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Improving geomorphological process understanding of complex glacier surfaces using aerial robotics

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In the last decade or so, improvements in unpiloted aerial systems (UAS) technology and the emergence of low-cost digital photogrammetry have democratised access to accurate, high-resolution topographic data products, particularly in remote, glacial environments. One such application of these tools has been for advancing understanding of debris-covered glaciers (DCG) which are an important component of the high-mountain cryosphere, but also where detailed, ground-based process analysis is challenging. In this work, we seek to improve meso-scale (<km) geomorphological understanding of DCG surface evolution over multi-annual timescales by quantifying how debris moves around on the surface of these glaciers, and how debris transport is reconciled with wider patterns and mechanisms of ice mass loss. We applied annual UAS-photogrammetry and DEM differencing alongside debris thickness and debris stability modelling to unravel the evolution of a 0.2 km^2 sub-region of the debris-covered Miage Glacier, Italy, between June 2015 and July 2018. Following corrections for glacier flow, DEM differencing revealed widespread surface lowering (mean 4.1 ± 1.0 m a^{-1}; maximum 13.3 m a^{-1}). We combined DEMs of difference with local meteorological data and a sub-debris melt model to produce high resolution (metre-scale) maps of debris thickness. Median debris thicknesses ranged from 0.12 – 0.17 m and were highly spatially variable. Debris thickness differencing revealed localised debris thinning across ice cliff faces, except those which were decaying, where debris thickened, as well as ingestion of debris by a newly exposed englacial conduit. Debris stability mapping showed that 18.2 - 26.4% of the survey area was theoretically subject to debris remobilisation in a given year. By linking changes in stability to changes in debris thickness, we observed a net debris thinning signal across slopes which become newly unstable, and a net thickening signal across those which stabilise between years. Finally, we linked morphometric descriptors of the glacier surface with debris thickness change data to derive empirical relationships which describe observed rates of downslope debris thickening as a function of slope-distance and slope angle. These UAS-enabled data provide new insight into mechanisms and rates of debris redistribution on glacier surfaces over sub-decadal timescales, and open avenues for future research to explore patterns of debris remobilisation and the morphological evolution of glacier surfaces at much larger spatiotemporal

scales.