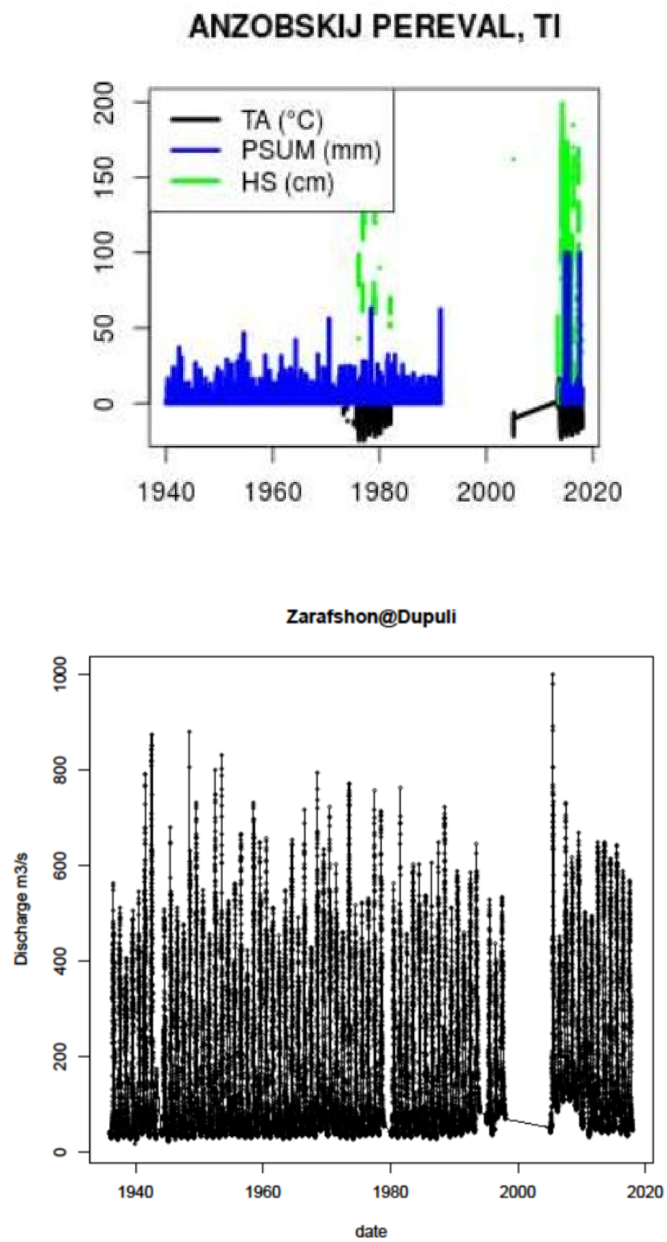

Figure 20. Historical hydrometeorological records are available in Central Asia such as this meteo station data at Anzob Pass or discharge at Dupuli, both in Tajikistan

Source: Fiddes 2018, 2019

While the main hydrometeorological records (meteorology, hydrology and snow) have, in general been well archived in several locations, albeit requiring access and digitization efforts, the data from glaciological studies often remained buried in paper-based reports that exist only at the national agencies. Certain glaciers have been well documented over the twentieth century and submitted to WGMS (Figure 14) and are documented in Hoelzle et al. (2017), as discussed previously. As part of the Swiss Polar Institute financed flagship project "PAMIR" one research cluster is focused on History of Glacier Science (PI C. Bichsel UNIFR). Research exchanges were planned with Moscow which became untenable in 2022. However, the team were able to refocus on archives in Tashkent, with a thorough digital inventory of sources relevant to the topic.

4. STATUS OF REMOTELY SENSED DATA AVAILABLE AND USED IN THE REGION

Satellite based remote sensing is a key part of cryosphere monitoring today globally with many platforms delivering cryosphere specific products or products used by the cryosphere community. The requirements of mountain cryosphere are different from polar and sub-polar cryosphere products as high-resolution products are needed to capture the spatial variability of mountain topography. The following sections provide a brief overview of the various platforms for remote sensing available for the region, e.g. multispectral, radar and LiDAR.

Table 1. Overview of commonly used satellite platforms in cryosphere applications.

Type	Platform	Time range	Resolution	Typical applications
Multispectral/ optical	CORONA (declassified US spy satellite)	1959 – 1972	1.8 – 7.5 m	DEM (geodetic mass balance)
	Landsat 1–8	1972 – ongoing	15 – 80 m	Snow cover, glacier outlines, ELA, thermal (100 m)
	Sentinel-2	2016 – ongoing	10 – 20 m	Snow cover, glacier outlines, ELA
	MODIS	2000 – ongoing	250 m -1 km	Snow cover, surface temperature
	Pleiades	2011 – ongoing	2 m	Surface elevation changes (snow cover, glacier, avalanche)
	Aster	1999 – ongoing	15 – 90 m	DEM (geodetic mass balance)
Radar	Sentinel-1	2014 – ongoing	10 – 90 m	Velocity, melt
	SRTM	2002	30/90 m	DEM
LiDAR	ICESAT-2	2018 – ongoing	13 m (footprint)	Elevation

Multispectral satellites

Multispectral satellites are, perhaps, the most well-known and used source of cryosphere data due to ease of use and interpretation. Multispectral platforms such as MODIS, Landsat and more recently ESA's Sentinel-2 have been producing optical data and various resolutions and frequencies since the 1970s and provide the longest most continuous record of global surface change. They are used for snow cover studies where the parameter snow covered area (SCA) or even sub-pixel SCA known as fractional snow-covered area (fSCA) typically through a band differencing algorithm such as Normalized Difference Snow Index (NDSI). These products are used to reconstruct a time series of snow cover variability (e.g. Ackroyd et al. 2021) and assimilate into numerical models (Margulis et al. 2015, Aalstad et al. 2018, Fiddes et al. 2019). Optical products have been fundamental in constructing glacier inventories available at WGMS where accumulation, ablation zones and debris covered sections can be discerned either automatically or manually. Very high-resolution optical imagery such as Pleiades, SPOT or

Worldview have been used to generate space borne photogrammetry to generate high-resolution surface models to be employed in geodetic glacier mass balance studies (e.g. Brun et al. 2022) or even assessment of snow depth (Deschamps-Berger et al. 2020, Eberhard et al. 2021). These products are not generally used operationally in the region, with the exception of the MODIS based snow monitoring tool MODSNOW (Gafurov et al. 2016) which is used by the Hydromet Services in the region in support of water resource management. Optical satellites, which are affected by cloudiness, provide reduced volumes of usable data especially during the times of the year where precipitation is frequent.

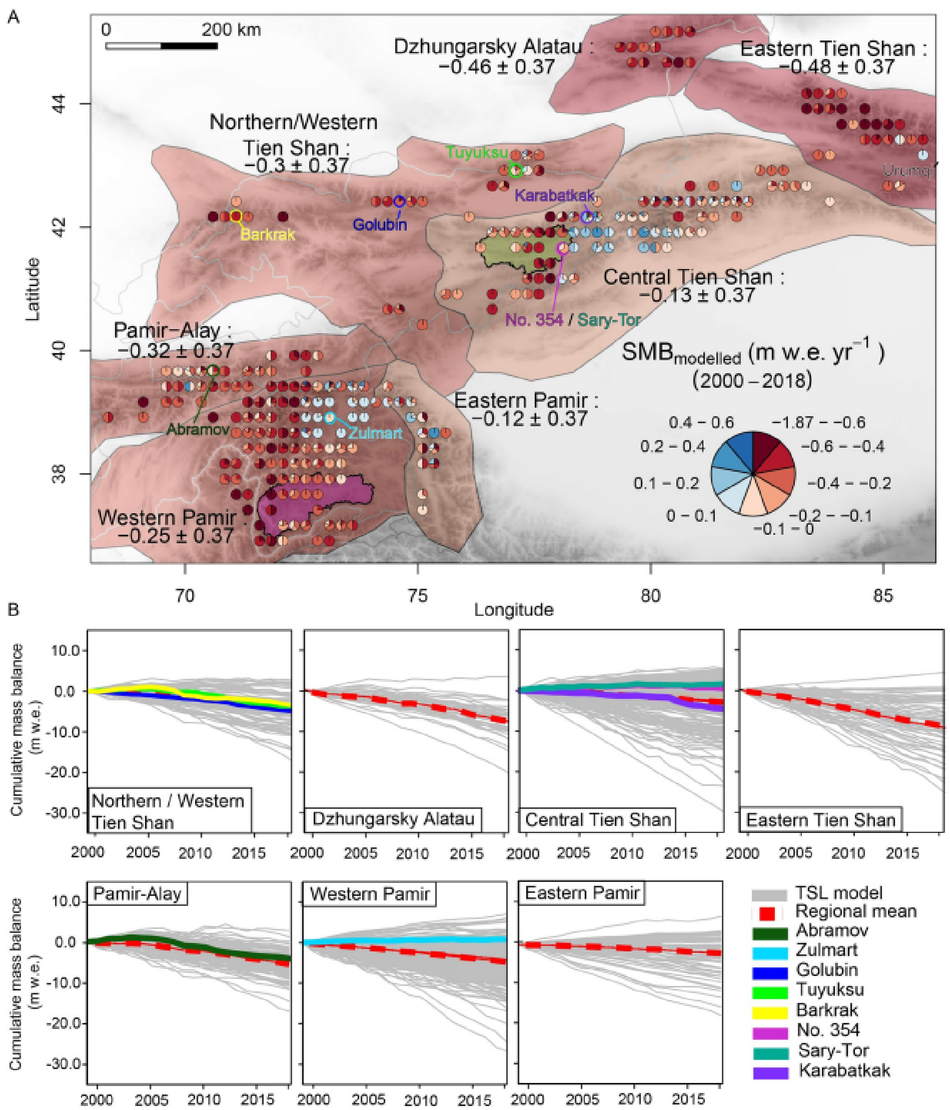

Figure 1. (a) Mean annual mass balances (1999/00–2017/18) for different subregions. Pie slice sizes representing percentage of glaciers in each category (binned to 0.25-degree grid cells using glacier centroids provided in the RGI) not scaled to total number of glaciers per grid cell (Figure S11: pies scaled to number of glaciers on 0.75° ERA-Interim grid). Regional mass balances are area-weighted means of glacier values. Colored circles indicating location of monitored glaciers. Magenta polygon showing Gunt (Western Pamir) catchment, and green polygon Naryn River (Central Tien Shan) catchment. (b) Reconstructed cumulative mass balance series (gray lines) compared with regional mean (red dashed lines) and reconstructed mass balances of monitored glaciers (colored continuous lines) per subregion.

Figure 21. Modelled regional glacier mass balance constrained by satellite observed snowlines (or Equilibrium Line Altitude, ELA) which corresponds to the separation between the ablation and accumulation zones of the glacier and therefore is correlated to its mass balance

Barandun et al. 2021

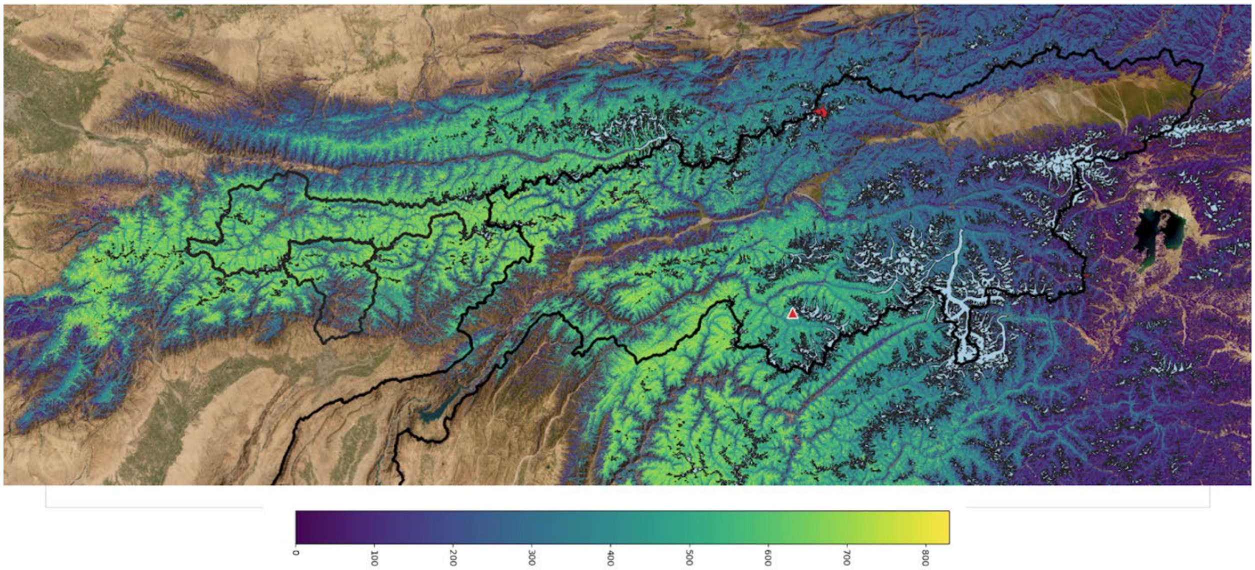

Figure 22. Modelled peak snow water equivalent (mm) across the Pamir Alay and Western Pamir on 22 March 2022 constrained by observations from MODIS fSCA product according Fiddes et al. 2019. The black polygons indicate the Vahksh, Varzob and Yagnob basins, glacier areas are given in light blue. Abramov glacier is given in red at the top of the scene.

Radar satellites

Radar based products are generally more complex to use beyond the ubiquitous Shuttle Radar Topography Mission (SRTM) elevation dataset produced by the National Aeronautics and Space Administration (NASA) in the early 2000s and which supports many mountain studies globally.

Radar products have been used to estimate the Water Equivalent of Snow Cover (SWE) (e.g. the Advanced Microwave Scanning Radiometer – Earth Observing System, AMSR-E) but suffer from coarse resolution and difficulty in interpretation during melt conditions. Sentinel-1 data has been used to monitor glacier surface velocities and distinguish debris covered glacier tongues which are difficult to automatically classify with optical imagery. A recent study produced a global snow depth dataset from Sentinel-1 at moderate resolution (1 km) that starts to be useful in mountain regions (Lievens et al. 2019, Figure 2). This has been updated to 300 m in the European Alps. While not currently an operational tool, it shows much promise especially in light of the fact that a number of future missions are addressing the use of L-band InSAR for snow applications, such as the NASA–Indian Space Research Organization (ISRO) Synthetic Aperture Radar (SAR) (NISAR) and potentially the Radar Observing System for Europe – L-Band (Rose-L).

A key advantage of radar over optical sensors is that they are not dependent on daylight or clear atmosphere as optical sensors are and therefore large volumes of usable data are obtained.

LiDAR satellites

Space borne LiDARS such as ICESat-2 can be used for precise spot retrievals of surface elevation. There is therefore much interest in using this for glacier surface elevation change studies as well as snow height monitoring (e.g. Treichler and Kääb 2017) and research plans exist to trial this approach in Central Asia as a joint activity of researchers from the University of Oslo and the Swiss Development Cooperation (SDC) funded CROMO-ADAPT project.

5. STATUS OF AVAILABLE NWP PRODUCTS RELEVANT TO CENTRAL ASIA

Numerical Weather Prediction (NWP) models are used to produce weather forecasts (short term and seasonal) and are the basis of reanalysis products (long-term reconstructions of past climate), as well as climate models used to investigate future climate scenarios.

The NWP products are crucial to modern cryosphere monitoring programmes yet, underutilized in the region. Reanalysis products such as ERA5 or later, from the European Centre for Medium-Range Weather Forecasts (ECMWF), provide a description of climate variables, globally, at 25 km and at 1H timesteps from 1950 to current time.

Reanalysis data offers the most comprehensive depiction of historical weather and climate. They combine observations with past short-range weather forecasts, which are rerun using modern weather forecasting models. The data is globally complete and temporally consistent. Climate reanalysis is invaluable in climatological studies of cryosphere variables and in driving cryosphere models to understand ongoing trends, e.g. snow reanalysis products driven by global reanalysis (Margulis et al. 2015, Fiddes et al. 2019), reconstructed glacier mass balances (Kronenberg et al. 2022) and permafrost distribution maps (Gruber 2012, Figure 2). These products fill an important gap in data-scarce regions where surface data does not exist. However, due to course resolution (10–50 km), some form of downscaling is generally required before use in cryosphere models (e.g. Fiddes et al. 2014).

With respect to the cryosphere, NWP for short-term forecasts is crucial for predicting winter storms likely to create dangerous avalanches, adverse road conditions or other hazards. As part of the World Bank CAHMP project, two COSM0–10 limited area models were set up at 6.6 km and 2.2 km (mountain areas) resolutions, producing forecasts every 6 hours, at the RSMC Tashkent (the Regional Specialized Meteorological Centre hosted by Uzhydromet). This required expensive dedicated high-performance computing (HCP) infrastructure and expert staff. The RSMC has struggled to operate, having regular service interruptions and regional challenges in connectivity for sharing and receiving data.

Cloud computing has become more affordable and offers greater flexibility without the need for substantial capital investments. The German Weather Service (DWD), World Bank, COSMO consortium and World Meteorological Organization (WMO) have collaborated to test the feasibility of running an operational NWP Limited Area Models (LAM) on commercial cloud computing services. Feasibility studies have shown that running NWP on a commercial cloud provider is an attractive alternative to procuring and maintaining an HPC, particularly for resource constrained National Hydrometeorological Services (World Bank 2022). The project ICON-In-the-Cloud (ICONIC): Piloting Numerical Weather Prediction on Commercial Cloud Services for Central Asia was launched in October 2022 to trial this approach.

Another NWP development is the release of short-term forecast from ECMWF in 2022, as part of their open data initiative. This provides access to high-resolution forecast products for up to 10 days for surface and pressure level data. This has been used by the CARITAS-led Weather, Water and Climate Services project in Tajikistan which has developed targeted bias-corrected (performed by MeteoSwiss) climate services such as cold wave forecasts or heavy snow events, suitable for mountainous regions.

6. INVENTORY OF INTERNATIONALLY-FUNDED PROJECTS ON THE CRYOSPHERE IN THE REGION

Over the last decade, there has been increasing attention to monitoring the cryosphere in Central Asian countries, given its critical contribution to regional water security and its vulnerability to climate change. Projects supported by the international community have focused on glacier monitoring, high altitude hydrological and-meteorological observations, permafrost and seasonal snow cover. In remote areas at high elevation, the costs for observing infrastructure, maintenance and data transmission, are high. For that reason, the collaboration and engagements across projects are essential.

A list of current or recent internationally funded projects related to the cryosphere in Central Asian countries is provided in Table 2. This is not an exhaustive list as new projects are initiated on a regular basis. The purpose of this list is to provide a snapshot and to highlight the opportunities for enhanced cooperation and coordination.

Of particular benefit to the national institutions in the region are the activities leading to building technical and expert capacity. This is a shared responsibility between national agencies and internationally funded project proponents which would guarantee the sustainability of the investments made through these projects.

Table 2. Currently or recently active internationally funded projects related to the cryosphere in Central Asia

Project	Donor	Duration	Implementer	Target	Reference	Data
CATCOS 1 + 2	SDC	2011 – 2016	UNIFR	Glacier monitoring	https://www.unifr.ch/geo/cryosphere/en/projects/glacier-monitoring-and-dynamics/archive/catcos.html	WGMS
CICADA	SDC	2017 – 2020	UNIFR	Glacier monitoring	https://www.unifr.ch/geo/cryosphere/en/projects/glacier-monitoring-and-dynamics/cicada.html	WGMS
CROMO-ADAPT	SDC	2021 – 2025	UNIFR/ SLF	Glacier, snow, permafrost monitoring, hydrology	https://www.eda.admin.ch/deza/en/home/themes-sdc/water.html/content/dezaprojects/SDC/en/2019/7F10279/phase1	WGMS, GTN-P, Hydromet agencies
CAHMP	WB	2011 – 2021	CA Hydromets	Meteorology		Hydromet agencies
WWCS	SDC/ CARITAS	2021 – 2014	CARITAS (Meteo Swiss, SLF)	Mountain Meteorology	https://www.caritas.ch/en/what-we-do/worldwide/climate/tajikistan-weather-data-helps-farmers-to-improve-their-productivity.html	http://wwcs.tj/

Project	Donor	Duration	Implementer	Target	Reference	Data
CAWA/ GREEN CENTR AL ASIA	DAA	2008 – ongoing	GFZ	Glaciers, snow, hydrology	http://www.cawa-project.net/	http://sdss.caiag.kg/sdss/
CHARIS	USAID	2012 – 2019	University of Boulder	Glaciers, snow, hydrology	https://nsidc.org/charis/	Glaciers, Snow, Hydrology
PAMIR	SPI (Swiss Polar Institute)		WSL/ UNIFR	Glaciers, snow, permafrost, natural hazards, ecology, science history	https://pamir-project.ch/	WGMS, Zenodo, GTNP,
GEF	Multilateral /UNFCCC		UNIFR	Glaciers	https://www.thegef.org/projects-operations/projects/10077	WGMS
GLOFCA	UNESCO/ Adaptation Fund	2022 – 2025	UZH	GLOFS	https://www.glofca.org/	Local partners
FINTAJ 1 – 3	Finnish Ministry of Foreign Affairs	2014 – Ongoing	FMI	Glaciers, atmospheric pollutants		Local partners

CATCOS I/II, CICADA, CROMO-ADAPT

The University of Fribourg, Switzerland, has led several SDC-funded projects to rehabilitate glacier monitoring in Central Asia since 2011 (Hoelzle et al. 2017), e.g. CATCOS, CICADA and CROMO-ADAPT, in collaboration with other Swiss institutions. These projects have been delivered, engaging local academic and government agencies, to support the development of a new generation of young scientists and practitioners, at a national level. In addition to monitoring and providing expedition equipment, these projects have included a strong focus on developing local expertise on all aspects of running a glacier mass balance monitoring programme. All glaciological data from these projects have been made available through WGMS. The project CROMO-ADAPT also included seasonal snow and permafrost monitoring.

Global Environment Facility (GEF)

The Global Environment Facility (GEF)-funded project “Strengthening the resilience of Central Asian countries by enabling regional cooperation to assess glacio-nival systems to develop integrated methods for sustainable development and adaptation to climate change” started in 2023. The project was designed to build technical and scientific capacity at country level on cryosphere monitoring by promoting activities based on a science-based consensus among the participating countries in Central Asia. The project has also supported national and regional strategic action programmes (SAP), including implementation and demonstrations that support climate change adaptation in the affected regions. Finally, the project has aimed to develop a consensus on a common assessment and monitoring programme for the cryosphere in Central Asia, raise awareness among stakeholders and develop a knowledge platform. UNIFR has been the implementing international partner.

Glacier Lake Outburst Floods in Central Asia (GLOFCA)

The United Nations Educational, Scientific and Cultural Organization (UNESCO) Adaptation Fund (AF) funded the project "Reducing vulnerabilities of populations in the Central Asia region from glacier lake outburst floods in a changing climate". The objective of the project has been to strengthen adaptation to climate change in Central Asia by reducing societal risks and vulnerabilities associated with Glacier Lake Outburst Floods (GLOFs), and addresses Sustainable Development Goals (SDGs) 11 (sustainable cities and communities) and 13 (climate action) of the 2030 Agenda, particularly targeting 11.5 (reducing disaster impacts on vulnerable communities), 13.1 (strengthening resilience to climate-related hazards) and 13.3 (improving climate education and awareness).

Central Asia Flood Early Warning Systems (CAFEWS)

The World Bank and WMO combine resources and knowledge to support the countries of Central Asia and Afghanistan to improve transboundary flood, flash flood and landslide forecasting, warning and advisory services in the Amu Darya and Syr Darya River Basins.

CARITAS Weather, Water and Climate Services (WWCS)

The CARITAS-led Weather, Water and Climate Services (WWCS) project, co-funded by SDC, has focused on augmenting existing observation networks through low-cost sensors and community-based monitoring in a pilot region in the Rasht Valley, Tajikistan. Mountain regions generally suffer from poor forecasts due to low density of observations and insufficient resolution of the forecasting models. With the support of MeteoSwiss, this project post-processes existing NWP products, using data from low-cost in situ sensors distributed to communities, to deliver targeted climate services such as warnings on cold waves or heavy snowfall events.

Central Asia Hydrometeorology Modernization Pproject (CAHMP)

The objective of the Central Asia Hydrometeorology Modernization Project (CAHMP) was to improve the provision of hydrometeorological services in Central Asia, with a focus on the Kyrgyz Republic and the Republic of Tajikistan. The project was funded through the World Bank.

The project focused on strengthening regional coordination and information sharing, with the goal of ensuring that each of the National Hydrometeorological Services (NHMSs) in the region can share, use, exchange and archive common hydrometeorological data and information, and that each agency has a comparable level of expertise in the production of information and delivery of hydrometeorological services.

As part of CAHMP, the national Hydromet networks have been upgraded to include modern automatic observations. One key station considered under this project has been the Gorbunov station on the Fedchenko glacier, although its completion is still work in progress.

Contributions to High Asia Runoff From Ice and Snow (CHARIS)

The Contributions to High Asia Runoff from Ice and Snow (CHARIS) project aimed to distinguish the specific contributions of seasonal snow and glacier ice melt to runoff in five major river basins of High Mountain Asia: Ganges, Brahmaputra, Indus, Amu Darya, and Syr Darya. The model used for this project partitions melt contributions to stream flow into volume originating from seasonal snow and volume originating from glacier ice. Input data consist of surface temperature, along with the areas of exposed glacier ice (EGI), snow on glacier ice (SOI) and snow on land (SOL). Output data are the volume of melt originating from each of those three surface types. Data are available online.

Across High Mountain Asia, the amount, timing and spatial patterns of snow and ice melt play important roles in providing water for downstream users such as irrigation, hydropower generation and population. CHARIS was funded by the United States Agency for International Development (USAID) (Armstrong et al. (2019)). The project included numerous field expeditions and capacity building activities across High Mountain Asia.

Swiss Polar Institute Flagship Programme (PAMIR)

The Swiss Polar Institute Flagship Programme PAMIR is an interdisciplinary undertaking to characterize the current state of the Pamir cryosphere to an unprecedented degree, as well as its impacts on ecosystems, hazards and water resources. The focuses of PAMIR include: extracting an ice core to unlock a climate archive of the past millennium; assessing the distribution of permafrost; measuring the mass balance and accumulation of glaciers at a regional level; and disentangling regional cryospheric hazards by understanding glaciological and permafrost drivers. These ambitious scientific objectives aim to generate important historic and contemporary understanding of this key headwater region, enabling a better understanding of the future of this water tower.

Green Central Asian Water Initiative (CAWa-Green)

The CAWa-Green project was launched in February 2020 as a follow-up project of the previously-accomplished CAWa Project (2008–2019), funded by the German Federal Foreign Office as the scientific-technical component of the Water Initiative for Central Asia ("Berlin Process" and "Green Central Asia"). The CAWa-Green project, in the frame of the "Green Central Asia Initiative", was intended to contribute to a sound scientific and reliable regional data basis for the development of sustainable water management strategies in Central Asia.

The regional research network Central Asian Water (CAWa) consisted of 18 remotely operated multiparameter stations (ROMPSs) in Central Asia (Schöne et al. 2013, Zech et al. 2021). These stations were installed by the German Research Centre for Geosciences (GFZ) in Potsdam, Germany, in close cooperation with Central Asia Institute for Applied Sciences (CAIAG), the National Hydrometeorological Services of Tajikistan and Uzbekistan, the Ulugh Beg Astronomical Institute in Tashkent (Uzbekistan) and the Kabul Polytechnic University (Afghanistan).

These stations support the establishment of a reliable basis of meteorological and hydrological data, especially in remote areas with extreme climate conditions, for applications in climate and water monitoring in Central Asia. Over ten years of data have been provided for an area of scarce station distribution and with limited open-access data, which can be used for a wide range of scientific or engineering applications. The data are made publicly available with the digital object identifier (DOI) https://doi.org/10.5880/GFZ.1.2.2020.002 (Zech et al., 2020) or via the Sensor Data Storage System (SDSS) at http://sdss.caiag.kg
(last access: 24 April 2025).

Finnish – Tajikistan Meteorology Project (FINTAJ)

Three phases of the Finnish Meteorological Institutes (FMI) programme have supported both Tajik and Kyrgyz Hydromet Agencies with activities that included objectives on improving the glaciological and atmospheric observations at selected glaciers, e.g. installing AWSs in the proximity of glaciers, utilizing Uncrewed Aerial Vehicles (UAVs) for airborne studies of glaciers, as well as holding joint international summer schools (Aalto et al. 2017).

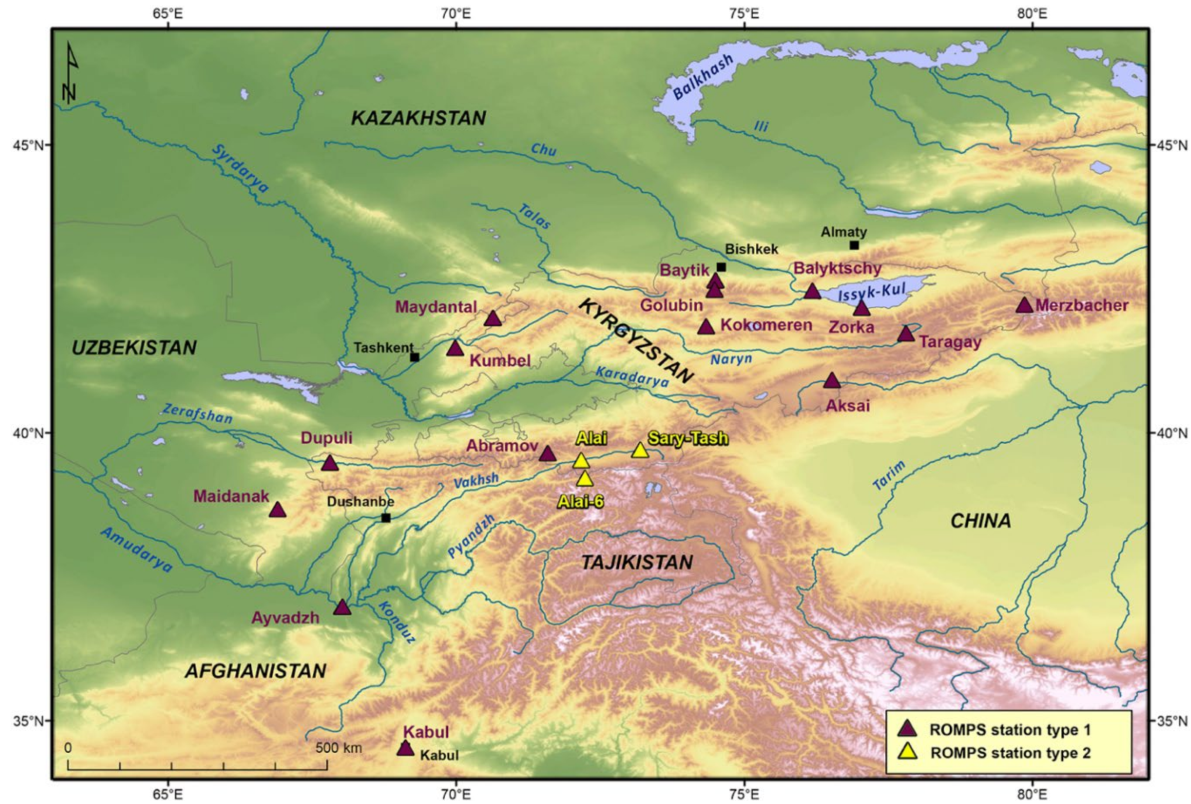

Figure 23. CAWa/ CAWa-Green network consisting primarily of hydro-meteo stations

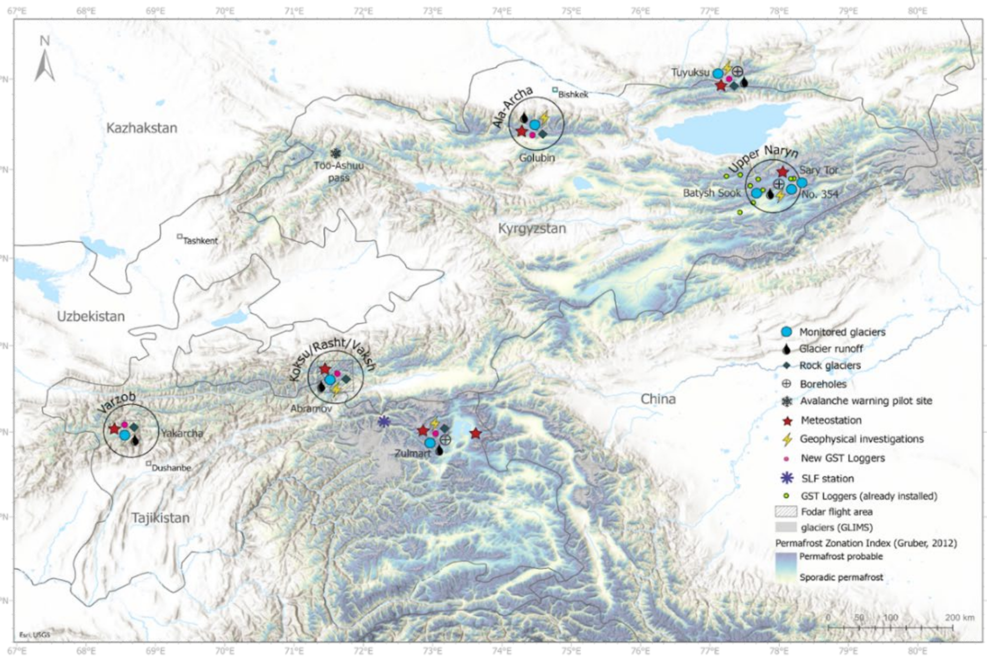

Figure 24. CROMO-ADAPT measurement network aims to monitor the entire Cryosphere system with collocated measurements of snow, glaciers and permafrost.

Figure 25. High-mountain hydrometeorological station near Golubin Glacier, Kyrgyzstan (CAWa)

7. ANALYSIS OF INSTITUTIONS RESPONSIBLE FOR CRYOSPHERE MONITORING

The pre-1990 system of "Hydrometeorological Agencies", inherited by the countries of Central Asia, integrate the functions of meteorological and hydrological monitoring and forecasting. The Hydromet agencies have historically played a centralized role in monitoring of weather, climate, water, snow and glaciers. While there is a rich history of organized cryosphere research and exploration expeditions throughout the 20th century, today cryosphere monitoring is mostly under the remit of region's Hydromet agencies. Their primary focuses are water resources, support for extensive irrigation schemes and hydropower production.

During the last two decades, research-based institutes have started to play a greater role in these monitoring activities, partially supported by international projects. An example is CAIAG, which was founded in 2002 by the Government of the Kyrgyz Republic and the German Centre for Geosciences in Potsdam. CAIAG plays an important role in geodynamics and geo-hazards, climate, water and geoecology, and the use and protection of natural resources. Additionally, CAIAG plays an important role in capacity building of the next generation of domain experts, and supports national agencies in their mandates, e.g. joint CAIAG-Hydromet glacier monitoring expeditions.

Considering the transboundary nature of the cryosphere in the region, particularly the water resources that stem from it, regional engagements are crucial to promote shared research programmes, which engage the Hydromet agencies and other institutions with similar interests. Currently, there are several regional engagement mechanisms, for example:

- The Interstate Commission for Water Coordination of Central Asia (ICWC), founded in 1992, is one of the oldest examples of transboundary cooperation post-USSR. The ICWC is responsible for cooperation among Aral Sea Basin countries in joint management of transboundary water resources (surface, ground and return water) and maintenance of sustainable natural and hydro-ecological processes on transboundary water resources.

- Central Asia Regional Environmental Centre (CAREC) is a regional non-governmental organization, with a climate portal that includes several country-level and global data platforms.

- The Central Asian Regional Glaciological Centre, in Almaty (Kazakhstan) operates under the auspices of UNESCO as a Category 2 organization. It aims to improve the coordination of research projects, to increase the capacity in Central Asian countries to conduct glaciological research, and to coordinate the development of regional activities and training programmes on monitoring systems for glaciers, snow and permafrost.

- The University of Central Asia (UCA) is based in Khorog (Tajikistan), with a branch in Naryn (Kyrgyzstan). It has a research unit that conducts interdisciplinary research to support mountain regions in Central Asia, as well as a Mountain Societies Research Institute (MSRI), which acts as a knowledge centre for data and information. The centre has published research on transboundary freshwater use in Kyrgyzstan and Tajikistan.

- Blue Peace Central Asia, supported by SDC and with the secretariat based at CAREC, promotes regional water cooperation in order to: address increasing competing interests in water; foster understanding of the region as interdependent; and support common solutions on water for the benefit of all.

A special note on Afghanistan

Without the strong historical monitoring legacy of the post-Soviet Central Asian states, Afghanistan had an opportunity to modernize rapidly. An example of this was the water reform law in the 2000s that brought modern basin centric water management to the country. This also served as a blueprint for neighbouring Tajikistan.

However, despite modernization programmes from large infrastructure investments that included about 200 new hydrometeorological stations during the 2000s, security challenges have constantly limited progress beyond the capital Kabul. Since 2021, all internationally supported activities have been stopped and even basic meteorological observations are at risk.

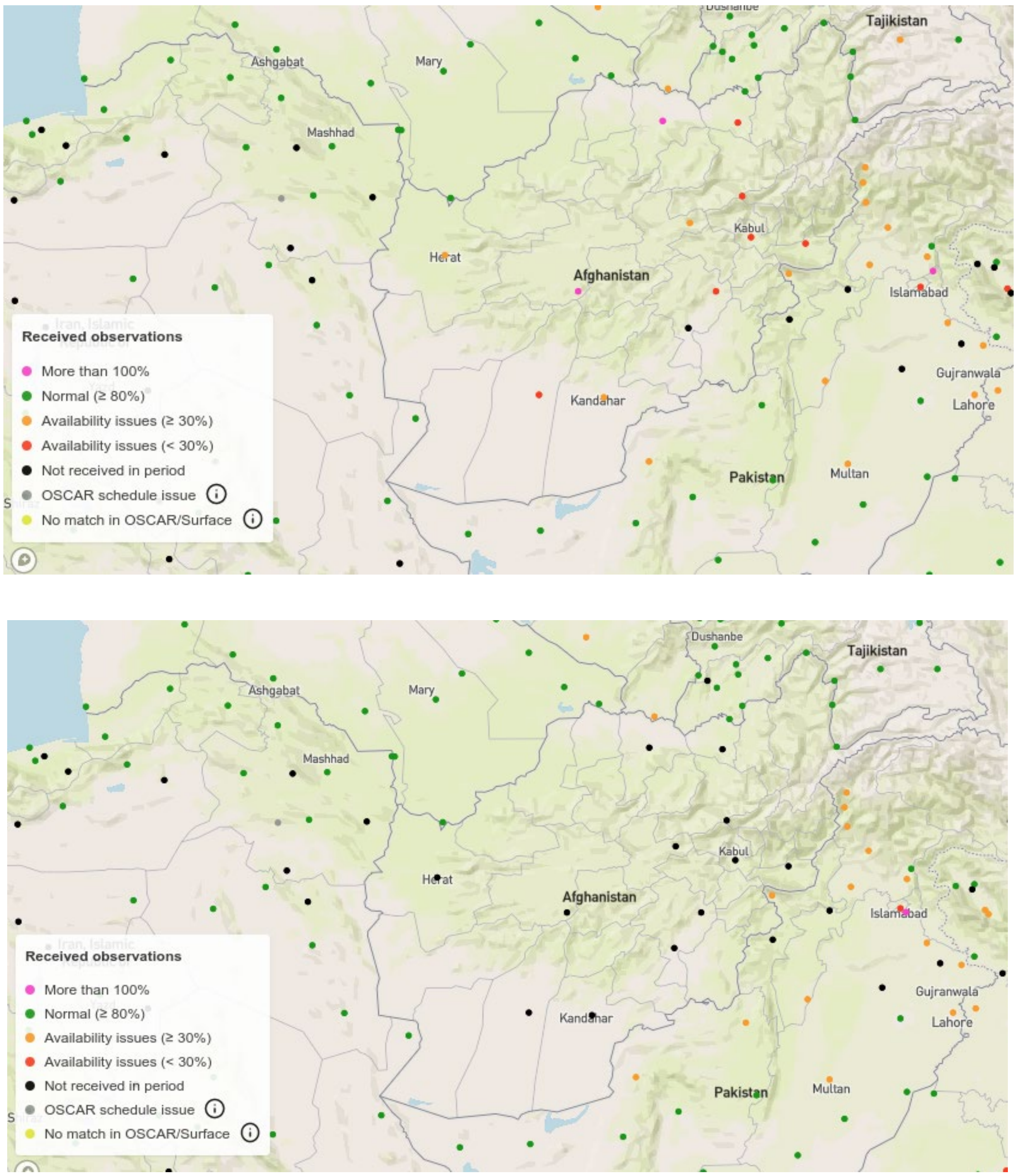

Figure 26. Status of the Afghan Meteo Network 2019–09–01 (top) and 2022–09–01 (bottom) showing the collapse of WMO reporting after 2021.

Source: https://wdqms.wmo.int/

8. RECOMMENDATIONS ON GAPS AND OPPORTUNITIES FOR CRYOSPHERE MONITORING IN CENTRAL ASIA

Inter-institutional collaboration

A key marker of success is the ability for different institutions, whether scientific or operational, to collaborate and mutually benefit from diverse focus and expertise. This requires clarity of mandates which limit the perception of competition (often related to external funding). CAIAG can be considered a good example of healthy collaboration between science and operations, which promotes scientific progress and development of innovative operational systems.

Developing the next generation of experts

Capacity building related to cryosphere monitoring and prediction is key in all of the Central Asian institutions. While much knowledge exists in Central Asia with well-trained experts, there still remains a dependence on Soviet-era syllabi, methodologies and protocols. While these can be robust and should not be simply dismissed as outdated, efforts need to be made to enable local experts to take advantage of cutting-edge data management techniques, data products and methodologies, and to integrate new tools into existing decision-making processes. This process starts in schools and universities to ensure that students with the required skills are entering the workforce.

Furthermore, international projects need to include sustained and diverse capacity-building activities by working with local academics and training the next generation of scientists. This can be achieved through joint expeditions, scientific study exchanges, thesis supervision and summer schools, with the aim of transferring sites entirely to national partners, as exemplified by the CATCOS/CICADA/CROMO-ADAPT projects, the GFZ support for CAIAG, and projects by other institutes as part of the Green Central Asia framework. To ensure a real and lasting impact, this is a long-term process that requires multiple project cycles and sustained commitment.

Modern data transmission and data management

Many donors and international projects are promoting new data products, measurement equipment and analytical methods. There are multiple benefits from the operational agencies integrating these new data streams into their decision-making infrastructure. However, despite over a decade of investment in automatic observation equipment (AWS, Hydroposts), the Hydromet Agencies often struggle to integrate these high-frequency data streams into operational decision making.

To achieve this goal, proposals for internationally-funded projects need to treat data transmission capabilities as a core deliverable, together with solutions to ensure that data is confirmed as received by the operational institutions, e.g. by using the innovative technologies promoted through WMO or other collaborative mechanisms.

Real-time data transmission from stations installed in remote high mountain locations requires sustained communication solutions that are costly to operate but provide significant benefits. The connection between the server collecting gigabytes/terabytes of automatic monitoring data streams and the hydrological or meteorological forecaster, which is often missing, has to be designed from the onset of new projects.

At the same time, digitizing existing non-digital datasets, derived from decades of previous cryospheric monitoring, is a crucial step in developing digital inventories of long-term cryospheric changes in the region.

Standardization and Open Data

Open data is key to progress, as defined in the WMO Unified Data Policy. While primary data is often regarded as a commodity, particularly in Central Asia, there are significant benefits in viewing raw data as a resource upon which value-added services can be built.

To avoid duplication of measurements and maximise the benefits of limited resources, access to national-level data products would significantly enhance the ability to make scientific progress and provide results to relevant institutions. Given the transboundary nature of the cryosphere in Central Asia, data sharing at a regional level is critical in solving regional issues and adapting to the impacts of climate change.

Furthermore, internationally funded projects in the region have generated significant amounts of data over the last decade, and many more datasets are expected to be generated in the future. The ability to consolidate existing data sources into standardised formats, and make them discoverable through existing mechanisms, e.g. WMO's Information System (WIS), would advance the ability to accurately assess current and future observation gaps, and enable the directing of future investments to address these gaps and avoid further duplication.

International observation network

Most of the high-mountain observations in Central Asia are supported by international research projects, which have provided financial and technical support for the successful deployment and maintenance of these networks. These observing stations provide significant national and global scientific value, without which global and regional understanding of changes of the global cryosphere in the changing climate would not be possible.

Therefore, there are strong arguments for recognizing and incorporating such monitoring sites into national and international networks (e.g. WMO Global Cryosphere Watch (GCW)) and registering them in WMO observation databases (e.g. OSCAR/Surface) to ensure sustainable future operation and integration with well-established data management systems operated by national or international institutions. To ensure this, national agencies will need to agree to implement international scientific standards for data sharing, such as those developed by WMO, which form an important basis for enhancing the use of data from these networks.

9. REFERENCES

Aalstad, K., S. Westermann, T. V. Schuler, J. Boike, and Bertino, L., 2018: Ensemble-based assimilation of fractional snow-covered area satellite retrievals to estimate the snow distribution at Arctic sites. *The Cryosphere*, 12(1), 247–270, https://doi.org/10.5194/tc-12-247-2018

Aalto, J., Kämäräinen, M., Shodmonov, M., Rajabov, N., and Venäläinen, A., 2017: Features of Tajikistan's past and future climate. *International Journal of Climatology*, 37(14), 4949–4961, https://doi.org/10.1002/joc.5135

Ackroyd, C., S. M. Skiles, K. Rittger, and Meyer, J., 2021: Trends in Snow Cover Duration Across River Basins in High Mountain Asia from Daily Gap-Filled MODIS Fractional Snow Covered Area. *Frontiers in Earth Science*, 9(713145), https://doi.org/10.3389/feart.2021.713145.

Armstrong, R.L., Rittger, K., Brodzik, M.J. , Racoviteanu, A., Barrett, A.P., Khalsa, S.J.S., Raup, B., Hill, A.F., Khan, A.L., Wilson, A.M. and Kayastha, R.B., 2019: Runoff from glacier ice and seasonal snow in High Asia: separating melt water sources in river flow. *Regional Environmental Change*, 19, 1249–1261, https://doi.org/10.1007/s10113-018-1429-0

Barandun, M., J. Fiddes, M. Scherler, T. Mathys, T. Saks, D. Petrakov, and Hoelzle, M., 2020: The state and future of the cryosphere in Central Asia. *Water Security*, 11(100072), https://doi.org/10.1016/j.wasec.2020.100072

Bedford, D. and Tsarev, B., 2001: *Central Asian Snow Cover from Hydrometeorological Surveys, Version 1*. Boulder, Colorado USA, NSIDC: National Snow and Ice Data Center, https://doi.org/10.7265/N51Z4291 [accessed: 24.04.2025]

Brun, F., Lambrecht, A., Mayer, C., Berthier, E., Dehecq, A., Rezaei, J., and Deschamps-Berger, C., 2022: Multi-temporal elevation changes of Fedchenko Glacier, Tajikistan (1928-1958-1980-2010-2017-2019), *EGU General Assembly Conference Abstracts* (EGU22-5833), https://doi.org/10.5194/egusphere-egu22-5833, 2022

Deschamps-Berger, C., S. Gascoin, E. Berthier, J. Deems, E. Gutmann, A. Dehecq, D. Shean, and Dumont, M., 2020: Snow depth mapping from stereo satellite imagery in mountainous terrain: evaluation using airborne laser-scanning data, *The Cryosphere*, 14(9), 2925–2940, https://doi.org/10.5194/tc-14-2925-2020

Dyurgerov, M.B., Meier, M. and Armstrong, R.L., 2002: *Glacier mass balance and regime: data of measurements and analysis* (Vol. 55), Boulder, Colorado, USA: Institute of Arctic and Alpine Research, University of Colorado.

Eberhard, L. A., P. Sirguey, A. Miller, M. Marty, K. Schindler, A. Stoffel, and Bühler, Y., 2021: Intercomparison of photogrammetric platforms for spatially continuous snow depth mapping, *The Cryosphere*, 15(1), 69–94, https://doi.org/10.5194/tc-15-69-2021

Fiddes, J., K. Aalstad, and Westermann, S., 2019: Hyper-resolution ensemble-based snow reanalysis in mountain regions using clustering. *Hydrology and Earth System Sciences*, 23(11), 4717–4736, https://doi.org/10.5194/hess-23-4717-2019

Fiddes, J., and Gruber, S., 2014: TopoSCALE v.1.0: downscaling gridded climate data in complex terrain. *Geoscientific Model Development*, 7(1), 387–405, https://doi.org/10.5194/gmd-7-387-2014

Gafurov, A., S. Lüdtke, K. Unger-Shayesteh, S. Vorogushyn, T. Schöne, S. Schmidt, O. Kalashnikova, and Merz, B**.,** 2016: MODSNOW-Tool: an operational tool for daily snow cover monitoring using MODIS data. *Environmental Earth Sciences*, 75(1078), https://doi.org/10.1007/s12665-016-5869-x

Gruber, S., 2012: The Cryosphere Derivation and analysis of a high-resolution estimate of global permafrost zonation. *The Cryosphere*, 6(1), 221–233, https://doi.org/10.5194/tc-6-221-2012

Hoelzle, M., Azisov, E., Barandun, M., Huss, M., Farinotti, D., Gafurov, A., Hagg, W., Kenzhebaev, R., Kronenberg, M., Machguth, H. and Merkushkin, A., 2017: Re-establishing glacier monitoring in Kyrgyzstan and Uzbekistan, Central Asia. *Geoscientific Instrumentation, Methods and Data Systems*, 6(2), 397–418, https://doi.org/10.5194/gi-6-397-2017

Lievens, H., Demuzere, M., Marshall, H.P., Reichle, R.H., Brucker, L., Brangers, I., de Rosnay, P., Dumont, M., Girotto, M., Immerzeel, W.W. and Jonas, T., 2019: Snow depth variability in the Northern Hemisphere mountains observed from space. *Nature Communications*, 10(4629), https://doi.org/10.1038/s41467-019-12566-y

Kuzmichenok, V., 2006: Monitoring of water, snow and glacial resources of Kyrgyzstan. in Assessment of snow, glacier and water resources in Asia. Almaty, Kazakhstan. *UNESCO-IHP and German IHP/HWRP National Committee*, 8.

Marchenko, S. S., a. P. Gorbunov, and Romanovsky, V.E., 2007: Permafrost warming in the Tien Shan Mountains, Central Asia. *Global and Planetary Change*, 56(3-4), 311–327, https://doi.org/10.1016/j.gloplacha.2006.07.023

Margulis, S. A., M. Girotto, G. Cortés, and Durand, M., 2015: A Particle Batch Smoother Approach to Snow Water Equivalent Estimation. *Journal of Hydrometeorology*, 16(4), 1752–1772, https://doi.org/10.1175/JHM-D-14-0177.1

Noetzli, J., Arenson, L.U., Bast, A., Beutel, J., Delaloye, R., Farinotti, D., Gruber, S., Gubler, H., Haeberli, W., Hasler, A. and Hauck, C., 2021: Best Practice for Measuring Permafrost Temperature in Boreholes Based on the Experience in the Swiss Alps. *Frontiers in Earth Science*, 9(607875), https://doi.org/10.3389/feart.2021.607875

Pertziger, F., 1996: Abramov glacier data reference book: climate, runoff, mass balance. *Central Asian Regional Research Hydrometeorological Institute, Tashkent, Republic of Uzbekistan*.

RGI Consortium, 2017. *Randolph Glacier Inventory – A Dataset of Global Glacier Outlines, Version 6*. Boulder, Colorado USA, NSIDC: National Snow and Ice Data Center, https://doi.org/10.7265/4m1f-gd79 [accessed: 24.04.2025]

Schöne, T., Zech, C., Unger-Shayesteh, K., Rudenko, V., Thoss, H., Wetzel, H.U., Gafurov, A., Illigner, J. and Zubovich, A., 2013: A new permanent multiparameter monitoring network in Central Asian high mountains – from measurements to data bases. *Geoscientific Instrumentation, Methods and Data Systems*, 2(1), 97–111, https://doi.org/10.5194/gi-2-97-2013

Stockton, E.J., Burn, C.R., and Nelson, F.E., (eds.), 2022: Country Reports 2021: Reports from the Adhering Bodies of the International Permafrost Association. *International Permafrost Association (IPA)*, https://doi.org/10.52381/CR.2021.1

Treichler, D., and Kääb, A., 2017: Snow depth from ICESat laser altimetry — A test study in southern Norway. *Remote Sensing of Environment*, 191, 389–401, https://doi.org/10.1016/j.rse.2017.01.022

World Bank, 2022: ICON-In-the-Cloud (ICONIC): Piloting Numerical Weather Prediction on Commercial Cloud Services for Central Asia (English). *Washington, D.C.: World Bank Group*, Zech, C., Schöne, T., Illigner, J., Stolarczuk, N., Queißer, T., Köppl, M., Thoss, H., Zubovich, A., Sharshebaev, A., Zakhidov, K. and Toshpulatov, K., 2021: Hydrometeorological data from a Remotely Operated Multiparameter Station network in Central Asia. *Earth System Science Data*, 13(3), 1289–1306, https://doi.org/10.5194/essd-13-1289-2021