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Eddy covariance and lysimeter measurements of moisture fluxes over supraglacial debris

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Supraglacial debris covers have the potential to evaporate large quantities of water derived from either sub-debris ice melt or precipitation. Currently, knowledge of evaporation and condensation rates in supraglacial debris is limited due to the difficulty of making direct measurements. This paper presents eddy covariance and lysimeter measurements of moisture fluxes made over a 0.2 m debris layer at Miage debris covered glacier, Italian Alps, during the 2013 ablation season. The meteorological data are complimented by reflectometer measurements of volumetric water fraction in the saturated and vadose zones of the debris layer. The lysimeters were designed specifically to mimic the debris cover and were embedded within the debris matrix, level with the surface. Over the ablation season, the latent heat flux is dominated by evaporation, and the flux magnitude closely follows the daily cycle of daytime solar heating and night time radiative cooling of debris. Mean flux values are of the order of 1 kg m^{-2} day^{-1}, but often higher for short periods following rainfall. Condensation rates are relatively small and restricted to night time and humid conditions when the debris-atmosphere vapour pressure gradient reverses due to relatively warm air overlying cold debris. The reflectometer measurements provide evidence of vertical water movement through capillary rise in the upper part of the fine-grained debris layer, just above the saturated horizon, and demonstrate how debris bulk water content increases after rainfall. The latent heat flux responds directly to changes in wind speed, indicating that atmospheric turbulence can penetrate porous upper debris layers to the saturated horizon. Hence, vertical sorting of debris sediments and antecedent rainfall are important in determining evaporation rates, in addition to current meteorological conditions. Comparison of lysimeter measurements with rainfall data provides an estimate that between 45% and 89% of rainfall is evaporated directly back to the atmosphere. Rainfall evaporation rates increase with debris impermeability and temperature, with highest rates occurring when a shower falls on hot debris. If these point measurements are representative of larger scales, evaporation rates of the order of 1000 tonnes km^{-2} day^{-1} are implied, with higher rates following rainfall. This has important implications for downstream runoff, sub-debris ice melt rates (due to consumption of evaporative latent heat energy) and, possibly, convective atmospheric processes.