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Interactive comment on "Modelling environmental influences on calving at Helheim Glacier, East Greenland" *by* S. Cook et al.

J. Bassis (Referee)

jbassis@umich.edu

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General comments: This manuscript describes a viscous glacier flowline model that is applied to simulated the advance and retreat of Helheim Glacier. The model builds on previous work by Benn et al. (2007) and Nick et al. (2010) in applying a calving law that assumes a calving event will occur when surface crevasses penetrate to the water line. Overall, with the exception of some technical issues associated with the model description (described below), the manuscript is sound. The manuscript has a bit of an engineering feel to it in that it reads as though the authors found a few equations in the literature and applied them using a numerical framework, but haven't critically examined the implications or assumptions associated with the model. This avoidance of some of the deeper issues makes the manuscript somewhat less satisfying in the

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end. But these complaints, may, however, be primarily philosophical and subject to a small number of technical clarifications and corrections the manuscript should be appropriate for the Cryosphere.

Detailed comments:

Central to this manuscript is the question of what is an appropriate calving law, a question that has bedeviled several generations of glaciologists. The authors chose to use a calving law proposed by Benn et al., (2007) in which a calving event is assumed to occur when a surface crevasse penetrates to a depth comparable to the water level, assuming a hydrologic connection exists between the ocean and crevasses in the interior of the glacier. This model has been used successfully by Nick et al., (2010) and elsewhere. However, Nick et al. (2010) also apply the criterion that a calving event occurs when surface and basal crevasses intersect and show that this model does just as well as the former model when suitably tuned to predict terminus positions. Why then have the authors chosen to focus exclusively on basal crevasses? Do they have reasons to believe that basal crevasses do not exist? Presumably basal crevasse depths would be more sensitive to basal water pressures . . .

My discomfort with the calving criterion used by the authors stems in part from the fact that it is not obvious to me that this law is consistent with the laws of thermodynamics. Given the fact that the authors are assuming that the temperature within the glacier is cold and sub-freezing throughout, is it possible to maintain unfrozen conduits within cold ice that connects the ocean to the cold interior of the glacier without freezing these conduits shut or warming the glacier? What is the time scale over which these conduits stay open and how does this compare to the freezing time of fractures and the time scale between calving events? For crevasses at the surface, what is the time scale over which these will freeze shut and how does it compare to the characteristic interval between calving events? Do these surface crevasses stay water filled in winter or do they freeze shut?

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Related to this, the authors argue that their model is "physically realistic". I suppose this is meant to distinguish their model from others that are not deemed to be as physically realistic or perhaps to distinguish their model from one that is empirically based? I think the main point of the calving model Benn proposed is that you can use it to relate calving to the dynamics stress field within the ice. Perhaps a better term would be "dynamically based" rather than the more pejorative physically based?

A similar issue that merits a slightly more involved analysis is the question of how to test if the calving law is correct. As the authors note this is not easy and one can merely tune the water depth in crevasses to replicate observed terminus advance and retreat. But given the fact that calving events are so tightly controlled by crevasse water depth, it seems like one could use a positive degree day approach, energy balance model or equivalent to compute how much melt is produced each melt season and adjust water depth in crevasses accordingly. This might inform if the trend in predicted terminus position is at least broadly correct or not. Because I presume that this implies that water depths in crevasses are at their minimum level in winter, this would also seem to imply that their should be no calving events during winter unless the glacier is in an extraordinary geometrical configuration that promotes large stresses. Is this not correct? This also seems like it should be straightforward to test with the model and observations presented.

Finally, I think crevasse depths are computed based on contouring the stress field and finding the level where the horizontal stress vanishes. This is based on the Nye formulation of fracture mechanics and is appropriate for closely spaced crevasses. Aside from providing some additional details about how crevasse depths are computed in the model, it seems as though a high resolution model like the one used here could go a bit further than passively observing the stress field. The existence of crevasses will actually change the stress field around crevasses and so it seems like a high resolution finite element model could resolve crevasses, including water within crevasses and make sure that crevasse depths computed using the Nye approximation are consistent

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with those simulated in a vertically resolved ice model.

Technical comments:

page 4410 near line 5: The authors make the strong statement that shallow models of ice dynamics will yield large inaccuracies in modeled crevasse penetration. This statement needs to be substantiated either by references to previous work that shows this or, preferably, by demonstrating that this true by comparing the authors model with a shallow model. What worries me most about this statement is that surface crevasse penetration depth appears to be largely controlled by the amount of meltwater added to crevasses. Because this is used as a tuning parameter it looks like inaccuracies associated with different approximations to the ice dynamics may be small compared to uncertainties associated with surface melt water penetration. In this case improved ice dynamics may be fiddling around in the noise. Moreover, the (partial) Stokes solution combined with a crude parameterization of lateral stresses via conservation of mass may not provide a self-consistent approximation to the state of stress within the glacier. To make this argument more forcefully, the authors could show that the model that they use is a better approximation to the stress field or–and this seems like the easier route–argue that effects that are not included in shallow models, like bending, are important drivers of surface crevasse penetration.

Equation 2: give number used for gravity.

Equation 4 is wrong. The effective viscosity should depend on the strain rate invariant $\epsilon_{ij}\epsilon_{ij}$ and not the strain rate. The equation given implies a non-objective tensor viscosity, which I assume is not what the authors intended.

Section 2.3: Surface boundary condition: The glacier surface should be traction free (i.e., dot product of the stress tensor with the outward normal vector). I don't believe it is permissible to apply a boundary condition directly to the stress tensor?

Equation 6: Is there also an equivalent kinematic boundary condition at the glacier

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bed? Is a no-penetration boundary condition applied?

page 4414, line 10: Are the surface mass balance value accessible to the public? Can a table be provided in supplementary material so that readers can more ably replicate the authors results?

page 4415, line 20: Give the equations used for the basal boundary condition so that the model description is self-contained here and readers don't need to go rooting around through the literature if they want to seek to reproduce results of the model.

page 4415, line 25: Is the backforce from melange applied evenly across the calving face or across some representative cross-section that corresponds to the thickness of the melange? I see this is given later. It would help readers to warn them that this stress will be applied over an interval appropriate for the melange thickness.

page 4418, line 25: Can the authors comment on what is physically going on that is causing the glacier terminus to get pinned at topographic highs?

Figure 3: It would help readers if the authors showed water depth so that we can more easily see how close the surface crevasse field comes to penetrating to this depth.

Interactive comment on The Cryosphere Discuss., 7, 4407, 2013.