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The Cryosphere Discussions

Interactive comment on "A numerical study of glacier advance over deforming till" *by* G. J.-M. C. Leysinger Vieli and G. H. Gudmundsson

G. J.-M. C. Leysinger Vieli and G. H. Gudmundsson

g.j.m.c.leysinger-vieli@durham.ac.uk

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I would like to thank the two referees D. Benn and M. Sharp and the editor I. Howat for their very positive and generous general comments on our paper. I will address their specific comments point by point here:

Specific Comments by D. Benn (Referee):

None

Specific Comments by M. Sharp (Referee):

I found that for some comments the page and line numbers didn't seem to fit to the actual text. I tried to find the passage that was most likely meant by the referee (referenced by page and line number in brackets). The points below are referenced as M. Sharp did.

2.10: changed 'An inverse depth-age...' to 'For the cases of both overriding and mixed-flow, an inverse depth-age relationship within the ice is obtained.'

2.9: changed 'mixed-flow, where the ...' to 'mixed-flow, where the glacier advances through both ice and sediment deformation.'

2.18: Tracking particle sediment through time is sort of in the paper - in Figures 5 and 6 for the plug-flow and Figure 12 for the mixed-flow. The motion of a sediment particle resembles a parabolic curve downglacier. The nearer it is to the surface the larger the vertical and horizontal component. The sediment at particles at the bed are fixed. The particle is picked up by the sediment 'wave' and transported down stream but not at the same speed as the bulge. The particles shown in the figures do change their place with time but the movement within the bulge seems to be the same at different times. However, this would need a separate study to investigate this.

2.19: This is an interesting point and I don't think that the push moraines have been described by aspect ratio. One could however try to do this by going through the literature. The resemblance stated in this paper is from photos and figures of push moraines from the literature compared with the observed model output. And as shown with the example in Kuriger et al's (2006) paper resembles very much their observations. The height of the bulge is most likely a result of the sediment stiffness. Therefore I believe the height of the bulge and the position of the bulge in relation to the glacier gives a better indication for field based studies to decide on the likely viscosity of the till. To put some bounds on the rheological values one would need to do a sensitivity study. This would be a whole new project. With this study we cannot answer these questions.

2.23: sentence changed to: 'Glacier length changes have been recorded by measurements of their snout position and their mass-balance ...' The connection between mass-balance and glacier advance is not usually direct but, positive mass-balance would lead eventually to a glacier advance even if much later. This paragraph is intended to give a quick overview of the many observational studies used to observe/measure glacier length changes. I believe that this is still useful to have it in the paper, even if not very elegant.

3.6: changed to: 'Glacier flow can occur by several mechanisms: ..'

3.8: We agree with the M. Sharp that the shape of the front very much depends on the rate of melt or calving. What we meant by this sentence was that only with no melting at all can we observe the material points at the surface touching the sediment below by overriding this overriding motion at the front. We change the sentence to: 'A glacier advance by ice deformation only, i.e. where the ice is frozen to the bed, leads to an advance by 'overriding', which means that the advancing glacier snout rolls its surface over the glacier forefield, potentially giving rise to inverse depth-age relationship within the ice behind the glacier front.' Added in the discussion part - where 'realistic mass balance distribution' is mentioned (18.8): 'Although incomplete, one would still expect to find the overfolded ice layers within the glacier front for the overriding and the mixed-flow case, as widely seen in terminal ice cliffs (e.g. Hooke and Hudleston, 1978, Benn and Evans, 2010). Due to ablation the surface layers are continously truncated, and therefore, the completeness of the folding structure depends very much on the prevailing melt and/or dry calving rate.'

7.2 (7.10): For the moment the conception of the model is so that the ice is in contact with the sediment everywhere. This assumption doesn't allow any cavities but it allows the sediment to form bumps. Another assumption is the uniformity of the material. I would expect that to produce glacial landforms such as drumlins it would need to be non-uniform or have a trigger to behave in a different way. Hilmar: I'm not sure if adding sth here to the paragraph would be useful or later in the discussion. The model is constrained by the choice of slope and also by the chosen sediment thickness - however looking at the figures as described in the next point there might not be much

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change.

7.5 (7.13): As we do not know what to expect it is easiest to start a model with the most simple assumptions. A constant thickness shows what is happening as a result of the interaction between glacier flow and the sediment. Regarding the specific thickness: the same forces of the glacier would be received by an either thinner or thicker sediment. The Figures show that most of the deformation is taken up by the sediment nearest to the ice. I would expect the same happening for thinner or thicker sediment. The sediment would be squeezed to the front. It might be that the bumps are less large if there is not enough sediment. Added to this section (7.18): 'Our choice for the initial geometry and the slope of the base of the till layer does not affect our final conclusions.'

7.18-7.20: We left the ELA, as it is easier to understand where this point is when comparing with a 'real' case in nature. We added to this passage: '... in the vicinity of the snout. Due to this chosen mass-balance distribution no equilibrium is reached and the glacier is in a perpetual state of advance.'

7.24 (8.6): The geometry obtained by SIA model is solely a product of slope and accumulation. We have not varied the slope nor the accumulation, therefore haven't experimented with different geometries. The starting geometry from the SIA used in the full-system model quickly adjusts to what the full system model would have had. The changes occur mainly at the front as the SIA uses finite differences and calculates velocity from the local slope and thickness and therefore the flow field at the terminus are not well resolved. This has been investigated in a previous study where the flow of extreme geometries are calculated and compared with both models (Leysinger Vieli and Gudmundsson, 2004).

7.24-7.26 (8.6-8.8): We changed 'Our conclusions are not affected..' to 'Our conclusions are not affected by the details of the starting geometry, as the geometry obtained from the SIA model is, except for the frontal region, similar to the one calculated for the FS model (see Leysinger and Gudmundsson, 2004) and the differences at the front are quickly adjusted by the different flowfield obtained by the FS model (see e.g. adjustment for the initial surface marked with 'b' in Fig. 2a).'

10.24 (11.14): changed ' The thickness of the till...' to 'The surface of the till is also plotted in Fig. 2a for the same times but, as expected, no change in till thickness is visible due to its relative stiffness in this experiment.' Figure 2b-d show the temporal evolution of the ice and sediment and how various material particles (dots in the figures) within the ice move as the glacier front advances over the sediment.'

11.8/9 (11.24/25): added the no-melt condition into this paragraph. Changed 'Figures 2b-d show...' to 'Figures Fig2b-d show how various material particles (dots in the figures) within the ice move as the front advances under no-melt conditions.' and 'As the front..' to 'As the front advances, and owing to our assumption of no-melt, ice particles that previously were located at the glacier surface come in contact with the till surface. This leads to overfolding within the ice of the glacier front near the ice-sediment interface, and forms a new basal layer of ice giving rise to depth-age inversion.' I discuss implications of melt in Discussion part.

11.17 (12.4): The meaning of depth-age relationship should now be clearer from the beginning. Some mention of recumbent folding in glacier termini comes in the discussion bit where we refer to a photo of a folding structure of Crusoe Glacier from Axel Heiberg Island.

11.21/22 (12.8/9): I believe that the reviewer means effective stress instead of velocity. In all experiments the velocity is higher at the sediment surface than at the bottom of the sediment - as there the boundary condition requires it to be zero. This is nothing exceptional, therefore I think the reviewer is referring to Figure 3d where the effective stress is highest at the ice-sediment interface and I will try to answer this. To explain the maximum in effective stress at the ice-sediment interface near the glacier front it helps to consult Figure 8c, which is another plot to see the effective stress of the frontal region (the position of profile C in Figure 3d is located at 1.90 in horizontal distance).

In Figure 8c we can see that the effective stress is concentrated at the ice-sediment interface shows a concentration in effective stress where the steep and overhanging ice front meets the sediment. Because we are using the full-system model these stresses are ’felt’ by the sediment near this point, as they are transferred within the sediment (up and down stream). Usually effective stress increases with depth due to increasing overburden but in this case this is lower than the peak produced at the ice-sediment interface. We added a discussion for Figure 8c in the text where the Figure 8 and 7 are discussed and changed ’The stresses are transferred ..’ to ’Figs. 7c and 8c show the distribution of the effective stress for Experiments B and A, respectivily. In both cases the stress distribution is continuous across the interface between the ice and the till. This is the required stress condition for the stress fields of two bodies in contact. The continuity of the stress field seen in Figs. 7c and 8c is a demonstration of the accuracy of the numerical solution.’

12.20 (13.8): The reviewer is right that it should be ’velocity distribution’ instead of ’vertical velocity distribution’. We changed the sentence to: ’The velocity distribution within the sediment bulge is shown in detail with velocity vectors in Fig. 9.’.

13.2/3 (13.20/21): This has been answered with the point above (11.21/22).

13.8/9 (13.26/27): I’m not sure why this shouldn’t be clear. Here we describe the two motions previously described in experiment A and B acting in combination. We changed ’At the same time the till ..’ to: ’At the same time the till deforms giving rise to a propagating till wave similar to that seen in Experiment B (Figs. 11a-e).’

13.11-13 (14.2-4): (a) the internal structure is shown in Figure 12b-c at different times compared to the initial state 12a. As in Figures 5 and 6 we can see that the sediment particles are uplifted into the approaching sediment ’wave’, where the wave gently flattens to the back (below the glacier). In this study we were not able to show the internal structure in a different way. (b) Showing an aspect ratio is a good point but measuring the width is not so clear. We do show the vertical bulge size for the different experiments as H_b (Figures 4b and 11b). We found that the height is the best measure as the width is not so clearly defined, and the position of the bulge makes it quite clear to distinguish between the type of advance - which is in front of the glacier or beneath the glacier.

15.13-15 (16.7-9): I believe that the sentence referred to by the reviewer is: 'To our knowledge ... , the first numerical model of glacier advance over till that produces a feature closely resembling push moraines as they are observed.' It is difficult for us to say sth about internal structure other than what we have observed from our model. The discussion of features observed in the field are often more complex. However in the discussion we discuss the the similar shape between described in the literature and modelled and also the movement described by Van der Wateren as a wave. Our finding match those findings from the literature without us knowing about them when we investigated our modelling results.

16.8 (17.3): We do mean 'deformation' but not 'deformation rate'. We replace it by 'displacement' so that: 'Their measured sediment displacement, especially at the higher end, is in the ...'.

16.22-26 (17.20-24): The similarities between the sediment bulge and the surge front is that both move as a kinematic wave but as the surge front is on the glacier and the bulge is produced through the weight of the glacier I do not think that this should be mentioned together. The processes are different.

16.29 (17.26/27): A retreat happens when ice at the front is wasted away. So during a retreat the glacier has still the same motion as during an advance but as the material is wasted away it won't have the weight at the front to transfer this into the sediment to produce a bulge. If the retreat slows down - would this mean that the front is stagnant - neither advancing nor retreating? Then it might be possible to transfer stresses into the sediment to build up a bulge. But I'm guessing and it would need to be investigated - in this study I haven't tried this. To try this would be a next step.

17.2 (17.29): changed ' Where the till is too stiff...' to: '..., the glacier advances through "overriding" or "mixed-flow" .' and 'A possible example...' to 'A possible example of a glacier advance by overriding or by mixed-flow is Crusoe Glacier from Axel Heiberg Island where the folding structure revealed in a photo taken of the west front by Alean (2009) could be interpreted as the inverse layering obtained from overfolding within the glacier front.'.

Specific Comments by I. M. Howat (Editor):

- 825, 23: 'area' does mean the location on the glacier, so the glacier front. The assumptions used for the shallow ice approximation model are valid for large ice masses (10 times the ice thickness). The flow velocity is given by the local slope and ice thickness only. For vertical slopes this model predicts infinitely large velocities. No deviatoric stresses are included - therefore, the ice surrounding a point does not affect it's flow. This is mentioned on page 833, lines 19-21. changed text to: '.... vicinity of the glacier terminus. Here, assumptions commonly used ...' as suggested by M. Sharp.

- 826, 7: the 'assumptions' here are by purpose held in general - as different models have different assumptions. What is new with our model is that the grid points at the glacier front are moving with the ice. They are exactly where the glacier is calculated, as the grid is moving with the glacier. Most models make some simplifications with the equilibrium equations - our model does solve the full set of equilibrium equations. This is mentioned in the 'model description' section 2.1 on page 827.

- 826, 14: We changed 'For isotopic ice a viscous ...' to 'For isotropic ice Glen's flow law is commonly used as a constitutive law (Glen, 1955).'

- 831, 19: changed to 'normalisation'.

- 837, 26: Yes the contrast in effective viscosity between ice and till is the single most important model parameter - as the rate factor for ice A stays constant it is the change of the rate factor of the sediment A' which changes this relation. B is defined by the rate factor of the sediment A' and the flow exponent m.

Comments on discussion/conclusion:
I am sorry that the discussion/conclusion is felt as a let down. We discussed most observed/investigated features and that even though the discussion is rather short many observations from our modelling study have been put in context with observations in nature and other research. We will add more about our assumption of no ablation. We do not want to speculate too much on topics we haven't fully investigated.

- 'If the model results can guide future field data collection....': From this study it seems that the shape and height of the bulge can give some information about the 'stiffness' of the till (the viscosity). However, in nature this will most likely vary seasonably by changes in stiffness due to temperature and/or water content in the sediment. This study shows that we won't be able to differ between viscous or plastic flow from the sediment feature shape as both produce the same features. For a more detailed answer a separate study would be needed.

- 'Most of what we know about till deformation... ': Figures 10b, 13b and 14b show the ratio between horizontal velocity at the ice-sediment interface U_b to the one at the glacier surface U_s. We can see that the ratio can change quite quickly from a region where sediment deformation is the main contributor to the measured glacier velocity to a region where there is almost no contribution from the sediment. Best would be to make several measurements along the glacier flow and to compare them in relation to each other. A relative high sediment deformation everywhere might indicate a relatively soft sediment with a moderately non-linear till, as shown in Figure 10b. By several measurements one might also be able to find the case as in Figure 14b where there are regions with no contribution of sediment deformation followed by large contribution to the observed glacier flow. This might give some indication on how highly non-linear the till behaviour is and help in constraining till rheology in a numerical model. However, this is for an assumption of till uniformity, in nature this might not always be a valid assumption. The last sentence in the conclusion is referring to the problem of taking measurements at the front and using this info for the whole glacier.

- 'What are the next-steps for development of the model and future experiments?...': There really is so much that could be done to extend this work:

– One could continue with allowing ablation at the terminus and repeat the experiment, this can then lead to modelling retreat with the same model set up and investigate what happens to the sediment, then continue with an advance and retreat and the also add seasonal variation in stiffness of the sediment. This investigation could further continue in having sediment sections of different viscosity.

– The model itself could be improved by including pore water pressure and see what the influence of this is.

– One should investigate the influence of the sediment thickness - are there any changes in the features. This could then lead to a sensitivity study in testing if there are bounds on the plausible range of values for rheological parameters, as suggested by M. Sharp.

– An interesting study would also be to investigate the trajectories in the sediment further. Not just in the frontal region but also upstream especially if the sediment is non-uniform, as suggested above by incorporating sections with different viscosity.

– The model could be changed by adding a further, very thin, layer between ice and sediment. This layer could be used to simulate sliding between the ice and the sediment.

Greetings,

Gwendolyn Leysinger Vieli

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