https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

Open Access Earth System Science Data Discussions

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 of supraglacial debris are scarce. Here, we compile a database of measured and reported physical properties and 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% has not been published before. DebDab contains 8,737 data entries for supraglacial debris thickness, of which 1,941 entries also include sub-debris ablation rates, 177 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 83 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 Østrem curves for the 19 glaciers with sufficient debris thickness and ablation data. 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 of the entire manifestations of debris across elevations. DebDab is an openly available dataset that aims at evolving and being updated with 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., 2024).

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

Open Access Earth System Science Data Discussions

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 (1–2 centimetres) enhancing melt through energy absorption and thicker debris reducing it 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). Understanding debris-covered glaciers 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 insufficient 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 measurements can be labour-intensive, economically expensive, or have a large degree of uncertainty in time and space. These measurements often involve a combination of field measurements, laboratory experiments, remote sensing techniques, or model optimisations. Although the development of remote sensing methods to estimate debris properties may be promising (Racoviteanu et al., 2022), these methods require in situ measurements for evaluation. Unfortunately, supraglacial debris 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.

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

Open Access Earth System Science Data Discussions

Here we aim to compile as many existing and new measurements of debris thickness and physical properties, 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 the scientific community for their modelling efforts 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 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 debris (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 due to 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, affecting the 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 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, or 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).

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

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, 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 can 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 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 with increasing debris cover area (Brock et al., 2010; Azzoni et al., 2016), and is therefore important for melt modelling.

3 Data compilation

DebDab targets the supraglacial debris 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 a compilation of 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 properties to which the scientific community can refer to instead of searching over hundreds of research articles. The dataset acknowledges the data source and 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 1.1m.

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 are provided in metres, surface roughness length in metres and thermal conductivity in W m^{-1} K^{-1}. Albedo, emissivity and porosity are dimensionless values ranging between 0 and 1. As detailed data descriptions as possible are included in the database by 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. The dates of the measurements are also included, usually sourced from the methods sections

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

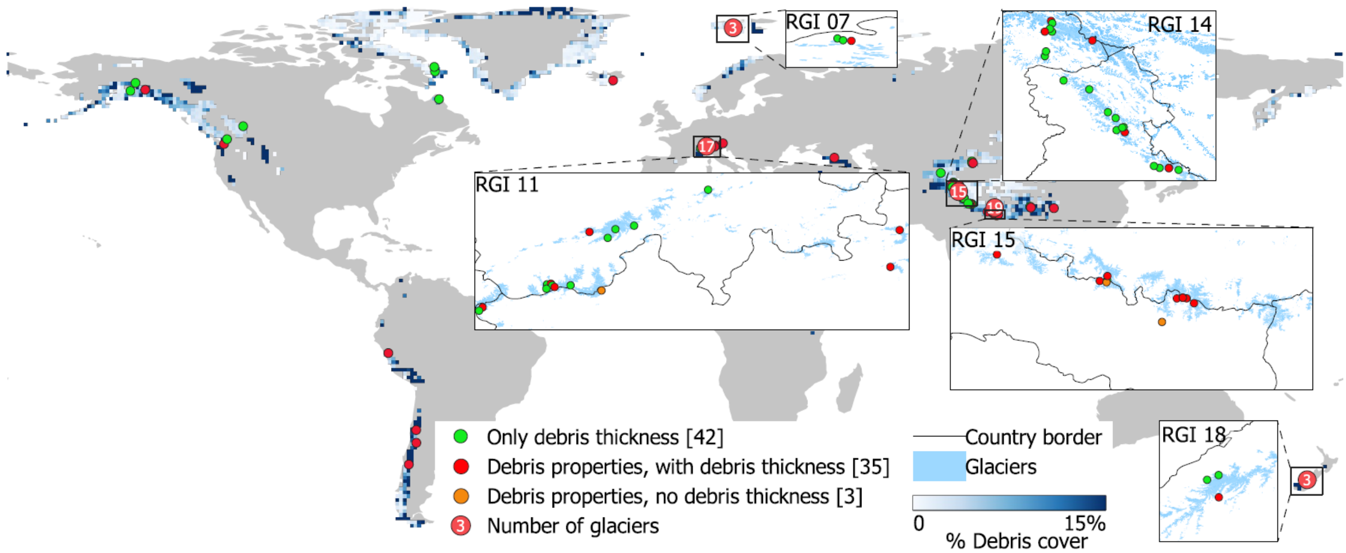

Figure 1. Spatial distribution of the data in DebDab. Points show the locations of all the glaciers with at least one data entry for a debris property. The underlying pixel colours show the percentage of debris cover on glaciers in that pixel area, based on Scherler et al. (2018).

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 are provided without a precise location.

4 DebDab

4.1 Spatial distribution of data

DebDab includes data from 83 glaciers across various regions (Figure 1). The majority of the glaciers with data are located in High Mountain Asia (44) 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 and New Zealand (3) contain fewer data (Figure 1). The majority of the glaciers (76) have debris thickness measurements, with a total of 8,737 measurements in the dataset to date, of which 1,941 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

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

Open Access Earth System Science Data Discussions

177 for thermal conductivity and as low as 37 for porosity (Table 1), although every property has at least 30 glaciers reporting values. Most data entries for debris thickness contain spatial information with latitude, longitude and elevation information, 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.

Table 1. Summary of data entries in DebDab.

DebDab data entries	Total number	With coordinates	With elevation only	Number of glaciers
Debris thickness	8,737	5,375	1,675	74
Sub-debris ablation	1,941	546	1,088	41
Thermal conductivity	177	31	44	30
Surface roughness	160	26	4	28
Albedo	79	2	9	25
Emissivity	59	10	0	27
Porosity	37	11	0	19

4.2 Observed variability of physical properties

Figure 2 and Figure 3 show a high 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 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 regional differences in debris thickness apparent (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). 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.

Along with debris thickness measurements, many glaciers have measurements of sub-debris ablation rates, enabling the fitting of Østrem curves (Østrem, 1959). 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 debris thickness and ablation rates yet, with Østrem curves fitted for 19 glaciers, based entirely on observational data (Figure 4). 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).

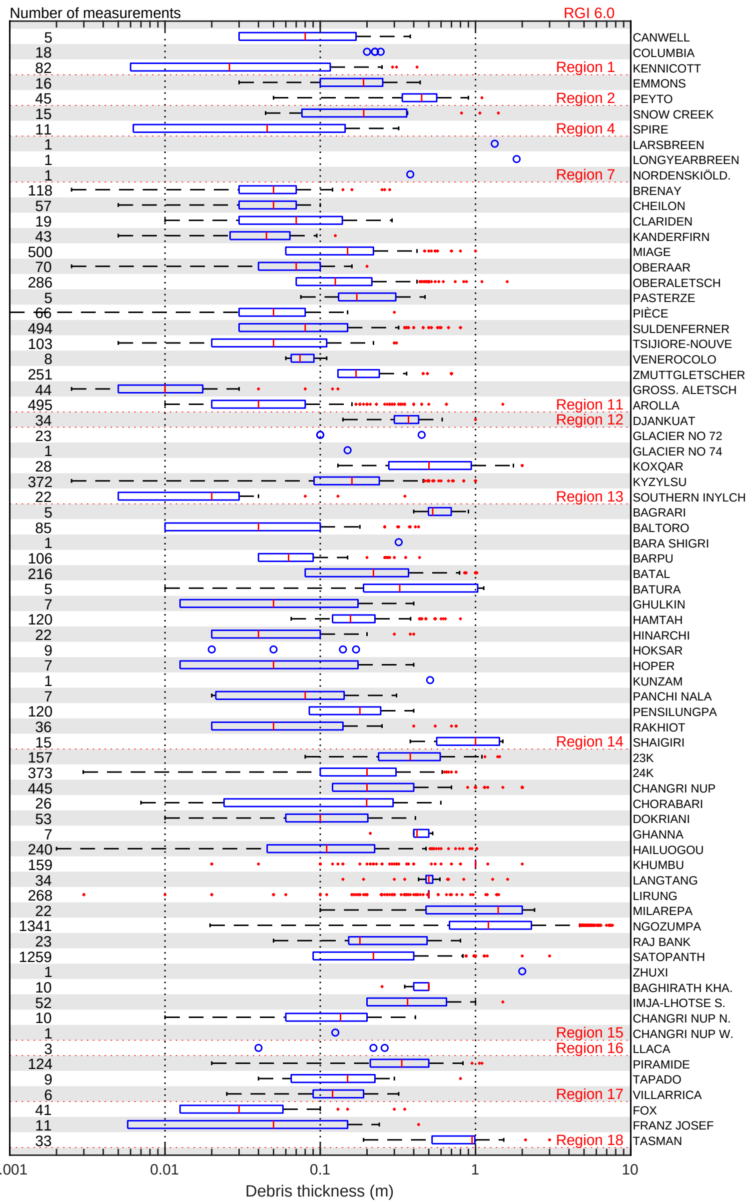

Figure 2. The distribution of debris thickness measurements for each glacier in DebDab. Glaciers are sorted per RGI region (RGI 6.0). The number of debris thickness measurements is shown on the left. Note the logarithmic x-axis scale.

The observed variability of thermal conductivity and surface roughness per glacier is shown in Figure 3, the variability of all other debris properties in DebDab is shown in Figure 5, 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 very similar to the 0.96 W m^{-1} K^{-1} value that (Brock et al., 2010) provide and that is widely used in the literature. However, the range of thermal conductivities is large,

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

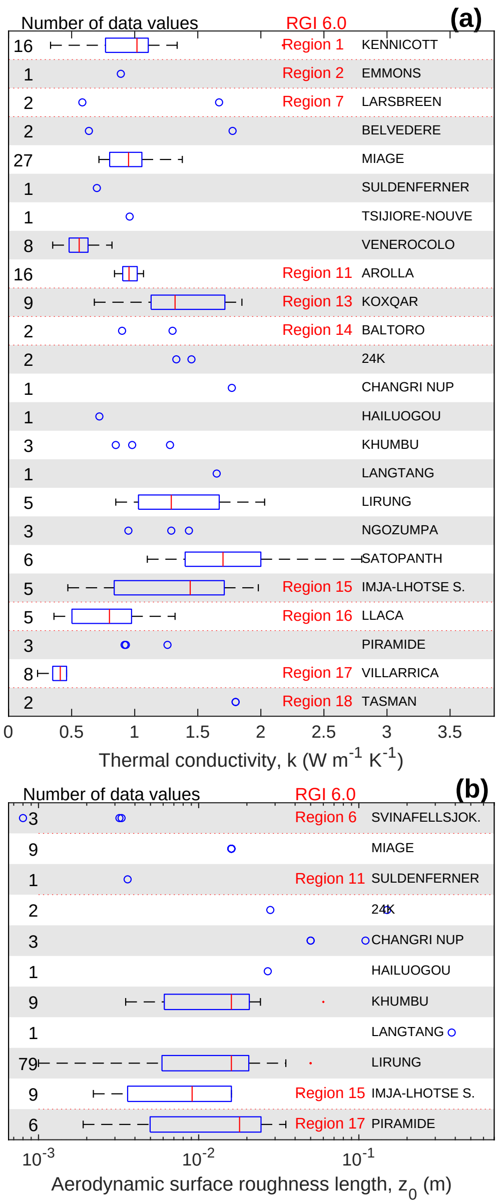

Figure 3. The distribution of thermal conductivity and surface roughness length data values for each glacier in DebDab. Glaciers are sorted per RGI region (RGI 6.0). The number of data entries is shown on the left. Note the logarithmic x-axis scale for surface roughness.

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, 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).

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

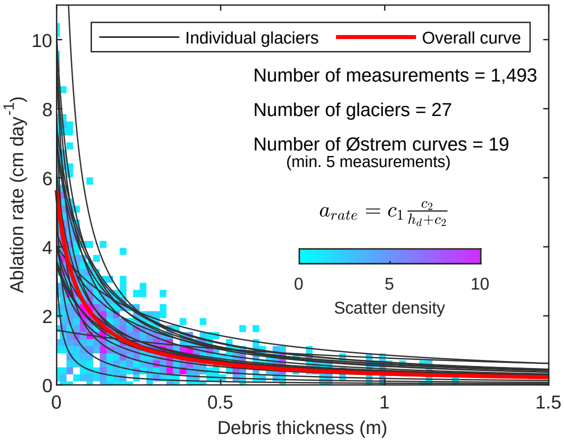

Figure 4. Østrem curves (Østrem, 1959) based on observations of debris thickness and observations of sub-debris ablation rates. All measurements are plotted in the scatter, but Østrem curves are only fitted for the 19 glaciers that have at least five measurements. Equation shows the form of the curve, as in Anderson and Anderson (2016). The fitted parameters and R^2 for each curve are shown in Table A1.

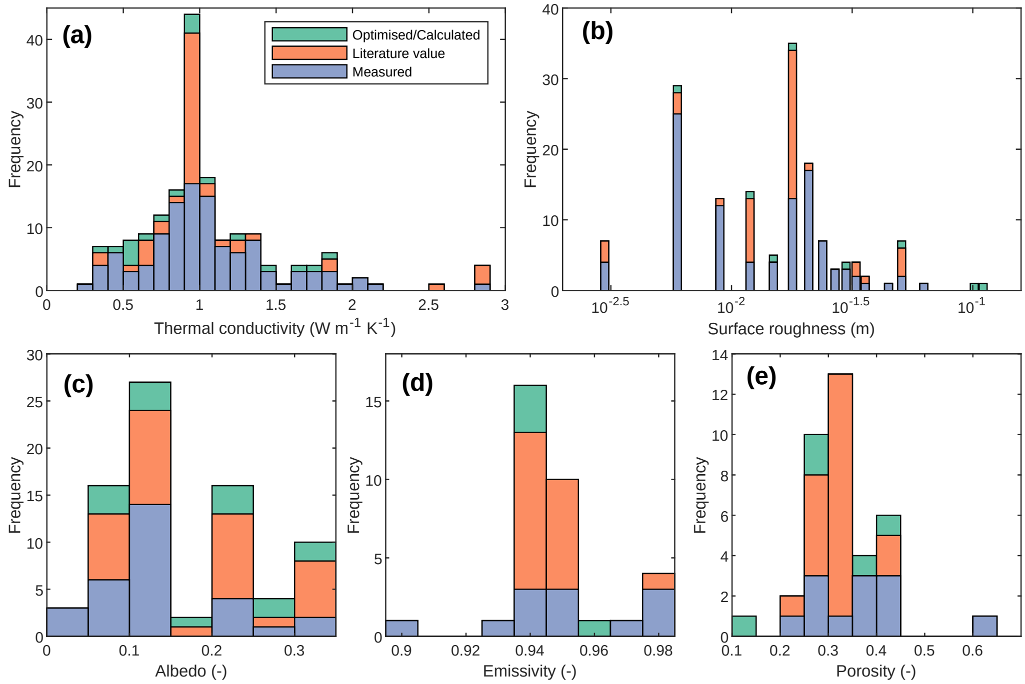

Figure 5. Frequency distributions of the physical properties of debris in DebDab, except debris thickness. Histogram bars are stacked.

The variability of surface roughness length reported values is large, too, 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

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

literature values using the 0.016 m from (Brock et al., 2010) too. 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 common between 0.2 and 0.45, with most literature using values around 0.3 (Figure 5e). 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).

We explore potential links between debris properties in Figure A2. For this, we compare measurements of different debris properties taken at locations not further away than 10 m (arbitrarily chosen) from each other, and try to find a correlation between them. Of the 10 possible correlations, 3 show p-values < 0.05: debris thickness and thermal conductivity, debris thickness and emissivity, and thermal conductivity and emissivity. However, due to the small sample sizes and weak correlations ($R^2 < 0.2$), these results should be interpreted with caution, and no strong inferences can be made about actual relationships between the debris properties at this time.

5 Discussion

5.1 Potential applications

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

The debris properties in DebDab may be used for 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 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, often around ±10% (Reid and Brock, 2010). The

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

variability of debris properties from actual measurements and reported values 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 to understand broad changes in properties such as debris thickness and surface roughness, which can have implications for the non-linear response of glaciers 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 provided by 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 once more data become available. 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 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 6 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 6 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 6), is most prominent on the lower 40% of glacier elevation

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

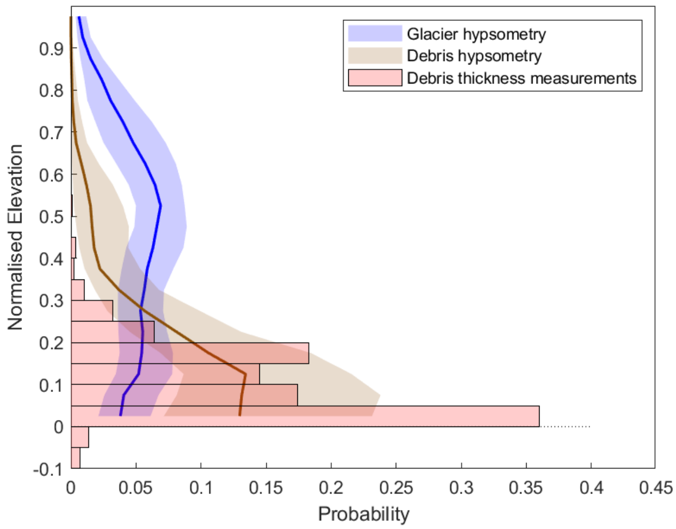

Figure 6. Glacier hypsometry vs elevation of the debris thickness measurements in DebDab. Hypsometry is based on RGI 6.0 (RGI Consortium, 2017). Shaded areas show interquartile ranges and solid lines the medians of the normalised hypsometries of all glaciers with debris thickness measurements. Note that 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.

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. This shows that for the middle segment of the glacier in particular debris thickness measurements are undersampled. These 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 4). 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 A4 and A5), although the number of measurements are much lower.

Interestingly, Figure 6 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 A3), 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.

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

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.

Finally, despite the strong efforts in collecting as much data as possible, and as detailed as possible, some metadata, notes, and details on sampling and measurements have escaped the data collection of 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 to keep evolving and updating 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 on a yearly basis be included into an updated version 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, gran 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 seek to link with efforts by the IACS DCGWG to host raw datasets (e.g. meteodata, 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 categorization 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

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

Open Access Earth System Science Data Discussions

measurement efforts must include, if possible, measurements from the 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., 2006), which coincidentally is a central value to the 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 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. DebDab also enables an updated multi-glacier Østrem curve 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 for any use of the dataset, as well as for prioritising future measurements of debris properties.

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

Open Access Earth System Science Data Discussions

7 Data availability

The Debris Database (DebDab) is publicly available on Zenodo at https://doi.org/10.5281/zenodo.14224835 (Groeneveld et al., 2024). 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., 2024), the DebDab zenodo repository (Groeneveld et al., 2024), 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., 2024) includes data from the following 171 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

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

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).

Authors from published literature that check, verify or update their data on DebDab will become co-authors on the DebDab database on Zenodo.

Previously unpublished:

DebDab (Groeneveld et al., 2024) 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), and Petersen et al. (2012). 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.

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

Appendix A

Table A1. Coefficients, number of measurements, and R^2 of fitted Østrem curves in Figure 4.

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

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

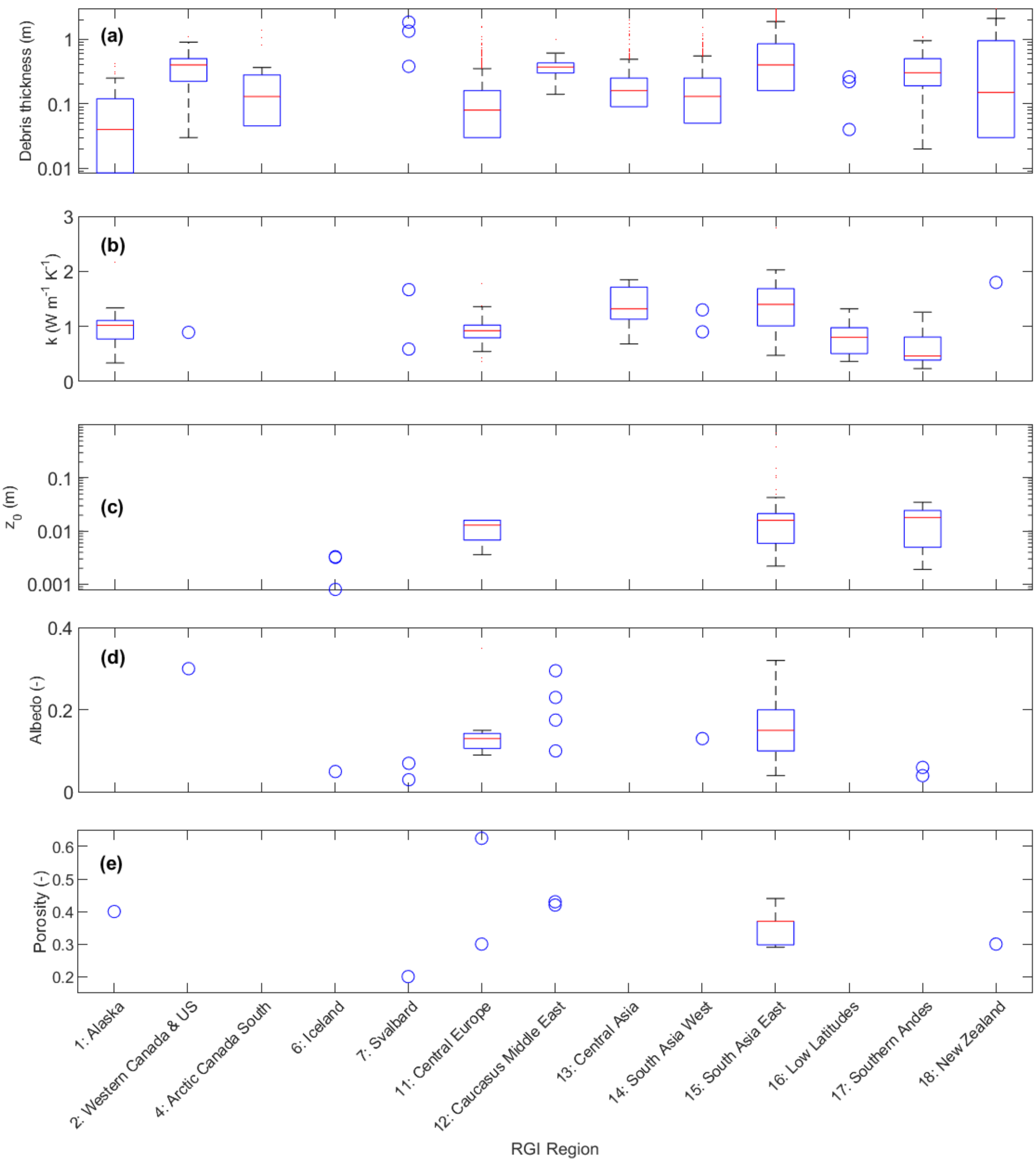

Figure A1. Debris properties in DebDab averaged per RGI region. A boxplot is shown if there are at least 5 data entries of a property in a region, otherwise individual points are shown. Literature values are not included in this figure.

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

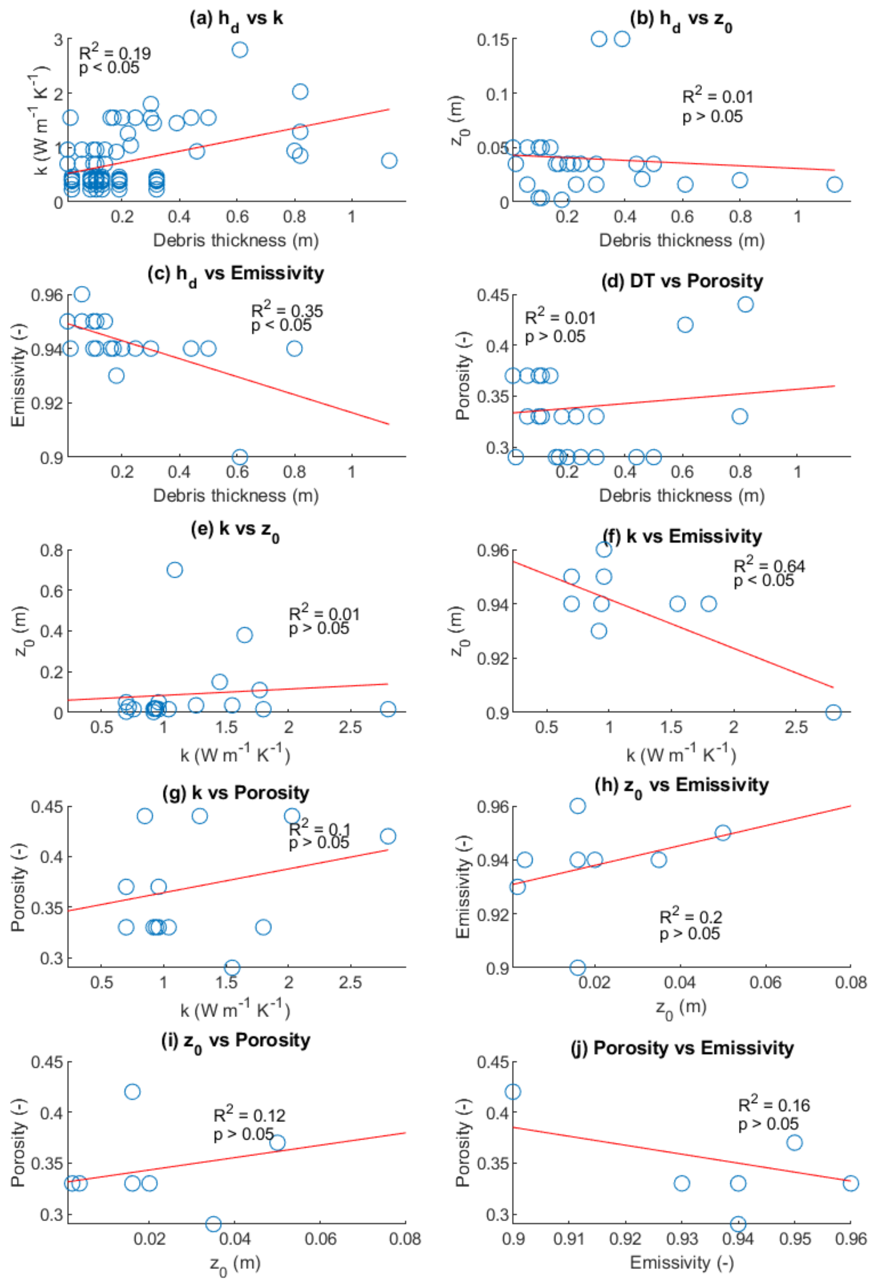

Figure A2. Links between all possible combinations of debris properties. Red lines show the fitted line according to a least squares linear regression model. R^2 and p-value of each correlation are also shown.

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

Open Access Earth System Science Data Discussions

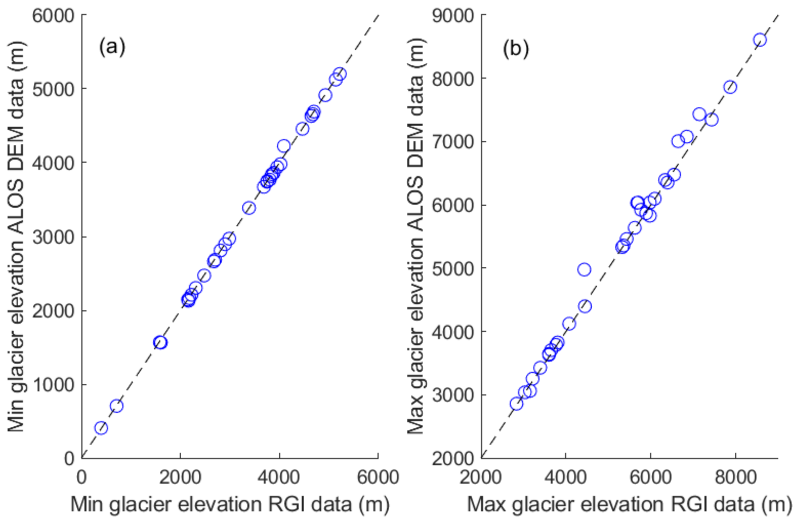

Figure A3. Minimum (left) and maximum (right) glacier elevations on ALOS (DEM) and RGI metadata, per glacier.

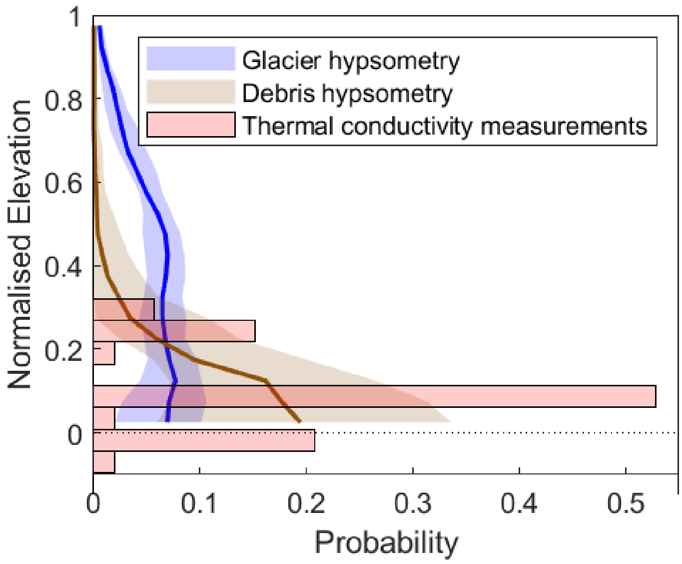

Figure A4. Glacier hypsometry vs elevation of thermal conductivity measurements in DebDab. Hypsometry is based on RGI 6.0 (RGI Consortium, 2017). Shaded areas show interquartile ranges and solid lines the medians of the normalised. Note thermal conductivity measurements are only 51.

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

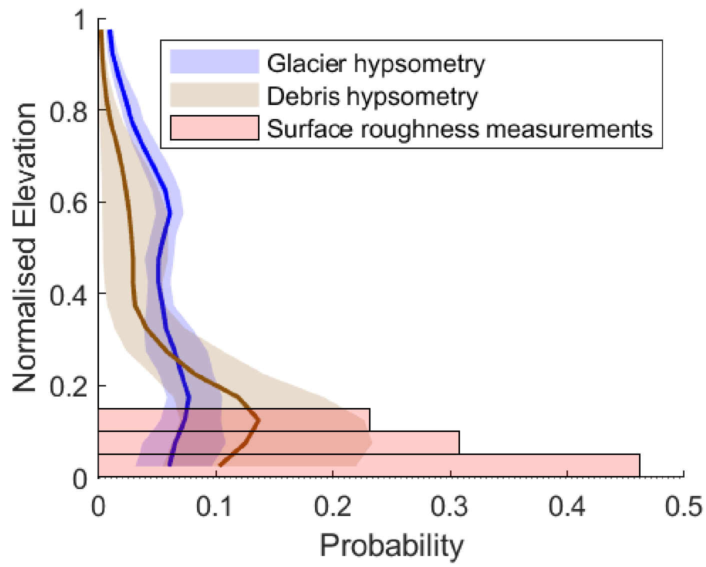

Figure A5. Glacier hypsometry vs elevation of surface roughness length measurements in DebDab. Hypsometry is based on RGI 6.0 (RGI Consortium, 2017). Shaded areas show interquartile ranges and solid lines the medians of the normalised. Note surface roughness measurements are only 9.

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

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.

Acknowledgements. This work was supported by the SNF project RENOIR "Resolving the thickness of debris on Earth's glaciers and its rate of change (RENOIR)", project number 204322.

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme grant agreement No 772751, RAVEN, "Rapid mass losses of debris covered glaciers in High Mountain Asia".

References

Adhikary, S., Nakawo, M., Seko, K., and Shakya, B.: Dust influence on the melting process of glacier ice: experimental results from Lirung Glacier, Nepal Himalayas, IAHS PUBLICATION, 43, 52, 2000.

Anderson, L. S. and Anderson, R. S.: Modeling debris-covered glaciers: response to steady debris deposition, The Cryosphere, 10, 1105–1124, https://doi.org/10.5194/tc-10-1105-2016, 2016.

Anderson, L. S. and Anderson, R. S.: Debris thickness patterns on debris-covered glaciers, Geomorphology, 311, 1–12, https://doi.org/10.1016/j.geomorph.2018.03.014, 2018.

Anderson, L. S., Armstrong, W. H., Anderson, R. S., and Buri, P.: Measurements and datasets from the debris-covered tongue of Kennicott Glacier, Alaska, https://doi.org/10.5281/ZENODO.4118671, publisher: Zenodo Version Number: 1.0.0, 2020.

Anderson, L. S., Armstrong, W. H., Anderson, R. S., and Buri, P.: Debris cover and the thinning of Kennicott Glacier, Alaska: in situ measurements, automated ice cliff delineation and distributed melt estimates, The Cryosphere, 15, 265–282, https://doi.org/10.5194/tc-15-265-2021, 2021.

Aubry-Wake, C.: Debris-cover surface temperature from TIR imagery, Peyto Glacier, http://www.hydroshare.org/resource/d2768996e761412381c2051b99d02c87, 2022.

Aubry-Wake, C., Lamontagne-Hallé, P., Baraër, M., McKenzie, J. M., and Pomeroy, J. W.: Using ground-based thermal imagery to estimate debris thickness over glacial ice: fieldwork considerations to improve the effectiveness, Journal of Glaciology, 69, 353–369, https://doi.org/10.1017/jog.2022.67, 2023.

Ayala, A., Pellicciotti, F., MacDonell, S., McPhee, J., Vivero, S., Campos, C., and Egli, P.: Modelling the hydrological response of debris-free and debris-covered glaciers to present climatic conditions in the semiarid Andes of central Chile, Hydrological Processes, 30, 4036–4058, https://doi.org/10.1002/hyp.10971, 2016.

Azzoni, R. S., Senese, A., Zerboni, A., Maugeri, M., Smiraglia, C., and Diolaiuti, G. A.: Estimating ice albedo from fine debris cover quantified by a semi-automatic method: the case study of Forni Glacier, Italian Alps, The Cryosphere, 10, 665–679, https://doi.org/10.5194/tc-10-665-2016, 2016.

Banerjee, A.: Supplemental materials for preprint: Estimation of the total sub-debris ablation from point-scale ablation data on a debris-covered glacier, https://doi.org/10.17605/OSF.IO/KR2Q7, publisher: [object Object], 2022.

Banerjee, A. and Wani, B. A.: Exponentially decreasing erosion rates protect the high-elevation crests of the Himalaya, Earth and Planetary Science Letters, 497, 22–28, https://doi.org/10.1016/j.epsl.2018.06.001, 2018.

Benn, D., Bolch, T., Hands, K., Gulley, J., Luckman, A., Nicholson, L., Quincey, D., Thompson, S., Toumi, R., and Wiseman, S.: Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards, Earth-Science Reviews, 114, 156–174, https://doi.org/10.1016/j.earscirev.2012.03.008, 2012.

Benn, D. I. and Lehmkuhl, F.: Mass balance and equilibrium-line altitudes of glaciers in high-mountain environments, Quaternary International, 65-66, 15–29, https://doi.org/10.1016/S1040-6182(99)00034-8, 2000.

Bishop, M. P., Shroder, J. F., Hickman, B. L., and Copland, L.: Scale-dependent analysis of satellite imagery for characterization of glacier surfaces in the Karakoram Himalaya, Geomorphology, 21, 217–232, https://doi.org/10.1016/S0169-555X(97)00061-5, 1998.

Bisset, R. R., Nienow, P. W., Goldberg, D. N., Wigmore, O., Loayza-Muro, R. A., Wadham, J. L., Macdonald, M. L., and Bingham, R. G.: Using thermal UAV imagery to model distributed debris thicknesses and sub-debris melt rates on debris-covered glaciers, Journal of Glaciology, 69, 981–996, https://doi.org/10.1017/jog.2022.116, 2023.

Bocchiola, D., Senese, A., Mihalcea, C., Mosconi, B., D'Agata, C., Smiraglia, C., Diolaiuti, G., and others: An ablation model for debris-covered ice: the case study of Venerocolo Glacier (Italian Alps), Geografia Fisica e Dinamica Quaternaria, 38, 113–128, https://doi.org/10.4461/GFDQ.2015.38.11, 2015.

Bozhinskiy, A. N., Krass, M. S., and Popovnin, V. V.: Role of Debris Cover in the Thermal Physics of Glaciers, Journal of Glaciology, 32, 255–266, https://doi.org/10.3189/S0022143000015598, 1986.

Brock, B., Rivera, A., Casassa, G., Bown, F., and Acuña, C.: The surface energy balance of an active ice-covered volcano: Villarrica Volcano, southern Chile, Annals of Glaciology, 45, 104–114, https://doi.org/10.3189/172756407782282372, 2007.

Brock, B. W.: Seasonal and spatial variations in the surface energy-balance of valley glaciers, PhD Thesis, University of Cambridge, 1996.

Brock, B. W.: 5_Miage Data, https://doi.org/10.5281/ZENODO.3050557, 2019.

Brock, B. W., Willis, I. C., and Sharp, M. J.: Measurement and parameterization of albedo variations at Haut Glacier d'Arolla, Switzerland, Journal of Glaciology, 46, 675–688, https://doi.org/10.3189/172756500781832675, 2000.

Brock, B. W., Willis, I. C., and Sharp, M. J.: Measurement and parameterization of aerodynamic roughness length variations at Haut Glacier d'Arolla, Switzerland, Journal of Glaciology, 52, 281–297, https://doi.org/10.3189/172756506781828746, 2006.

Brock, B. W., Mihalcea, C., Kirkbride, M. P., Diolaiuti, G., Cutler, M. E. J., and Smiraglia, C.: Meteorology and surface energy fluxes in the 2005–2007 ablation seasons at the Miage debris-covered glacier, Mont Blanc Massif, Italian Alps, Journal of Geophysical Research: Atmospheres, 115, 2009JD013 224, https://doi.org/10.1029/2009JD013224, 2010.

Brook, M., Hagg, W., and Winkler, S.: Debris cover and surface melt at a temperate maritime alpine glacier: Franz Josef Glacier, New Zealand, New Zealand Journal of Geology and Geophysics, 56, 27–38, https://doi.org/10.1080/00288306.2012.736391, 2013.

Brook, M. S. and Paine, S.: Ablation of ice-cored moraine in a humid, maritime climate: fox glacier, new zealand, Geografiska Annaler: Series A, Physical Geography, 94, 339–349, https://doi.org/10.1111/j.1468-0459.2011.00442.x, 2012.

Buri, P., Truffer, M., Fochesatto, J., and Aschwanden, A.: Automatic weather station data from the debris-covered Kennicott Glacier, Alaska (May-Aug 2019), https://doi.org/10.5281/zenodo.6424158, 2022.

Carenzo, M., Pellicciotti, F., Mabillard, J., Reid, T., and Brock, B.: An enhanced temperature index model for debris-covered glaciers accounting for thickness effect, Advances in Water Resources, 94, 457–469, https://doi.org/10.1016/j.advwatres.2016.05.001, 2016.

Casey, K. and Kääb, A.: Estimation of Supraglacial Dust and Debris Geochemical Composition via Satellite Reflectance and Emissivity, Remote Sensing, 4, 2554–2575, https://doi.org/10.3390/rs4092554, 2012.

CEAZA: Modelación del balance de masa y descarga de agua en glaciares del Norte Chico y Chile Central, Informe Final, Centro de Estudios Avanzados en Zonas Áridas. Ministerio de Obras Públicas, Dirección General de Aguas, Gobierno de Chile, Santiago, https://snia.mop.gob.cl/repositoriodga/handle/20.500.13000/6866, 2015.

CEAZA: Apoyo para el Monitoreo de Detalle Intensivo del Glaciar Tapado, Región de Coquimbo, Macrozona Norte, 2020-2021, Informe Final, Centro de Estudios Avanzados en Zonas Áridas. Ministerio de Obras Públicas, Dirección General de Aguas, Gobierno de Chile, Santiago, https://snia.mop.gob.cl/repositoriodga/bitstream/handle/20.500.13000/125424/GLA5935.PDF?sequence=1, 2021.

Chambers, J. R., Smith, M. W., Quincey, D. J., Carrivick, J. L., Ross, A. N., and James, M. R.: Glacial Aerodynamic Roughness Estimates: Uncertainty, Sensitivity, and Precision in Field Measurements, Journal of Geophysical Research: Earth Surface, 125, e2019JF005 167, https://doi.org/10.1029/2019JF005167, 2020.

Chand, M. B. and Kayastha, R. B.: Study of thermal properties of supraglacial debris and degree-day factors on Lirung Glacier, Nepal, Sciences in Cold and Arid Regions, 10, 357–368, https://doi.org/10.3724/SP.J.1226.2018.00357, 2018.

Chand, M. B. and Kayastha, R. B.: Debris temperature and ablation measurements from the Lirung Debris-Covered Glacier (2013-2014), Nepal, https://doi.org/10.5281/ZENODO.4446387, 2021.

Collier, E., Nicholson, L. I., Brock, B. W., Maussion, F., Essery, R., and Bush, A. B. G.: Representing moisture fluxes and phase changes in glacier debris cover using a reservoir approach, The Cryosphere, 8, 1429–1444, https://doi.org/10.5194/tc-8-1429-2014, 2014.

Collier, E., Maussion, F., Nicholson, L. I., Mölg, T., Immerzeel, W. W., and Bush, A. B. G.: Impact of debris cover on glacier ablation and atmosphere–glacier feedbacks in the Karakoram, The Cryosphere, 9, 1617–1632, https://doi.org/10.5194/tc-9-1617-2015, 2015.

Comitato Ev-K2-CNR: Plan de Accion para la Conservación de Glaciares ante el Cambio Climático, Informe Final, Volumen II, Ministerio de Obras Públicas, Dirección General de Aguas, Unidad de Glaciología y Nieves, Gobierno de Chile, Santiago, https://www.researchgate.net/publication/292145572_PLAN_DE_ACCION_PARA_LA_CONSERVACION_DE_GLACIARES_ANTE_EL_CAMBIO_CLIMATICO_Vol_II, 2012.

Conway, H. and Rasmussen, L.: Summer temperature profiles within supraglacial debris on Khumbu Glacier, Nepal, IAHS-AISH Publication, 264, 2000.

Crump, S. E., Anderson, L. S., Miller, G. H., and Anderson, R. S.: Interpreting exposure ages from ice-cored moraines: a Neoglacial case study on Baffin Island, Arctic Canada, Journal of Quaternary Science, 32, 1049–1062, https://doi.org/10.1002/jqs.2979, 2017.

Das, S., Sharma, M. C., and Murari, M. K.: Spatially heterogeneous glacier elevation change in the Jankar Chhu Watershed, Lahaul Himalaya, India derived using ASTER DEMs, Geocarto International, 37, 17 799–17 825, https://doi.org/10.1080/10106049.2022.2136254, 2022.

del Gobbo, C.: Debris thickness investigation of Solda glacier, southern Rhaetian Alps, Italy: Methodological considerations about the use of ground penetrating radar over a debris-covered glacier, Master's thesis, University of Innsbruck, Innsbruck, 2017.

Dobhal, D., Mehta, M., and Srivastava, D.: Influence of debris cover on terminus retreat and mass changes of Chorabari Glacier, Garhwal region, central Himalaya, India, Journal of Glaciology, 59, 961–971, https://doi.org/10.3189/2013JoG12J180, 2013.

Drewry, D. J.: A Quantitative Assessment of Dirt-Cone Dynamics, Journal of Glaciology, 11, 431–446, https://doi.org/10.3189/S0022143000022383, 1972.

Evatt, G. W., Abrahams, I. D., Heil, M., Mayer, C., Kingslake, J., Mitchell, S. L., Fowler, A. C., and Clark, C. D.: Glacial melt under a porous debris layer, Journal of Glaciology, 61, 825–836, https://doi.org/10.3189/2015JoG14J235, 2015.

Evatt, G. W., Mayer, C., Mallinson, A., Abrahams, I. D., Heil, M., and Nicholson, L.: The secret life of ice sails, Journal of Glaciology, 63, 1049–1062, https://doi.org/10.1017/jog.2017.72, 2017.

Foster, L., Brock, B., Cutler, M., and Diotri, F.: A physically based method for estimating supraglacial debris thickness from thermal band remote-sensing data, Journal of Glaciology, 58, 677–691, https://doi.org/10.3189/2012JoG11J194, 2012.

Fugger, S., Fyffe, C. L., Fatichi, S., Miles, E., McCarthy, M., Shaw, T. E., Ding, B., Yang, W., Wagnon, P., Immerzeel, W., Liu, Q., and Pellicciotti, F.: Understanding monsoon controls on the energy and mass balance of glaciers in the Central and Eastern Himalaya, The Cryosphere, 16, 1631–1652, https://doi.org/10.5194/tc-16-1631-2022, 2022.

Fujita, K. and Sakai, A.: Modelling runoff from a Himalayan debris-covered glacier, Hydrology and Earth System Sciences, 18, 2679–2694, https://doi.org/10.5194/hess-18-2679-2014, 2014.

Fyffe, C., Brock, B., Kirkbride, M., Mair, D., Arnold, N., Smiraglia, C., Diolaiuti, G., and Diotri, F.: Do debris-covered glaciers demonstrate distinctive hydrological behaviour compared to clean glaciers?, https://doi.org/10.17863/CAM.36254, publisher: Elsevier BV, 2019.

Fyffe, C. L., Reid, T. D., Brock, B. W., Kirkbride, M. P., Diolaiuti, G., Smiraglia, C., and Diotri, F.: A distributed energy-balance melt model of an alpine debris-covered glacier, Journal of Glaciology, 60, 587–602, https://doi.org/10.3189/2014JoG13J148, 2014.

https://doi.org/10.5194/essd-2024-559
Preprint. Discussion started: 16 January 2025

Fyffe, C. L., Woodget, A. S., Kirkbride, M. P., Deline, P., Westoby, M. J., and Brock, B. W.: Processes at the margins of supraglacial debris cover: Quantifying dirty ice ablation and debris redistribution, Earth Surface Processes and Landforms, 45, 2272–2290, https://doi.org/10.1002/esp.4879, 2020.

Garg, P. K., Garg, S., Yousuf, B., Shukla, A., Kumar, V., and Mehta, M.: Stagnation of the Pensilungpa glacier, western Himalaya, India: causes and implications, Journal of Glaciology, 68, 221–235, https://doi.org/10.1017/jog.2021.84, 2022.

Gibson, M. J., Glasser, N. F., Quincey, D. J., Mayer, C., Rowan, A. V., and Irvine-Fynn, T. D.: Temporal variations in supraglacial debris distribution on Baltoro Glacier, Karakoram between 2001 and 2012, Geomorphology, 295, 572–585, https://doi.org/10.1016/j.geomorph.2017.08.012, 2017.

Giese, A., Boone, A., Wagnon, P., and Hawley, R.: Incorporating moisture content in surface energy balance modeling of a debris-covered glacier, The Cryosphere, 14, 1555–1577, https://doi.org/10.5194/tc-14-1555-2020, 2020.

Giese, A., Arcone, S., Hawley, R., Lewis, G., and Wagnon, P.: Detecting supraglacial debris thickness with GPR under suboptimal conditions, Journal of Glaciology, 67, 1108–1120, https://doi.org/10.1017/jog.2021.59, 2021.

Giese, A. L.: Heat Flow, Energy Balance, and Radar Propagation: Porous Media Studies Applied to the Melt of Changri Nup Glacier, Nepal Himalaya, Doctoral dissertation, Dartmouth College, Hanover, 2019.

Groeneveld, L., Fontrodona-Bach, A., Miles, E., McCarthy, M., Shaw, T., Melo Velasco, V., and Pellicciotti, F.: DebDab: A database of supraglacial debris thickness and physical properties (Version v1), https://doi.org/10.5281/zenodo.14224835, 2024.

Groos, A. R., Mayer, C., Smiraglia, C., Diolaiuti, G., and Lambrecht, A.: A first attempt to model region-wide glacier surface mass balances in the Karakoram: findings and future challenges, Geografia fisica e dinamica quaternaria, 40, 137–159, publisher: Comitato Glaciologico Italiano, 2017.

Gök, D., Scherler, D., and Anderson, L. S.: High-resolution debris cover mapping using UAV-derived thermal imagery, https://doi.org/10.5880/GFZ.3.3.2022.003, language: en, 2022.

Gök, D. T., Scherler, D., and Anderson, L. S.: High-resolution debris-cover mapping using UAV-derived thermal imagery: limits and opportunities, The Cryosphere, 17, 1165–1184, https://doi.org/10.5194/tc-17-1165-2023, 2023.

Hagg, W., Mayer, C., Lambrecht, A., and Helm, A.: Sub-debris melt rates on southern inylchek glacier, central tian shan, Geografiska Annaler: Series A, Physical Geography, 90, 55–63, https://doi.org/10.1111/j.1468-0459.2008.00333.x, 2008.

Haidong, H., Yongjing, D., and Shiyin, L.: A simple model to estimate ice ablation under a thick debris layer, Journal of Glaciology, 52, 528–536, https://doi.org/10.3189/172756506781828395, 2006.

Han, H.-d., Ding, Y.-j., Liu, S.-y., and Wang, J.: Regimes of runoff components on the debris-covered Koxkar glacier in western China, Journal of Mountain Science, 12, 313–329, https://doi.org/10.1007/s11629-014-3163-5, 2015.

He, Z., Yang, W., Wang, Y., Zhao, C., Ren, S., and Li, C.: Dynamic Changes of a Thick Debris-Covered Glacier in the Southeastern Tibetan Plateau, Remote Sensing, 15, 357, https://doi.org/10.3390/rs15020357, 2023.

Heimsath, A. M. and McGlynn, R.: Quantifying periglacial erosion in the Nepal high Himalaya, Geomorphology, 97, 5–23, https://doi.org/10.1016/j.geomorph.2007.02.046, 2008.

Herreid, S.: What Can Thermal Imagery Tell Us About Glacier Melt Below Rock Debris?, Frontiers in Earth Science, 9, 681 059, https://doi.org/10.3389/feart.2021.681059, 2021.

Herreid, S. and Pellicciotti, F.: The state of rock debris covering Earth's glaciers, Nature Geoscience, 13, 621–627, https://doi.org/10.1038/s41561-020-0615-0, 2020.

Huang, L., Li, Z., Tian, B. S., Han, H. D., Liu, Y. Q., Zhou, J. M., and Chen, Q.: Estimation of supraglacial debris thickness using a novel target decomposition on L-band polarimetric SAR images in the Tianshan Mountains, Journal of Geophysical Research: Earth Surface, 122, 925–940, https://doi.org/10.1002/2016JF004102, 2017.

Huang, L., Li, Z., Han, H., Tian, B., and Zhou, J.: Analysis of thickness changes and the associated driving factors on a debris-covered glacier in the Tienshan Mountain, Remote Sensing of Environment, 206, 63–71, https://doi.org/10.1016/j.rse.2017.12.028, 2018.

Huo, D., Bishop, M. P., and Bush, A. B. G.: Understanding Complex Debris-Covered Glaciers: Concepts, Issues, and Research Directions, Frontiers in Earth Science, 9, 652 279, https://doi.org/10.3389/feart.2021.652279, 2021.

Inoue, J. and Yoshida, M.: Ablation and Heat Exchange over the Khumbu Glacier, Journal of the Japanese Society of Snow and Ice, 41, 26–33, https://doi.org/10.5331/seppyo.41.Special_26, 1980.

Juen, M., Mayer, C., Lambrecht, A., Wirbel, A., and Kueppers, U.: Thermal properties of a supraglacial debris layer with respect to lithology and grain size, Geografiska Annaler: Series A, Physical Geography, 95, 197–209, https://doi.org/10.1111/geoa.12011, 2013.

Kellerer-Pirklbauer, A.: The Supraglacial Debris System at the Pasterze Glacier, Austria: Spatial Distribution, Characteristics and Transport of Debris, Zeitschrift für Geomorphologie, Supplementary Issues, 52, 3–25, https://doi.org/10.1127/0372-8854/2008/0052S1-0003, 2008.

Khan, M. I.: Ablation on Barpu glacier, Karakoram Himalaya, Pakistan: A study of melt processes on a faceted, debris-covered ice surface, Ph.D. thesis, Wilfrid Laurier University, https://scholars.wlu.ca/etd/311, 1989.

Kirkbride, M. P. and Deline, P.: The formation of supraglacial debris covers by primary dispersal from transverse englacial debris bands, Earth Surface Processes and Landforms, 38, 1779–1792, https://doi.org/10.1002/esp.3416, 2013.

Kirkbride, M. P. and Warren, C. R.: Tasman Glacier, New Zealand: 20th-century thinning and predicted calving retreat, Global and Planetary Change, 22, 11–28, https://doi.org/10.1016/S0921-8181(99)00021-1, 1999.

Kneib, M., Miles, E. S., Buri, P., Fugger, S., McCarthy, M., Shaw, T. E., Chuanxi, Z., Truffer, M., Westoby, M. J., Yang, W., and Pellicciotti, F.: Sub-seasonal variability of supraglacial ice cliff melt rates and associated processes from time-lapse photogrammetry, The Cryosphere, 16, 4701–4725, https://doi.org/10.5194/tc-16-4701-2022, 2022.

Kraaijenbrink, P. D. A., Bierkens, M. F. P., Lutz, A. F., and Immerzeel, W. W.: Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers, Nature, 549, 257–260, https://doi.org/10.1038/nature23878, 2017.

Kääb, A., Jacquemart, M., Gilbert, A., Leinss, S., Girod, L., Huggel, C., Falaschi, D., Ugalde, F., Petrakov, D., Chernomorets, S., Dokukin, M., Paul, F., Gascoin, S., Berthier, E., and Kargel, J. S.: Sudden large-volume detachments of low-angle mountain glaciers – more frequent than thought?, The Cryosphere, 15, 1751–1785, https://doi.org/10.5194/tc-15-1751-2021, 2021.

Laha, S., Winter-Billington, A., Banerjee, A., Shankar, R., Nainwal, H., and Koppes, M.: Estimation of ice ablation on a debris-covered glacier from vertical debris-temperature profiles, Journal of Glaciology, 69, 1–12, https://doi.org/10.1017/jog.2022.35, 2023.

Lejeune, Y., Bertrand, J.-M., Wagnon, P., and Morin, S.: A physically based model of the year-round surface energy and mass balance of debris-covered glaciers, Journal of Glaciology, 59, 327–344, https://doi.org/10.3189/2013JoG12J149, 2013.

Lukas, S., Nicholson, L. I., Ross, F. H., and Humlum, O.: Formation, Meltout Processes and Landscape Alteration of High-Arctic Ice-Cored Moraines—Examples From Nordenskiold Land, Central Spitsbergen, Polar Geography, 29, 157–187, https://doi.org/10.1080/789610198, 2005.

MacPhee, J., Ayala, , and MacDonell, S.: 8_Tapado Data, https://doi.org/10.5281/ZENODO.3362402, 2019.

Mattson, L., Gardner, J., and Young, G.: Ablation on Debris Covered Glaciers: An Example from the Rakhiot Glacier, Punjab, Himalaya, in: Snow and Glacier Hydrology, vol. 218, p. 289, International Association of Hydrological Sciences (IAHS), Kathmandu, 1993.

Mayer, C. and Licciulli, C.: The Concept of Steady State, Cyclicity and Debris Unloading of Debris-Covered Glaciers, Frontiers in Earth Science, 9, 710 276, https://doi.org/10.3389/feart.2021.710276, 2021.

Mayer, C., Lambrecht, A., Mihalcea, C., Belò, M., Diolaiuti, G., Smiraglia, C., and Bashir, F.: Analysis of Glacial Meltwater in Bagrot Valley, Karakoram: Based on Short-term Ablation and Debris Cover Observations on Hinarche Glacier, Mountain Research and Development, 30, 169–177, https://doi.org/10.1659/MRD-JOURNAL-D-09-00043.1, 2010.

McCarthy, M., Pritchard, H., Willis, I., and King, E.: Ground-penetrating radar measurements of debris thickness on Lirung Glacier, Nepal, Journal of Glaciology, 63, 543–555, https://doi.org/10.1017/jog.2017.18, 2017.

McCarthy, M., Miles, E., Kneib, M., Buri, P., Fugger, S., and Pellicciotti, F.: Supraglacial debris thickness and supply rate in High-Mountain Asia, Communications Earth & Environment, 3, 269, https://doi.org/10.1038/s43247-022-00588-2, 2022.

McCarthy, M. J.: Quantifying supraglacial debris thickness at local to regional scales, https://doi.org/10.17863/CAM.41172, publisher: Apollo - University of Cambridge Repository, 2018.

McPhee, J., MacDonnel, S., and Shaw, T.: 6_Pirámide Data, https://doi.org/10.5281/ZENODO.3056072, 2019.

Melo Velasco, V., Miles, E. S., McCarthy, M., Shaw, T. E., Fyffe, C. L., Bach, A. F., and Pellicciotti, F.: Inferring Debris Properties on Debris-Covered Glaciers, https://doi.org/10.22541/au.172168451.12963281/v1, 2024.

Mihalcea, C., Mayer, C., Diolaiuti, G., Lambrecht, A., Smiraglia, C., and Tartari, G.: Ice ablation and meteorological conditions on the debris-covered area of Baltoro glacier, Karakoram, Pakistan, Annals of Glaciology, 43, 292–300, https://doi.org/10.3189/172756406781812104, 2006.

Mihalcea, C., Brock, B., Diolaiuti, G., D'Agata, C., Citterio, M., Kirkbride, M., Cutler, M., and Smiraglia, C.: Using ASTER satellite and ground-based surface temperature measurements to derive supraglacial debris cover and thickness patterns on Miage Glacier (Mont Blanc Massif, Italy), Cold Regions Science and Technology, 52, 341–354, https://doi.org/10.1016/j.coldregions.2007.03.004, 2008a.

Mihalcea, C., Mayer, C., Diolaiuti, G., D'Agata, C., Smiraglia, C., Lambrecht, A., Vuillermoz, E., and Tartari, G.: Spatial distribution of debris thickness and melting from remote-sensing and meteorological data, at debris-covered Baltoro glacier, Karakoram, Pakistan, Annals of Glaciology, 48, 49–57, https://doi.org/10.3189/172756408784700680, 2008b.

Miles, E. S., Steiner, J. F., and Brun, F.: Highly variable aerodynamic roughness length (z_0) for a hummocky debris-covered glacier, Journal of Geophysical Research: Atmospheres, 122, 8447–8466, https://doi.org/10.1002/2017JD026510, 2017.

Miles, E. S., Steiner, J. F., Buri, P., Immerzeel, W. W., and Pellicciotti, F.: Controls on the relative melt rates of debris-covered glacier surfaces, Environmental Research Letters, 17, 064 004, https://doi.org/10.1088/1748-9326/ac6966, 2022.

Miles, K. E., Hubbard, B., Irvine-Fynn, T. D., Miles, E. S., Quincey, D. J., and Rowan, A. V.: Hydrology of debris-covered glaciers in High Mountain Asia, Earth-Science Reviews, 207, 103 212, https://doi.org/10.1016/j.earscirev.2020.103212, 2020.

Minora, U., Senese, A., Bocchiola, D., Soncini, A., D'agata, C., Ambrosini, R., Mayer, C., Lambrecht, A., Vuillermoz, E., Smiraglia, C., and Diolaiuti, G.: A simple model to evaluate ice melt over the ablation area of glaciers in the Central Karakoram National Park, Pakistan, Annals of Glaciology, 56, 202–216, https://doi.org/10.3189/2015AoG70A206, 2015.

Moore, P. L., Nelson, L. I., and Groth, T. M. D.: Debris properties and mass-balance impacts on adjacent debris-covered glaciers, Mount Rainier, USA, Arctic, Antarctic, and Alpine Research, 51, 70–83, https://doi.org/10.1080/15230430.2019.1582269, 2019.

Muhammad, S., Tian, L., Ali, S., Latif, Y., Wazir, M. A., Goheer, M. A., Saifullah, M., Hussain, I., and Shiyin, L.: Thin debris layers do not enhance melting of the Karakoram glaciers, Science of The Total Environment, 746, 141 119, https://doi.org/10.1016/j.scitotenv.2020.141119, 2020.

Mölg, N., Bolch, T., Walter, A., and Vieli, A.: Unravelling the evolution of Zmuttgletscher and its debris cover since the end of the Little Ice Age, The Cryosphere, 13, 1889–1909, https://doi.org/10.5194/tc-13-1889-2019, 2019.

Nakawo, M. and Young, G.: Estimate of Glacier Ablation under a Debris Layer from Surface Temperature and Meteorological Variables, Journal of Glaciology, 28, 29–34, https://doi.org/10.3189/S002214300001176X, 1982.

Nicholson, L.: Supraglacial debris thickness data from Ngozumpa Glacier, Nepal, https://doi.org/10.5281/ZENODO.1451560, 2018.

Nicholson, L.: 7_Suldenferner Data, https://doi.org/10.5281/ZENODO.3056524, 2019.

Nicholson, L. and Benn, D. I.: Calculating ice melt beneath a debris layer using meteorological data, Journal of Glaciology, 52, 463–470, https://doi.org/10.3189/172756506781828584, 2006.

Nicholson, L. and Benn, D. I.: Properties of natural supraglacial debris in relation to modelling sub-debris ice ablation, Earth Surface Processes and Landforms, 38, 490–501, https://doi.org/10.1002/esp.3299, 2013.

Nicholson, L. and Boxall, K.: Supraglacial debris thickness measurements from excavation pits at Suldenferner, https://doi.org/10.5281/ZENODO.3711581, 2020.

Nicholson, L. and Mertes, J.: Thickness estimation of supraglacial debris above ice cliff exposures using a high-resolution digital surface model derived from terrestrial photography, Journal of Glaciology, 63, 989–998, https://doi.org/10.1017/jog.2017.68, 2017.

Nicholson, L. and Stiperski, I.: Comparison of turbulent structures and energy fluxes over exposed and debris-covered glacier ice, Journal of Glaciology, 66, 543–555, https://doi.org/10.1017/jog.2020.23, 2020.

Nicholson, L. I., McCarthy, M., Pritchard, H. D., and Willis, I.: Supraglacial debris thickness variability: impact on ablation and relation to terrain properties, The Cryosphere, 12, 3719–3734, https://doi.org/10.5194/tc-12-3719-2018, 2018.

Nield, J. M., Chiverrell, R. C., Darby, S. E., Leyland, J., Vircavs, L. H., and Jacobs, B.: Complex spatial feedbacks of tephra redistribution, ice melt and surface roughness modulate ablation on tephra covered glaciers, Earth Surface Processes and Landforms, 38, 95–102, https://doi.org/10.1002/esp.3352, 2013.

Patel, L. K., Sharma, P., Thamban, M., Singh, A., and Ravindra, R.: Debris control on glacier thinning—a case study of the Batal glacier, Chandra basin, Western Himalaya, Arabian Journal of Geosciences, 9, 309, https://doi.org/10.1007/s12517-016-2362-5, 2016.

Patel, L. K., Sharma, P., Singh, A., Oulkar, S., Pratap, B., and Thamban, M.: Influence of Supraglacial Debris Thickness on Thermal Resistance of the Glaciers of Chandra Basin, Western Himalaya, Frontiers in Earth Science, 9, 706 312, https://doi.org/10.3389/feart.2021.706312, 2021.

Pellicciotti, F. and Fontrodona-Bach, A.: 1_Arolla Data, https://doi.org/10.5281/ZENODO.3047649, 2019.

Pellicciotti, F., Fugger, S., and Miles, E.: 4_Lirung Data, https://doi.org/10.5281/ZENODO.3050327, 2019.

Pelto, M. S.: Mass balance of adjacent debris-covered and clean glacier ice in the North Cascades, Washington, IAHS-AISH Publication, 264, 35–42, https://www.researchgate.net/publication/267966629, 2000.

Petersen, E., Hock, R., Fochesatto, G. J., and Anderson, L. S.: The Significance of Convection in Supraglacial Debris Revealed Through Novel Analysis of Thermistor Profiles, Journal of Geophysical Research: Earth Surface, 127, e2021JF006 520, https://doi.org/10.1029/2021JF006520, 2022.

Popovnin, V. V. and Rozova, A. V.: Influence of Sub-Debris Thawing on Ablation and Runoff of the Djankuat Glacier in the Caucasus, Hydrology Research, 33, 75–94, https://doi.org/10.2166/nh.2002.0005, 2002.

Popovnin, V. V., Rezepkin, A. A., and Tielidze, L. G.: Superficial Moraine Expansion On The Djankuat Glacier Snout Over The Direct Glaciological Monitoring Period, Earth Cryosphere, 19, 79–87, https://www.researchgate.net/publication/326551119, 2015.

Postnikova, T., Rybak, O., Gubanov, A., Zekollari, H., Huss, M., and Shahgedanova, M.: Debris cover effect on the evolution of Northern Caucasus glaciers in the 21st century, Frontiers in Earth Science, 11, 1256 696, https://doi.org/10.3389/feart.2023.1256696, 2023.

Pratap, B., Dobhal, D., Mehta, M., and Bhambri, R.: Influence of debris cover and altitude on glacier surface melting: a case study on Dokriani Glacier, central Himalaya, India, Annals of Glaciology, 56, 9–16, https://doi.org/10.3189/2015AoG70A971, 2015.

Pratap, B., Sharma, P., Patel, L. K., Singh, A. T., Oulkar, S. N., and Thamban, M.: Differential surface melting of a debris-covered glacier and its geomorphological control — A case study from Batal Glacier, western Himalaya, Geomorphology, 431, 108 686, https://doi.org/10.1016/j.geomorph.2023.108686, 2023.

Purdie, H.: Intra-annual Variations in Ablation and Surface Velocity on the lower Fox Glacier, South Westland, New Zealand, Ph.D. thesis, Massey University, http://hdl.handle.net/10179/6733, 2005.

Purdie, H.: 9_Tasman Data, https://doi.org/10.5281/ZENODO.3354105, 2019.

Purdie, H., Anderson, B., Mackintosh, A., and Lawson, W.: Revisiting glaciological measurements on Haupapa/Tasman Glacier, New Zealand, in a contemporary context, Geografiska Annaler: Series A, Physical Geography, 100, 351–369, https://doi.org/10.1080/04353676.2018.1522958, 2018.

Purdie, J. and Fitzharris, B.: Processes and rates of ice loss at the terminus of Tasman Glacier, New Zealand, Global and Planetary Change, 22, 79–91, https://doi.org/10.1016/S0921-8181(99)00027-2, 1999.

Puyu, W., Zhongqin, L., Wenbin, W., Huilin, L., Ping, Z., and Shuang, J.: Changes of six selected glaciers in the Tomor region, Tian Shan, Central Asia, over the past ∼50 years, using high-resolution remote sensing images and field surveying, Quaternary International, 311, 123–131, https://doi.org/10.1016/j.quaint.2013.04.031, 2013.

Quincey, D., Luckman, A., and Benn, D.: Quantification of Everest region glacier velocities between 1992 and 2002, using satellite radar interferometry and feature tracking, Journal of Glaciology, 55, 596–606, https://doi.org/10.3189/002214309789470987, 2009.

Quincey, D., Smith, M., Rounce, D., Ross, A., King, O., and Watson, C.: Evaluating morphological estimates of the aerodynamic roughness of debris covered glacier ice, Earth Surface Processes and Landforms, 42, 2541–2553, https://doi.org/10.1002/esp.4198, 2017.

Racoviteanu, A., Nicholson, L., Glasser, N., Miles, E., Harrison, S., and Reynolds, J.: Debris-covered glacier systems and associated glacial lake outburst flood hazards: challenges and prospects, Journal of the Geological Society, 179, jgs2021–084, https://doi.org/10.1144/jgs2021-084, 2022.

Rana, B., Nakawo, M., Fukushima, Y., and Agkta, Y.: Application of a conceptual precipitation-runoff model (HYGY-MODEL) in a debris-covered glacierized basin in the Langtang Valley, Nepal Himalaya, Annals of Glaciology, 25, 226–231, https://doi.org/10.3189/S0260305500014087, 1997.

Reid, T. and Brock, B.: Assessing ice-cliff backwasting and its contribution to total ablation of debris-covered Miage glacier, Mont Blanc massif, Italy, Journal of Glaciology, 60, 3–13, https://doi.org/10.3189/2014JoG13J045, 2014.

Reid, T. D. and Brock, B. W.: An energy-balance model for debris-covered glaciers including heat conduction through the debris layer, Journal of Glaciology, 56, 903–916, https://doi.org/10.3189/002214310794457218, 2010.

Reid, T. D., Carenzo, M., Pellicciotti, F., and Brock, B. W.: Including debris cover effects in a distributed model of glacier ablation, Journal of Geophysical Research: Atmospheres, 117, 2012JD017 795, https://doi.org/10.1029/2012JD017795, 2012.

Rets, E., Popovnin, V., and Shahgedanova, M.: 3_Djankuat Data, https://doi.org/10.5281/ZENODO.3049871, 2019.

RGI Consortium: Randolph Glacier Inventory - A Dataset of Global Glacier Outlines, Version 6, https://doi.org/10.7265/4M1F-GD79, 2017.

Robertson, E. C.: General and Engineering Geology of the Northern Part of Pueblo, Colorado, Open-File Report 88-441, U.S. Geological Survey, https://pubs.usgs.gov/of/1988/0441/report.pdf, 1988.

Rogerson, R., Olson, M., and Branson, D.: Medial Moraines and Surface Melt on Glaciers of the Torngat Mountains, Northern Labrador, Canada, Journal of Glaciology, 32, 350–354, https://doi.org/10.3189/S0022143000012028, 1986.

Romshoo, S. A., Murtaza, K. O., and Abdullah, T.: Towards understanding various influences on mass balance of the Hoksar Glacier in the Upper Indus Basin using observations, Scientific Reports, 12, 15 669, https://doi.org/10.1038/s41598-022-20033-w, 2022.

Romshoo, S. A., Nabi, B., and Dar, R. A.: Influence of debris cover on the glacier melting in the Himalaya, Cold Regions Science and Technology, 222, 104 204, https://doi.org/10.1016/j.coldregions.2024.104204, 2024.

Rounce, D. R. and McKinney, D. C.: Debris thickness of glaciers in the Everest area (Nepal Himalaya) derived from satellite imagery using a nonlinear energy balance model, The Cryosphere, 8, 1317–1329, https://doi.org/10.5194/tc-8-1317-2014, 2014.

Rounce, D. R., Quincey, D. J., and McKinney, D. C.: Debris-covered glacier energy balance model for Imja–Lhotse Shar Glacier in the Everest region of Nepal, The Cryosphere, 9, 2295–2310, https://doi.org/10.5194/tc-9-2295-2015, 2015.

Rounce, D. R., Hock, R., McNabb, R. W., Millan, R., Sommer, C., Braun, M. H., Malz, P., Maussion, F., Mouginot, J., Seehaus, T. C., and Shean, D. E.: Distributed Global Debris Thickness Estimates Reveal Debris Significantly Impacts Glacier Mass Balance, Geophysical Research Letters, 48, e2020GL091 311, https://doi.org/10.1029/2020GL091311, 2021.

Rounce, D. R., Hock, R., Maussion, F., Hugonnet, R., Kochtitzky, W., Huss, M., Berthier, E., Brinkerhoff, D., Compagno, L., Copland, L., Farinotti, D., Menounos, B., and McNabb, R. W.: Global glacier change in the 21st century: Every increase in temperature matters, Science, 379, 78–83, https://doi.org/10.1126/science.abo1324, 2023.

Rowan, A. and Gibson, M.: Supraglacial debris thickness data from Khumbu Glacier, Nepal, https://doi.org/10.5281/ZENODO.3775571, 2020.

Rowan, A., Stewart, R., and Foster, L.: Supraglacial debris thickness measurements from Miage Glacier, Italy, https://doi.org/10.5281/ZENODO.3971785, 2020.

Rowan, A. V., Nicholson, L. I., Quincey, D. J., Gibson, M. J., Irvine-Fynn, T. D., Watson, C. S., Wagnon, P., Rounce, D. R., Thompson, S. S., Porter, P. R., and Glasser, N. F.: Seasonally stable temperature gradients through supraglacial debris in the Everest region of Nepal, Central Himalaya, Journal of Glaciology, 67, 170–181, https://doi.org/10.1017/jog.2020.100, 2021.

Röhl, K.: Characteristics and evolution of supraglacial ponds on debris-covered Tasman Glacier, New Zealand, Journal of Glaciology, 54, 867–880, https://doi.org/10.3189/002214308787779861, 2008.

Schauwecker, S.: Mapping supraglacial debris thickness on mountain glaciers using satellite data: validation of a new, physically-based method presented by, https://doi.org/10.13140/2.1.2176.6087, publisher: [object Object], 2012.

Schauwecker, S., Rohrer, M., Huggel, C., Kulkarni, A., Ramanathan, A., Salzmann, N., Stoffel, M., and Brock, B.: Remotely sensed debris thickness mapping of Bara Shigri Glacier, Indian Himalaya, Journal of Glaciology, 61, 675–688, https://doi.org/10.3189/2015JoG14J102, 2015.

Scherler, D., Bookhagen, B., and Strecker, M. R.: Spatially variable response of Himalayan glaciers to climate change affected by debris cover, Nature Geoscience, 4, 156–159, https://doi.org/10.1038/ngeo1068, 2011.

Scherler, D., Wulf, H., and Gorelick, N.: Global Assessment of Supraglacial Debris-Cover Extents, Geophysical Research Letters, 45, https://doi.org/10.1029/2018GL080158, 2018.

Shah, S. S., Banerjee, A., Nainwal, H. C., and Shankar, R.: Estimation of the total sub-debris ablation from point-scale ablation data on a debris-covered glacier, Journal of Glaciology, 65, 759–769, https://doi.org/10.1017/jog.2019.48, 2019.

Sharma, P., Patel, L. K., Ravindra, R., Singh, A., K, M., and Thamban, M.: Role of debris cover to control specific ablation of adjoining Batal and Sutri Dhaka glaciers in Chandra Basin (Himachal Pradesh) during peak ablation season, Journal of Earth System Science, 125, 459–473, https://doi.org/10.1007/s12040-016-0681-2, 2016.

Shaw, T. E., Brock, B. W., Fyffe, C. L., Pellicciotti, F., Rutter, N., and Diotri, F.: Air temperature distribution and energy-balance modelling of a debris-covered glacier, Journal of Glaciology, 62, 185–198, https://doi.org/10.1017/jog.2016.31, 2016.

Shroder, J. F., Bishop, M. P., Copland, L., and Sloan, V. F.: Debris-covered glaciers and rock glaciers in the nanga parbat himalaya, pakistan, Geografiska Annaler: Series A, Physical Geography, 82, 17–31, https://doi.org/10.1111/j.0435-3676.2000.00108.x, 2000.

Shukla, A. and Garg, P. K.: Evolution of a debris-covered glacier in the western Himalaya during the last four decades (1971–2016): A multiparametric assessment using remote sensing and field observations, Geomorphology, 341, 1–14, https://doi.org/10.1016/j.geomorph.2019.05.009, 2019.

Sicart, J. E., Litt, M., Helgason, W., Tahar, V. B., and Chaperon, T.: A study of the atmospheric surface layer and roughness lengths on the high-altitude tropical Zongo glacier, Bolivia, Journal of Geophysical Research: Atmospheres, 119, 3793–3808, https://doi.org/10.1002/2013JD020615, 2014.

Soncini, A., Bocchiola, D., Confortola, G., Minora, U., Vuillermoz, E., Salerno, F., Viviano, G., Shrestha, D., Senese, A., Smiraglia, C., and Diolaiuti, G.: Future hydrological regimes and glacier cover in the Everest region: The case study of the upper Dudh Koshi basin, Science of The Total Environment, 565, 1084–1101, https://doi.org/10.1016/j.scitotenv.2016.05.138, 2016.

Steiner, J. F., Pellicciotti, F., Buri, P., Miles, E. S., Immerzeel, W. W., and Reid, T. D.: Modelling ice-cliff backwasting on a debris-covered glacier in the Nepalese Himalaya, Journal of Glaciology, 61, 889–907, https://doi.org/10.3189/2015JoG14J194, 2015.

Steiner, J. F., Litt, M., Stigter, E. E., Shea, J., Bierkens, M. F. P., and Immerzeel, W. W.: The Importance of Turbulent Fluxes in the Surface Energy Balance of a Debris-Covered Glacier in the Himalayas, Frontiers in Earth Science, 6, 144, https://doi.org/10.3389/feart.2018.00144, 2018.

Steiner, J. F., Kraaijenbrink, P. D. A., and Immerzeel, W. W.: Distributed Melt on a Debris-Covered Glacier: Field Observations and Melt Modeling on the Lirung Glacier in the Himalaya, Frontiers in Earth Science, 9, 678 375, https://doi.org/10.3389/feart.2021.678375, 2021.

Stewart, R. L., Westoby, M., Pellicciotti, F., Rowan, A., Swift, D., Brock, B., and Woodward, J.: Using climate reanalysis data in conjunction with multi-temporal satellite thermal imagery to derive supraglacial debris thickness changes from energy-balance modelling, Journal of Glaciology, 67, 366–384, https://doi.org/10.1017/jog.2020.111, 2021.

Takeuchi, Y., Kayastha, R. B., and Nakawo, M.: Characteristics of ablation and heat balance in debris-free and debris-covered areas on Khumbu Glacier, Nepal Himalayas, in the pre-monsoon season, IAHS PUBLICATION, pp. 53–62, 2000.

Vincent, C., Wagnon, P., Shea, J. M., Immerzeel, W. W., Kraaijenbrink, P., Shrestha, D., Soruco, A., Arnaud, Y., Brun, F., Berthier, E., and Sherpa, S. F.: Reduced melt on debris-covered glaciers: investigations from Changri NupGlacier, Nepal, The Cryosphere, 10, 1845–1858, https://doi.org/10.5194/tc-10-1845-2016, 2016.

Wagnon, P.: 2_Changri Nup Data, https://doi.org/10.5281/ZENODO.3048780, 2019.

Wang, P., Li, Z., Li, H., Wang, W., Zhou, P., and Wang, L.: Characteristics of a partially debris-covered glacier and its response to atmospheric warming in Mt. Tomor, Tien Shan, China, Global and Planetary Change, 159, 11–24, https://doi.org/10.1016/j.gloplacha.2017.10.006, 2017.

Wei, Y., Tandong, Y., Baiqing, X., and Hang, Z.: Influence of supraglacial debris on summer ablation and mass balance in the 24k glacier, southeast tibetan plateau, Geografiska Annaler: Series A, Physical Geography, 92, 353–360, https://doi.org/10.1111/j.1468-0459.2010.00400.x, 2010.

770 Westoby, M. J., Rounce, D. R., Shaw, T. E., Fyffe, C. L., Moore, P. L., Stewart, R. L., and Brock, B. W.: Geomorphological evolution of a debris-covered glacier surface, Earth Surface Processes and Landforms, 45, 3431–3448, https://doi.org/10.1002/esp.4973, 2020.

Winter-Billington, A., Dadić, R., Moore, R. D., Flerchinger, G., Wagnon, P., and Banerjee, A.: Modelling Debris-Covered Glacier Ablation Using the Simultaneous Heat and Water Transport Model. Part 1: Model Development and Application to North Changri Nup, Frontiers in Earth Science, 10, 796 877, https://doi.org/10.3389/feart.2022.796877, 2022.

775 Yang, W., Yao, T., Zhu, M., and Wang, Y.: Comparison of the meteorology and surface energy fluxes of debris-free and debris-covered glaciers in the southeastern Tibetan Plateau, Journal of Glaciology, 63, 1090–1104, https://doi.org/10.1017/jog.2017.77, 2017.

Zhang, Y., Fujita, K., Liu, S., Liu, Q., and Nuimura, T.: Distribution of debris thickness and its effect on ice melt at Hailuogou glacier, southeastern Tibetan Plateau, using in situ surveys and ASTER imagery, Journal of Glaciology, 57, 1147–1157, https://doi.org/10.3189/002214311798843331, 2011.

780 Zhao, C., Yang, W., Miles, E., Westoby, M., Kneib, M., Wang, Y., He, Z., and Pellicciotti, F.: Thinning and surface mass balance patterns of two neighbouring debris-covered glaciers in the southeastern Tibetan Plateau, The Cryosphere, 17, 3895–3913, https://doi.org/10.5194/tc-17-3895-2023, 2023.

Østrem, G.: Ice Melting under a Thin Layer of Moraine, and the Existence of Ice Cores in Moraine Ridges, Geografiska Annaler, 41, 228–230, https://doi.org/10.1080/20014422.1959.11907953, 1959.