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An energy-balance model for the debris layer on debris-covered glaciers

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Many glacier ablation zones are mantled in near-continuous blankets of rock debris. These debris-covered glaciers are important drivers of the water cycle in many mountain regions, for example, in the headwaters of the Ganges and Indus Rivers. The debris layers have a very significant impact on glacier thermodynamics, and have been seen to expand in recent years, so it is essential to assess exactly how their presence affects a glacier's response to climate changes. However, while many studies have investigated the surface energy balance on clean or debris-free glaciers, there is still a lack of models of the processes that influence debris-covered snow and ice. This paper presents a physically-based, one-dimensional energy balance model for the surface of a debris-covered glacier. The model is driven by meteorological variables and specified debris thermal properties without the need for surface temperature measurements, and was developed and tested using data collected hourly at Miage Glacier, Italy, which has an extensive cover of rock debris, during the ablation seasons (June to September) of 2005, 2006 and 2007. In the model, fluxes of solar shortwave and atmospheric longwave radiation can be entered directly from measurements or calculated using appropriate parameterisations. All other surface fluxes including upwelling longwave from the debris surface, sensible and latent heat transfer, and the conductive flux into the debris, depend on equations requiring the debris surface temperature. Therefore, the surface temperature is solved using an iterative Newton-Raphson procedure, assuming that it will adjust to a value such that the total sum of fluxes at the air-debris interface is zero. Temperatures within the debris are found by dividing the debris into several layers and solving the heat conservation equation numerically, with boundary conditions defined by the newly-calculated surface temperature and the temperature at the debris-ice interface (which is assumed to remain at or very close to 0°C throughout the ablation season, as supported by data). Finally, the conductive flux into the ice is calculated based on the temperature gradient at the bottom of the debris layer, and used to infer a melt rate in millimetres water equivalent for the season. The predicted hourly surface temperatures and debris internal temperatures provide a good fit to temperatures measured at a site on Miage Glacier over three ablation seasons, and at a tephra-covered glacier in Chile, with Nash-Sutcliffe goodness of fit values up to r2 = 0.95. The model also predicts melt rates similar to those measured on Miage Glacier for a variety of debris thickness values. We discuss how such a model can reproduce the well-known 'Østrem' curve (which shows that thin debris enhances melt, while thicker debris covers reduce melt), by simulating how thinner debris covers grow more 'patchy', with exposed portions of ice increasing the surface albedo. A sensitivity analysis of the model is presented to assess which model variables and processes are most important, and we perform model optimisation to provide insight into the best values of debris thermal properties – in particular, is it sufficient to assume that these properties are constant with depth?