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Uncovering glacier dynamics beneath a debris mantle

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Debris-covered glaciers (DCGs) have an extensive sediment mantle whose low albedo influences their surface energy balance to cause a buffering effect that could enhance or reduce ablation rates depending on the sediment thickness. The last effect suggests that some DCGs may be less sensitive to climate change and survive for longer than debris-free (or 'clean') glaciers under sustained climatic warming. However, the origin of DCGs is debated and the precise impact of the debris mantle on their flow dynamics and surface geometry has not been quantified. Here we investigate these issues with a numerical model that encapsulates ice-flow physics and surface debris evolution and transport along a glacier flow-line, as well as couples these with glacier mass balance. We model the impact of surface debris on ablation rates by a mathematical function based on published empirical data (including Ostrem's curve). A key interest is potential positive feedback of ablation on debris thickening and lowering of surface albedo. Model simulations show that when DCGs evolve to attain steady-state profiles, they reach lower elevations than clean glaciers do for the same initial and climatic conditions. Their mass-balance profile at steady state displays an inversion near the snout (where the debris cover is thickest) that is not observed in the clean-glacier simulations. In these cases, where the mantle causes complete buffering to inhibit ablation, the DCG does not reach a steady-state profile, and the sediment thickness evolves to a steady value that depends sensitively on the glacier surface velocities. Variation in the assumed englacial debris concentration in our simulations also determines glacier behaviour. With low englacial debris concentration, the DCG retreats initially while its mass-balance gradient steepens, but the glacier re-advances if it subsequently builds up a thick enough debris cover to cause complete buffering. We identify possible ways and challenges of testing this model with field observations of DCGs, given the inherent difficulty that such glaciers may not be in steady state.