Review of Harmeier et al. (2025): Modelling debris-covered glacier dynamics: transient response to changes and feedbacks in debris and climate forcing

Summary

This manuscript of Hardmeier et al. (2025) investigates the dynamics of debris-covered glaciers using 1D numerical flowline modelling, with the aim of improving understanding of how debris affects glacier behavior. The study focuses on the coupled evolution of glacier flow and debris cover, exploring the feedbacks between debris thickness, melt rates, and glacier geometry. The authors implement a modelling framework that simulates debris transport and glacier evolution, enabling the investigation of the development of spatial debris thickness patterns, the influence of debris on melt rates and glacier mass balance, and feedbacks between debris cover and glacier flow dynamics. The study aims to contribute to improved understanding of debris-covered glacier evolution under climate change.

The manuscript addresses a relevant scientific problem and poses a clear motivation for attempting the research. Debris-covered glaciers namely represent a significant fraction of glacierized area in many mountain regions and strongly modify glacier response to climate forcing. Numerical modelling studies are essential to investigate the corresponding debris-ice interactions because direct field observations remain sparse and time scales at which these processes work are long. In that sense, the manuscript is scientifically valuable and should ultimately be suitable for publication. However, some scientific and structural issues here and there need to be addressed before publication. I recommend major revisions to (i) strengthen the readability of the paper and improving its structure, (ii) explicitly elaborate more on novelties and distinguishing it from confirmed previous findings, and (iii) better frame the outcomes of the study within the specific model setting and parameter choices. I suggest publication once the comments below have been addressed.

Major comments:

1. **Paper structure and length**: I think this paper is very extensive, and sometimes even a bit too much. Some parts of the paper are very large (e.g. the introduction). Sometimes it reads a bit more like a thesis rather than a scientific publication. Anyway, I think some parts of the manuscript can be reduced in longevity of the text to avoid that the reader gets lost in huge amounts of information, either by condensing the text, avoiding repetition of earlier-stated stuff, or moving text to other paragraphs in the manuscript. See for example my comments on L12, L94-104, L225-236 below. Some relevant information (such as justification of the chosen value of the reference debris input rates, or aspects related to the D_0 parameter) is also

intertwined within different sections or mentioned too early/too late in the manuscript (e.g. comments L164, L298, L476-482, L490-495, L622-624). Some statements also deserve more references (e.g. L15-19, L30, L52-53).

2. **Distinction between new and confirmed model physics and findings**: In several occasions, the authors mention that they have found newly discovered effects and integrated new model capabilities. I think the authors can be clearer about what exactly is new in their model when compared to previous models (see e.g. comment on L87, L89, L630) and which findings are new or confirm previous findings (see e.g. comment on L265-274, L440, L635-656). This has not become very clear from the text. The authors should also state explicitly how their (newly found) findings advance the science and understanding of debris-covered glacier behavior (e.g. comment L663).
3. **Interpretation of main findings within the context of model setting/limitations**: I think it is important that the authors stress more clearly that their findings must be interpreted within the context of the main model setting (see for example comments on L367 and S3.4.2, L656). Also the model limitations and how this can affect the main findings can be discussed more extensively, as this paragraph misses some important aspects (e.g. resolution-dependency of results, explicit quantification of debris mass conservation (i.e. is the debris input flux equal to the debris output flux at the terminus in steady state?, see comment appendix B2), and more general limitations related to the model physics, see comments L135, L627).

Minor comments:

L1: ‘parts’ -> maybe ‘aspects’ is a better word.

L2: insulating effect -> maybe state it corresponds to relatively thicker debris, since thin debris can enhance melt.

L11: What do you specifically mean with ‘non-linearity of transient glacier response’?

L12: The introduction is quite extensive, maybe try to compact some of the information. For example, I question whether L34-40 are already necessary here but can maybe be moved to S3.1.1 where you mention the effect of debris supply rates; maybe L54-84 can be moved to the Methods section before you explain your own model; or L94-104 may be integrated into S2.7.

L15: I think you can give more references here about work that has attempted to model debris-covered glacier behavior

L16-17: can you give some specific examples here?

L19: are there not more recent references that you can add?

L21 ‘leads’ -> maybe better state ‘can potentially lead’

L30: Kneib et al. (2023) is not the first to argue this, maybe add some more references

L52-53: References needed

L87: Can you elaborate more about what is ‘new’? Is it not the same model set-up as in Anderson and Anderson (2016) but with the glacier geometry from Ferguson and Vieli (2021)?

L88-89: uses ‘many’ elements, but you mention only one example.

L89: ‘novel’ -> again mention what is new about it.

L95: ELA -> define acronym when using it for the first time

L94-104: These are a lot of mentioning of conducted and planned experiments, cannot this information be condensed a bit more to decrease the information load?

L116-124: Can be condensed.

L129: There is no basal sliding, correct?

L135: Can you maybe add something about the ice rheology of your model? The equations that you mention here are only valid for isothermal ice (constant A). Also, what are the kinematic boundary conditions in the model and do they correspond to their theoretical values? Did you check the overall mass conservation within the ice dynamic model (i.e. du/dx = -dw/dz)?

L139: Can you mention the units of C?

L158: Why does accumulation need to be limited at higher elevations? An alternative would be to just use two SMB gradients, one above and below the ELA.

L163: How does it describe the shape of the Ostrem curve? Does ‘characteristic’ mean here according to a e^-1 length scale? Explicitly state that melt enhancement for thin debris is omitted.

L164: Because there is a substantial reported variability of the parameter D_0, do you do some sensitivity experiments with respect to this parameter? Maybe already mention the info from lines L474-476 here. Maybe it would also be an idea to integrate the relationship between melt modification and debris thickness as an inset somewhere (for example in Fig. 1) to better visualize the patterns instead of mentioning it only in the Appendix (I think it is quite an important figure and an important parameter to keep in mind for interpreting your results). Is there for example a debris thickness where melt goes to 0 (we don't see what happens for a debris thickness >0.45m in your Fig. C2)?

L181: You say you keep the entrainment rate independent of the accumulation rate, but is it also not logical that if the accumulation layer remaining at the end of the balance year is smaller, less debris can get buried into the glacier? By the way, in L192 you mention that it is dependent on the accumulation rate. Please be clear here.

L184-195 and Figure 1. Not the easiest to understand. What do you mean with the 'surface grid cell' in L187? Only at the debris input location or the surface grid cells along the entire flow line? I also might be confused but why does the advected concentration C_s(t-1,j-1) in Eq. 11 only have an index related to horizontal (j) and not vertical directions (for example in the ablation area the movement of ice is upward relative to the ice surface)? And why does the surface debris concentration (Eq. 11) specifically need to be calculated in a different way then the rest (Eq. 6)? How does C_s(t) relate to ψ here?

Figure 1: Can you maybe explicitly state that the red box inset with title 't-1' corresponds to the red box in the debris deposition zone? Also you mention grid point 'j' in the caption as the uppermost cells, but 'j' in the insets is placed at the lowermost cells? And what is 'm' (it is not yet defined up to this point)? Which grid point is 'j' here? Also C_0 enters the image here to influence C_s(t), but it is not mentioned in Eq. 11, where does it come from? I'm sure the figure makes sense when you know the model and equations well, but for first-time readers I think the figure deserves some extra clarification.

L216: Can you justify the chosen geometry? Or why do you think this geometry is representative for the reference tests?

L222: What do you numerically define as steady state?

L225-236: overlap with L94-104. I feel there is a lot of repetition, and the info can be condensed.

L232: Model 'robustness' -> so in the end, based on which qualifications or findings would you call your model 'robust' or not?

Table 1 and S3.1.1: d_in -> Can you also transform it into a debris mass input flux (kg yr-1)? And where does this specific value for d_in come from? Can you justify this as being a representative value?

L249-256 and Fig. 2. That is a nice figure. Can you maybe integrate the flow vectors into the plot? This could enhance the visibility of the englacial flow paths. I also feel like the debris does not go that deep inside the glacier, despite the input location being quite close to the headwall. How should the little step of the debris thickness at the glacier terminus be interpreted in panel b?

L257-264 and Fig. 3. Looks cool. Are the different d_in values chosen arbitrarily? Please clarify in the text. Can you also maybe include a scatter plot of the debris surface volume vs. d_in as an inset to visualize your statement in L260? Also, it seems the mass balance still has quite a bit of melt (around ~-0.5 m w.e. yr-1) despite the debris being almost 1.5 m thick in the red curve in panel 3b. I would expect it to go even more towards 0. In your figure C2, we cannot see how much a debris thickness of 1-1.5m modifies the melt.

L256: Can you confirm here that both the glacier geometry and debris mass is in steady state based on how do you defined it (i.e. what is steady state quantitatively here)? Does the debris model conserve mass (i.e. is the debris input equal to the debris output mass at the terminus) in steady state? It would be nice to show the transient evolution of (i) the glacier volume and (ii) debris input/output terms or debris mass towards steady state to get an indication of how long it takes to reach it.

Table 2: very useful. Can you maybe also include the respective sections where you treat the experiments?

L265-274 and Fig. 4: All very cool, but is this not just a repetition of the experiments of Anderson and Anderson? What is the added value? Maybe you can frame it within a qualitative model validation attempt or something, where you check whether the model does what is expected from earlier models and theory.

L275-287 and Fig. 5: I wonder if this linear trend can be extrapolated when even higher debris input values are inserted into the model. Maybe you can include an additional experiment or two/three with even higher debris input rates to see whether the relationship also holds under very extensive and very thick debris zones (or maybe some non-linearity kicks in?). Therefore, I would also add in L287: “linearly dependent within the explored debris input magnitude range” or something.

L298: Change of ELA of 100 m corresponds to what typical temperature change? (This is later mentioned in L369 but could already be moved to here.)

L305: Can you please define how you calculate glacier length and volume in the case of detached dead ice bodies? Is it the sum of all ice-covered grid points or only the index of the last ice-covered grid point of the active glacier?

Figure 6. Panels e and f have no units in the vertical axis labels.

L337: You say here you change d_in from 1 to 9 mm yr-1, but in Table 2 you indicated 0-22.5 mm yr-1 for this experiment?

L342: A bit confusing to start talking about the deb-3 experiment here (within the section about deb-1 and without even talking about deb-2 first).

Figure 8. Difficult to read from the graph what the actual d_in value is with the logarithmic scale in panel a.

L367: 'changes in ELA seem much more impactful than changes in debris input' -> Yes, but I think this statement should be interpreted within the context of your reference values. Maybe for another characteristic debris thickness value in the melt-modification parametrization or bedrock slope (which impacts ice flow velocity and hence debris accumulation on the surface), changing d_in could become more important?

S3.4.2: Do you think this detachment is solely caused by irregular bedrock topographies? Could it be that this feature is more easily produced by your model if you incorporate the relative melt enhancement for thin debris? As before, I think this statement should be interpreted within the context of your model setting. By the way, why specifically choose this glacier? What makes it representative enough for applying your model to it?

Figure 10b: add the to label whether this is glacier or debris volume for clarity.

Figure 11: this is the same experiment as the grey curve in Fig. 10, right? Maybe add in the caption for clarification. Re-arrange the labels of the vertical axis on the left, they almost touch each other.

Figure 12: can you explain why the debris thickness profile is much more irregular (zig-zag) for the ELA=2800m case here?

Figure 11 vs. 13: I'm a bit confused here because you say the ELA forcing is from SSP2-4.5 scenarios in both (a) panels of the figures but the ELA forcing looks different in both graphs (one goes up to 3000m and the other up to 3300m at time=3000yr)? Maybe it should be clarified more in the caption if I missed something here. Can you also add labels to the vertical axis of panels (c) and (e) in Fig. 13?

L440: 'which has not been documented in any other study.' -> I think the paper of Anderson et al. (2018) demonstrated this behavior.

L476-482 and L490-495: I think this can be moved to the limitations section.

L588: Formatting of the in-text reference.

L596: Should also be mentioned in the limitations section.

L600: I think the point before '(ii)' should be a comma here.

L605-610: Why is that, do you have an explanation for this phenomenon? How much mass is (not) conserved when you compare the debris input flux to the debris output flux at the terminus in steady state? You should be more explicit in stating whether your model conserves debris mass or not and illustrate it quantitatively.

L620: nothing is mentioned here about the relative melt enhancement that could occur for thin debris…

L622-624: Should have been mentioned earlier (e.g. in S3.1.1).

L627: I think some more detailed processes could be mentioned here: for example, climate-dependent debris input rates (L490-495), simple geometry (what about more complex geometries and the omission of multi-dimensionality in your model?), coupling of debris thickness-melt modification to an energy balance model, spatially and temporally varying debris properties, supraglacial pond formation/meltwater redistribution or other cryokarst-type features, omission of subglacial debris entrainment and basal debris production in your model, omission of gravitational redistribution processes of debris (i.e. rock tumbling and stuff), or any adjustment of the ice rheology associated with the entrainment of debris fragments in the ice or heavy debris loads on top of the ice impacting the driving stress, other processes that can impact debris thickness (i.e. debris compaction/densification over time, falling of debris into crevasses, …), etc. These statements also deserve some references. By the way, concerning limitations, did you test resolution-dependency of your model results? I think this at least deserves a mentioning in the text.

L627: Imagine I want to apply your model to a specific glacier, what should I consider? Is this model easily transferrable and which input data do I need?

L630: Okay, but what specifically has been improved?

L632: 'assess the numerical robustness' -> how? You didn't do any experiments related to numerical resolution-dependency and I think the debris mass conservation could be more explicitly mentioned.

L635-656: which of these findings are new, and which confirm previous findings?

L656: I think it is again important to frame your findings within the specific context of your model, maybe including relative melt enhancement for thin debris (for example for dead ice body formation) or a different terminal boundary condition implementation would result in (slightly) different conclusions?

L663: I'm missing here an overarching statement why your findings would be important and society relevant (for example glacio-hydrological and glacio-geomorphological processes, natural hazard management, water resources, etc.).

Appendix B: Model 'robustness' -> so in the end, based on which qualifications or findings would you call your model 'robust' or not?

Appendix B2: I think this is an important aspect of the model and should be moved and discussed more properly into the main text. Can you specifically quantify how much mass is conserved? How do debris input fluxes compare to output fluxes at the terminus in steady state (should be the same amount of mass is conserved)? Does the Smolarkiewicz scheme impact mass conservation?

Fig. C2: Also this is an important figure and should be kept in mind when properly interpreting your results. Should also be moved to the main text.