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

Anya Schlich-Davies[1], Ann Rowan[2], Duncan Quincey [1] , Andrew Ross[1] and David Egholm[3]

[1] University of Leeds, UK, [2] University of Sheffield, UK and [3] Aarhus University, Denmark

Funding: Priestley International Centre for Climate and the University of Leeds

The Khumbu glacier

- World's highest accumulation area, with avalanching contributing up to 75% to accumulation (Inoue, 1977 and Benn and Lehmkuhl, 2002).
- 7km flat tongue with thick supraglacial debris cover (Fig 1).
- Theoretical assumption that debris-covered glaciers (DCGs) will lose mass more slowly than clean ice glaciers given insulating effect of thick supraglacial debris (Östrem, 1959).
- However DCGs are losing mass at similar rates to clean-ice glaciers, termed "the debris cover anomaly" (Pellicciotti et al., 2015).
- Glacier mass balance (MB) profile is characterised by highest ablation rates in the clean ice area just below the ELA, and lower ablation rates on the flat tongue, though this is spatially heterogenous with surface ponds and ice cliffs acting as 'ablation hotspots'.
- More realistic representations of glacier MB are needed in ice flow modelling to resolve the feedbacks between ice dynamics, mass balance and debris transport.

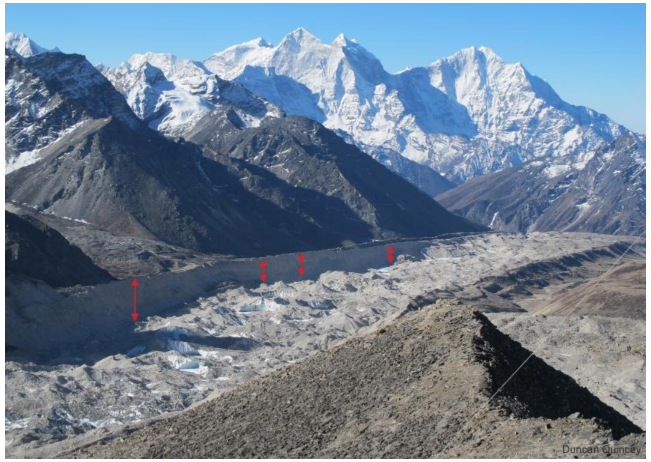

Fig 1: Looking down towards the terminus of Khumbu Glacier where surface lowering is clearly visible (red arrows). The surface of the glacier is pitted with supraglacial ponds and exposed ice cliffs. Photo taken by Duncan Quincey.

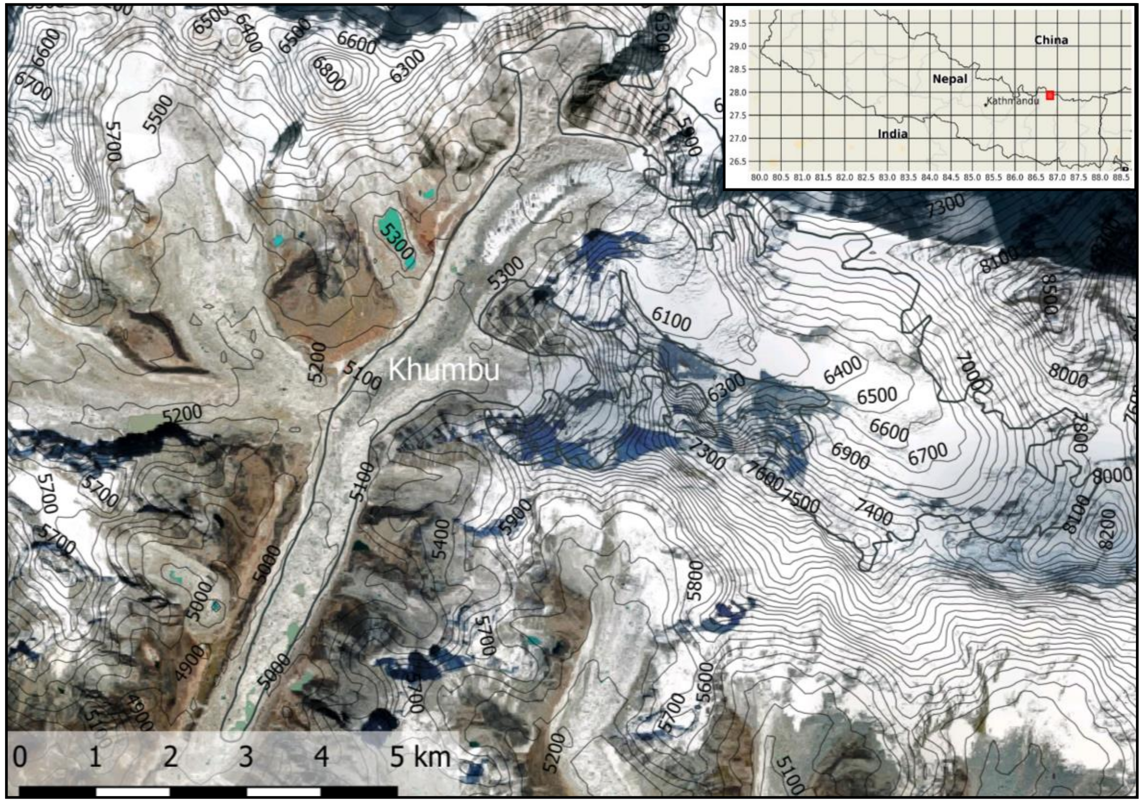

Fig 2: Khumbu glacier and its location in the Everest region of Nepal (top right).

Correspondence with Anya Schlich-Davies eeasd@leeds.ac.uk

Ice flow modelling experiments

- Little Ice Age maximum glacier (Fig 3) forced with present day (PD) MB as starting point for simulations.

Debris forcing / MB Forcing	Exponent of 0.72 (Rowan et al., 2015)	h_0 = 0.4 m	h_0 = 0.8 m	h_0 = 1.1 m
IPSL PD	1	2	3	4
CCCma PD	5	6	7	8
NOAA PD	9	10	11	9

Present day iSOSIA experiments

- Parameterisations of sub-debris ablation used in these simulations are explained here: https://doi.org/10.5194/egusphere-egu2020-20189

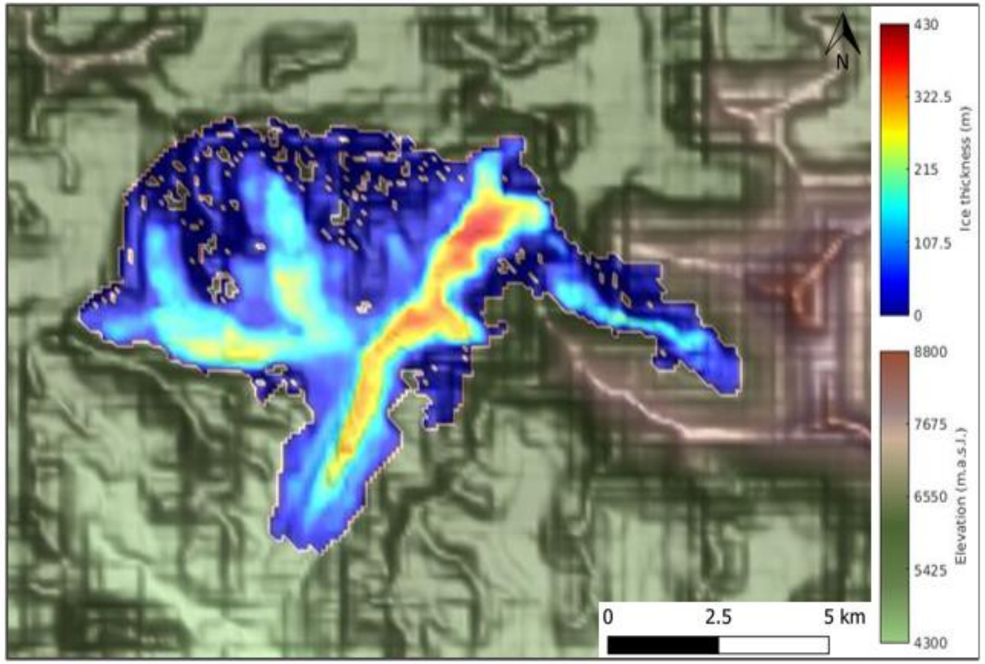

Fig 3: Simulated Khumbu glacier at Little Ice Age Maximum.

Correspondence with Anya Schlich-Davies eeasd@leeds.ac.uk

Mass balance forcing

- The mean of 5 annual clean-ice mass balance grids (100 m resolution) were used to force transient ice flow simulations.

- Present day mass balance sensitivity studies helped inform downscaling and disaggregation approach of the 7 climate variables used to force the MB model COSIPY (Sauter et al., 2020).

- Low glacier-wide mass balances (Fig 4) stem from enlarged glacier area required to couple the mass balance and ice flow model. It was important to include the hydrological catchment for avalanching to be resolved, and so there is a larger proportion of lower elevation than real glacier area.

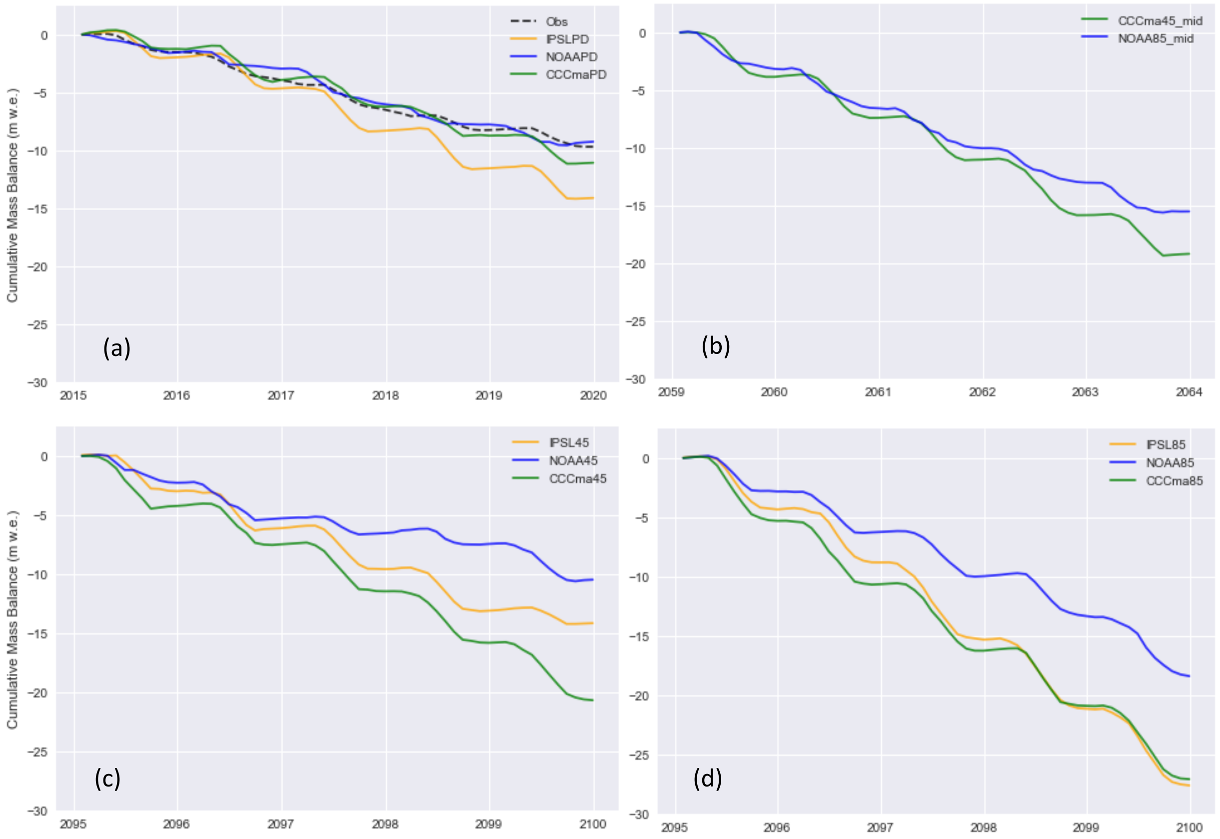

Fig 4: Spatially averaged clean-ice cumulative mass balance for (a) the present day time-slice (including the MB forced by the observations used in downscaling) (b) the mid-century time-slice (c) the future time-slice under RCP 4.5 (d) the same, but under RCP 8.5.

Correspondence with Anya Schlich-Davies eeasd@leeds.ac.uk

Present day glacier

- Active ice terminus thickness is ~120 m indicating thinning of 30 m since Gades (2000) radar measurements. This agrees well with observations from King et al. (2020).
- The value of improved representation of MB is seen in velocities in Khumbu icefall (Fig 5A), with maximum velocities of 320 m a^{-1} (much better match to remote-sensing observations of ~1 m d^{-1} (Altena and Kaab (2020)).
- Simulated velocities in the upper ablation area of up to 30-40 m a^{-1} agree well with feature-tracking estimates for this glacier section (Quincey et al., 2009).

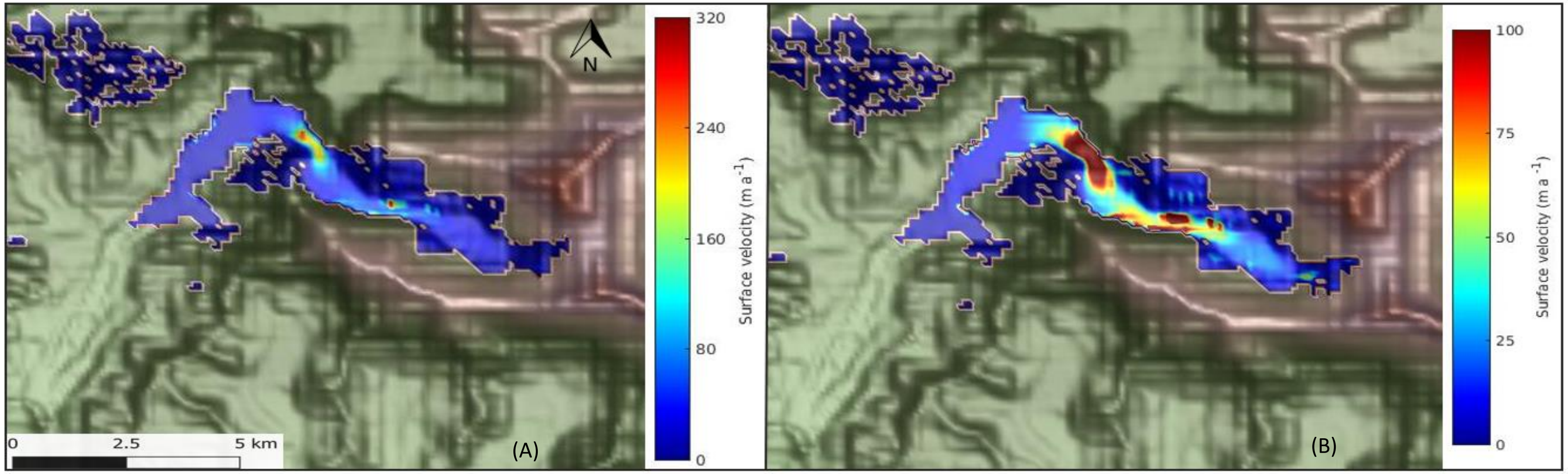

Fig 5 (A) Present day surface velocity and (B) capped at 100 m a^{-1}

Correspondence with Anya Schlich-Davies eeasd@leeds.ac.uk

Future precipitation increase can offset mass loss from warming

- The downscaled end of century NOAA climate under RCP 4.5 is 1.4℃ higher than present day (mean annual temperatures of -0.75℃ and -2.15℃, respectively).
- Glacier MB is similar under an end of century NOAA climate to present day as mass loss from warming is likely offset by the projected increased in precipitation (annual precipitation totals are 581 mm in the present day, against 665 mm per year in the future under RCP4.5).
- Despite this, the end of century glacier has receded by 2 km and thinned because of the delayed response of glaciers to a change in atmospheric forcing.
- Preliminary results from other simulations reveal substantial mass loss despite precipitation increase, under all future climate scenarios.

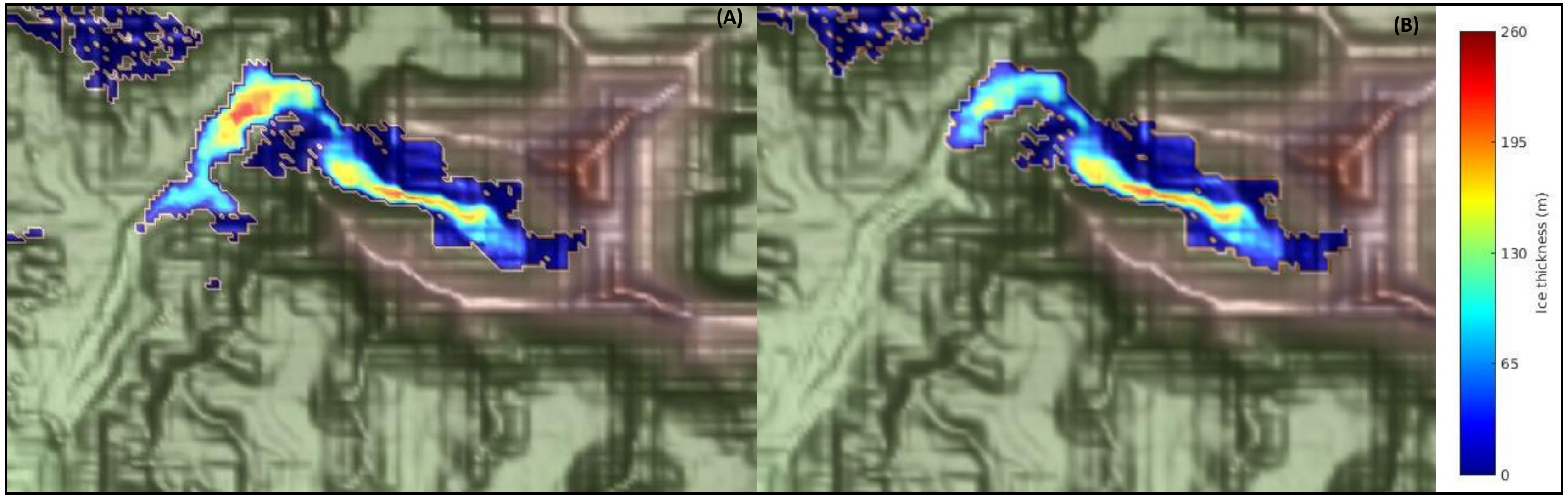

Fig 6: (A) Present day active glacier forced by NOAA driven MB and (B) End of century glacier forced by NOAA driven MB

Correspondence with Anya Schlich-Davies eeasd@leeds.ac.uk