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Evolution of surface topography, debris cover, ice flow, and downwasting features: a holistic reconstruction of a heavily debris-covered Alpine glacier from 1860-2017

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Previous studies have shown that supraglacial debris cover is increasing during glacial recession, influencing flow speed, geometry and, thus, the future glacier development. Many studies on debris-covered glaciers have given us insights into some of the links, although most studies focus only on parts of the system or only include a limited time period of observations.
In our study we have documented the transition period of Zmuttgletscher –a large Alpine valley glacier – from a lightly to a strongly debris-covered glacier in order to capture the effects and links between different aspects. From maps and aerial images we reconstructed surface elevation changes and patterns, and linked them to the distribution of debris cover, which we derived from terrestrial photos and orthoimages. Surface displacements were extracted by manual and automatic feature tracking over the lower part of the tongue. We mapped the existence of ice cliffs in the debris-covered part using semi-automatic methods, and attributed them to a process of origin. In a comparison to the evolution of nearby clean-ice Findelgletscher we estimated a potential debris-free scenario by transferring respective mass balance gradients to the geometry of Zmuttgletscher.
Across the glacier tongue we found an average elevation change from 1860-2017 of -96 $\pm$9.6 m. The development has been non-linear, although always negative except at the beginning of the 1980's. Debris coverage has increased its area share from $\sim$10% to over 30%. A continuous debris cover immediately leads to a visible effect on elevation change, and the change patterns allow to draw rough conclusions on debris thickness. During recent decades a flattening effect at the tongue was detected along a profile from debris-free to debris-covered surface. Flow speed patterns have not changed during the last 6-7 decades, although absolute flow speed has decreased, and the location of the almost stagnant part of the glacier tongue has extended and moved upglacier with the general recession of the terminus. Number and area of downwasting features such as lakes and ice cliffs have on average remained similar. Among others, their location is confined by a flow speed between 10-15 m/yr. Without debris coverage, Zmuttgletscher would have undergone stronger melt, especially in the lower parts of the tongue, resulting in a shorter length and higher terminus elevation. The observational data is used to train a numerical model that incorporates the entrainment of debris in order to better represent the long-term evolution of debris-covered glaciers, and first results will be presented.
The results on the relation between flow speed and ice cliffs as well as the effect of ice cliffs on local melt enhancement will be compared to other debris-covered glaciers in the Alps and the Himalaya to see whether physical rules can be deduced to aid in melt and flow modelling of debris-covered glaciers.