Author's response to the comments received for tc-2021-31

The following pages contain a point-by-point reply to the comments provided by the two referees that reviewed our first submission (TC-2021-31)

Each of the referee's comment (**RC**) is numbered. If a comment contained several points, we numbered them, and address them individually in our author replies (**AR**).

REVIEWER 2 - LEIF S. ANDERSON

Overview

[RC 2.01] (i) This is an interesting study that simulates the expansion and thickening of debris and its affect on the response of debris-covered glaciers to climate change in HMA. There are new, simple parameterizations presented to represent the expansion and thickening of debris for application on both the individual and regional scales. It is shown that based on these parameterizations of debris thickness change and the assumptions held within that debris cover plays a minor role in glacier-wide mass balance evolution for simulations of HMA glaciers run out to 2100.

I applaud the immense effort put into this work and the novel contributions made. There are a number of exciting inferences and conclusions. **(ii)** But there are some major issues that need to be addressed before it is ready for publication.

[AC 2.01] (i) We thank the reviewer for the positive feedback and for the thorough review.
(ii) Below, we have addressed all issued raised by the reviewer. The manuscript was updated accordingly.

Major comments

[RC 2.02] *Correct citing of Equation 1*
Some important citations are omitted. Some of which need to be cited or (I hate to have to say it) plagiarism is occurring. I am directly referring to Eq. (1) which was derived in its exact form by Anderson and Anderson (2016). This model is also presented in detail in the debris cover melt model intercomparison project manuscript (Pellicotti et al., in prep). This form of Ostrem's curve is also referred to as the hyper-fit model by (Anderson et al., 2021a, b). I am personally glad it is useful it but please cite it appropriately.

[AC 2.02] It was far from our intentions to commit plagiarism, and we are very sorry that the references pointed out were missing. We now make mention of the reviewer's work when introducing Eq. 1:

l. 106-108: '*Note that equation 1 has similarities with the Hyper-fit model of Anderson and Anderson (2016), and Anderson et al. (2021a, b), although we note that the two approaches differ in the number of parameters and their interpretation.*'

[RC 2.03] *Neglected role of surface velocity in thickening and expanding debris*
(i) The mass conservation equation for surface debris thickness change in time on a glacier surface includes debris melt out and dynamic re-distribution of debris:

$$\frac{\partial h_{debris}}{\partial t} = \frac{C\dot{b}}{(1-\phi)\rho_r} - \frac{\partial u h_{debris}}{\partial x} - \frac{\partial v h_{debris}}{\partial y} \qquad (3)$$

where C is near-surface englacial debris concentration, φ is the porosity of the debris, ρ_r is the density of the rock composing the debris, and u is surface velocity in the x-direction and v is surface

Debris melt out is represented by the first term on the right and dynamic re-distribution of debris is represented by the second two terms on the right. This form is taken form Anderson et al. (2021b).

The parameterizations for debris thickness change presented here (Eqs. 4 and 6) do not include the effect of ice dynamics in changing debris extent or thickness. Equation 6 in this paper really only takes into account the debris melt out term in that debris thickness change is directly related to the melt rate as it varies in time by a factor (Eq. 4 is very similar):

$$h_{z,t} = h_{z,t-1} + abs(b_{z,t}) \cdot \overline{B_{(t-9,t)}} \cdot (-1) \cdot \overline{h_0} \cdot c_{thickening}, \quad \text{if } \gamma_{z,t-1} = 0 \qquad (6)$$

where $h_{z,t}$ is the debris thickness for elevation z and time t. $c_{thickening}$ is a calibration parameter for the debris-cover thickness evolution, constrained based on observations (see section 4.2). As for lateral debris expansion, the local mass balance $b_{z,t}$ relates linearly to debris thickness change. Higher melt rates will lead to faster debris thickening, thus implicitly assuming that debris concentrations within the ice are homogeneous. The long-term glacier-wide mass balance $\overline{B_{(t-9,t)}}$ mimics ice-dynamical processes. It leads to constant debris thickness for steady-state conditions ($\overline{B_{(t-9,t)}} = 0$), and to decreasing local debris thickness for consistent mass balances, thus mimicking the evacuation of debris with enhanced flow. This is in line with the few direct observations that are available (e.g. Gibson et al., 2017; Verhaegen et al., 2020). $\overline{h_0}$ is the mean debris thickness of the glacier at the inventory year. It parametrizes the effect that glaciers with a low mean debris thickness will thicken slower compared to glaciers with a high mean debris thickness. This is motivated by the assumption that glaciers with thick debris are likely to have a higher englacial debris concentration, indicative for high debris supplies from the surroundings.

(ii) Anderson and Anderson (2018) notes, using a theoretical analysis, that debris thickness patterns are strongly controlled by the inevitable decline of surface velocity down glacier. This is also basically outlined by Kirkbride (2000) and further supported by the modeling presented in Ferguson and Vieli (2021). I have not seen a compelling a reason in this manuscript why surface velocities should be neglected when considering the evolution of debris covers.

(iii) Furthermore, Anderson et al. (2021b) presents evidence that the dynamic effects of debris thickening (debris advection and debris compression) are unavoidably important for the thickening of debris in response to climate change. The dynamic affects on debris thickness are especially important where surface velocities are low and debris already tends to be thick. Meaning that debris might thicken substantially right where the model/parameterizations presented here is not accounting for it. This is because the thickening parameter is tuned with debris thickness estimates from the upglacier end of debris covers.

(iv) Anderson et al. (2021b) also shows how changes in flow patterns can change debris extent (I do believe this is mentioned breifly). I recognize that Anderson et al. (2021b) was published as this paper was coming out in TCD, but the work has direct implications for the parameterizations presented in this study.

(v) I don't think the neglect of the role of ice dynamics makes this work invalid, rather the fact that the dynamical terms in the debris conservation equation are neglected should really be discussed and stated very clearly in this paper. Right now half of the continuity equation for debris change is assumed to be negligible in this manuscript, but the affect of surface velocities on debris thickness is not negligible even where surface velocities are low.

(vi) It is difficult to evaluate this work without reading McCarthy et al., submitted and understanding how the debris thicknesses across HMA were estimated. I am not sure where to access that manuscript. How many validation data points are used to evaluate the debris thickness estimates in that study? What do the debris thickness patterns look like? In some way this pre-requisite work needs to be made available be thorough description here or elsewhere.

[AC 2.03]

(i) We thank the reviewer for providing us with the formula. From a theoretical point of view, it makes certainly sense to divide the debris thickness evolution into debris melt out and dynamic re-distribution of debris. However, note that this formula also assumes that the englacial debris concentration, the porosity of the debris, and the density of the rock composing the debris are completely known. At the regional scale (and mostly even at the local scale), such data are not available, leaving the formula with a number of unknowns. In our approach (Eq. 4 and Eq. 7), we do not account explicitly for the effect of surface velocity change. This is because during calibration it would be impossible to divide the observed debris-thickness change into the two necessary components (i.e. debris melt out and dynamic redistribution of debris). The latter would only be possible if the englacial debris concentration, the porosity of debris and the density of the rock composing the debris were known for each of the modelled glaciers. We emphasize that the physics-based analyses of debris evolution are vital for advancing understanding, but this is a reasonable first approach to represent the major changes in debris thickness patterns that should be expected, consistent with the modelling scope (climate projections).

That said, the dynamical redistribution of debris is not entirely omitted with our parameterizations. Rather, it is implicitly accounted for thanks to our calibration strategy. Indeed, the calibration of $c_{thickening}$ (and also $c_{lateral}$) with observations ensures that changes due to both debris melt out as well as dynamic re-distribution of debris are reproduced.

(ii) See above: our approach accounts for dynamical re-distribution implicitly (cf. 2.03 i). We agree that taking this into account explicitly (as done in Kirkbride (2000), Andrerson and Anderson (2018), and Ferguson and Vieli (2021), for example) would be ideal. It is impossible however at the scale of our investigation. Indeed that the mentioned studies either refer to synthetic glaciers (Andrerson and Anderson (2018), Ferguson and Vieli (2021)), or were only applied to extremely well-studied individual glaciers (Tasman Glacier in the case of Kirkbride, 2000). Applying similar methods to more than 6'000 glaciers in combination with climate forcing taken from more than 50 global circulation models would be computationally impossible, and severely limited by the lack of necessary input data. In brief, we argue that some simplifications are indispensable for regional-scale modelling, and this is exactly what our approach does.

(iii) This is not true. With our parameterization, the debris thickness will growth at a faster rate for areas with already thick debris cover compared to where debris is thinner (the debris thickness of a given elevation band is accounted for in in the second term of Equation 7). The same applies for Equation 4. Again, we note that our parameterization takes the effect of dynamic redistribution of debris into account implicitly. For an example of the results, see Fig. 8a, S6a and S6(b).

(iv) We added a reference to the mentioned paper, and we reformulated l. 262-265 to make our parameterization clearer:
'Combined with $b_{(z,t)}$, the long-term glacier-wide mass balance $B_{(t-9,t)}$ mimics ice-dynamical processes. It leads to constant debris thickness for steady-state conditions ($B_{(t-9,t)}$=0), to a

growth of debris thickness with negative mass balances (thus mimicking dynamic re-distribution of debris and its compression, e.g. Kirkbride, 2000; Anderson et al., 2021b; Ferguson and Vieli, 2021), and to decreasing debris thickness for positive mass balances (thus mimicking the evacuation of debris with enhanced flow).'

(v) We added a paragraph in the discussion section to discuss this topic:
l.497-503:*' Additional uncertainties arise also from the parameterizations themselves (Eqs. 4, 5 and 7). In a simplified but realistic way, our approach parameterizes the evolution of debris cover on glaciers, and it is based on debris-evolution patterns observed in the last decades. We acknowledge that this is not the only way that debris evolution could be parameterized. Accounting for debris re-distribution dynamics explicitly (as opposed to implicitly, see section 3.2.3) could be an option, as done by Anderson et al. (2021b), for example. We decided to include such processes implicitly (1) because the absence of data to calibrate and validate a more complex parameterization at regional/global scales, and (2) due to the small sensitivity of volume and area evolution to changes in the debris-cover evolution when considering the entire region (see previous paragraph).'*

(vi) We admit that it was our mistake not to provide the reviewers with the manuscript in review by McCarthy et al. The manuscript is now available at https://doi.org/10.31223/X5WW5B . Note that we reformulated the section referring to McCarthy et al. (in review) to clarify the methods (cf. AR 1.01). We used 148007 individual data points of 13 glaciers. However, the majority of these points come from closely spaced GPR measurements made on Ngozumpa Glacier. The median number of in-situ data points per glacier is 37. For the thickness pattern, there are typically an increase in debris thickness down-glacier toward the terminus, but there is also substantial variability between glaciers with different morphologies.

Minor comments

[RC 2.04] (a) There are places in the manuscript where the modelling results seem to be presented as reality but are really still just modeling results that rely on all of the assumptions inherent to the model design. More care should be taken to avoid overstatements.
(b) I also wonder: How do the debris change evaluations change if the evaluating datasets are not used in the tuning process?

[AR 2.04]
(a) We reworded many sentences in the results section, in order to clarify that we are presenting modelling results based on parameterizations, and not observations.

E.g.:

l 379-380: *'Figure 8a shows a profile view of the glacier and debris-cover evolution of Langtang Glacier according to our model results and SSP245.'*

l 394-395: '*As a result of the projected up-glacier migration, instead, the maximum elevation with supraglacial debris would increase by 280 m for the same time period.'*

l 397-398: *'With higher mass loss, our model results show that both debris-covered area and debris thickness increase, thus reducing ice melt.'*

l 409: *'Compared to 2020, the modelled mean debris thickness of Langtang Glacier is expected to […]'*

l 437-438: *'Locally, however, much higher debris thickness increases are modelled but these are offset at many places by the overall reduction in glacier area.'*

l 469-475: reformulated, see line by line comment AR 2.26.

(b) For calibration and validation different datasets are used. We imagine that here the reviewer is referring to the calibration and evaluation of the lateral spread out of debris cover (see **RC 2.22**).

In this case, it is correct that for the evaluation we use a subset of glaciers also used for the calibration. However, the analysis is initialized with different datasets and time periods. In the calibration, we used three to five Landsat scenes between 1989 and 2020. The model is initialized with debris extents of each of these scenes, and then compared with the older scenes. In the evaluation, we use Hexagon images of around 1974 as initial condition, and then we compare the model results with the Landsat scenes.

To investigate the sensitivity to these choices, we re-calibrated the model omitting all glaciers used in the evaluation. By doing so, the mean of the parameter $c_{lateral}$ is again found to be c_lateral=2.0 (as already used before in the manuscript). This shows that the results would not change if the glaciers used in the evaluation would not be used in the calibration, see figure below).

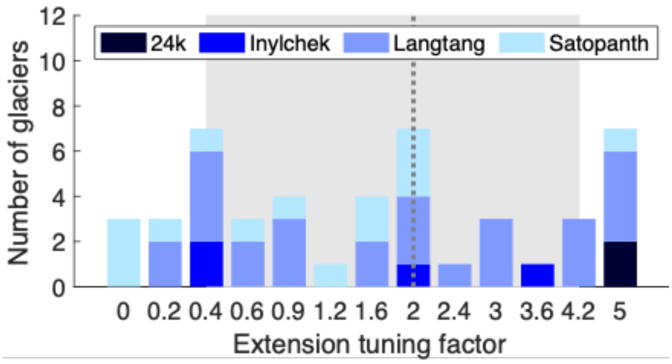


Figure AR1: Distribution of the extension tuning factor $c_{lateral}$ resulting in the lowest misfit between observed and modelled debris-fraction evolution (given per number of glaciers). In contrast to Figure 4, glaciers used in the evaluation are omitted during calibration. The grey dashed line shows the mean value while the grey rectangle shows values within the 0.25 and 0.75 quartiles.

Line-by-line comments

[RC 2.05] Line 3: You could remove 'potential' here

[AR 2.05] Removed

[RC 2.06] Line 5-8: The sentence should be split in two as it is hard to follow as written.

[AR 2.06] We split the sentence:
L. 5-8: *'The module is initialized with both glacier-specific observations of the debris' spatial distribution and estimates of debris thickness. These data sets account for the fact that debris can either enhance or reduce surface melt depending on thickness. Our model approach also enables representing the spatio-temporal evolution of debris extent and thickness.'*

[RC 2.07] Line 10: ‘previous projections’ would maybe be better here.

[AR 2.07] We rewrote the sentence into:
‘Explicitly accounting for debris cover has only a minor effect on the projected mass loss, which is in line with previous projections. Despite this small effect, we argue that the improved process representation is of added value when aiming at capturing intra-glacier scales, i.e. spatial mass balance distribution.’

[RC 2.08] Line 15: no need for a ‘-’ between debris and cover.

[AR 2.08] Removed

[RC 2.09] Line 48-51 see the inversion for debris thickness change by Anderson et al. (2021b) as an example of debris thickening. This paper also highlights how the change in direction in flow can lead to debris expansion.

[AR 2.09] cf. AR 2.03

[RC 2.10] Line 86. remove plural from ‘glaciers’

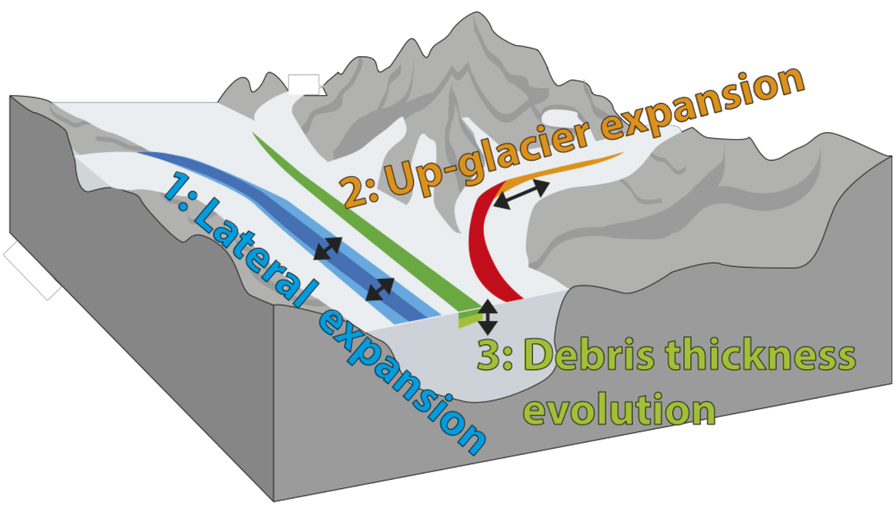
[AR 2.10] Corrected

[RC 2.11] Line 97. What do the variables represent beyond free parameters? I am surprised that Anderson and Anderson (2016) are not cited here. As that work originally derived this form of Ostrem curve and discussed what these free parameters represent in detail. The model is called ‘Hyper-fit’ in Anderson et al., (2021a) and Anderson et al. (2021b). I hate to have to say this by as the text is written this is plagiarism. Please cite this appropriately.

[AR 2.11] The two parameters have been fitted to results of an energy-balance model. For more details see AR 2.02. We have now acknowledged that this is similar to the ‘Hyper-fit’ model, although we derived, formulated, and interpreted the form of the equation independently.

[RC 2.12] Figure 3. The text in the figure is not legible in places.

[AR 2.12] We increase the font size and added a black border to the text in order to make it more legible.



[RC 2.13] Line 205. not sure what 'from the surroundings' means here.

[AR 2.13] We re-wrote the sentence into:
l. 223-224: *'Areas with abundant debris cover may grow faster due to enhanced debris supply from melt-out, or due to ice flow changes (Anderson, 2000; Anderson et al. 2021b)'*

[RC 2.14] Line 207. Deline (2005) is a valuable citation here.

[AR 2.14] We added the suggested reference in the manuscript.

[RC 2.15] (i) Section 3.2.2 this is an interesting parameterization but it should be stated that you assume that debris expansion is directly related to ELA change. **(ii)** As far as I am aware there are no datasets that show this as a direct relationship. Snowline change on glaciers is instantaneous but debris melt out does not need to be. **(iii)** This relationship is dependent on where englacial debris is present within the glacier.

[AR 2.15] (i) Yes, with this parametrization we assume that the debris expansion is directly related to the ELA change. We added this information to the manuscript:
l. 228-229: *'We assume that this is related to the rise of the ELA and to the melt-out of debris in areas that transit from the accumulation to the ablation zone (Anderson, 2000).'*

(ii) We agree that snowline change on glaciers is instantaneous but debris melt out does not need to be, therefore we compute the moving average of the ELA change over the last 10 years.

(iii) The parameterization expands the debris upglacier only from where it already exists (i.e. not in the middle of a clean ice glacier), thus accounting for the fact that englacial debris must not be present in every glacier or everywhere on the glacier.
Note that we reformulated also other parts of the section, as requested by reviewer 1 (cf. AR 1.16)

[RC 2.16] Line 221. "As for the lateral expansion of debris, the evolution of debris thickness is linked to internal debris concentration and glacier mass balance (e.g. Gibson et al., 2017; Mölg et al., 2019; Verhaegen et al., 2020)."
Please see Anderson et al. (2021b) for a detailed process-based simulation of debris thickening that shows the importance of debris advection and compression (both highly dependent on surface velocities) as well as debris melt out.

[AR 2.16] We added this information. We also discussed it in detail in AR 2.04.
l. 242-244: *'As for the lateral expansion of debris, the evolution is linked to internal debris concentration and glacier mass balance (e.g. Gibson et al., 2017; Mölg et al., 2019; Verhaegen et al., 2020), as well as to changes in ice flow velocity (e.g. Anderson et al., 2021b)'*

[RC 2.17] Line 221. Also the change in surface velocity of the glacier: see Anderson et al (2021b)

[AR 2.17] cf. AR 2.03 and cf. AR 2.16

[RC 2.18] 252. 'w.e.a –1' add a space.

[AR 2.18] We added the spaces (w.e. a^{-1})

[RC 2.19] 270. At this point I had forgotten what S1 was. Might be helpful for readers to remind them here?

[AR 2.19] We added what set S1 is:
'To determine $c_{lateral}$, we use the debris-cover observations obtained from the Landsat scenes (set S1, composed of 55 glaciers with debris. See section 2 and e.g. Fig. 4a).'

[RC 2.20] Section 4.2.2 This is a clever approach but again this is emphasizing the role of debris melt out as the only process that causes debris thickening. It is again hard to know though the validity of the McCarthy dataset without access to the errors from in situ debris thickness measurements.

[AR 2.20] Please refer to AR 2.03.

[RC 2.21] Section 5.2 It would be helpful to remind the reader where the pre-2000s climate forcings are coming from for the evaluation of the debris change. Maybe just re-state it or reference the section.

[AR 2.21] Before 2020 we always use ERA5 reanalysis. We added this information in the manuscript.
l. 339-341: *'To evaluate the parametrization for lateral debris expansion, 18 glaciers (set S1 with Hexagon satellite observations) within three sub-regions (Central Himalaya, West Himalaya and West Tien Shan) are simulated from 1974 to 2020 (forcing the model with ERA5 climate).'*

[RC 2.22] 313. So you evaluate the lateral expansion parameretrization against the data that you used to tune it? I wonder how the parameterization works on glaciers that are independent of the tuning dataset?

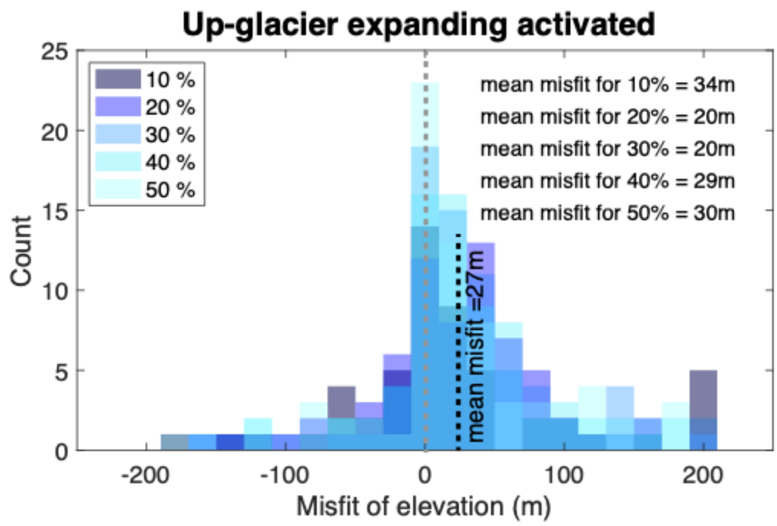
[AR 2.22] Please see AR 2.04 b

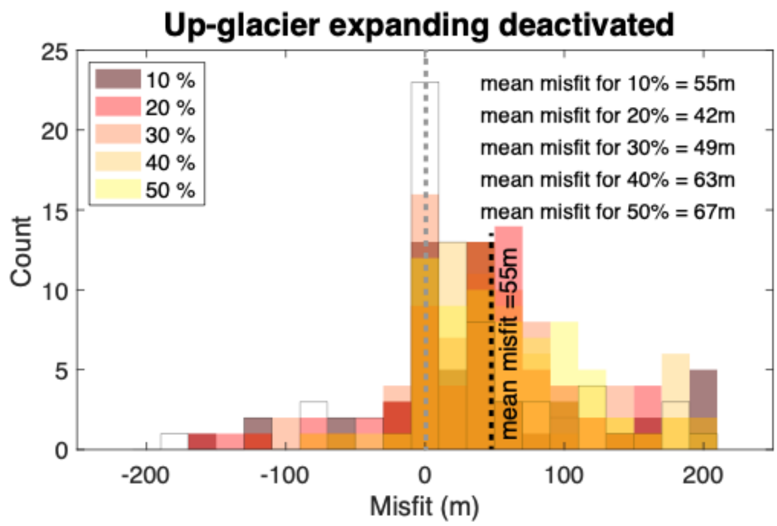
[RC 2.23] 344-346. This is an overstatement. Being off by 10 cm or ~20 cm of debris thickness, using the h_star values (same as (k_debris) in Equation 1) (the debris thickness change needed to reduce sub-debris melt rates by 50%) from A and A (2106) mean sub-debris melt rates are off by 50 to 100% or 200 to 400%. This uses h_star values = 5 cm and 10 cm. These percentages will be even bigger with melt amplification effects included. Since the evaluation of the debris thickness change estimates are coming
from the upglacier end of debris covers the errors are actually quite large.

[AR 2.23] We need evaluation data for debris thickness changes and englacial concentration that are representative for different parts of debris-covered glaciers, including the debris emergence region (Stewart et al., 2020) as well as the terminus. It is noteworthy that a single debris concentration is a key step forward for this (e.g. Anderson et al, 2021b) but insufficient given the variations in englacial debris concentration (e.g. Anderson and Anderson, 2018; Miles et al, 2021).

[RC 2.24] Figure 7. It would be helpful for the reader if the x axis was extended beyond +-200 m

[AR 2.24] We changed the limit of the axis to +-250 m, highlighting that there is no data beyond this range.





[RC 2.25] 358. In the ablation zone or across the whole glacier?

[AR 2.25] In the ablation zone. We changed the sentence into:
L. 385-386: *'This leads to a nearly homogeneous downwasting of the ablation zone (e.g. Pellicciotti et al., 2015; Ragettli et al., 2016) rather than to a retreat of the terminus (e.g. Benn et al., 2012).'*

[RC 2.26] 439-440. "In fact, accounting for the debris cover explicitly enables the model to correctly represent the driving processes, rather than compensating the lack of model capabilities through a suitable parameter choice."
I suggest that this be re-written as it is a significant overstatement from my reading. The explicit model presented here neglects the role of debris advection and compression and is evaluated with highly uncertain modelled debris thickness estimates. I would replace 'correctly' throughout this paragraph.

[AR 2.26] We adapted the sentence in order to avoid the impression of an overstatement. As suggested by the reviewer, we also adapted the rest of this paragraph:
l.469-475: *'In fact, accounting for the debris cover explicitly enables the model to mimic the driving processes, rather than compensating the lack of model capabilities through a suitable parameter choice. This is important, especially when results other than area and volume changes are of interest. Indeed, quantities such as the local mass balance, the glaciers' ice flow velocity and mass turnover, the glacier's length change or water runoff, are only captured adequately when explicitly accounting for supraglacial debris and its temporal evolution. These quantities, in turn, have to be*

modelled appropriately when aiming at anticipating other glacier-related processes, such as hazards from ice-dammed or proglacial lakes, or potential slope instabilities.'

[RC 2.27] 446. Citations would be helpful here.

[AR 2.27] We added two citations: Kraaijenbrink et al. and 2017 and Rounce et al., 2021. l.450-476-479: *'Compared to the static representation of supraglacial debris cover that is presently included in some regional to global glacier models (e.g. Kraaijenbrink et al., 2017; Rounce et al., 2021), the expected increase in both debris-cover fraction and local debris thickness will enhance the insulating effects of the debris cover.*

[RC 2.28] Section 7.2 Nice to have this clear statement of the sensitivity!

[AR 2.28] We thank the reviewer.

[RC 2.29] 457. Also from the assumptions held within each parameterization.

[AR 2.29] True. We added a paragraph describing this (cf. AR 2.03 v)

[RC 2.30] Section 7.3 Interesting analysis/results.

[AR 2.30] We thank the reviewer.

[RC 2.31] 519. when only debris melt out is included.

[AR 2.31] We added 'with our approach' to clarify:
l. 557-558*:'Averaged over the transient glacier area, our approach anticipates the mean debris thickness to increase only slightly'*

[RC 2.32] 528. typo

[AR 2.32] We are somewhat embarrassed but can't find any typo at this line. Possibly it is a different line than former L. 528?

REFERENCE:

Compagno, L., Zekollari, H., Huss, M. & Farinotti, D. Limited impact of climate forcing products on future glacier evolution in Scandinavia and Iceland. *J. Glaciol.* **67**, 727–743 (2021b).

Stewart, L. G., Lavers, J. L., Grant, M. L., Puskic, P. S. & Bond, A. L. Seasonal ingestion of anthropogenic debris in an urban population of gulls. *Marine Pollution Bulletin* **160**, 111549 (2020).