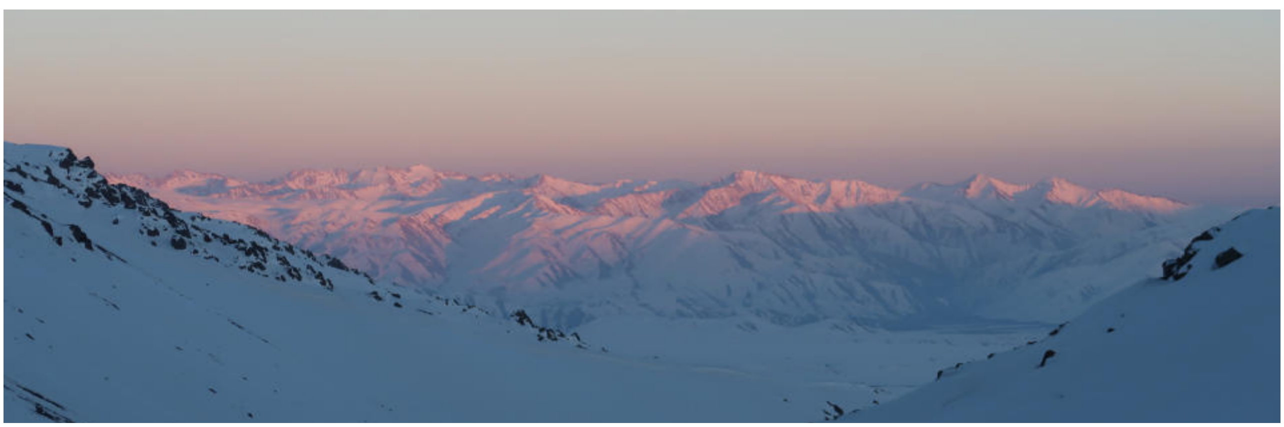
High-Resolution Climate Change Impact Scenarios for Central Asian Snow Cover



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Snow modelling expert contribution to GEF-UNDP-UNESCO Cryosphere project on "Strengthening the resilience of Central Asian countries by enabling regional cooperation to assess glacio-nival regional systems to develop integrated methods for sustainable development and adaptation to climate change."

Contents

Abbreviations

CMIP6:	Coupled Model Intercomparison Project Phase 6
DEM:	Digital Elevation Models
ECMWF:	European Centre for Medium-Range Weather Forecasts
GEF:	Global Environment Facility
GLOF:	Glacier Lake Outburst Flood
GLIMS:	Global Land Ice Measurements from Space
HS:	Snow Height
ISIMIP:	Inter-Sectoral Impact Model Intercomparison Project
RCP:	Representative Concentration Pathway
RGI:	Randolph Glacier Inventory
ROF:	Runoff from Snowpack
SRTM:	Shuttle Radar Topography Mission
SSP:	Shared Socioeconomic Pathway
SWE:	Snow Water Equivalent
UNESCO:	United Nations Educational, Scientific and Cultural Organization

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Executive Summary

This report presents a comprehensive assessment of future snow climate scenarios in Central Asia, with a focus on informing water resource management, climate adaptation, and regional planning. Using the TopoCLIM framework, we generated high-resolution topoclimatic projections that capture the complex interactions between terrain and climate in mountainous regions. These projections serve as the foundation for simulating future snowpack dynamics - including snow height (HS), snow water equivalent (SWE), and runoff (ROF) - under multiple climate change scenarios.

We analyzed historical and projected snow conditions across key watersheds in Central Asia, identifying shifts in snow accumulation timing, snow-covered area, and meltwater availability. Our findings indicate a trend toward earlier snowmelt, declining snowpack volume at lower elevations, and significant regional variability linked to elevation and exposure.

To support knowledge dissemination and accessibility, we developed a suite of interactive web applications (Figure 21, 22) that allow stakeholders to visualize climate-driven snow changes at both regional and basin scales. These tools empower decision-makers, researchers, and practitioners to explore scenario-based outputs and incorporate them into adaption plans.

The combination of advanced downscaling methods, robust scenario modeling, and user-facing tools positions this work as a resource for anticipating and managing snow-related impacts in Central Asia's vulnerable mountain systems.

1. Background

Importance of the cryosphere for regional development

The cryosphere, comprising all areas on Earth where water is in its frozen form, such as glaciers, ice sheets, snow cover, and permafrost, plays an important role in regulating the planet's climate, supporting ecosystems, and sustaining human livelihoods. Covering vast regions of the polar areas and high-altitude mountain ranges, the cryosphere acts as a vital source of freshwater, influences atmospheric circulation, and serves as a sensitive indicator of climate change. Therefore, monitoring the cryosphere and improving our understanding of its dynamics is of critical importance, particularly for regions heavily dependent on snowmelt and glaciers for water resources, agriculture, hydropower, and regional stability.

In many parts of the world, especially in mountainous regions such as Central Asia, glaciers and seasonal snowpacks are essential sources of freshwater. According to Immerzeel et al. (2020), the Hindu Kush-Himalaya region alone supports the livelihoods of nearly 240 million people downstream, providing irrigation for agriculture, drinking water, and hydropower generation. As the climate warms, changes in glacier mass and snowpack duration are projected to disrupt these hydrological patterns, leading to water shortages in the long term (Huss et al., 2017).

Impacts of climate change on regional snow cover

Future snow cover scenarios are critical for understanding the long-term impacts of climate change, especially in regions like Central Asia where snowmelt can be up to 80% of total runoff (Armstrong et al 2019, Kraaijenbrink e al 2021) and therefore plays a key role in water availability. Snowpacks act as natural reservoirs, storing precipitation during winter months and gradually releasing it as meltwater in spring and summer. This seasonal runoff is essential for agriculture, hydropower, drinking water supplies, and ecosystem health. However, rising temperatures are altering the dynamics of snow accumulation and melt, which can have profound consequences for water resources, disaster management, and regional economies.

One of the primary reasons snowpack climate change scenarios are so important is that they can help to predict shifts in snow season length, snow volume, and the timing of snowmelt. Warmer winters and springs may lead to earlier snowmelt, reducing the amount of water available later in the year, when demand is often highest for irrigation and human consumption. In some areas, this could lead to severe water shortages during critical growing seasons, affecting agricultural productivity and food security. Central Asia, in particular, relies heavily on snowmelt to sustain its agricultural sectors, making it highly vulnerable to these changes.

Snowpack scenarios are also essential for assessing the potential for increased natural hazards. Rapid snowmelt, exacerbated by climate warming, can trigger more frequent and severe floods, threatening infrastructure and communities downstream. This is especially relevant in mountainous regions, where snowmelt-driven rivers can experience sudden increases in flow, causing flash floods and damaging critical infrastructure such as dams, bridges, and irrigation systems. Understanding future snowmelt patterns through climate scenarios helps in designing early warning systems and adapting infrastructure to withstand these evolving risks.

Moreover, snowpack scenarios are crucial for managing transboundary water resources. In Central Asia, countries share water systems that originate from snow-fed mountain ranges like the Tien Shan and Pamirs. Changes in snowmelt timing and volume could disrupt existing water-sharing agreements and exacerbate tensions between upstream and downstream nations. Having accurate snowpack climate change scenarios enables policymakers to anticipate these shifts and negotiate water management strategies that are more adaptive to future conditions.

In summary, snowpack climate change scenarios provide vital insights into how warming temperatures will affect water availability, disaster risks, and regional stability. They allow for better planning and adaptation strategies, ensuring that water resources are managed sustainably and communities are protected from the emerging threats posed by climate change.

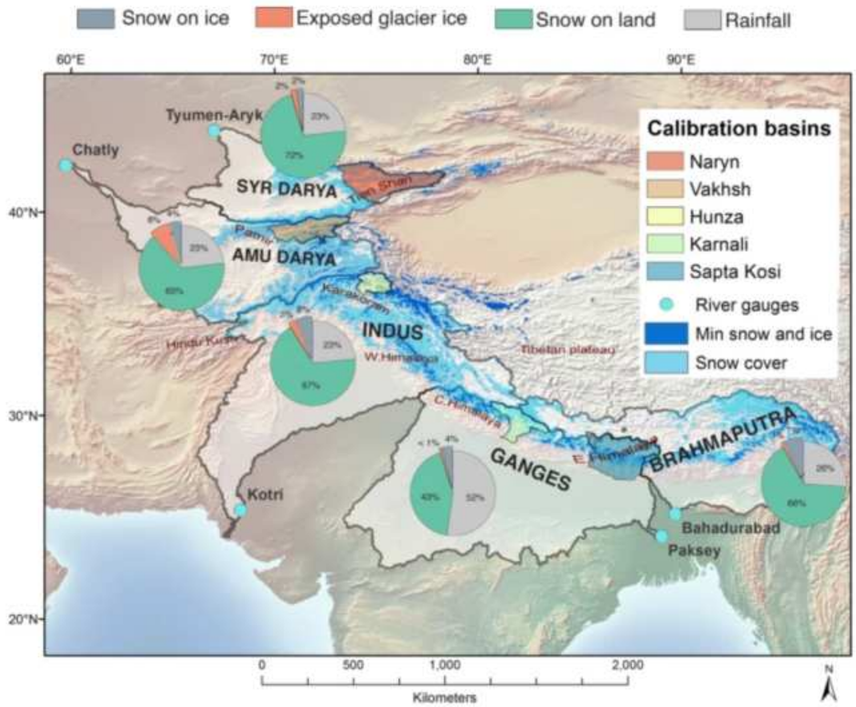

Figure 1: Results from the CHARIS project demonstrated the dominance of snow cover based runoff in all major basins of high mountain Asia, except for the monsoon dominated Ganges (Armstrong et al 2019).

2. Methodology

The methodology for generating 21st Century snow climate scenarios in Central Asia employs the TopoCLIM model chain (Fiddes et al. 2022), which combines climate downscaling, subgrid spatial model and a snow model. This integrated approach allows for high-resolution downscaling of both current and future climate data, accounting for the region's complex topography. The TopoCLIM model chain is especially suited to mountainous and topographically diverse regions like Central Asia, where localized climate effects are critical for accurate projections

Step 1: TopoSUB – Topographical clustering

The first step involves TopoSUB., a model that clusters the landscape into representative units based on key topographic parameters such as elevation, slope, aspect, and sky view factor (Fiddes & Gruber, 2012). Central Asia's complex terrain, particularly the high-altitude regions, demands this clustering to simplify the landscape while retaining critical variability.

By grouping areas with similar topographical features, TopoSUB reduces the computational load, making it feasible to conduct high-resolution modeling over vast regions. These topographical clusters will serve as the foundation for downscaling climate data in the following steps.

Step 2: TopoSCALE – Downscaling current climate

Once the topographic clusters are created, TopoSCALE is used to downscale historical and current climate data. This step utilizes ERA5 reanalysis data, which provides high-quality atmospheric variables for the present climate. TopoSCALE adjusts these coarse-resolution data to better represent localized climate conditions by accounting for topographic effects such as altitude, exposure, and terrain-induced variations (Fiddes & Gruber, 2014).

For Central Asia, where local climate patterns are heavily influenced by mountain ranges such as the Pamirs, Tien Shan, and the Altai, this downscaling is crucial for accurately capturing temperature, precipitation, and wind patterns. The resulting high-resolution data provide a baseline of current climate conditions, enabling statistical downscaling of future projections.

Step 3: TopoCLIM – Quantile mapping and bias correction of future scenarios

The TopoCLIM framework (Fiddes et al. 2022) is then applied to downscale future climate scenarios. TopoCLIM takes CMIP6 global climate model data, which are coarse in resolution, and downscales them using the previously generated TopoSCALE baseline data. We use a routinely applied statistical downscaling technique, quantile mapping, which corrects biases in future climate projections by aligning them with the observed distributions from downscaled ERA5 reanalysis (Fiddes et al., 2022), which we consider to be our best guess current climate.

Quantile mapping ensures that future climate data, particularly those related to snowpack dynamics, like temperature and precipitation, reflect more realistic conditions in the Central Asian context. This is particularly important given the inherent biases in global climate models when applied to regions with complex terrain. The debiased projections are generated for different Shared Socioeconomic Pathways (SSPs), including SSP2-4.5 (moderate emissions) and SSP5-8.5 (high emissions), to evaluate a range of future climate trajectories. The calibration period representing the overlapping period of of the historical climate model runs and the downscaled ERA5 virtual observations (best guess reality) runs from 1995-2015.

Step 4: Snow modelling and output generation

With the debiased and downscaled future climate data from TopoCLIM, the snow model FSM (Essery 2015) is run to simulate key variables such as snow water equivalent (SWE), snow depth (HS), and snowmelt runoff (ROF). These models will help assess the impact of climate change on snowpack in Central Asia throughout the 21st century. For instance, the model chain will project shifts in the seasonal snowmelt timing, snow cover duration, and overall snow volume under different warming scenarios. The results will be provided for various time periods, curent (2000-2020) near-future (2040-2060) and far-future (2080-2100), offering projections at high spatial resolutions. These outputs will include detailed maps and time series that depict the changing snowpack conditions across Central Asia.

3. Data

ERA5 current climate data

The ERA5 dataset (Hersbach et al. 2020) is a global atmospheric reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) as part of the Copernicus Climate Change Service. It provides high-resolution hourly data on various atmospheric, land, and oceanic variables, dating back to 1950, making it one of the most comprehensive and widely used datasets for studying historical climate and weather patterns. ERA5 includes data on temperature, precipitation, wind speed, humidity, surface pressure, and radiation, among others, with a spatial resolution of approximately 31 km globally. By combining vast amounts of observational data with advanced weather forecasting models, ERA5 offers a consistent and accurate reconstruction of past weather and climate conditions. This dataset is crucial for climate research, climate impact studies, and long-term monitoring, as well as for downscaling efforts to provide localized climate data for specific regions, especially those with complex topography. This methodology uses an energy balance snow model, therefore hourly variables related to mass and energy exchange are required.

Future climate data

The CMIP6 (Coupled Model Intercomparison Project Phase 6) dataset is a comprehensive collection of climate model simulations that form the backbone of the IPCC's Sixth Assessment Report (AR6) and broader climate research. CMIP6 is the most recent iteration of the CMIP series, designed to improve our understanding of climate dynamics, future projections, and the potential impacts of different emissions scenarios. It involves contributions from climate models developed by research institutions around the world, with simulations spanning from pre-industrial times to various future projections (often extending to 2100 or beyond). CMIP6 explores a wide range of scenarios, including those based on Shared Socioeconomic Pathways (SSPs), which incorporate different assumptions about global socioeconomic development, technology, and policy decisions. The dataset provides critical insights into variables like temperature, precipitation, atmospheric composition, and more, making it essential for studying climate change, adaptation, and mitigation strategies across a range of scales and regions. In this study we employ the following four Shared Socioeconomic Pathways (SSPs) - SSP1-RCP2.6, SSP2-RCP4.5, SSP3-RCP7.0, SSP5-RCP8.5 scenarios representing the full range of development and emission scenarios covered by CMIP6 (Figure 4). Global climate model selection follow that of ISIMIP (Inter-Sectoral Impact Model Intercomparison Project) framework and includes, UKESM1.0-LL (Seller et al. 2019), IPSL CM6A-LR (Boucher et al. 2018), MRI-ESM2-0 (Yukimoto et al. 2019), and GFDL-ESM4 (Krasting et al. 2018). The models were chosen to ensure they represent the uncertainty range of future projections, especially for temperature and precipitation being relatively warm, cold, dry and wet models (Figure 2 & 3).

Table 1: Climate models and scenarios used in this study. All scenarios run from 2015-2100 and historical from 1970-2015.

Model	Historical	SSP1-RCP2.6,	SSP2-RCP4.5	SSP3-RCP7.0	SSP5-RCP8.5
UKESM1.0-LL	x	x	x	x	x
GFDL-ESM2M	x	x	x	x	x
IPSL-CM5A-LR	x	x	x	x	x
MRI-ESM2-0	x	x	x	x	x

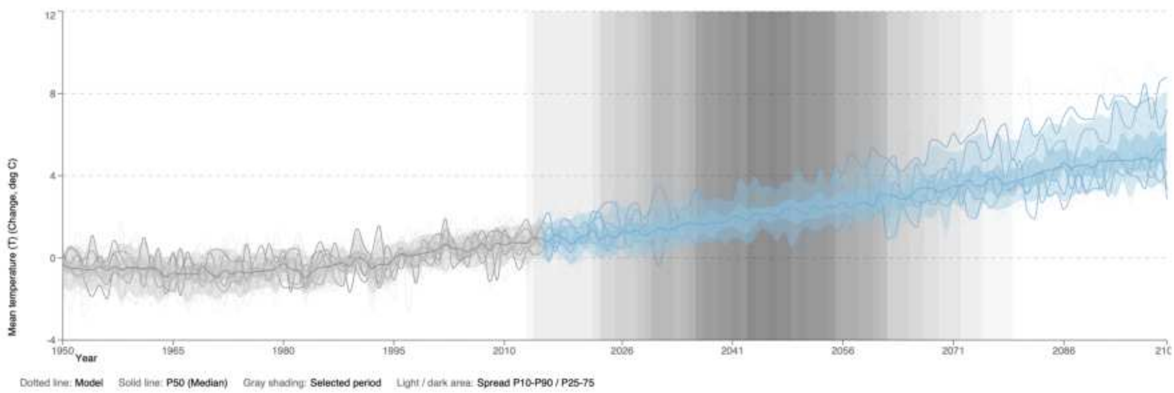

Figure 2: CMIP6 - Mean temperature (T) Change °C - Warming 2°C SSP3-7.0 (rel. to 1981-2010) - Annual (30 models) Regions: Amu Darya. Bold lines pick out the models in this study from the 30-model ensemble, demonstrating the representativeness of this subset of the ensemble. (Generated at: https://interactive-atlas.ipcc.ch/).

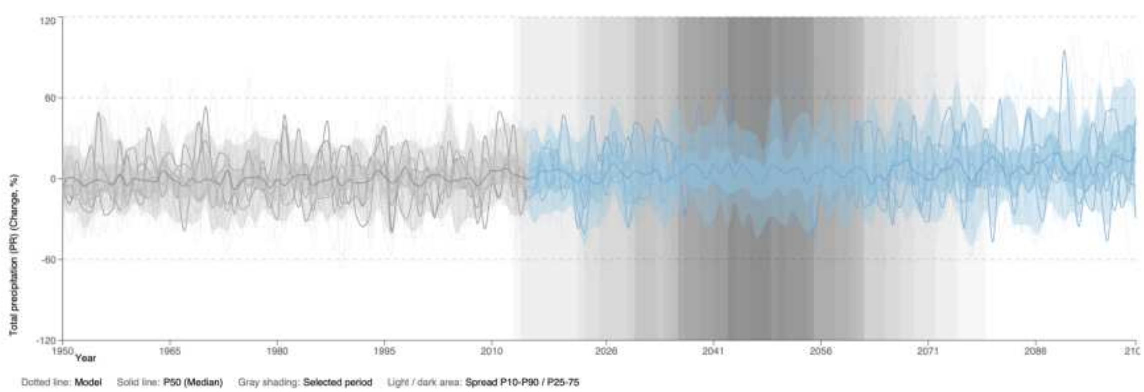

Figure 3: CMIP6 - Total precipitation (PR) Change % - Warming 2 °C SSP3-7.0 (rel. to 1981-2010) - Annual (28 models) Regions: Amu Darya. Bold lines pick out the models in this study from the 30-model ensemble, demonstrating the representativeness of this subset of the ensemble. (Generated at: https://interactive-atlas.ipcc.ch/).

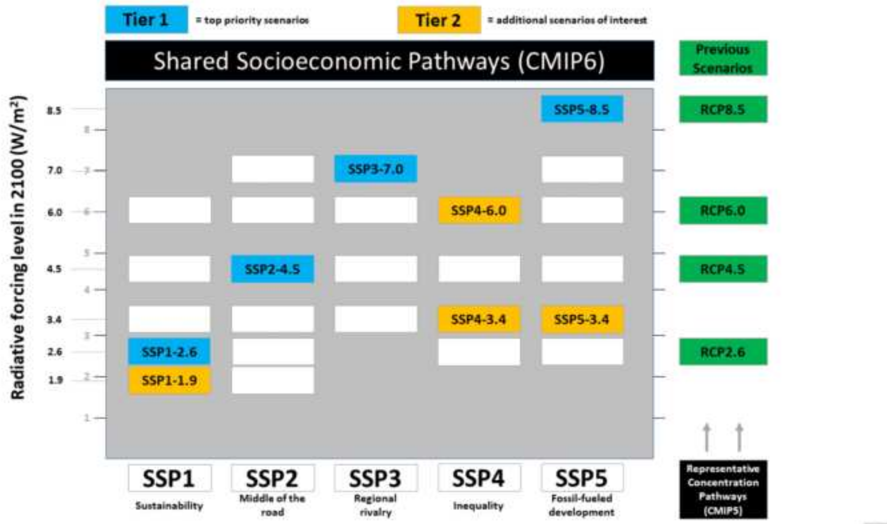

Figure 4: Shared Socio-economic Pathways and year 2100 radiative forcing combinations used in this study (source: https://climate-scenarios.canada.ca/).

Terrain data

The Shuttle Radar Topography Mission (SRTM) is a global dataset that provides high-resolution digital elevation models (DEMs) of the Earth's surface. Collected by radar instruments aboard the Space Shuttle Endeavour during an 11-day mission in February 2000, SRTM data covers nearly 80% of the Earth's land surface, including most of the populated world, between latitudes 56°S and 60°N. SRTM provides elevation data at 30-meter resolution (1-arc second) for regions globally. The dataset is resampled to 500m and used to derive parameters slope, aspect and sky view factor.

Glacier data

Glacier outlines are obtained from the Randolph Glacier Inventory (RGI) which is a globally comprehensive dataset that provides detailed information on the outlines and attributes of glaciers outside the Greenland and Antarctic ice sheets. Developed by the scientific community as part of the Global Land Ice Measurements from Space (GLIMS) initiative, the RGI is used extensively in climate and hydrological research to monitor glacier changes in response to climate warming. In this study glacier outlines will be used to mask out glaciated regions in order to dilineate seasonal snow areas.

4. Model Implementation

Climate Impact Model Chain

Figure 5 illustrates the model chain used in this report, beginning with the primary input datasets on the left. The process includes surface preprocessing, climate data downscaling and bias correction, and snow modeling, ultimately leading to the final output datasets.

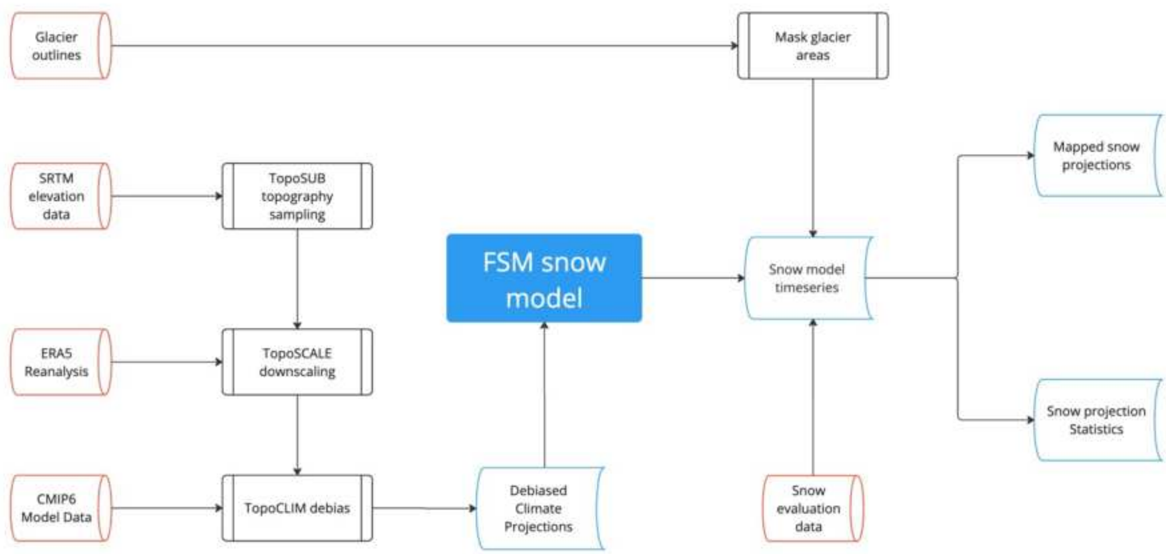

Figure 5: Schematic of the climate impact model chain implemented in this report.

Climate Impact Assessment Periods

For climate impact assessment we define three modelling periods, (1) Historical reference period (HIST) that runs **1981-2010**. (2) Near future climate scenario period (NEAR) **2021-2040** and finally (3) Far future climate scenario period (FAR) **2081-2100**. These periods follow those defined in IPCC AR6 https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-4/. A far future period impact assessment would therefore be simply obtained as follows:

Impact = FAR - HIST

Forcing Variables

The FSM snow model is driven by a set of meteorological forcing variables downscaled by TopoPyScale, precipitation is also pre-partitioned into rain and snow components, and all variables are provided at a consistent temporal resolution of 1H (Table 2). These inputs are essential for simulating snow accumulation, energy exchange, melt, and runoff.

Table 2: Forcing variables used to drive the FSM model.

Variable	Units	Description
Tair	°C	Near-surface air temperature
Sf	kg m^{-2} s^{-1}	Snowfall rate (solid precipitation), partitioned by TopoPyScale
Rf	kg m^{-2} s^{-1}	Rainfall rate (liquid precipitation), partitioned by TopoPyScale
SW	W m^{-2}	Downwelling shortwave radiation
LW	W m^{-2}	Downwelling longwave radiation
WS	m s^{-1}	Wind speed at standard height (typically 10 m)
RH	%	Relative humidity (%)
Psurf	Pa	Surface air pressure (optional, used if required by configuration)

Simulated Variables

The Table 3 presents the key simulated variables used in the study. These include snow-related parameters such as **snow depth (snd)** and **snow water equivalent (SWE)**, which are essential for understanding snow accumulation and melt. Additionally, **albedo (alb)** represents the surface reflectivity and used as a proxy for snow cover in this study, while **runoff (Rof)** quantifies the total water runoff from snow and rain. The dataset also includes **surface temperature (GST)** providing insights into energy balance and ground thermal conditions.

Table 3: Key variables simulated in this study.

Variable	Units	Description
alb	-	Effective albedo
Rof	kg m^{-2}	Cumulated runoff from snow (including rain input)
snd	m	Average snow depth

Variable	Units	Description
SWE	kg m^{-2}	Average snow water equivalent
GST	°C	Average surface temperature

5. Development of CMIP6 Climate Forcings

A fundemental task to generate the snow scenarios is the production of high-resolution (meteorological forcings. The snow model requires a full set of forcing variables as shown in Table 2. We then generated a subset of spatial grids at 1km as an additional product to be used by temperature index models. These include: daily sum of precipitation (PSUM), mean daily air temperature (TAMEAN), minimum daily air temperature (TAMIN) and maximum daily air temperature (TAMAX). The main application of these forcings is to drive the hydrological model SPHY in the GEF hydrology component as well as a product in its own right under the meteorological forcing component. The dataset is large and composed of 4 models and 4 scenarios (16 individual model chains) listed in Table 4 and constitutes around 5TB of data (1’985’600 NetCDF files).

To generate these high-resolution meteorological forcing datasets, downscaling of CMIP6 climate model outputs was a crucial step. Global Climate Models (GCMs), such as those from CMIP6, operate at coarse spatial resolutions (typically 100–200 km), which are insufficient for capturing the complex topography and microclimates characteristic of mountainous regions. Downscaling — both dynamical and statistical - bridges this gap by translating coarse-scale climate projections into fine-scale data that reflects local terrain influences such as elevation, slope, and aspect. This is particularly important in mountainous areas, where precipitation and temperature gradients can vary sharply over short distances, significantly impacting snow accumulation, melt dynamics, and hydrological processes. High-resolution downscaled data thus enables more accurate modeling of water availability, runoff, and climate impacts in these sensitive and often water-critical regions.

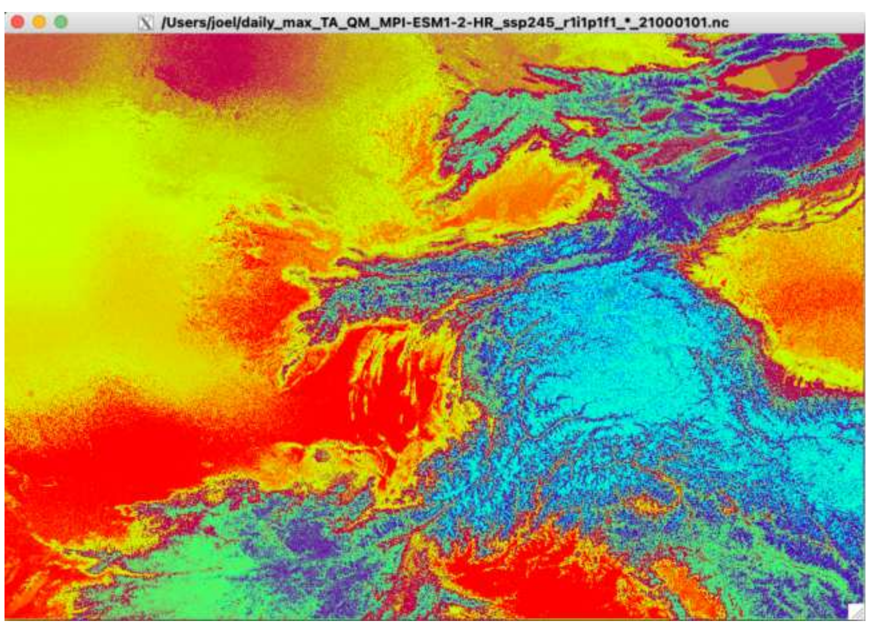

Figure 6: Example of one parameter from one model chain on a single day: TAMAX for MPI-ESM1-2-HR and scenario ssp245 on 1 January 2100.

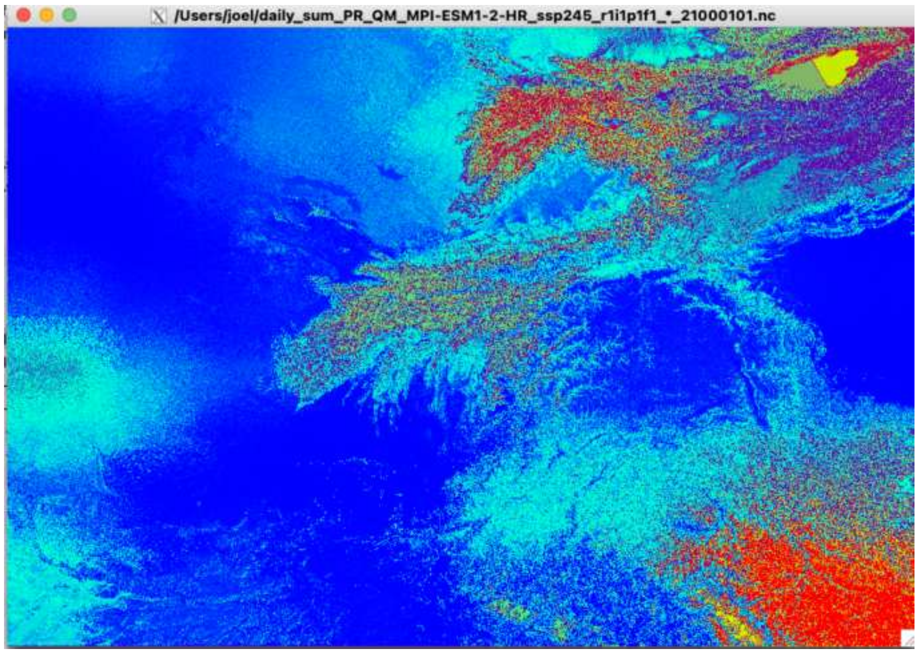

Figure 7: Example of one parameter from one model chain on a single day: PSUM for MPI-ESM1-2-HR and scenario ssp245 on 1 January 2100.

Table 4: CMIP6 Model chains developed in this report.

MODEL	SCENARIO	PSUM	TAMEAN	TAMIN	TAMAX
GFDL	ssp126	x	x	x	x
	ssp245	x	x	x	x
	ssp370	x	x	x	x
	ssp585	x	x	x	x
IPSL	ssp126	x	x	x	x
	ssp245	x	x	x	x
	ssp370	x	x	x	x
	ssp585	x	x	x	x
UKESM	ssp126	x	x	x	x
	ssp245	x	x	x	x
	ssp370	x	x	x	x
	ssp585	x	x	x	x
MPI	ssp126	x	x	x	x
	ssp245	x	x	x	x
	ssp370	x	x	x	x
	ssp585	x	x	x	x

6. Snow Scenario Results

Model Domains

Central Asia is split into two distinct modelling domains – (1) High Mountain Central Asia (HMCA) which covers the main ranges of the Hindu Kush, Pamir and Tien Shan, (2) Kazahkstan (KAZ) which covers the Tien Shan but with main focus on the vast Steppe of Kazahkstan. This report delivers analysis for the HMCA domain due to delays in obtaining forcing data from ECMWF due to systematic issues at ECMWF during Q42024 (cf. CDS forum discussions). In any case it makes sense to use the smaller HMCA to define the final analysis that will be Deliverable 3.

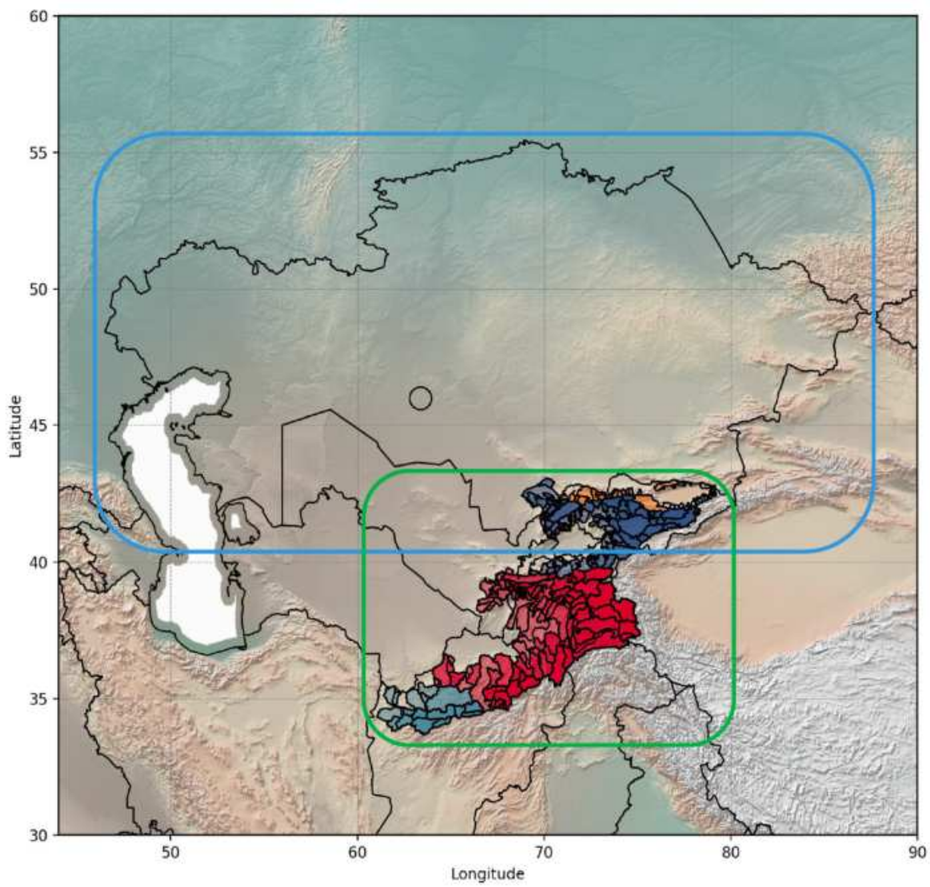

Figure 8: Overview map of the two modelling domains (1) High Mountain Central Asia (HMCA) (2) Kazakhstan (KAZ).

Domain High Mountain Central Asia

The High Mountain Central Asia (HMCA) region encompasses the rugged terrains of Northern Afghanistan, Tajikistan, Kyrgyzstan, and the eastern mountains of Uzbekistan. This domain is characterized by complex topography, high elevations, and significant seasonal snow accumulation, making it a crucial water source for downstream populations. The region includes key hydrological basins such as the Amu Darya, Syr Darya, Issyk-Kul, Chu-Talas, and Harirud, which are fed primarily by snowmelt and glacial contributions. These basins support agriculture, hydropower, and drinking water supplies for millions of people across Central Asia. Given the region's dependency on seasonal snow cover, understanding future snow dynamics under climate change scenarios is critical for water resource planning and adaptation strategies. Figure 7 illustrates these 5 basins and 221 sub-catchments used in this report and obtained from Marti et al. (2023).

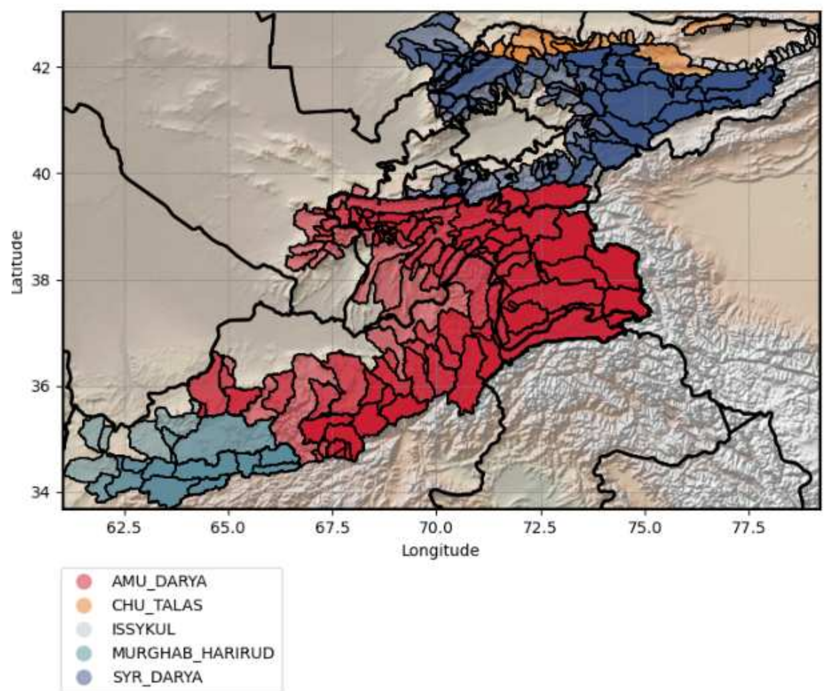

Figure 9: Model domain High Mountain Central Asia.

CMIP6 scenarios for basic trends and climate context

The CMIP6 climate projections provide essential insights into long-term trends in temperature (T), precipitation (P), and snowfall across High Mountain Central Asia and Kazahkstan. Using an ensemble of simulations, these projections allow for an assessment of seasonal variations, categorized into September–November (SON), December–February (DJF), and March–May (MAM). This seasonal breakdown is crucial for understanding shifts in snowfall accumulation and melt patterns, which directly impact regional hydrology. The analysis considers two key Shared

Socioeconomic Pathways (SSPs): SSP2-4.5, representing a moderate emissions scenario, and SSP5-8.5, reflecting a high-emissions trajectory. These large-scale climate forcings provide the climate context of this analysis and therefore highlight the broad trends that we will investigate in depth in this report.

Key observations

- Warming in all seasons, elevations and scenarios. Stronger warming in winter (DJF) at high elevations and latitudes.
- Uncertainty in precipitation, increased winter (DJF) precipitation, particularly Northern Tien Shan and Tibetan Plateau and Eastern Pamir.
- Reduced snowfall all regions in edge season of autumn (SON) and spring (MAM). Increased snowfall in winter (DJF) high latitudes, Eastern Pamir, Northern Tien Shan.
- Very strong reduction in spring snowfall (MAM) in high emission scenario SSP5-8.5.

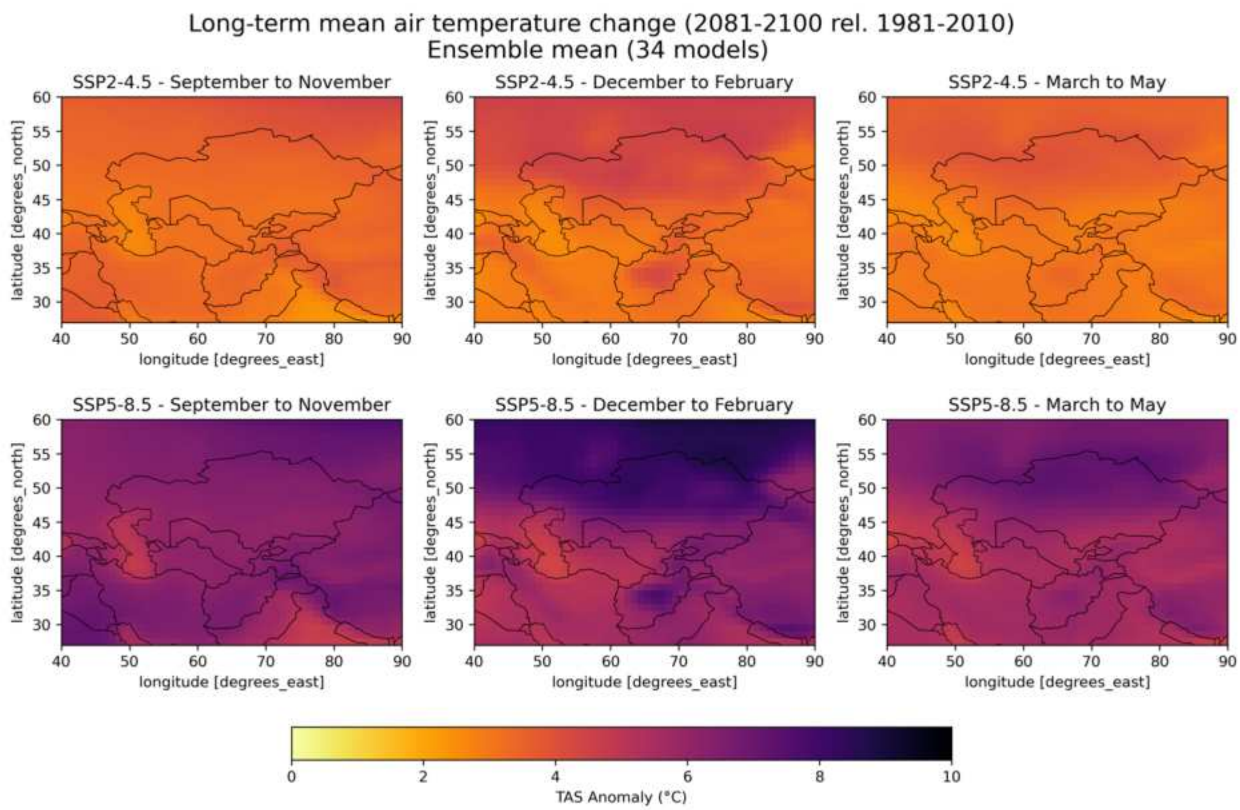

Figure 10: CMIP6 climate projections for near surface air temperature anomaly (TAS) over the model domains for moderate (SSP2-4.5) and high (SSP5-8.5) emission scenarios and three seasons (SON, DJF, MAM).

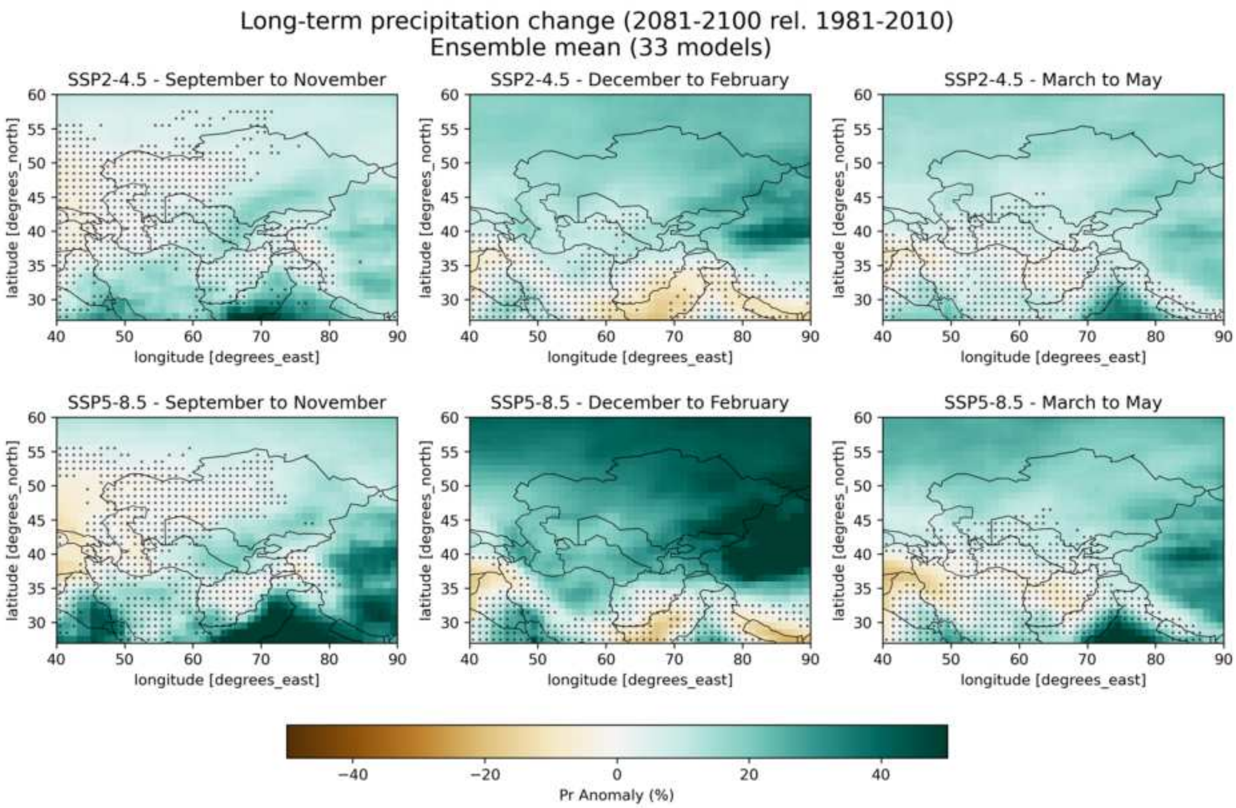

Figure 11: CMIP6 climate projections for precipitation anomaly (Pr) over the model domains for moderate (SSP2-4.5) and high (SSP5-8.5) emission scenarios and three seasons (SON, DJF, MAM).

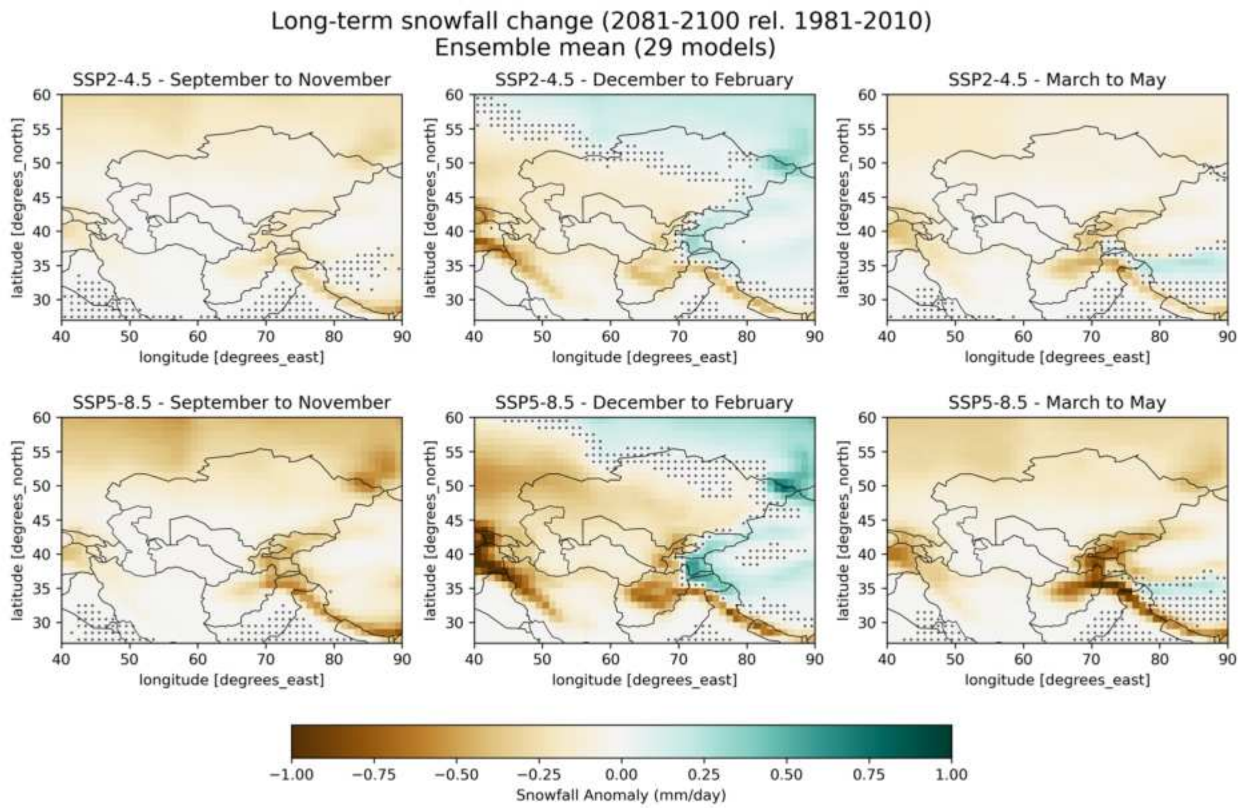

Figure 12: CMIP6 climate projections for snowfall over the model domains for moderate (SSP2-4.5) and high (SSP5-8.5) emission scenarios and three seasons (SON, DJF, MAM).

Timeseries entire region

The aim of this section is to show consolidated key timeseries results for the entire region. Figure 13 presents the evolution of climate impacts over the 21st century for a set of five time series plots showing the annual mean values of various snow and climate-related variables for the entire HMCA domain over the period 1981–2100. The historical period (1981–2015) is shown in black, while future projections under different Shared Socioeconomic Pathways (SSPs)—SSP126, SSP245, SSP370, and SSP585—are represented by different colors. Results are mean annual values, smoothed over a 10 year period to highlight long term trends.

Key observations

- Continued warming in surface temperature (GST) over the century with stabilisation mid-century only in the lowest emission scenario SSP1-2.6. 4deg of warming exceeded by end of century in highest emission scenarios.
- Decreased SWE and snd in all scenarios with greater decreases in higher emission scenarios. However at regional level some sub trends are masked such as increased winter precipitation (snowfall) at high elevations in some Northern and Eastern regions.
- Decreased albedo due to areal decrease in snow cover overall.

- Runoff is variable but shows some increase overall due to increased winter precipitation in certain areas. Decrease runoff trends are revealed in subsequent analysis

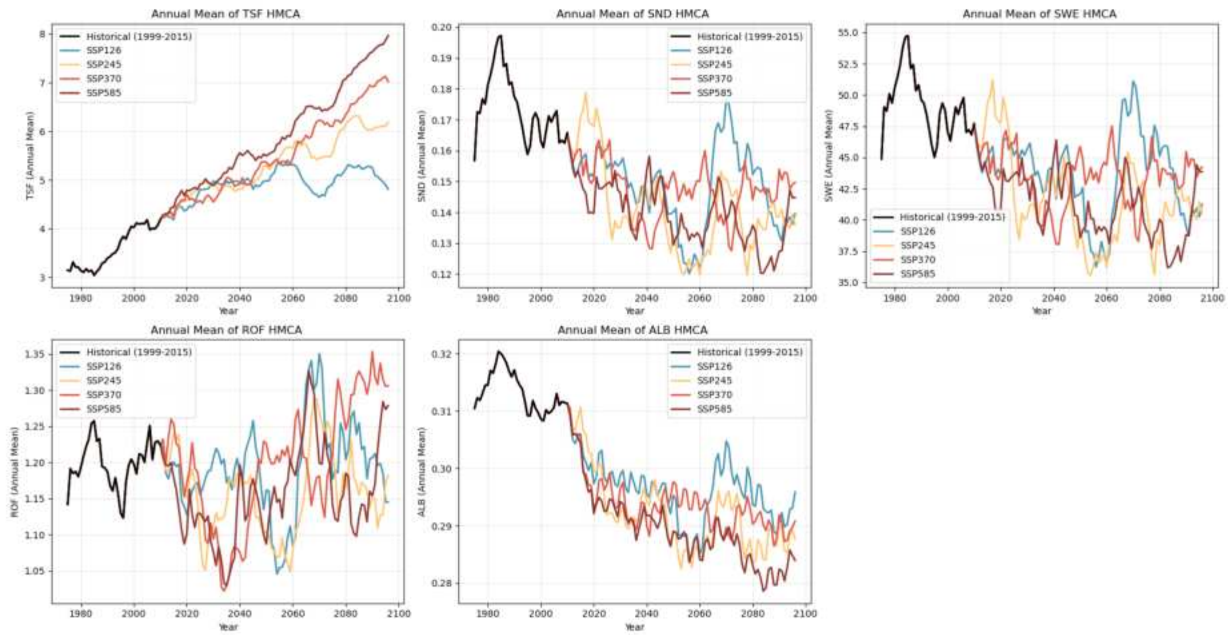

Figure 13:Timeseries plots of all four scenarios SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. Parameters are mean values over entire model domain.

Seasonality Graphs

This analysis explores the effects of climate change on the seasonality of key output variables—snow water equivalent (SWE), snow depth (snd), albedo (alb), surface temperature (GST), and runoff (Rof)—for the far-future period (2081-2100) compared to the reference period (1981-2010). The analysis is conducted across three climate scenarios: SSP1-2.6, SSP2-4.5, and SSP5-8.5. The results are visualized as average values for each period, spanning a full hydrological year (from September 1 to August 31 of the following year). The impact of climate change is further differentiated by elevation zone and hydrological basin, providing insights into regional variations in seasonality under different future climate conditions.

Key Observation

- Ground surface temperature increases in all scenarios, seasons, elevations and basins. There is a seasonal dependence on the warming with greater values in winter (DJF) and spring (MAM) than summer (JJA) or autumn (SON). This finding is in line with seasonal trends evident in the CMIP6 TAS forcing.
- Decrease SWE in all scenarios, elevations and regions.

- More frequently there occurs an earlier ablation of SWE in spring than delayed start of accumulation in winter.
- Highest values of SWE occur at 3000-4000m in the region
- Majority runoff is generated above 2000m in all regions
- Increase in highest elevation (5000m+) runoff in SSP5-8.5, due to increase in winter precipitation.
- Reduction in snow cover below 2000m strong in all scenarios and particularly non-existent in highest scenario.
- Snowmelt peaks start and end earlier in season, with strength of effect increasing with emission scenario up to a month in the strongest emission scenarios.
- Decreases in albedo (representing snow cover) very strong below 2000m in Sry Darya and below 3000m in Amu Darya basin.

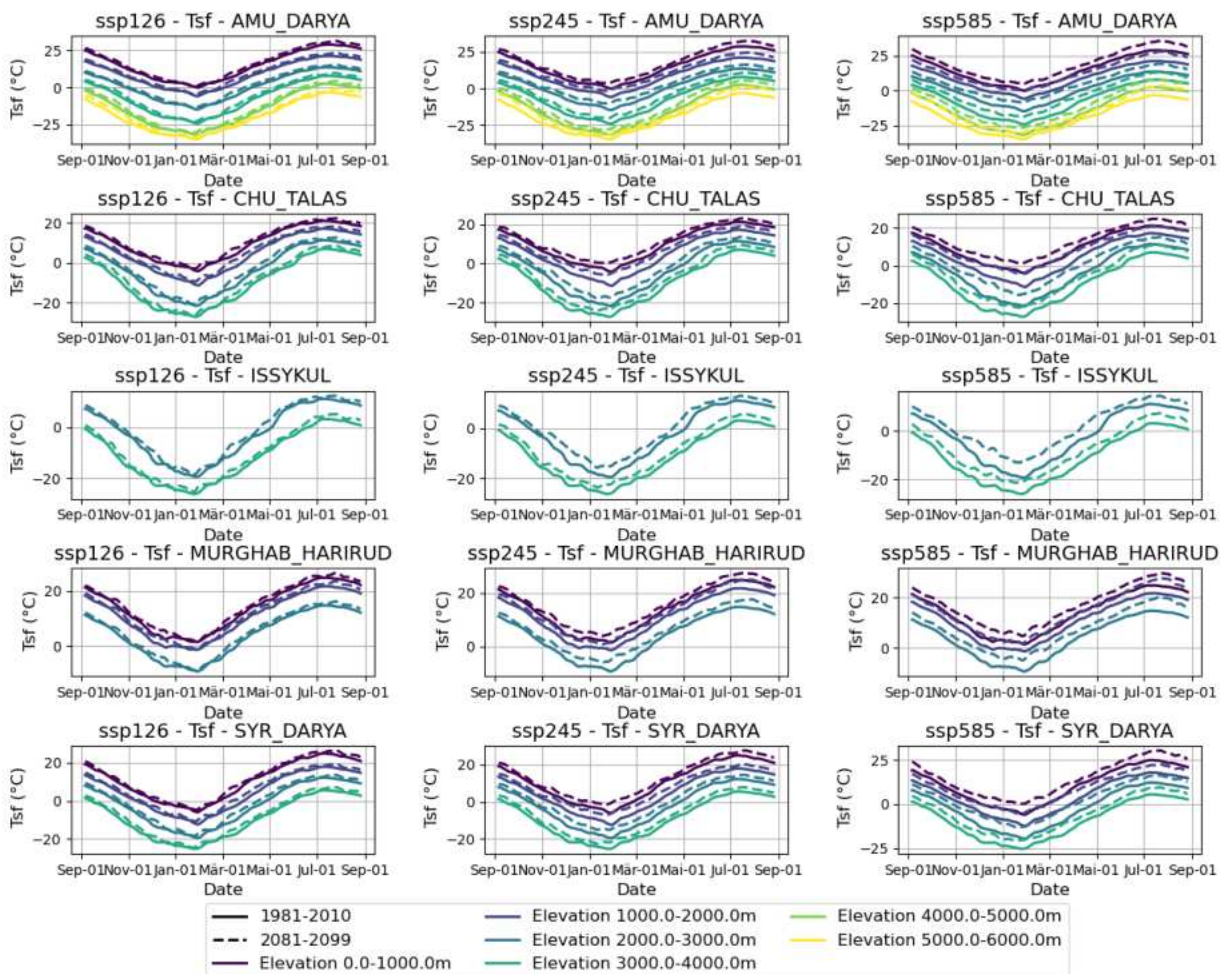

Figure 14: Seasonality of climate change for ground surface temperature (GST) the far-future period (2081-2100) compared to the reference period (1981-2010). The analysis is conducted across three climate scenarios: SSP1-2.6, SSP2-4.5, and SSP5-8.5. The results are visualized as average values

for each period, spanning a full hydrological year (from September 1 to August 31 of the following year). (seasonalCycle_multiplot_hist_multiscenario.py)

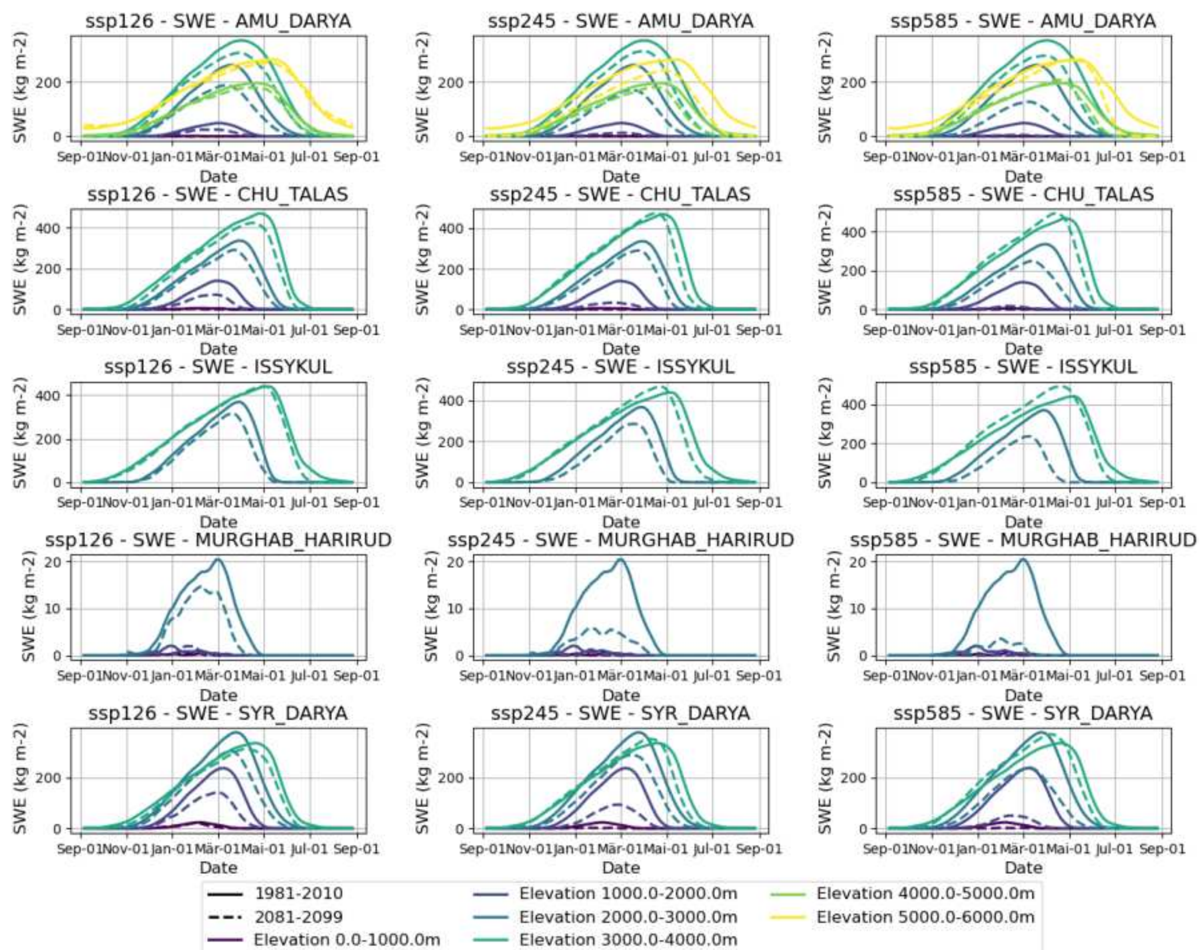

Figure 15: Seasonality of climate change for snow water equivalent (SWE) the far-future period (2081-2100) compared to the reference period (1981-2010). The analysis is conducted across three climate scenarios: SSP1-2.6, SSP2-4.5, and SSP5-8.5. The results are visualized as average values for each period, spanning a full hydrological year (from September 1 to August 31 of the following year).

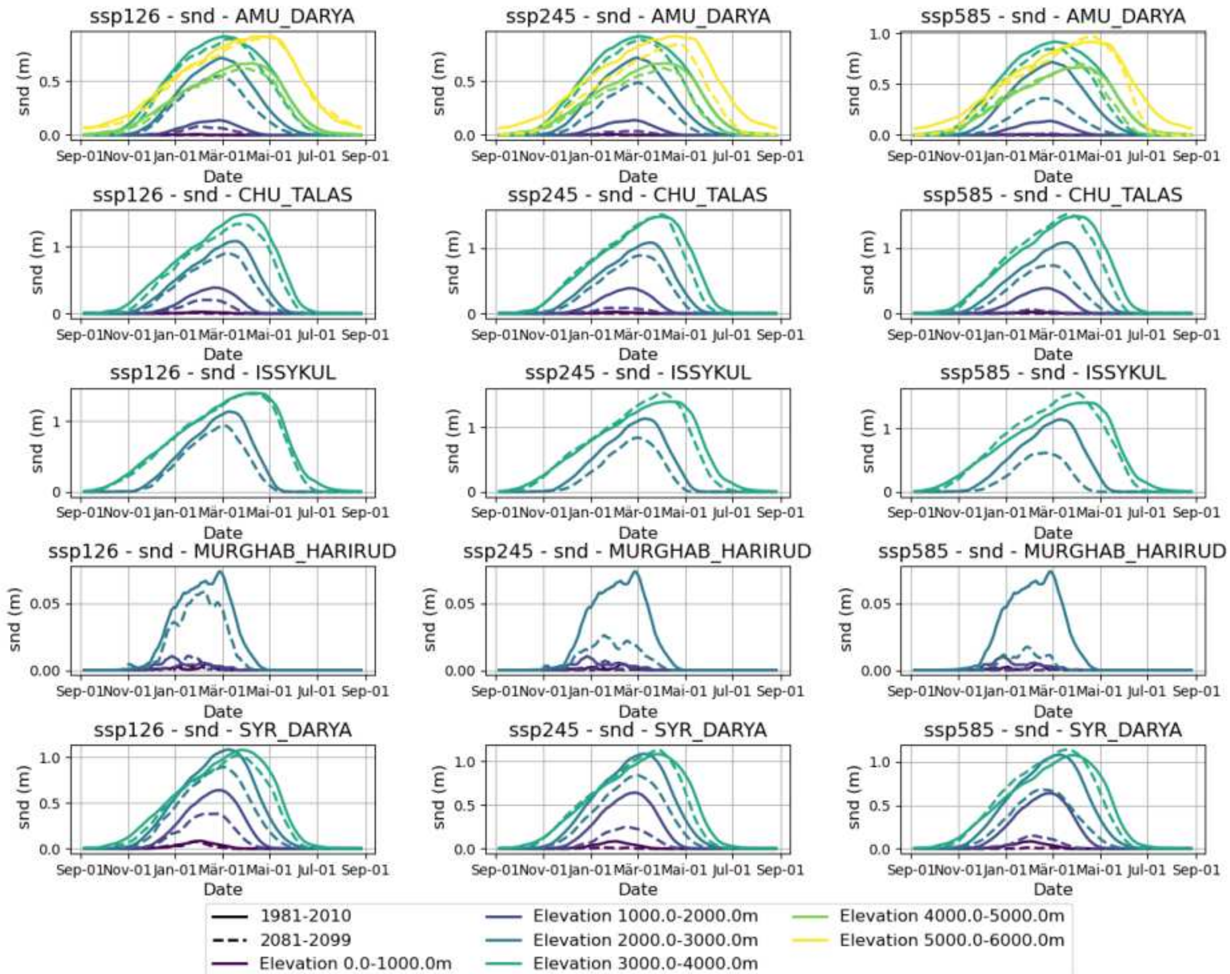

Figure 16: Seasonality of climate change for snow depth (snd) the far-future period (2081-2100) compared to the reference period (1981-2010). The analysis is conducted across three climate scenarios: SSP1-2.6, SSP2-4.5, and SSP5-8.5. The results are visualized as average values for each period, spanning a full hydrological year (from September 1 to August 31 of the following year).

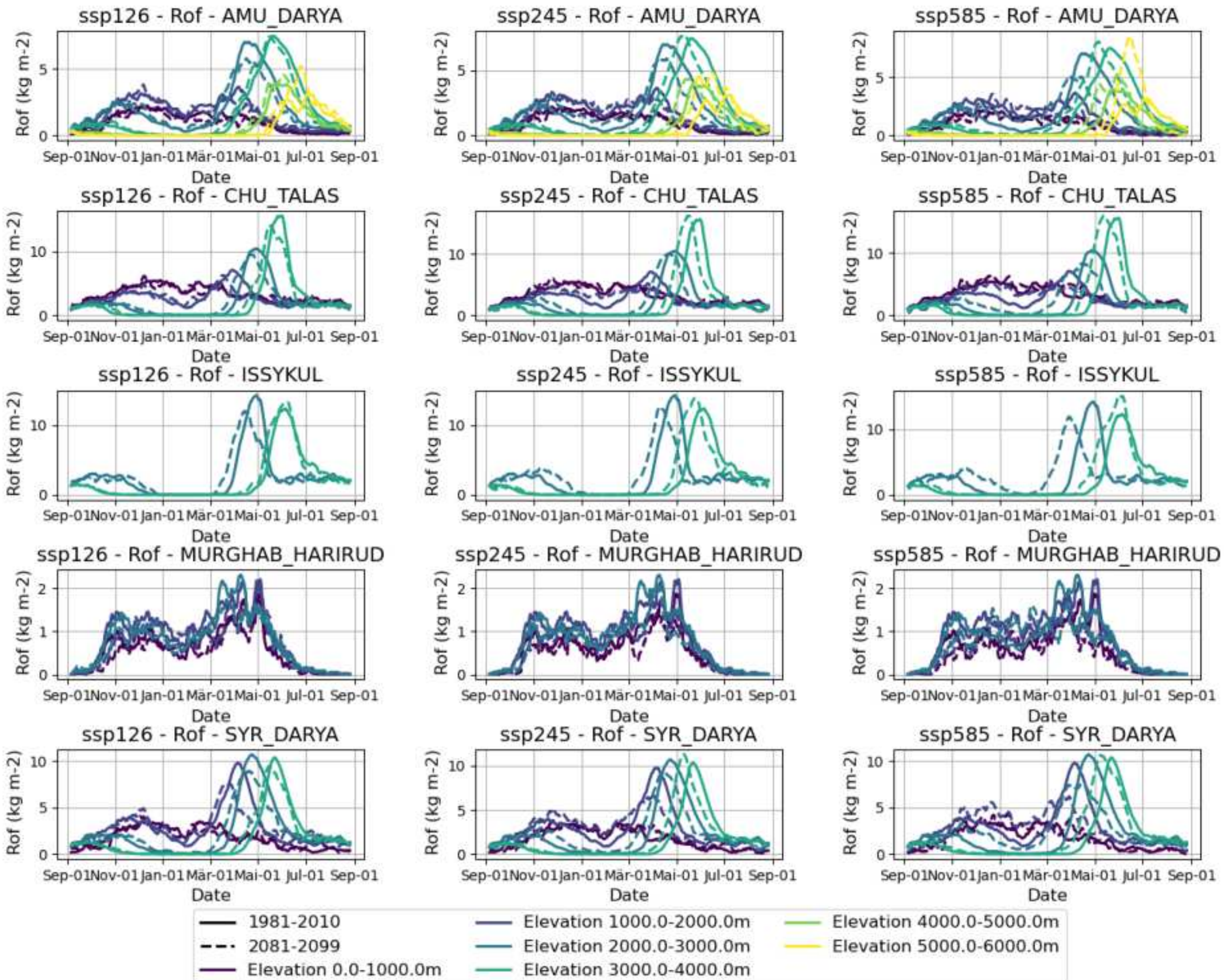

Figure 17: Seasonality of climate change for snowmelt (Rof) the far-future period (2081-2100) compared to the reference period (1981-2010). The analysis is conducted across three climate scenarios: SSP1-2.6, SSP2-4.5, and SSP5-8.5. The results are visualized as average values for each period, spanning a full hydrological year (from September 1 to August 31 of the following year).

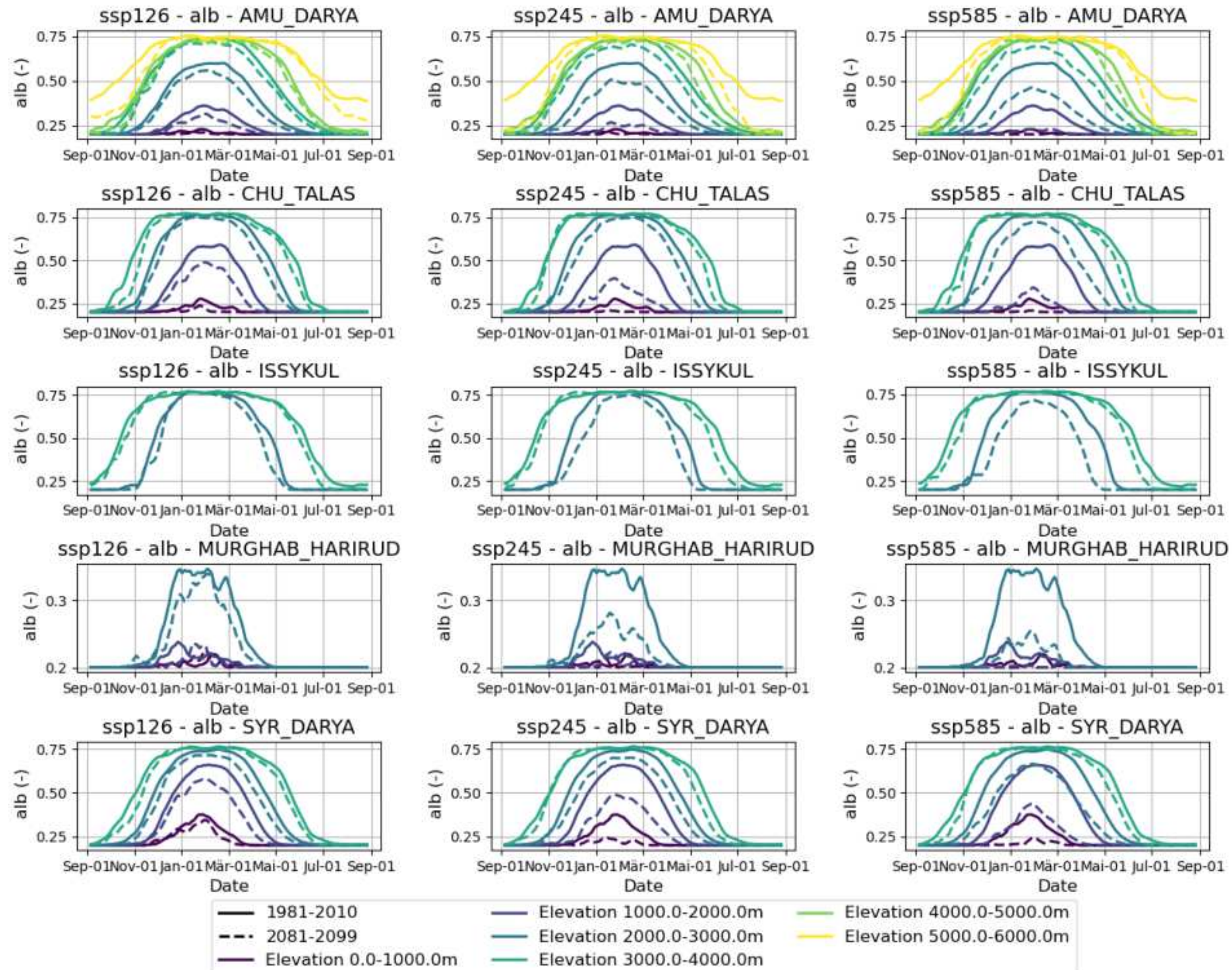

Figure 18: Seasonality of climate change for surface albedo (alb) the far-future period (2081-2100) compared to the reference period (1981-2010). The analysis is conducted across three climate scenarios: SSP1-2.6, SSP2-4.5, and SSP5-8.5. The results are visualized as average values for each period, spanning a full hydrological year (from September 1 to August 31 of the following year).

Indicator maps

Presented in this section are key indicators averaged per main HMCA catchment (221). This provides a regionalistaion of results relevant to water management in central Asia. Each of these catchments is defined by a gauge operated by respective Hydromet at its outlet and has been used as a key management unit for decision makers in various projects and studies (e.g. Siegfried et al. 2024).

Key Observations

- Warming in all regions and scenarios, strongest in high altitude elevation areas (Pamir, Tien Shan).

- Runoff decreases on western margin and increases in North and East Pamir. Decrease occurs in most significant runoff generation region.
- SWE and snow height decrease throughout scenarios, regions except Eastern Pamir (increase winter precipitation signal).
- Albedo decreases throughout the region indicating reduced snow cover in all scenarios, particularly where there is no compensating winter precipitation increases (western margin / current high precipitation regions).

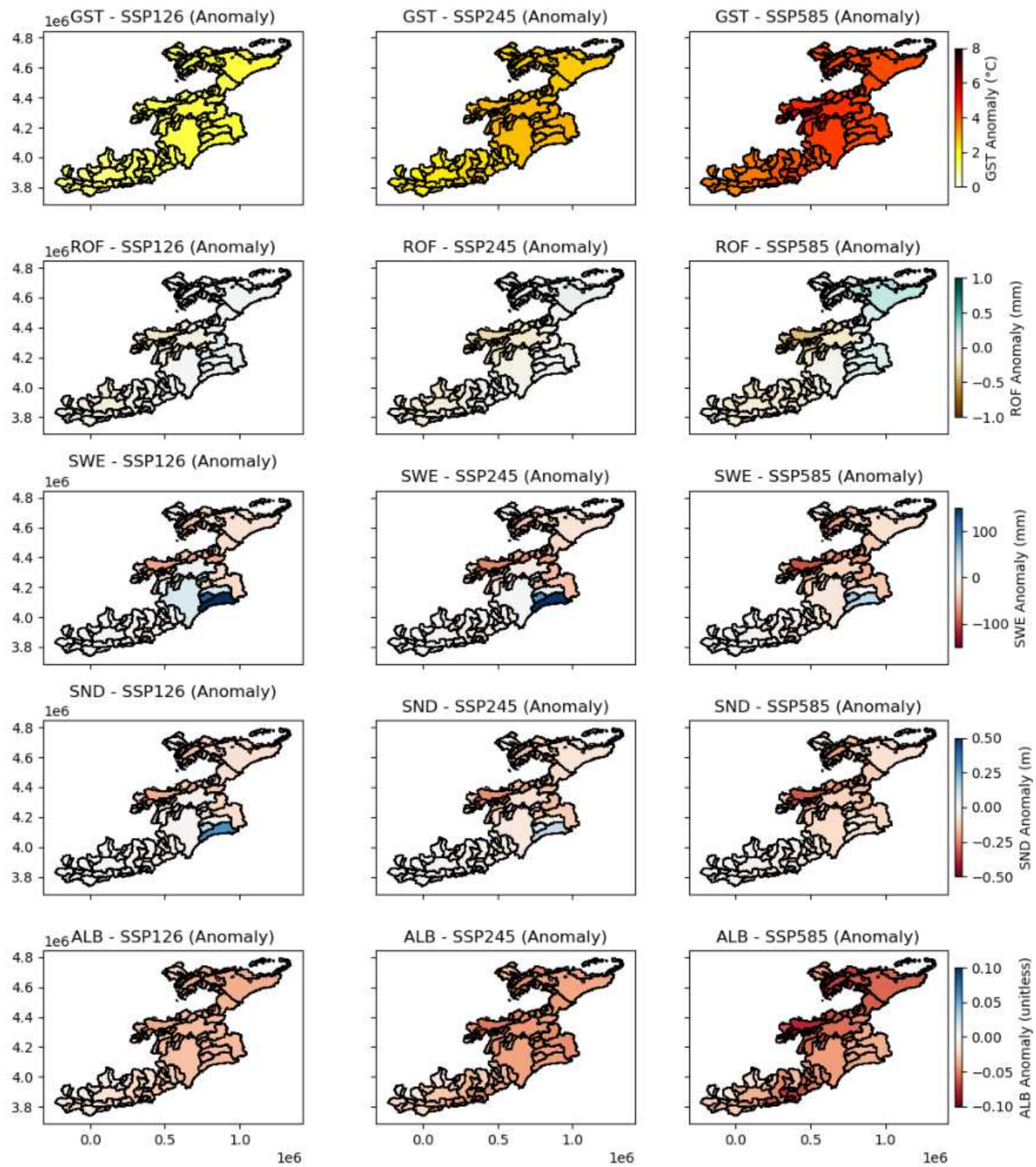

Figure 19: Indicator anomaly maps for far future aggregated by catchment in HMCA for 3 scenarios SSP1-2.6, SSP2-4.5, SSP5-8.5. Anomalies computed as far future period as (2081-2100) from historical period (1981-2010). Variable shown are ground surface temperature (GST), runoff (ROF), snow water equivalent (SWE), snow height (snd), albedo (alb).

Full Raster Maps

In this section we show full 500m raster datasets of each variable for historical period (1981-2010) and far future SSP5-8.5 (2081-2100). Main trends discussed so far are visualised in map form close to raw data.

Key observations

- **GST** increases across the entire domain.
- **ROF** decreases in the west (e.g., Zerafshan) but increases in the north (e.g., Northern Tien Shan) and east (e.g., Eastern Pamir).
- **SWE and SND** decrease throughout the domain, with the most pronounced decline occurring in the west.
- **ALB**, representing snow cover, declines across the domain, with the most significant reductions at lower elevations—below 2000m in the north and 3000m in the south.

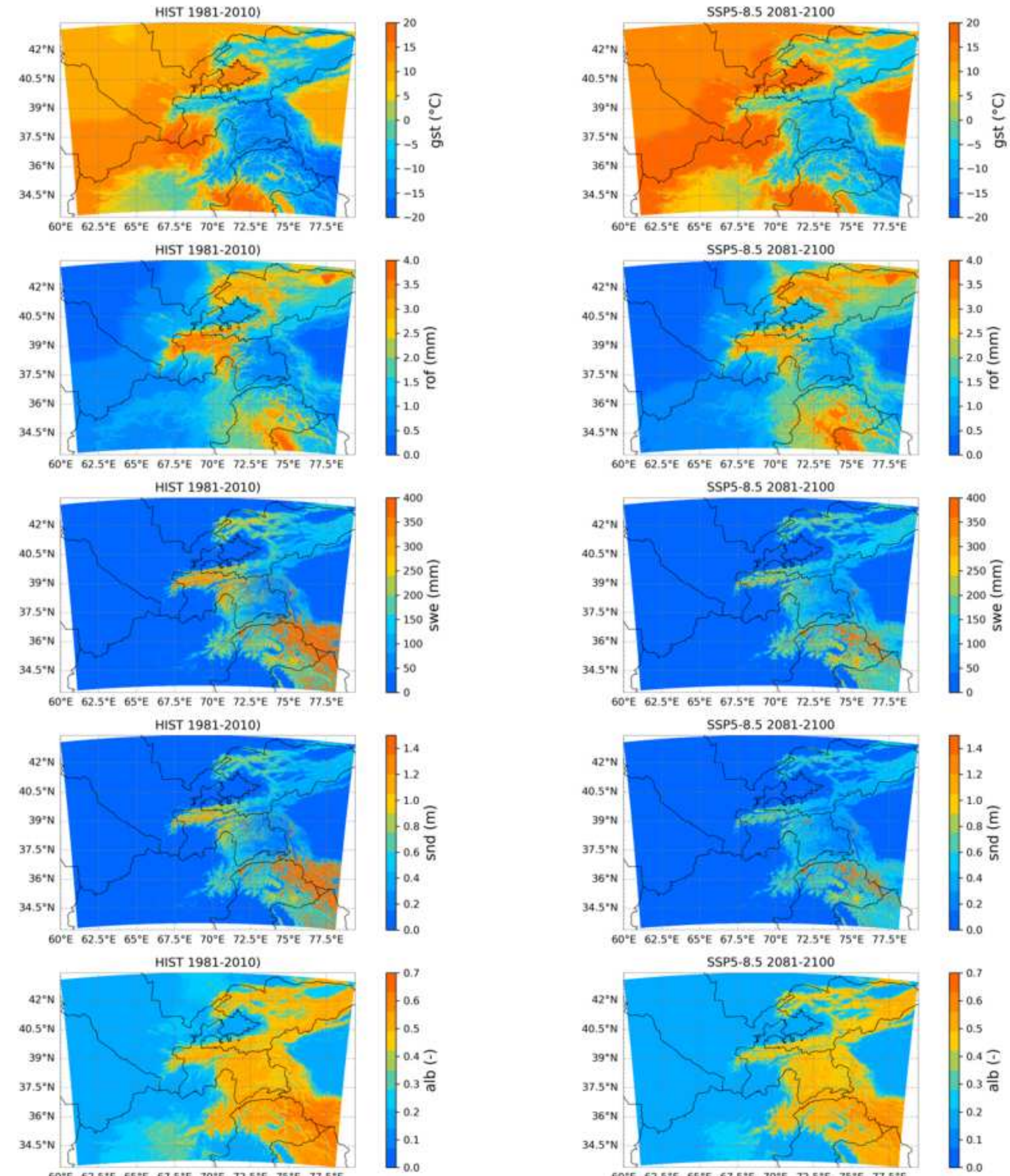

Figure 20: Raster maps of all scenarios for historical period (1981-2010) and SSP5-8.5 for far future period (2081-2100).

7. Web Apps

A key component of this project's dissemination strategy is the development of **two interactive online Scenario Explorers**. These web-based applications allow users to intuitively explore the results of complex snow and climate model outputs across multiple scenarios, time periods, basins, and elevation bands. Their goal is to make the data accessible and useful for a wide range of stakeholders, including water managers, researchers, and policymakers.

Seasonal Patterns Explorer

The Snow Climate Scenario Explorer provides interactive plots of seasonal evolution for key snow parameters, including Snow Water Equivalent (SWE), snow depth (HS), runoff (ROF), and albedo. The user can select a variable, river basin (e.g., Amu Darya, Syr Darya), elevation band, and climate scenario to examine how seasonal snow patterns change across the 21st century.

This app effectively mirrors the content shown in Figures 12–16 of the report, offering a user-driven way to investigate:

- Changes in the timing and magnitude of peak SWE or runoff;
- Shifts in snow cover duration across elevations;
- Differences across SSP emission scenarios.

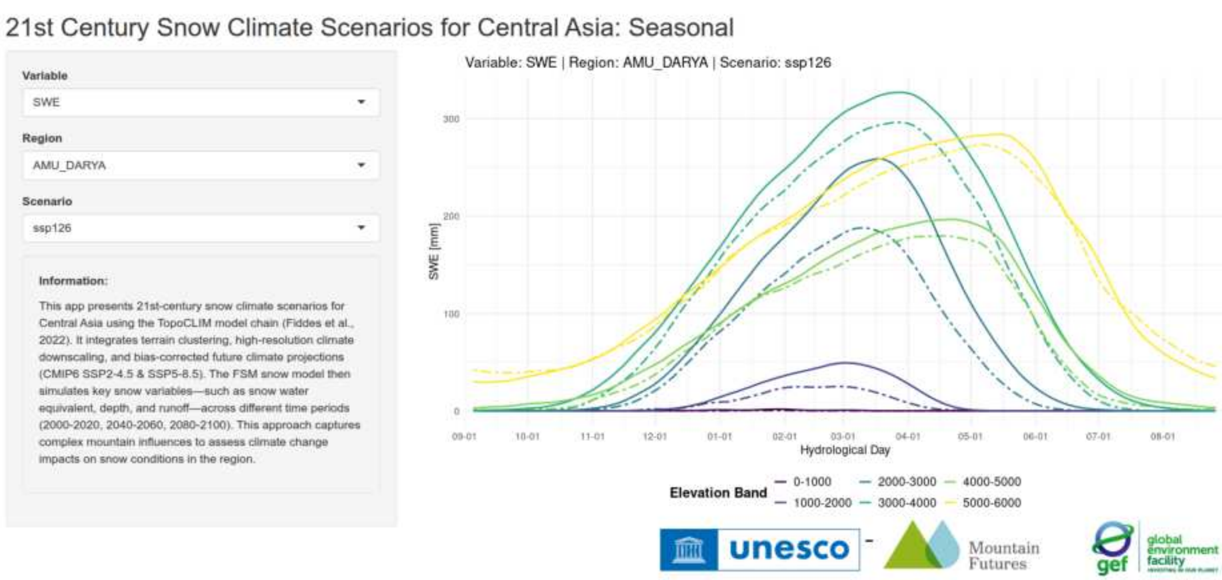

Figure 21: Snow Climate Scenario Explorer

Snow Scenario Anomaly Atlas

The Snow Anomaly Atlas offers a spatial view of modelled climate impacts. Users can explore maps of projected anomalies for key variables compared to the historical baseline, such as SWE loss or albedo reduction under different scenarios and time periods. These maps highlight regional differences in vulnerability, helping to visualize which parts of Central Asia are most affected by declining snow resources.

This tool corresponds to Figure 19 in the report and supports detailed spatial interpretation of snow climate change signals.

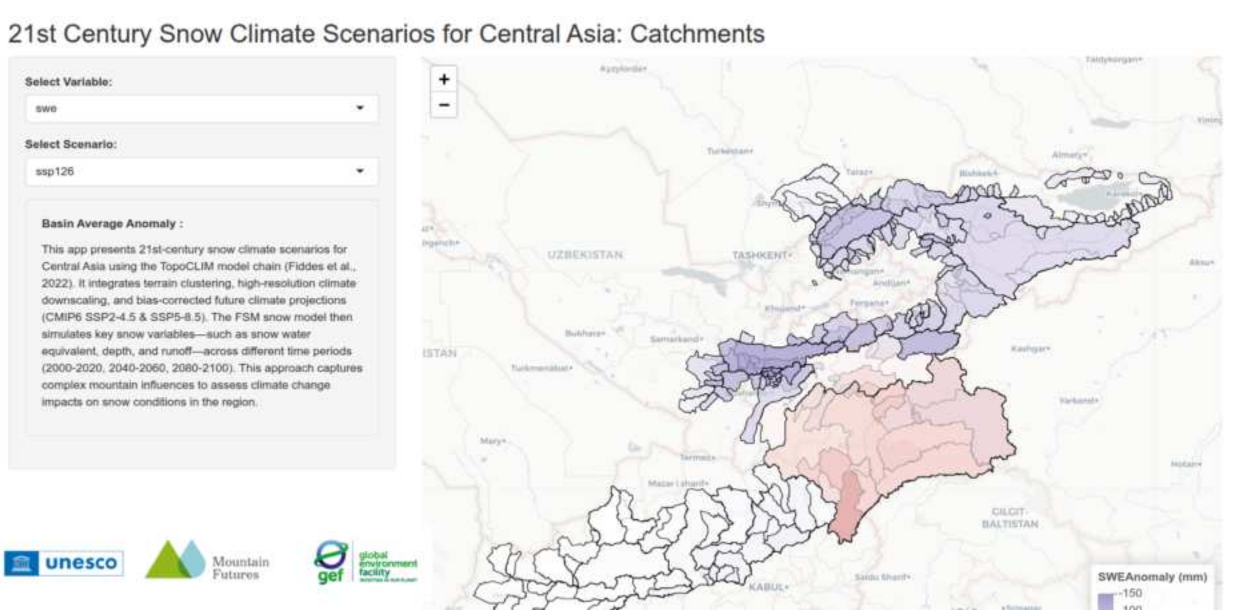

Figure 22: Snow Anomaly Atlas

8. Key Messages

Ground Surface Temperature (GST)

Ground Surface Temperature (GST) is a critical variable for understanding surface energy balance and land–atmosphere interactions. It integrates the effects of solar radiation, thermal conduction, and convective heat transfer, and plays a key role in controlling snowmelt dynamics, permafrost stability, and vegetation growth.

Across all modeled climate scenarios, time periods, and regions in Central Asia, we observe a clear and robust warming trend in GST. Notably, this warming is not uniform:

- **Winter months (December–February) show the strongest warming**, which may lead to more frequent snowmelt-refreeze cycles, thinner snowpacks, and reduced snow cover duration, even in traditionally cold periods.
- **Higher elevations show enhanced warming**, a phenomenon often described as *elevation-dependent warming*, which threatens the long-term persistence of alpine permafrost and accelerates cryospheric change in key headwater basins.
- These patterns signal fundamental changes in the thermal regime of mountain environments and have broad implications for hydrology, ecology, and infrastructure in high-altitude regions.

Snow Water Equivalent (SWE) and Snow Depth (HS)

Snow depth (HS) is a familiar and widely observed parameter that provides insight into seasonal snow accumulation and spatial variability. However, Snow Water Equivalent (SWE) is the more hydrologically meaningful measure, representing the total volume of water stored in the snowpack that will be available for runoff during melt seasons.

Our modeling reveals a consistent reduction in SWE across all scenarios, particularly at lower elevations:

- In the **Syr Darya basin**, SWE losses are most pronounced below ~2000 m; in the **Amu Darya basin**, this threshold rises to ~3000 m due to the more southerly latitude and higher baseline snowline.
- **Peak SWE occurs earlier in the season** - by several weeks under medium and high emission scenarios and the **melt-out date also shifts earlier**, compressing the snow season and increasing the risk of water availability mismatches.

- In **low-elevation basins such as the Afghan Murghab**, **SWE losses are near-total** in all but the most optimistic scenarios and elevation bands, which could have severe consequences for spring and summer water availability in downstream regions.
- These changes threaten the reliability of snowpack as a natural water reservoir, especially in regions that depend heavily on meltwater for agriculture, domestic use, and hydropower.

Runoff from Snowpack (ROF)

Runoff in this study includes contributions from both snowmelt and liquid precipitation, offering a comprehensive view of how water availability may evolve under changing climate conditions.

Model results reveal strong spatial contrasts in future runoff trends:

- In the **northern and eastern high mountains**, particularly at elevations above 3500 m, **runoff is projected to increase**, consistent with higher winter precipitation falling as snow and more frequent winter melt events.
- Conversely, in the **western runoff-generating regions** (including the Zarafshan, Chatkal, and Talas catchments), **runoff is expected to decrease across all climate scenarios**, driven by declining snow accumulation and earlier melt-out.
- The **timing of runoff is also shifting**, with peak flows occurring earlier—by up to one month in high emission scenarios—which may lead to a mismatch between peak water availability and peak agricultural demand during late spring and summer.
- This shift in runoff seasonality and volume could place additional stress on already water-stressed regions and necessitates rethinking reservoir operations, irrigation planning, and transboundary water sharing agreements.

Albedo as a Proxy for Snow Cover Area

Albedo, the reflectivity of the Earth's surface, is closely tied to snow cover. Fresh snow typically exhibits high albedo values (~0.8 or higher), reflecting most incoming solar radiation and playing a critical role in surface energy balance. In this study, we use albedo as a **proxy for fractional snow-covered area (fSCA)**, which provides spatially integrated insight into snow extent.

Key findings include:

- **Strong decreases in albedo values below 2000 m in Syr Darya and below 3000 m in Amu Darya** signal major reductions in snow cover at lower elevations, with particularly steep declines under medium and high emission scenarios.

- The **snow cover season becomes shorter at both ends**, with later onset in autumn and earlier melt-out in spring. These changes are consistent across all modeled time periods and climate pathways.
- In vulnerable low- and mid-elevation zones, the **loss of snow cover is near-total** in some scenarios, resulting in a dramatic decline in surface albedo. This not only accelerates local warming through albedo feedback but also alters ecosystem functioning and the timing of snowmelt runoff.
- These albedo-driven changes reflect and reinforce broader cryospheric degradation and underscore the urgency of adapting water resource strategies to a rapidly warming mountain environment.

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