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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.