



Mapping permafrost distribution and thaw depths in the Inner Tien Shan: A CryoGrid-based modeling approach integrating geophysical data

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Abstract. Permafrost degradation poses increasing risks to infrastructure in high-mountain regions, yet quantitative and spatially distributed assessments remain scarce in data-limited areas such as Central Asia. This study focuses on a 1,563 km² area in Inner Tien Shan, Kyrgyzstan, including the Kumtor gold mine and the Arabel plateau. We applied the numerical permafrost model CryoGrid to simulate permafrost distribution and thaw depth across the study area, informed by geophysically derived stratigraphies and assessed against borehole temperatures and ground-based observations. To represent subsurface heterogeneity, surface-type-specific stratigraphies were developed for six landscape classes derived from petrophysical joint inversion of co-located Electrical Resistivity Tomography (ERT) and Refraction Seismic Tomography (RST) data. Legacy borehole measurements from 1986–1992 were incorporated to provide a multi-decadal validation of ground thermal conditions.

The resulting 30 m resolution maps indicate continuous permafrost across the study area, with mean ground temperatures at 5 m depth ranging from -0.1°C to -6.5°C and a spatial mean of -2.9°C . Mean thaw depth at the end of August 2024 is 2.0 m, with surface type exerting a strong control on spatial patterns. Fine-grained and vegetated sediments on the Arabel plateau show comparatively deep thaw, coinciding with thermokarst features and ground subsidence, whereas coarse-blocky debris and rock glaciers exhibit shallow thaw depths. Comparison with ERT-derived thaw depths from 15 profiles shows agreement generally within about 1 m. Simulated ground temperatures show warming trends of 0.20°C and 0.18°C per decade at 5 m and 20 m depth since 1975, corresponding to approximately 1°C warming since the 1980s. These results demonstrate the value of integrating geophysical data and surface-type-specific stratigraphies into modeling studies to represent spatial variability of mountain permafrost in data-scarce regions.



1 Introduction

Permafrost distribution in high-mountain regions is highly heterogeneous and controlled by topography, surface characteristics, and climatic conditions. Modeling its spatial extent is therefore particularly challenging, as small-scale variations in surface and subsurface properties can lead to strong differences in ground thermal regimes over short distances (Schneider et al., 2012; Hanson and Hoelzle, 2005). This is especially relevant in regions such as Central Asia, where permafrost distribution is still poorly characterized by in-situ observations and existing distribution maps are limited to global-scale models (Gruber, 2012; Obu et al., 2019; Karjalainen et al., 2019; Ran et al., 2022a) that do not resolve this local variability. This spatial variability affects the ground thermal regime, including the seasonal thawing and refreezing of the near-surface layer, i.e., the active layer. The active layer is the uppermost ground layer in permafrost terrain that thaws and refreezes on a seasonal basis. Its thickness, referred to as active layer thickness (ALT), is a key indicator of ground thermal conditions and a sensitive proxy for detecting climate change impacts in cold regions. In high-altitude mountain permafrost zones such as the Tien Shan and Pamir, ALT varies considerably as a function of topography, surface cover, and climatic gradients (Zhao et al., 2010; Ran et al., 2022b). As the layer through which heat and moisture seasonally penetrate, ALT plays a central role in controlling ground stability, hydrological flow paths, and carbon cycling (Aumer et al., 2025; Walvoord et al., 2016). Therefore, observed increases in ALT over recent decades, closely linked to atmospheric warming, pose growing risks to infrastructure and can lead to an increase in natural hazards by altering hydrological regimes and triggering thaw-related ground deformation, slope destabilization, and subsidence processes (Biskaborn et al., 2019; Wu et al., 2022). Understanding the spatial and temporal evolution of ALT is therefore essential for climate impact assessments, water resource planning, and infrastructure resilience in permafrost-affected mountain regions.

The surface type plays a crucial role in modulating energy exchange processes at the ground surface and within the subsurface (Schneider et al., 2012), and therefore strongly influences both the general permafrost distribution and ALT. A comparison of in-situ measurements, as well as empirical and modeling studies across different mountain regions (e.g., the Alps, Andes, Tibetan Plateau, and Scandinavia) reveals substantial variability in ALT linked to substrate characteristics (Bonnaventure and Lamoureux, 2013; Hanson and Hoelzle, 2005). Vegetated organic-rich soils typically show shallow ALTs (0.5–2 m), whereas bedrock surfaces exhibit depths exceeding 10 m due to high thermal conductivity and minimal insulation (Gruber et al., 2004a, b). In coarse-blocky terrain such as rock glaciers and talus slopes, thaw depths generally range from 2 to 7 m. The high porosity of the blocky material promotes air circulation and modifies heat transfer, leading to complex subsurface thermal conditions that influence thaw depth and permafrost occurrence (Amschwand et al., 2025; Zenklusen Mutter and Phillips, 2012; Villarroel et al., 2020; Kenner et al., 2017; Gorbunov et al., 2004, 1992; Mittaz et al., 2000; Hanson and Hoelzle, 2004; Hoelzle et al., 1999). Fine-grained mineral soils show intermediate ALTs (1–5 m), largely influenced by moisture (water) and snow insulation effects (Burn and Smith, 1988; Smith and Riseborough, 1985; Bonnaventure and Lamoureux, 2013; Wu et al., 2022; Haberkorn et al., 2015, 2016). However, distributed in-situ measurements of thaw depth are rare, particularly in remote, high-altitude mountain regions.



Methods for assessing permafrost conditions, including both active layer thickness (ALT) and the spatial distribution of permafrost, have advanced over the past two decades, combining in situ observations, geophysical imaging, remote sensing, and modeling. In all approaches, field measurements remain essential for model calibration and validation. ALT can be monitored through mechanical probing and monitoring of borehole temperatures (e.g. PERMOS 2024, 2024). To extend such assessments beyond the point scale, geophysical methods can be used in the field. Electrical Resistivity Tomography (ERT) and Refraction Seismic Tomography (RST) are able to map the depth of the thawed layer by exploiting contrasts in electrical and seismic properties between frozen and unfrozen ground (Draebing, 2016; Herring et al., 2023). Such surveys provide 2D profiles of the subsurface, including spatial information on thaw depth in heterogeneous terrain as well as broader insights into subsurface structure. At even larger spatial scales, remote sensing approaches can offer more regional estimations of thaw depths. Interferometric SAR (InSAR), for example, has been used to infer ALT over large areas by detecting seasonal ground subsidence from freeze–thaw cycles (e.g. Chang et al., 2024; Schaefer et al., 2015). To bridge the gap between local-scale observations and regional-scale permafrost distribution, numerical models can be used for understanding permafrost dynamics under changing climatic conditions over longer time scales. Among these, the CryoGrid Community model (CryoGrid hereafter) has emerged as a widely used land surface model capable of simulating ground thermal and hydrological regimes (Westermann et al., 2023; Martin et al., 2023; Pedro Baptista et al., 2025). CryoGrid is designed to represent various permafrost landscapes, ranging from Arctic tundra to mountain permafrost, by incorporating a variety of small-scale physical processes such as freezing and thawing cycles, hydrological fluxes, snowpack dynamics, and subsurface water flow. Its modular structure allows for the integration of different physical processes, enabling the simulation of complex land surface interactions in many different settings. Such models provide a means to integrate process understanding and spatial variability, allowing both permafrost distribution and active layer dynamics to be assessed consistently across complex mountain terrain.

In this study, we use CryoGrid in an integrated modeling approach for the Akshiirak range in the Tien Shan of Central Asia, a region that includes the Kumtor gold mine and its associated infrastructure. Our primary goals are (i) Our primary goals are (i) to produce a high-resolution map of permafrost distribution and associated spatial variability in thermal conditions (ground temperatures) and thaw depth, constrained by both contemporary observations and legacy borehole data (i.e., historical borehole temperature measurements from Soviet-era monitoring campaigns), (ii) to simulate the spatial distribution of thaw depths and evaluate the results using ERT-derived thaw depths as an independent spatial proxy, and (iii) to compare the resulting permafrost distribution with a global-scale permafrost map (Gruber, 2012) in order to assess how regional-scale modeling can improve the representation of permafrost variability in complex mountain terrain. The CryoGrid model is calibrated using a combination of geophysical measurements alongside ground surface temperature (GST) loggers and (shallow and deep) borehole data. We leverage the geophysical in-situ data to better represent subsurface heterogeneity, incorporating mineral fractions (= porosity) derived from Petrophysical Joint Inversion (PJI, Mathys et al. (2025)) into the model's initial soil stratigraphies. Water and ice contents are simulated dynamically within the CryoGrid model and are therefore not directly prescribed from the geophysical measurements. Given the limited spatial coverage of borehole observations and other in-situ methods for assessing thaw depth, ERT-derived thaw depths at the time of the measurements are used as an independent spatial proxy to evaluate modeled thaw depth patterns. This integrated approach enables a more physically consistent representation



of subsurface heterogeneity and provides new insights into the spatial variability of thaw depth and permafrost conditions in data-scarce, high-altitude mountain environments.

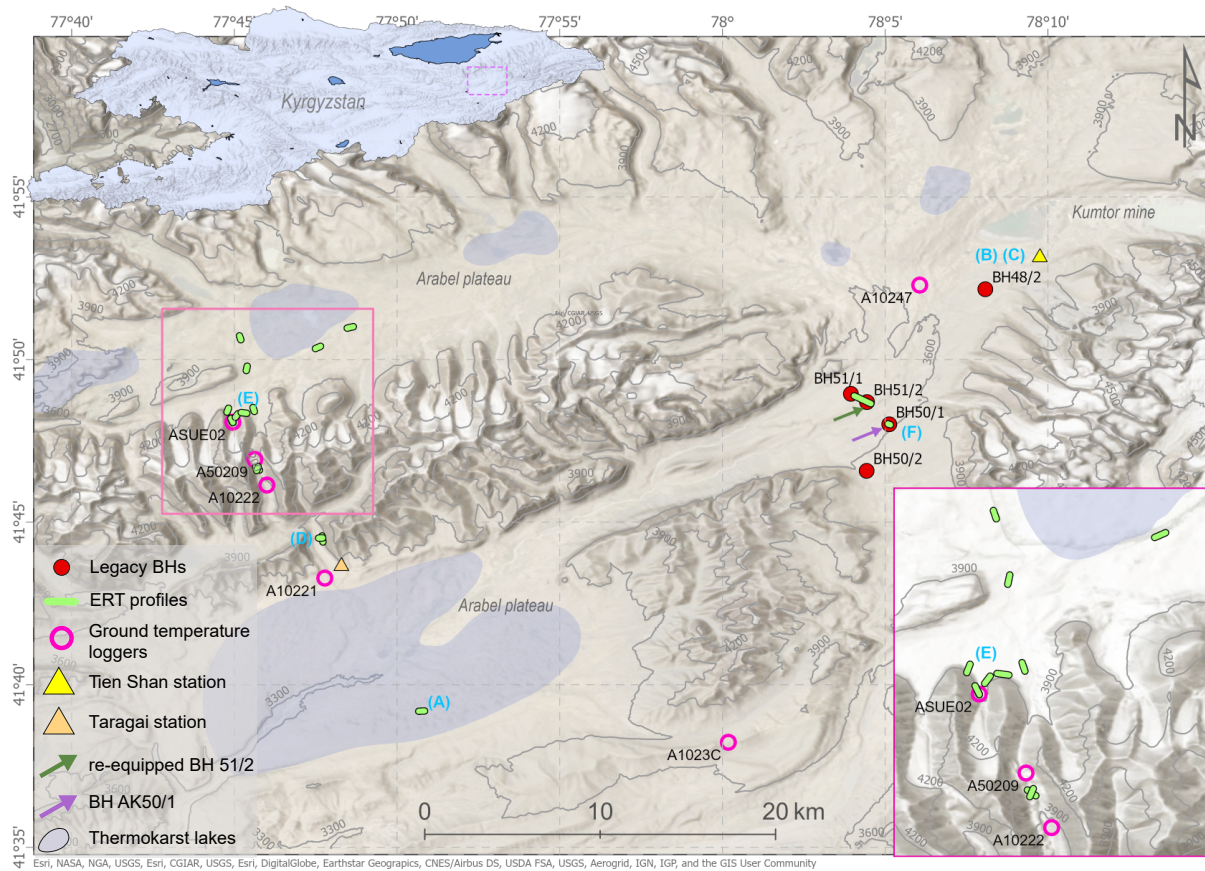


Figure 1. Study site overview showing the distribution of observational datasets (Ground temperature loggers, boreholes, meteorological stations, and geophysical profiles). The new borehole (AK50/1, installed in 2022) is located approximately 20 m from the legacy borehole 50/1 (1986–1992) (region F), enabling a multi-decadal comparison of ground temperatures. Borehole 51/2 was re-equipped with temperature sensors in 2022 and provides additional data for spatial validation of the model. All legacy boreholes are marked by red points. Blue letters indicate the locations of the photographs shown in Figure 2. RST profiles were always co-located at ERT profiles and are not explicitly added for clarity reasons. Sources of the background maps: Esri, NASA, NGA, CGIAR, DigitalGlobe, Earthstar Geographics, CNES/Airbus DS, USDA FSA, Aerogrid, IGP, GIS User Community | Powered by Esri.

2 Study site

The study area is located in the Akshiirak Range of the Central Tien Shan, Kyrgyzstan, at elevations ranging from approximately 3'200 to 4'900 m a.s.l. It includes the high-elevation Arabel plateau, which is predominantly characterized by fine-



grained and vegetated sediment surfaces. Figure 1 shows the extent of the study area, as well as the location of automatic weather stations (AWS), ground temperature loggers, boreholes, and geophysical measurements used in this study. The region is characterized by a cold, arid, continental high-mountain climate. Long-term meteorological data from the nearby Tien Shan weather station (3'614 m a.s.l.) indicate a mean annual air temperature of approximately -6.84°C , with winter minima reaching below -30°C and mean annual precipitation between 200 and 400 mm, falling mostly as snow. Snow cover in general is quite shallow (< 50 cm) (Aizen et al., 2006; Marchenko et al., 2007; Kronenberg et al., 2020). The study area encompasses a range of surface types, from coarse-blocky debris, rock glaciers, bedrock outcrops to fine-grained and vegetated sediments. In particular, the Arabel plateau is predominantly covered by vegetated (grassy) sediments, which represent the most widespread surface type in the study area. Representative examples of some of these surface types are shown in Figure 2.

According to previous studies, permafrost is widespread and continuous above 3,500 m in the region and reaching thicknesses of up to several hundred meters in some locations (Marchenko et al., 2007). Duishonakunov (2014) calculated ALTs of 2-3 m from ground temperature measurements (2001-2011), with maximum ALTs observed at the beginning of August. Observational evidence suggests that the permafrost in this region is warming and gradually degrading under recent climatic trends (Hoelzle, 2025). Clear geomorphological indicators of permafrost degradation can be observed across the Arabel high plateau, including thermokarst lakes (Figure 2A), ground subsidence and infrastructure damage (Figure 2B), and water accumulation around legacy borehole sites (Figure 2C). These (geomorphological) features reflect local degradation of ice-rich permafrost and provide visible evidence of active layer thickening and changing subsurface thermal conditions.

3 Materials and methods

The workflow of this paper is summarized in Figure 3. In the following, the different materials (data) and methods used in this study are introduced.

3.1 Field measurements and observations

3.1.1 Geophysical measurements

The subsurface conditions at the study site were characterized using Electrical Resistivity Tomography (ERT) and Refraction Seismic Tomography (RST) data collected by Mathys et al. (2025), as well as data from a continuous ERT station (A-ERT).

These data from geophysical surveys provide information on resistivity and seismic P-wave velocity, allowing the identification of frozen and unfrozen ground layers. The profiles cover various landforms, including moraines, rock glaciers, talus slopes, fine-grained sediments, and vegetated sediments, and thus capture a wide range of permafrost conditions with varying ground ice contents and thaw depths. In total, 15 ERT profiles (electrode spacing 2–5 m) and 6 RST profiles (geophone spacing 2–5 m) were acquired in the study area. For profiles with co-located ERT and RST measurements, the Petrophysical Joint Inversion (PJI) approach of Wagner et al. (2019) was applied to estimate volumetric fractions of rock, water, ice, and air, as presented in Mathys et al. (2025). Overall, evidence of permafrost occurrence was found at all geophysical profile locations,



Figure 2. Field photographs from the study area. The upper row shows indicators of permafrost degradation: (A) thermokarst lake, (B) cracked building, and (C) a legacy borehole site now surrounded by surface water. The lower row illustrates representative surface types: (D) coarse-blocky material (debris), (E) talus slope with bedrock outcrops, and (F) sparsely vegetated (grassy) sediments at the re-equipped BH51/2. Pictures: Tamara Mathys, Christin Hilbich.

indicating widespread permafrost conditions in the study area. Both the geophysical and borehole data further suggest relatively homogeneous subsurface conditions beneath the vegetated sediments that dominate the Arabel plateau.

In this study, because the geophysical measurements used for the permafrost assessment are not always acquired at the time of maximum seasonal thaw, we use the term thaw depth for date-specific thaw conditions, while active layer thickness (ALT) refers strictly to the annual maximum thaw depth. Thaw depth was estimated for each ERT profile using the maximum gradient method following Herring and Lewkowicz (2022). This approach defines thaw depth as the depth of the maximum vertical resistivity gradient, corresponding to the transition between the thawed active layer and the underlying frozen ground. By relying on gradients rather than absolute resistivity thresholds, the method avoids the need for site-specific calibration. However, ERT-derived thaw depth represents a geophysical proxy that does not necessarily coincide with a thermally defined thaw depth at the time of the measurement. The method performs best where clear resistivity contrasts exist between the thawed active layer and the underlying frozen ground, for example in fine-grained or ice-rich sediments where thawing strongly increases liquid water content and decreases resistivity. In contrast, the approach is less reliable in dry coarse-blocky material, where the active layer itself can exhibit very high resistivities, thereby reducing the contrast to the underlying permafrost. Furthermore, because ERT surveys were not always conducted at the time of maximum seasonal thaw, the values reported here represent thaw depth at the time of measurement rather than end-of-summer ALT. All ERT tomograms used in this study,

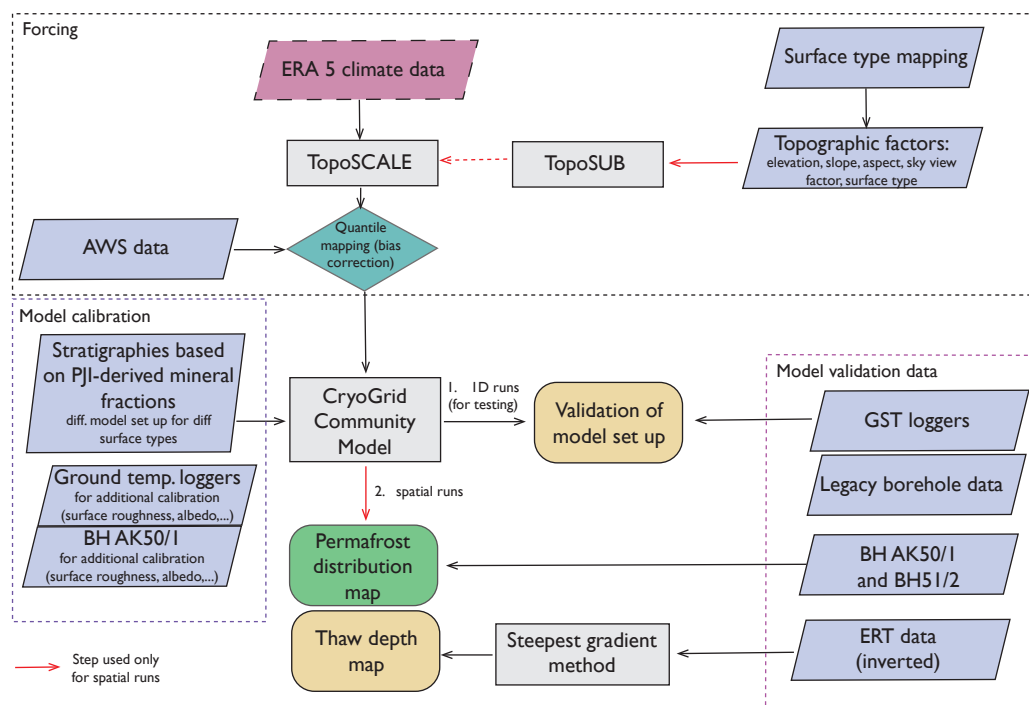


Figure 3. Workflow of the CryoGrid modeling approach. Climate forcing is derived from ERA5 and downscaled using TopoSCALE (Fiddes and Gruber, 2014). PJI-derived mineral fractions define stratigraphies for different surface types. The model is calibrated and validated using GST loggers, shallow and deep borehole data, and then applied spatially using TopoSUB. Model outputs include permafrost distribution and active layer thickness.

including the estimated thaw depths, are provided in the Appendix (Figure A1 and Figure A2). In some profiles, thaw depths were only determined for selected sections of the transect because the profiles crossed multiple landforms.

3.1.2 Boreholes and ground temperature loggers for model calibration and validation

140 The study uses a set of ground temperature observations with different vertical extents across the study area (Fig. 4). These include near-surface measurements from ground surface temperature (GST) loggers, shallow subsurface temperature profiles from shallow boreholes, and deep borehole observations.

Near-surface conditions are captured by two GST loggers, which measure temperature close to the ground surface and are installed to be shielded from direct radiation. In addition, several shallow boreholes provide temperature measurements at multiple depths down to approximately 1.3 m, allowing characterization of thermal conditions within the active layer. Most of these measurements were installed in the framework of the study by Duishonakunov (2014) and cover the period 2010-2012. The measurement sites are located on different surface types (see Table 1).



Table 1. Overview of ground temperature datasets used in this study. Temperature loggers A10247, ASUE02, and A10221 were used for model calibration (model setup), while the remaining loggers and legacy borehole data (1986–1992) were reserved for validation.

Name	Data Type	Alt. (m)	Surface Type	Period	Max Depth (m)	Use in Study
A1023C	shallow borehole	3727	SED	2010–2011	1.3	Validation
A10222	shallow borehole	3865	DEB	2010–2012	1.3	Validation
A50209	GST logger	4043	DEB	2010–2012	0.1	Validation
Taragai	shallow borehole	3530	VEG	2012–2024	1.0	Validation
BH48/2	Borehole (legacy)	3640	VEG	1986–1992	30	Validation
BH50/1	Borehole (legacy)	3585	VEG	1986–1992	30	Validation
BH50/2	Borehole (legacy)	3670	VEG	1986–1992	30	Validation
BH51/1	Borehole (legacy)	3575	VEG	1986–1992	30	Validation
BH51/2	Borehole (legacy)	3560	VEG	1986–1992	30	Validation
A10247	shallow borehole	3650	VEG	2010–2012	1.3	Model setup
A10221	shallow borehole	3495	SED	2010–2012	1.3	Model setup
ASUE02	GST logger	3860	DEB	2021–2024	0.1	Model setup
AK50/1	Borehole	3422	VEG	2022–2024	30	Model setup

Deeper thermal conditions are constrained by borehole observations. A borehole installed in 2022 (AK 50/1, installed in proximity to legacy BH 50/1) provides continuous temperature measurements down to 30 m depth and was used for model calibration. Additionally, the legacy borehole 51/2 was re-equipped with temperature sensors in 2022, providing additional observations of the deep thermal regime for model evaluation.

We also incorporated previously unpublished legacy borehole measurements from the Soviet period (1986–1992), provided by S. Marchenko prior to his passing. These datasets consist of discrete temperature observations at selected depths and dates. They provide independent information on subsurface thermal conditions in the late 20th century and allow a comparison between past and present conditions. For model setup and evaluation, the available observations were divided into calibration and validation subsets. Table 1 summarizes all ground temperature data, and Fig. 4 illustrates their temporal and vertical coverage.

Table 1 summarizes the available ground temperature observations used for calibration and validation, and Figure 4 illustrates their temporal coverage. The CryoGrid model setup is described in detail in the following sections.

3.2 CryoGrid model setup

CryoGrid is a land surface model developed to simulate ground thermal processes in regions affected by seasonal frost and permafrost (Westermann et al., 2023). Upper boundary conditions are prescribed using a Surface Energy Balance (SEB) scheme, including shortwave and longwave radiation, latent heat, and sensible heat fluxes, requiring meteorological forcing data such

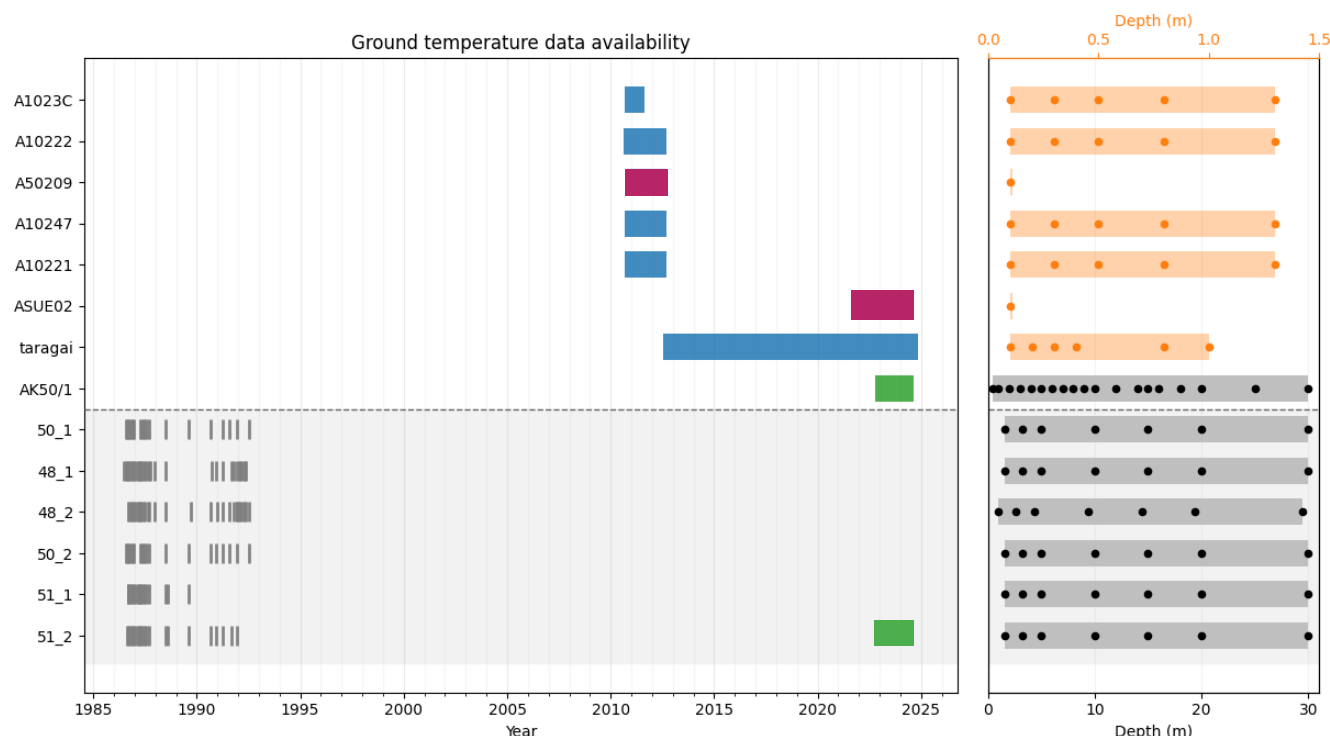


Figure 4. Temporal and vertical distribution of ground temperature observations across the study area. Ground surface temperature (GST) loggers (purple bars), shallow boreholes (blue bars) and the re-equipped boreholes AK50/1 and 51/2 (green bars) provide recent measurements, while legacy borehole data from 1986–1992 extend the record back to the late 20th century. The right panel illustrates the depth coverage of each data source, distinguishing shallow measurements (≤ 1.5 m, orange) from deeper borehole observations reaching 30 m. Points indicate individual measurement depths.

as air temperature, precipitation, radiation, wind speed, humidity, and air pressure. The subsurface is represented by 1D soil stratigraphies defined by volumetric fractions of mineral material, organic matter, water, and ice. Heat transfer is simulated through conduction following Fourier's law and advection associated with vertical water fluxes. Soil freezing behaviour is represented either by soil-specific freezing curves (Painter et al., 2014) or by a free-water scheme with phase change at 0 °C. Snow processes are simulated using the CROCUS scheme (Vionnet et al., 2012; Zweigel et al., 2021). Vertical water movement is calculated using either Richards equation (?) or a gravity-driven bucket scheme, and lateral water flow is represented using a lateral water reservoir. A constant geothermal heat flux defines the lower boundary condition. The general model structure is illustrated in Figure A6.

Model initialization was performed using the accelerated spin-up procedure described in Westermann et al. (2023). In this approach, a short meteorological forcing period is repeated sequentially, with the model state transferred between runs, allowing subsurface temperatures and soil ice conditions to approach equilibrium efficiently without requiring very long simulations.



175 We applied a 40-year spin-up (four repetitions of the first 10 years of forcing data), after which the model was run transiently for the period 1975–2024. This approach implicitly assumes that the subsurface is initially in equilibrium with a stationary climate represented by the repeated 10-year forcing period.

To account for spatial heterogeneity, CryoGrid was implemented with surface-type-specific stratigraphies and parameter settings. These setups were first tested in 1D simulations and evaluated against ground temperature observations and legacy
180 borehole data. The model was then applied spatially across the study area using the TopoSUB clustering approach (Fiddes and Gruber, 2012). Details on the forcing data, surface type classification, and model parameterization are provided in the following sections.

3.2.1 Model forcing data

To capture the spatial variability of climatic conditions within the study area for the model forcing data, reanalysis data from
185 ERA5 (Hersbach et al., 2020) were first statistically downscaled using the TopoSCALE framework (Fiddes and Gruber, 2014). The downscaled variables include air temperature, precipitation, specific humidity, wind speed, atmospheric pressure, and radiation components, which are required for CryoGrid simulations. The downscaled data were subsequently bias-corrected using a quantile mapping approach on all necessary CryoGrid input data (e.g. Themeßl et al., 2011; Rajczak et al., 2016; Marmy et al., 2016), based on observations from two automatic weather stations (AWS) located within the study area (Fig. 1). Figure
190 A4 shows the temporal coverage of the Tien Shan and Taragai stations for the different variables. This procedure improves the representation of local climatic conditions and increases the reliability of the forcing dataset. Integrated within the CryoGrid framework, the TopoSCALE downscaling and bias-correction scheme can be applied to any point within the study area. The bias-correction functions derived at the AWS locations were therefore spatially transferred to all model grid cells, assuming that the observed distributional shifts between ERA5-derived and measured meteorological conditions are representative across
195 the study area. Figure A5 illustrates the improvement achieved through bias correction for selected meteorological variables at one representative location.

3.2.2 Surface-type-specific model parameterization

First, surface types relevant for this study were derived using the ESA WorldCover dataset (Zanaga et al., 2022) as a starting point. Some ESA land cover classes were used directly, while others were reclassified or newly defined to better represent
200 landforms relevant for permafrost modeling. BED areas, which are not represented as a separate ESA class, were identified by reclassifying the "bare/sparse vegetation" class on slopes steeper than 30°, where sediment accumulation is expected to be limited. Rock glaciers (RG) and other coarse blocky landforms were manually delineated using geomorphological and geophysical indicators following RGIK guidelines (RGIK, 2023). For this manual mapping, a 50 × 50 m grid was used to systematically interpret ESRI imagery (ArcGIS Pro) and Google Earth. Moraines and talus slopes were both grouped into the
205 debris (DEB) category.

The VEG class corresponds to the ESA “grassland” category, while SED is based on the ESA “bare/sparse vegetation” class. Fine-grained sediments were further subdivided into thick plateau sediments and shallow sediment cover over bedrock



(BED–SED) using a slope threshold of 10° , reflecting differences in sediment thickness and moisture conditions observed in the field. Glaciers and water bodies were excluded from the simulations.

210 Of the total study area ($1,563 \text{ km}^2$), 54 % were classified as VEG, 10 % as SED, 13 % as BED–SED, 6 % as BED, 5 % as DEB, and 2 % as RG, while 10 % corresponds to glaciers. The spatial distribution of surface types is shown in Figure 6d.

Table 2. Soil stratigraphies for the different surface types. Hydraulic properties are given as permeability. Where needed, saturated hydraulic conductivity values were converted assuming a water temperature of 5°C . $f_{w/i}$ = fraction water/ice, f_m = mineral fraction, f_o = organic fraction. α = albedo, z_0 = surface roughness.

Surface Type	Depth (z [m])	$f_{w/i}$ [-]	f_m [-]	f_o [-]	FC [-]	Permeability (m^2)	Soil Type	α	z_0 [m]
RG	0.0 - 1.0	0.05	0.45	0.0	0.001	10^{-13}	sand	0.15	0.15
	1.0 - 3.0	0.10	0.50	0.0	0.05	10^{-14}	sand		
	3.0 - 30.0	0.50	0.50	0.0	0.05	10^{-15}	sand		
DEB	0.0 - 1.5	0.30	0.55	0.0	0.15	10^{-14}	sand	0.15	0.05
	1.5 - 3.0	0.35	0.65	0.0	0.20	10^{-15}	sand		
	3.0 - 30.0	0.35	0.65	0.0	0.15	10^{-15}	sand		
SED	0.0 - 1.0	0.15	0.70	0.0	0.30	10^{-9}	sand	0.20	0.002
	1.0 - 4.0	0.25	0.70	0.0	0.25	10^{-11}	sand		
	4.0 - 20.0	0.25	0.75	0.0	0.20	10^{-11}	silt		
	20.0 - 30.0	0.20	0.80	0.0	0.10	10^{-13}	silt		
VEG	0.0 - 2.0	0.40	0.50	0.10	0.30	10^{-11}	sand	0.25	0.006
	2.0 - 4.0	0.40	0.60	0.00	0.30	10^{-12}	sand		
	4.0 - 20.0	0.25	0.75	0.00	0.20	10^{-12}	silt		
	20.0 - 30.0	0.20	0.80	0.00	0.10	10^{-12}	silt		
BED–SED	0.0 - 1.0	0.15	0.70	0.0	0.15	10^{-15}	sand	0.15	0.01
	1.0 - 30.0	0.03	0.97	0.0	0.03	10^{-16}	sand		
BED	0.0 - 30.0	0.03	0.97	0.0	0.03	10^{-16}	sand	0.15	0.01

Soil stratigraphies were constructed using a combination of petrophysical joint inversion (PJI) results and literature-based parameter values. CryoGrid requires the specification of volumetric fractions of mineral material, organic matter, liquid water, ice, and air for each model layer. Virtual borehole data derived from the PJI results (Mathys et al., 2025) are available for RG, DEB, VEG, and SED surface types, as geophysical profiles are limited to these terrain classes. To derive representative Cryo-Grid stratigraphies, mean vertical profiles of the PJI-derived volumetric fractions were evaluated for each surface type. Based on these profiles, representative depth intervals with similar subsurface characteristics were manually defined and translated



into simplified layered stratigraphies required by CryoGrid. Consequently, gradual transitions observed in the geophysical data are simplified into discrete model layers with constant properties. We used these PJI results to constrain the vertical layering of the mineral fraction, which is assumed to remain constant over the simulation period and determines the solid matrix and resulting porosity. For vegetated sediments, additional organic content was introduced in the top layer relative to the SED stratigraphy. For BED and BED–SED, where geophysical data were unavailable, stratigraphies were defined using parameter values from previous CryoGrid studies (Westermann et al., 2023; Martin et al., 2023). Bedrock was assumed below 30 m depth for all surface types.

Although PJI also provides estimates of water and ice contents at the time of geophysical acquisition, these values were not directly prescribed as initial conditions because they represent present-day subsurface conditions and are not representative of the beginning of the simulation period. In CryoGrid, liquid water and ice contents are dynamic state variables that adjust internally already during spin-up. Therefore, stratigraphies were primarily defined using the solid fractions, while pore space conditions were initialized according to the characteristic properties of each surface type. For fine-grained and vegetated sediments, we assume little air content (= porosity) in the top layers and saturated conditions below 4 m. For coarse blocky materials such as rock glaciers and debris, distinct air-filled pore space was explicitly prescribed in the upper layers based on the PJI-derived volumetric fractions, reflecting the presence of large voids typical for these substrates. All surface-type specific values used in the model setup are given in Table 2. Figure 5 further illustrates the different stratigraphies visually and shows the virtual boreholes derived from the PJI results in comparison.

Several additional parameters required by CryoGrid, including field capacity, permeability, hydraulic conductivity, surface roughness, and albedo, are not directly constrained by the PJI results. Initial values for these parameters were therefore selected based on literature values or CryoGrid default parameterizations. For each logger location, 1D CryoGrid simulations were performed using the corresponding surface type stratigraphy, and parameter values were iteratively adjusted within plausible ranges to improve agreement between modeled and observed ground temperatures. No ground temperature data were available for RG, BED, and BED–SED areas, so parameter values for these surface types were adopted from literature sources (Westermann et al., 2023; Martin et al., 2023; Stocker-Mittaz et al., 2002; Amschwand et al., 2024; Miles et al., 2017; Fontrodona-Bach et al., 2025).

To represent differences in subsurface hydrology, two water transport schemes were applied depending on surface type. For fine-grained (SED) and vegetated sediments (VEG), Richards equation was used to simulate unsaturated flow and capillary effects, which are important for reproducing the relatively humid near-surface conditions observed in the field and the ground temperature measurements. In contrast, for coarse-grained materials such as talus slopes, rock glaciers, and bedrock, a simplified gravity-driven bucket scheme was applied, reflecting rapid drainage and limited water retention capacity characteristic of these substrates. All hydraulic properties are expressed as vertical permeability. In the model, only the surface types using Richards' equation account for the temperature dependence of water viscosity when converting permeability to hydraulic conductivity.

The remaining observation data (5 legacy borehole data sets and 4 ground temperature datasets) not used for calibration were used for validation of the 1D model setups. In this step, the influence of the snow factor on model performance was also

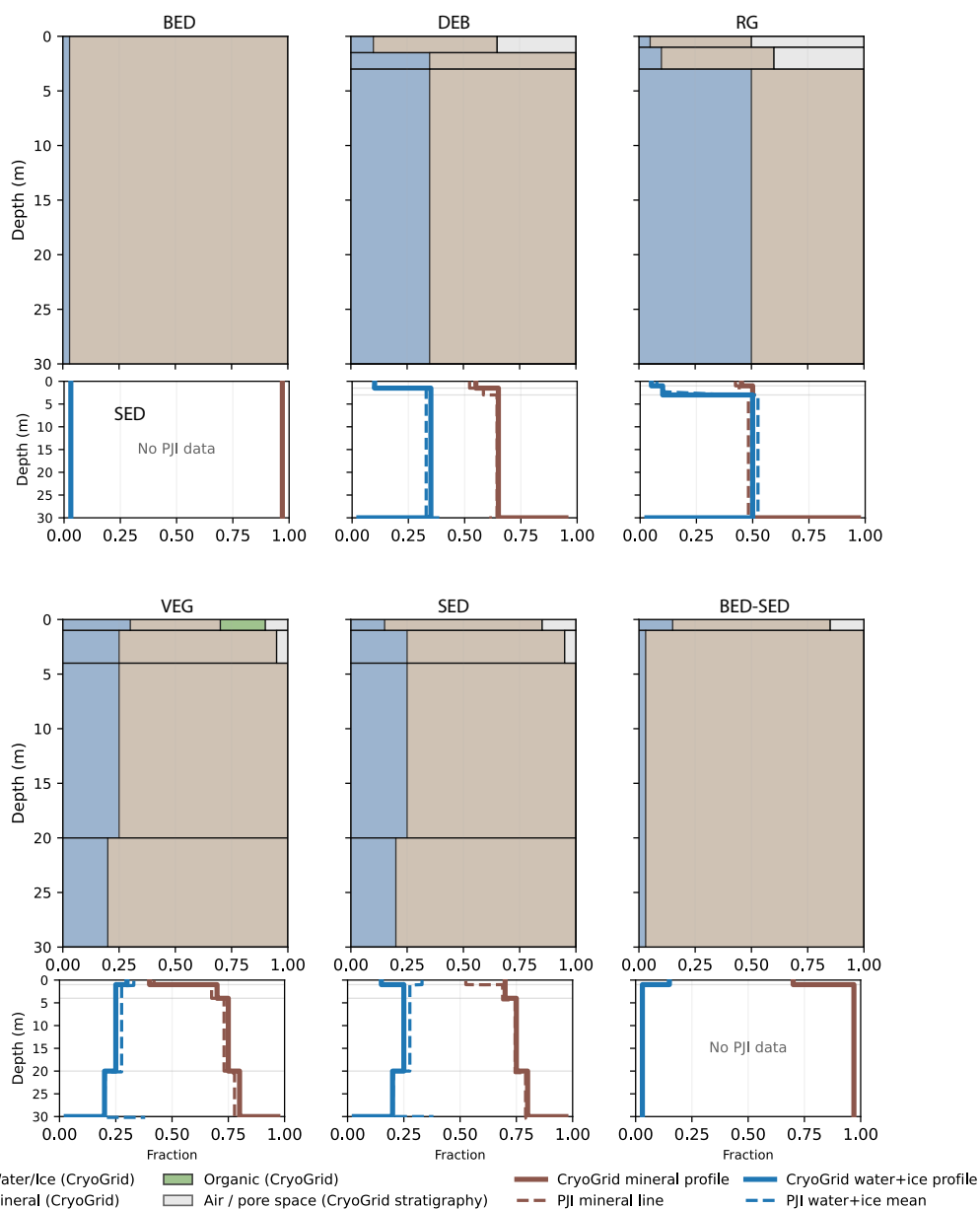


Figure 5. Visualization of the surface-type stratigraphies based on geophysical PJI results (Mathys et al., 2025), where applicable. The plot shows the composition of the different soil layers, as well as the mean PJI results for mineral and water+ice contents, which were used as a reference for the soil stratigraphies.

evaluated and different snow factors were tested. Model performance was assessed using Mean Absolute Error (MAE) and bias, which describe the magnitude and direction of deviations between modeled and observed temperatures.

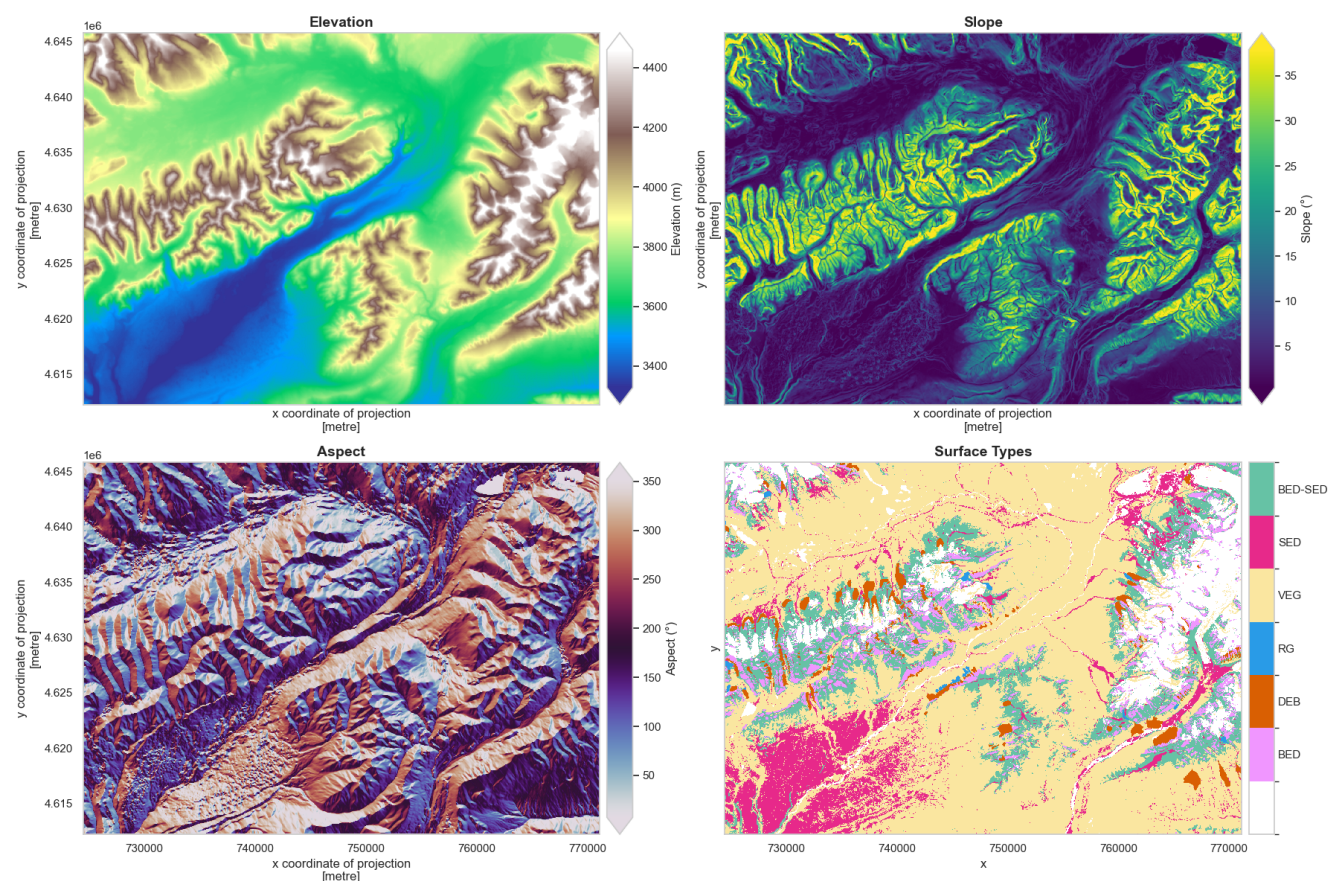


Figure 6. Clustering factors: elevation, slope, aspect, surface types. For the surface types: BED = bedrock; DEB = debris; RG = rock glaciers; VEG = vegetated sediments; SED = fine-grained sediments; BED-SED = bedrock with shallow sediment on top. © ESA WorldCover project 2021 / Contains modified Copernicus Sentinel data (2021) processed by ESA WorldCover consortium

255 Finally, CryoGrid was applied spatially to derive permafrost distribution and thaw depth patterns using the meteorological forcing described in section 3.2.1. For the distributed simulations, one reference stratigraphy per surface type was used. Solid-phase properties and air-filled pore space were constrained by geophysical information where available, while water and ice contents evolved dynamically throughout the simulation.

3.2.3 TopoSUB clustering for spatial simulations

260 To reduce computational demands in spatially distributed CryoGrid simulations, we applied the TopoSUB clustering approach (Fiddes and Gruber, 2012). This method groups grid cells with similar topoclimatic characteristics into representative clusters, allowing the model to simulate only a subset of the study region and extrapolate results to all grid cells within each cluster. Clustering was based on five key parameters influencing ground thermal regimes: elevation, slope angle, aspect, sky view factor,



and surface type (Figure 6). This ensures that modeled stratigraphies and forcing conditions represent distinct combinations of terrain and land cover across the study area.

After testing different clustering resolutions, we selected 200 clusters as a compromise between spatial detail and computational efficiency, consistent with previous applications in high-mountain environments (e.g. Fiddes and Gruber, 2012). The spatially distributed CryoGrid simulations produced high-resolution (30 m) maps of (1) mean ground temperatures at 5 m depth and (2) thaw depth representing active layer thickness at the end of August 2024.

4 Results

4.1 Model validation (point simulations)

To evaluate the performance of the calibrated CryoGrid model in reproducing ground thermal dynamics across different surface types, a set of 1D simulations was conducted at the locations of ground temperature measurements distributed throughout the study area. Figure 7 shows the comparison between measured and modeled ground temperatures for both contemporary GST loggers, shallow boreholes and legacy borehole measurements. Overall, the model reproduces observed mean temperatures and variability reasonably well across the investigated surface types, including fine-grained sediments, vegetated sediments, and debris surfaces. Mean absolute errors (MAE) range from 0.27 °C to 2.11 °C, with generally small biases (Table 3). The lowest errors occur for the legacy boreholes, where MAE values are consistently below 0.6 °C at approximately 5 m depth.

Table 3. Validation of the model setup using ground temperature loggers and borehole data. For GST loggers, and shallow boreholes MAE and bias are calculated from daily temperature time series at the deepest available sensor depth. For legacy boreholes (1986–1992), metrics are calculated from modeled and measured temperatures at or closest to 5 m depth.

Station	Altitude (m)	Exposition	Surface Type	Depth (m)	MAE (°C)	Bias (°C)
<i>Ground temperature loggers</i>						
A1023C	3727	W	fine-grained sediments	1.3	1.67	-0.56
A10222	3865	SE	debris	1.3	1.61	-1.09
A50209	4043	W	debris	0.10	2.11	0.81
Taragai	3530	S	vegetated sediments	1.0	1.87	0.85
<i>Legacy boreholes (1986–1992)</i>						
48_2	3640	NW	vegetated sediments	4.4	0.54	-0.17
50_1	3585	NW	vegetated sediments	5.0	0.27	-0.07
50_2	3670	W	vegetated sediments	5.0	0.33	0.28
51_1	3575	SE	vegetated sediments	5.0	0.51	-0.01
51_2	3560	SW	vegetated sediments	5.0	0.37	0.07

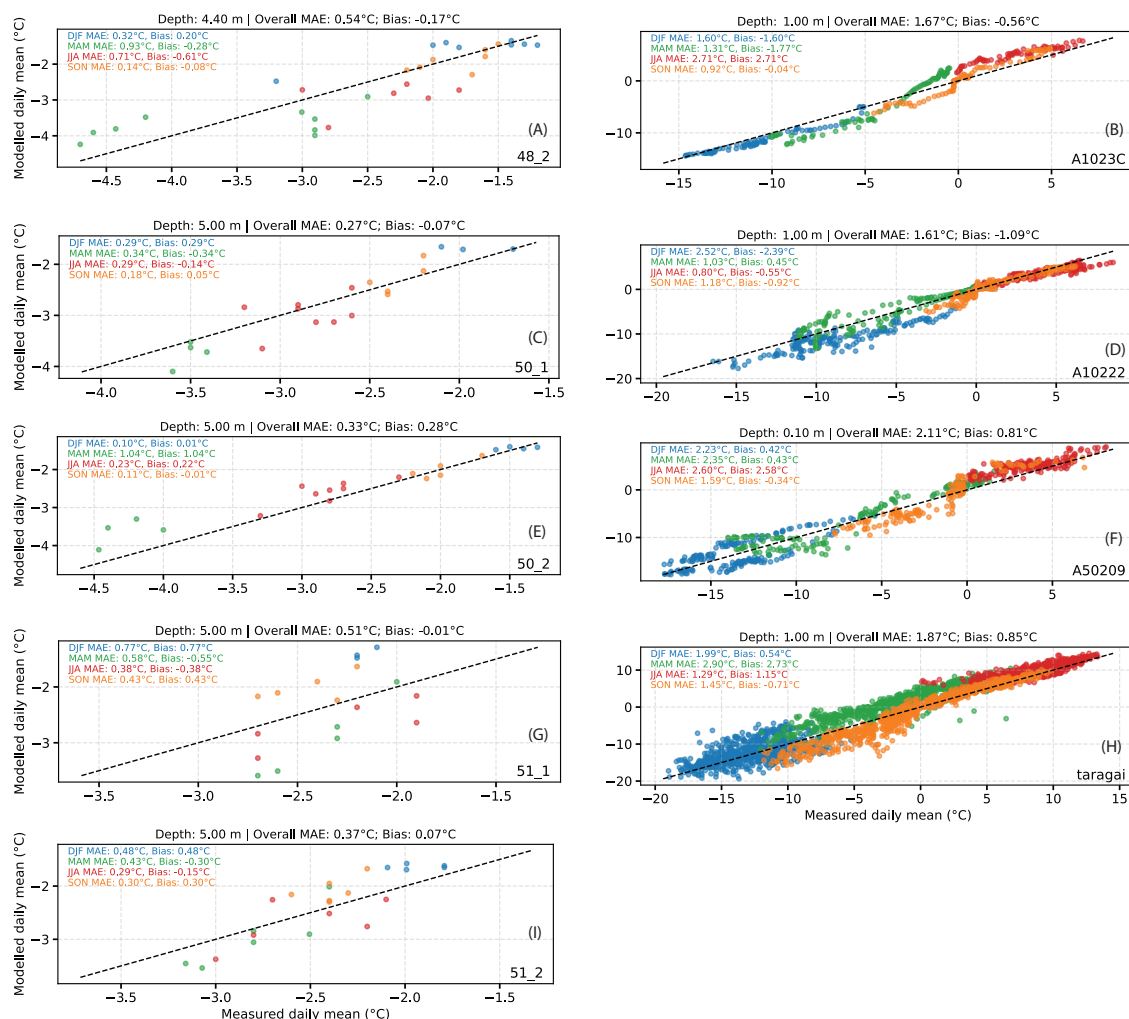


Figure 7. Model validation scatterplots: Scatter plots are shown for near-surface measurements at the deepest available sensor depth and for legacy boreholes at the sensor closest to (or at) 5 m depth. Points are colour-coded by season. Subplot titles indicate logger depth as well as overall bias and MAE (mean absolute error), while seasonal error statistics are shown within each subplot.

Seasonal differences in model performance are evident in the scatterplots (Fig. 7). Agreement between measured and simulated temperatures is generally strongest during autumn (SON), whereas the largest deviations predominantly occur during spring (MAM). This pattern is particularly pronounced for the shallow temperature measurements, where seasonal MAE values are highest in spring for most sites (Fig. 7). Seasonal differences are less pronounced at greater depths, where overall MAE values are lower and the spread of seasonal errors is smaller. This might reflect limitations in the model's ability to represent snow cover accurately. Because seasonal model performance varied systematically across the validation sites, several snow scaling factors were tested during calibration. Model performance was evaluated using MAE and bias metrics derived from the

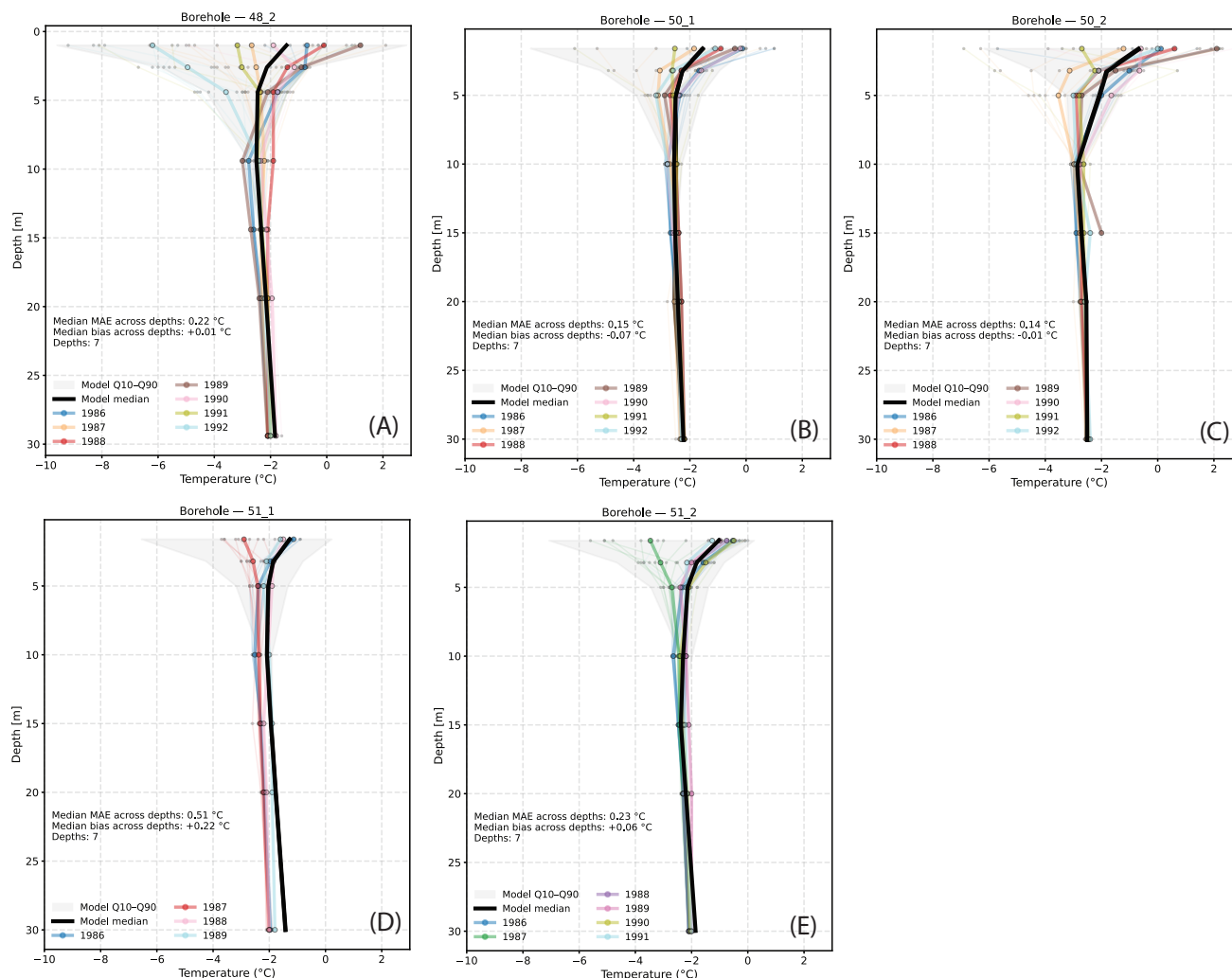


Figure 8. Comparison of modeled ground temperature profiles with legacy borehole observations. Colored lines show mean temperature profiles for individual observation years, while grey points represent raw borehole measurements. For each borehole, the modeled temperature profiles are extracted for the corresponding observation period of the legacy data. The shaded envelope indicates the modeled temperature range (10th–90th percentile) during this period, and the black line shows the median modeled temperature profile with depth.

ground temperature logger time series. A snow factor of 0.7 provided the best overall compromise between bias and variance across sites and was therefore adopted for the spatial simulations. The importance of accurately representing snow conditions in permafrost modeling has been highlighted in numerous previous studies (e.g. Zweigel et al., 2021; Gissnäs et al., 2014; Lehning et al., 2006; Haberkorn et al., 2015, 2016; Zhang et al., 2001; Mittaz et al., 2002; Martin et al., 2020).



290 The comparison of vertical temperature profiles further demonstrates good agreement between simulated and measured ground temperatures (Fig. 8). For most boreholes (48_2, 50_1, 50_2, 51_2), the modeled temperature ranges and median temperatures are well reproduced across depths, indicating that the stratigraphies provide a realistic representation of subsurface thermal properties. Median MAE values range between 0.14 °C and 0.23 °C for these boreholes. Borehole 51_1 shows larger deviations compared to the other legacy sites, with a median MAE of approximately 0.51 °C at 5 m depth. The measured
295 temperatures show a smaller seasonal amplitude than the modeled values. This difference is visible both in the scatterplot distribution (Fig. 7G) and in the temperature–depth profiles (Fig. 8D), where the observed temperature range is narrower than the modeled range.

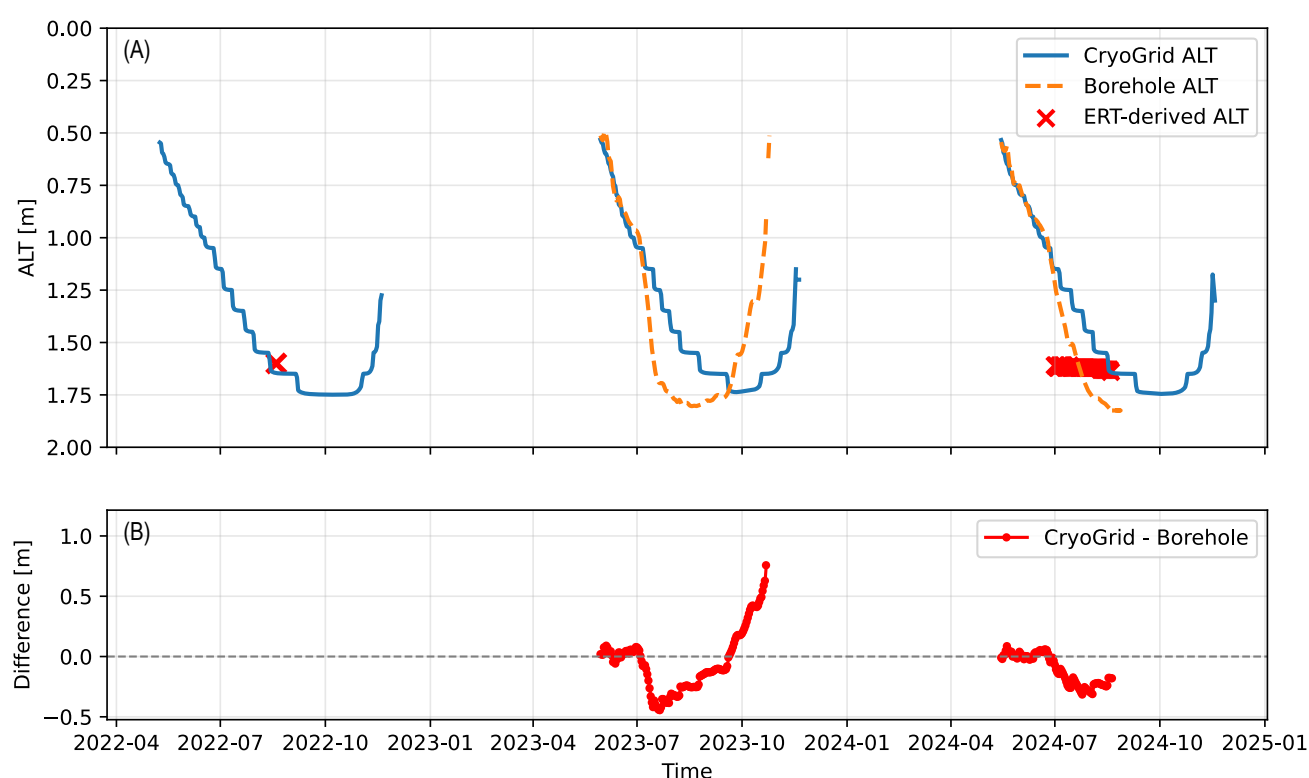


Figure 9. Seasonal evolution of thaw depth at the borehole site. (A) Comparison of CryoGrid-simulated ALT, borehole-derived thaw depths, and ERT-derived thaw depths for the observation periods. (B) Difference between modeled and borehole-derived thaw depths (CryoGrid – borehole).

We further evaluated CryoGrid’s ability to reproduce the observed seasonal evolution of thaw depth at the new borehole site (AK 50/1) (Fig. 9). The comparison includes modeled active layer thickness (ALT) evolution, borehole-derived thaw
300 depths obtained by linear interpolation between temperature sensors, and ERT-derived thaw depths defined as the depth of the maximum vertical resistivity gradient. Overall, CryoGrid captures the onset and initial progression of thaw well and reproduces



the end-of-season maximum thaw depth closely in both 2023 and 2024. However, the deepening of the thaw front proceeds more slowly than observed. A similar pattern is visible during autumn refreezing, when the model remains thawed for longer and refreezing occurs later than indicated by the borehole data. Thus, the main mismatch is less related to the final maximum thaw depth than to the rate and timing of seasonal thawing and refreezing. we also compared the ERT-derived thaw depths to the measured and modeled thaw depths (Fig. 9. Those show much less temporal variability and remain comparatively stable over the measurement periods. A slight increase in the thaw depth with time is, however, visible in the A-ERT data of 2024. The relatively stable ERT-derived thaw depth at the beginning of the thaw season shows that ERT does not directly detect the position of the 0 °C isotherm.

4.2 ERT-derived thaw depths

We used the maximum gradient method, as described by Herring and Lewkowicz (2022), to derive thaw depths across different ERT profiles and associated surface types. Since this method depends on inversion results, we assessed the influence of inversion parameters on the estimated ERT-derived thaw depth. In particular, the influence of two parameters was tested: zWeight, which controls the vertical smoothness of the inversion (higher values promote smoother vertical transitions) (Wagner et al., 2019), and the depth constraint, which limits the shallowest depth included in the gradient calculation to avoid incorporation of near-surface artifacts and is implemented as a parameter in the script to calculate the maximum gradients (Herring and Lewkowicz, 2022). The tested zWeight values are consistent with the inversion settings used in Mathys et al. (2025), while depth constraints between 0.1 and 1 m were evaluated to assess the sensitivity of thaw depth estimates to near-surface resistivity variations.

Figure A3 illustrates the sensitivity of the maximum gradient method across all ERT profiles for varying values of zWeight and depth constraint. As expected, low zWeight values result in shallower estimates of the depth of the maximum gradient, while higher depth constraint values increase the depth of the maximum gradient. However, not all profiles respond equally to these parameter changes. Some, such as profile E04, show relatively stable thaw depth estimates across a wide range of settings, likely due to their lateral homogeneity and the presence of well-defined horizontal resistivity boundaries. Other inversion parameters, such as the mesh used for the inversion, could potentially influence the results. However, this was not tested systematically in this study.

For the subsequent comparison with modeled thaw depths, representative thaw depths were defined as the mean values across all tested parameter combinations to account for the sensitivity of the method to inversion settings rather than relying on a single inversion result, while the corresponding standard deviation was used to indicate the sensitivity of the method to inversion parameters.

4.3 Modeled permafrost distribution and thermal state

Figure 10 presents the results of the spatial simulation, illustrating the modeled mean ground temperatures at 5 m depth for the period of 2020 - 2024 throughout the investigation area. The results indicate continuous permafrost across the entire study area, with ground temperatures ranging from values close to the melting point (-0.14°C) to as low as -6.5°C. The mean temperature



across the whole study site is -2.9°C . The modeled ground temperature map is supported by the borehole measurement data (BH AK50/1) that confirm permafrost conditions on the high plateau at around 3600 m a.s.l, with mean temperatures of -1.5°C at 5 m depth. Furthermore, even for the lowest elevation band (3200–3300 m a.s.l.) negative temperatures are modeled, indicating that permafrost conditions are likely present throughout the study area. However, large parts of the study area show ground temperatures close to 0°C at 5 m depth, suggesting comparatively warm permafrost conditions.

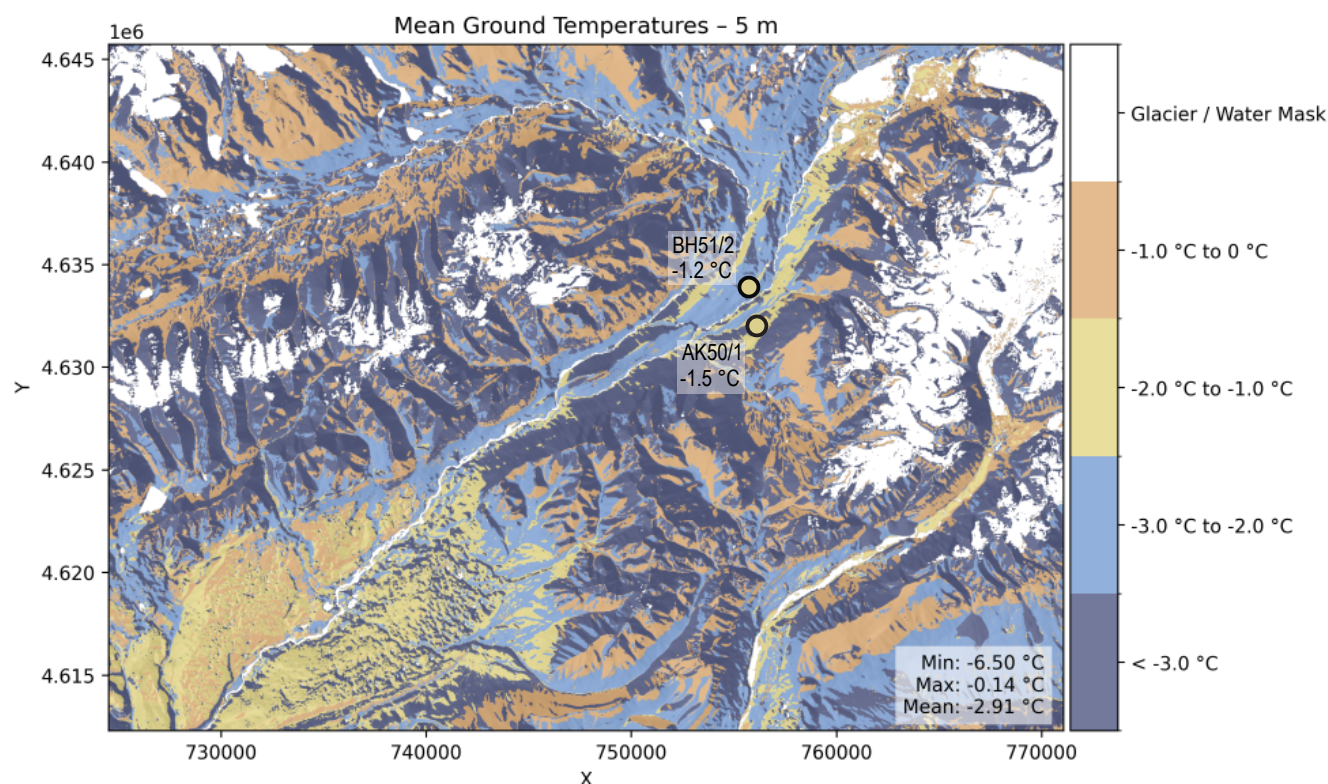


Figure 10. Modeled mean ground temperatures (2020-2024) at 5 m depth. White areas are either glaciers or water bodies (lakes, rivers), which were masked out.

We further analyzed the spatial temperature distribution by assessing the influence of key topoclimatic variables used in the modeling setup. Figure 11 shows the variation in ground temperatures across different elevation ranges (Fig. 11A), surface types (Fig. 11B), aspect orientations (Fig. 11C), and slope classes (D). Fig. 11A shows a temperature dependence from altitude. Mean ground temperatures decrease gradually from approximately -2°C in the lowest elevation bands (3200–3500 m a.s.l.) to values below -6°C above approximately 4300 m a.s.l. The strongest temperature decrease occurs between approximately 3800 m and 4300 m a.s.l., while the highest elevation bands (4500–4900 m a.s.l.) consistently show median temperatures below -5.5°C . At the same time, the spread of temperatures within individual elevation bands is large, especially for elevations between 3400 and 4300 m a.s.l, indicating substantial variability of ground thermal conditions at similar elevations.



Fig. 11B shows that ground temperatures are generally lowest for BED, RG and DEB surface types, while the highest temperatures are observed for SED surfaces. VEG surfaces also show comparatively warm conditions, with median temperatures typically between approximately -2 °C and -3 °C. As VEG and SED surface types cover large parts of the study area, particularly on the high plateau, they contribute to a significant fraction of comparatively warm permafrost conditions in the study area.

Fig. 11C demonstrates a clear influence of slope orientation on ground temperatures. North- and northeast-facing slopes show the lowest median temperatures, generally between -4 °C and -5 °C, whereas south-facing slopes show substantially warmer conditions with median temperatures around -2 °C. West- and southwest-facing slopes also exhibit relatively warm conditions, confirming a strong sensitivity of ground temperatures to solar radiation (Hoelzle, 1992; Funk and Hoelzle, 1992; Hoelzle, 1996; Hoelzle and Haeberli, 1995). East-facing slopes show comparatively colder conditions than west-facing slopes.

Fig. 11D indicates that steeper slopes are generally associated with colder ground temperatures. Slopes steeper than approximately 30–40° show median temperatures around -5 °C to -6 °C, whereas gentle slopes (0–10°) exhibit warmer and more variable conditions, with median temperatures around -2 °C to -3 °C. Gentle slopes are predominantly associated with VEG and SED surface types, generally show comparatively warm ground temperatures, partly because gentler terrain favours snow accumulation, which provides thermal insulation during winter and contributes to higher ground temperatures.

4.4 Ground temperature evolution

The CryoGrid simulations indicate a clear warming trend in mean annual ground temperature (MAGT) throughout the modeled period. Figure 12 illustrates the temporal evolution of MAGT at 5 and 20 m depth at the new borehole site (AW50/1), both showing a statistically significant increase. The simulated warming rates are on the order of 0.20 °C per decade at 5 m and 0.18 °C per decade at 20 m. At 20 m depth, the temperature signal is considerably smoother, reflecting the damping of short-term variability by the thermal inertia of the subsurface. Nevertheless, the long-term warming trend remains clearly visible at both depths. Measurements from the new borehole (AK50_1), based on complete annual records (only 2 full years are available for the modeling period), indicate an increase of about 1 °C since the 1980s. For the legacy boreholes, only discontinuous campaign-based measurements are available rather than continuous annual records (called "Campaign mean" in Fig. 12). Therefore, mean temperatures derived from these observations do not represent true MAGT values. However, because measurements were conducted repeatedly throughout different seasons of the year, the resulting mean values are not expected to be strongly biased toward either summer or winter conditions.

4.5 Modeled thaw depth distribution

Figure 13 presents the modeled thaw depth distribution across the study area at the end of August 2024, illustrating spatial variability with shallowest thaw depths observed in rock glacier (RG) and debris-covered (DEB) areas (see Fig. 14), whereas the deepest thaw depths are modeled for bedrock (BED), fine-grained sediments (SED), and bedrock with shallow sediment cover (BED-SED). Comparatively deep thaw depths occur particularly in the lower-elevation parts of the Arabel plateau. This

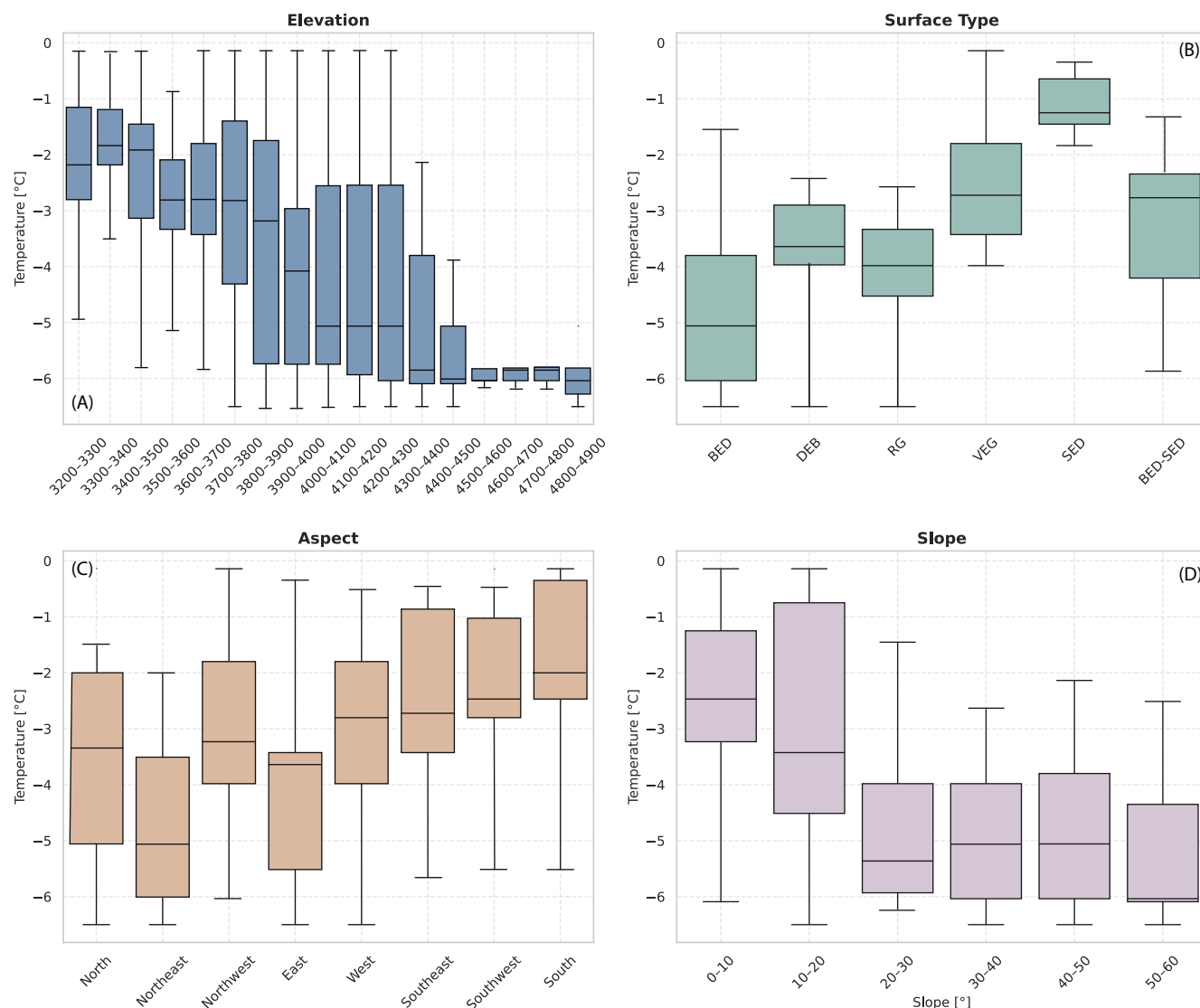


Figure 11. Influence of the different topoclimatic factors (elevation, surface type, aspect, slope) used in the spatial modelling on the modeled ground temperatures at 5 m depth.

380 corresponds well with the observed existence of thermokarst lakes (cf. Figure 1, southwestern and northwestern part of the study area).

Figure 14 further illustrates the influence of topoclimatic factors on thaw depth distribution. Surface type (Fig. 14B) shows the strongest impact on thaw depth variability. The elevation plot (Fig. 14A) shows only a weak relationship between thaw depth and altitude. While some of the lowest elevation bands display slightly deeper thaw depths, the variability within eleva-

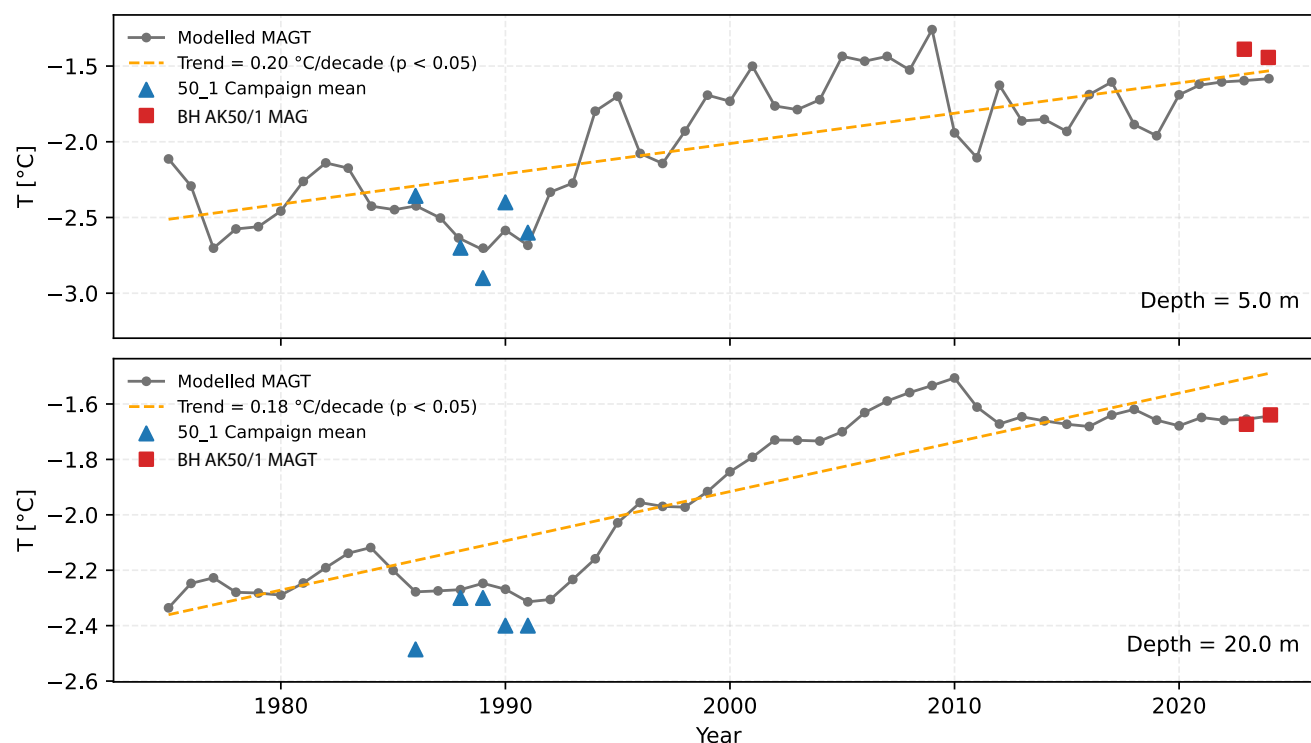


Figure 12. Modeled and measured ground temperatures at 5 m and 20 m depth at the new borehole site (AW50/1). Grey lines show modeled MAGT with linear trends (yellow dashed). Red squares indicate MAGT from the new borehole (AK50/1; complete years only), while blue triangles show campaign-based mean temperatures from the legacy borehole (50/1). Note, that the temperature scale on the y-axis differs between the two sub-plots.

tion classes is large. The aspect plot (Fig. 14C) indicates clearer differences between slope orientations. South-facing slopes show the deepest median thaw depths and the largest variability. Southeast- and southwest-facing slopes also tend to show comparatively deep thaw depths, whereas north-, northeast-, and east-facing slopes generally exhibit shallower thaw depths. The slope plot (Fig. 14D) shows no strong systematic relationship between slope angle and thaw depth for slopes up to about 30°. However, steeper slopes (> 40°) tend to show slightly deeper thaw depths and a larger spread of values. Overall, the variability within slope classes remains considerable, suggesting that slope mainly influences thaw depth indirectly through its association with different surface types rather than acting as an independent control.

Figure 15 illustrates the modeled change in end-of-August thaw depth between the periods 1980–2000 and 2001–2024. For each pixel, mean thaw depth at the end of August was calculated separately for both periods, and the difference between these period means was subsequently derived. Overall, the results indicate a deepening of the active layer across the study area, with a median increase of approximately 0.24 m. The spatial pattern of thaw depth change is heterogeneous and closely follows topographic structures. Large parts of the study area show only little or moderate change (< 0.2 m), particularly in

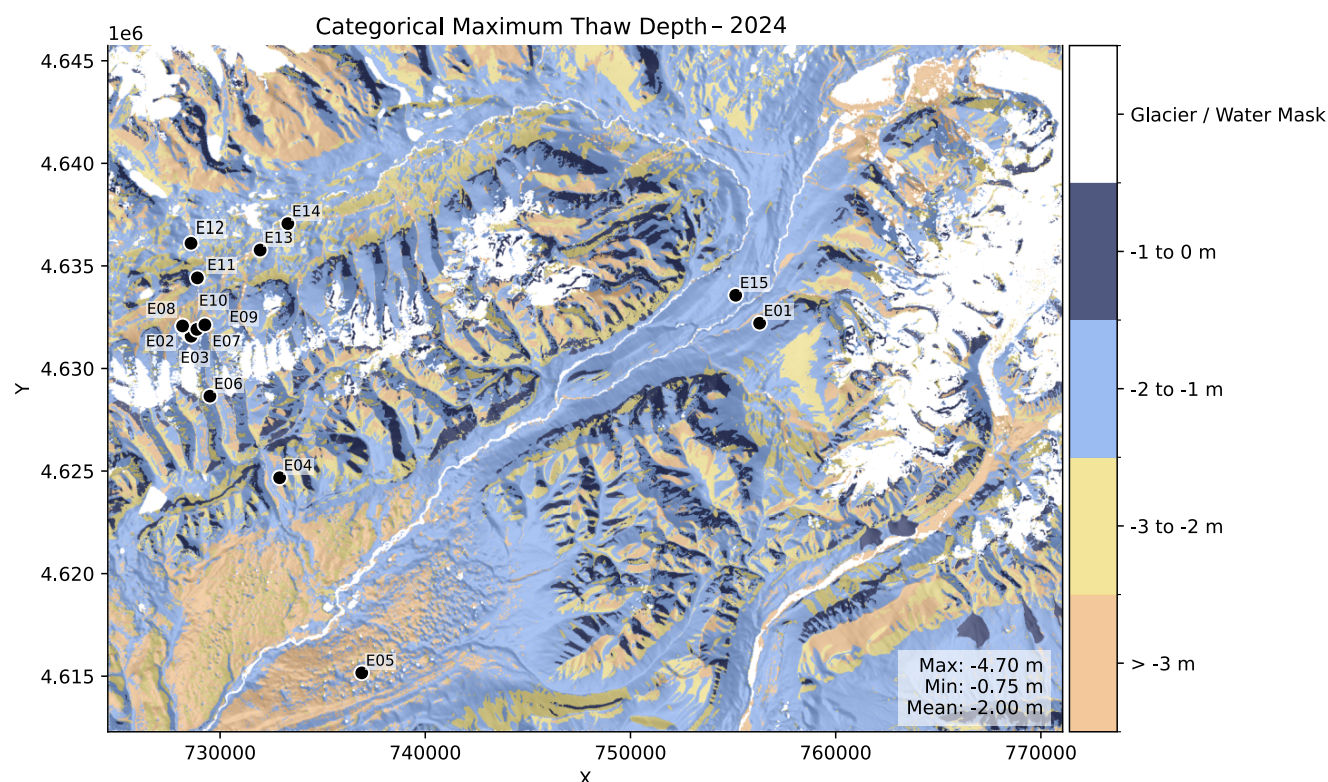


Figure 13. Thaw depths spatially modeled for end of August 2024. White areas are either glaciers or water bodies (lakes, rivers), which were masked out. The position of the ERT profiles is plotted as well.

higher elevation areas and in terrain dominated by RG and DEB surface types. Intermediate increases between 0.2 and 0.5 m occur over extensive areas, especially on gently sloping terrain parts of the Arabel plateau. Stronger increases exceeding 0.5 m are observed locally, mainly in lower-elevation parts of the study area (southwest of the study site) and in areas characterized by SED, VEG and BED-SED surface types. The largest increases (> 0.7 m) are predominantly found on south-facing slopes, highlighting the importance of slope orientation for the sensitivity of the active layer to recent climatic warming. Overall, areas with stronger active layer thickening broadly correspond to comparatively warm permafrost conditions (Figure 10).

4.6 Spatial model validation with ERT-derived thaw depths

Spatial validation of the CryoGrid simulations was performed by comparing modeled thaw depths with independently derived ERT-based thaw depth estimates across the study area. ERT profiles in the study area are consistently longer than 30 meters, meaning they typically span multiple grid cells in the CryoGrid model output. To account for this, the mean modeled thaw depth was extracted across all grid cells intersected by each ERT transect. This ensures that the spatial variability along the ERT profile is represented in the model evaluation. Figure 16 presents a comparison of the thaw depths estimated from ERT

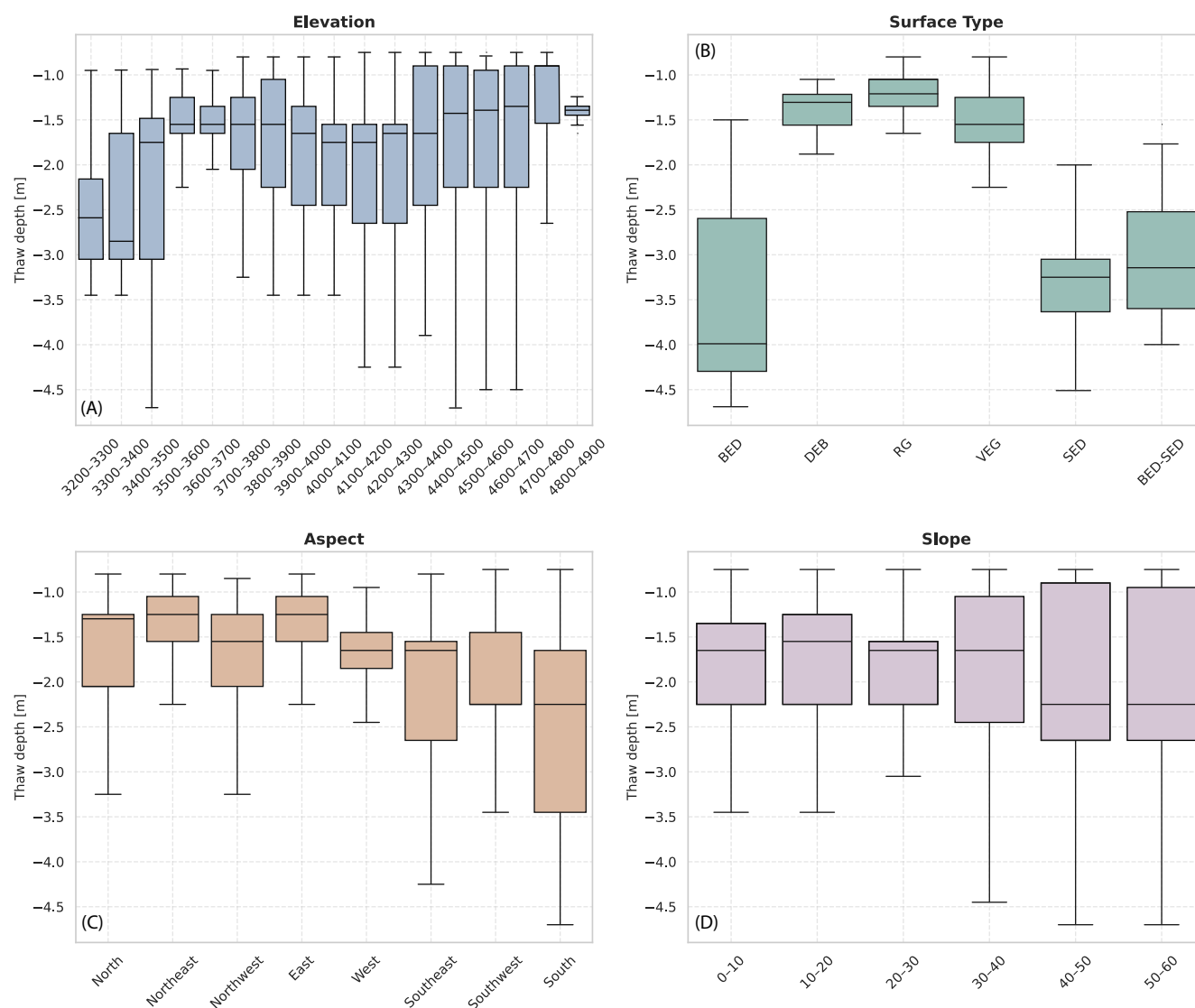


Figure 14. Influence of the different topoclimatic factors used in the spatial modelling on the modeled thaw depths.

profiles and those simulated by CryoGrid for all available ERT transects. For each profile, the mean maximum-gradient-derived
 410 ERT-thaw depth along the entire transect was compared with the corresponding modeled thaw depth. In Figure 16B, negative
 bars indicate that the modeled thaw depth is deeper than the ERT-derived depth, while positive bars represent the opposite.

In general, modeled and ERT-derived thaw depths show similar overall spatial patterns, although discrepancies remain substantial for some profiles. While most profiles differ by less than 1 m, this still represents a considerable relative deviation given the generally shallow thaw depths observed in many locations. The largest discrepancies occur primarily for profiles

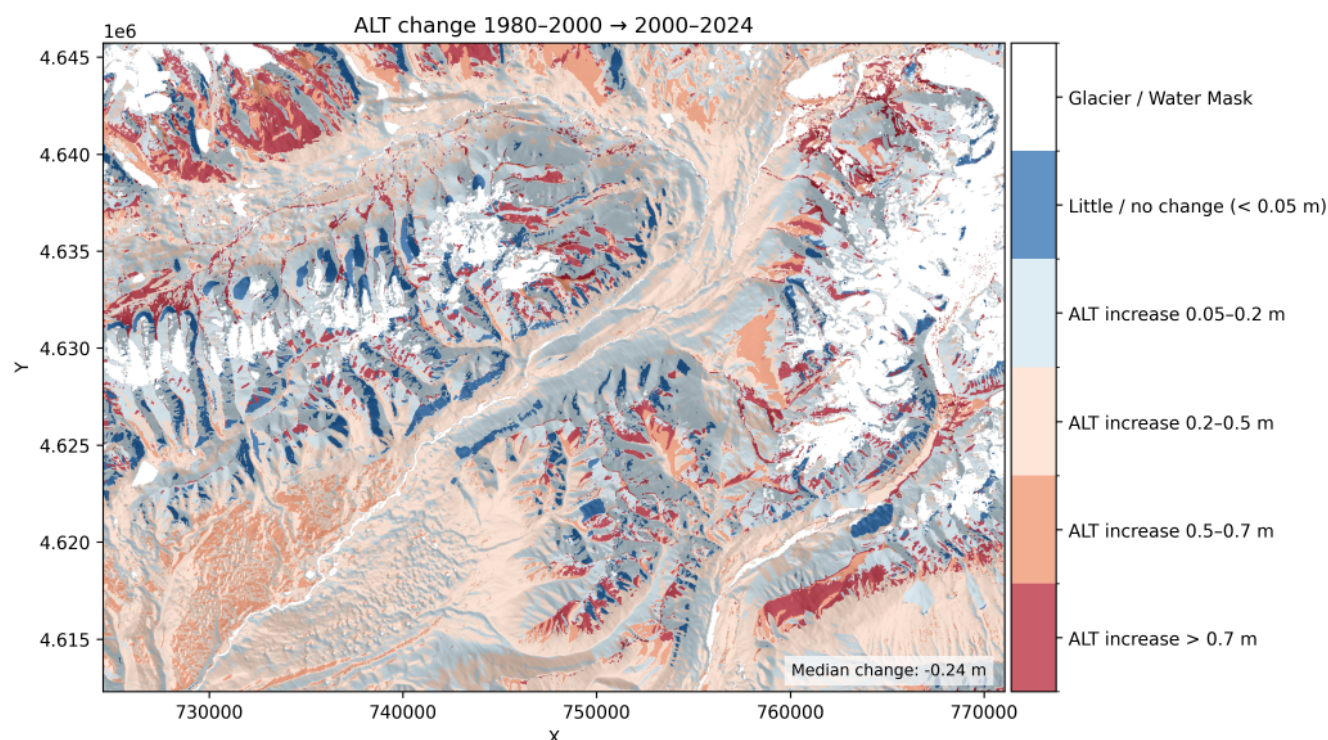


Figure 15. Temporal changes in mean end-of-August thaw depth between the periods 2000–2012 and 2013–2024. The map highlights areas of thaw depth deepening or relatively stable thaw conditions over time. White regions indicate glaciers or water bodies (lakes, rivers), which are masked out from the analysis.

415 situated on rock glaciers and coarse blocky debris slopes (profiles E02, E03, E04, E06, and E08), where modeled thaw depths are often substantially smaller than the ERT-derived estimates. In several cases, CryoGrid simulates only approximately half of the thaw depth indicated by the ERT data. This systematic deviation suggests that the current model setup may underestimate thaw penetration in coarse blocky terrain. At the same time, comparison between modeled and ERT-derived thaw depths in coarse blocky terrain remains challenging because ERT-derived thaw depths are sensitive to inversion settings, profile resolution, electrode spacing, and the strength of resistivity contrasts. In highly resistive coarse blocky terrain, high resistivities may also occur within the active layer itself, thereby reducing the contrast to the underlying frozen ground and increasing uncertainty in the detected depth of maximum gradients. Overall, the results highlight both the value of ERT measurements as an independent spatial validation dataset and the challenges of representing highly heterogeneous mountain permafrost terrain in spatially distributed process-based models.

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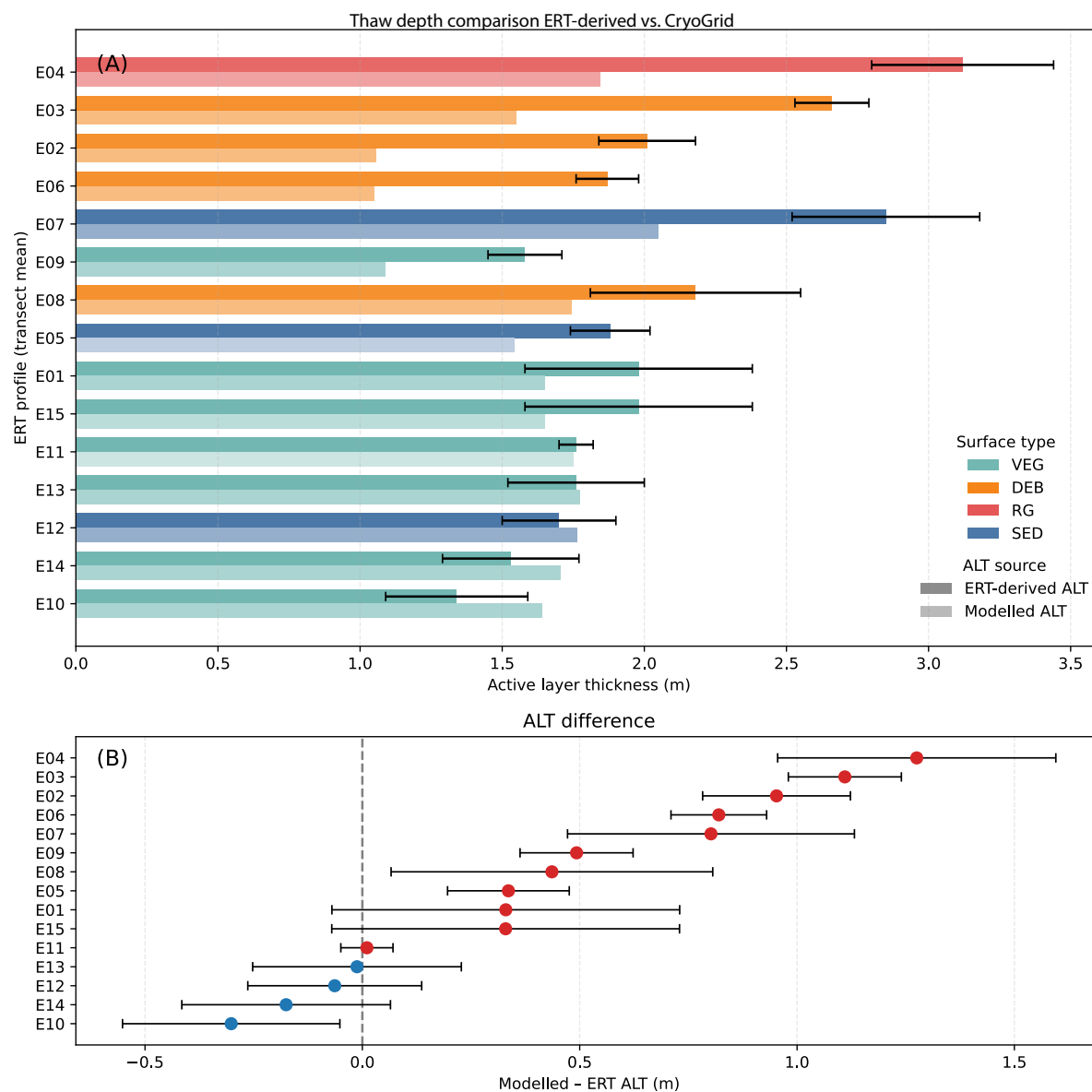


Figure 16. Comparison of CryoGrid-modeled and ERT-derived thaw depths for each ERT transect (mean values). (A) Horizontal bars show ERT-derived and modeled thaw depths, colored by surface type (VEG, DEB, RG, SED). Error bars indicate the standard deviation of ERT-derived thaw depths across tested inversion parameterizations. (B) Difference between modeled and ERT-derived thaw depths (modeled - ERT); negative values indicate deeper modeled thaw depth relative to ERT estimates.



4.7 Comparison to a global permafrost distribution model

To explore how the CryoGrid results differ from an existing large-scale permafrost model, the modeled ground temperatures were compared with the global permafrost distribution model developed by Gruber (2012). This model provides a permafrost zonation index (PZI) derived from relationships between MAAT, elevation-dependent topographic effects, and potential incoming solar radiation, where higher percentage values indicate a higher probability of permafrost occurrence, and which primarily reflects climatic and topographic controls at the global scale. Together with the global maps by Obu et al. (2019) and (Ran et al., 2022a), it represents the only available spatially continuous permafrost model for the study region. The PZI map of the study region is shown in Figure A7.

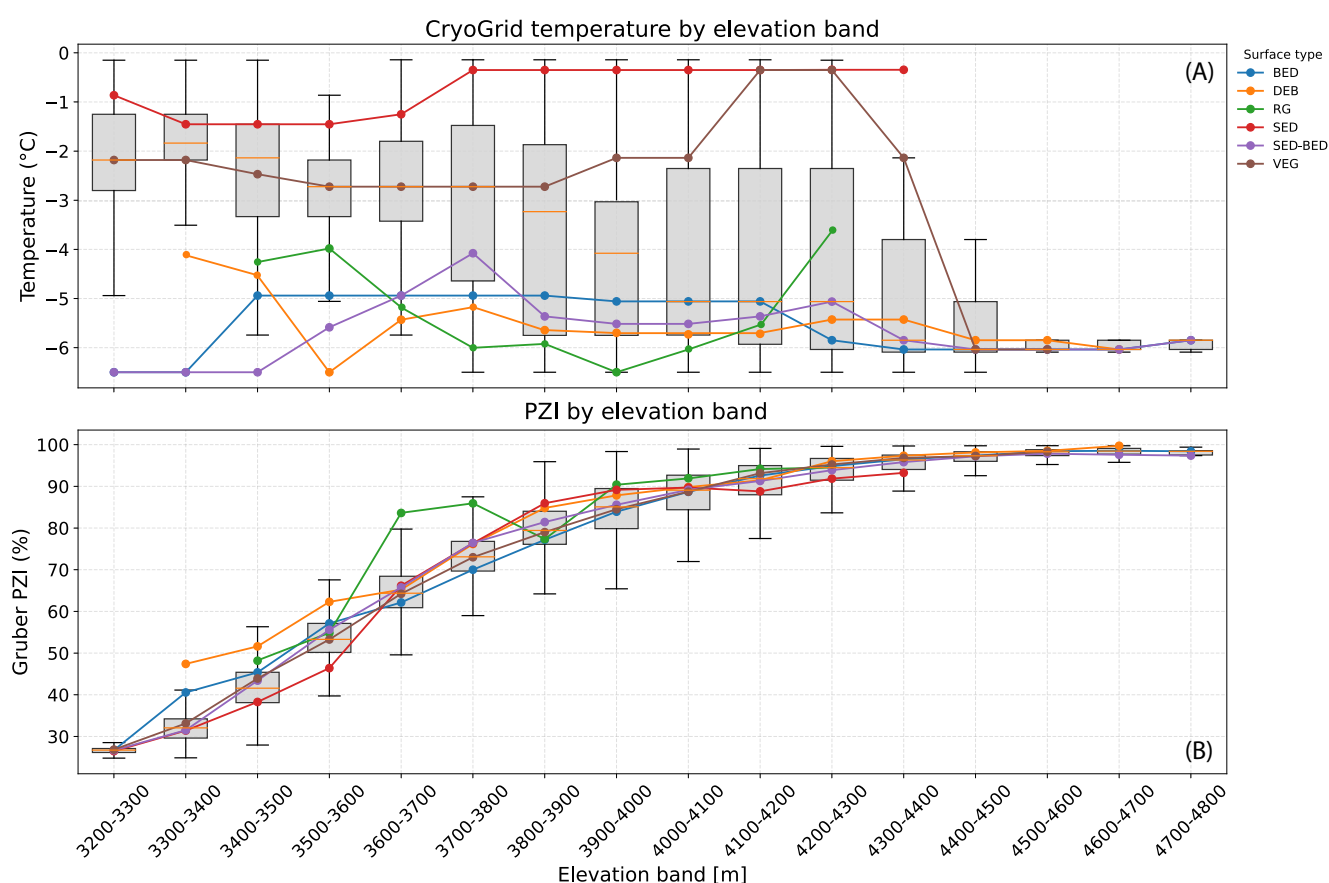


Figure 17. CryoGrid ground temperature at 5 m depth (A) and the permafrost zonation index (PZI) (Gruber, 2012) (B) across elevation bands. Boxplots show the distribution within each band, while colored lines indicate median values for different surface types.

Figure 17 compares the CryoGrid-derived ground temperatures at 5 m depth and the permafrost zonation index (PZI) (Gruber, 2012) across elevation bands. Within the study area, the PZI assigns relatively low probabilities (30 %) to parts of the modelling domain, particularly the lowest elevation part of the high-plateau, where thermokarst lakes are abundant. Because



the PZI represents a probabilistic estimate of permafrost occurrence rather than a direct measure of ground temperature, a direct quantitative comparison between both datasets is difficult. Therefore, the comparison is performed relative to elevation bands to assess their large-scale spatial patterns and altitudinal trends. In both models, higher elevations are associated with colder modeled ground temperatures and higher permafrost probabilities, as a result of the first-order altitudinal control on permafrost occurrence underlying both approaches. At the same time, the distributions within individual elevation bands differ strongly. The CryoGrid results reveal a high degree of heterogeneity, with strong contrasts over short distances. Part of this difference likely reflects the substantially higher spatial resolution and process complexity of the CryoGrid approach compared to the PZI, which is based primarily on large-scale topographic and climatic predictors with a resolution of approximately 1 km (Gruber, 2012). In particular, distinctly colder conditions are simulated in coarse blocky terrain such as rock glaciers and debris-covered areas, while adjacent bedrock or sediment-covered surfaces exhibit comparatively warmer ground temperatures at similar elevations. These contrasts arise because CryoGrid explicitly incorporates surface-type-specific stratigraphies and subsurface properties, allowing the model to represent thermal differences between landforms that are not resolved in the PZI approach. This results in a patchy distribution of permafrost conditions, especially across the high plateau where different surface types coexist.

In contrast, the PZI map displays a much smoother and more gradual spatial pattern. Permafrost probability increases consistently with elevation, but variations within the same elevation range are limited. As visible in Fig. 17, the terrain-specific contrasts that are prominent in the CryoGrid simulations are largely absent in the large-scale model, where such surface-type-specific effects are not explicitly represented.

5 Discussion

5.1 Evaluation of the model results

Overall, the surface-type-based CryoGrid setup provides a plausible representation of permafrost distribution and thaw depths across the study area. The model captures systematic differences between surface classes such as vegetated sediments (VEG), fine-grained sediments (SED), debris-covered terrain (DEB), and rock glaciers (RG), mostly reflecting the expected influence of substrate properties on ground thermal regimes. In particular, coarse blocky terrain such as rock glaciers and debris-covered areas cause consistently colder ground temperatures and smaller thaw depths than sediment-dominated surfaces (VEG and SED) at comparable elevations, demonstrating that the model resolves variability beyond the first-order control of elevation.

The influence of the surface-type-specific parameterization becomes particularly evident in the comparison with the global permafrost distribution model by Gruber (2012). While both approaches reproduce the generally expected relationship between elevation and permafrost occurrence, the CryoGrid simulations show substantially stronger variability within individual elevation bands. Different surface types at similar elevations exhibit markedly different ground temperatures, reflecting the explicit representation of surface-type-specific subsurface properties in the CryoGrid setup. This additional process representation allows the model to simulate spatial heterogeneity that is not resolved in the PZI approach, and also missing from other global distribution maps (Ran et al., 2022a; Obu et al., 2019).



Where observations are available, modeled ground temperatures generally agree well with measurements (Fig. 8), indicating
470 that the dominant processes controlling ground thermal dynamics are adequately represented. Nevertheless, some systematic
deviations occur. The seasonal scatterplots (Fig. 7) show the largest deviations during spring, suggesting a mismatch in the
representation of snow depth and melt timing, which influences the onset of ground warming and the seasonal evolution of
subsurface temperatures (Zhang, 2005). In addition, latent heat effects associated with phase change may contribute to the
mismatch, as small differences in ice content or unfrozen water characteristics can influence the duration of the zero-curtain
475 period and therefore the simulated timing of thaw progression (Outcalt et al., 1990; Romanovsky and Osterkamp, 2000).
At BH51_1, modeled temperatures show slightly larger seasonal amplitudes and somewhat warmer conditions at depth than
observed (Fig. 8D, suggesting stronger thermal buffering in the subsurface than represented in the model. This may indicate
locally higher ice content, finer-grained material, or increased moisture availability, which increase effective heat capacity and
latent heat effects and thereby reduce seasonal temperature amplitudes (Romanovsky and Osterkamp, 2000; Cosenza et al.,
480 2003). A similar discrepancy is observed in the comparison of modeled and measured thaw evolution at the new borehole
site (Fig. 9). While the model reproduces the maximum thaw depth well, the seasonal evolution of thaw shows a bias towards
delayed thaw progression and refreezing compared to observations. A similar discrepancy has been reported by Pedro Baptista
et al. (2025) in their CryoGrid setup. While the model achieved a reasonable maximum thaw depth, it also showed slower
thaw progression and delayed refreezing relative to observations. This recurring pattern suggests that accurately capturing the
485 seasonal timing of thaw and refreezing may be inherently difficult, and the underlying reasons warrant further investigation.

Our simulations further highlight the importance of soil moisture in permafrost modeling (Pellet et al., 2016; Zwieback et al.,
2019). The sensitivity of simulated thaw evolution to soil moisture conditions is consistent with previous studies showing
that soil hydraulic properties strongly influence active layer thickness. For example, Schuh et al. (2017) demonstrated that
variations in soil water retention parameters alone can lead to differences in simulated ALT of several tens of centimeters,
490 underlining the importance of hydraulic parameterization for ground thermal dynamics. In our simulations, the use of Richards'
equation was necessary to reproduce realistic seasonal temperature amplitudes in sediment-dominated surfaces, indicating that
vertical redistribution and retention of soil moisture are important processes in the study area. Soil moisture affects active layer
thickness through two competing mechanisms: higher water contents increase the latent heat required for phase change, which
can slow thawing and refreezing, but also increase thermal conductivity, which enhances heat transfer into the ground (Clayton
495 et al., 2021; Cosenza et al., 2003; Romanovsky and Osterkamp, 2000). This may partly explain the delayed simulated refreezing
observed at the position of borehole BH/AK50/1 as well as locally strong temporal increases in active layer thickness. In
particular, the pronounced thaw depth increases simulated for vegetated sediment surfaces on south-facing slopes (Fig. 15) may
be related to enhanced moisture retention combined with higher incoming radiation. While Richards' equation improves the
representation of seasonal temperature dynamics, uncertainties in soil water retention characteristics, hydraulic conductivity,
500 permeability, and lateral drainage may lead to excessive moisture accumulation in some model cells. The magnitude and spatial
distribution of simulated thaw depth changes, especially the strong increases on south-facing VEG surfaces, should therefore
be interpreted with caution, as they may partly reflect limitations in the representation of subsurface hydrological processes.



For coarse blocky terrain such as rock glaciers and debris-covered slopes, CryoGrid simulates consistently low ground temperatures and limited thaw depths, reflecting reduced conductive heat transfer and efficient preservation of subsurface ice. Furthermore, the modeled ground temperatures for some rock glacier areas are substantially colder than temperatures commonly reported from monitored rock glaciers in the European Alps, where mean annual ground temperatures are often close to 0 °C despite the presence of permafrost (e.g. Delaloye et al., 2010; Noetzli et al., 2024). This suggests that, although the model successfully reproduces the expected cooling effect of coarse blocky terrain, the current parameterization may overestimate the thermal insulation or cooling efficiency of these landforms in some locations, potentially due to uncertainties in porosity, snow conditions, thermal properties, or the simplified representation of highly heterogeneous subsurface structures. However, substantially colder temperatures have also been reported from rock glaciers in Svalbard, where mean annual ground temperatures between approximately -6.1 and -3.4 °C were observed (Strand and Christiansen, 2025). At the same time, CryoGrid does not explicitly represent convective heat transfer processes within coarse blocky material, which have been shown to influence thermal regimes in talus slopes and rock glaciers (Wicky and Hauck, 2017, 2020). While the omission of these processes does not directly explain the comparatively cold modeled temperatures observed here, their integration and systematic testing in CryoGrid would likely improve the physical realism of heat transport simulations in coarse blocky terrain.

Despite the generally good agreement between simulations and observations, validation of the presented CryoGrid maps remains limited by the sparse spatial coverage of boreholes, temperature loggers, and ERT profiles in the study area. These observations cover only a small fraction of the spatial variability present in the landscape, making it difficult to fully assess the simulated heterogeneity. Nevertheless, the inclusion of ERT-derived thaw depths substantially improves the spatial validation of the CryoGrid simulations compared to relying solely on boreholes and temperature loggers. In particular, the model reproduces the ERT-derived thaw depths reasonably well for fine-grained sediment and vegetated surfaces (SED and VEG).

Overall, our results indicate that the presented CryoGrid model setup captures the dominant controls on ground thermal conditions across the defined surface types in the study area. At the same time, the comparison with observations shows that substantial heterogeneity exists even within individual surface classes. Local variations in porosity, ice contents, snow accumulation, and moisture availability can significantly influence ground temperatures and thaw depths, and can not be fully represented by generalized stratigraphies on the chosen spatial scale. This highlights both the advantage of the surface-type-based approach and the remaining challenges in representing highly heterogeneous mountain permafrost environments in spatial distribution models.

Furthermore, the CryoGrid simulations indicate substantial permafrost warming and active layer deepening since 1975. Modeled ground temperatures increased by approximately 0.20 °C per decade at 5 m depth and 0.18 °C per decade at 20 m depth, corresponding to roughly 1 °C warming since the 1980s. At the same time, median thaw depths over the entire study area increased by approximately 0.24 m between the periods 1980–2000 and 2001–2024. These trends are broadly consistent with observations from other permafrost regions of High Asia (e.g. Marchenko et al., 2007; Shen et al., 2024; Zhou et al., 2022; Liu and Chen, 2000; Wu et al., 2010; Zhao et al., 2010). Marchenko et al. (2007) reported permafrost warming of approximately 0.1–0.2 °C per decade in the Central Tien Shan over the last 30 years, accompanied by an approximately 23 % increase in active layer thickness. Similarly, Zhao et al. (2010) summarized warming rates of approximately 0.1–0.3 °C per decade across



Central Asian mountain permafrost regions, with substantial active layer deepening observed in the Tien Shan and on the Tibetan Plateau. On the Tibetan Plateau, Zhou et al. (2022) reported active layer thickening rates of approximately 2–9 cm per year over an observation period of about 20 years, corresponding to a total increase of roughly 0.4–1.8 m, while temperatures near the permafrost table increased by approximately 0.2–1.2 °C over the same period.

Finally, an important aspect emerging from the simulations is that a considerable proportion of the modeled ground temperatures are close to 0 °C, indicating the presence of relatively warm permafrost conditions across substantial parts of the study area. Such near-threshold thermal conditions suggest increased susceptibility to future permafrost degradation, consistent with geomorphological evidence of ground ice loss on the Arabel plateau, such as subsidence induced infrastructure damage.

5.2 Uncertainties in model settings

The CryoGrid model requires specification of a wide range of parameters related to soil physics, hydrology, and surface energy balance. While the stratigraphies were informed by geophysical data and further calibrated using the ground temperature loggers in the study area, many other parameters, such as thermal conductivity, albedo, roughness length, hydraulic conductivity and permeability were not systematically tested for their sensitivity. Given the complexity of mountain permafrost systems, small changes in these parameters can significantly change thermal dynamics and could impact the resulting ground temperature and thaw depth maps. This is particularly true for parameters controlling snow accumulation and water retention, which strongly influence seasonal energy budgets. Furthermore, the calibration approach used in this study does probably not fully capture the intra-class variability in ground conditions. This is highlighted by the comparably weak model performance at BH51_1 (Figure 7 and Figure 8). Therefore, uncertainties in parameter choice remain a source of potential bias in the results.

In addition, the mapping of surface types, which determines the stratigraphy assigned to each model cell, introduces a further source of uncertainty. Surface classification relied on a combination of modified ESA Landcover data and manual delineation using satellite imagery (Esri and Google Earth) for the rock glaciers and debris surface classes, but image resolution and quality were not always sufficient to reliably distinguish between fine-grained and coarse-grained debris surfaces. It is particularly difficult to reliably distinguish between fine-grained and coarse debris surfaces. Although recent studies (e.g. Zegers et al., 2025a) have demonstrated that coarse blocky substrates can be mapped using high-resolution drone imagery, such approaches require very detailed data and are not applicable at the spatial scale of this study.

5.3 Limitations of model validation approach

Validation of model results was primarily based on GST and ground temperature measurements in shallow (down to 1.3 m depth) and deep (down to 30 m depth) boreholes, which provide limited vertical and spatial coverage. Most of the temperature loggers are usually installed quite close to the surface and, therefore, are not directly representative of thermal conditions at depth, particularly in coarse-blocky terrains where ventilation, porosity, and ice content can significantly alter subsurface thermal regimes (Delaloye and Lambiel, 2005; Wicky and Hauck, 2017, 2020; Zegers et al., 2025b; Scherler et al., 2014). Additionally, the DEB class encompasses diverse landforms, from well-ventilated talus slopes to matrix-filled moraines, which



570 complicates the use of a single stratigraphy for modeling. The scarcity of deeper temperature loggers or boreholes in other surface types than VEG further restricts direct comparison with modeled thaw depths on the various surface types.

Furthermore, the ERT-derived thaw depths are sensitive to inversion settings such as zWeight as well as depth constraints, as well as the electrode spacing. The maximum gradient method used to estimate thaw depth can yield variable results across profiles, and depending on the electrode spacing of the ERT measurements (mostly 5 m electrode spacing in this study) shallow 575 thaw depths may be overestimated in some cases.

More generally, the ERT-derived thaw depth does not always correspond directly to the thermal active layer thickness. Electrical resistivity is primarily controlled by liquid water content, ice content, porosity, and pore connectivity rather than temperature alone (e.g. Archie, 1942; Hauck, 2002; Herring et al., 2019; Oldenborger and LeBlanc, 2018). Consequently, the depth of the strongest resistivity gradient may reflect the transition between subsurface units with contrasting hydrogeophysical 580 properties rather than the position of the 0 °C isotherm. In fine-grained sediments and vegetated soils, thawing typically leads to an increase in liquid water content and therefore a decrease in resistivity, meaning that the ERT-derived thaw depth can represent a reasonable approximation of thaw depth. However, the comparison at the vegetated sediment borehole site (Fig. 9) shows that ERT-derived thaw depths are already close to the end-of-season ALT early in the thaw period, when the soil has only begun to thaw. This indicates that the maximum gradient method may initially detect a persistent subsurface contrast, such 585 as the upper boundary of ice-rich permafrost or a lithological transition, rather than the instantaneous position of the thermal thaw front.

For rock glaciers and coarse-blocky debris, resistivity contrasts are even more strongly dominated by the transition from relatively dry or air-filled coarse material to ice-rich layers or massive ground ice. In these environments, the strongest resistivity gradient typically occurs at the boundary to ice-rich permafrost. As a result, the detected gradient may not correspond to the 590 thermally defined active layer as modeled with CryoGrid. This effect is reflected in Fig. 16, where several ERT-derived thaw depths in coarse-blocky terrain exceed the modeled ALT.

Moreover, only a limited number of ERT profiles are available for these surface types at the study site, with two on rock glaciers and three on debris-covered terrain, which is a further constraint for the comparison. However, the method should work quite well for VEG and SED surface types. Nevertheless, we opted for this automated method to estimate thaw depths 595 from the ERT data in order to maintain consistency and reduce subjective bias in the results.

5.4 Spatial resolution and clustering constraints

The spatial resolution of 30 m, inherited from the DEM, does not fully capture fine-scale surface heterogeneities, especially within coarse-grained sediments or narrow landform transitions. Furthermore, while clustering (TopoSUB) effectively reduces computational demand, the number and characteristics of clusters involve disadvantages. Some clusters may group grid cells 600 with different thermal behaviors or misclassify surface types, potentially assigning inappropriate stratigraphies. This can introduce localized discrepancies in simulated thaw depth and permafrost extent, especially in areas with high geomorphological complexity. Since the number of clusters must be defined by the model user, the clustering configuration inevitably reflects a compromise between computational efficiency and process representation.



6 Conclusions

605 This study advances the estimation of permafrost distribution and thaw depths in the Inner Tien Shan by applying a surface-type-specific modeling approach with CryoGrid. Instead of assuming uniform subsurface conditions, the model distinguishes between major surface types such as vegetated sediments, fine-grained sediments, debris, bedrock, and rock glaciers. The stratigraphies assigned to these surface types are informed by results from numerous geophysical surveys in the study area, allowing subsurface material properties to be represented in a more physically consistent way. In contrast to approaches that
610 only distinguish surface characteristics, the prescribed subsurface stratigraphies extend vertically to depths of up to 30 m and are constrained by geophysical observations, allowing surface-type-specific subsurface conditions to be represented throughout the modeled ground column. This approach aims to better capture the strong spatial variability of ground thermal conditions that characterizes high-mountain permafrost environments.

The simulations indicate widespread permafrost across the study area, but with pronounced differences in ground temper-
615 ature and thaw depth between surface types. Coarse blocky terrain such as rock glaciers and debris tends to maintain colder ground conditions and shallower thaw depths, whereas sediment-covered areas, particularly on the Arabel Plateau, show comparatively warmer conditions and deeper thaw. While the comparison with the global permafrost distribution map by Gruber (2012) confirms the general relationship between elevation and permafrost occurrence, the CryoGrid simulations reveal substantially stronger spatial variability within the same elevation range. This highlights that local surface and subsurface char-
620 acteristics exert an important control on ground thermal conditions that is not fully captured by large-scale elevation-based models. The results therefore demonstrate the relevance of accounting for surface-type-specific subsurface properties when representing permafrost distribution in heterogeneous high-mountain terrain.

By combining legacy borehole measurements with recently collected borehole and ground temperature data, this study also provides a first estimate of long-term permafrost warming for the study region. The model reproduces the observed
625 evolution of ground temperatures and suggests a warming of approximately 1 °C since the 1980s both at 5 and 20 m depth, accompanied by an increase in active layer thickness. The strongest increases in thaw depth occur mainly in sediment-covered areas and on south-facing slopes. These findings are consistent with geomorphological evidence such as thermokarst features and ground subsidence observed on the Arabel plateau and indicate that permafrost in the region is particularly sensitive to climate warming. Due to the limited availability of validation data across all surface material classes, the pronounced contrasts
630 in simulated ground temperatures and thaw depths between surface types should be interpreted with caution.

Because mountain permafrost systems are highly heterogeneous, additional observations would help to further improve the evaluation of spatial model performance and reduce uncertainties in simulated ground thermal conditions. While the combination of boreholes, distributed temperature measurements, and geophysical surveys used in this study already represents an extensive observational dataset for the region, complementary remote sensing approaches could provide valuable additional
635 spatial constraints. In particular, methods such as high-resolution optical imagery, InSAR, or drone-based surveys may help to better characterize surface heterogeneity, ground deformation, and thermokarst development across larger spatial scales.



Overall, the study demonstrates that integrating geophysically informed stratigraphies into a distributed modeling framework can improve the representation of spatial permafrost variability in mountain permafrost regions. At the same time, the results highlight the importance of additional field observations to better constrain spatial heterogeneity and reduce uncertainties in model-based estimates of permafrost distribution and change.

Code availability. The CryoGrid community model (version 1.0) and related documentation are available at https://github.com/CryoGrid/CryoGridCommunity_source.

Data availability. All data can be obtained through the corresponding author. The geophysical data (ERT and RST), as well as the GST data, are provided on <https://github.com/tamsima/central-asia-permafrost-geophysics>. Additionally, the ERT datasets used in this study are available through the RESIBASE repository (<https://resibase.unifr.ch/>). Meteorological data from the Tien Shan meteorological station are available through the RP5 weather archive. Data from the Taragai monitoring station are available through the CAIAG Spatial Data Sharing System (SDSS). The GST dataset used was previously published in the PhD thesis of M. Duishonakunov and is available through the corresponding source. Borehole data are currently not publicly available because they are part of an independent study that is in preparation by the data owners. These data will be made publicly available following publication of the associated manuscript. Until then, borehole data can be obtained from the corresponding author upon request.

Author contributions. TM led the study, including research design, fieldwork organization, geophysical data collection, figure development, data analysis, modeling (using the CryoGrid model), and writing the majority of the manuscript. MH, CHa, and CHi contributed to the conceptual design and data analysis. SW developed the CryoGrid code and assisted with model setup, debugging, and data analysis. LG provided code for spatial runs and data analysis. TS digitized and translated legacy borehole data (from Russian). MD provided GST and shallow borehole data. TH provided the original maximum gradient code. MF provided data from the automatic ERT station. RK and ME provided AWS data. TMu and ZB provided part of the ERT data. CHi, TS, MH, RK, ME, TMu, and ZB all assisted with geophysical data collection. CHi, TS, and MH also helped install the new borehole. IB manually inventoried coarse-blocky landforms. All co-authors reviewed and contributed to the manuscript.

Competing interests. The authors declare they have no competing interests.

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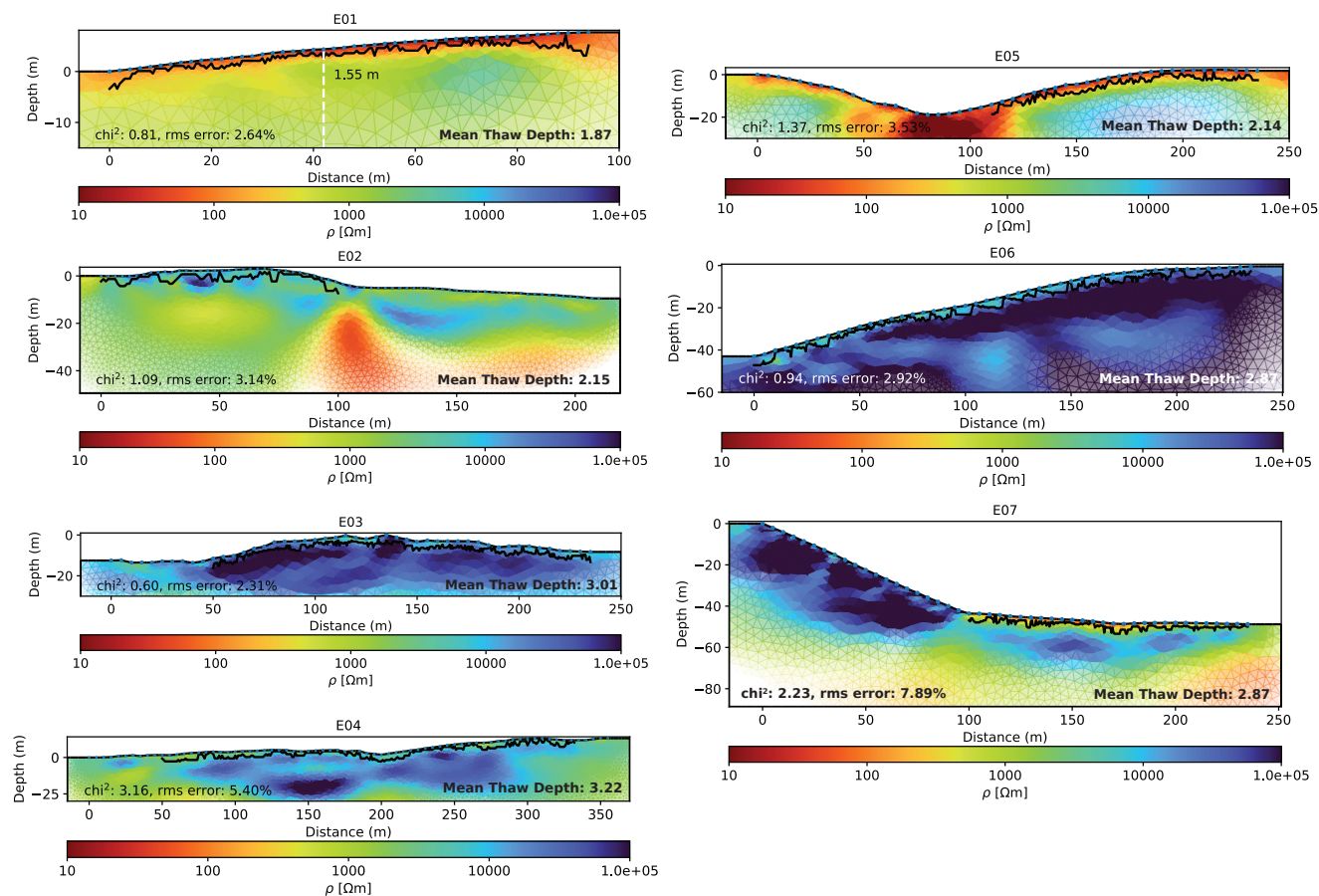


Figure A1. ERT tomograms: Thaw depths are marked by the black line for each profile.

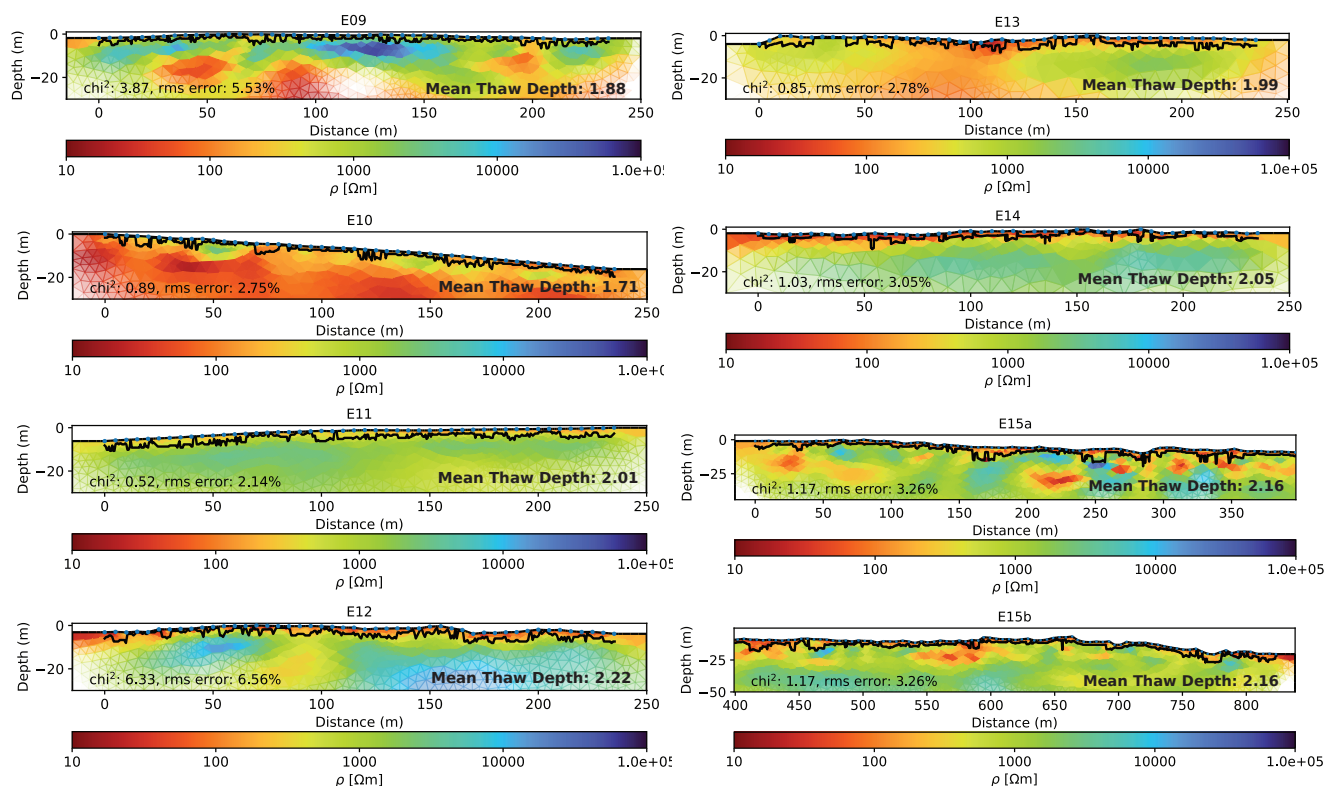


Figure A2. ERT tomograms: Thaw depths are marked by the black line for each profile.

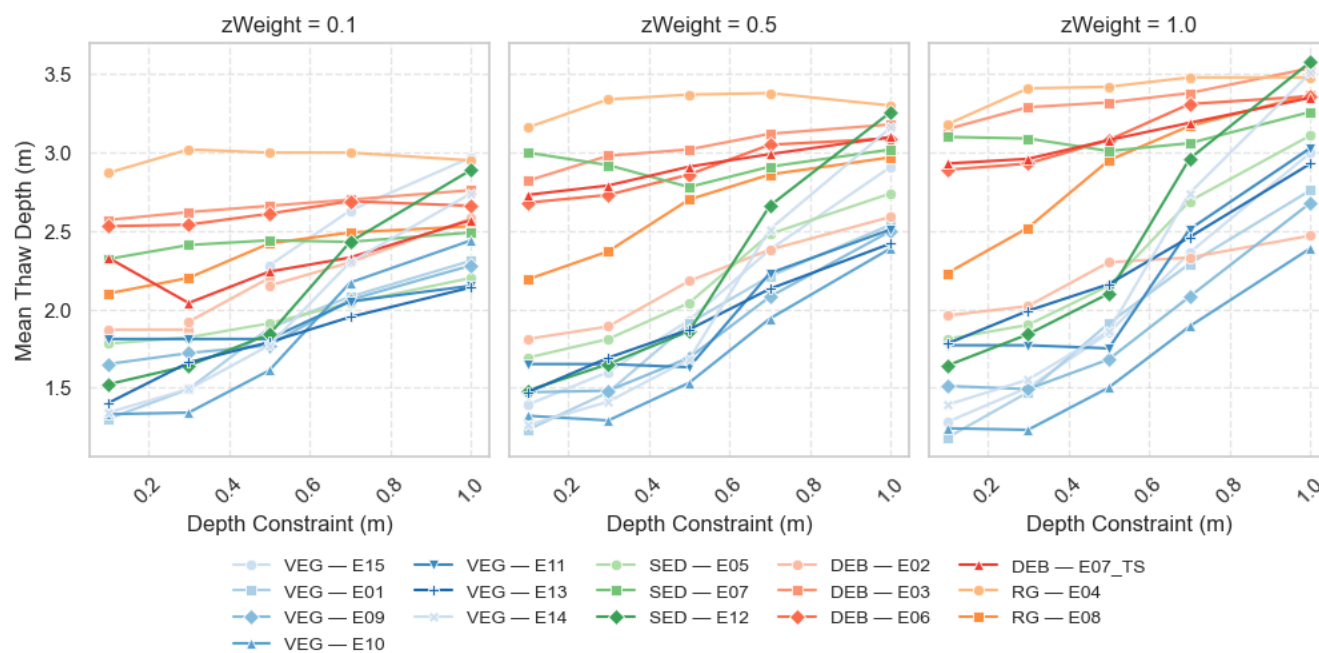


Figure A3. Sensitivity of the maximum gradient method to settings in $zWeight$ and depth constraint for deriving ERT-based thaw depths for all profiles in the study area.

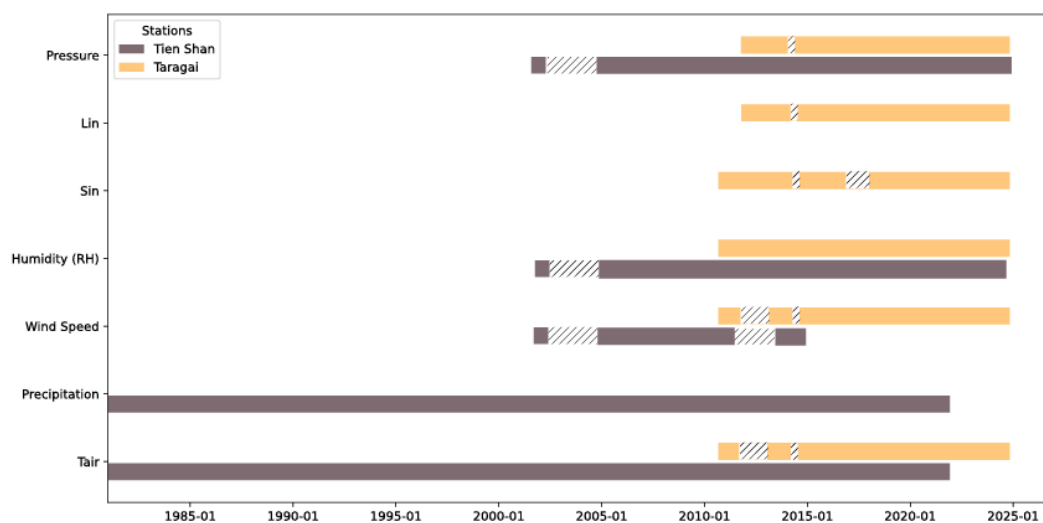


Figure A4. Availability of meteo data from the two AWS stations. Data gaps are marked by white-dashed boxes.

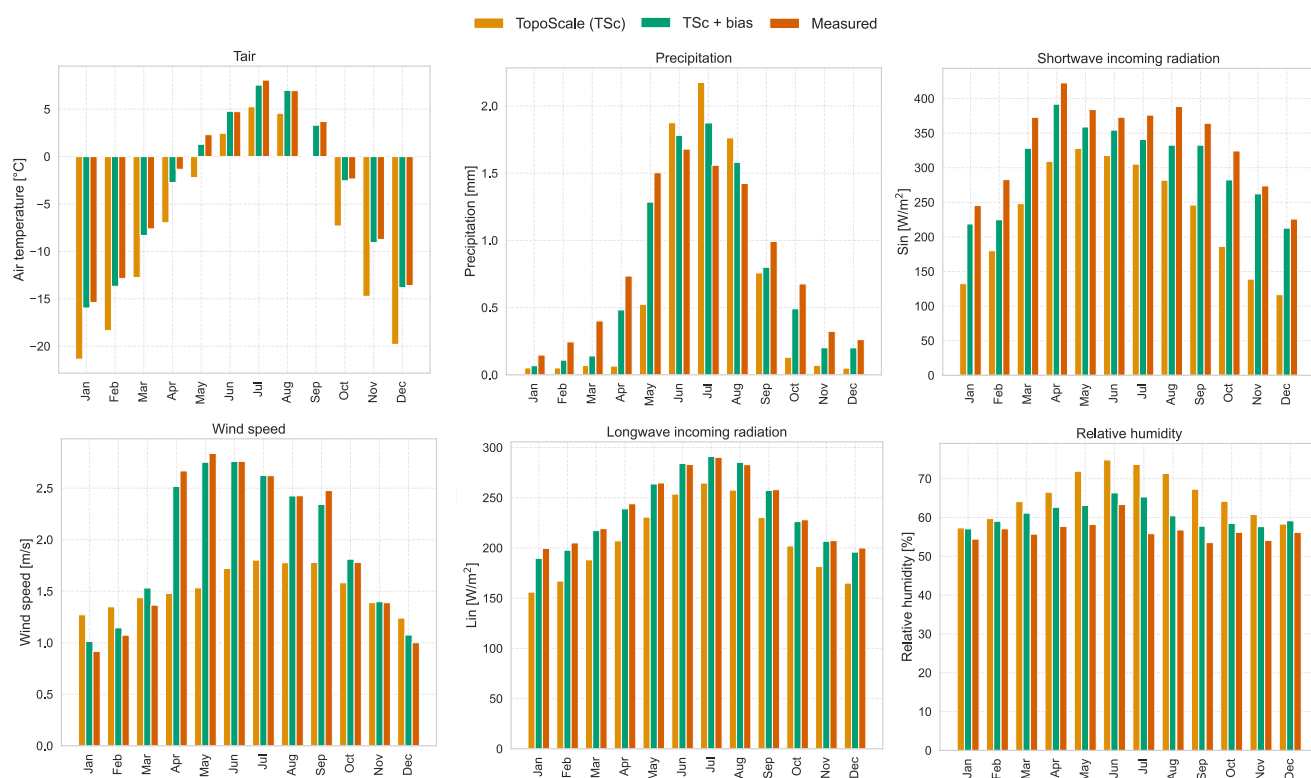


Figure A5. Forcing variables: measured data vs. TopoScale vs. TopoScale + bias correction.

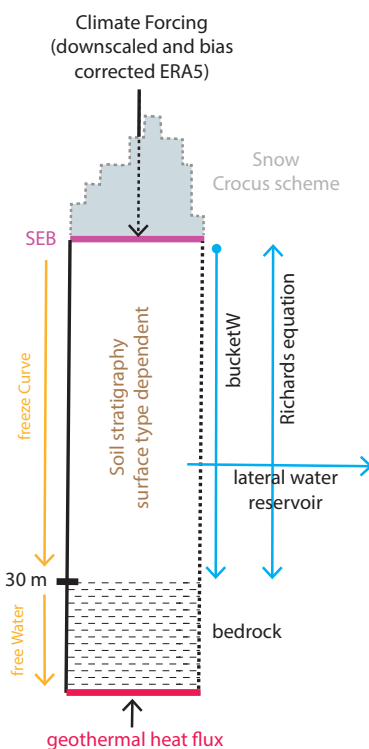
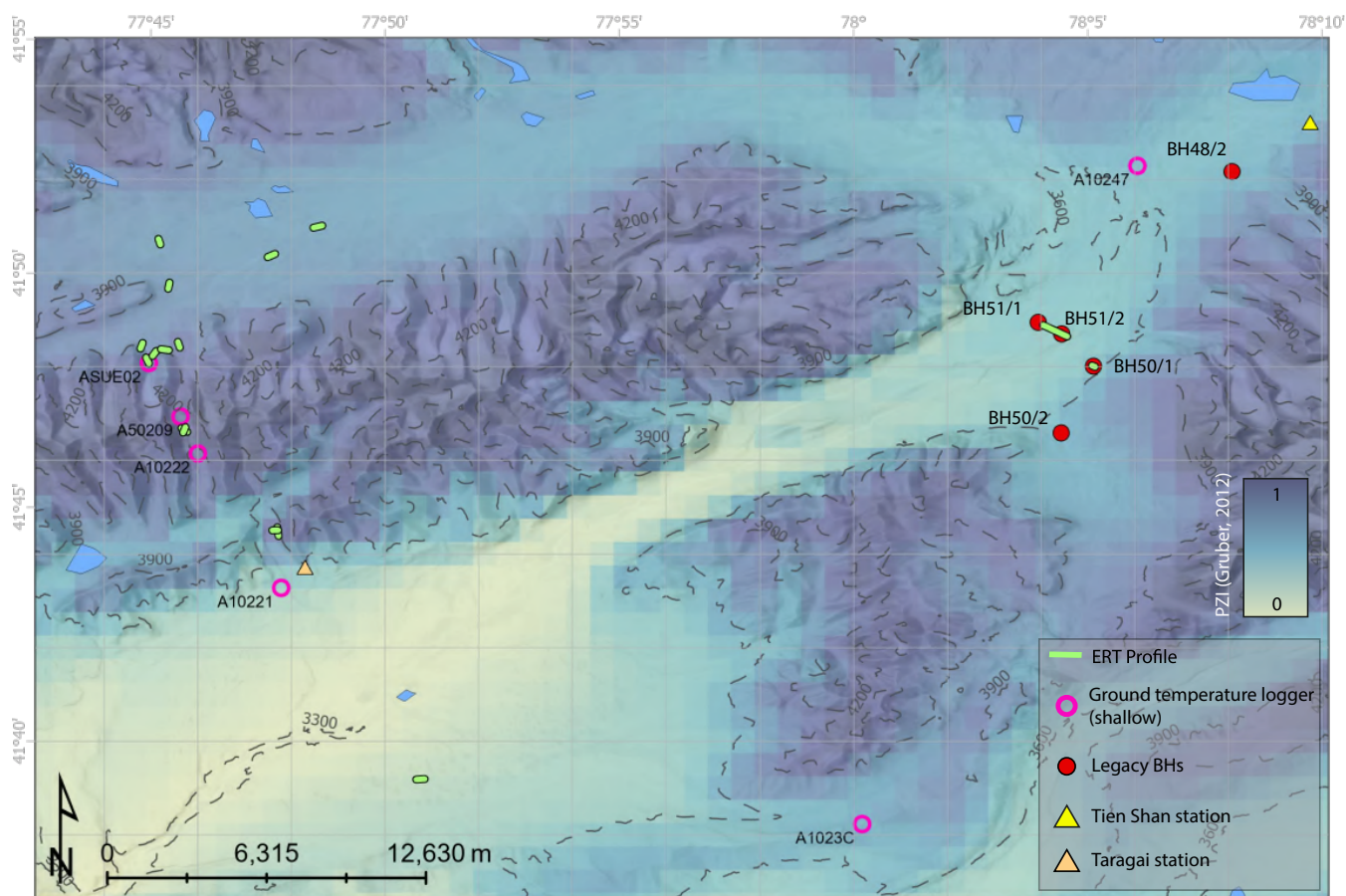


Figure A6. General CryoGrid model setup. The soil stratigraphy above a maximum of 30 m is surface type dependent (see detailed stratigraphies in Table 2), below bedrock is assumed for all surface type classes. Vertical water fluxes are governed by Richards equation for vegetated and fine-grained sediments, and the bucket water scheme for all other surface types. Lateral water fluxes are simulated using a lateral water reservoir. Snow build up and melt are modeled using the Crocus scheme. Lower boundary condition = constant geothermal heatflux, upper boundary condition = surface energy balance (SEB).



Esri, Intermap, NASA, NGA, USGS, Esri, DigitalGlobe, Earthstar Geographics, CNES/Airbus DS, USDA FSA, USGS, AeroGRID, IGN, IGP, and the GIS User Community

Figure A7. Global permafrost zonation index (PZI) from Gruber (2012) for the study area. The PZI expresses the probability of permafrost occurrence based primarily on large-scale relationships with elevation and mean annual air temperature. Locations of ERT profiles, legacy boreholes, and meteorological stations are shown for reference. Sources of the background map: Esri, Intermap, NASA, NGA, USGS, DigitalGlobe, Earthstar Geographics, CNES/Airbus DS, USDA FSA, AeroGRID, IGN, IGP, and the GIS User Community | Powered by Esri.