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Interactive comment on "Modelling the dynamic response of Jakobshavn Isbræ, West Greenland, to calving rate perturbations" *by* J. H. Bondzio et al.

G. Jouvet (Referee)

jouvet@vaw.baug.ethz.ch

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General comments

This study introduces a Level-Set Method (LSM) in order to follow dynamically the migration of the calving front in the Ice Sheet System Model (ISSM). Several experiments are led on the Jakobshavn Isbrae ice stream. In particular, the authors study its geometrical response after applying different perturbations to a given calving rate, which itself accounts for seasonality. The results show that the model is capable to reproduce the subsequent change (retreat, thinning, steepening, acceleration) of the ice stream under enhanced calving rates consistently to physical observations. More-

over, the model reproduces well how the whole system stabilizes after releasing the perturbation, showing a reversible calving front.

This is an interesting paper which presents original results. LSM are well-designed methods to track complex geometries with possible changes in topologies. This makes it fully relevant for calving fronts. Overall, I found convincing that ice flow models should indeed incorporate such (or similar) *ad-hoc* tracking methods of the calving front for projections of future contributions to SLR. However, I think the paper can still be improved before to be published. I have two main concerns, plus lists of specific and technical comments, which I hope will help the authors to improve this article. My two main concerns are:

- LSM can greatly deal with complex interfaces including changes of topology. However, LSM also have counterparts, namely, i) they are usually not mass conserving unless solved by finite volume (this is not the case here) ii) gradients of φ near the interface $\varphi = 0$ tend to flatten after few iterations (if nothing it done) so that the interface gets less and less accurate with time. (I did experiment both problems in a previous work). A classical trick to deal with the last issue is to regularly regularize φ by solving another Hamilton-Jacobi PDE, which admits the signed distance to the interface $\varphi = 0$ as a solution. Indeed, re-initializing with the signed distance function ensures to have safe gradients equal or close to 1. It would be worth to further discuss numerical issues when solving the KCFC, and in particular, to include in the test-setup (Appendix) the two following checks: i) how the numerical volume of the moving disk change over time, and if it is controllable by the mesh size (as this is the case for the advection velocity) ii) how the gradient of the LS φ near the interface $\varphi = 0$ behave after few iterations.
- The authors describe well the Experiments setup, and also introduce a measure P for the time integration of the applied perturbation. Although the discussion part explains well all ice flow mechanisms and how they feedback each other, the

direct outcomes of Experiments A, B and C in term of impact of the perturbation w.r.t. p_0 and Δt are little discussed. In addition, we expect that the measure P you introduced (arbitrarily) takes its sense after being corroborated with the results, but this come later on in a single sentence and without clear evidence. I therefore recommend the authors to better emphasize all the outcomes of Experiments A, B and C (in particular the consequences of changes in parameters p_0 and Δt) in the discussion (and in the conclusion as well).

Specific comments:

abstract The abstract is not very efficient. In particular, the 5 first sentences should be made further concise so that the "Here, we present ..." comes earlier.

.3-4 p5488 "It is well suited ...partial differential equations". I don't see the point. PDEs are by nature challenging to implement in parallel since partial derivatives couple nodes by contrast to systems of ODEs (for instance).

-10 p.5491 Quantities should be more rigorously introduced. E.g. the time interval $[0, \infty)$ comes before the time variable t is introduced, "then" in "if ... , then x belongs to ..." are in fact are all "$\Leftrightarrow$". In addition, Ω_i is defined as an abstract domain, and one has to wait 3 more pages before it is said that Ω_i corresponds to the ice domain.

.10 p.5492 This is an interesting point to use the LSM horizontally while keeping vertically the traditional ice thickness. You should motivate your choice even if this is easy to guess for ice modellers. From a general LSM perspective, this is not obvious.

eq. (9) should be motivated, or at least say that by requesting $n \cdot \nabla S = 0$, we want to be sure that S keeps constant at the interface (or the calving front) when following the normal unit, which points outside the ice domain. In what is it important that

the thickness and the velocity keep constant in the neighbourhood of the calving front?

-11 p.5494 "The strongly ... updates", any evidence to support this statement? "High viscosity of ice makes that computing the BC exactly at the front or at one mesh size distance does makes a big difference", is that what you mean? This doesn't look obvious to me.

.28 p.5498 Last sentence of Section 3: This measure P should come later. It makes no sense to introduce it in Section 3.

·14 p-5499 several times, "local high" or "topographic high" should be "local maximum"? At that point, I would briefly recall for unaware readers that grounding line on retrograde slopes are usually unstable and briefly explain why (+ references).

-19 p.5500 You mostly comment the time derivative of Δ Vol, maybe drawing the derivative instead of the function Δ Vol would make more sense for Fig. 8?

.17 p.5500 "Enhanced calving causes additional ... measure P", how did you corroborate Δ Vol to P? Is it a coarse/visual estimate from Fig 8? If P proves to be a good measure, you should show it more accurately.

- The expression "ice modelling" comes often and stands for "ice flow modelling". I find "ice modelling" too general. It would be better replaced by a more precise expression. Also, "calving front" sounds to me more common term that "ice front", which is adopted in this paper.

Technical comments:

l.9 p.5490 "B the ice viscosity parameters", this is confusing, one might think that B is the viscosity.

.17 p.5491 you should recall the meaning of the acronym "LSF" in Section 2.2.

.17 p.5491 "We can propagate the unit ..." ⇒ "We can **define** the unit ..."?

p.5492 You could maybe rename eq. (7) into (KCFC)?

l.1 p.5493 "we need to propagate them ..." ⇒ "we need to **prolong/extend** them ..."?

.14 p.5493 "semi-implicit finite difference scheme", I think "finite difference" comes implicitly with "semi-implicit" and doesn't need to be said.

23 p. 5493 "using the Continuous Galerkin FEM", I would remove "Continous Galerkin" since the statement also applies to "Discontinous Galerkin", the problem is the subgrid scale, not the type of approximation functions, isn't it?

l.6 p. 5494 "Then we consider ... of ice", is this sentence correct?

.16 p.5494 Sentences normally never start by a mathematical symbol.

.28 p.5494 How "correct" must be understood? Be more precise.

.29 p.5494 "cancels out over time"? you mean over mesh refinements?

.15 p.5495 Some readers might be more familiar with the acronym CFL, so I would employ both.

eq. (10) You should replace the oblique symbol by a true letter to denote the kind of mask function which applies the calving only near the front. Also, better not use a dot $\cdot$ for a simple multiplication by contrast to scalar products.

.16 p.5497 I don't see why π multiplies the $\sin$.

l.8 p.5498 "Increased ... retreats", you say twice the same thing in the same sentence.

-12 p.5498 "Resulting ... (Fig.2)", consider rephrasing.

.15 p.5498 say that this refers to Exp. C4.

.26 p.5498 "peaking at the point of further retreat" sounds redundant.

.12 p.5499 "discrete location", could you clarify me what you mean by "discrete"?

l.8 p.5502 "The non-linear rheology softens" could be further accurate like "The ice rheology softens" or "The Glen's flow rheology softens" since "non-linear" could also mean the other sense (higher strain implies more viscous).

.20 p.5504 the velocity would better read $v = (\cos(\pi/4), \sin(\pi/4))$ km a^{-1} (without dot $\cdot$ and without mixing unit in the definition).

.25 p.5504 What means the "standard deviation of the numerical error", standard deviation means you have a large number of point? I would have expect to simply consider one norm of the error with respect to mesh size.

Figs 5,7 It would be simpler to print "exp. A, B1, B2 and B3" on each figure instead of using intermediary letters a), b), c) and d).

Fig. 7 Even if this is for improving the readability, I'm not sure I like the shift by 0.5 factor because the curve gets wrong. What about simply splitting the y axis into several ones (shifted each other)?

- Suggestion: "along-trough" ⇒ "longitudinal", "across-trough" ⇒ lateral/transversal.

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