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Modelling supraglacial debris-cover evolution from the single-glacier to the regional scale: an application to High Mountain Asia

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This Supplementary Material consist of (i) a Supplementary Method, (ii) Supplementary Results, (iii) a Supplementary Discussion section, (iv) 11 Figures and (v) 1 Table.

S1 Supplementary Methods

S1.1 2-D interpolation of the results

In Figures 9, S4 and S5, a graphical 2-dimensional extrapolation of the 1-dimensional modelled results is shown. This extrapolation is not physical-based, but is instead a geometrical extrapolation based on the RGI glacier extent. The 2-D images illustrate how glaciers (both glacier geometry and debris cover) could look in the future.

The extrapolation method works as follows: for each elevation band, the plotted ice and debris covered area correspond to the the modelled results by adapting the plotted glacier and debris width on that elevation band, where the 'redistribution' starts from the centre of the elevation band.

S2 Supplementary Results

In Addition to Langtang Glacier (Fig. 9 in main manuscript), here we also analyse the evolution of Baltoro Glacier (Fig. S4) and Inylcheck Glacier (Fig. S5).

Baltoro Glacier - like Langtang Glacier - shows a slower retreat when debris is explicitly accounted for compared to the simulations where debris is modelled implicitly. By the end of the century and according to the medium emission scenario SSP245, the glacier retreat difference between the explicitly and implicitly modelling debris reaches more than 15 km (Fig. S4a–c) by the end of the 21st century. The modeled fraction of the debris covered area is expected to increase from 25±1 % in 2020 to between 27±3 % (SSP119) and 38±8 % (SSP585) in 2100 (Fig. S4d). For the same time period (i.e. between 2020 and 2100), the mean debris thickness is projected to increase between 35±12 % (SSP119) and 140±85 % (SSP585) (Fig. S4g). This significant debris thickness increase is due to the long-term negative mass balance and today's thick debris cover (mean of 40 cm for the 2000-2016 reference period). Baltoro Glacier will lose between 24±17 % (SSP119) and 53± 26% (SSP585) of its 2020 ice volume by 2100 when modelling debris explicitly (Fig. S4e). The numbers change to between 30±28 % (SSP119) and 70±20 % (SSP585) when modelling debris implicitly (Fig. S4f). Similar differences are obtained when comparing the evolution of the glacier area with and without explicit representation of debris cover (Fig. S4h – i). This results shows the importance of explicitly modelling debris and its evolution.

Inylcheck Glacier has less debris cover compared to Langtang and Baltoro Glacier (both in terms of debris covered area fraction and mean thickness). The fraction of the debris-covered area is 22±1 % in 2020, and is projected to change to between 21±2 % (SSP119) and 44±8 % (SSP585) by the end of the century (vs. 2020). The mean debris thickness is projected to change between − 29±1 % (SSP119) and +35±13 (SSP585). The expected mean debris thickness decrease with low

SSPs (SSP119 and SSP126) is attributed to the loss of the frontal ca. 5 km of ice, which is covered by 0.5-0.8 m of debris, and which cannot be counterbalanced by the debris thickness increase of the up-glacier debris-covered areas of the glacier (which occurs under the warmer SSPs, see Fig. S5a-c). Due to the fact that Inylcheck Glacier has a small debris covered area fraction and generally thin debris thickness, the difference in geometry and therefore in volume and area evolution is relatively limited. Indeed, by 2100, Inylcheck Glacier is anticipated to lose between 16±2 % (SSP119) and 62±11 %(SSP585) of its 2020 ice volume when accounting for debris explicitly, and between 17±8 % (SSP119) and 61±10 % (SSP585) of its 2020 ice volume when using the implicit approach.

S3 Supplementary Discussion

S3.1 Glacier specific studies

Until now, only few studies have implemented in their model a time-dependent debris-cover evolution module (e.g. Jouvet et al., 2011; Rowan et al., 2015; Kienholz et al., 2017; Verhaegen et al., 2020). Despite that three of the four above-cited studies focus on glaciers outside the HMA region, here we qualitatively compare our methodology and results with those of the above cited studies. The aim of this section is to show that, in general, our debris evolution module has similarities with previous higher-order approaches, and that our debris evolution projections are in line with previous findings.

Jouvet et al. (2011) modelled the debris evolution of Grosser Aletschgletscher, Switzerland, initialising their model with observations of spatial debris distribution. In their model, debris-front propagates in the outward normal direction, and the debris divergence speed is prescribed by the mass balance and by a calibration parameter. This method is similar to our debris lateral expansion parametrization. The simulation showed that Grosser Aletschgletscher - which has two central moraines and a debris-cover of only 4 % in 2010 - can significantly gain debris with time, so that by 2100, depending on the calibration parameter, it could become a full debris-covered tongue. This significant debris-cover increase is also simulated on HMA glaciers using our module. E.g. for Kangjiaruo Glacier (which today has a debris-covered area of 14 %), debris covered fraction is modelled to increase in the future, resulting in a completely debris covered glacier tongue.

Herreid and Pellicciotti (2020) also described such a significant potentially increase in the debris covered fraction for Kangjiaruo Glaciers and the other HMA glaciers. In a nutshell, Herreid and Pellicciotti (2020) explain that in a warming climate, debris-covered glaciers with remaining debris expansion potential will gain debris through time, until reaching a glacier-specific maximum amount of debris, which show this hypothesis for Kangjiaruo Glacier, in close correspondence to our own results. However, as a second hypothesis, Herreid and Pellicciotti (2020) also indicate that another possible trajectory consists of a rapid glacier decline that outpaces debris-cover evolution. This second hypothesis is also confirmed by some of our results (e.g. Langtang Glacier). Indeed, especially for high SSPs (e.g. SSP370 and SSP585), glacier shrinkage is faster than the debris lateral expansion and up-glacier migration, resulting in a loss of the debris covered fraction.

Rowan et al. (2015) modelled the future evolution of Khumbu Glacier. Debris transport is simulated englacially and supraglacially, so that the feedback between ice flow and mass balance is accounted for. They showed that the debris-cover of Khumbu Glacier will develop on the tongue of the glacier near the upper part of the icefall by the end of the century. Indeed, at present, the icefall divides the debris-covered tongue from the debris-free accumulation area. Rowan et al. (2015) simulated that the debris cover will thicken by around 0.25-0.5 m between 2015 and 2100 across the glacier tongue. Although our method is strongly simplified, we also simulate a debris expansion in the upper part of Khumbu's Glacier icefall by the end of the century. Additionally, our model also shows a debris thickening by around 0.2 — 0.5 m for the same location and time period as modelled by Rowan et al. (2015).

Kienholz et al. (2017) modelled lateral expansion of debris for each elevation band based on a relationship between normalized elevation range and moraine lateral expansion on Black Rapids Glacier (Alaska). Again, our debris lateral expansion method - despite its simplicity - is similar to the author's method. As a result, Kienholz et al. (2017) showed that the debris-covered fraction of Black Rapids in the future will increase, principally due the debris lateral expansion. Although a direct comparison is not possible, our modelled debris cover evolution is generally comparable with the findings by Kienholz et al. (2017).

Verhaegen et al. (2020) modelled the future debris evolution of Djankuat Glacier (Caucasus). The authors simulated the debris lateral expansion through a parametrization based on an exponential relationship between the debris lateral expansion on a specific location on the glacier and its distance from the terminus. Debris thickness is modelled according to melt-out from ice, downstream advection of supraglacial debris and the intake or removal of supraglacial debris from the glacier surface. This relatively sophisticated model needs many input parameters, such as debris input location, the time of release of debris source, and debris flux magnitude (see Verhaegen et al., 2020, for more details). The authors demonstrated that changes in the input parameters, and therefore also accounting for debris-cover explicitly or implicitly, can have important implications in the future evolution of Djankaut Glacier. Similar to Verhaegen et al. (2020), our study shows that the expected evolution of glaciers can differ considerably if debris-cover is accounted for or omitted, and that parameter calibration can strongly influence model results.

S4 Supplementary figures

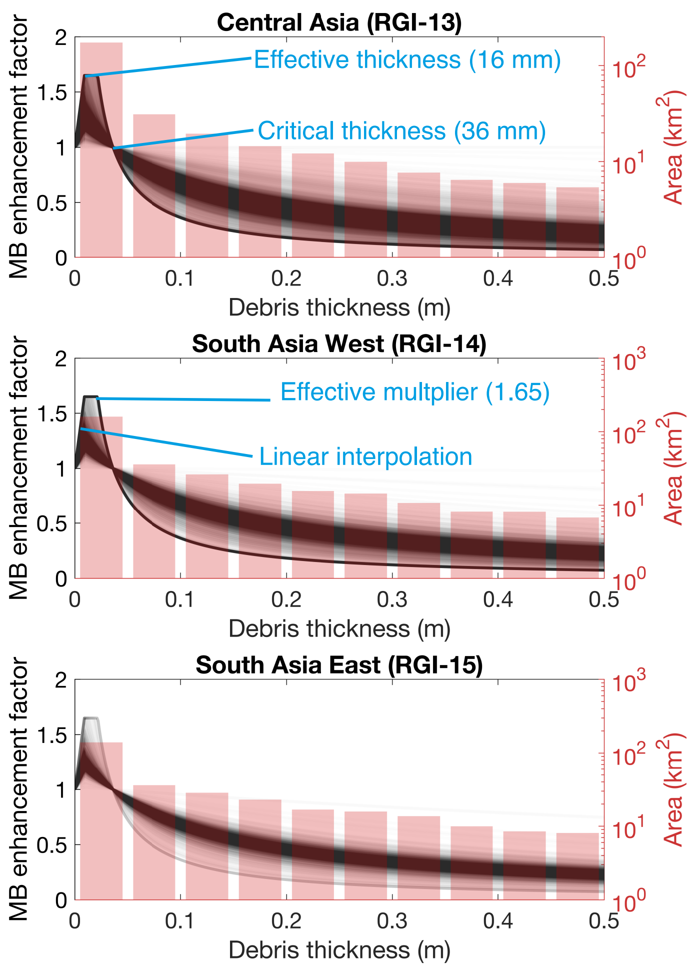

Figure S1: Mass balance (MB) enhancement factor as a function of debris thickness for the three RGI regions considered in this study. For every glacier a semi-transparent black line is potted. Overlapping lines thus become darker. Each semi-transparent black line corresponds to a glacier specific Østrem-curve. The red bars show debris covered area for a given debris thickness.

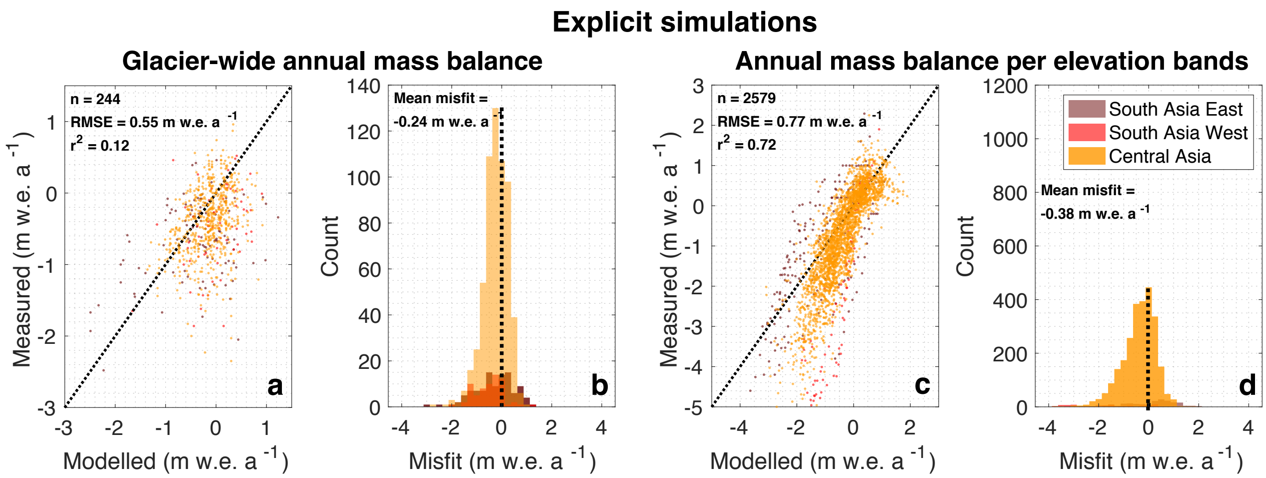

Figure S2: Evaluation of modelled annual glacier-wide and per elevation bands mass balance when explicitly modelling debris cover with observations from 21 glaciers provided by the World Glacier Monitoring Service (WGMS, 2020)

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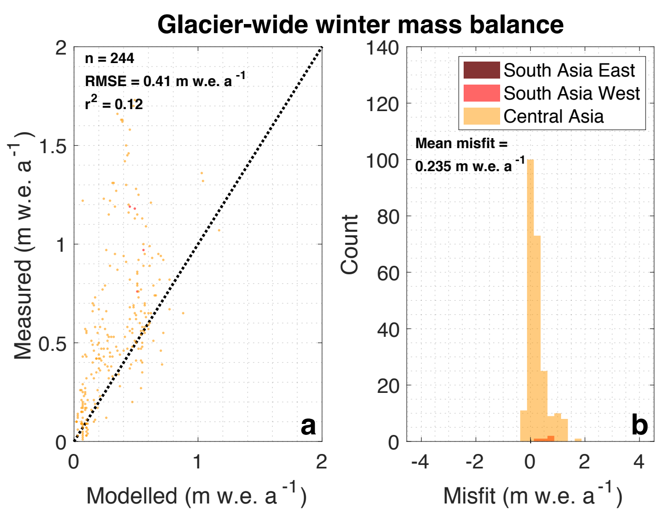

Figure S3: Evaluation of modelled glacier-wide winter mass balance with observations from 21 glaciers provided by the World Glacier Monitoring Service (WGMS, 2020)

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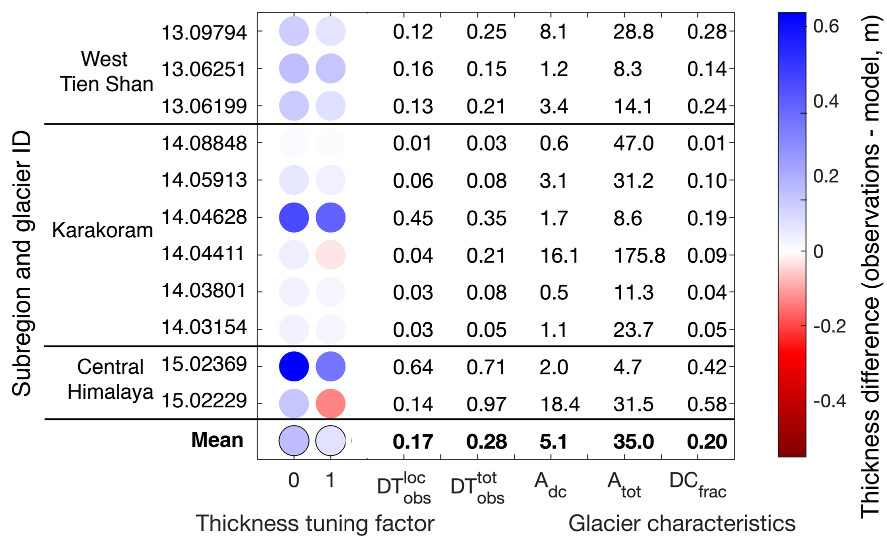

Figure S4: Same as Figure 5, but on glaciers set S2 and using 0 and 1.0 as $c_{thickening}$.

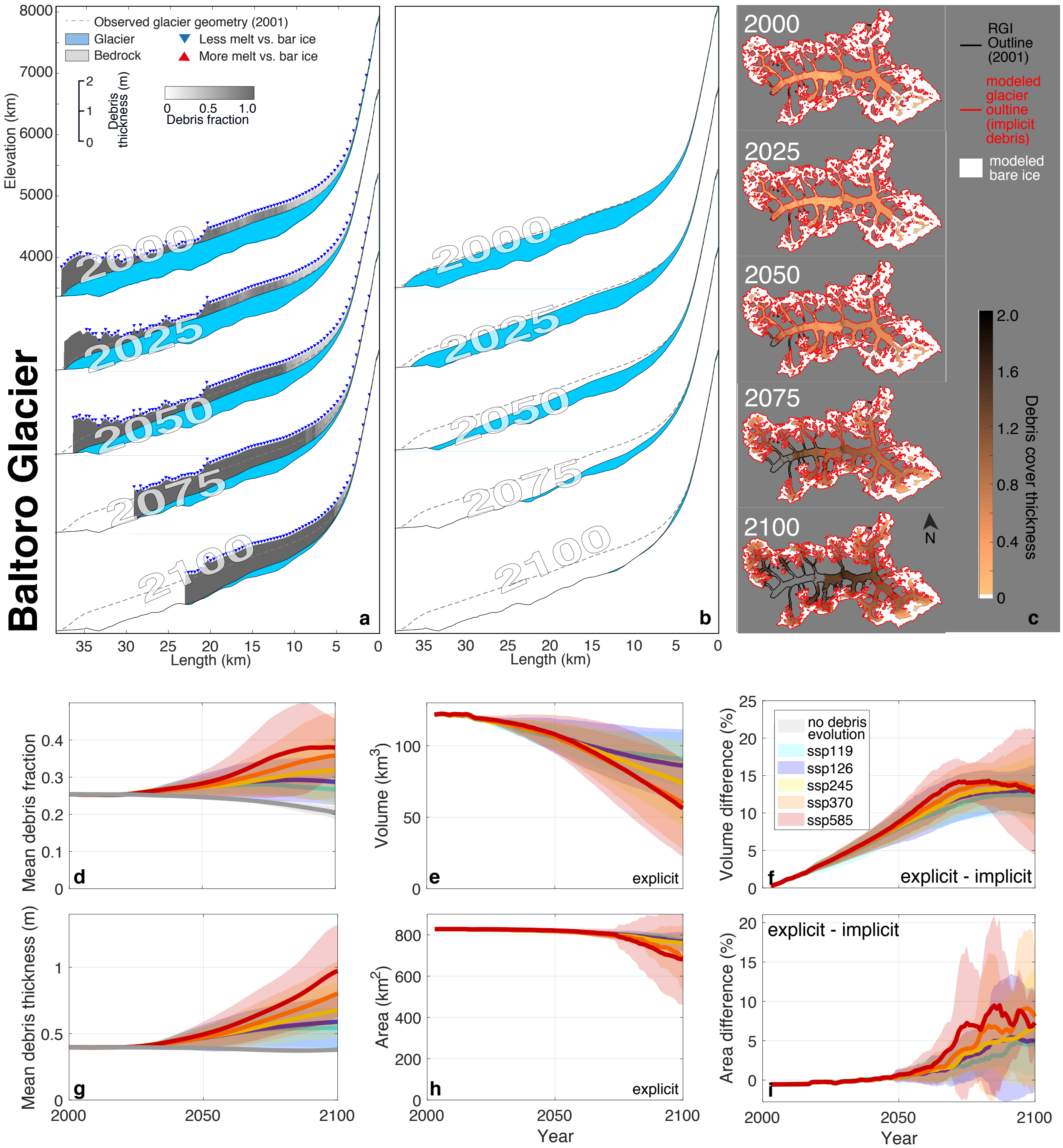

Figure S5: (**a**) Modelled evolution of Baltoro Glacier when debris is explicitly accounted for. The results refer to SSP245. Note that the debris thickness (grey) is exaggerated by a factor of 500 for visibility. The three parametrizations included in the debris-cover module (cf. section 3.2 and Figure 3) are indicated by the circled, colored numbers, and described in the text. (**b**) Same as (**a**), but accounting for debris implicitly, i.e. glacier evolution is not modelled with the new debris module, but by re-calibrating some of the model parameters to match observed long-term mass balance (see section 4.1 for details). (**c**) Model results extrapolated to 2D (see Supplementary Material for one to two dimensional extrapolation method). For every SSP, the evolution of (**d**) debris-cover fraction, (**e**) glacier volume with explicit debris-cover modelling, (**g**) debris thickness, and (**h**) glacier area with explicit modelling is shown. For every SSP (**f** and **i**) show the difference in glacier volume and area obtained when explicitly and implicitly debris-cover modelling the debris cover. The shaded ranges represent one standard deviation of all climate model members included in a given SSP. Note that Baltoro is a surging glacier.

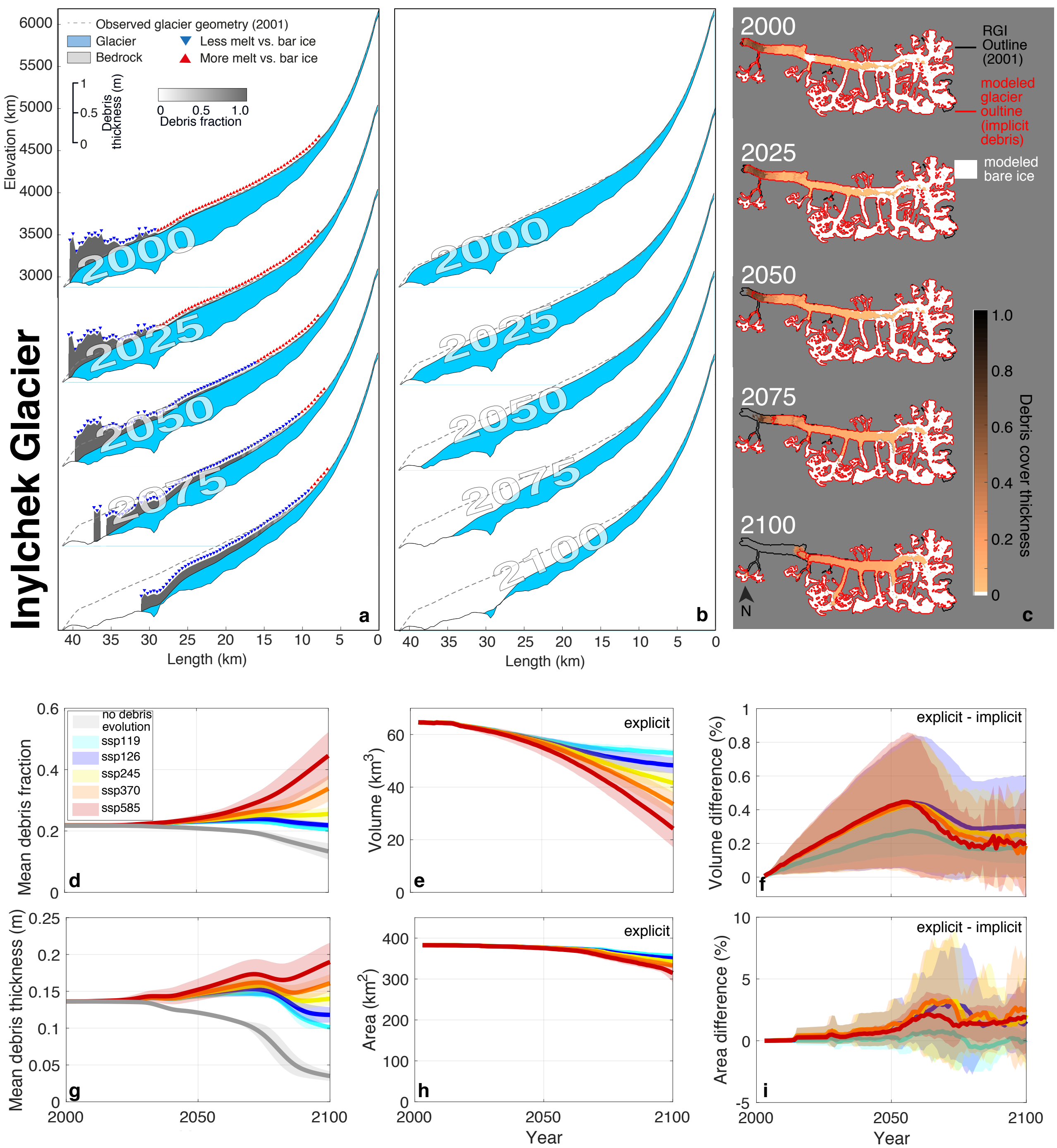

Figure S6: Like S5, but for Inylchek Glacier

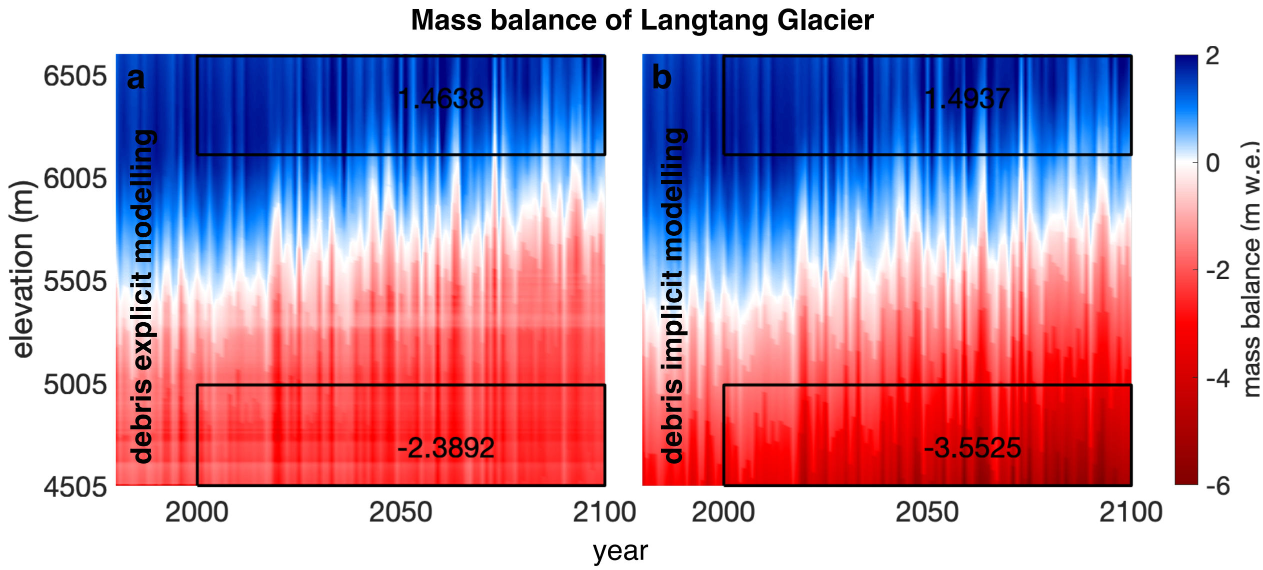

Figure S7: Mass balance evolution of Langtang Glacier with SSP245 when (**a**) modelling debris explicitly and (**b**) modelling debris cover implicitly. Note the higher mass balance gradient with elevation of (**b**).

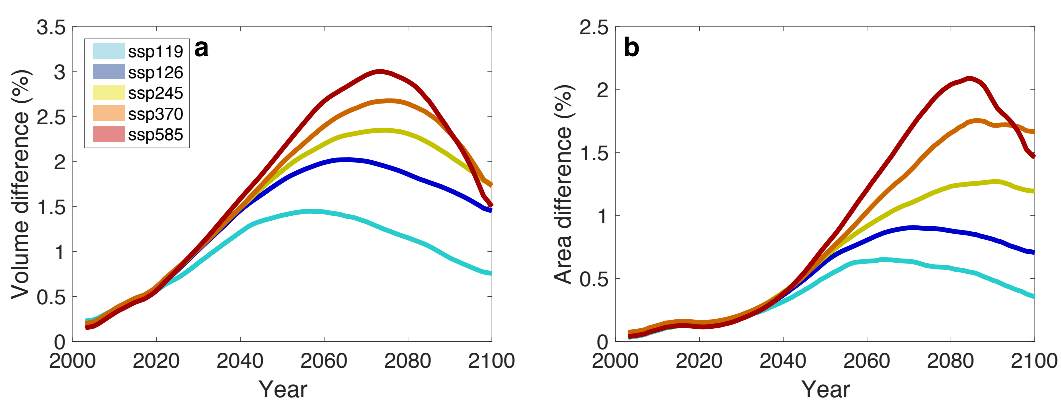

Figure S8: (**a**) Difference in volume evolution for all glaciers in HMA when modelling debris cover and evolution explicitly vs. implicitly. Positive numbers means that less ice volume is lost when debris cover is explicitly modelled. (**b**) Like (**a**), but for the area evolution.

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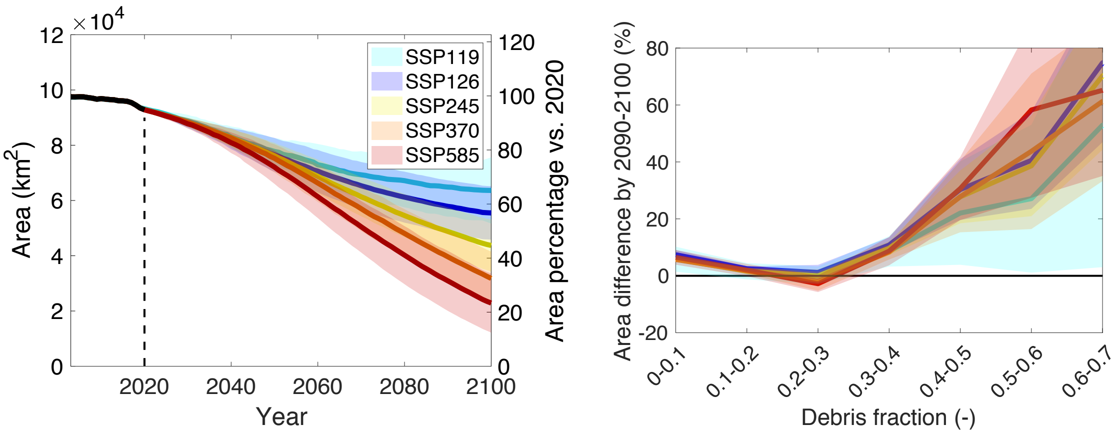

Figure S9: (**a**) Evolution of glacier area for all glaciers in HMA when explicitly modelling debris-cover changes. Results are aggregated to five SSPs (**b**) Difference in area (mean over 2090-2100) between implicit and explicit debris-cover modelling. The shaded bands represent one standard deviation of all climate model members for a given SSP.

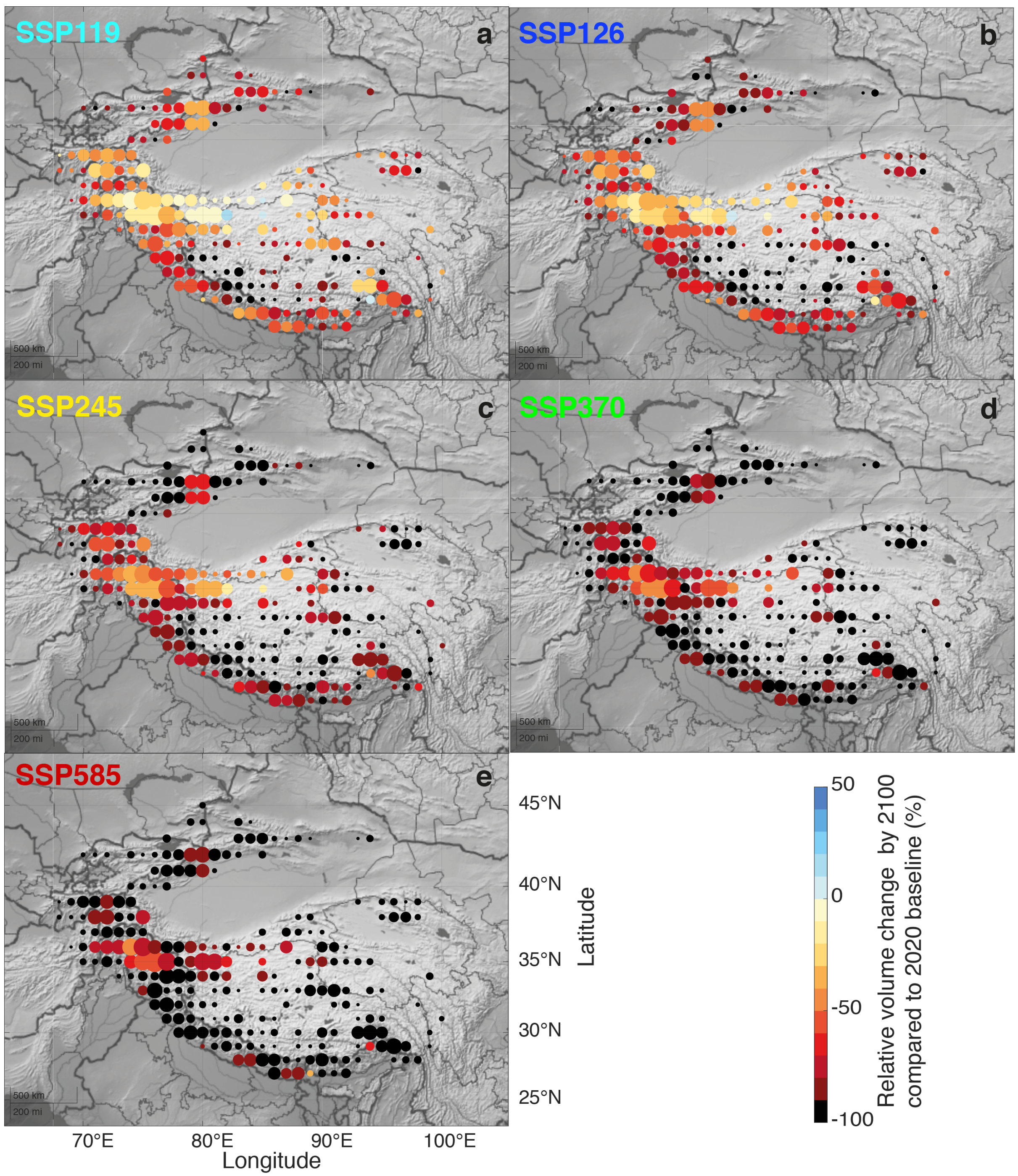

Figure S10: Regional volume evolution of HMA glaciers. The data is divided into a grid with 1° horizontal resolution.

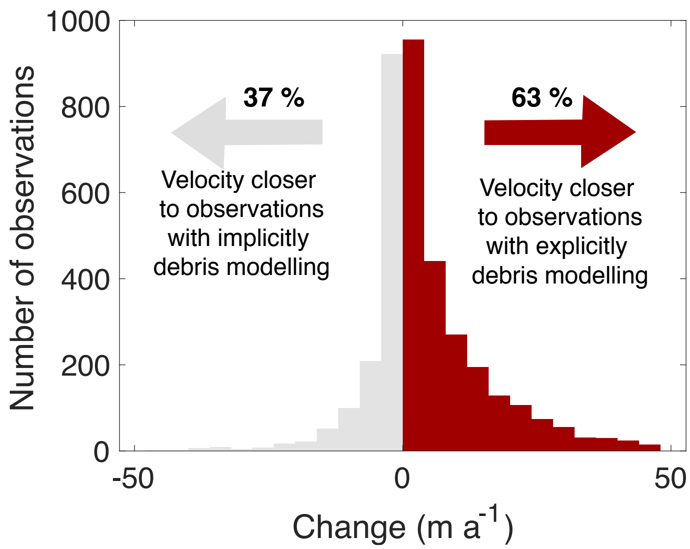

Figure S11: Change of the modelled velocity ($\mathrm{m\,a^{-1}}$) when modelling debris cover explicitly and implicitly. A positive change means that modelled velocity is closer to the ITS_LIVE surface velocity data set (Gardner et al., 2019).

S5 Supplementary Table

Table S1: Overview of studies containing value for critical thickness, effective thickness and effective multiplier.

Glacier	Country	Latitude (deg)	Elevation (m.a.s.l.)	Critical thickness (mm)	Effective thickness (mm)	Effective multiplier	Source
Khumbu	Nepal	27.57	5400	50	10	1.6	Kayastha et al. (2000)
Lirung	Nepal	28.13	4400	80	30	2	Tangborn and Rana (2000)
Rakhiot	Pakistan	35.21	3400	30	15	1.62	Mattson and Gardner (1989)
Barpu	Pakistan	36.11	4000	25	18	1.65	Khan (1989)
Baltoro	Pakistan	35.7	3500	20	10	1.36	Mihalcea et al. (2006)
Koxkar	China	41.76	3000	15	14	1.06	Juen et al. (2014)
Batal	India	32.3	4500				Sharma et al. (2016)
Baltoro	Pakistan	35.7	3500	35	15	1.3	Groos et al. (2018)
24K	China	29.7	4000	40	15	1.4	Wei et al. (2010)
Chorabari	India	30.8	4000	30	15	1.32	Dobhal et al. (2013),
Inylchek	Kyrgyzstan	42.16	3000				Hagg et al. (2008)
mean HMA				36	16	1.65	

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