DebDaB: A database of supraglacial debris thickness and physical properties

Adrià Fontrodona-Bach[1,*], Lars Groeneveld[2,*], Evan Miles[3,4,5], Michael McCarthy[1,3,6], Thomas Shaw[1], Vicente Melo Velasco[1], and Francesca Pellicciotti[1,3]

[1]Institute of Science and Technology Austria ISTA, Earth Science Faculty, Klosterneuburg, Austria.
[2]Remote Sensing Laboratories, Department of Geography, University of Zurich, Switzerland
[3]Swiss Federal Institute for Forest- Snow and Landscape Research WSL, Mountain Hydrology and Mass Movements Unit, Birmensdorf, Switzerland.
[4]Glaciology and Geomorphodynamics Group, Department of Geography, University of Zurich
[5]Department of Geosciences, University of Fribourg, Switzerland
[6]British Antarctic Survey, Natural Environment Research Council, Cambridge, United Kingdom
[*]These authors contributed equally to this work.

Correspondence: Adrià Fontrodona-Bach (adria.fontrodona-bach@ista.ac.at)

Abstract. Rocky debris covers around 7.3% of the global glacier area, influencing ice melt rates and the surface mass balance of glaciers, making the dynamics and hydrology of debris-covered glaciers distinct from those of clean-ice glaciers. Accurate representation of debris in models is challenging, as measurements of the physical properties and thickness of the supraglacial debris layer are scarce. Here, we compile a database of measured and reported bulk physical properties and layer thickness of supraglacial debris that we call DebDaB and that is open to community submissions. The majority of the database (90%) is compiled from 172 sources in the literature, and the remaining 10% are previously unpublished. DebDaB contains 8,741 data entries for supraglacial debris layer thickness, of which 1,770 entries also include sub-debris ablation rates, 179 data entries of thermal conductivity of debris, 160 of aerodynamic surface roughness length, 79 of debris albedo, 59 of debris emissivity and 37 of debris porosity. The data are distributed over 84 glaciers in 13 regions in the Global Terrestrial Network for Glaciers. We show regional differences in the distribution of debris thickness measurements in DebDaB, and fit simplified Østrem curves to 19 glaciers with sufficient debris thickness and ablation data. The data within DebDaB can be used for energy balance, melt, and surface mass balance studies by incorporating site-specific debris properties, or to evaluate remote sensing estimates of debris thickness and surface roughness. It can also help future field campaigns on debris-covered glaciers by identifying observation gaps. DebDaB's uneven spatial coverage points to sampling biases in community efforts to observe debris-covered glaciers, with some regions (e.g., Central Europe and South Asia) well-sampled, but gaps in other regions with prevalent debris (e.g., Andes and Alaska). Debris thickness measurements are mostly concentrated at lower elevations, leaving higher-elevation debris-covered areas under-sampled, suggesting that our knowledge of debris properties might not be representative for all elevations. The aim of DebDaB, as an openly available dataset, is that it evolves over time and is updated and added to through community submissions as new data of supra-glacial properties become available. Data described in this manuscript can be accessed at Zenodo under https://doi.org/10.5281/zenodo.14224835 (Groeneveld et al., 2025).

1 Introduction

Debris-covered glaciers are characterised by a layer of rock debris on part of their surfaces. Debris covers approximately 7.3% of the global glacier area, and about 20% of Earth's glaciers have a substantial debris cover of at least 7% or 10 km^2 (Herreid and Pellicciotti, 2020; Scherler et al., 2018). Crucially, this debris influences ice melt rates and therefore surface mass balance, depending on its thickness and physical properties, with thin debris (less than a few centimetres) enhancing melt through energy absorption, whilst thicker debris reduces melt by insulating the glacier ice (Østrem, 1959; Nicholson and Benn, 2006). The thickness-dependent melt can lead to an inverted mass balance profile and elongated, low-gradient glacier tongues that extend to lower elevations than expected for clean-ice glaciers in the same locations (Benn and Lehmkuhl, 2000; Quincey et al., 2009; Benn et al., 2012). Due to the different melt and geometric characteristics of debris-covered glaciers, their glacier dynamics and hydrology are also distinct compared to clean-ice glaciers (Scherler et al., 2011; Anderson and Anderson, 2016; Fyffe et al., 2019; Miles et al., 2020). As such, debris cover has been recognised as an essential mountain climate variable (Thornton et al., 2021). Understanding debris-covered glaciers (in the current study excluding the Antarctic and Greenland ice sheets) is essential for predicting water availability in regions with substantial debris cover such as Alaska, South Asia East, and New Zealand, to understand regional and global patterns of glacier response to climate (Scherler et al., 2011; Kääb et al., 2021), and for long-term reconstruction of glacier dynamics (Anderson and Anderson, 2016).

Improved understanding of the response of debris-covered glaciers to climate change (Rounce et al., 2023; Postnikova et al., 2023) is currently hampered by insufficient data regarding key debris parameters (Rounce et al., 2021; Miles et al., 2022), as well as limited understanding of debris thickness patterns (Anderson and Anderson, 2018; Nicholson et al., 2018) and sub-debris melt rates (Rounce et al., 2021). Direct measurements of debris thickness and sub-debris ice melt are essential to evaluate sub-debris melt models (Nicholson and Benn, 2006; Reid and Brock, 2010; Evatt et al., 2015; Rounce et al., 2015). Furthermore, gaining insights into the surface mass balance of debris-covered glaciers through energy balance modelling requires a detailed understanding of the physical properties of the debris layer, such as thermal conductivity, aerodynamic surface roughness length, emissivity, porosity, and albedo (Nicholson and Benn, 2006; Rounce et al., 2015). Accurate representation of debris thickness and debris properties in energy balance models is necessary for predicting the melt rates of debris-covered glaciers and their contribution to water resources (Lejeune et al., 2013; Brock et al., 2010). However, estimating these physical properties for a particular glacier usually presents several challenges, as collecting such measurements can be labour-intensive, economically expensive, or have a large degree of uncertainty in time and space. These measurements are often a combination of field measurements, laboratory experiments, remote sensing techniques, or model optimisations. Although the development of remote sensing methods to estimate debris properties is promising (Racoviteanu et al., 2022), these methods require in situ measurements for evaluation. Unfortunately, supraglacial debris layer thickness and physical properties of relatively few glaciers have been measured. Many studies therefore optimise debris properties for the purpose of ice melt modelling or rely on literature values (Rounce et al., 2015; Fugger et al., 2022). In addition, some measured debris properties and thicknesses have not been openly published, and, to date, there is no central repository with debris properties data which could facilitate individual glacier studies as well as large-scale model studies.

Here we aim to compile as many existing and new measurements of debris thickness and physical properties into one database, as well as reported literature values and reported optimised debris properties from modelling efforts, for as many glaciers as possible. Our goal is to create an open central repository for use by the science community to support and enhance numerical modelling at the glacier, regional and global scales when involving debris-covered glaciers. We call this database DebDaB. We briefly describe each of the supraglacial debris layer properties considered in DebDaB below. Thereafter, we describe the data compilation and curation process and show key features of the dataset as well as the spatial distribution of measurements and reported values and their variability. Finally, we discuss potential applications of the dataset, limitations and priorities for future measurements.

2 Debris properties

Debris thickness is a key control on the melt enhancement or reduction of the bulk debris layer (Østrem, 1959), and is typically measured in situ by manual excavations from the debris surface to the ice surface. However, these measurements are labour-intensive and remote sensing estimates of debris are becoming more available. For example, debris thickness can be inferred from its relation to debris surface temperatures using thermal band satellite images, either empirically (Mihalcea et al., 2008a; Kraaijenbrink et al., 2017) or using a physically based approach (Foster et al., 2012; Rounce and McKinney, 2014; Stewart et al., 2021). At the glacier scale, ground-penetrating radar (GPR) (McCarthy et al., 2017; Giese et al., 2020) and ground-based thermal infrared radiometry (Aubry-Wake et al., 2023) have also been used to estimate debris thickness. Sub-debris melt modelling has provided fully distributed estimates of debris thickness at regional and global scales (Rounce et al., 2021; McCarthy et al., 2022), sometimes also making use of satellite thermal data (Rounce et al., 2021). L-band synthetic aperture radar also shows promise to retrieve debris thickness through its internal volume scattering (Huang et al., 2017). Despite the advancements in remote sensing and modelling techniques, all of these methods require direct in situ measurements to validate the estimates.

The thermal conductivity of the debris influences the rate at which heat is transferred through the debris layer, affecting melt rate of the underlying ice, and it depends on factors such as composition, moisture content and grain size, which can vary widely in space (Juen et al., 2013) and time (Nicholson and Benn, 2013). Thermal conductivity can be determined through laboratory analysis of debris samples, or in the field by placing thermistors within the debris layer and analysing the vertical temperature profiles (Nakawo and Young, 1982; Conway and Rasmussen, 2000). Importantly, however, discrepancies between methods to derive thermal conductivity can be substantial and significantly affect modelled melt in energy balance simulations (Laha et al., 2023; Melo Velasco et al., 2024).

The aerodynamic surface roughness length of the debris layer, which is the height above the debris surface at which the mean horizontal wind speed theoretically becomes zero, affects the turbulent heat fluxes at the glacier surface. It can be derived from wind profile data, microtopographic, or eddy-covariance methods (Chambers et al., 2020; Rounce et al., 2015; Nicholson and Stiperski, 2020) and can vary significantly with surface conditions and debris distribution (Miles et al., 2017; Quincey et al., 2017; Sicart et al., 2014). Methods to derive surface roughness can be financially expensive but remain independent from melt modelling choices and are therefore preferable compared to approaches that might optimise surface roughness through a model routine (Melo Velasco et al., 2024).

The emissivity of the debris, which is the efficiency with which the debris surface emits thermal radiation, influences the longwave radiation balance. Emissivity is mostly assumed constant in time and usually taken from published literature values for the specific type of rock (Brock et al., 2007, 2010), although it can also be estimated from thermal imagery and site-specific measurements (Herreid, 2021) or satellite datasets (Casey and Kääb, 2012).

The porosity of the debris layer, defined as the void space within the debris material, influences the thermal properties and water retention capabilities of the debris layer (Juen et al., 2013). Porosity can be measured by filling the air spaces in a known volume of surface debris with water, and has been found to range from ∼20% to ∼60% (Brock et al., 2006). Porosity has been assumed to linearly decrease with depth in the debris layer, decreasing from ∼40% at the surface to ∼20% at the debris–ice interface (Collier et al., 2014), but often a bulk porosity of 30% is adopted (Nicholson and Benn, 2013). Ultimately it is difficult to measure or estimate porosity while maintaining the original structure of the debris layer untouched, and measurements are therefore scarce.

Albedo, the reflectivity of the debris surface, depends on properties such as the colour and moisture of the debris. It determines the amount of solar radiation absorbed by the glacier surface, such that a lower albedo promotes higher melt rates and a higher albedo lower melt rates. It can be measured using ground-based albedometers or pyranometers (Brock et al., 2000) or estimated from multitemporal satellite imagery (Fujita and Sakai, 2014). The albedo of a debris-covered glacier decreases as the proportion of the debris covered glacier surface increases (Brock et al., 2010; Azzoni et al., 2016), and is therefore important for melt modelling.

3 Data compilation

DebDaB targets the supraglacial debris layer properties described above. The dataset compiles measurements, literature values, and optimised or calculated debris properties from modelling exercises.

3.1 Published data

The majority (90%) of the data entries in DebDaB are published data from 172 different sources. These data are obtained from tables, digitised figures, text and supplementary files in research articles or scientific reports, as well as publications in data repositories and personal communications from data collectors. DebDaB is therefore a central database of supraglacial debris thickness and bulk properties to which the scientific community can refer to instead of searching hundreds of research articles. The dataset acknowledges the data source and provides a citation for each data entry that has previously been published elsewhere (see Table A1 in the Appendix). For the current version of DebDaB, there was no public call for gathering data except for advertising it at scientific conferences.

3.2 Unpublished data

The remaining 10% of data in DebDaB have not been previously published and correspond almost exclusively to debris thickness measurements. These are from 10 different field campaigns undertaken by the authors and colleagues at 10 different glaciers that took place between 2013 and 2023. These are briefly described below:

- Baghirath Kharak, Satopanth and Raj Bank (Kneib et al., 2022, unpublished): 162 debris thickness measurements were taken on Satopanth, Baghirath Kharak and Raj Bank Glaciers in September 2022. Debris thickness ranged between a few centimetres and several metres.

- Clariden Glacier, Switzerland (McCarthy et al., 2020, unpublished): 19 debris thickness measurements were made by manual excavation on Clariden Glacier, Switzerland, in September 2020. Debris thickness ranged between 1 and 29 cm.

- Ghanna Glacier, Nepal McCarthy et al., 2019, unpublished): 7 debris thickness measurements were made by manual excavation on Ghanna Glacier, Nepal, in May 2019. Debris thickness ranged between 21 cm and more than 53 cm.

- Kyzylsu Glacier, Tajikistan (Miles et al., 2021, unpublished; Melo Velasco et al., 2023, unpublished): Ongoing field campaigns in the western Pamir, Tajikistan have provided debris thickness measurements by excavation or at the time of ablation stake installation on the debris-covered terminus of Kyzylsu Glacier. In 2021, a total of 249 measurements of debris thickness were collected by manual excavation. Additionally, in August 2023, 123 debris thickness measurements were made on the glacier. In both field campaigns, debris thicknesses ranged between less than 1 cm and a maximum digging depth of 1 m.

- Lirung Glacier, Nepal (Petersen et al., 2012, unpublished; Buri et al., 2014, unpublished): Short description of field measurements. Between 2012 and 2014, 227 measurements of debris thickness were collected on the Lirung Glacier, along with corresponding debris classification descriptions. Debris thickness ranged from 6 cm to 70 cm.

- Oberaletsch Glacier, Switzerland (Melo Velasco et al., 2023, unpublished): Between June and August 2023, 196 measurements of debris thickness were made on the glacier to investigate spatio-temporal evolution of the debris layer. Debris thicknesses ranged from 1 cm to 87.5 cm.

- Piramide Glacier, Chile (Melo Velasco et al., 2023, unpublished): In March 2023, 103 distributed measurements of debris thickness measurements were made on this glacier as part of a dedicated survey to understand debris thickness variability (Melo-Velasco et al., 2024). Debris thicknesses ranged from less than 1 cm to 1.1 m.

- Gangotri Glacier, India (Mishra et al., 2023, unpublished): In Juny 2023, 12 measurements of debris thickness were made on this glacier, ranging from 14 cm to 1.05 m.

3.3 Data curation

The data from different sources were collected, organised and structured in a logical, consistent and standardised manner. Errors and inconsistencies in the source data were identified and corrected, in some cases by contacting the authors, and the units of the data were standardised in Metric units: debris thickness values and surface roughness length are provided in metres and thermal conductivity in W m^{-1} K^{-1}. Albedo, emissivity and porosity are dimensionless values ranging between 0 and 1. The data descriptions provided in the database are as detailed as possible integrating the information from tables, figures, text and metadata from the original source data. The origin of the data is noted by a data and/or paper citation and the corresponding DOI. At present, a glacier name and a glacier ID based on the Randolph Glacier Inventory 6.0 (RGI Consortium, 2017) is given for each data entry. Dates on which measurements were collected are also included, usually sourced from the methods sections of research articles or table and figure captions. In some cases an exact date was not stated or clear, and thus a quality flag for the date entry is included. The coordinates of the measurement location, where available, were all standardised and are provided in decimal degrees, along with the elevation in metres above sea level at the time of the measurement. Other location data such as the specific site name in a study is also included, as well as any relevant notes (e.g., type or size of debris, average of measurements, moisture conditions). The methods used to obtain each debris property value is also shown in the database together with any relevant notes. Where available, measurements are provided with uncertainty estimates, or with a range if multiple debris thickness measurements are provided without a precise location.

4 DebDaB

4.1 Spatial distribution of data

DebDaB includes data from 84 glaciers across various regions (Figure 1). The majority of the glaciers with data are located in High Mountain Asia (45) and the European Alps (18), showing that these regions have been a major focus of study and field campaigns for debris-covered glaciers, while other regions such as the Andes (4), North America (9), Svalbard (3) and New Zealand (3) contain fewer data (Figure 1). The majority of the glaciers (76) have debris thickness measurements, with a total of 8,741 measurements in the dataset to date, of which 1,770 contain data on sub-debris ablation as well (Table 1), although 965 of those are from Satopanth glacier (Banerjee, 2022). There are also 188 sub-debris ablation measurements on clean ice areas of debris-covered glaciers. The number of data entries of other debris properties is considerably lower, with 179 for thermal conductivity and as low as 37 for porosity (Table 1), although every property has values for at least 30 glaciers. Most data entries for debris thickness contain spatial information with latitude, longitude and elevation provided, but this is rarely the case for the other debris properties, which are usually only assigned to a glacier but not to a specific location on the glacier.

4.2 Observed variability of physical properties

Figure 2 highlights the variability in the distribution of debris thickness measurements, thermal conductivity and surface roughness values. Debris thicknesses range from dirty ice or patchy debris (< 1 cm, Fyffe et al. (2014)) to thick debris (> 1 m). The

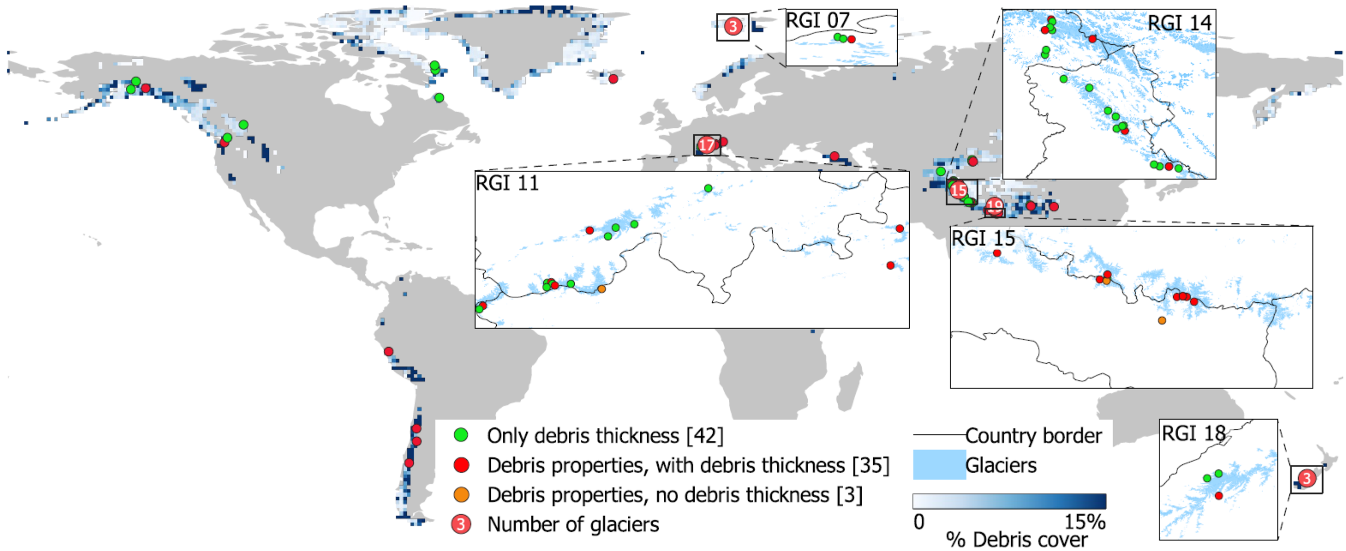

Figure 1. Spatial distribution of the data in DebDaB. Points show the locations of all the glaciers with at least one data entry for a debris property. The underlying pixel colours show the percentage of debris cover on glaciers in that pixel area, based on Scherler et al. (2018).

Table 1. Summary of data entries in DebDaB.

DebDaB data entries	Total number	With coordinates	With elevation only	Number of glaciers
Debris thickness	8,741	4,369	1,675	76
Sub-debris ablation	1,770	546	1,088	41
Thermal conductivity	179	33	44	31
Surface roughness	160	26	4	28
Albedo	79	2	9	25
Emissivity	59	10	0	27
Porosity	37	11	0	19

interquartile range of measurements is also highly variable across glaciers and regions, with some glaciers having the majority of their measured debris thicknesses below 10 cm, some measuring predominantly above 10 cm, and some which span the whole range of thicknesses. The measured glaciers are from 13 RGI regions, with some apparent regional differences in debris thickness (Figure A1). The three regions with highest median debris thickness (with a minimum of measurements on three different glaciers) are Region 2 (Western Canada & US, 40 cm), Region 15 (South Asia East, 40 cm) and Region 17 (Southern Andes, 30 cm). The regions with lowest median debris thickness are Region 1 (Alaska, 4 cm) and Region 11 (Central Europe, 8 cm). However, the regional differences observed could also simply be due to sampling biases (see Sect. 5.2 on limitations). The number of data entries per glacier varies greatly: 49 glaciers have fewer than 50, only 21 glaciers exceed 100, and just two glaciers (Ngozumpa and Satopanth) have over 1,000 entries.

Figure 2. The distribution of debris thickness measurements (a), thermal conductivity (b) and surface roughness length (c) for each glacier in DebDaB. Glaciers are sorted per RGI region (RGI 6.0). The number of measurements or data values is shown on the left. Literature values are not shown. Note the logarithmic x-axis scale for debris thickness and surface roughness length.

Along with debris thickness measurements, many glaciers have measurements of sub-debris ablation rates, enabling the fitting of simplified Østrem curves (Østrem, 1959) in the form of a rational curve that depicts only the declining limb of melt with debris thickness (see Equation in Fig. 3). Note that application of this curve to derive melt rates based on debris thickness can lead to unrealistically high melt rates for very thin debris. These are typically derived from modelling exercises or based on measurements from a single glacier. To the best of our knowledge, this paper provides the most detailed scatter plot of

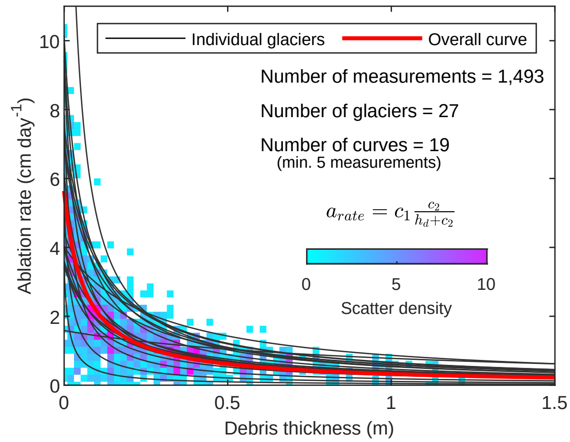

Figure 3. Simplified Østrem curves (Østrem, 1959) based on observations of debris thickness and observations of sub-debris ablation rates. All measurements are plotted in the scatter, but simplified Østrem curves (rational curves) are only fitted for the 19 glaciers that have at least five measurements. Equation shows the form of the curve, as in Anderson and Anderson (2016). The fitted parameters and R^2 for each curve are shown in Table A1.

debris thickness and ablation rates yet, with simplified Østrem curves fitted for 19 glaciers, based entirely on observational data (Figure 3). The alignment of data points along the characteristic negative exponential curve of the Østrem curve strongly supports the well-documented reduction in melt rates after the initial few centimetres of debris and the subsequent minimal reduction in melt rates for thicker debris. Only one glacier (Venerocolo Glacier) displays nearly no reduction in ablation for increasing debris thickness, instead of the expected exponential reduction, and a poor R^2 (Table A1).

The observed variability of thermal conductivity and surface roughness per glacier is shown in Figure 2b and Figure 2c, the variability of all other debris properties in DebDaB is shown in Figure 4, and regional differences are shown in Figure A1. The median of all data entries for thermal conductivities across the dataset is 0.98 W m^{-1} K^{-1}, which is near to the 0.96 W m^{-1} K^{-1} value that Brock et al. (2010) calculated, which is widely used in the literature. However, the range of thermal conductivities is large, from 0.3 W m^{-1} K^{-1} at Villarrica Glacier (Brock et al., 2007) and up to 2.8 W m^{-1} K^{-1} at Satopanth Glacier (Laha et al., 2023). There is also regional variability in thermal conductivity values, which is apparent despite the fewer data available. The highest median thermal conductivity is observed in Central Asia and South Asia East, while the lowest is observed in the Southern Andes (Figure A1).

The variability of surface roughness length reported values is also large, considering it varies at a logarithmic scale, between 0.008 m at Svinafellsjokull Glacier (Nield et al., 2013) and 0.06 m at Khumbu Glacier (Lejeune et al., 2013), with most literature values using the 0.016 m, also from Brock et al. (2010). Albedo ranges from 0.03 at Larsbreen Glacier (Nicholson and Benn, 2006) to 0.35 at Venerecolo Glacier (Bocchiola et al., 2015), but the most common reported values are around 0.1.

Regarding emissivity, no actual measurements are reported, only literature values and assumed values, ranging from 0.9 to 1, making it the least variable of all the debris properties in the database. Measurements of porosity are also scarce and most

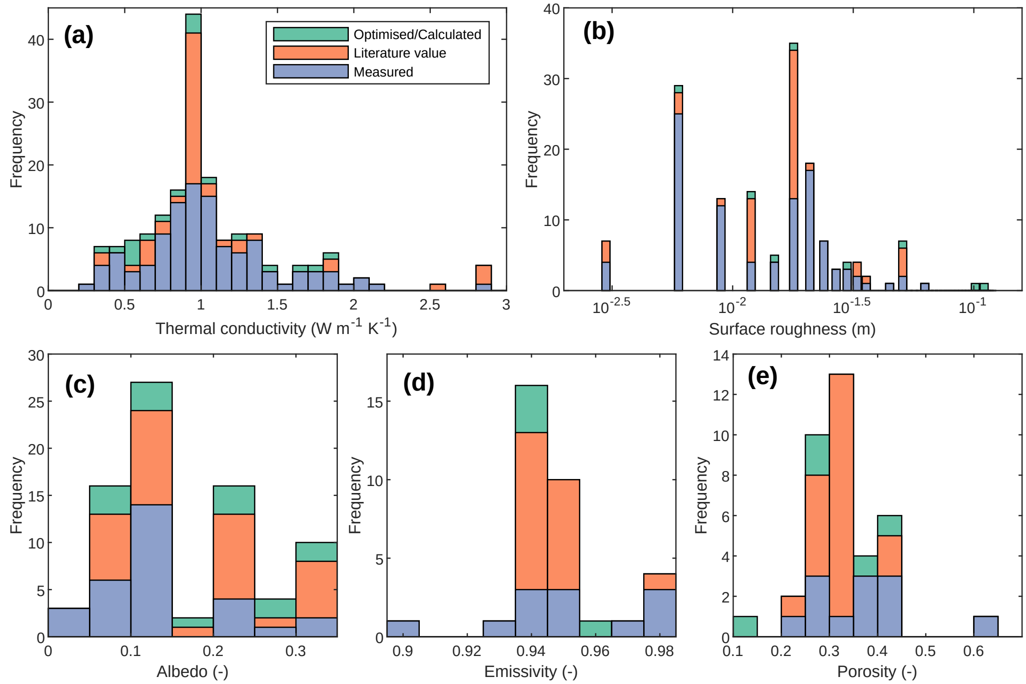

Figure 4. Frequency distributions of the physical properties of debris in DebDaB, except debris thickness. Histogram bars are stacked.

common between 0.2 and 0.45, with most literature using values around 0.3 (Figure 4e). Optimised values from modelling exercises for all debris properties fall within the overall range (not site-specific) of reported field measurements in DebDaB, except for the highest reported value of surface roughness, which is an assumption by Fujita and Sakai (2014) and is above any surface roughness measurement reported in DebDaB. The number of measurements is too low to observe any regional differences for surface roughness, albedo, porosity, and emissivity (Figure A1).

4.3 Variability of methods

The debris layer properties in DebDaB are measured, derived and calculated with a variety of methods, which can result in large differences in estimates (Melo Velasco et al., 2024). Debris thickness is primarily measured by excavating the debris until reaching the ice surface. In case of thick debris, manual excavations may not reach the ice surface, usually stopping at 0.5 meter. The debris thickness data in DebDaB contain a column indicating whether or not the ice surface was reached by manual excavation. Manual excavations are also performed when installing ablation stakes, and the debris is restored to its original configuration as much as possible afterwards. Other manual measurement methods include experimentally adjusting the debris cover (Muhammad et al., 2020; Winter-Billington et al., 2022), or placing metal rods in between the debris stones down to the ice surface (Popovnin and Rozova, 2002). Debris thickness is also measured directly at exposed ice cliffs or using a laser theodolite and reflector positioned at the upper debris surface, in case it is dangerous to access the edge of the cliff (Nicholson and Benn, 2013). Close range remote sensing measurements from photogrammetric terrain models and ground penetrating radar (GPR) (McCarthy et al., 2017; Nicholson and Mertes, 2017) are also present in DebDaB.

Debris thermal conductivity is calculated using the one-dimensional heat conduction equation and measurements of vertical temperature profiles within the debris (Conway and Rasmussen, 2000; Nicholson and Benn, 2006), or based on the Fourier heat conduction equation with different combinations of meteorological and glaciological data (Brock et al., 2010; Reid et al., 2012). Some studies use some optimising equations of energy balance to match measurements of ice ablation (Bocchiola et al., 2015; Fugger et al., 2022). Laha et al. (2023) use a Bayesian inversion approach, and Kirkbride and Warren (1999) use a weighted average of the present parent rock type and of interstitial media.

Surface roughness values in DebDaB are estimated using four methods: the profile aerodynamic method, microtopographic methods, optimisation method, and eddy covariance systems. The profile aerodynamic method determines aerodynamic surface roughness length using Monin-Obukhov similarity theory (Miles et al., 2017; Quincey et al., 2017). Microtopographic approaches estimate roughness through (i) mechanistic methods, which identify surface obstacles from elevation profiles, and (ii) empirical techniques, which calculate the standard deviation of elevations from a detrended digital elevation model (DEM) of equal height and width (Miles et al., 2017). Alternatively, optimisation methods used in energy-balance modelling adjust surface roughness to best reproduce observed surface temperature, ice melt, or mass loss (Steiner et al., 2021; Fugger et al., 2022). Finally, point-scale estimates can be obtained from turbulent fluxes measured with eddy covariance systems (Steiner et al., 2018).

The rest of the properties have fewer measurements and therefore fewer methods. Albedo is measured with albedometers (Brock et al., 2007; Nicholson and Benn, 2006), handheld luxmeters (Steiner et al., 2015) or with the ratio of incoming and reflected shortwave radiation (Steiner et al., 2021). Porosity measurements are done by placing a known amount of debris in a graduated bucket and measuring the volume of water required to fill the interstitial pore spaces (Collier et al., 2014; Giese et al., 2020), or estimated from matrix particle size determined by laser diffraction (Nicholson and Benn, 2006), or using a soil corer and drying, weighing and sieving the debris in the lab (Steiner et al., 2021). Emissivity, however, lacks direct measurements in DebDaB, relying only on literature and assumed values.

The variability of approaches described above should be carefully considered when assessing the variability in debris properties across sites and climates.

5 Discussion

5.1 Potential applications

The DebDaB dataset presents a large collection of reported supraglacial debris layer property values, and can be a valuable resource for numerous scientific applications, some of which we outline here.

The debris property values within DebDaB may be used for constraining energy balance, melt and surface mass balance models, potentially improving the performance of these models by incorporating site-specific physical properties of debris. DebDaB serves as a central public repository of physical properties of supraglacial debris layers that modellers can refer to in case they need a property value for their modelling efforts. When data for a specific glacier are not available, modellers have sometimes chosen values from other similar glaciers, and DebDaB makes relevant values accessible. However, regional differences between debris properties were not apparent in DebDaB, except for debris thickness, with glaciers in High Mountain Asia consistently having thicker debris than in Central Europe, although this could also be due to an observational bias. Future research could explore whether using the most common literature values for debris properties, or the average from DebDaB values, is better than using a value from a nearby glacier. Furthermore, evaluation of energy balance models is usually limited by the number of measurements available. The data provided by DebDaB could be used to re-evaluate remote sensing efforts (Miles et al., 2017; Chambers et al., 2020; Rounce et al., 2021) more broadly and understand their wider applicability and expected uncertainties.

DebDaB can be used to assess the sensitivity of glacier melt modelling to varying debris properties. Previous studies have assessed melt model sensitivity using assumed ranges for debris properties, varying values by up to $\pm10\%$ (Reid and Brock, 2010). The variability of debris properties from actual measurements and reported values available in DebDaB allows future research to use more realistic ranges of debris property values in model sensitivity tests (Miles et al., 2022).

Researchers planning field campaigns on debris-covered glaciers can use DebDaB to identify gaps in current datasets and prioritise regions or glaciers that have not been thoroughly studied. By leveraging existing debris property data, field campaigns can be more efficiently designed, focusing on collecting missing or complementary data to fill the gaps identified from DebDaB. Moreover, campaigns on previously monitored glaciers could be repeated and compared to existing data to understand broad temporal changes and trends in properties such as debris thickness and surface roughness, which can have implications for the non-linear response of glacier evolution to ongoing climate change.

Recent efforts have estimated spatially distributed debris thickness from remote sensing data by inverting sub-debris melt models or surface temperature data (Rounce et al., 2021). Distributed surface roughness estimates have also been obtained from digital elevation models (Miles et al., 2017; Chambers et al., 2020). For both, evaluation is usually limited by the number of measurements available. The data available in DebDaB could be used to re-evaluate remote sensing efforts more broadly and understand their wider applicability and expected uncertainties.

DebDaB's coverage across multiple glaciers in various regions allows for comparative studies of debris properties on a regional and global scale. The dataset could be used to explore regional differences in debris characteristics and their influence on glacier melt as more data become available. When more fully populated, the database could form the basis for investigating links between different debris parameters. Such analyses can provide insights into how different environmental conditions, as well as geology and glacier morphology, can shape debris properties on glaciers.

5.2 Limitations

The main limitations of DebDaB come from potential sampling biases and an unbalanced spatial coverage. Some regions, such as Central Europe and South Asia are well sampled with data from at least 10 different glaciers, while other highly glacierised regions such as the Andes or Alaska only have data from 4 and 3 glaciers, respectively. There are also many RGI regions for which no data are available (3, 5, 8, 9, 10, 19, and 20), and some glaciers or regions for which only one data entry is

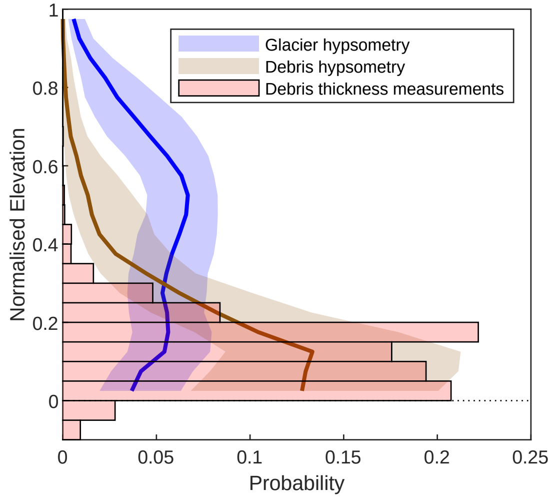

Figure 5. Glacier hypsometry vs elevation of the debris thickness measurements in DebDaB. Hypsometry is based on RGI 6.0 (RGI Consortium, 2017). Shaded areas show interquartile ranges and solid lines the medians of the normalised hypsometries of all glaciers with debris thickness measurements. Note that negative values in normalised elevation for debris thickness measurements may be due to inaccuracies in the delineation of the debris cover outlines used (see text). The debris thickness measurements histogram is based on 5,756 measurements.

available (Caucasus and Middle East). It is therefore difficult to assess whether measurements on those sampled glaciers are representative of their wider regions or not. Furthermore, the initial effort to compile DebDaB did not include a community-wide call for data submissions, biassing data inclusion towards open data sources, as well as submissions by the authors and their immediate networks.

Debris thickness is the property with most spatial and temporal representation in DebDaB. Some regional differences are apparent, for instance between South Asia, showing consistently thicker debris, and Central Europe, showing consistently thinner debris. However, it could also be that thinner debris areas in South Asia are more inaccessible due to their high elevation compared to Central Europe. Figure 5 shows the overall representativeness of debris thickness measurements considering the hypsometry of the debris and of the glaciers in DebDaB. Using a 30 m resolution digital elevation model, the glacier outlines from RGI 6.0, and the debris outlines from Scherler et al. (2018), Figure 5 compares debris hypsometry, glacier hypsometry, and the altitudinal distribution of debris thickness measurements. It shows that debris may already be present on the upper 50% of glacier elevations (>0.5 of normalised elevations in Figure 5), is most prominent on the lower 40% of glacier elevation ranges, and peaks on the lowest 20% of the elevation ranges. The debris thickness measurements from DebDaB, however, are mostly located on the lower 20% part of the glacier elevations, and almost no debris thickness measurements are collected above the lower 30% of glaciers. Consequently, these results highlight that there is a lack of data available for the middle segments of glaciers. The middle glacier areas are usually more inaccessible areas where elevation, surface topography or crevassing might pose problems, but may also present a large sampling bias, as these higher areas closer to the debris-free glacier are usually areas with thinner debris where ablation of ice may be enhanced (e.g., Figure 3). Meanwhile, on the lower portion of the glacier, the upper quantiles of actual debris thickness may also be under-estimated given the inability to manually excavate debris due to large clast sizes or infilling of excavation pits beyond a given depth (McCarthy, 2018). Similar conclusions can be obtained from the elevation distribution of thermal conductivity and surface roughness measurements (Figures A3 and A4), although the number of measurements is much lower.

Interestingly, Figure 5 shows the hypsometry of debris thickness measurements may be below the minimum glacier elevation according to the debris cover outlines from Scherler et al. (2018). This makes the elevation of those measurements when normalised to the glacier elevation negative (i.e., below the glacier minimum). The minimum and maximum glacier elevations extracted from the DEM used here correlate almost perfectly to those in the metadata of RGI 6.0 (Figure A2), which suggests that the DEM used is not the cause of the negative normalised elevations. Instead, these may be due to inaccuracies in the delineation of the debris cover outlines, showing that some glaciers may extend beyond the published outlines on RGI 6.0. Indeed, the delineation of debris-covered glaciers remains a major challenge for the remote sensing community (Racoviteanu et al., 2022). For some older debris thickness measurements, it could also be that the elevation at which the debris thickness measurement was taken in the past is now glacier-free due to glacier retreat.

As discussed in Sect. 4.3, DebDaB contains values of debris properties measured, derived and estimated using a number of approaches, which should be considered when comparing values. It is increasingly apparent that different approaches can lead to largely varying estimates of thermal conductivity and surface roughness even when applied to the same sites (Melo Velasco et al., 2024). Even simple measurement such as manual excavation to determine debris thickness might differ for distinct data collectors. More systematic intercomparisons of methods to derive debris properties seem thus important, and DebDaB can offer the baseline data for such intercomparisons.

Finally, despite the effort to collate as much detailed data as possible, some metadata, notes, and details on sampling and measurements were not available for inclusion in DebDaB. Despite the data curation and quality control, some data may still have inaccuracies or incomplete information or notes on the data collection procedure.

5.3 Future development of DebDaB

The aim of DebDaB is for it to keep evolving and being updated as more data of supraglacial debris properties become available, making it an up-to-date central repository for research on debris-covered glaciers and the potential applications outlined above. We suggest the scientific community submit new data entries to DebDaB, using standard templates for each type of supraglacial debris data, which are already included in the repository. These data can then be included in future updated versions of DebDaB. In addition to continuing to maintain DebDaB and ensuring its availability to the community, we envision the following efforts to update and improve DebDaB in the coming years:

- We will undertake a community call for data submissions to the database. This will include specific data requests from some known data sources, as well as a Cryolist call and broad advertising at relevant conferences.

- We will migrate the database from RGI6.0 to RGI7.0 glacier identifications, for consistency with current standards.

- We will consider the inclusion of other debris parameters, as requested by the community. This could include other physical parameters for which few measurements currently exist, such as water content, predominant lithology, grain size distribution, internal debris layer temperatures, or possibly empirical parameters (e.g., critical thickness or effective thickness) that may be useful for other models.
- We will consider the inclusion of data from debris-covered glaciers in Greenland and Antarctica, if available.
- We will seek to link with efforts by the Debris Covered Glaciers Working Group (DCGWG) from the International Association of Cryospheric Sciences (IACS) to host raw datasets (e.g., meteorological data, thermistor data, UAV, etc), and to reprocess those data according to new methods, for inclusion in DebDaB.
- We will support efforts to homogenise debris parameter measurement methods, enabling improved annotation and categorisation of data entries within DebDaB.

5.4 Priorities for future measurements

DebDaB shows that despite the tremendous progress with data collection on debris-covered glaciers, considerably more measurements are needed to complement the existing dataset and to improve the aforementioned sampling biases and representativity of measurements. Nearly 10,000 debris thickness measurements are included within DebDaB but these are still limited to relatively few (<100) glaciers, and are not representative of the global distribution of supraglacial debris. As seen in Figure 1, areas with prominent debris cover, such as North America and South America, are highly undersampled. Future debris thickness measurement efforts must include, if possible, measurements from the middle and upper reaches of the debris-covered areas of glaciers, aiming to cover the full elevation range of debris, on glaciers that have not been sampled before, or at similar locations to previous measurements to focus on the temporal evolution of debris thickness. Mitigation of the undersampling of very thick debris areas might be achieved through ground-penetrating radar and ice cliff exposure surveys (Nicholson et al., 2018).

DebDaB contains about 150 entries for debris thermal conductivity and aerodynamic surface roughness length each. Our literature review highlighted that most modelling studies have used literature values from one study (Brock et al., 2010). Interestingly, the value of thermal conductivity of Brock et al. (2010) is similar to the central value of measurement entries in DebDaB. This highlights the need for more in situ measurements of these properties, although the variability of methods used to derive these properties undermine the comparability of values between sites and even studies. Using the same measured data with different methods can lead to substantial differences in the derived property values, and the established methods may be difficult to implement successfully at some sites (Melo Velasco et al., 2024). For energy balance modelling, the choice of method for thermal conductivity has proven to be more critical than for aerodynamic surface roughness length (Rounce et al., 2015; Miles et al., 2022; Melo Velasco et al., 2024).

The other debris properties within DebDaB have even fewer measurements, so any additional measurements are useful to understand how variable these properties may be. In some cases, these values can be supported by remote sensing efforts (Racoviteanu et al., 2022). One parameter of particular note is broadband surface albedo, for which DebDaB only includes effective values reported from automatic weather stations and literature. Albedo can also be inferred from satellite remote sensing, given the appropriate bihemispheric reflectance distribution function. However, for this physical property, as for thermal conductivity and surface roughness, it is important to recall that the value can vary temporally. As such, future measurements are needed to assess the temporal (not only spatial) variability of physical properties (Quincey et al., 2017).

6 Conclusions

DebDaB is an open-access central repository database that compiles supraglacial debris layer properties from various sources, and that will be updated as more data become available. It is a database for the scientific community to refer to for a variety of applications related to debris-covered glaciers.

There is considerable variability in the number of measurements per debris property, as well as their range of values, regionally and per glacier. Some regions, such as South Asia East and West, show consistently thicker debris than other regions, such as Central Europe or Alaska, although this could be due to sampling biases. DebDaB also enables the production of an updated multi-glacier simplified Østrem curve, in the form of a rational curve depicting the declining limb of melt with debris thickness, based on observations from many glaciers (currently 19), supporting the general understanding of melt reduction under thicker debris layers.

Despite the comprehensive nature of the dataset, there are gaps in regional coverage and in the measurement of certain debris properties, especially at higher glacier elevations where thinner debris layers are likely present. Sampling biases are present in DebDaB and should be taken into account when using the dataset, as well as for prioritising future measurements of debris properties.

7 Data availability

The Debris Database (DebDaB) is publicly available on Zenodo at https://doi.org/10.5281/zenodo.14224835 (Groeneveld et al., 2025). The dataset is organised in a spreadsheet with a separate tab for each debris property (debris thickness and sub-debris ablation, thermal conductivity, surface roughness, albedo, emissivity and porosity). Each tab has one row per data entry. All data entries provide (where possible) a citation, a DOI, a glacier name and RGI identifier, a date, coordinates and elevation of the measurement, the debris property value, an uncertainty range, the measurement method, measurements notes, and quality control flags for the date and for the location of the measurements. More detailed information can be found in the metadata file in the repository.

DebDaB data users should cite this data descriptor manuscript (Fontrodona-Bach et al., 2025), the DebDaB zenodo repository (Groeneveld et al., 2025), as well as the original data sources when using the database, given that DebDaB is mostly a compilation of previously published data. To facilitate the citation of original data sources, each of the data entries in DebDaB contains the corresponding original reference and corresponding DOI.

8 DebDaB data sources

Published literature:

DebDaB (Groeneveld et al., 2025) includes data from the following 172 published literature sources: Adhikary et al. (2000); Anderson and Anderson (2016, 2018); Anderson et al. (2020, 2021); Aubry-Wake (2022); Aubry-Wake et al. (2023); Ayala et al. (2016); Azzoni et al. (2016); Banerjee (2022); Banerjee and Wani (2018); Benn and Lehmkuhl (2000); Benn et al. (2012); Bishop et al. (1998); Bisset et al. (2023); Bocchiola et al. (2015); Bozhinskiy et al. (1986); Brock (1996); Brock et al. (2000, 2006, 2007, 2010); Brock (2019); Brook and Paine (2012); Brook et al. (2013); Buri et al. (2022); Carenzo et al. (2016); Casey and Kääb (2012); CEAZA (2015, 2021); Chambers et al. (2020); Chand and Kayastha (2018, 2021); Collier et al. (2014, 2015); Comitato Ev-K2-CNR (2012); Conway and Rasmussen (2000); Crump et al. (2017); Das et al. (2022); del Gobbo (2017); Dobhal et al. (2013); Drewry (1972); Evatt et al. (2015, 2017); Foster et al. (2012); Fujita and Sakai (2014); Fyffe et al. (2014, 2019, 2020); Fugger et al. (2022); Garg et al. (2022); Gibson et al. (2017); Giese (2019); Giese et al. (2020, 2021); Gök et al. (2022, 2023); Groos et al. (2017); Hagg et al. (2008); Haidong et al. (2006); Han et al. (2015); He et al. (2023); Heimsath and McGlynn (2008); Herreid (2021); Herreid and Pellicciotti (2020); Huang et al. (2017, 2018); Huo et al. (2021); Inoue and Yoshida (1980); Juen et al. (2013); Kääb et al. (2021); Kellerer-Pirklbauer (2008); Khan (1989); Kneib et al. (2022); Kirkbride and Warren (1999); Kirkbride and Deline (2013); Kraaijenbrink et al. (2017); Laha et al. (2023); Lejeune et al. (2013); Lukas et al. (2005); MacPhee et al. (2019); Mattson et al. (1993); Mayer et al. (2010); Mayer and Licciulli (2021); McCarthy (2018); McCarthy et al. (2017, 2022); McPhee et al. (2019); Melo Velasco et al. (2024); Mihalcea et al. (2006, 2008a, b); Miles et al. (2017, 2020, 2022); Minora et al. (2015); Mölg et al. (2019); Moore et al. (2019); Muhammad et al. (2020); Nakawo and Young (1982); Nicholson and Benn (2006, 2013); Nicholson and Stiperski (2020); Nicholson (2018, 2019); Nicholson et al. (2018); Nicholson and Boxall (2020); Nicholson and Mertes (2017); Nield et al. (2013); Østrem (1959); Patel et al. (2016, 2021); Pellicciotti et al. (2019); Pellicciotti and Fontrodona-Bach (2019); Pelto (2000); Petersen et al. (2022); Popovnin and Rozova (2002); Popovnin et al. (2015); Postnikova et al. (2023); Pratap et al. (2015, 2023); Purdie and Fitzharris (1999); Purdie (2005, 2019); Purdie et al. (2018); Puyu et al. (2013); Quincey et al. (2009, 2017); Racoviteanu et al. (2022); Rana et al. (1997); Reid and Brock (2010, 2014); Reid et al. (2012); Rets et al. (2019); Robertson (1988); Rogerson et al. (1986); Röhl (2008); Romshoo et al. (2022, 2024); Rounce and McKinney (2014); Rounce et al. (2015, 2021, 2023); Rowan and Gibson (2020); Rowan et al. (2020, 2021); Schauwecker (2012); Schauwecker et al. (2015); Scherler et al. (2011, 2018); Shah et al. (2019); Sharma et al. (2016); Shaw et al. (2016); Shroder et al. (2000); Shukla and Garg (2019); Sicart et al. (2014); Soncini et al. (2016); Steiner et al. (2015, 2018, 2021); Stewart et al. (2021); Takeuchi et al. (2000); Vincent et al. (2016); Wagnon (2019); Wang et al. (2017); Wei et al. (2010); Westoby et al. (2020); Winter-Billington et al. (2022); Yang et al. (2017); Zhang et al. (2011); Zhao et al. (2023).

According to the authors' understanding of FAIR principles, authors of published literature and published data, that:

– Correct existing data within DebDaB, in case of errors

– Send the raw data from digitised figures

– Submit additional data that was previously unavailable (for example, accurate coordinates or additional data or metadata which is not already available)

will have the right to be added as co-authors on the database in Zenodo. The authors are working to reevaluate their policies to conform to changes or unusual circumstances in authorship contributions, and are happy to involve eager people in the core team.

Previously unpublished:

DebDaB (Groeneveld et al., 2025) includes previously unpublished data from Buri et al. (2014), Kneib et al. (2022), McCarthy et al. (2019, 2020), Miles et al. (2021), Melo Velasco et al. (2023), Petersen et al. (2012), Mishra et al. (2023) and Schmid et al. (2023). See database entries for full details.

DebDaB is open to new data submissions, and therefore future data submissions of previously unpublished data to DebDaB will entail co-authorship on the DebDaB database on Zenodo. Data submissions to DebDaB should be sent to debriscoveredglaciers@ista.ac.at.

Appendix A

Table A1. Coefficients, number of measurements, and R^2 of fitted simplified Østrem curves (rational curves) in Figure 3.

Glacier	c_1	c_2	**Number of measurements**	R^2
BALTORO	4.414	0.16	54	0.55
BARPU	9.368	0.036	104	0.76
EMMONS	4.024	0.275	16	0.46
FOX	7.074	0.102	16	0.88
FRANZ JOSEF	9.515	0.051	10	0.98
GHULKIN	3.599	0.114	6	0.98
HINARCHI	6.892	0.095	21	0.54
HOPER	3.985	0.089	6	0.97
KENNICOTT	6.099	0.066	66	0.73
LIRUNG	3.36	0.015	22	0.38
MIAGE	4.046	0.115	66	0.49
RAKHIOT	10.118	0.056	13	0.79
SATOPANTH	3.43	0.128	965	0.45
SNOW CREEK	7.834	0.025	10	0.91
SPIRE	3.589	0.086	9	0.48
TASMAN	38.019	0.015	28	0.79
TSIJIORE-NOUVE	5.29	0.021	13	0.53
VENEROCOLO	1.586	0.965	8	0.05
ZMUTTGLETSCHER	7.511	0.097	6	0.95
Overall curve	5.621	0.061	1493	0.59

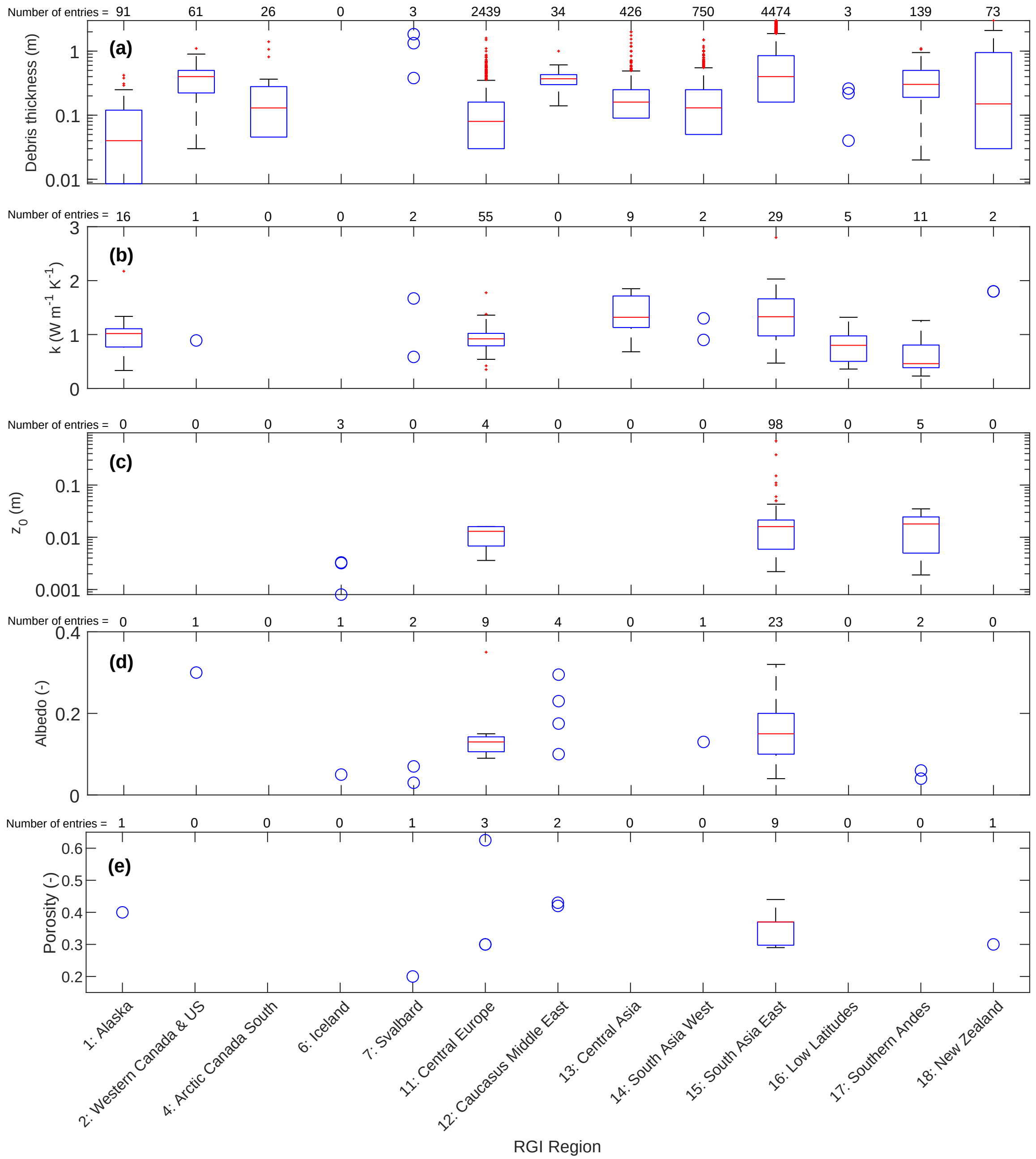

Figure A1. Debris properties in DebDaB averaged per RGI region. A boxplot is shown if there are at least 5 data entries of a property in a region, otherwise individual points are shown. Literature values are not included in this figure.

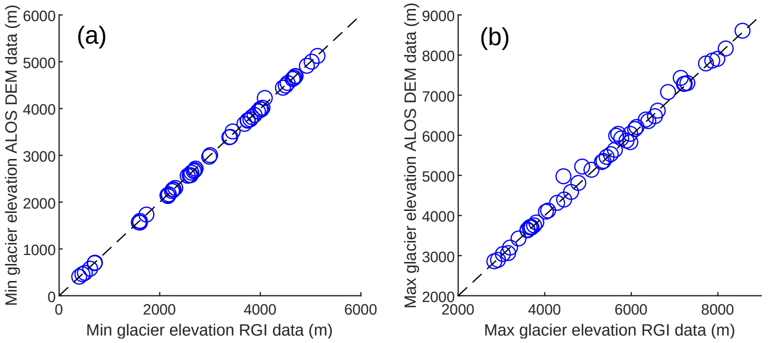

Figure A2. Minimum (left) and maximum (right) glacier elevations on ALOS (DEM) and RGI metadata, per glacier.

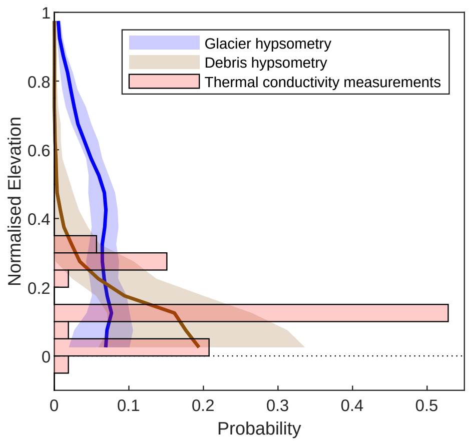

Figure A3. Glacier hypsometry vs elevation of thermal conductivity measurements in DebDaB. Hypsometry is based on RGI 6.0 (RGI Consortium, 2017). Shaded areas show interquartile ranges and solid lines the medians of the normalised. Note thermal conductivity measurements are only 51.

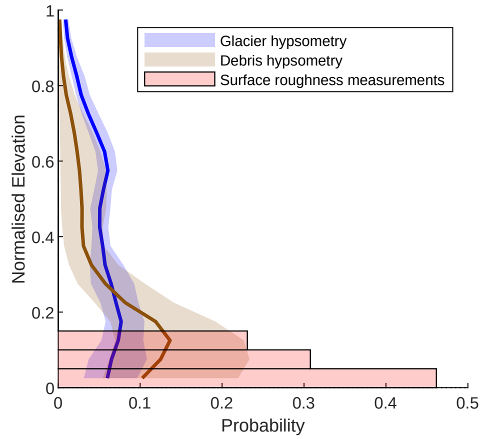

Figure A4. Glacier hypsometry vs elevation of surface roughness length measurements in DebDaB. Hypsometry is based on RGI 6.0 (RGI Consortium, 2017). Shaded areas show interquartile ranges and solid lines the medians of the normalised. Note surface roughness measurements are only 9.

Author contributions. AFB and LG contributed equally to this work. EM, MM, and FP together conceived the database. LG created and compiled the dataset under the guidance of EM, MM, and FP, and contributed to the final stages of the manuscript. AFB curated the data, wrote the manuscript and created most figures. EM, MM, TS, VM and FP provided unpublished data to the dataset and contributed to the manuscript preparation and figures.

Competing interests. The authors declare that they have no conflict of interest.

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