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Interactive comment on "Fracture-induced softening for large-scale ice dynamics" *by* T. Albrecht and A. Levermann

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Response to the interactive comment by Anonymous Referee #3

Our point-by-point responses to the comments by Anonymous Referee #3 follows below. Referee comments are printed in blue font followed by our responses in black.

In their manuscript Fracture-induced softening for large-scale ice dynamics, T. Albrecht and A. Levermann describe the implementation of a feedback from their continuum fracture damage model described in Albrecht and Levermann (2012) to the ice flow solver in the Parallel Ice Sheet Model (PISM). In the course of this description,

improvements to the damage model are described, and different fracture initiation criteria are evaluated. In the following, the authors present results from the application of the model to several ice shelves in Antarctica. The test cases show a better representation of the steep velocity gradients in shear margins and an overall better fit of the velocity fields with the damage mechanics included.

The manuscript is well written and structured. The topic perfectly fits into the scope of the cryosphere. The questions addressed are highly relevant to ice shelf modeling since a prognostic damage field seems necessary to realistically model the future evolution of ice shelves. The relevance can also be seen by a growing body of literature covering various aspects of this topic. All in all, the manuscript is clearly worth publishing after adjustments.

General remarks:

The similarities and differences to Pralong and Funk (2005) could be made more clear throughout the description of the method. There also was a poster by Vieli et al. (2011) at EGU 2011 covering similar ideas. The poster sadly is not online. It might be worth contacting them for a copy of the poster and/or citing.

We thank the reviewer for these positive and constructive comments. We have rewritten parts of the manuscript pointing out more clearly the differences between the damage approach and our fracture density approach. Basically, our approach is a simplification of the continuum damage approach with a limited number of parameters. And we wanted to proof that this simplified model is able to represent relevant aspects of fracture-flow interaction, at least to first order.
We are familiar with Vieli's ideas that he presented at EGU 2011. We discussed the described run-away feedback mechanism for the Pine Island region and considered

different ways of stabilizing the dynamics. However, the application to the Pine Island region will be saved to following submissions, as it involves more complexity.

How much of the damage occurs in the grounding line region with prescribed velocities? How does the picture change, if you let the model freely evolve here, too (shifting the prescribed velocities upstream).

The grounding line region is subjected to strong tensile stresses. However, in our current applications to the Filchner-Ronne, Ross and Larsen B Ice Shelves, only shear stresses can reach the critical fracture-thresholds. This occurs to both sides of the fixed grounding line along the inlet margins: in the upstream grounded part for prescribed velocities and in the freely-evolving ice shelf downstream. This situation may change if the grounded part can freely evolve too, as we have learned in the Pine Island example. Since this example will not be further discussed in this paper, we leave this discussion to future applications.

How thoroughly were the standard-SSA and the fracture setups tuned for the individual cases? What were the tuning targets? Can the standard-SSA results be fitted better with reasonable effort and parameters?

For the standard-SSA, we ran a two-dimensional ensemble analysis varying the parameters of the enhancement factor E_{SSA} and the FESOM melting factor, in order to minimize the relative misfit between computed and observed velocity components (scatter plot) and ice thickness. Surface mass balance, boundary temperatures etc. were fixed during this process. This tuning exercise may provide even better results if for example density variations with depth would be taken into account. For the advanced model with fracture-induced softening we expanded the parameter space with respect to the four fracture-related parameters γ, σ_{t}, γ_{h} and $\dot{\epsilon}_{\text{h}}$, minimizing the misfit of the velocity in the considered freely-evolving regions (scatter plot) and along

the cross sections (profiles).

How sensitive are the results to the fracture threshold? Fig. 7 shows a runaway effect. Is this runaway close to the thresholds applied in the real-world applications?

Sensitivity is of course an important issue and depends on the individual stress regimes. The brown contours in the Figs. 8–12 indicate the steady-state fracture formation areas. Their size depends on the stress threshold for the prevailing loads, the supply by fractures from the ice streams and on the applied healing. In the real-world examples of Byrd and Evans Inlets as well as in Filchner Ice Shelf, stress thresholds of σ_{cr} =110–140 kPa are chosen comparably high, such that self-enforced fracture formation is active within some limited part of the ice shelf (close to the inlet margins). The effective stress further downstream is usually far below the threshold, and no additional fractures can form, i.e., the fracture band just fates out by healing (off-mode). In contrast, along the shear margin of Filchner Ice Shelf at Bjerknes Ice Rise, the run-away feedback is active along the whole length. The fracture bands in Larsen B Ice Shelf reaches far into the inner ice shelf region due to the much lower threshold of $\sigma_{\text{cr}} = 60$ kPa. The fracture bands are wide and the self-amplified fracture growth affects strongly the entire domain. Hence, sensitivity to the changes in the applied healing parameters is comparably high. We transferred some points of this argumentation into the modified manuscript. However, a comprehensive sensitivity analysis of the parameters is beyond the scope of this paper.

Two dimensional (difference) plots of the resulting velocity fields for the two solutions would be helpful, as would be 2-D plots of the modeled damage softening effects. The damage seems to lead to complete decoupling in several cases. The linear color scale for the damage does represent the viscosity changes well.

We decided to show velocity anomaly plots between the *standard* and the *soft-*

ened model for all examples as supplement fugures. We chose the scatter plot, since it simplifies the comparison of both models to the observations. The softening map is difficult to plot on a linear scale. On a logarithmic scale, however, the pattern would be similar to the modeled damage, since both are connect by a power-law function $E_\phi = (1 - \phi)^{-n}$.

In the scatter plots of the velocities, the colors for the two solutions are very similar. A stronger contrast might help distinguishing them. It might also end up in strong visual noise. Please give it a try, if you have not already done so.

We have chosen the colors analogous to the colors in the cross sections, but graphic format conversion turned the colors dark. We modified the colors slightly to counteract this effect.

Please discuss Pine Island and Thwaites either with the resulting velocity fields or leave them out completely. Considering the number of examples discussed, I don't see much damage done by leaving this case out.

Considering the case of Pine Island and Thwaites Glaciers opens a whole new field of involved mechanisms and should be discussed in more detail elsewhere. We leave this section out in the modified mansucript.

In the discussion, a comparison with other studies that investigate damage in ice shelves or the effect of damage mechanics for ice shelf velocity fields would be interesting. Could you compare your viscosity field with one inferred from satellite data inversion for one of the test cases?

This is indeed interesting and we had some discussions with Chris Borstad (Referee #2) during the preparations of this manuscript on the differences between

inversely modeled damage and the fracture density, that has been inferred with our approach (see Fig. 1 for comparison). In fact, this comparison is not trivial, because the inversely modeled damage (ϕ_{inv}) quantifies the macroscopic fracture softening effect for a short time interval (of observed surface velocities), while the fracture density approach (ϕ_{pism}) identifies areas of likely fracture accumulation (on time average, in a steady state) compared to the observations of the ice shelf surface (ϕ_{obs}). However, we can compare patterns: And in fact, there is quite a match along the inlet boundaries and close to the ice rises of Seal Nunataks. The modified manuscript refers to this comparison.

Specific comments:

• p. 4511: In the definition of the advection scheme, there is a problem when $v\Delta x = u\Delta y$. Some $\leq$ have to change to $<$ (resp $\geq$ to $>$) to avoid double advection. Is this scheme described somewhere in literature? A few words on its characteristics would be interesting. It does not seem conservative at first sight. What is the price for the reduced diffusion? Just the extra if-else-statements?

Absolutely correct, we modified the scheme in the manuscript accordingly. The eight cases represent the eight sectors of the circle, in which the velocity vector can be found, here starting with the case ($0 = v\Delta x < u\Delta y$) counter-clockwise. Vector component u points in the direction of i, whereas v points in the direction of j, according to Fig. 3, where case number 8 is represented. The so calculated finite differences take into account the eight next neighboring grid cells. In the standard upwind scheme, however, only four cases exist, based on the four direct neighbor grid cells. In this sense the improved scheme is more accurate with respect to the direction of the advective flow. And this is relevant for our applications, where we advect narrow stripes of a tracer, that are elongated in flow direction. We have not found these specific considerations in literature so far. The benefit of the improved scheme becomes most clear in the diagonal case ($|u|\Delta y = |v|\Delta x$), where only the finite difference to the upstream diagonal neighbor is taken into account, instead of an average of the finite differences to the two direct upstream neighbors. This reduces transversal numerical diffusion. Unfortunately this scheme is not conservative, which may become problematic for large gradients in the velocity field (shocks). Considering the integral along the transects of Fig. 3, total mass does not vary by more than 5% along the 90 km transport in a comparably smooth velocity field, for both schemes. This characteristic informations were adopted in the revised manuscript.

• p. 4515: Why does the fracture density first decrease downstream of the boundary and then suddenly increase for $\sigma_{\text{cr}} = 83$ (might be 82 or 84, hard to tell)?

Fig. 7 shows steady states here for different critical thresholds σ_{cr}. For constant supply of fracture density at a certain point and no healing, ideally a band of constant fracture density forms downstream. Since we are in a diverging shear environment and due to numerical dispersion, fracture density decreases slightly downstream of the source ($0.7 \rightarrow 0.6$), if there is no additional fracture growth. If σ_{cr} is chosen small enough, such that locally the load exceeds this threshold (in a single grid cell or more), additional fractures form and a self-enforcing feedback is switched on, that influences fracture formation in neighboring grid cells. A new steady state forms with a fracture band that accumulates fracture density all the way downstream of the source ($0.7 \rightarrow 1.0$). This is a classic threshold behavior, but the involved time scales are not considered here. We added some clarifying words to the manuscript.

• p. 4516 line 23f: $E_{\text{SSA}} = 0.05$ indicates there's something strange going on in the model. Is the temperature field realistic? Could you please also show the scatter plot of the velocities, that you show for the following examples?

We have previously not included the scatterplot of calculated velocities in the case of Byrd Inlet, because of the shift of the main stream, which leads to the result, that the RMSE is larger for the softened case as compared to the standard model and just not the appropriate measure. Though the sharp gradients at its margins are much better represented by fracture-induced softening. For consistence reasons, we have added the scatterplot now.
The value $E_{\text{SSA}} = 0.05$ may seem unrealistically low considering the assumptions by Ma et al. (2010), where values of about $E_{\text{SSA}} = 0.6$ can account for anisotropy effects in ice shelves. Indeed, there might be some temperature effect in the inlets: Some modelers decrease the temperatures in the boundaries by some degrees accounting for the colder ice draining from the upper mountains into the deeper regions of the ice shelf. In contrast, we do not prescribe the vertical temperature distribution at the inlet boundary, but let it freely evolve with the flow (also in the grounded upstream region). Temperature is only prescribed at the upper and lower surface. It might be the case, that the drainage of cold ice may be underestimated in our model or the strain heating along the inlet boundary may be overestimated. The hardening compared to the value by Ma et al. (2010) corresponds to a temperature difference of more than $10°K$ in the entire ice column. According to the used FESOM data for the mass balance underneath the ice shelves, marine ice accretion may not provided an explanation here (Jansen et al., 2013).

• p. 4517: What is the E_{SSA} in the fracture model case for Evans Inlet?

The parameter choice in the case of fracture-softening has been named in the figure captions, for Evans Inlet the same small value of $E_{\text{SSA}} = 0.05$ has been used as in the Byrd Inlet case. This choice is now motivated in the modified manuscript.

• p. 5421 lines 6ff: "This study does not aim at a conclusive investigation of the influence of fracture on the flow field, but is meant to introduce the concept and provide results on the qualitative changes in the flow field when fracture density is accounted for." The basic idea of accounting for damage on ice shelf flow fields has been covered before (see your introduction). As far as I can tell, the new aspect rather lies in prognostically including it.

The referee is abolutely right, we reformulated this conclusive sentence to make this clear: "This study does not aim at a conclusive investigation of the influence of fracture on the flow field. It is rather meant to introduce the first-order concept and to provide results on the qualitative changes in the flow field when fracture density is accounted for in this way."

• p. 4535: Why does the maximum shift to the side in the 45 degree case? The numerics promise perfect advection.

This shift is purely an effect of the post-processing of the simulation results. In order to plot transects, that are inclined with respect to the underlying grid, we interpolated the results onto a much finer grid. With regard to the comment of Referee #2, we rearranged the plots of Figs. 4+5 and corrected for the shift.

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Fig. 1. Comparison Larsen B Ice Shelf. a) Observed fracture density as in Fig. 6c, b) inversely modeled damage as in Fig. 1 d by Borstad et al. (2012) and c) fracture density as shown in Fig. 12b.