The Cryosphere Discussions

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Comment on tc-2021-41

Anonymous Referee #1

Referee comment on "Controls on Greenland moulin geometry and evolution from the Moulin Shape model" by Lauren C. Andrews et al., The Cryosphere Discuss., https://doi.org/10.5194/tc-2021-41-RC1, 2021

This paper introduces a new model, MouSh, designed to emulate the seasonal evolution of moulins and examine the impact of this on the basal drainage system. A model like this has been long overdue and it’s exciting to see it implemented to investigate both the evolution of the englacial system but also the subglacial system, which may be controlled strongly by moulin capacity and fill and drain rates.

The paper is nicely written and details many aspects of the model which has a lot of components. Looking at the results for the viscous deformation, turbulent melting and the application of Glen’s Flow law provides interesting information about the evolution of these features and how they might significantly change radius even on a daily basis, which is not something that I was aware could happen.

I do have some major concerns which I list below but, once these are taken into account, I think this will be a strong addition to glaciological modeling.

Major issues

1. I’m confused by the implementation of elastic equations in this context. Most applications of elastic equations in glaciology, that I’m familiar with, are for a situation with a bending beam or plate (e.g. ice shelf flexure) in response to a changing force. I have a difficult time understanding how this can apply from constant ice force inwards into a moulin in an elastic rather than viscous form, particularly since elastic deformation should be instantaneous with changing force but here it is from the change in resistance (the water), and I’m not convinced that they are equivalent. As far as I know, this type of calculation with both elastic and viscous deformation in a moulin or borehole is new to glaciology and so the approach needs more explanation/justification.

Part of the problem is that equation 4 is difficult to follow in its current form. If this is a new way to apply elasticity to a moulin then the equation needs to be fully derived in an appendix. If it has been applied in glaciology before you need citations. You base your equations from Aadnoy (1987), but this isn't even included in the reference list.

Both the elastic and viscous deformation rates that you plot are higher than I would have assumed for this situation. Previous analysis on borehole deformation has closure rates one or two orders of magnitude smaller (e.g. Paterson, 1977). Also Catania and Newmann (2010) argued closure would primarily occur in the base of the moulin and not the top 80%. A discussion on why yours are so much higher and/or examples of other systems that deform this rapidly would help.

2. Following on from this, where have you got your Maxwell times of 10-100 hours from? I believe the Maxwell time should be more in the range of a few hours. Therefore viscous deformation should be the primary application for moulin shape evolution. I'm also very unclear how you're transitioning between elastic and viscous deformation with this model and applying the Maxwell time. It seems these are both being calculated separately but continuously given that you are plotting both over sub-hourly, multi-day timescales?

3. The treatment of turbulent melting and refreezing is confusing. Why only include refreezing outside of the melt season? Do you assume no refreezing overnight during the melt season? I see you say refreezing occurs only when water flow is laminar but it's not clear to me that water flow will be always turbulent from the beginning to the end of the melt season. This needs more justification in the text by reporting the expected Reynolds numbers.

4. I understand why you've applied a simplified subglacial model given the complexity of the moulin model. However, both the description of the basal channel model and the application are confusing. From what I can gather you're calculating channel characteristics at the moulin outlet (using ice pressure and moulin head pressure) but are applying a constant hydraulic potential gradient from the moulin to the terminus, so only producing one output point. The length scale calculations from moulin to terminus are not ideal in application to a continuously evolving channel (which will not be linear in terms of pressure) and are likely unrealistic. Instead why not apply a range of hydraulic potential gradients to test how those impact the moulin evolution? That would be much clearer to show how the pressure change at the bed impacts and is impacted by the moulin head.

One of the significant concerns I have about the channel is the necessity of a large base flow. Looking at Figure 7 the base flow is the main driver for channel evolution and at an input rate of ~20m3/s that's not surprising it's the primary control. To better determine the role of the changing moulin head it would be better to avoid adding additional time-varying water inputs at the bed since it's not clear that it's at all realistic. Instead, a static background water flux and/or a larger initial channel size could help with stability issues.

It's generally hard to believe the channel outputs that you present as it's not clear what the differences are between basins and experiments in terms of the hydraulic potential gradient, and because of that large base flow rate. However, as this paper focuses on the moulin model, so should the results and discussion. The role of a basal channel in this case is to present semi-realistic evolution characteristics to feedback with the moulin water levels. This does not give you much information about what is happening at the bed anywhere downstream of the moulin so that should not be widely discussed. Along these lines, before you begin your moulin model methods, you look at subglacial channel routing in section 2.1, which is misleading for the reader. This section does not seem relevant to this paper because of the highly simplified nature of the channel model that you apply and it would be better to start the paper with the moulin model methods.

5. The discussion at the moment focuses a lot on how moulins are formed, the subglacial system, and englacial void ratios. These don't seem directly relevant to your main findings from this complex model, which are the changes in shape, melt rate and deformation of the moulin. Particularly given that the subglacial model is much more simple and this is the first step in coupling to a more dynamic subglacial model, the discussion in this paper should be focused on the moulin evolution. There are many interesting outputs from your model runs that you could discuss in terms of the deformation of the ice possibly moving the input of the moulin at the bed along with stretching the length of the moulin; where in the moulin and at what time of the season water would be stored at higher or lower pressure influencing the subglacial system; the influence of the moulin shape on the head etc.

Line-by-line comments

- where does that 10-14% number come from?
- they constitute most of the englacial system – what about englacial channels?

38-39. you already said this in your first sentence of the introduction.

- what do you mean 'relative path length'? This whole paragraph is confusing because you're discussing basal hydraulic potential rather than moulins.

84-95. I'm very confused. what do you mean by theoretical flow accumulation? Are you saying you're defining the catchments at the base of the ice? You're defining channel lengths at the bed? What is a subglacial channel node? Channels should join up dendritically towards the terminus in any case and are therefore linked rather than in separate segments.

- why do you initiate with a semi-circular, semi-elliptical shape? There doesn't seem to be any reason for this and it primarily serves to complicate your equations and your analysis.
- undefined parameters for Maxwell time. Where do you get the equation in parenthesis from?
- if moulins form by drainage into crevasses and hydrofracture why do you assume it's compressive?
- you say viscous deformation is the dominant process over a 1 day timescale but you plot your viscous deformation on much smaller timescales showing diurnal variation.

154-156. specify here this opening and closure is relative to the pressure difference at depth – moulin should not open at all depths when above flotation – only in regions of the moulin where the relative pressure is higher than flotation. Looks like you're calculating this in the next section but this should be clarified here.

- why have both equation 5 and equation 6?
- laminar flow is when the Reynold's number is less than 2300.
- do you mean all ice is at the melting point, not water?
- what difference do you find with these alternative approaches?
- you haven't told us about the equation you use for turbulent melt. I see that you have it later in the paragraph but it's confusing in this line because it implies we already know how you calculate it.
- but you do assume it's at the pressure melting temperature in your refreezing section. I'm getting confused.
- how modest?
- what is S in equation 18? Again I thought the ice on the moulin wall was at the pressure melting point?

- presumably the unit hydrograph is to allow a lag for the runoff to reach the moulin? If so, you should state that.

322-329. this last paragraph seems more appropriate in the next section

- specify what you mean by englacial void ratio here? Why would that impact flow from upstream?
- what two elements?
- assuming b is elevation above sea level, why include it if you have zero bed slope?
- where is the base flow added?
- you mentioned Qin above in section 2.2.4.1, which included the baseflow. That's not being added directly into the moulin I assume? This should be clarified.
- You need a justification for your choice of enhancement factor. It seems like you're applying this factor between 1 and 9, but measurements by Luthi et al (2002) in Greenland ice suggested it can reach up to 2.5 in Holocene ice but is closer to 1 above that depth.
- what are these basins?
- why are these lengths so different? I don't think these lengths scales help your model application – it makes it confusing (see comment at the beginning).
- how can they reach equilibrium with constantly changing water input and a constantly evolving basal channel? Or is this with a constant input?

440-445. Changing Youngs modulus for elastic expansion increased moulin volume by 38% and capacity by 56%? This seems like a much more significant change than I would assume from elastic deformation in this context.

- it would be more appropriate here to say the outflow is sensitive to the steepness of the basal pressure gradient.
- but the increase in water level should increase the pressure gradient and cause faster flow through the subglacial channel and melt opening?
- this discussion and Figure 6 show a diurnal change in viscous deformation by up to 20cm and 10cm elastically. Then the diurnal phase change up to 30cm/day. Is that saying you melt up to an extra 30cm a day? And that the moulin diameter pulses in and out every day due to melt countered by viscous and elastic deformation? Is there any evidence for this from moulin measurements.
- what would cause a moulin to change radius diurnally more in thicker vs. thinner ice?
- the similarity between Basin 1 and 2 is likely because the basal channel model is driven by a similarly large background influx rather than by the changing conditions of the moulin itself.
- how could thick ice viscously close channels if water is above overburden pressure?
- specify which system sees the increase.
- you have elastic processes in the channel too? Any references to show this is justified in basal channels?
- I'm unsure why you're discussing initial moulin formation processes which aren't the focus of your study. Moulin evolution, yes, and you have plenty of interesting things to talk about on that subject.

- exploration would be good to validate your model so I wouldn't discount it.
- can you clarify this sentence. You are saying field measurements show 103-112% of overburden, or 3-12% of overburden? The former seems more likely. But 20% above overburden? That should be on the surface?
- some boreholes hit more efficient systems, as explored by Meirbachtol et al (2013).
- rephrase 'variations in diurnal water level variability'
- I don't think an englacial void ratio is used to resolve diurnal basal pressure. How would you get a spatially variable englacial void ratio? What has this got to do with moulins?
- you said earlier in the paper that moulins are used as source inputs for models. How does this link to englacial void ratio? The change in water level is a moulin because of increase/decrease in diameter will impact the water supply to the base via the pressure. Perhaps you mean a storage parameter in models? I certainly think it's worth coupling with subglacial hydrology, but I'm not sure this paragraph makes sense. Line 696 covers this possibility and is an important point to make.
- what do you mean a static shape instead of static cylinder? The Trunz et al, in review paper is mentioned a lot which is frustrating since we don't have access to see what it discusses.

731-739. see my above comments about elastic deformation. You need more justification for these statements given that it hasn't been included in subglacial models to date.

- are you sure it's not that subglacial channels form where there are moulin inputs?
- rephrase this sentence.

Figures

Figures 4 and 5. Why does the y axis of the diurnal range go up to 0.4 if values don't go above 0.2?

Figure 6. I'm intrigued by the shapes in f. Why is there more turbulent melting in the middle of the borehole? What are the factors contributing to the differences between elastic and viscous deformation shapes and rates? In g since it seems to have reached equilibrium within a day or so it would be useful to zoom in so we can see the lines better.

Figure 7. In your thickest ice example for moulin water level, it looks like your moulin is overflowing. Also in d) where is the 741m example? The channel size looks almost entirely dictated by the background flow you input with small diurnal variability on top.

Figure 8. This is a really interesting figure. Why not discuss the shape changes (particularly due to Glen's Flow law) more in the manuscript?

Figure 9 b. What happened around day 32?

References

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