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Budgets of ice and rock debris, erosion rates, and climate change at Khumbu Glacier, Nepal

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The crest of the Himalaya is deeply dissected by broad rivers of ice that typically disappear under a thick debris cover at lower elevations. Much as the ice is sustained by accumulating snow, the debris cover is sustained by input of rock fragments to the glacier, which must result from glacial and periglacial erosion of the catchment. The downvalley emergence of debris from the interior of the glacier is controlled by the ablation rate, the debris concentration in the ice and the ice velocity. In turn, supraglacial debris strongly impacts ablation, and hence affects the mass balance, spatial extent, and response to climate change of the glacier. At the base of Mount Everest, Khumbu Glacier and its debris cover have been studied extensively, starting with the earliest maps of the region in the 1920's. In spite of this long record we still know very little about the interaction between debris and ablation. This is especially true for the lower reaches where the glacier rates of thinning have averaged $\sim$0.5 m a-1 since the late '50s and where debris cover is thick (>2 m), but difficult to measure. Herein, we present our recent radar measurements of debris thickness in the lower few kilometers of the glacier using two techniques: electrical resistivity tomography (Wenner and Dipole-Dipole arrays) and ground penetrating radar (40 MHz frequency). We use these measurements to investigate the effect of the debris cover on the glacier evolution during changing climatic conditions, and to estimate the flux of ice and debris. From the latter, we infer that contemporary basin-averaged erosion rates required to sustain this debris flux for the Khumbu basin average $\sim$0.04 to 0.1 m a-1. Seasonal mass balance components (i.e. accumulation and ablation) derived from meteorological variables in the NCEP-NCAR Reanalysis database for the region provide context helpful in understanding the ice flux as well as the recent thinning of Khumbu Glacier. The negative mass balance that has dominated since the 1950's, and more likely earlier, is consistent with climatic trends during the last few decades. According to published long-term volume changes, the mean annual surface mass balance at Khumbu Glacier declined from -0.24 m w.e. in 1971-2002 to -0.45 m w.e. in 2003-2007. Between those two periods, summer (May-Sept) precipitation decreased by 23%. Additionally, the average annual number of 5000-m positive degree days during 1988-2010 was 16% greater than the average during 1948-1967; these periods are the first third and last third of the NCEP-NCAR period of record.