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Interactive comment on "Modelling debris transport within glaciers by advection in a full-Stokes ice flow model" *by* Anna Wirbel et al.

Anonymous Referee #2

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Review of Wirbel et. al 2017 manuscript submitted to The Cryosphere

In this contribution, Wirbel et. al. develop and test a new 3D physics-based model for the transport of englacial debris. The authors build off of an existing full-Stokes model for ice velocities, but (1) develop a new model for the debris advection component and (2) spend a considerable amount of effort developing and testing a scheme for efficient mesh optimization. The resulting model is evaluated against benchmark tests and a few idealized 2-D and 3-D englacial debris transport scenarios.

This paper is an excellent example of thorough attention to detail in model development. The authors should be commended. Furthermore, the paper is well written,

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well organized, and displays a solid command of the numerical challenges involved in addressing their intended problem. From a technical and execution perspective, I have very little criticism. This work will make a significant contribution to an important and increasingly topical aspect of mountain glaciology. I very much look forward to future developments of the model (coupled ablation / mass-balance routines based on surface debris, surface transport, non-steady state evolving glacier geometries, etc.).

General Comments

My only general concern is related to the fit of this paper to the readers of The Cryosphere. Apart from the introduction, and the (understandably) preliminary 2-D and 3-D steady state glacier tests this paper contains very little that is relevant to the more general glaciology audience. The vast majority of the manuscript is concerned with the numerical model development, optimization, and benchmark testing. I am not criticizing the paper and think that it should be essentially published as is, but I will leave it to the editor to decide if it may be more appropriate for a different journal.

It would be a significant change, and I suggest this as being purely optional, but you may consider moving more of the benchmark results (and the detailed discussion thereof into the supplementary documents). This would serve to focus the paper more on the glaciological applications of the model. I have also made some suggestions below on where you can add more references to relevant field work that shows these types of englacial debris features. Including these may also help broaden this paper and bring it back to a more general glaciology audience.

You go to great lengths to model the change in the concentration of the debris deposit as it is advected. However, all that can be seen from your figures of the 2-D test are the modelled changes in the geometry of the debris deposit. This is too bad, because,

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(as you say in P3, L7), the basic location and hence changing geometry of the overall debris deposit could be modelled using simple streamlines. What you bring to the table is much more powerful, however. If possible, I suggest changing the color bar / color scheme on the panels of Figure 9 so that the change in concentration as the material is advocated can actually be seen. However, I realize this may be impossible now.

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Specific comments

P1, L18: This is still true for debris covered glacier systems that undergo no melt (cold-based alpine glaciers in Antarctica, for example. See [Kowalewski et al., 2011] or [Mackay and Marchant, 2016]). Change "melt " to "ablation "

P1, L18: I suggest that you change "... *and* transport of rock... " to "...*or* transport of rock... " Although it is unusual to find these decoupled, there could be situations, where debris supply is high and yet, due to a significant slope, the transport is so efficient that you never develop a large debris-covered ablation zone.

P2, L2-7: Several other authors have suggested / developed this idea as well. You may want to include some additional references. i.e. [Ackert, 1998 ; Clark et al., 1998 ; Monnier and Kinnard, 2015 ; Shroder et al., 2000] and others.

P2, L9: Also look at the work of [Reznichenko et al., 2011]

P3, L11: Other field studies have shown or inferred this as well. Look at the work of [Mackay et al., 2014]

P3, L18: This is a reasonable assumption for this iteration of the model. However, I hope that future models versions may be able to assign spatially heterogeneous rheological properties based on debris concentration.

P5, L23. P6, L1: It is not required, but I suggest you consider moving these sections (3.1 and 3.2) from the main text and putting this information into the supplemental documents. You are mostly describing tools and models that are already published.

Unless you have modified them, then you don't really need to describe them here again.

P6, L33. This adaptive mesh refinement is excellent. Do you also coarsen the mesh behind (upstream) of the deposit once it has transitioned down the streamline?

P7, L11. You did not show results of this "comparison " in this manuscript correct? I think that you mean that in general, the results are similar to those in Frutos et. al. 2014. - which is fine - but the way this sentence is written it sounds like you have actually done the comparison and included them in your results here. For clarity, I suggest that you change the sentence slightly to read: "Comparing *Results* of the benchmark test in Sec 5.1 derived with our approach *compare well* with adaptive mesh refinement based on a posteriori error estimation (de Frutos et al., 2014), *and* demonstrate that. . .. "

P9, L21: Define *uh*, *ue* and *L2* in the equation

P9, L26: here you have defined *T* as total time. I do not think that that is what you are using for *T* in equations (1a) and P4, L18.

P10, L2: It is interesting that you choose a value for *A* that is best suited to temperate glaciers, but then use a no-slip boundary condition at the glacier –bed interface. I understand the no-slip boundary for these tests, but this condition is more consistent with cold-based polar glaciers which would have colder ice and a different value of *A*.

P10, L27: Remove sentence beginning: "Thereby, analysis of. . . " This sentence is unnecessary.

P11, L9: How big of a "bump" did you put in the subglacial topography? The reader has no way of knowing the characteristics of this or any other subsurface features based on the information and figures shown (see also my comment on Figure 5). Without this knowledge we cannot evaluate the impact (which I suspect is very little) that this should have on the simulation results.

P13, L7: You describe the results of the rotational flow test (Fig 6) in great detail, but then barely mention the swirling flow case (Figure 7). Is there a reason for this? In any case, I suggest that you move the swirling flow case (Fig. 7) to the Sup docs.

P15, L24-25: It is too bad that you did not show results from these simulations (using layer-shaped features). Although the sphere test is interesting, the layer deposits are more applicable to glaciological problems and questions. Perhaps these results were too difficult to visualize in 3D?

P17, L1-3: It would be helpful if you include a reference as examples of instances where this has been the assumption.

P17, L1-13: It is interesting in this discussion that you have not emphasized the importance of also of now being able to quantify the changes in the debris *concentration* as it moves and deforms down-glacier. I would mention this. Although out of scope of this study, determining the rate of debris cover formation in the ablation zone (which is one of the main potential applications of this model once it is linked to an ablation model) is directly linked to the debris concentration and thickness of the emerging debris bands. Your model allows this to now be predicted.

P17, L7-12: I'd would also recommend that you take a look at the work of [Mackay and Marchant, 2017] where englacial debris layers are directly linked to modelled changes

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in the environmental conditions in the accumulation zone (at orbitally-paced time scales). Mentioning that being able to test theories like this and similar shows another area in which your model can be very useful and adding this into the discussion would broaden the perceived applicability of your work.

P18, L1-2: How hard would it be to implement a debris concentration - dependent rheology into your modelling framework? This would be excellent to have in future iterations of the model. See similar comment above.

Technical Corrections

P1, L4: Change "As debris is. . . " to "Because debris is. . . "

P1, L6: Change "...surface requires that the englacial transport pathways and deformation can be known. " to "...surface requires knowledge of the englacial transport pathways and deformation. "

P2. L13: Change "...get the full. . . " to "...model the full. . . "

P2. L17: Add comma "... Anderson, 2016), but as. . . "

P3. L25: Remove: " as incompressibility enforces conservation of ice density and hence ice volume. " this clause is not necessary.

P3, L29: Start a new paragraph at the sentence "To solve the . . . "

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P3, L35: Consider deleting or moving the rest of this paragraph starting with the sentence: "In a later stage..." This information is better suited to the "Conclusions and outlook" section at the very end of the paper.

P4, L6, L7: Be consistent with using either "Section" or "Sec."

P4, eqn. (1a) and P4, L18: define "*T*" somewhere

P5, eqn. (5b): define $\partial\Omega_D$. I assume that this is supposed to be $\partial\Omega_{bed}$. If not, then unless *D* is for the diffusion coefficient, choose another notation.

P6, L19: At sentence: "For 2D simulations..." Start new paragraph?

P6, L26: At sentence: "For 3D simulations..." Start new paragraph?

P6, L27: You have not yet introduced the refinement time step and thus this is confusing. I suggest ending the sentence with a reference to section 3.4. I.e.: "...at every refinement time step (see Sec. 3.4)."

P7, L2: This sentence is awkward and should be reworded.

P7, L15: Switch the order of sections 3.4 and 3.5. This improves readability and otherwise the reader does not know what SUPG is when you introduce it in P8, L3.

P9, L19: Reword the sentence starting with "Here, we..." It does not make sense as written.

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P12, L9: Edit this sentence for better clarity. I suggest: "The results of benchmark tests 1 and 2 following the Bochev et. al (2004) are shown in . . . "

P12, L13: delete ", exemplary "

P12, L16: You refer to the case of *both* refinement time steps. However, so far you have only talked about the single time step (0.1 π) that is used in Figure 6. I know that you are also talking about the 0.01 π time step (shown in the sup docs), but it is not clear the way it is written right now. Please edit for clarity.

P15, L22: change ". . .glacier is becoming narrower. . . " to ". . .glacier becomes narrower. . . "

P16, L1-3: This sentence is too long and confusing and needs to be edited. I suggest deleting the unnecessary extra qualifiers: ". . .that uniformly cover wider portions of the accumulation area. . . " and "resulting in thick debris deposit but limited in area. . . "

P16, L2: Change ". . .inclusion as a possible. . . " to ". . .inclusion representative of a possible. . . "

P18, L15: change start of line to . . . "*that is* as course as possible. . .

P18, L27: Start a new paragraph at this sentence.

Figure Comments:

Figure 1: Include a north arrow and scale bar

Figure 3:

- Please mark the ELA / beginning of the ablation zone. Although the reader can infer this from where the vertical velocity component passes zero from negative to positive, the addition of a simple arrow or line would be appreciated and aid in interpretation of Figure 9.

Figures 3 and 4:

- Since this geometry represents a glacier, but I suggest that you label x-axis and y-axis accordingly. i.e, "distance (m)" and "elevation (msl)"

Figure 5:

- I'm not sure why you have rotated the view individual panels unless you are trying to show the overall geometry. If this is the case, then it is not effective but rather just makes the figure look rather messy and less clear. It is not required, but if possible, I suggest that you show all output in the same orientation.

- Rather than using the axis labels x-axis, y-axis z-axis, consider using the physical interpretations for the labels (i.e. elevation, distance down-valley, distance cross-valley)

- A wireframe showing just the glacial bed would be appreciated. As it is now, the reader has no way of knowing what the subglacial topography looks like or where the bedrock "hump" is located.

- This is out of main scope of the debris transport focus of the paper, but I am curious as to why there is such a pronounced positive vertical velocity component at the upper right side of the glacier near the valley bend. There is compressive strain encouraging the emergence of ice here, but the magnitude surprises me.

Figure 6:

- The figure is fine. The caption could use some style adjustments for readability.

- In this and all figure captions where you have separate panels, you do not need to use the phrase: ”In (a) etc. . ...is shown ” Just start with the intended panel letter and say what it is as a separate sentence.

- Remove the sentence: ”The data ranges from -0.14 to 1.11. ” We can see that from the figures.

- Move the sentence ”Color scales show concertation values ” to the beginning or end of the caption.

- Shorten the final sentence to: (f) Results of the convergence test as a function of mesh refinement parameter *cvol*.

Figure 7 caption:

- Same style change comments as for figure 6.

Figure 8:

- The first two panels fail to convey the intended information. I think that there are two separate surfaces represented for each contour (except 90) when I zoom way in, but it is barely possible to resolve these as separate at the print level of figure zoom. Also, which surface is the FEM solution and which is the analytical? These are the same color and are not labeled or marked. I recognize that they are basically the same – which may be the point of the figure, but as it is now, it is just unclear. I suggest removing the panels (a) and (b) and just leaving in panel (c) which does convey usable information.

Figure 9:

- The color scale (red gradient) for concentration is not effective at conveying any information as all the lines basically look like the same shade of red. It may be impossible now, but if possible, consider changing this to a multiple-color colors scheme so that the change in concentration can actually be seen.

- Panels (a-c): Label the x-axis (‘distance down-valley (m)). You probably only need to do this once for all panels.

- Label (draw an arrow or something) the various debris layers (D1, D2, D3, etc.). Right now, it is not possible to track which is which layer.

- Why not label the actual panel somewhere with their simulation times (24 yrs, 62 yrs, 85 yrs)

- Panel (d): label the x and y-axis correctly and put in at least two number values on each of the axes. Otherwise, the reader has no idea of the spatial scale.

- Why not label the actual panels with their simulation times (0.2 yrs, 8, yrs, 20 yrs, 26 yrs)

- Caption: Remove unnecessary sentence: ”Concentrations are displayed in the range of 0 to 100. ” You already show this on the color scale.

Figure 10:

- A rough 2-d outline of the glacier (surface, bedrock along the centerline in the x-z plane and the glacier sides in the x-y plane) would be helpful for interpretation. This does not have to be exact.

Please label the axis relative to the glacier model (i.e. elevation, distance down-valley, distance cross-valley)

- Label the debris distributions with their simulation times directly on the figure. There is plenty of room and this would make interpretation easier.

-Caption: Remove unnecessary sentence: ”Concentrations are displayed in the range of 0 to 100. ” You already show this on the color scale.

Supplementary Material comments

This may be a problem with my video player (I tried several) or my download, but I cannot play some of the .avi movie files. Please check that these are not damaged.

These play successfully:

3d _benchmark1.avi

2d _glaciercase.avi

These do not load (error):

2d _benchmark _exp1t20.avi

2d _benchmark _exp1t200.avi

2d _benchmark _exp2t15.avi

2d _benchmark _exp2t150.avi

Figure A1:

Please put a scale or tick marks on the x-axis and y-axis. the reader ha no idea what the scale is. Or is this dimensionless?

Label the color bar in panels (a) and (b).

In panel (b), if all the velocities are the same, then state that in the caption. Putting the "1.22 " beneath the panel looks strange and does not convey any useful information.

Figure A2 and A3:

Label the panels in the left hand column (2D concentrations) with the dt used in that row. The left hand panels need x-axis and y-axis labels/tick marks (0 – 1?), otherwise the reader has no way of knowing where the profiles in the middle and right hand panels are taken from. You may also want to put two dashed lines across the concentration panels that show the location of the profiles.

It is odd that you put your *References* section in the middle of the document before Figure A2. Maybe this is something that happened in the auto-collate process during submission? I suggest just moving all Sup Doc references to the end of the document.

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