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Constraining debris input to Oberaletsch Glacier using ensemble-based Lagrangian modelling

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Debris-covered glaciers play an important role in alpine hydrology, yet the origin and transport pathways of debris within the glacier remain difficult to constrain. This is a major limitation in glacier evolution models, many of which have tended to ignore debris transient effects, especially for assessment of catchment hydrological processes. Supraglacial debris coverage is an integrated signal of debris supply, climate forcing, glacier geometry and debris physical properties, all of which vary in time, resulting in a complex inverse problem for model-based reconstructions.

Here, we apply the Instructed Glacier Model (IGM) with a newly implemented Lagrangian debris transport module combined with an ensemble of climate forcing, to explore constraints on debris input at Oberaletsch Glacier in the Swiss Alps. This framework allows debris particles to be tracked within a dynamically evolving glacier geometry and enables a likelihood-based assessment of inferred debris source regions across the ensemble. Rather than seeking a unique reconstruction, we identify spatially persistent and statistically robust seeding areas that are compatible with the observed historical evolution of debris extent derived from debris-cover maps for 1965, 1985, 1995, 2000, 2010 and 2015. These areas are identified by tracing debris particles backward from their final positions within the observed debris-covered zone to their upstream seeding locations.

Our results show that our inverse filtering strategy effectively identifies potential debris input zones that are primarily controlled by glacier dynamics and geometry. Notably, including or excluding the effect of debris on surface mass balance does not significantly alter the reconstructed debris extent in the ablation zone, highlighting the dominant role of ice flow in shaping supraglacial debris patterns at glacier scale. The reconstructed debris input patterns allow us to reproduce the observed historical evolution of debris extent and glacier geometry with good agreement. Debris extent matching between simulations and observations reaches around 80%, while the percentage of the total particles ending up in the target debris area remains above 70%. Ongoing work addresses the reconstruction of debris thickness, which is sensitive to both the debris weight (i.e. the assigned debris volume) prescribed for each particle and, crucially, the

climatic forcing, requiring an iterative approach to capture the full transient characteristics of the glacier debris cover.

This study demonstrates that ensemble-based Lagrangian modelling provides a powerful framework to constrain debris input to glaciers. By explicitly coupling debris transport to the evolving glacier dynamics, this approach opens new perspectives for interpreting present-day debris cover and for projecting the future evolution of debris-covered glaciers under changing climatic conditions.