Response to referee 1: 'Ice shelf fracture parameterization in an ice sheet model' by Sainan Sun et al.

Received and published: 3 May 2017
The authors have implemented a new representation of continuum damage mechanics into the ice dynamics model BISICLES, providing a way to study feedbacks between flow dynamics and damage-induced softening of the ice. To compare results from their modified model to standard results in the absence of damage, they follow the design of the MISMIP+ experiment. We believe that a number of points need to be addresses before publication. We also suggest additional experiments and an expansion of the discussions section, which could strengthen the manuscript.
We would like to thank the referee for this detailed review.

In keeping with previously published papers, the authors adopt an advection scheme for damage. However, to the best of our knowledge, the authors suggest a new way to treat the source of damage in the advection equation, as detailed in section 2.2. The source is proportional to the local crevasse depth (surface + basal), where crevasse depths are calculated from a zero-stress criterion following (Nye 1957). We encourage the authors to expand on the differences/parallels with existing research on continuum damage mechanics, to put their work into context, and to better motivate this approach. How and why is it better than previous work such as [Krug et al. 2014, Borstad et al. 2012, Pralong and Funk 2005]?
We think the main aim of the study is not so much to propose a new damage model, but to look at the impacts of implementing one versus neglecting it. To that extent, we chose a simple relationship between damage and tensile stress. If we consider only surface crevasses and neglect the threshold stress (more on that later), our model would be rather more similar to Krug et al 2014: they have a non-zero damage source when the Cauchy stress is positive, so as $t \to \infty$ they will see $D \to 1$ to the depth given by Nye zero-stress model, at least as far as vertically integrated models are a good approximation to Stokes models. Basal crevasess could be included in a model along the lines of Krug 2014 by adding the water pressure to the Cauchy stress, as in the Nye zero-stress model for basal crevasses. Assuming that crevases open at least as quickly as the viscous deformation, we decided to compute the strain rate and damage simultaneously rather than by choosing some rate (as in Krug 2014).
We added a note on the timescale: "Specifying the damage-stress

relationship in this way assumes that damage evolves on a similar or faster timescale to the ice velocity field. Many authors specify instead a damage evolution rate, which, in Krug et al 2014, and given typical stresses in an ice shelf, amounts to a timescale of around 1 year." and a note on the similarity with Krug 2014 "Inasmuch as a shallow shelf model is a good approximation to the full Stokes model, our choice of the Nye zero stress model above is similar to the long-term behaviour of Krug et al 2014, at least for surface crevasses. In that model, damage grows where and only where the Cauchy stress is tensile, just as in the Nye model, giving the depth of surface crevasses. Basal crevassing could be included in such a model by adding the water pressure to the Cauchy stress, as in Keller and Hutter (2014)."

For example, contrary to these studies, the authors do not implement a stress threshold for the formation of damage, and assume that non-zero damage is present in any tensile stress environment. Is this realistic, and how does it affect the results? Presumable the qualitative nature of the results remains the same, but it might become important at a later stage, when e.g. calving criteria are considered?
Indeed, we do not impose a lower stress threshold for the formation of damge - this is in line with e.g the use of the same crevasse depth calculation in Nick 2010. Like them, we have assumed that the differences will be minor. At any rate, they will be limited to the upstream, slowing flowing parts of the ice where damage is low. We don't expect that such a threshold would make much difference to calving criteria, because we would only expect those criteria to be satisfied only in regions of large stress in either case. We added a note: "We also ignore any lower limit on the stress needed to open a crevasse, so that we will tend to produce small crevasses where there should be none. As we will see in the results, the major impact of the damage model is in the ice shelf and around the grounding line, where large tensile stresses readily exceed such limits".

With regards to the results, the text provides an adequate description and explanation of the findings, although we would like to add a few comments or suggestions:
The authors should specify how d_w (crevasse water depth) in Eq. 8 is determined. Is it set to a constant value, and how is this value chosen?
We added a note: A water depth $d_w \sim h/2$ is in fact required in Nick et al (2010) for any calving to take place at all, and could clearly have a substantial impact on our calculations too, but for this paper we consider only dry surface crevasses, with $d_w = 0$.

In Figure 8, a compelling argument is made that evolving damage could play an important role in simulating grounding line retreat/advance. However, the results are only discussed very briefly, which is disappointing. To strengthen their point, could the authors perform inversions for a spatially varying rate factor, using the surface velocity and geometry at different timesteps in the IceD0 and IceD1 experiments? It would be interesting to see how the rate factor changes over time, as one incorporates the effects of damage into its value. This could

inform present-day model initialization methods, as most models treat damage in the form of a spatially varying rate factor, which is kept constant in time.
We did originally consider a set of synthetic inversions following the IceD1 experiment, but we would expect to simply recover the field D (or an approximation to it, with the difference being down to issues with the inverson method). Hence the experiment of figure 8 (now 9): in this case we do actually hold the damage constant in time as though it had been computed in an inversion at $t = 0$. We then see a much lower rate of retreat than either the full damage model (IceD1), or the original model with uniformly softer ice (Ice1). We made a poor job of describing and discussing this result in the original, and have re-written the relevant parts of both the result and the discussion sections, and added a short paragraph to the conclusion. As the reviwer suggests, this does have serious implications for present-day model initialization methods.

In order to increase the impact of this work, we suggest highlighting how the results have altered our understanding of damage, and indeed, whether it should be treated as a vital part of future ice flow modelling studies. Perhaps the authors could discuss in more detail the future directions of research (incl. possible calving laws?) they like to pursue, and whether this model can become a prognostic tool for calving?
We think the paragraph added to the conclusion summarises at least the immediate impact - modellers may need to reconsider their initilaization methods.

P2L5: “extremely sensitive to calving”: I believe this statement could be misinterpreted as “more likely to calve”. Therefore, please change the wording to “ice shelves in the Amundsen and Bellingshausen seas are thought to be more vulnerable in the event calving...” or similar.
Done.

P2L15: what do you mean by “magnify”? Do you mean that propagation and penetration of fractures causes calving?
Yes we mean that. We change the word to ’trigger’.

P5L25: point out that A’ is a constant, and not a spatially varying field
Done.

P6L1-3: The second question needs a better explanation. Perhaps write something along the lines of “If we adjust the rate factor such that the damaged model reaches a similar grounding line steady state compared to the undamaged model, how does the transient response between both setups differ, when subjected to an external forcing that leads to thinning of the ice shelf?
Done.

P6L12: reformulate this sentence as follows: “In order to start the MISMIP+ experiments from the required grounding line location at x=450m, we run a series of IceD simulations with different values of the rate factor A. For each value of A, a new steady state grounding line location is obtained, and we select the

value A' for which the location is closest to the originally required grounding line at x=450m. We will refer to this steady state as IceD0."
Done.

P6L24: The reference to this table comes too late. Preferably refer the reader to this table before you start listing all the experiments, i.e. before line 5 on page 6.
Done.

P7L3: from here on, the authors use capital letter D to refer to damage. Should this not be small letter d, in line with the definition in Eq. 10 as the vertical integral of the damage?
We use small letter d to represent the vertical integral of the damage, but often it makes sense to refer to the vertical average, which we now denote $\bar{D}(= d/h)$ to avoid the confusion caused by our earlier use of D.

P7L12: It is worth pointing out that a decrease in A leads to stiffer ice, making it intuitively easier to understand why this is the right thing to do.
Done.

P7L14: Reiterate that Figure 2 is for A' instead of A, and therefore the damage pattern looks different from Figure 1.
Done.

P7L14: Can you explain why the areas of high damage at the margins are not so well confined to narrow bands as in Figure 1?
The text should be "damage at the end of the IceD0 experiment". We modified now.

P7L18: From the small figure it is unclear that the damage starts to grow a few kilometers upstream of the GL. Perhaps provide a zoomed-in version as an inset in Figure 2?
Figure 2 (now 3) has been modified to include a zoomed in region around the GL as suggested, instead of showing the speed and effective viscosity, which appear in figure 3 (now 4).

Figures 1-5: There is a lot of white space in all these figures that could be used to better display the details of your results. You should also consider choosing a different color to make the grounding line stand out better.
We have remade all the figures with less white space, and in some cases fewer panels (which can then be larger). We changed the colormap for the damage field to one that is light for $\bar{D} \approx 0$, progressing through red and blu to black for $\bar{D} \approx 1$. This allows us to use a black line for the grounding line, and we then use cyan (which stands out well against red, dark blue, and black, even when printed in black and white) for the 200 m thickness contour.

And a list of typos/suggestions where the text can be imporved...
P1L22: "former" $-$ >replace by "previously"?
Done.

P1L24: “...Antarctica IN recent...”
Done.
P2L2: “...under THE present climate...”
Done.
P2L5: “...even A small amount...”
Done.
P2L6: “will trigger” is too strong, replace by “can trigger”
Done.
P2L13: “statistically continuum”: what does this mean?
We delete the word ’statistically’.
P2L17: “...based on THE calculation...”
Done.
P2L18: “...and THE calving rate...”
Done.
P2L22: reformulate sentence as follows: “...fields, and hence do not take into accountthe stress history in the development...”
Done.
P2L24: “damage has AN effect on THE viscous behaviour...”
Done.
P2L29: “glacier’S”
Done.
P3L1: “state of art” $->$ replace by “state-of-the-art”
Done.
P3L6: “...the evolution of THE ice sheet, such as the speed and behavior of THE grounding line...”
Done.
P3L15: “...well in ice shelves...” $->$ “...well FOR ice shelves...”
Done.
P3L16: “...so given A bed elevation b and ice thickness h, THE surface elevation...”
Done.
P3L20: “...and THE two dimensional...”
Done.
P3L21-22: reformulate as “...is THE basal melt rate of the ice shelf. In equation (3), tr is the trace operator, E is the horizontal strain rate tensor...”
Done.
P4L2: remove “inland” as it is the same as “upstream”
Done.
P4L12: “proved” replace by “proven”
Done.
P5L12: “...represent THE effect of...”
Done.
P5L22: replace “sited” by “positioned”
Done.
P5L22: remove “towards the ocean”
Done.
P6L15: remove “...see the models respond...”
Done.
P6L24: remove “in real world”
Done.

P8L2: “extruds”?? P8L19: “floating” $->$ replace by “become afloat”
Done.
P8L19: “...and THE grounded area...”
Done.
P9L4: rewrite as “...The experiments Ice0 and IceD, which explicitly show the result of adding damage to the ice shelf, produced ...”
Done.
P9L21: “as” $->$ replace by “at”
Done.
P9L25: rewrite as “...This does not mean that calving is unimportant for THE grounding line...”
Done.
P9L27: rewrite as “...the general case in reality, in particular for large ice shelves.”
Done.
P10L4-5: remove excessive use of commas
Done.
P10L15: “In BISICLES-D, THE viscosity...”
Done.
P10L16: “...we see THAT the retreat of THE grounding line...”
Done.