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Debris Degree Day Factor Glacier Melt Model in the Everest Region of Nepal

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Debris-covered glaciers have important implications on glacier melt and the development of glacial lakes. Detailed energy balance models have been greatly improving; however, these models require detailed meteorological data making them difficult to be used to estimate future melt in response to a changing climate. This study develops a debris degree day factor (dDDF) map for glaciers in the Everest Region of Nepal based on meteorological data and melt rates between 2003 and 2011. The dDDF map accounts for variations in debris thickness and the topography over the glacier. The performance of the dDDF model is assessed via comparison with more traditional energy balance models.

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A Landsat analysis of variability of supraglacial ponds for the debris-covered glaciers of the Langtang Valley

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Debris-covered glaciers have received renewed interest in recent years in an attempt to improve understanding of climate-glacier interactions in High Mountain Asia. Understanding of key processes occurring in supraglacial ponds has advanced conceptually to include conduit-collapse formation, subaqueous and waterline melting, calving, and englacial filling and drainage. The behaviour of systems of ponds, however, has received little attention, as most process observations have been made on individual features. Several studies have used satellite data to determine pond distributions at a single point in time or their variability across several years or decades. However, no attempt has been made to document the seasonal and inter-annual variability of ponds, even though individual ponds have been observed to fill and drain periodically.

We analyse 172 Landsat TM/ETM+ scenes for the period 1999-2013 to identify thawed supraglacial ponds for the debris-covered tongues of five glaciers in the Langtang Valley of Nepal. We apply an advanced atmospheric correction routine (LandCor/6S) and improve upon previous band-ratio and image morphological techniques to identify ponds, then apply this database of identified ponds to: 1) measure the density of supraglacial ponding for five glaciers with differing characteristics, and evaluate the dependency of pond density to those glaciers' characteristics; 2) evaluate the controls that surface gradient and glacier velocity in particular exert on pond occurrence; 3) document the seasonal cycle of pond thawing and formation followed by freezing and draining; 4) document pond persistence, recurrence, and evolution over the 15-year period; and 5) determine if surface ponding has increased over time for the study glaciers.

We find high variability between glaciers (0.08-1.69% of debris-covered area during ablation season), related primarily to glacier size, velocity, and surface gradient. At the glacier scale, pond cover is also correlated with the standard deviation of surface velocity, but shows no relationship with cumulative historical downwasting. Spatially, ponds are most commonly observed in zones of low surface gradient and velocity, with surface gradient exhibiting control on pond density and velocity controlling pond size. The ponds show a pronounced seasonality, appearing rapidly in the premonsoon as snow melts, peaking in cover in the monsoon at 2% of debris-covered area, then declining in the post-monsoon as ponds drain or freeze. Pond seasonality has strong implications for the glacier's energy budget, as pond inject atmospheric energy to the glacier interior, bypassing the thick debris mantle. Ponds at the study site are highly recurrent and persistent, with 40.5% of pond locations apparent in multiple years, while many locations appear to persist or recur for the entire analysis. Individual pond locations show simple expansion and disappearance as well as complex patterns of coalescence and division. Accounting for biases of seasonality and observable glacier area, the glaciers show strong interannual variability rather than a steady increase in total cover.

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Variations in debris distribution and thickness on Himalayan debris-covered glaciers

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Many Himalayan glaciers are characterised by extensive supraglacial debris coverage; in Nepal 33% of glaciers exhibit a continuous layer of debris covering their ablation areas. The presence of such a debris layer modulates a glacier's response to climatic change. However, the impact of this modulation is poorly constrained due to inadequate quantification of the impact of supraglacial debris on glacier surface energy balance. Few data exist to describe spatial and temporal variations in parameters such as debris thickness, albedo and surface roughness in energy balance calculations. Consequently, improved understanding of how debris affects Himalayan glacier ablation requires the assessment of surface energy balance model sensitivity to spatial and temporal variability in these parameters.

Measurements of debris thickness, surface temperature, reflectance and roughness were collected across Khumbu Glacier during the pre- and post-monsoon seasons of 2014 and 2015. The extent of the spatial variation in each of these parameters are currently being incorporated into a point-based glacier surface energy balance model (CMB-RES, Collier et al., 2014, The Cryosphere), applied on a pixel-by-pixel basis to the glacier surface, to ascertain the sensitivity of glacier surface energy balance and ablation values to these debris parameters. A time series of debris thickness maps have been produced for Khumbu Glacier over a 15-year period (2000–2015) using Mihalcea et al.'s (2008, Cold Reg. Sci. Technol.) method, which utilised multi-temporal ASTER thermal imagery and our in situ debris surface temperature and thickness measurements. Change detection between these maps allowed the identification of variations in debris thickness that could be compared to discrete measurements, glacier surface velocity and morphology of the debris-covered area.

Debris thickness was found to vary spatially between 0.1 and 4 metres within each debris thickness map, and temporally on the order of 1 to 2 m. Temporal variability was a result of differential surface lowering, spatial variability in glacier surface velocities and intermittent input of debris to the glacier surface through mass movement. Most debris thickening is seen in initially thin areas of debris (< 0.4 m) or within ∼1 km of the glacier terminus. Surface energy balance modelling is currently underway to determine the effect of these variations in debris thickness, and other parameters mentioned previously. Future work will be to calculate debris transport flux on the surface of Khumbu Glacier using the time series of debris thickness maps. Debris flux and refined energy balance calculations will then be incorporated into a 3-D ice flow model to determine the response of Khumbu Glacier to debris transport and climatic changes.

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Characterizing aerodynamic roughness length (z0) for a debris-covered glacier: aerodynamic inversion and SfM-derived microtopographic approaches

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Aerodynamic surface roughness is an essential parameter in surface energy balance studies. While actual measurements on bare ice glaciers are rare, a wide range of literature values exist for ice and snow surfaces. There are very few values suggested for debris covered glaciers and actual measurements are even scarcer – studies instead optimize z0 or use a reference value. The increased use of photogrammetry on glaciers provides an opportunity to characterize the range of z0 values meaningful for debris-covered glaciers.

We apply Agisoft's Structure-from-Motion process chain to produce high resolution DEMs for five 1m x 1m plots (1mm resolution) with differing grain-size distributions, as well as a large ∼180m x ∼180m depression (5cm) on Lirung Glacier in the Nepalese Himalayas. For each plot, we calculate z0 according to transect-based microtopographic parameterisations. We compare individual-transect z0 estimates based on profile position and direction, and develop a grid version of the algorithms aggregating height data from all bidirectional transects. This grid approach is applied to our larger DEM to characterize the variability of z0 across the study site for each algorithm.

For the plot DEMs, z0 estimated by any algorithm varies by an order of magnitude based on transect position. Although the algorithms reproduce the same variability among transects and plots, z0 estimates vary by an order of magnitude between algorithms. For any algorithm, however, we find minimal difference between cross- and down-glacier profile directions. At the basin scale, results from different algorithms are strongly correlated and results are more closely clustered with the exception of the Rounce (2015) algorithm, while any algorithm's values range by two orders of magnitude across the study depression. The Rounce algorithm consistently produced the highest z0 values, while the Lettau (1969) and Munro (1989) methods produced the lowest values, and use of the Nield (2013) regression-fits based on topographic metrics produced intermediate values.

A tower of wind and temperature sensors was installed in the depression in October 2014. Using an iterative method to derive friction velocity and temperature scale, we derive the Monin-Obukov length and subsequently surface roughness values for each data pair (Garratt 1992, Hogstrom 1988, Brock 2006). Values range from 0.01 to 0.2 m over the observation period for this single location.

Clearly, the surface of debris-covered glaciers is extremely variable spatially and temporally, so what should be used in models? Our results suggest z0 varies between 0.004 m (smooth cobbles) to 0.5m (large boulders), and that 0.015m is a reasonable central value for Lirung Glacier. As the grain-size distributions closely reproduce the distribution of obstacle sizes determined by the zero-up-crossing method, and d80 preserves the plot ranking of z0 magnitudes, it may be possible to develop a representative z0 lookup table based on grain sizes, which would provide a straightforward method to roughly vary z0 across the debris surface for energy-balance modelling applications.

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Multi-temporal high resolution monitoring of debris-covered glaciers using unmanned aerial vehicles

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Debris-covered glaciers in the Himalayas are relatively unstudied due to the difficulties in fieldwork caused by the inaccessible terrain and the presence of debris layers, which complicate in situ measurements. To overcome these difficulties an unmanned aerial vehicle (UAV) has been deployed multiple times over two debris covered glaciers in the Langtang catchment, located in the Nepalese Himalayas. Using differential GPS measurements and the Structure for Motion algorithm the UAV imagery was processed into accurate high-resolution digital elevation models and orthomosaics for both pre- and post-monsoon periods. These data were successfully used to estimate seasonal surface flow and mass wasting by using cross-correlation feature tracking and DEM differencing techniques. The results reveal large heterogeneity in mass loss and surface flow over the glacier surfaces, which are primarily caused by the presence of surface features such as ice cliffs and supra-glacial lakes. Accordingly, we systematically analyze those features using an object-based approach and relate their characteristics to the observed dynamics. We show that ice cliffs and supra-glacial lakes are contributing to a significant portion of the melt water of debris covered glaciers and we conclude that UAVs have great potential in understanding the key surface processes that remain largely undetected by using satellite remote sensing.

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Debris-covered glaciers extend the lifespan of water supplies in the European Alps

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Debris-covered glaciers have a slower melting rate than clean-ice glaciers due to the insulating effect of their debris layer. In the European Alps, debris-covered glaciers have received little attention due to their small contribution to sea-level rise. However, glaciers provide water supplies for the five main watersheds draining the European Alps (Danube, Rhine, Rhone, Po and Adige, in order of size), an area inhabited by more than 145 million people (20% of Europe's population). It is unclear what volume of ice (and so quantity of potential meltwater) is affected by a debris layer, and what the effect of this layer is for water resources in the Alps.

Combining the Randolph Glacier Inventory (RGI) and online imagery services, we calculated that more than 40% of ice volume in the Alps is influenced by debris cover. In this presentation, we will show the different elements leading to this number, including our evaluation of the RGI, the volume calculation method and what percentage of ice is actually covered (0.6 to 99% of glacier surface area). Our analysis has allowed a comprehensive understanding of the debris-covered glaciers in each watershed by revealing their distribution (i.e. where they will extend water supply lifespan), and hypsometry and equilibrium line altitude (how sensitive they are to climate change). The prolonged lifespan of water supply is visible at the scale of an individual debris-covered glacier: comparing the evolution of Glacier Noir and Glacier Blanc (France) over the last 150 years indicates that Glacier Noir (debris covered) has retained 2.5 times more ice than Glacier Blanc (clean-ice) under the same climatic conditions.

The number of debris-covered glaciers will increase as the >1°C rise in temperature in the European Alps since the start of the 20th Century increases the instability of rock faces and scree slopes. The evolution of these glaciers is therefore likely to have a major impact on human populations. This work shows that Alpine debris-covered glaciers are the main glaciological actor in Europe's water supply and can significantly extend the lifespan of this water resources even in the face of climate change.

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Investigating ice cliff evolution and contribution to glacier mass-balance using a physically-based dynamic model

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Supraglacial cliffs are a surface feature typical of debris-covered glaciers, affecting surface evolution, glacier downwasting and mass balance by providing a direct ice-atmosphere interface. As a result, melt rates can be very high and ice cliffs may account for a significant portion of the total glacier mass loss. However, their contribution to glacier mass balance has rarely been quantified through physically-based models. Most cliff energy balance models are point scale models which calculate energy fluxes at individual cliff locations. Results from the only grid based model to date accurately reflect energy fluxes and cliff melt, but modelled backwasting patterns are in some cases unrealistic, as the distribution of melt rates would lead to progressive shallowing and disappearance of cliffs.

Based on a unique multitemporal dataset of cliff topography and backwasting obtained from high-resolution terrestrial and aerial Structure-from-Motion analysis on Lirung Glacier in Nepal, it is apparent that cliffs exhibit a range of behaviours but most do not rapidly disappear. The patterns of evolution cannot be explained satisfactorily by atmospheric melt alone, and are moderated by the presence of supraglacial ponds at the base of cliffs and by cliff reburial with debris. Here, we document the distinct patterns of evolution including disappearance, growth and stability.

We then use these observations to improve the grid-based energy balance model, implementing periodic updates of the cliff geometry resulting from modelled melt perpendicular to the ice surface. Based on a slope threshold, pixels can be reburied by debris or become debris-free. The effect of ponds are taken into account through enhanced melt rates in horizontal direction on pixels selected based on an algorithm considering distance to the water surface, slope and lake level.

We use the dynamic model to first study the evolution of selected cliffs for which accurate, high resolution DEMs are available, and then apply the model to the entirety of Lirung and Langtang glaciers to quantify the total contributions of cliffs to glacier mass balance.

Observations and model results suggest a strong dependency of the cliffs' life cycle on supraglacial ponds, as the water body keeps the cliff geometry constant through a combination of backwasting and calving at the bottom and maintenance of steep slopes in the lowest sections. The absence of ponds causes the progressive flattening of the cliff, which finally leads to complete disappearance. Modelled volume losses from May to October 2013 range from 2650 to 9415 m^3 w.e., in agreement with the estimates with the SfM-approach. Mean error of modelled elevation within the cliff outline ranges from -1.3 to 0.6m.

This work sheds light on mechanisms of cliffs' changes by quantifying them for the first time with a physically-based, dynamic model, and presents the first complete estimate of the relevance of supraglacial ice-cliffs to total glacier mass-balance for two distinct glaciers.

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Debris cover influence on surface heat balance, ice melt-rate and its diurnal pattern: a case study of the Djankuat Glacier, Central Caucasus, Russia

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Supraglacial moraine currently covers 61% of the ablation area on the Djankuat Glacier, Northern Caucasus. It considerably predetermines ice melting, affecting not only the melt-rate, but also its diurnal pattern. Debris study on Djankuat is carried out alongside with mass balance monitoring programme since 1968, and evidence on its thermo-physical effect on ice melting has been consistently accumulating since then. A thin debris layer (<6-7 cm) was found out yet in the 1980s to induce higher sub-debris ablation in comparison with debris-free ice, whereas a thicker one gradually reduces melt-rate down to its full cessation by its thickness reaching ca.150 cm (insignificant deviations can be caused by different thermo-physical properties dependent on moraine lithology). Obtaining more detailed information about debris influence upon the underlying glacier ice becomes crucial under the conditions of supraglacial morainic cover constantly expanding (13% of the entire glacier area in 2010 compared to 3% in 1968), thickening (the dominant thickness gradation shifted from 0-10 cm in 1983 to 31-50 cm in 2010) and increasing in volume (141% increment from 1983 to 2010). Two AWSs coupled with ablation meters, erected on clean and debris-covered ice surface, are functioning on Djankuat during ablation seasons since 2006 for this purpose. Diurnal distribution of subdebris ablation on clean ice (timing of peak rates, peak duration) slightly differs from year to year. It depends on the prevailing weather conditions. For instance, cloudy weather moves the ablation peak towards 2-3 pm, decreasing its total value and diurnal amplitude. Mean diurnal ablation maximum on clean ice occurs about 1-2 pm (∼ 5-6 mm w.e. per hour) and minimum happens at roughly 6 am (∼ 1 mm/hr), and the ablation process is mostly influenced by radiation balance on ice surface. Ablation meter revealed mostly shielding effect in case of 60-cm-thick debris layer: peak melt- rate of sub-debris ice is 6-7 times lower and diurnal variation is insignificant. This is consistent with vertical temperature profiles within the lithogenic layer, demonstrating diurnal cycle attenuation with depth. Diurnal variation almost disappear at the foot of the layer, while they are observed clearly at the depth of 5 cm. The ablation meter data are corroborated with the ablation stake measurements, installed at debris-covered sites: the most intensive ablation is observed under debris cover 3-7 cm thick. As a result, ablation reduction is registered on 93% of debris-covered glacier area and only 7% of this surface experiences accelerated melting. Glacier-derived run-off loses about 20% of its volume annually due to supraglacial moraine growth. Continuous debris expansion and thickening can become in the nearest future a factor of glacier evolution comparable to climate change.

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Glacial lakes amplify glacier recession in the central Himalaya

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The high altitude and high latitude regions of the world are amongst those which react most intensely to climatic change. Across the Himalaya glacier mass balance is predominantly negative. The spatial and temporal complexity associated with this ice loss across different glacier clusters is poorly documented however, and our understanding of the processes driving change is limited. Here, we look at the spatial variability of glacier hypsometry and glacial mass loss from three catchments in the central Himalaya; the Dudh Koshi basin, Tama Koshi basin and an adjoining section of the Tibetan Plateau. ASTER and SETSM digital elevation models (2014/15), corrected for elevation dependant biases, co-registration errors and along or cross track tilts, are differenced from Shuttle Radar Topographic Mission (SRTM) data (2000) to yield surface lowering estimates. Landsat data and a hypsometric index (HI), a classification scheme used to group glaciers of similar hypsometry, are used to examine the distribution of glacier area with altitude in each catchment.

Surface lowering rates of >3 m/yr can be detected on some glaciers, generally around the clean-ice/debris-cover boundary, where dark but thin surface deposits are likely to enhance ablation. More generally, surface lowering rates of around 1 m/yr are more pervasive, except around the terminus areas of most glaciers, emphasising the influence of a thick debris cover on ice melt. Surface lowering is only concentrated at glacier termini where glacial lakes have developed, where surface lowering rates are commonly greater than 2.5 m/yr.

The three catchments show contrasting hypsometric distributions, which is likely to impact their future response to climatic changes. Glaciers of the Dudh Koshi basin store large volumes of ice at low elevation (HI > 1.5) in long, debris covered tongues, although their altitudinal range is greatest given the height of mountain peaks in the catchment. In contrast, glaciers of the Tama Koshi store large amounts of ice in broad accumulation zones and are more equidimensional (HI -1.2 to 1.2). Glaciers flowing onto the Tibetan Plateau have a similar hypsometric distribution to glaciers of the Dudh Koshi, but terminate at a higher altitude overall, approximately 500 m higher than glaciers of the Dudh Koshi or Tama Koshi. We estimate the approximate Equilibrium Line Altitudes (ELA) of the last 15 years to be above a substantial portion (66%- Dudh Koshi; 87%- Tama Koshi; 83% Tibetan Plateau) of the glacierised area for all three catchments. Future ice recession may therefore be governed primarily by glacier hypsometry, but is likely to be amplified by the continued development of new, or growth of current glacial lakes.

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Influence of a debris layer on the melting of ice on a Himalayan Glacier: A case study from Lirung Glacier, Langtang valley, Rasuwa, Nepal

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Total runoff from glacierized river basins has been commonly modeled using two approaches: physically-based energy-balance models and more empirical temperature-index models. This study uses the Debris Energy Balance model (DEB) developed by Tim Reid and Ben Brock at the point scale to calculate melt under a debris-covered glacier. Because of the high heterogeneity of the surface layer, the ablation rate varies throughout the glacier. The debris surface temperature is numerically estimated by considering the balance of heat fluxes at the air/debris interface, and heat conduction through the debris is calculated in order to estimate melt rates at the debris/ice interface. The predicted hourly debris surface temperatures and debris internal temperatures provide a good fit to temperatures measured on debris-covered Lirung Glacier ($R^2 \sim 0.90$). The model can also be used to reproduce observed changes in melt rates below debris layers of varying types and thicknesses, an important consideration for the overall ice melt estimation under a debris layer.

This work provides information about the influence of a debris cover on the melting of Lirung Glacier in Langtang Valley, Rasuwa district, Nepal. An extensive field campaign is carried out from May to October 2012 during which different data of meteorological variables and physical properties of debris are collected and many ablation stakes are installed. Direct measurements of surface lowering at the ablation stakes are done during May (installation period), late June, early September and late October 2012. Observed meteorological variables and debris parameters are used in the DEB model and point melt rate of 2.9 mm w.e. d^{-1} is estimated beneath the debris thickness of 1.4 m at the AWS site. A time lag of 3-4 hours in a day, between the maximum temperature at the surface and 20 cm depth in a debris layer is also seen. The performance of model changes remarkably upon changing any of external variables including radiation and air temperature and physical properties of debris, illustrating the effect of the debris layer on ablation of glacier ice should be studied in association with these variables. Change in the debris thermal conductivity (k_d) by +10 % produces up to 11 % change in melt rate, highlighting the importance of k_d in the DEB model.

Thus accurate melt modeling at different locations of the debris covered glacier is important to understand the effect of a highly variable debris layer on melt and thus improve the distributed modelling, which in turn gives estimates of the amount of discharge from the glacier, an important component of the local water resources.

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The life cycle of Ice Sails

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The Karakoram mountain region is host to many debris-covered glaciers. A notable feature from a sub-set of mainly larger glaciers with flat tongues, is the phenomenon of ‘Ice Sails’. These Ice Sails are clean ice structures that protrude out of the surrounding debris-covered glacier. They can be up to 20 meters in height, with widths of up to 90 meters, and generally have flat-sided faces. They appear to grow out of areas of glacier with thin debris coverage, then persist for decades as the glacier flows downstream, before declining back into the glacier several kilometres later. Here we aim to define and categorise these ice structures, and then explain their growth, persistence and decay. In particular, we show that their growth is due to the melt rate of inclined clean-ice being smaller than that of the surrounding flat thinly-debris-covered ice, allowing these structures to appear to grow out of the debris layer. But as the glacier flows downstream, this debris thickness slowly thickens, causing the corresponding melt-rate of the underlying ice to decline. Eventually, the melt-rate of the debris-covered ice becomes lower than that of the Ice Sail’s melt-rate, at which point the decaying process of the Ice Sail commences. We develop a model to quantify this process, and in so doing, draw out the key parameters that govern the existence of Ice Sails.

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Incorporating moisture content in modeling the surface energy balance of debris-covered Changri Nup Glacier, Nepal

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Glaciers whose ablation zones are covered in supraglacial debris comprise a significant portion of glaciers in High Mountain Asia and two-thirds in the South Central Himalaya. Such glaciers evade traditional proxies for mass balance because they are difficult to delineate remotely and because they lose volume via thinning rather than via retreat. Additionally, their surface energy balance is significantly more complicated than their clean counterparts' due to a conductive heat flux from the debris-air interface to the ice-debris boundary, where melt occurs. This flux is a function of the debris' thickness; thermal, radiative, and physical properties; and moisture content.

To date, few surface energy balance models have accounted for debris moisture content and phase changes despite the fact that they are well-known to affect fluxes of mass, latent heat, and conduction. In this study, we introduce a new model, ISBA-DEB, which is capable of solving not only the heat equation but also moisture transport and retention in the debris. The model is based upon Meteo-France's Interactions between Soil, Biosphere, and Atmosphere (ISBA) soil and vegetation model, significantly adapted for debris and coupled with the snowpack model Crocus within the SURFEX platform. We drive the model with continuous ERA-Interim reanalysis data, adapted to the local topography (i.e. considering local elevation and shadowing) and downscaled and de-biased using 5 years of in-situ meteorological data at Changri Nup glacier [(27.859N, 86.847E)] in the Khumbu Himal. The 1-D model output is then evaluated through comparison with measured temperature in and ablation under a 10-cm thick debris layer on Changri Nup. We have found that introducing a non-equilibrium model for water flow, rather than using the mixed-form Richard's equation alone, promotes greater consistency with moisture observations. This explicit incorporation of moisture processes improves simulation of the snow-debris-ice column's temperature gradient—and, thus, energy fluxes—through time.

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Surface terrain characteristics and monsoon season mass balance of debris-covered glaciers in the Khumbu Himal, Nepal, obtained from high resolution Pléiades imagery.

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Debris-covered glaciers in the eastern Himalaya have pronounced surface relief consisting of hummocks and hollows, ice cliffs, lakes and former lake beds. This relief and spatially variable surface properties are expected to influence the spatially distributed surface energy balance and related ice mass loss and atmospheric interactions, but only a few studies have so far explicitly examined the nature of the surface terrain and its textures .

In this work we present a new high-resolution digital terrain model (DTM) of a portion of the Khumbu Himal in the eastern Nepalese Himalaya, derived from Pléiades satellite imagery sampled in spring 2015. We use this DTM to study the terrain characteristics of five sample glaciers and analyse the inter- and intra- glacier variability of terrain characteristics in the context of glacier flow velocities and surface changes presented in previous studies in the area. In parallel to this analysis we also present the seasonal geodetic mass balance between spring and fall 2015, and relate it to the terrain properties, surface velocity and limited knowledge of the local lapse rates in meteorological conditions during this monsoon season.

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Short term dynamics of the debris-covered Miage Glacier

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Due to the often inaccessible nature of debris-covered glaciers, studies of their dynamics tend to be restricted to those using remotely sensed data. This paper presents data on the short-term glacier dynamics of the debris-covered Miage Glacier, Western Italian Alps. The glacier velocity was calculated from repeat occupation of up to 22 points using a differential GPS system over two melt seasons. Meteorological, hydrological and water chemistry data were collected over the same time periods, and the nature of the hydrological system was studied using dye tracing, to allow the short term variations in glacier dynamics to be understood in terms of the likely glacial drainage system and its evolution. The highest glacier velocities and the greatest velocity variability was found near to where a cluster of moulins enter the glacier, close to the limit of continuous debris cover. The melt from the clean and dirty ice occasionally led to inputs overcoming the channelized system (both in spring and mid-summer), leading to increased velocities. On the debris-covered lower glacier however velocities were lower and less variable, and significant speed-up was confined to a period when subglacial water was thought to have been transferred subglacially from higher upglacier. The subdued sub-debris melt signal is thought to be the cause of the reduced velocity variability, in spite of the hydrological system beneath this part of the glacier remaining inefficient.

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The influence of supraglacial debris on proglacial runoff fluctuations and water chemistry

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This paper seeks to explore how the debris' influence on glacial ablation, topography and drainage structure impacts on the water chemistry and runoff signal of the proglacial stream. This was achieved through analysis of the supraglacial and proglacial water chemistry and the proglacial hydrograph of Miage Glacier, Western Italian Alps. Although the supraglacial water chemistry was influenced by the debris, there was also evidence that the less efficient hydrological system beneath the debris-covered lower tongue also increased the ion concentration of the proglacial stream. Compared to published data for clean glaciers, fewer diurnally classified daily hydrographs were found in the proglacial discharge record, with the amplitude of the diurnal signal peaking later and being relatively low in amplitude. These hydrograph characteristics were thought due to the debris' attenuation of the melt signal, and the smaller input streams and less efficient subglacial drainage system beneath the debris-covered lower tongue. Warmer than average weather conditions were required for strongly diurnal hydrographs to be shown, with a 'saw-toothed' hydrograph shown under average conditions. The diurnal relationship between conductivity and discharge often demonstrated anti-clockwise hysteresis, indicating that the more rapidly routed dilute melt component from the mid-glacier peaked before the peak in discharge. Components from higher up glacier and the lower debris-covered tongue likely had longer transit times and reached the proglacial stream later.

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A possible climate signal in the surface morphology and internal structure of Galena Creek Rock Glacier, Wyoming

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Galena Creek Rock Glacier (GCRG) has been shown in previous studies to be a debris-covered glacier (e.g. Ackert, Jr., 1998), and is thus a target of interest as a record of climate and an element of the mountain hydrological system. The goal of this study was to investigate possible relationships between surface morphology and internal structure and composition of GCRG. This was achieved using ground-penetrating radar (GPR), time-domain electromagnetic sounding (TEM), and photogrammetry to produce digital terrain models (DTMs).

We acquired 6 longitudinal GPR surveys at 50 and 100 MHz, 2 common midpoint GPR surveys, and 28 TEM soundings on GCRG from the head to the toe, and ground-based photogrammetry data were collected to produce a DTM of its cirque at 10 cm resolution. TEM soundings locally constrained the bulk thickness of GCRG to 26-75 meters. Common midpoint and hyperbola analyses of GPR surveys produced dielectric constants in the near subsurface of 4 in the upper glacier to 5-9 in the middle and lower glacier. These are consistent with clean ice and a mélange of rock with air and/or ice, respectively. GPR revealed a pervasive shallow reflector at 1-2.5m depth that we interpret to be the interface between the surface debris layer and glacier ice. There is increased structure and clutter in the GPR data beneath this interface as one moves down glacier.

Observations were additionally made of a 40m wide, 4-5m deep circular thermokarst pond located on upper GCRG in the cirque. The walls of the pond revealed a cross-section of the top several meters of GCRG's interior: a dry surface layer of rocky debris 1-1.5m thick overlying pure glacier ice. An englacial debris band was also observed, roughly 50 cm thick and presenting at an apparent up-glacier dip of $\sim$30 degrees, intersecting the surface near a subtle ridge resolved in the photogrammetry DTM.

A GPR transect conducted near the pond over 6 similar ridges imaged 6 corresponding up-glacier dipping reflectors that intersected the surface at 15-35 degrees at each ridge. Each of these reflectors is interpreted to be a debris band similar to the one observed in the thermokarst pond. These debris bands are hypothesized to represent climatic "tree rings:" they are formed in interglacial periods as rockfall accumulates and preserves underlying ice and then buried by subsequent ice deposition in the accumulation zone during positive mass balance periods. The up-glacier dip is the 2D expression of "nested spoons" morphology, expected from glacier flow.

The potential connections between surface ridge morphology, englacial debris bands, and regional climate-driven ice accumulation make GCRG a prime candidate for further investigation.

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Dynamics and internal structure of an Alaskan debris-covered glacier from repeat airborne photogrammetry and surface geophysics

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Debris-covered glaciers and rock glaciers encompass a range of compositions and activity, and can be useful paleoclimate indicators. They also respond differently to ongoing climate change than glaciers without a protective cover. Their flow dynamics are not well understood, and their unique surface morphologies, including lobate fronts and arcuate ridges, likely result from viscous flow influenced by a combination of composition, structure, and climatic factors. However, basic connections between flow kinematics and surface morphology have not yet been established, limiting our ability to understand these features. In order to begin to address this problem we have undertaken airborne and surface studies of multiple debris-covered glaciers in Alaska and the western U.S.

Sourdough Rock Glacier in the St. Elias Mountains, Alaska, is completely debris-covered and exhibits numerous transverse compressional ridges. Its trunk also exhibits highly regular bumps and swales with a wavelength of ~175 m and amplitudes up to 12 m. In the middle trunk, lineations (boulder trains and furrows) bend around a point roughly 200m from the eastern edge.

We acquired five high-resolution airborne surveys of Sourdough Rock Glacier between late 2013 and late 2015 using lidar and photogrammetry to assess annual and seasonal change at the sub-meter level. Differencing the DTMs provides vertical change while feature tracking in orthophotos provide horizontal velocities that indicate meters of annual motion. The flow field is highly correlated with surface features; in particular, compressional ridges in the lower lobe. Stranded, formerly active lobes are also apparent.

Surface geophysical studies were undertaken to constrain internal structure and composition using a combination of ground-penetrating radar (GPR) at 50 and 100 MHz in six transects, and time-domain electromagnetic (TDEM) measurements at 47 locations, primarily in an along-flow transect and two cross-flow transects. We infer from the GPR and TDEM data that Sourdough Rock Glacier is 40-50 m thick and consists of a core of relatively pure glacier ice preserved under a 2.5-3 m thick debris mantle.

In conclusion, Sourdough is actively flowing, with surface velocities that correlate with surface slope and thickness. A bedrock restriction is inferred from bending flow lines, low surface velocities, and localized thinning of the ice. This comprehensive suite of observations provides the potential to model ice flow and to ultimately link details of the surface morphology to accumulation and rheology through flow kinematics and internal structure.

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The role of debris covered glaciers in the high altitude water cycle in the Himalayas

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Between 14-18% of the Himalayan glaciers is debris covered and they provide a significant amount of the total glacial melt water. Yet, their behaviour and response to climate change remains relatively unstudied. It was always assumed debris covered glaciers melt less quick than debris-free glaciers at similar altitudes due to the insulating effect of debris thicker than a few centimetres. However, recent remote sensing and field based studies reveal that their melt rates are similar to those of debris covered glaciers. The underlying mechanism may be related to the formation of supra-glacial lakes, ice cliffs, and englacial hydrological processes which may act as a catalyst for melt. In this study we review the current state of knowledge regarding novel techniques to monitor and map debris covered glaciers, recent progress in understanding the growth and survival of supra-glacial lakes and ice cliffs and we explore possible hypotheses to explain the anomalous behaviour of debris covered glaciers. Finally, we attempt to quantify the role that melt from debris covered glaciers play in the high altitude water cycle and we suggest future research priorities in this field.

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Evolution of supraglacial brittle and ductile structures and drainage systems at a partly debris-covered alpine valley glacier during a 15 yr period

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Based on five glacier stages (1998, 2003, 2006, 2009 and 2012) covering a period of 15 years, supraglacial crevasses and other structures as well as the drainage system at the tongue of Pasterze Glacier were mapped and interpreted. Pasterze Glacier is the largest glacier (c.16.5 km2) of the entire Eastern European Alps located in the Hohe Tauern Range, Central Austria at 47°05'N and 12°43'E. The glacier is in a stage of rapid recession and downwasting. The tongue is connected with the firn area by a mighty ice fall. 75% of the c.4.5 km long glacier tongue is covered by a supraglacial debris cover affecting glacier surface morphology related to differential ablation influencing the glacier's stress and strain field. High resolution orthoimagery and digital elevation models/DEM (both data sets with 20-50 cm grid resolution) were analysed. A structure glaciological mapping key was applied to discern relevant brittle (normal faults, thrust faults, strike-slip faults commonly associated with and en èchelon structures, and ice disintegration expressed as normal faults) and ductile structures (band ogives). Additionally, a geometric mapping key was used differentiating between chevron, splaying, transverse, and longitudinal crevasses as well as complex crevasse fields related to ice disintegration (commonly circular and semi-circular collapse features). The drainage system was mapped differentiating between supraglacial channels and moulins. Observations made during annual glacier measurement campaigns were additionally considered. Results indicate that the lower half of the glacier tongue was characterised during the observation period by ice disintegration (with semi-circular collapse features since 2003 near the glacier terminus and since 2009 in the central part) and thrust faults with downslope convexity (steady upslope migration of first occurrence during the observation period). In general, the crevasse density increased towards the left (NE), less debris covered margin. Since 2009 the number of crevasses (particularly normal faults) increased at the continuously debris-covered part of the tongue related to differential ablation. In contrast, a reduction of en èchelon structures since 2006 was observed related to decreasing glacier movement rates. The total length of mapped brittle structures increased by trend with 38.3 km in 1998, 49.4 km in 2003, 53.3 km in 2006, 64.2 km in 2009, and 56.9 km in 2012. The length of mapped supraglacial channels was 6.2 km in 1998, 11.7 km in 2003, 10.9 km in 2006, 18.1 km in 2009, and 12.1 km in 2012. Based on the mapped band ogives (in some years mappable >3km below the ice fall) three different flow units were detected related to different source areas of the glacier. However, an increase in the spatial extent of the supraglacial debris cover hampered ogive mapping for the more recent stages. DEM differencing revealed a strong correlation between high surface differences and spatial distribution of brittle structures. A large number of brittle structures can therefore be described as being increasingly independent from glacier motion. These structures can be rather seen as adjustment to high relief. Therefore, we can conclude that the tongue of Pasterze Glacier is currently slowly turning into a large dead ice body characterized by movement cessation and ice disintegration and related normal fractures.

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Life and death of ice cliffs and lakes on debris covered glaciers – insights from a new dataset from the Nepalese Himalaya

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Numerous studies suggest that supraglacial ice cliffs and lakes could be one contributing factor to relatively high overall ablation rates on debris covered glaciers. While some studies have quantified backwasting rates, developments over the larger scale have not yet been assessed. Field work and earlier studies during three seasons in the Langtang catchment in the Nepalese Himalaya has given some insights into how these landforms develop, from initial emergence to persistence and disappearance.
From 6 sets of concurrent high-resolution satellite imagery and DEMs between 2006 and 2015 and an additional image from 1974, we assembled an extensive dataset of these landforms on all glaciers in the catchment, including nearly 4000 individual lakes and cliffs. We show that ice cliffs appear in combination with lakes or without and there are lakes that are not bordered by a cliff. Numbers vary strongly between seasons, especially as lakes show strong seasonal variability. There are furthermore different types of cliff forms – circular, lateral and longitudinal – that give an indication of their formation process. Circular cliffs form with either collapsing subglacial channels or overdeepenings caused by water accumulating on the surface, while lateral cliffs are likely associated with underlying crevasses. Some of the cliff and lake systems remain at the same location on-glacier over a number of years, while most move with the whole glacier body down valley.
From the DEMs determine preferential slopes and expositions of the cliffs in the catchment which have been shown to be essential aspects in explaining the backwasting process.
In combination with field observations from one glacier, where most of these types were present, we can infer development processes of a number of systems over the whole catchment. It is also apparent that densities of these landforms vary greatly over the glacier surface, which can be explained with velocities or underlying bed topography in different cases.
The event of the Gorkha earthquake of April 2015, that resulted in massive avalanches mixed with debris covering many of the landforms provides another case of investigation. In the subsequent imagery the emergence of new and old cliffs under the initially flat debris cover point to the initial formation process of these landforms.

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Applying an energy balance model of a debris covered glacier through the Himalayan seasons – insights from the field and sensitivity analysis

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Although some recent studies have attempted to model melt below debris cover in the Himalaya as well as the European Alps, field measurements remain rare and uncertainties of a number of parameters are difficult to constrain. The difficulty of accurately measuring sub-debris melt at one location over a longer period of time with stakes adds to the challenge of calibrating models adequately, as moving debris tends to tilt stakes. Based on measurements of sub-debris melt with stakes as well as air and surface temperature at the same location during three years from 2012 to 2014 at Lirung Glacier in the Nepalese Himalaya, we investigate results with the help of an earlier developed energy balance model. We compare stake readings to cumulative melt as well as observed to modelled surface temperatures.

With timeseries stretching through the pre-Monsoon, Monsoon and post-Monsoon of different years we can show the difference of sensitive parameters during these seasons. Using radiation measurements from the AWS we can use a temporarily variable time series of albedo. A thorough analysis of thermistor data showing the stratigraphy of the temperature through the debris layer allows a detailed discussion of the variability as well as the uncertainty range of thermal conductivity. Distributed wind data as well as results from a distributed surface roughness assessment allows to constrain variability of turbulent fluxes between the different locations of the stakes.

We show that model results are especially sensitive to thermal conductivity, a value that changes substantially between the seasons. Values obtained from the field are compared to earlier studies, which shows large differences within locations in the Himalaya. We also show that wind varies with more than a factor two between depressions and on debris mounds which has a significant influence on turbulent fluxes. Albedo decreases from the dry to the wet season and likely has some spatial variability that is considered in the sensitivity analysis.

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An improved method to compute supra glacial debris thickness using thermal satellite images together with an Energy Balance Model in the Nepal Himalayas

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A significant proportion of Himalayan glaciers is debris covered. Knowing the thickness of the debris cover is essential to obtain accurate estimates of melt rates. Due to the remoteness of these glaciers, collecting field measurements of debris thickness for a large number of glaciers is not realistic.
For this reason, previous studies have proposed an approach based on computing the energy balance at the debris surface using surface temperature from satellite imagery together with meteorological data and solving the energy balance for debris thickness. These studies differ only in the way they account for the nonlinearity of debris temperature profiles and the heat stored in the debris layer.
In our study we aim to 1) assess the performance of three existing models, and 2) develop a new methodology for calculating the conductive heat flux within the debris, which accounts for the history of debris temperature profiles by solving the advection-diffusion equation of heat numerically. Additionally, we found that in the previous studies several input variables are considered as uniform and we improved this by using distributed representations.
As a study case we use Lirung glacier in Langtang valley, Nepal, and we work with Landsat satellite thermal images. Results are validated using measurements of debris thickness on the glacier from October 2012 and 2015.
In some cases the existing models yield realistic results. But there is very little consistency between results for different satellite images. In general, computed debris thickness is frequently too thin compared to reality. Two of the existing models were able to accurately reproduce the extent of thin debris cover on the upper part of Lirung glacier. The mean debris thickness on Lirung obtained with the existing models lies between 0.1 m and 0.3 m depending on the model used, whereby the upper value of 0.3 m corresponds best to the field measurements.
Preliminary results from our new model show a larger spatial variability of debris thickness on the glacier as compared to existing models. Mean debris thickness on Lirung glacier computed with the new model is 0.4 m and is therefore closer to the field measurements than with the existing models. All models are most sensitive to effective thermal conductivity, shortwave radiation and albedo. We conclude that there is a large potential for improvement in debris thickness modelling.

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The response of debris-covered glaciers to climate change: A numerical modeling approach

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Debris-covered glaciers are common in rapidly-eroding alpine landscapes. When thicker than a few centimeters, surface debris suppresses melt rates. Continuous debris cover can therefore reduce the mass balance gradient in the ablation zone, leading to increases in glacier length. In order to quantify feedbacks in the debris-glacier-climate system, we developed a 2D long-valley numerical glacier model that includes deposition of debris on the glacier surface, and both englacial and supraglacial debris advection. We ran 120 simulations in which a steady state debris-free glacier responds to a step increase of surface debris deposition. Simulated glaciers advance to new steady states in which ice accumulation equals ice ablation, and debris input equals debris loss from the glacier. The debris flux onto the glacier surface, and the details of the relationship between debris thickness and melt rate strongly control glacier length. Debris deposited near the equilibrium-line altitude, where ice discharge is high, results in the greatest glacier extension when other debris-related variables are held constant. Continuous debris cover reduces ice discharge gradients, ice thickness gradients, and velocity gradients relative to debris-free glaciers forced by the same climate. Debris-forced glacier extension decreases the ratio of accumulation zone to total glacier area (AAR). The model reproduces first-order relationships between debris cover, AARs, and glacier surface velocities reported from glaciers in High Asia. We also explore the response of debris-covered glaciers to increases in the equilibrium-line altitude (climate warming). We highlight the conditions required to generate a low surface velocity 'dead' ice terminal reach during a warming climate, and the associated increase of fractional glacier surface debris. We also compare our debris-covered glacier climate response results with data from glaciers in High Asia. Our model provides a quantitative, theoretical foundation to interpret the effect of debris cover on the moraine record, and to forecast the likely effects of climate change on debris-covered glaciers.

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Quantifying surface roughness over debris covered ice

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Aerodynamic roughness length (z0) remains a major uncertainty when determining turbulent heat fluxes over glacier surfaces, and can vary by an order of magnitude even within a small area and through the melt season. Defining z0 over debris-covered ice is particularly complex, because the surface may comprise clasts of greatly varying size, and the broader-scale surface relief can be similarly heterogeneous. Several recent studies have used Structure from Motion to data model debris-covered surfaces at the centimetric scale and calculate z0 based on measurements of surface microtopography. However, few have validated these measurements with independent vertical wind profile measurements, or considered how the measurements vary over a range of different surface types or scales of analysis.

Here, we present the results of a field investigation conducted on the debris covered Khumbu Glacier during the post-monsoon season of 2015. We focus on two sites. The first is characterised by gravels and cobbles supported by a fine sandy matrix. The second comprises cobbles and boulders separated by voids. Vertical profiles of wind speed measured over both sites enable us to derive measurements of aerodynamic roughness that are similar in magnitude, with z0 at the second site exceeding that at the first by < 1 cm. During our observation period, snow covered the second site for three days, but the impact on z0 is small, implying that roughness is predominantly determined by major rock size obstacles rather than the general form of the surface. To complement these aerodynamic measurements we also conducted a Structure from Motion survey across each patch and calculated z0 using microtopographic methods published in a range of recent studies. We compare the outputs of each of these algorithms with each other and with the aerodynamic measurements, assess how they perform over a range of scales, and evaluate the validity of using microtopographic methods where aerodynamic measurements do not exist.

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Surface characteristics and evolution of debris covered glaciers

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Global climate change has led to increasing glacier retreat in most parts of the world. However, many heavily debris-covered glaciers have shown much smaller recession rates than their clean-ice neighbours. This can be attributed to the insulation effect of the supraglacial debris. Remote-sensing based investigations revealed that recent mass balances of debris-covered glaciers are equally negative. This fact is partly due to enhanced melting at supra-glacial lakes and ice cliffs but can also be caused by reduced mass flux. In this context, insufficient process understanding constitutes a major challenge for large scale glacier change assessment and modelling.

In this project, we aim at better understanding the evolution of glaciers in connection with changes in supra-glacial debris coverage. It is performed on Zmutt Glacier in Matter valley in Switzerland and on Gangotri Glacier in Garwhal Himalaya in India. Changes in glacier length, area, debris coverage, and surface elevation were compiled based on topographic maps, oblique photos, aerial and satellite orthoimages, digital terrain models (DTMs), and glacier monitoring data for a 50 (Gangotri) and 120 (Zmutt) year period, respectively. The subsequent analysis revealed that Zmutt Glacier has been in a slow but almost continuous retreating state since the end of the 19th century and showed a clear reduction in glacier area and volume. Similarly, Gangotri Glacier has retreated and, to a smaller degree, lost volume. However, the change in glacier length and area is clearly smaller than for other nearby, less debris-covered or debris-free glaciers. This fact is attributed to the larger debris-covered area that has steadily increased.

Further in the project, this data will serve as an important input and validation for the envisaged 3D flow modelling and, hence, will contribute to the understanding of the development of glaciers and debris-covered ice in a period of fast climatic changes.