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Combining distributed glacier mass balance and ice flow models to improve projections of mass change for debris-covered Khumbu Glacier, Nepal

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Debris-covered glaciers in the Himalaya are losing mass more rapidly than expected. Quantifying and understanding the behaviour of these glaciers under climate change requires the use of numerical glacier models that represent the important feedbacks between debris transport, ice flow, and mass balance. However, these approaches have, so far, lacked a robust representation of the distributed mass balance forcing that is critical for making accurate simulations of ice volume change. This study forces a 3D higher-order ice flow model, with the outputs from an ensemble of distributed models of present day and future mass balance of Khumbu Glacier, Nepal. Distributed mass balance modelling, using the open access COupled Snowpack and Ice surface energy and mass balance model in PYthon (COSIPY) model (Sauter et al., 2020), was forced by three statistically downscaled climate models from the Coordinated Regional Climate Downscaling Experiment (CORDEX) project.

Climate models were selected based on their ability to reproduce observed present-day seasonality and to account for several future climate and monsoon scenarios, the latter being of particular importance for these summer-accumulation type glaciers. Two emission scenarios, RCP4.5 and RCP8.5, were also chosen to simulate glacier change to 2100. Statistical downscaling involved Quantile Mapping and Generalized Analog Regression Downscaling, and the efficacy of these approaches was informed by present day mass balance sensitivity studies. Downscaled daily climate data were trained with data from two weather stations to aid disaggregation to an hourly resolution.

The integration of the mass balance and ice flow models posed some interesting challenges. The COSIPY model was run as if Khumbu Glacier were a clean-ice glacier (with no supraglacial debris) with sub-debris ablation resolved in the ice flow model. The value of using distributed mass balance forcing is seen in the simulated present-day velocities in the Khumbu icefall, which give a better fit to remote-sensing observations than previous simulations using a simple elevation-dependent mass balance forcing. The simulated present-day glacier extent is considerably smaller than the existing glacier outline. The debris-covered tongue, known to be losing mass at an

accelerating rate, is virtually absent from these results, and is indicative of a stagnant tongue that is now or very soon to be dynamically disconnected from the active upper reaches of Khumbu Glacier.