

The Impact of Dust Deposition from an Open Pit Mine to Surrounding Glaciers in Central Asia



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Abstract

Light-absorbing impurities (LAI) such as mineral dust can reduce snow and ice albedo and thereby enhance glacier melt. Large mining activities may represent locally important sources of such particles. The Kumtor gold mine in the Ak-Shyrak massif (Central Tien Shan, Kyrgyzstan) is one of the world's highest-altitude large open-pit mines and is located in close proximity to several glaciers. Dust generated during excavation, crushing, and transport of ore and waste rock may therefore be transported by wind and deposited onto nearby glacier surfaces.

This thesis investigates whether dust emissions from the Kumtor mining operation may influence glacier surface properties and melt dynamics. A multi-method approach is employed that combines mineralogical field sampling, satellite remote sensing, and numerical modeling. First, glacier surface deposits collected from six glaciers at varying distances from the mine were analysed using X-ray diffraction to identify mineralogical signatures potentially associated with mining-related material. Second, a multi-decadal glacier albedo dataset derived from Landsat satellite imagery (2000–2025) was used to assess regional albedo variability and to identify potential deviations in the albedo evolution of Sary-Tor glacier, which is adjacent to the mine, relative to surrounding glaciers. Third, a surface mass balance (SMB) modeling sensitivity experiment was conducted to evaluate how the observed albedo differences could influence glacier mass balance.

Mineralogical analyses reveal a spatial pattern of pyrite occurrence and bulk mineral density consistent with deposition of mining-derived dust on glaciers located closest to the mine. Satellite observations reveal that while regional glacier albedo increased over the study period of 25 years, Sary-Tor glacier (located adjacent to the mine) exhibits a weaker long-term increase, resulting in a cumulative negative albedo deviation of roughly 0.1 relative to the regional mean. Sensitivity modelling suggests that this deviation could contribute to one third of observed cumulative glacier mass loss over a quarter century.

Together, these results provide multiple lines of evidence consistent with the hypothesis that mining-related dust deposition may influence glacier surface properties in the immediate vicinity of the Kumtor mine. The study highlights the importance of considering local anthropogenic sources of LAIs when interpreting glacier albedo evolution and assessing glacier mass balance in high-mountain environments.

Abbreviations

LAI	Light-absorbing impurities
SMB	Surface mass balance
XRD	X-ray diffraction
GoF	Goodness of fit
RGI	Randolph Glacier Inventory
SR	Surface reflectance
AWS	Automatic weather station
RMSE	Root mean square error
ME	Mean error

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1. Introduction

Mountain glaciers worldwide are experiencing widespread mass loss as a consequence of ongoing climatic change and the consequently altered atmospheric forcing (e.g. Dussaillant et al., 2025; Hugonnet et al., 2021). Next to air temperature and precipitation, radiative energy exchange at the glacier surface can strongly influence glacier mass balances. Therein, surface albedo plays a particularly important role, as it determines the fraction of incoming shortwave radiation absorbed by the glacier. Even relatively small reductions in albedo can significantly enhance surface melt and thereby influence glacier mass balance over seasonal to multi-decadal timescales (e.g. Naegeli and Huss, 2017 and 2015).

Glacier albedo is sensitive to the presence of LAI such as mineral dust (e.g. Oerlemans et al., 2009), black carbon (e.g. Kang et al., 2020), volcanic ash (e.g. Lliboutry, 1957), or biological material (e.g. Di Mauro et al., 2020). When deposited onto snow or ice surfaces, these particles can darken the surface and increase the absorption of solar radiation, thereby accelerating melt. LAI may originate from a variety of natural sources, including exposed bedrock, arid landscapes, or long-range atmospheric transport from desert regions. However, anthropogenic activities can also act as local sources of particulate deposition (e.g. Cereceda-Balic et al., 2022). Distinguishing between these potential sources represents a key challenge when investigating glacier surface darkening.

One potential anthropogenic source of mineral dust is large-scale open-pit mining (Fernández-Caliani et al., 2013). Mining operations involve mechanical excavation, crushing, and transport of large volumes of rock material, processes that generate fine mineral particles which can become airborne and disperse into the surrounding environment. When such operations occur in immediate proximity to glacierized terrain, the emitted dust may be transported by wind and deposited onto nearby glacier surfaces (Barandun et al., 2022). Despite this plausible mechanism, the magnitude of the potential influence of mining dust deposition on glacier melt dynamics remains relatively poorly quantified.

An example of such a setting is provided by the Kumtor gold mine in the central Tien Shan of Kyrgyzstan. Located at elevations exceeding 4000 m a.s.l., Kumtor is among the highest large-scale gold mining operations in the world and lies in close proximity to several glaciers of the Ak-Shyirak massif. This massif represents one of the largest glacierized regions of the Tien Shan and plays an important role in the hydrology of Central Asia, as meltwater from its glaciers contributes to river systems that support extensive downstream agricultural regions (e.g. Sorg et al., 2012).

This study investigates whether dust emissions from the Kumtor mining operation may influence glacier surface properties and melt dynamics in its vicinity. Because direct attribution of particulate deposition and its effect is challenging, the study adopts a multi-method approach combining field observations, satellite remote sensing, and numerical modeling. First, the mineralogical composition of local glacier surface deposits is analysed to identify potential spatial patterns in mining-related mineral constituents. Second, a multi-decadal satellite-derived glacier albedo dataset is used to assess regional albedo variability and to detect potential deviations in the albedo evolution of Sary-Tor glacier relative to surrounding glaciers. Third, a SMB modeling sensitivity experiment is performed to evaluate how such albedo deviations could influence glacier mass balance over multi-decadal timescales.

The objective of this study is therefore not to prove a direct causal link between mining activity and glacier mass loss, but rather to assess whether multiple independent lines of evidence are consistent with the hypothesis of mining-related dust deposition influencing nearby glacier

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surfaces. Specifically, the study aims to:

- evaluate whether mineralogical signatures associated with mining activity occur preferentially on glaciers close to the Kumtor mine,
- determine whether Sary-Tor Glacier exhibits a systematic deviation in albedo evolution relative to the regional glacier population, and
- quantify the sensitivity of glacier SMB to the observed albedo differences.

2. Study Area

2.1 Regional Setting

The study area is located in the central Tien Shan mountain range of Kyrgyzstan, within the northwestern sector of the Ak-Shyirak massif in the Inner Tien Shan (cf. Fig. 1). The Tien Shan extends for several thousand kilometres across Central Asia in a broad arc and contains extensive high-mountain glacier systems. The Ak-Shyirak massif forms a large glacierized area within the Central Tien Shan. Petrakov et al. (2016) describe the massif as consisting of "three subparallel ranges isolated from surrounding mountains". Elevations in the region range from valley floors at roughly 3000 m a.s.l. to peaks exceeding 5100 m a.s.l., with the northerly Arabel-Suu plateau forming a high-elevation basin at approximately 3800 m a.s.l.

Glaciological research in the Ak-Shyirak region has a long history dating back to early Soviet expeditions (e.g. described by Aizen et al., 2006). The glaciers of this massif are of particular hydrological importance because their meltwater feeds the Naryn and Sary-Dhaz rivers, which ultimately contribute to the Syr Darya and Tarim river systems. These rivers supply water to large irrigated agricultural regions across Central Asia, making glacier meltwater a critical resource for downstream societies.

The regional climate is high-continental, characterized by cold winters, relatively low annual precipitation (Fig. 2), and strong summer solar radiation at high altitudes. Recent studies indicate that climatic changes are affecting the regional glacier system: For example, Petrakov et al. (2016) report increasing summer temperatures (May–September), which enhance glacier melt next to a simultaneous reduction in the fraction of solid precipitation, leading to rising equilibrium line altitudes. Consistent with this, Vydra et al. (2024) identify decreasing late-season snow cover duration across the headwater catchments of the Syr Darya basin. Substantial spatial variability in regional glacier mass balance has been identified (Barandun et al., 2021) and peak glacial meltwater runoff timing is projected around mid-21st-century for this area (Van Tricht and Huybrechts, 2023). Together, these trends suggest increasing climatic pressure on glaciers in the region.

Several potential sources of light-absorbing impurities exist in the Tien Shan. Natural sources may include mineral dust from exposed bedrock and long-range transported dust originating from Central Asian deserts such as the Taklamakan. Studies have shown that meridional dust transport from the Tarim Basin can reach the region, particularly during periods of weak westerly circulation (Yuan et al., 2019). Individual dust events have been observed to reduce snow albedo in the Tien Shan by 0.028–0.079 (Xing et al., 2024).

2.2 The Kumtor Mine

Located on the northwestern flank of the Ak-Shyirak massif is the Kumtor gold mine (Fig. 1e), one of the highest-altitude open-pit gold mines in the world. Commercial production began in 1997, and by the end of 2024 the mine had produced 15.1 million ounces of gold (*Kumtor Gold Company 2024 Operating Results*, 2025). The operation represents a major component of the Kyrgyz national economy (Mogilevskii et al., 2015). The mine is situated at elevations around 4000 m a.s.l. and lies in direct proximity to several glaciers, including Davydov, Lysii, Petrov, Sary-Tor, and Bordu (Fig. 1). Mining infrastructure occupies a large concession area on the southeast Arabel plateau, and the main pit itself reaches several hundred metres in depth. The operation employs thousands of workers, requires substantial fuel consumption and employs

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heavy-duty machinery (*Kumtor Gold Company 2024 Operating Results*, 2025).

From a glaciological perspective, the location of the Kumtor mine is exceptional because of its immediate proximity to glacierized terrain (Fig. 1e). Large-scale excavation, ore crushing, and transport of rock material may generate substantial quantities of fine mineral particles. In such an arid high-mountain environment, where vegetation cover is sparse and surfaces are frequently exposed, these particles may be transported by wind and deposited on nearby glacier surfaces.

2.3 Investigated Glaciers

This study focuses on several glaciers located at varying distances from the Kumtor mine. Most of the investigated glaciers are situated on or near the Arabel plateau, which provides relatively comparable environmental conditions across the study area. Their differing distances from the mining complex nevertheless allow assessment of potential spatial gradients in dust deposition.

Investigated glaciers close to the mine are:

- **Sary-Tor** (Fig. 1e), located 3 km southwest of the mine’s main pit, serves as the primary focus of the analysis.
- **Bordu** (Fig. 1e), situated approximately 5 km from the mine, provides a near-field comparison site.

Additional glaciers located further from the mine serve as reference glaciers representing regional background conditions:

- **Grigoriev** (Fig. 1b) in 25 km distance,
- **Kara-Batkak** (Fig. 1c) in 33 km distance,
- **Batysh-Sook** (Fig. 1a) in 38 km distance,
- **Terekty** (Fig. 1d) in 50 km distance.

The region is particularly well suited for this type of study for several reasons. First, the glaciers are relatively easily accessible via the Arabel plateau road network, enabling field campaigns and surface sampling. Second, the existence of long-term glaciological monitoring programs and meteorological observations provides valuable contextual data. Finally, established collaborations with two local institutions facilitate fieldwork and data access: The Institute for Water Problems and Hydropower of the Kyrgyz National Academy of Sciences, and the Kumtor Gold Company.

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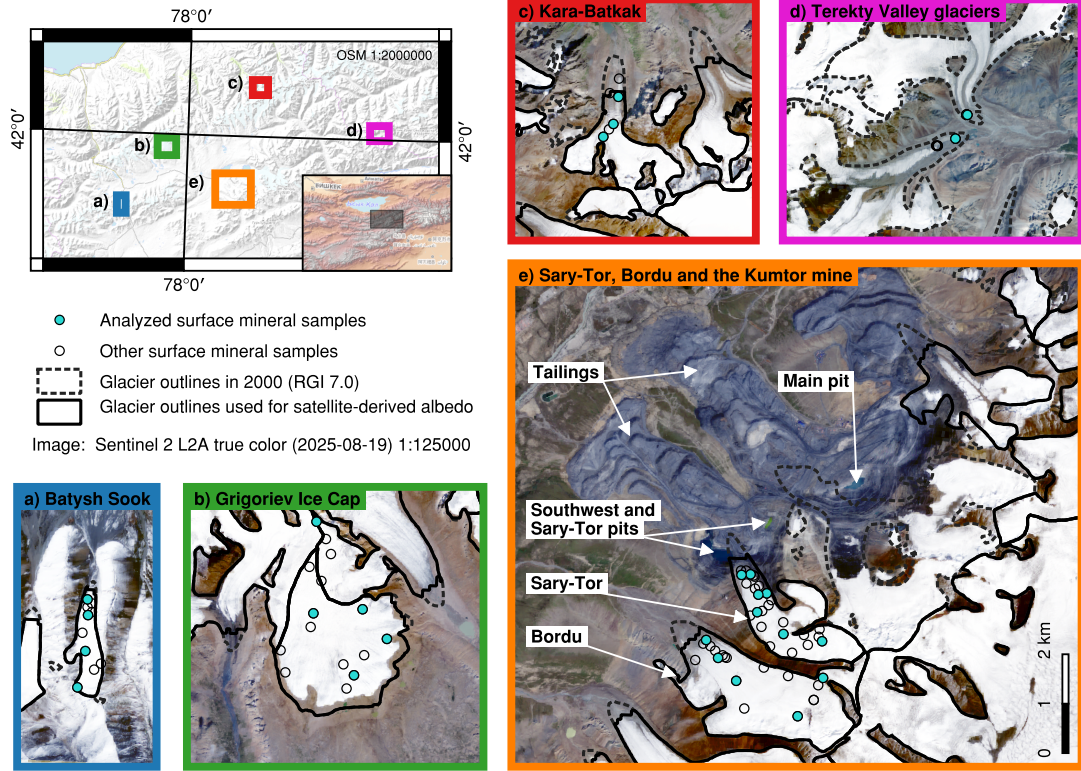


Figure 1: Overview map of investigated glaciers and mineral samples. Colored insets show the surroundings of the surveyed glaciers Sook (a), Grigoriev (b), Kara-Batkak (c), Terekty Valley glaciers (d), Sary-Tor and Bordu (both e). Inset (e) also depicts the pits and tailings of the Kumtor mine. The solid black glacier outlines denote the areas used for satellite-based albedo retrieval and were defined by excluding the lowest 10 % elevation range of each glacier's year 2000 outline (dotted). Davydov Glacier (center of e) was excluded from the albedo analysis, and the Terekty valley (d) lies outside the study area defined for satellite-based albedo derivation. Locations of surface mineral sampling are indicated by black circles; the analyzed samples are marked in cyan.

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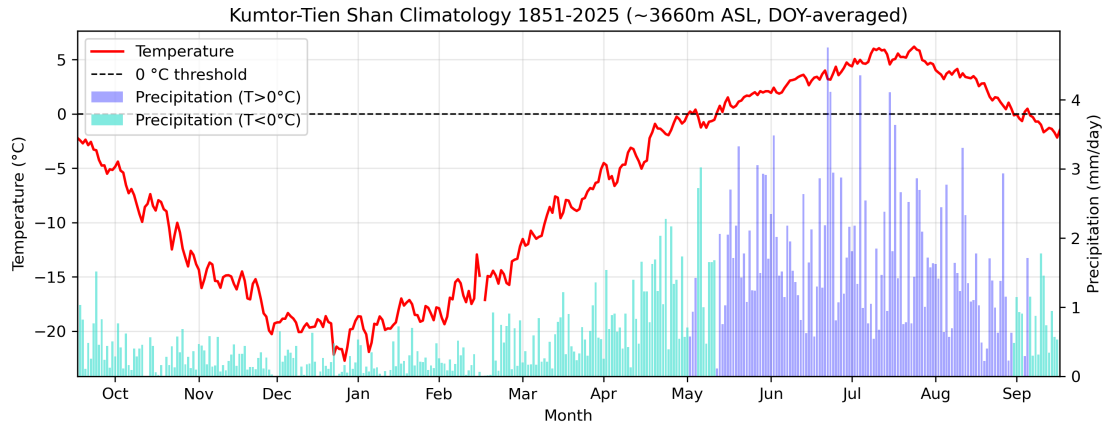


Figure 2: Climatology of the Kumtor-Tien Shan region for 1851-2025, based on the meteorological dataset for the Kumtor-Tien Shan region of Van Tricht et al. (2021) extended to 2025 as described in Sec. 3.3.2.

3. Methods

This section describes the methodological approaches used to investigate mining dust deposition to surrounding glaciers. First, the workflow to assess glacier surface deposit mineralogy is described. Then, the strategy and assumptions leading to a satellite-derived albedo time series are laid out. Lastly, the utilized SMB model to estimate Sary-Tor Glacier’s sensitivity to an albedo anomaly is introduced.

3.1 Mineralogy of Glacier Surface Deposit

3.1.1 Field Sampling

Glacier surface material was collected from six glaciers during field campaigns in August 2025. Five glaciers (Sary-Tor, Bordu, Batysh-Sook, Kara-Batkak, Grigoriev) were sampled at high spatial density in early August, whereas one glacier (Terekty valley) was sampled at lower spatial density toward the end of August. For each glacier, the sampling strategy aimed to obtain surface material samples distributed primarily along the main flow line, partially supplemented by transverse profiles. As depicted in Fig. 1, the number and spatial distribution of realized sampling sites varied among glaciers and were constrained by weather conditions and safety considerations during fieldwork. Sampling locations were selected in the field by visual assessment while traversing the glacier along predefined routes. On the vastly snow-free glaciers, sites were deliberately chosen to be approximately evenly spaced and to exhibit visible dust- or mud-like surface deposits (Fig. 3). At each site, surface material was collected from an area of approximately 20×20 cm to a maximum depth of roughly 1 cm using a clean steel spoon, until the sample container of volume 50mL was filled. The sampling procedure specifically targeted non-H₂O surface deposits; the inclusion of ice, snow, or meltwater was accepted where unavoidable. Geographic coordinates of all sampling sites were recorded using Trimble Geo7X and GeoExplorer 6000 handheld GNSS instruments. Samples were stored in sealed containers (Fig. 3), protected from light and transported to Zurich for laboratory processing at ETH ClayLab.

3.1.2 Laboratory Composition Analysis

Field-packaged samples exhibited unknown grain sizes and contained variable amounts of meltwater originating from incident ice, snow and water during sampling. Prior to analysis, all samples were therefore milled to grain sizes smaller than 20 μ m and dried at 65 °C. The resulting powders were subsequently prepared on carrier disks by careful manual conditioning to evade preferential crystal orientation in sample mounts (Fig. 3). This preparation procedure was time-intensive and therefore limited the total number of analysed samples to 27.

Powder X-ray diffraction (XRD) was performed using a Bruker AXS D8 Advance θ - θ diffractometer equipped with Co K α radiation ($\lambda = 1.78901$ Å) and a LynxEye XE-T detector, operated with a 15 mm beam mask. Diffraction patterns were analysed in Profex using the BGMN refinement engine. Quantitative phase analysis was performed by Rietveld refinement, and model quality was assessed using standard refinement statistics, including the weighted profile R-factor, χ^2 , and goodness of fit (GoF). Phase proportions for all identified crystalline components were considered together with their associated estimated standard deviations.

Rietveld refinements yielded GoF values between 3 and 5, reflecting the complexity of the natural polymineralic samples and the presence of minor or poorly crystalline phases that were

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not explicitly modelled. Phase proportions are therefore interpreted primarily in a relative sense when assessing spatial patterns. Formal uncertainties were scaled by $\sqrt{\chi^2}$ to account for elevated χ^2 values.



Figure 3: Photos from left to right: Glacier surface deposit sample collection in the field; An exemplary sample tube on top of ice visibly covered with impurities; Sample tube packs arriving in the laboratory; Solid material contained in samples prepared onto disk mounts for XRD analysis.

3.2 Satellite-Derived Glacier Albedo Timeseries

3.2.1 Imagery Acquisition & Narrow-to-Broadband Conversion

Surface reflectance (SR) imagery from the Landsat (*courtesy of the U.S. Geological Survey*) satellite sensors TM (Landsat 5), ETM+ (Landsat 7), OLI (Landsat 8), and OLI-2 (Landsat 9) was retrieved to derive glacier albedo time series. The Landsat record employed in this study spans multiple sensor generations and potential cross-sensor differences are minimized through the use of standard Landsat SR products. Most processing was carried out using the cloud-based geospatial analysis platform Google Earth Engine, accessed under a license for noncommercial and research use via a Python application programming interface.

Imagery from all mentioned sensors was assumed to provide comparable spatial resolution and radiometric consistency, enabling the construction of a time series spanning March 1990 to September 2025 whenever imagery from overflights was available. This was performed for an area of interest of approximately 68×59 km encompassing most of the Arabel-Suu valley and its surrounding glaciers (Fig. 4). Glaciers with a year-2000 area smaller than 0.2 km^2 (deduced from RGI Consortium, 2023) were excluded from further analysis. Davydov Glacier was additionally omitted due to extensive mechanical excavation associated with mining activities at Kumtor (Van Tricht et al., 2025; see Fig. 1e), rendering it unrepresentative for more subtle surface processes such as LAI-driven albedo changes.

The processing workflow was largely based on scripts provided by Dr. Hendrik Wulf. A scene-level cloud cover threshold of $< 30 \%$ was applied, and residual clouds as well as radiometrically saturated pixels were masked using the Landsat-provided QA_PIXEL (bits 0-3) and QA_RADSAT quality assessment bands. The effectiveness of the cloud-masking procedure was evaluated for ten randomly selected scenes by visual comparison with the corresponding true-color composites and was found to be sufficient for the purposes of this study.

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Finally, shortwave broadband glacier albedo was derived from narrowband SR data using the narrow-to-broadband conversion proposed by Liang (2001). This approach combines reflectance measurements from the visible, near-infrared, and shortwave infrared bands (Blue, Green, Red, NIR, SWIR1, SWIR2) and applies a parameterization to account for the unmeasured spectral regions, yielding an estimate of broadband shortwave albedo integrated over an electromagnetic wavelength range of 0.38–2.5 μm . While Liang (2001) developed this method for Landsat TM/ETM+, Naegeli et al. (2017) have shown that it is suitable for mountain glaciers and can be applied to Landsat OLI data, too. As they discuss, the approach does not account for material-specific reflectance anisotropy. The non-Lambertian forward scattering behavior of snow and ice (Klok et al., 2003; Cogley et al., 2010) was not considered in this study. Two exemplary scenes are presented in Fig. 4 to give an impression of narrow-to-broadband results as utilized here.

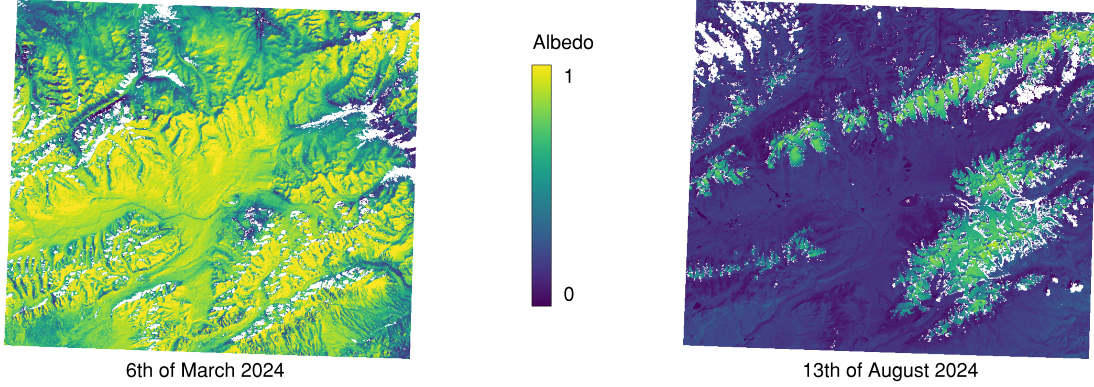


Figure 4: Two examples of satellite-derived albedo maps with low cloud cover. White pixels indicate invalid data due to cloud cover or radiometric saturation.

3.2.2 Signal Decomposition

It was deemed beneficiary to assemble a data set of sufficient size to distinguish systematic signals from natural variability or measurement noise. In spite of the fixed revisit frequency given by the orbits, optical satellite observations are inherently irregular in time due to occurrence of impenetrable cloud cover, rendering the method insensitive to albedo evolution beneath clouds. Consequently, the derived albedo time series represents only cloud-free conditions. However, because incoming shortwave radiation is itself attenuated during cloudy conditions, the satellite-derived albedo under clear-sky conditions is assumed to provide a reasonable approximation of the energetically most relevant surface state during periods of radiative forcing.

The resulting albedo time series is assumed to contain multiple superimposed signals, including instrument as well as processing artifacts, bare soil uncovering, a pronounced seasonal cycle, shorter-term responses to precipitation events, firn formation and weathering, surface melt and runoff, as well as changes associated with impurity (e.g. dust) deposition. As the primary focus of this study was to isolate one version of the latter effect, namely mining dust deposition, efforts were made to minimize the influence of other processes.

Glaciers were initially mapped using year-2000 outlines from the Randolph Glacier Inventory v7.0 (RGI Consortium, 2023). To account for bare soil uncovering due to glacier retreat since 2000, the lowest 10 % of each glacier’s elevation range were masked out and treated as either melted or retreated (compare solid and dotted outlines in Fig. 1). This threshold was determined

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through visual comparison with late-summer true-color imagery (Copernicus Sentinel-2 L2A, 19 August 2025) and was found to best approximate the multitude of observed glacier termini. These shortened glacier outlines form the scope for all glacier albedo estimations. After filtering of non-physical glacier albedo values (>1), this yielded a multi-decadal satellite-derived albedo data set for 371 glaciers within the area of interest, enabling the analysis of glacier albedo variability across a large spatial domain and over an extended time period. Overall, this yielded 414 620 single glacier albedo observations.

The availability of cloud-free satellite data was found to be temporally not uniform, as illustrated by the increasing density of observations over time in Fig. 5. To avoid spurious trends arising from an increase in sampling density rather than physical processes, a subsampling strategy was applied. A reference data density was defined using the period 2000–2004, and for subsequent years a random subset of observations was drawn such that both the number of samples and the distribution of cloud-free glacier tongue albedo values matched those of the reference period. This approach supports temporal comparability of the albedo statistics despite the increasing volume of satellite observations in later years.

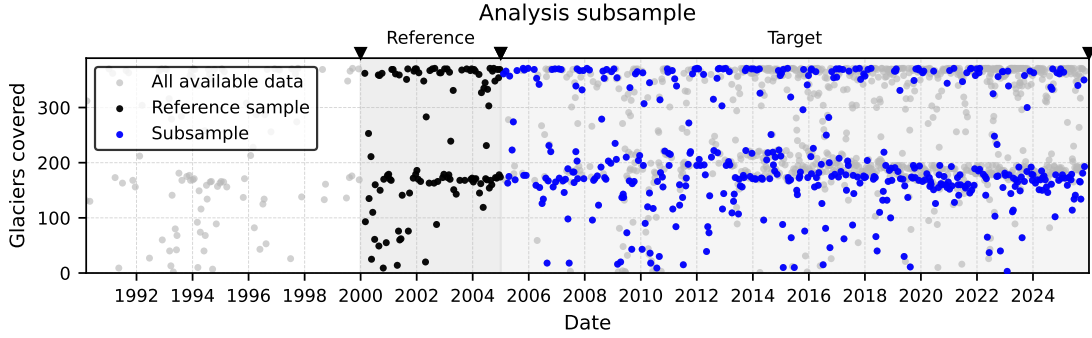


Figure 5: Timeline of satellite-derived glacier albedo observations showing all available cloud-free Landsat acquisitions (grey), the reference-period sample distribution (black), and the randomly selected subsample from subsequent years (blue) constructed to preserve the reference period’s glacier coverage and sampling density. All subsequent analyses were performed using the complete reference-period data together with the downsampled observations from later years (i.e. black and blue points from 2000 onward).

3.2.3 Uncertainty Estimation Using In-Situ Albedo Measurements

Uncertainty in the narrow-to-broadband albedo retrieval following Liang (2001) arises from a combination of sensor radiometric calibration, atmospheric correction, topographic effects, shading, and the assumption of Lambertian surface reflectance (e.g. Klok et al., 2003; Naegeli et al., 2017). Based on the high end of the uncertainty range assessment of Klok et al. (2003), these contributions collectively amount to an uncertainty on the order of 0.05–0.1 in broadband albedo. To independently quantify uncertainty at the pixel scale in the dataset at hand, in-situ albedo measurements collected during the August 2025 field campaign were used to cross-validate satellite-derived albedo and derive an empirical estimate of observation uncertainty.

In-situ albedo measurements were obtained using an Apogee SP-710-SS radiation balance sensor, consisting of an upward-facing Apogee SP-510 pyranometer (field of view 180°) and a downward-facing Apogee SP-610 pyranometer (field of view 150°; see sketch in Fig. 6). During

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measurements, the instrument was held approximately 1.5 m above the surface and aligned horizontally using an integrated bubble level. Albedo was calculated as the ratio of reflected to incoming shortwave radiative power integrated over the sensor footprint, corresponding to a circular ground area with a diameter of approximately 11 m.

Because Landsat imagery was not available at sufficient spatial resolution and temporal proximity to the field measurements, Copernicus Sentinel imagery acquired on the same day was used for the validation. While this introduces a cross-sensor comparison, the substitution is considered acceptable because (i) the spatial resolution of Sentinel imagery (10–20 m) is comparable to the effective footprint of the in-situ measurements, (ii) identical narrow-to-broadband conversion parameterizations were applied, and (iii) the validation focuses on estimating the magnitude of albedo uncertainty rather than sensor-specific absolute calibration.

Despite pronounced spatial heterogeneity in small-scale surface characteristics observed during fieldwork, the spatial patterns visible in the satellite imagery are broadly consistent with the in-situ measurements (cf. Fig. 7). Between satellite-derived and in-situ handheld albedo values α_{sat} and α_{hand} , the distribution of their difference $d = \alpha_{sat} - \alpha_{hand}$ (satellite minus in-situ) exhibits a mean offset $\mu_d=0.023$ and a standard deviation $\sigma_d=0.086$, as illustrated in Fig. 7c). We interpret μ_d as a systematic bias and σ_d as the random component of the satellite albedo observation error, and use this to define an observation uncertainty model for α_{sat} . The uncertainty estimates were derived from measurements on two adjacent glaciers (Sary-Tor and Bordu). Although this is limited spatial sampling, the resulting statistics are assumed to provide an independent first-order representation of satellite albedo uncertainty across the study area and were therefore generalized to all glaciers considered in this study. The resulting bias and random uncertainty estimates were subsequently propagated into the later SMB modeling (Sec. 3.3).

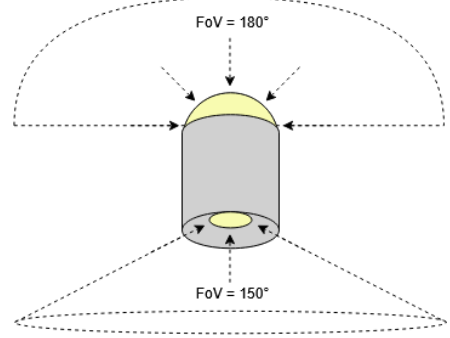


Figure 6: Sketch of the instrument used to measure albedo in the field.

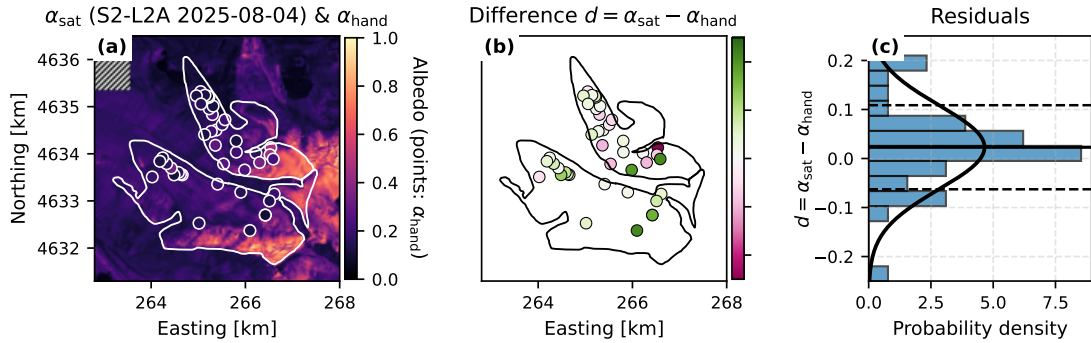


Figure 7: In-situ and satellite-derived albedo comparison used to quantify observational uncertainty: (a) spatial overlay of same-day measurements, (b) satellite-in-situ albedo differences, and (c) distribution of residuals with fitted normal Gaussian distribution $\mathcal{N}(\mu_d=0.023, \sigma_d^2=0.086^2)$. The color bar of (b) shares the vertical axis with (c).

3.3 Sensitivity Modeling

The sensitivity of Sary-Tor glacier SMB to satellite-observed albedo deviation was assessed using a simple numerical modeling framework. Rather than aiming to reproduce absolute mass balance with high process fidelity, the modeling approach was designed to quantify the relative impact of albedo perturbations on glacier SMB under otherwise identical forcing. To this end, two albedo scenarios, one representing the observed albedo and one representing a counterfactual albedo state, were imposed within a simple SMB model and their resulting mass balance responses were compared.

3.3.1 A Simple SMB Formulation

The utilized SMB model follows the structure of Van Tricht et al. (2021). It resolves accumulation and ablation in bands along the glacier elevation axis (cf. Fig. 8), lateral mass or energy exchange between elevation bands is neglected and meteorological forcing consists of air temperature, precipitation, which are spatially distributed throughout the glacier using fixed temperature lapse rates and precipitation gradients (cf. 3.3.2), and incoming shortwave radiation.

Within each discretized elevation band indexed by z , and per time step t , the SMB (Eq. 3.1) is solved by a forward-Euler numerical time integration of the sum of cumulative mass balance $B_z(t)$, solid accumulation $S_z(t)$, and ablation $M_z(t)$. A temporal resolution of 3h was used.

$$B_z(t+1) = B_z(t) + S_z(t) + M_z(t) \quad (3.1)$$

Solid accumulation $S_z(t)$ is derived from precipitation and partitioned into solid and liquid components based on air temperature, such that snowfall dominates at low temperatures ($T < 0.5^\circ\text{C}$) and transitions linearly into pure rainfall at a higher temperature threshold ($T = 2.5^\circ\text{C}$). Liquid rainfall is assumed to run off without mass or energy transfer.

Surface albedo $\alpha_z(t)$ evolves dynamically as a function of snow depth $s_z(t)$ following an e-folding transition between snow albedo $\alpha_s(t)$ and ice albedo $\alpha_i(t)$. The constant characteristic snow depth s^* controls the transition and was set to 0.03 m w.e.. Throughout single model years, snow depth $s_z(t)$ mirrors $B_z(t)$, with negative snow depths prevented by enforcing a lower bound of zero. For the subsequent next year, any previous snow is treated as turned into ice and initial snow depth is set to $s^*/4$.

$$\alpha_z(t) = \alpha_s(t) + [\alpha_i(t) - \alpha_s(t)] \cdot \exp[-s^* \cdot s_z(t)] \quad (3.2)$$

The model does not aim to reproduce the full energy balance. Instead, the available melt energy $\Phi_z(t)$ is parameterized as the sum of shortwave radiation $SW(t)$ being absorbed and a linear term depending on temperature $T_z(t)$:

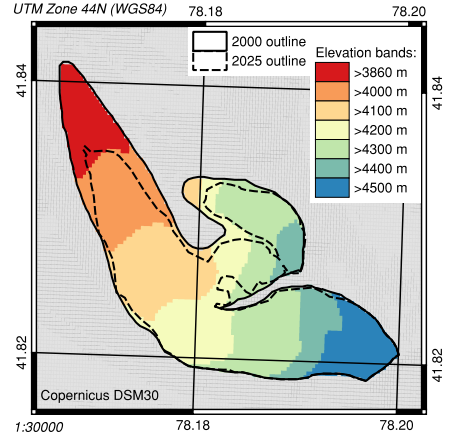


Figure 8: Elevation bands for SMB modeling. Respective band sizes were determined from a Copernicus DSM (European Space Agency and Airbus, 2022) with 30m resolution and Sary-Tor glacier’s outlines in the years 2000 (RGI v7) and 2025 (visually determined from Copernicus Sentinel S2-L2A true color image of 2025-08-19). Between both years, elevation band sizes were linearly interpolated.

$$\Phi_z(t) = [1 - \alpha_z(t)] \cdot \tau \cdot SW(t) + c1 \cdot T_z(t) + c0 \quad (3.3)$$

where $c1$ and $c0$ are empirical parameters tuned to calibrate the model to SMB observations (Sec. 3.3.4). $\tau = 0.626$ is the effective atmospheric transmissivity determined from comparison of orbit-based top-of-atmosphere radiation simulations (following Berger, 1978) with in-situ measurements of incoming short-wave radiation at the 35 km away Taragai AWS (Zech et al., 2021). When $\Phi_z(t) > 0$, melt energy is translated into ablation $M_z(t)$ using water’s latent heat of fusion of 334 kJ/kg. For $\Phi_z(t) < 0$, no melt occurs.

The now closed mass balance is subsequently solved and individual elevation bands’ results interpolated to a glacier-wide estimate by area-weighted averaging. The yearly areal extent of each elevation band was obtained by mapping glacier outlines to a 30m resolution Copernicus DSM (European Space Agency and Airbus, 2022) and linearly interpolating between the year 2000 (RGI v7) and 2025 (visually determined from Sentinel 2 L2A true color imagery of 2025-08-19, Fig. 8).

The simplified structure of the model and its close correspondence to the formulation of Van Tricht et al. (2021) allow for transparent attribution of simulated SMB differences to prescribed albedo perturbations, while minimizing the influence of additional process parameterizations that could obscure the interpretation of the sensitivity experiments.

3.3.2 Meteorological Forcing

Precipitation and air temperature forcing was provided by the Meteorological dataset for the Kumtor–Tien Shan region described by Van Tricht et al. (2021). It combines in-situ meteorological observations, regional reanalysis products, and lapse-rate-based downscaling to generate near-surface air temperature and precipitation representative for an altitude of 3659 m a.s.l.. In the original study, the dataset covers a period up to 2020. Using the same methodology, parameterizations, and raw data sources, the dataset was extended for this study to October 2025 by Van Tricht (2025), ensuring temporal consistency across the full analysis period.

Air temperature and precipitation were distributed over the glacier elevation range using a lapse rate of $-0.006 \text{ }^\circ\text{C m}^{-1}$ and precipitation scaling with altitude ($+0.5 \text{ mm w.e. m}^{-1}$ until 4400 m a.s.l., thereafter $-0.4 \text{ mm w.e. m}^{-1}$), following the approach described in Van Tricht et al. (2021). Incoming shortwave radiation was derived from top-of-atmosphere orbit-based simulations (Berger, 1978) corrected for atmospheric transmissivity (Eq. 3.3) and applied uniformly across the modeled elevation bands.

3.3.3 Scenario Definition

To isolate the impact of an albedo deviation on a single glacier’s SMB, two albedo forcing scenarios were defined for Sary-Tor glacier:

1. The *observed albedo scenario* uses the bias-corrected satellite-derived albedo time series described in Sec. 4.2 and represents the best estimate of Sary-Tor glacier’s observed albedo evolution, including the potential effects of mining-related dust deposition.
2. The *counterfactual albedo scenario* represents a hypothetical state in which Sary-Tor glaciers individual albedo development is forced by the regional glacier albedo trend, instead of Sary-Tor glacier’s trend, while preserving the seasonal cycle and interannual variability of the first scenario. This builds on details of the results in Sec. 4.2.

Both scenarios are forced with identical meteorological inputs and differ exclusively in the prescribed ice albedo $\alpha_i(t)$. This experimental design ensures that differences in simulated SMB can be attributed solely to the imposed albedo perturbation. The albedo forcing is applied consistently across all elevation bands z .

3.3.4 Model Calibration and Uncertainty Estimation

Two surface energy balance parameters ($c1$ and $c0$, cf. Eq. 3.3) were calibrated against glacier-wide SMB observations using the bias-corrected *observed albedo scenario*. For the period 2014–2025, calibration relied on in-situ SMB measurements provided by the Institute for Water Problems and Hydropower of the Kyrgyz National Academy of Sciences (formerly the Tien Shan High Mountain Scientific Centre). To extend the calibration period, the temporally downscaled geodetic mass balance estimates from Dussaillant et al. (2025) were used for earlier years (2000–2013). Calibration was performed by minimizing the mismatch between modeled and observed annual glacier-wide SMB described by the objective function J :

$$J = \sqrt{\text{RMSE}^2 + \lambda \cdot \text{ME}^2} \quad (3.4)$$

where RMSE is the root-mean-square error, ME is the mean error, and λ is a weighting parameter that penalizes the relative importance of bias versus variability. The best parameter combination ($c0 = -310 \text{ Wm}^{-2}$, $c1 = 23.5 \text{ Wm}^{-2}\text{K}^{-1}$) yields $J = 0.63$ with an RMSE of 0.62 m w.e. and ME of 0.03 m w.e for $\lambda = 10$ (Fig. 9).

As described in Sec. 3.2.3, uncertainty in the satellite-derived albedo forcing was quantified based on the comparison with in-situ albedo measurements. This yielded a mean difference $\mu_d = 0.023$ and a standard deviation $\sigma_d = 0.086$. Model calibration was performed using Sary-Tor glacier’s bias-corrected reference albedo forcing $\alpha_{sat} - \mu_d$. To propagate uncertainty in the estimated albedo bias into the model results, a Monte Carlo ensemble of $n=100$ simulations was generated by applying member-wise systematic perturbations as constant offsets to the calibrated albedo time series, drawn from a zero-mean Gaussian distribution $\mathcal{N}(0, \sigma_d^2)$. Each member was simulated independently, yielding an ensemble that isolates the impact of bias uncertainty in satellite-derived albedo on modeled SMB.

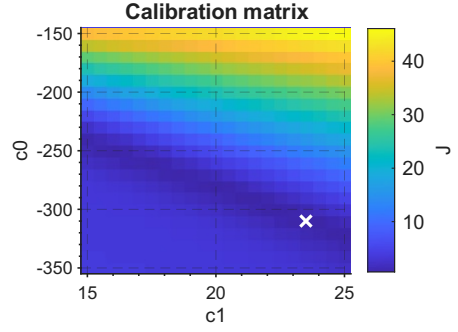


Figure 9: Calibration matrix showing model performance across the parameter space spanned by $c1$ and $c0$, with best-fit solution indicated at $c0 = -310$ and $c1 = 23.5$ (units omitted).

4. Results

The results presented below consist of the relevant surface deposit mineralogy distribution, the satellite-derived glacier albedo time series as well as anomaly, and the corresponding sensitivity of modeled glacier SMB. Implications are discussed in Sec. 5.

4.1 Glacier Surface Deposit Mineralogy

Fig. 10 illustrates the spatial variation of measured pyrite content and derived bulk mineral density of glacier surface samples depending on horizontal and vertical distance from the Kumtor mine. A total of 27 samples were analyzed, comprising 7 samples from Sary-Tor Glacier (in 3 km distance to the mine), 5 from Bordu (5 km), 5 from Grigoriev (25 km), 3 from Kara-Batkak (33 km), 4 from Batysh-Sook (38 km), and 3 from glaciers in the Terekty valley (50 km). While these very limited sample counts cannot claim to represent glacier-scale composition in the light of high spatial heterogeneity, they nevertheless can be meaningful if they sketch a coherent spatial pattern.

Pyrite mass fractions derived from XRD analyses range from below the detection limit (approximately 0.1–0.2 wt.%) to a maximum of 1.54 wt.% across all samples (Fig. 10a). Detectable pyrite is predominantly observed in samples collected from the glaciers closest to the mine: 5 out of 7 samples from Sary-Tor and 2 out of 5 samples from Bordu contain measurable pyrite. In contrast, no pyrite was detected in any samples collected at horizontal distances between 25 and 40 km, while only 1 of the 3 samples from the Terekty valley exhibits detectable pyrite (0.2 wt.%). Differences in pyrite content between near-mine and distant samples exceed the combined analytical uncertainties. Respecting that sample elevation is autocorrelated per glacier, no systematic relationship between pyrite content and the purely vertical distance to the mine becomes apparent.

Bulk mineral densities derived from the overall mineralogical composition show a consistent spatial pattern (Fig. 10b). The highest bulk densities are observed for samples from Sary-Tor and Bordu glaciers, whereas samples collected at intermediate distances (25–40 km) exhibit moderately lower densities. The lowest bulk densities are found for samples from the Terekty valley at a horizontal distance of approximately 50 km. No systematic dependence of bulk density on sample elevation is evident. Bulk densities were computed using mineral-specific density values compiled by Deer et al. (2013). Uncertainties in bulk density are not reported due to unquantified cross-dependencies between individual mineral phases in the mineralogical reconstruction.

4.2 Regional Albedo Variability and Sary-Tor Deviation

All data presented here stems from the down-sampled dataset (cf. Sec. 3.2.2) where observation density is controlled to match that of a reference period (Fig. 5), minimizing potential artifacts arising from increasing data availability in later years.

Fig. 11 shows the temporal evolution of all satellite-derived glacier albedo. Each of all 414 620 individual glacier albedo observations over the whole period 2000–2025 is shown in gray scatter. Across these observations, albedo values range from near 0 to just below 1, with the long-term mean clustered around approximately 0.3–0.6. A pronounced seasonal cycle is evident throughout the entire record, superimposed on substantial inter-annual variability, with some periods exhibiting systematically higher or lower albedo levels than others. Furthermore, there is

4 Results

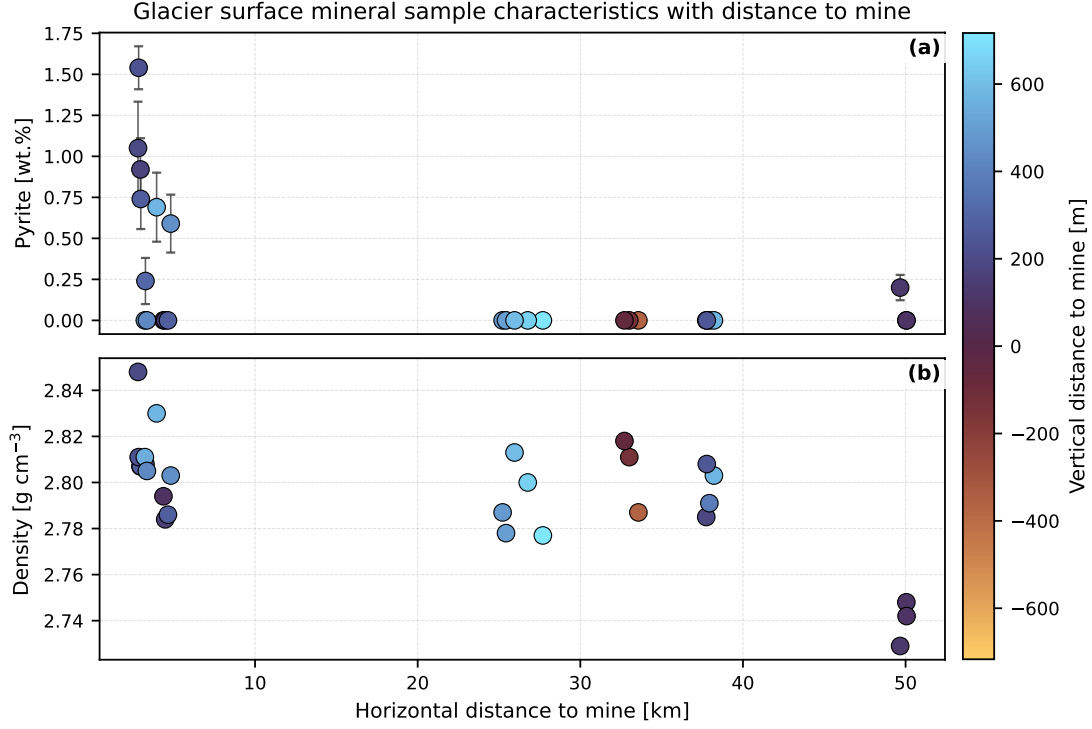


Figure 10: Some mineralogical characteristics of glacier surface deposit samples as a function of horizontal and vertical distance from the Kumtor mine: (a) Pyrite mass fractions derived from XRD analyses; the effective detection limit is approximately 0.1–0.2 wt.%, and error bars indicate formal uncertainties reported by the refinement procedure, scaled by $\sqrt{\chi^2}$. (b) Bulk sample density derived from the overall mineralogical composition inferred from XRD. Densities of individual minerals that constitute the overall sample content were extracted from Deer et al. (2013) and weighted according to their sample share to obtain sample bulk densities. Uncertainties in bulk density are not shown due to unquantified cross-dependencies between individual mineral phases.

an increase in individual glacier high-albedo observations (gray scatter > 0.6) after approximately 2012, while the lower bound of individual glacier albedo values remains largely unchanged.

The glacier-mean albedo, computed across all 371 glaciers and smoothed using a 1-year rolling mean, is depicted as a blue line and increases from approximately 0.35 at the beginning of the record to approximately 0.55 by the end of the study period, corresponding to an average increase of about 0.008 a^{-1} over 25 years. This long-term increase is accompanied by substantial short-term variability. The above described changes in the upper tail of the individual glacier albedo distribution might dominate the observed increase in glacier-mean albedo.

The 1-year rolling mean albedo of Sary-Tor Glacier (orange line) also increases over the study period, from approximately 0.45 to approximately 0.55, corresponding to a comparatively lower average increase of about 0.004 a^{-1} . The Sary-Tor and regional mean time series share many short-term variability features and exhibit a common decadal-scale evolution. For example, both show an intermittent albedo maximum in late 2016 followed by a return to lower values around 2018, indicating temporal coherence in the regional albedo signal.

4 Results

Despite this overall similarity, notable differences between Sary-Tor and the regional mean are evident. During the early part of the record, Sary-Tor albedo is comparable to or slightly higher than the all-glacier mean, whereas in later years it becomes more quasi-equal or lower. By 2023, Sary-Tor exhibits a sustained negative offset relative to the regional mean albedo. The difference in albedo trend between Sary-Tor and the regional glacier mean amounts to approximately 0.1 over 25 years. This divergence of 0.004 a^{-1} constitutes the *albedo deviation* investigated in the model sensitivity experiments (Sec. 3.3).

Short-term differences between the two rolling means are generally on the order of the $\pm\sigma_d$ estimated albedo uncertainty (shaded areas in Fig. 11), limiting the interpretability of small-amplitude deviations. A further discussion of the physical interpretation, limitations, and implications of these results is provided in Sec. 5.

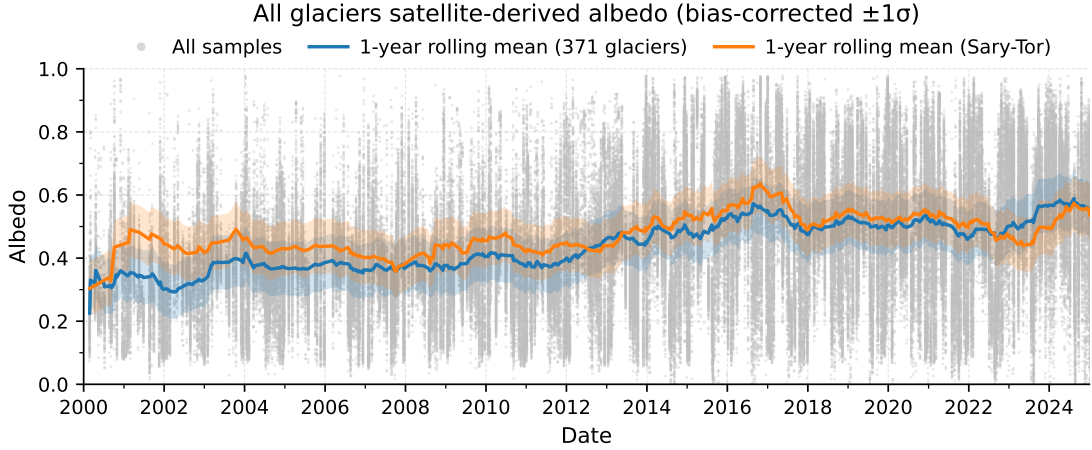


Figure 11: Evolution of all albedo values, regional mean and Sary-Tor glacier mean in the downsampled dataset. Each light grey marker displays the albedo of one of the 371 glaciers in the frame at that point in time. 1-year rolling means of the regional mean (blue) and only Sary-Tor glacier (orange) are depicted.

The spatial pattern of the previously described albedo behavior is shown in Fig. 12. The sub-figures present glacier-specific albedo trends aggregated over successive five-year periods across the study region. The black marker indicates the centre of the Kumtor mine’s main pit, with Sary-Tor glacier located immediately southwest of the mine. Consistent with the temporal evolution shown in Fig. 11, the maps reveal periods of increasing (e.g. 2010–2014), relatively stable (e.g. 2005–2009), and slightly decreasing albedo (e.g. 2015–2019) across the region. Compared to neighbouring glaciers, Sary-Tor generally exhibits a slightly more negative or similar albedo trend, with the exception of the period 2005–2009, when its albedo increases more rapidly than that of surrounding glaciers. During the most recent period (2020–2024), when the mean albedo of Sary-Tor falls below the regional mean (Fig. 11), Sary-Tor is nearly the only glacier in the region exhibiting a declining albedo trend.

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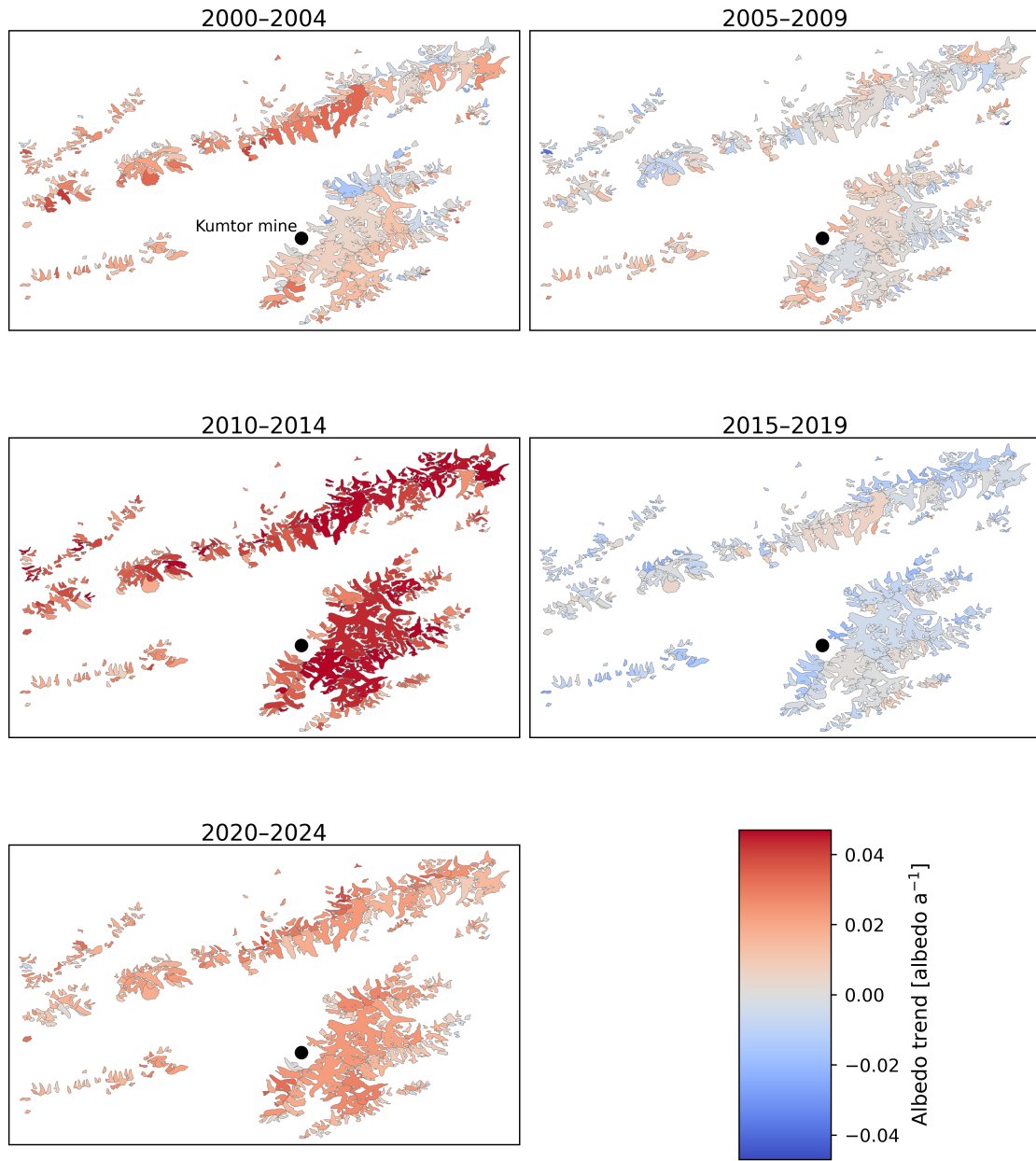


Figure 12: Five-year glacier albedo trends over the whole region of the Arabel-Suu plateau. The location of the Kumtor gold mine is indicated. Albedo trend is calculated over five year periods per individual glacier based on calendar year albedo means.

4.3 Deviation Correlation With Potential Drivers

To assess potential links between the observed albedo behavior and external forcing factors, the temporal evolution of the Sary-Tor albedo deviation, defined in Sec. 4.2 as the difference between the 1-year rolling mean albedo of Sary-Tor Glacier and of the regional mean, was compared with indicators of mining activity and regional meteorological conditions. Fig. 13 summarizes the co-evolution of the albedo anomaly with annual ore extraction (*Kumtor Gold Company 2024 Operating Results*, 2025), mean annual air temperature, and total annual precipitation (cf. Sec. 3.3.2), together with their respective Pearson correlation coefficients.

The albedo deviation exhibits pronounced variability on seasonal to inter-annual timescales (Fig. 13). It is initially positive in the early 2000s, with an early peak exceeding $+0.1$, followed by a gradual decline and oscillations around zero for much of the subsequent period. After approximately 2023, the anomaly shifts to negative values. Annual mining activity remains relatively stable until the late 2000s, it increases substantially during the following decade. The albedo deviation is moderately negatively correlated with annual ore extraction mass ($r=-0.51$), indicating lower albedo anomaly values during periods of higher mining activity.

In contrast, correlations between the albedo deviation and meteorological variables are smaller, specifically weak negative correlation with mean annual air temperature ($r=-0.34$) and no significant correlation with annual precipitation ($r=-0.09$), based on meteorological data from the extended *Kumtor–Tien Shan dataset* Van Tricht et al. (2021), cf. Sec. 3.3.2). A discussion of the physical interpretation and implications of these relationships is provided in Sec. 5.

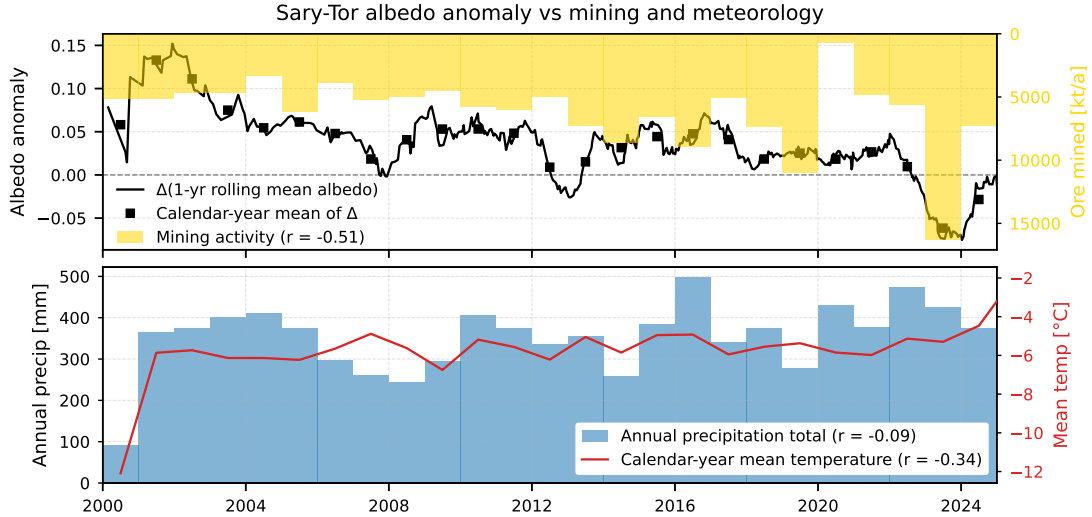


Figure 13: Comparison of the temporal evolution of the Sary-Tor albedo deviation with potential controlling factors. The top panel shows the difference in Sary-Tor’s 1-year rolling mean albedo relative to the regional glacier mean (black line; black squares denote calendar-year means). Yellow bars represent annual mining activity expressed as the mass of ore extracted per year (*Kumtor Gold Company 2024 Operating Results*, 2025); the axis is inverted for visual comparability with the albedo anomaly. The lower panel shows mean annual air temperature and total annual precipitation from the *Meteorological Dataset for the Kumtor–Tien Shan region* (Van Tricht et al., 2021). Pearson correlation coefficients (r) are reported for each variable with respect to the calendar-year mean albedo anomaly.

4.4 SMB Sensitivity to Albedo Forcing

The simulated responses of Sary-Tor Glacier SMB to the *observed albedo scenario* and the *counterfactual albedo scenario* (in which Sary-Tor’s albedo deviation is removed as defined in Sec. 3.3.3) are presented in Fig. 14. Differences between the two scenarios reflect the model sensitivity of glacier-wide SMB to this albedo perturbation under otherwise identical meteorological forcing and calibration settings. Modeled annual and cumulative glacier-wide SMB for both scenarios are shown, together with the observational time series used for model calibration. Uncertainty ranges are derived from the Monte Carlo ensemble described in Sec. 3.3.4.

Ensemble average of *measured* annual SMB accounts to a mean value of $-0.66 \text{ m w.e. a}^{-1}$ over the simulation period. Ensemble average of *modeled* annual SMB under the *observed albedo scenario* exhibits a mean of $-0.6 \text{ m w.e. a}^{-1}$, while the *counterfactual albedo scenario* yields a less negative mean of $-0.47 \text{ m w.e. a}^{-1}$. Ensemble spread (shading in Fig. 14) grows with increasingly negative annual SMB, whereas years with positive modeled SMB show negligible ensemble spread. Through the *annual* perspective, discrepancies between modeled and observed SMB persist under the *observed albedo scenario*, which calibration was performed to; this however improves when considering *cumulative* SMB. Over the full 25-year period, cumulative behavior is consistent with the measured time series (RMSE = 0.62 m w.e. ; ME = 0.03 m w.e.).

In both annual and cumulative SMB perspectives, the *counterfactual albedo scenario* consistently yields less negative (i.e. higher) SMB than the observed scenario. The maximum difference in *annual* SMB between the two scenarios exceeds 1 m w.e. a^{-1} , while the *cumulative* SMB difference after 25 a amounts to 5.5 m w.e. , or equivalently one third of the cumulative SMB measured over a quarter century. Differences between ensemble means remain within the ensemble spread throughout the simulation period.

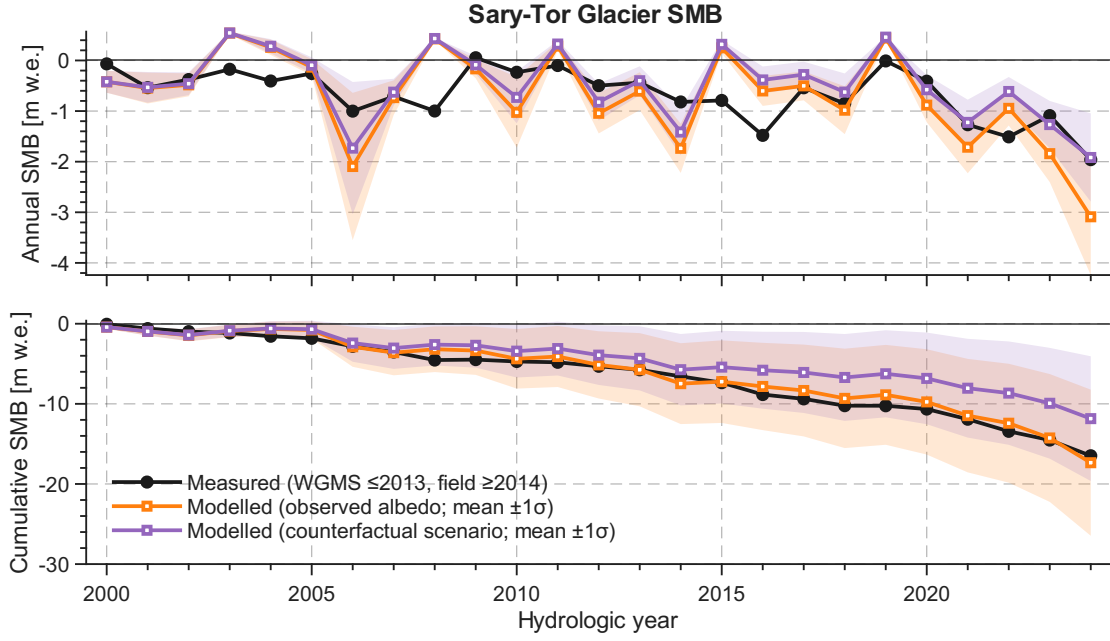


Figure 14: Comparison of Sary-Tor Glacier annual (upper panel) and cumulative (lower panel) SMB measurements with model simulations driven by the *observed albedo scenario* and the *counterfactual albedo scenario*. Satellite-derived albedo uncertainty is propagated through the model using a Monte Carlo ensemble, shown as their spread (1σ shading) and the resulting ensemble means (symbols connected by lines). No uncertainty estimates are available for the field observations after 2013 (black) and are therefore also omitted for the earlier period.

5. Discussion

After assessing the robustness of previous results (Sec. 4), this section synthesizes the mineralogical evidence, satellite-based albedo observations, and SMB sensitivity experiments to interpret existence and implications of the dust deposition on Sary-Tor glacier. Finally, its relevance and limitations for glacier–environment interactions in the Tien Shan are discussed.

5.1 Mineralogical Evidence of Dust Deposition

Pyrite is a common accessory mineral in many gold-bearing ore systems and associated waste material (e.g. Robb, 2021; Groves et al., 1998). The Kumtor gold deposit is hosted within black shale sequences and is classified as a typical orogenic gold system characterized by pyrite-(feldspar)-carbonate ore composition and pervasive sulfide mineralization (Mao et al., 2004; Shevkunov et al., 2018, 2023). Mechanical excavation, crushing, and handling of ore and waste rock at large open-pit mines generates dust, which can be transported and deposited in the surrounding environment (Castillo et al., 2013; Fernández-Caliani et al., 2013).

The glacier surface mineralogy results at hand (Fig. 10) show a clear spatial pattern of both pyrite occurrence and bulk mineral density with increasing horizontal distance from the Kumtor mine. Detectable pyrite is predominantly confined to samples collected from glaciers closest to the mine, whereas no pyrite is detected at intermediate distances (25–40 km). Differences between near-mine and distant samples exceed analytical uncertainties. Bulk mineral densities exhibit a consistent decline with distance, with the highest values on glaciers closest to the mine and the lowest values at the most distant sites. These patterns are consistent with aeolian transport and deposition of mineral dust originating from a localized source. Under otherwise similar conditions, mass-density-driven fractionation favors the preferential transport of finer and lighter particles with increasing distance from the source, while denser mineral phases are progressively depleted downwind (e.g. van der Does et al., 2016). Similar physical arguments (cf. Loskot et al., 2024) suggest that vertical fractionation may also occur, although this effect is not observed here, possibly due to sampling glaciers instead of vertical atmospheric profiles. The observed decrease in pyrite occurrence and bulk density with distance is therefore consistent with density-controlled survival of mineral particles during aeolian transport away from a point source, like the Kumtor mine.

At the same time, provenance may not be unique. Pyrite-bearing material may also derive from natural erosion of regional lithologies or background dust sources, and local wind fields and topographic shielding can introduce strong spatial heterogeneity. The limited number of samples per site and the finite pyrite detection threshold (ca. 0.1–0.2 wt.%) constrain quantitative source attribution. Consequently, mineralogical evidence alone cannot unambiguously identify mining as the sole dust source. Nevertheless, the systematic decay of pyrite occurrence and bulk mineral density with horizontal distance from the mine matches expectations for a strong, proximal dust source.

5.2 Glacier Albedo Derivation from Satellite Imagery

The satellite-derived albedo time series provides a long-term, spatially extensive view of glacier surface shortwave albedo variability across the Arabel–Suu valley and surrounding regions. The pronounced seasonal cycle reflects the expected alternation between snow-covered and bare-ice conditions, while the strong temporal coherence of short-term variability across the two running

means indicates that regional-scale meteorological forcing dominates albedo variability at sub-annual to inter-annual timescales. The use of temporal subsampling to match observation density to the reference period further reduces the likelihood that the observed long-term evolution is an artifact of changing data availability or irregular sampling.

Combining observations from multiple Landsat sensors introduces a source of uncertainty. Differences in radiometric characteristics between Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI can result in small reflectance offsets and low-frequency artifacts if not fully harmonized (Flood, 2014; Mancino et al., 2020). Notably, Landsat 8 became operational in 2013, coinciding with the period in which the frequency of high-albedo observations increases across the dataset. Although standard surface reflectance processing is intended to minimize these effects, residual cross-sensor inconsistencies cannot be entirely excluded and may contribute to step-like features or subtle trend modulations in long-term albedo records over the whole region but, importantly, not for individual glaciers.

The long-term increase in regional mean albedo, characterized by a strengthening upper tail of the albedo distribution and a largely unchanged lower bound, suggests that processes affecting high-albedo surface states play a dominant role regionally. A plausible contributing mechanism is a shift in the seasonal timing or persistence of snowfall, whereby increased early- or late-season precipitation promotes longer-lasting snow cover and higher mean albedo. Such changes in the temporal precipitation regime would be consistent with the observed pattern. Although a meteorological forcing correlation analysis was performed here, seasonal shifts are not resolved by its annual time scale.

Despite the overall robustness of the regional signal, several limitations inherent to optical satellite-derived albedo must be acknowledged. Residual uncertainties arise from cloud masking, terrain shadowing, cross-sensor harmonization, and the narrow-to-broadband conversion itself (Liang, 2001), which here does not explicitly account for surface anisotropy. All these effects are treated as systematic uncertainty common to all glaciers. As demonstrated by the comparison with in-situ measurements (Sec. 3.2.3), they limit the interpretability of short-term or highly localized albedo differences. Consequently, sustained deviations over multi-year timescales and spatially coherent patterns provide a more reliable basis for interpretation than individual seasonal outliers.

Overall, the satellite-derived albedo dataset captures a physically plausible and internally consistent picture of regional glacier albedo evolution, forming a robust foundation for identifying glacier-specific long-term deviations from the regional signal.

5.3 Attribution of the Albedo Deviation

Against the backdrop of the regional albedo mean, Sary-Tor glacier exhibits a long-term divergence. While its albedo evolution shares the same short-term variability and decadal-scale structure as the regional signal, its long-term trend is weaker, resulting in a cumulative difference of approximately 0.1 in 1-year rolling mean albedo over 25 years. Short-term differences between the two rolling-mean time series are generally on the order of the estimated albedo uncertainty ($\pm\sigma_d$), limiting the interpretability of small-amplitude deviations. However, the persistent temporal coherence of short-term variability across glaciers suggests that the sustained divergence observed in the long-term trends does not arise from random observational noise alone, but instead reflects a systematic glacier-specific signal.

In addition to the potential influence of dust deposition, several alternative mechanisms could contribute to glacier-specific albedo differences. Variations in glacier hypsometry, slope, and aspect could influence the duration of snow cover and the timing of seasonal melt, thereby af-

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fecting mean surface albedo. Differences in glacier dynamics, such as crevassing or surface runoff channeling, may also modify meltwater redistribution and surface scattering properties. Furthermore, localized meteorological effects, including wind redistribution of snow or spatial variability in snowfall, could influence albedo evolution at individual glaciers. While the glaciers considered here are located within a relatively confined region and share broadly similar climatic conditions, such local factors cannot be entirely excluded as contributors to the observed albedo deviation. Consequently, the satellite-derived albedo signal should be interpreted as the integrated outcome of multiple surface processes rather than a direct proxy for dust deposition alone.

The spatial distribution of glacier albedo trends provides some additional context for this divergence. When evaluated over successive five-year periods (Fig. 12), many glaciers in the study region exhibit broadly coherent albedo trends consistent with the regional temporal evolution described above. While it does not stand out in magnitude over the whole region, Sary-Tor glacier at some times displays slightly more negative or weaker albedo trends relative to neighbouring glaciers. This pattern is particularly pronounced in the most recent period (2020–2024), during which Sary-Tor is the upon the only glaciers in the region exhibiting a slightly declining albedo trend. The spatial coherence of albedo evolution among most glaciers suggests that regional climatic forcing dominates large-scale variability, while individual factors such as aspect, elevation, and topography might dominate individual glaciers. Additionally, the localized deviation at Sary-Tor for 2000–2024 points toward a further glacier-specific influence. This is temporally coherent with the strongest difference in regional and individual albedo evolution (cf. Fig. 13).

The correlation analysis of Sec. 4.3 provides context for potential drivers of this deviation. The moderate negative correlation between the albedo anomaly and mining activity indicates that periods of increased ore extraction coincide with relatively lower albedo at Sary-Tor Glacier. In contrast, correlations with meteorological variables are weak, particularly for precipitation, suggesting that weather variability alone is insufficient to explain the glacier-specific divergence. This contrast is important, as the regional albedo increase discussed in Sec. 5.2 can plausibly be explained by broad-scale meteorological changes, whereas the anomaly emerges only when Sary-Tor is evaluated relative to its regional context.

The statistical relationship between albedo anomaly and mining activity should nevertheless be interpreted with caution. The analysis is based on annual aggregates over a relatively limited time span, and the observed correlation coefficient ($r = -0.51$) reflects only a moderate statistical association. In addition, potential time lags between dust emission, atmospheric transport, and deposition onto glacier surfaces are not explicitly resolved by the annual correlation analysis. For these reasons, the correlation results are best interpreted as indicative of a possible linkage rather than definitive evidence for a causal relationship. Furthermore, satellite-derived albedo integrates multiple surface processes, including snow cover, meltwater redistribution, and debris exposure, which may respond differently to external forcing.

Despite these limitations, the combination of (i) a quasi-persistent temporal divergence from the regional albedo signal, (ii) a somewhat localized spatial deviation relative to neighbouring glaciers, and (iii) the preferential association of the anomaly with mining activity supports the interpretation of a local dust forcing superimposed on a regional signal. When considered together with the mineralogical indication for particulate deposition on nearby glaciers (Sec. 5.1), the satellite-derived albedo deviation provides a consistent observational basis for an impact of mining-related dust on nearby glacier surface properties.

5.4 Implications for Glacier SMB and Evolution

The sensitivity experiments (Sec. 4.4) demonstrate that relatively modest, sustained albedo perturbations (difference in tendency of $+0.004 \text{ a}^{-1}$) can exert a substantial influence on glacier SMB when integrated over a quarter century. Although the SMB difference between the observed and counterfactual albedo scenarios (Fig. 14) is small on an annual basis and often within the ensemble spread, the consistently less negative SMB simulated under the counterfactual scenario indicates a systematic response to the imposed albedo anomaly.

At the annual scale, ensemble spread increases markedly during strongly negative SMB years, while years with positive SMB show negligible ensemble spread, indicating limited sensitivity to albedo perturbations under accumulation-dominated conditions. This behavior reflects the physical role of albedo in modulating shortwave energy absorption during melt seasons: when melt energy is limited, albedo variations exert little influence, whereas during warm and radiatively intense times, albedo differences directly translate into enhanced or suppressed ablation. The persistence of discrepancies between *modeled* and *measured* annual SMB under the observed scenario further highlights the difficulty of reproducing year-to-year variability with a simplified model. The cumulative SMB curves show improved agreement with observations compared to annual values, which is consistent with the calibration statistics ($\text{RMSE} > \text{ME}$) and suggests that the model captures the dominant long-term signal, even if short-term variability remains imperfectly represented.

The imposed albedo difference of $+0.004 \text{ a}^{-1}$ leads to a reduced mass loss of approximately 5.5 m w.e. when integrated over 25 years, corresponding to $0.22 \text{ m w.e. a}^{-1}$ when expressed as a mean annual offset. Being equivalent to roughly one third of the cumulative *measured* SMB over the same period, this illustrates how small but systematic surface property changes can accumulate into meaningful mass. Our choice of difference in albedo tendency rather than absolute albedo doesn't allow for direct comparison with existing studies on SMB-sensitivity to albedo change on mining-affected glaciers specifically (Barandun et al., 2022) or mountain glaciers generally (e.g. Naegeli and Huss, 2017; Johnson and Rupper, 2020). Nevertheless, all studies agree that albedo alternation can enhance annual ablation substantially.

Importantly, differences between the ensemble means of the two scenarios remain within the ensemble spread throughout the simulation period. This stresses that the modeled albedo impact should be interpreted as a sensitivity estimate rather than a deterministic quantity. Nevertheless, there is a robust directional response: removing the albedo anomaly systematically reduces simulated mass loss under otherwise identical forcing.

Taken together, these results suggest that the satellite-identified albedo anomaly constitutes a potentially important modifier of glacier mass balance at Sary-Tor. Within the limitations of a simple SMB framework, the experiments demonstrate that persistent localized albedo changes contribute appreciably to long-term glacier mass loss. This finding supports the broader interpretation that surface darkening processes, whether driven by natural or anthropogenic particulate deposition, deserve consideration alongside climatic forcing when assessing glacier change.

5.5 Limitations and Outlook

The interpretation of mining-related dust deposition as a contributor to glacier surface darkening and enhanced mass loss at Sary-Tor is supported by two independent observational lines of evidence: glacier surface mineralogy and satellite-derived albedo deviation. While the consistency between these approaches strengthens the overall interpretation, there is no proven causal link and each is subject to methodological limitations that constrain the certainty of attribution. Mineralogical evidence is limited by sample number, spatial representativeness, finite detection

5 Discussion

thresholds, and potential equivalent background dust sources. Satellite-based albedo signal lumps all surface processes and is affected by residual uncertainties related to cloud masking, surface anisotropy, and cross-sensor harmonization. Consequently, confidence in attributing a specific fraction of observed mass loss to dust deposition remains qualitative rather than quantitative.

The transferability of the presented results is constrained. The Kumtor–Sary-Tor setting represents an extreme case of a large open-pit mine located in immediate proximity to glacierized terrain. While similar setups may exist in Earth’s many high-mountain regions, the spatial extent, magnitude, and persistence of dust impacts are expected to depend on local factors such as mine scale, topography, wind regime, and glacier geometry. The results therefore should not be generalized to infer universal influence distances or thresholds, but rather be viewed as a process-oriented case study highlighting the potential for localized anthropogenic activities to modify glacier surface properties.

Temporally intensive efforts in mineralogical analysis might improve attribution, like e.g. processing a larger number of glacier surface samples and employing additional mineralogical tracers (e.g. trace metal concentrations or isotopic signatures). From a remote-sensing perspective, incorporating reflectance anisotropy corrections and sub-glacier-scale pattern analyses may improve the physical interpretability of albedo changes. Finally, extending the sensitivity analysis to more sophisticated SMB or coupled ice-dynamical models, would allow more precise diagnosis of the implications of albedo deviation.

Several avenues for future research emerge from this work. Higher-temporal-resolution optical sensors such as Sentinel-2 offer the potential to resolve short-term albedo variability and deposition events with greater detail, albeit at the cost of shorter historical coverage. Coupling satellite-based albedo observations with atmospheric aerosol transport modeling could further constrain dust provenance. In addition, mining-derived aerosols may act as cloud condensation nuclei and thereby indirectly influence glacier surface energy balance through modifications of cloud cover, precipitation and radiation, a mechanism not considered here.

6. Conclusion

This study combined three complementary approaches to investigate potential dust deposition from the Kumtor open-pit gold mine to surrounding glaciers: mineralogical analysis of glacier surface deposits, satellite-derived albedo observations, and SMB sensitivity modeling. Taken individually, none of these approaches provides unequivocal proof of mining-related impacts. However, together they form mutually consistent indications that dust originating from the mine affects nearby glacier surfaces.

Mineralogical analyses reveal a clear spatial pattern in the composition of glacier surface deposits. Mining-related mineral constituents and bulk sample density decrease systematically with horizontal distance from the Kumtor mine, with the highest values observed on glaciers located closest to the mining site. This pattern is consistent with expectations for aeolian transport and deposition of mineral particles away from a localized dust source such as an open mining pit, although the employed mineralogical indicators alone do not allow for unequivocal source attribution.

Satellite-derived glacier albedo observations show that the regional mean albedo of glaciers in the study area increased over the past 25 years. While Sary-Tor Glacier exhibits a similar temporal evolution, its long-term albedo increase is only about half as strong as the regional trend. The resulting albedo deviation shows a distinct spatial anomaly at Sary-Tor for the period 2020-2024 and entails the strongest correlation with annual excavation volumes reported by the Kumtor mine, compared with regional temperature and precipitation records.

Sensitivity experiments using a simple SMB model demonstrate that even small but persistent albedo differences can substantially influence glacier mass balance over multi-decadal timescales. When integrated over the 25-year study period, the observed albedo deviation corresponds to a cumulative SMB difference of approximately 5.5 m w.e., equivalent to roughly one third of the measured mass loss of Sary-Tor Glacier.

All applied methodologies involve uncertainties and rely on simplifying assumptions. Except for the pronounced spatial pattern in pyrite occurrence near the mine, most short-term deviations remain within observational uncertainty ranges. Nevertheless, the persistence and temporal coherence of the observed signals support their interpretation as a systematic glacier-specific effect. Independent in-situ measurements confirm that the magnitude of uncertainties associated with satellite-derived albedo retrieval is consistent with values reported in previous studies.

Overall, the results suggest that, in addition to climatic forcing, localized anthropogenic activities can influence glacier surface properties and melt dynamics in high-mountain environments. In the Kumtor region, glaciers located within a few kilometers of the mining area appear most likely to be affected, although the spatial extent of the influence cannot be determined conclusively from the present analysis. Together with previous studies of mining-affected glaciers (e.g. Barandun et al., 2022), these findings provide further evidence that large high-mountain mining operations can modify the surface energy balance and long-term evolution of nearby glaciers.

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