Review of *"Iceberg calving of Thwaites Glacier, West Antarctica: Full-Stokes modeling combined with linear elastic fracture mechanics"* by Yu et al.,

Review by Till Wagner (tjwagner@ucsd.edu)

The authors develop a 2D ice-sheet model that includes the time-evolution of crevasses, by combining a Full Stokes (FS) model with an account of linear elastic fracture mechanics (LEFM). The results are compared to those obtained with higher-order (HO) and shallow-shelf approximations (SSA). The model is set up to represent a cross-section of Thwaites Glacier (TG), and the model output is compared to observed crevasses at TG. The results suggest that deviations from hydrostatic equilibrium are an important driver of crevasse propagation, and ultimately calving.

The study is concerned with a pressing topic in glaciology and climate science, and offers an innovative approach to the calving problem. A physically consistent combination of the FS model and LEFM under consideration of both surface and basal crevasses would constitute significant progress. The paper is furthermore clearly presented, well written, and nicely illustrated.

There are a few major points that I believe should be addressed. These are (i) a discussion of issues involving the complex rheology of ice, particularly that of combining a viscous flow model with an elastic fracture model (ii) the question of crevasse initiation; (iii) a more direct comparison with the observational crevasse data, and (iv) a more detailed analysis of the stress conditions that lead to crevasse propagation in LEFM. I will discuss these, together with a number of more minor comments, below.

Overall, I believe that this manuscript will — after some revisions — be a valuable contribution to the literature and a significant step toward adequately representing glacier calving in ice sheet and climate models.

Major Comments

1. The manuscript offers little discussion of the potential issues and limitations of its approach, and fails to put methods and results sufficiently into context with the existing literature. For one, LEFM is fundamentally somewhat at odds with the non-linear viscous-plastic rheology of glacier ice (e.g., Weiss 2004, Benn et al. 2007), a topic that merits at least some discussion. A particular issue is that of the different timescales of the viscous flow model and the LEFM crevasse propagation. In the paper, the LEFM routine is called every 20th time step of the FS model routine. Some justification or motivation for this particular coupling scheme should be given.

2. Previous studies have found that one of the main issues with applying LEFM is the requirement of sizable pre-existing fractures (Nath and Vaughan 2003, Krug et al. 2014). Here, on the other hand, crevasses can be initiated from infinitesimal cracks. Firstly, an explanation regarding the model features (in contrast to previous studies) that allow for such spontaneous initiations seems in order. Krug et al. (2014), for example, need to invoke a damage mechanics framework to "initiate" cracks.

Highlighting differences and similarities between the present model and that of Krug et al. (2014) —who also combine a Stokes model with LEFM — would be informative. Secondly, I must be misunderstanding something, because, if there's no initial threshold, it appears to me that this micro crack initiation would lead instantly to new crevasses wherever $K>K_c$? I understand that the authors are interested in the propagation, rather than initiation, of individual crevasses, but it seems that a physically plausible initiation process should be discussed in some form. Would a more complete model experiment initiate one crevasse at the location of maximum K, which then results in stress release in the vicinity, or similar?

3. In the abstract, the authors state that they "find that FS/LEFM produces surface and bottom crevasses that match the distribution of [observed] crevasse depth and width". Although the text mentions some ball-park numbers for the different observed and modeled crevasse depths and widths, a more direct comparison is missing. I believe it would be helpful to add a figure that shows such a direct comparison, e.g, a width-vs-height scatterplot for observed and modeled crevasses, color coded by the different model experiments (or maybe some other, more suitable, illustration). It would also be interesting to see how observed and modeled crevasses compare as a function of distance from the grounding line.

4. One of the key points of this study is that the HO and SSA approximations fail since, for these approximations, the stress intensity factor, K, does not surpass the fracture toughness beyond a limited crevasse depth. This is traced back to the hydrostatic assumption necessary for HO and SSA. It would be helpful to actually show a figure of how K(t,x) evolves for the different models and different crevasse locations, and compare this to K_c. This may also help explain why "spontaneous" crevassing can occur in the model. It may even be worthwhile to show how the longitudinal stress, and ice and water pressure terms in (19) evolve. I was surprised to read that the crevasses in the HO and SSA simulations grew at all in the first place, and why are they then confined to a limit depth of 50 m? Maybe some further analysis of the evolution of K and a figure or two along the lines suggested above could help in the interpretation?

<u>Minor Comments</u>

page 1

l 24. "iceberg calving *will* rise, which *will*" — replace with "is likely to rise, which would"? (This may not be as certain as the current version implies.)

page 2

l 7. "each process" — which process? replace with "…the role of the different processes involved …" ?

l 8. "where crevasses propagate"

l 11. change to "… it is necessary to use a fracture theory, such as LEFM"? (There may be other ways; currently it sounds like this is the one and only)

page 3

Sec 2.2: It may be helpful to point out that (almost?) the same equations apply for the grounded and floating ice — only the boundary conditions differ.

l 20. "values"

l 26. add a reference for the 2D Full-Stokes model

page 5

l 3. in previous work, (14) contains a N (pressure) factor. What happened to that?

l 9. is $z_b(t)$ only unknown in FS, but not in HO an SSA?

l 15. it is really the "ice-bedrock-ocean boundary"

l 17. "migration of *the* grounding line"

l 28. "avoids", or maybe better: "…term, invoked to avoid …"

page 6

l. 7 it's worth mentioning that K and the stresses depend on time and x (not just z)

l. 11 "equal"

l. 16 how is the width of the crevasse determined?

l. 18 a discussion of the coupling scheme between FS and LEFM model would be of interest here (see Major Point 1)

Sec 3.1. "FS model validation" —rather than evaluation (?) (see also l.26)

l. 27 "migration of *the* grounding line"

page 7

3.2. Model Setup: what's the duration of the integrations?

l. 1,2 "… *to* within X km"

l. 9 “In all ~~the~~ following experiments …”

l. 12 These are not really “micro” crevasses, but rather “infinitesimal” crevasses, no? Although the latter is of course more cumbersome to use.

l. 13 I found the choice of initial crevasse positions somewhat surprising. I presume the high density of crevasse locations near the grounding line was initially motivated to better resolve the potentially more variable crevasse dynamics in this region? It might be worth justifying this choice with half a sentence. Otherwise, I’d believe a linear or logarithmic spacing throughout the shelf may have made more sense.

l. 14 The “respectively” doesn’t really work here. Maybe something like “In these experiments, the numbers 1—7 indicate crevasses initiated near the grounding line (at distances x = 0.5, …, 3.5km from the grounding line); the numbers 8, 9 indicate crevasses in the middle of the ice shelf (x = 18, 28 km); and numbers 10, 11 indicate crevasses near the ice front (x = 35, 36 km).

l. 21 “…positions for Experiments D and E are …”

page 8

Sec 4.2. — related to Major Comment 2: it would be nice to have some more information about the observed crevasses, i.e., how many, what’s the spread, etc. I believe this could be summarized in a figure as suggested above.

l. 11 Can the authors elaborate on why the ice is “tens of meters below equilibrium” near the grounding line?

page 9

l. 5 (However, undercutting presumably occurs due to sustained ocean melt, i.e., it’s not usually the case that undercutting occurs as a one-off sudden event, which then relaxes back to its normal state, but rather is maintained by a long-term temperature gradient in the water. So a fixed undercut profile might be more realistic.)

l. 16 equation (20) — not (19), same for l. 17

l. 20 “… grounding line *region* stop …”

Paragraph starting l.24: this is where a figure of the stresses depending on the model, experiment, and crevasse depth/shape would be insightful

l. 26 “crevasses”

page 11

l. 4 “crevasses”

Figures

2. the blue lines are hard to see on my print version - choose green instead? also differentiate the two red lines somehow more clearly?

3. annotation: the β in the equation for bed drag should be α^2 (or $\alpha^2 N$?) caption: “… red line is the hydrostatic *bottom elevation* calculated …”

5. color code the lines in (b) and the corresponding dots in (a), and then use different symbols for Elmer/Ice and ISSM? Or at least put numbers onto the profiles in (b). Also: in a dynamical systems context, the unstable equilibrium state for the analytical solution (i.e. the negatively sloped part of the black curve) is commonly given as a dashed line
caption: something seems to have gone wrong with the parentheses around the references

6. Why does the FS friction coefficient suddenly become large again at 0 (yellow line overlaying the black box line)?

7. There is this interesting behavior that the crack height for profiles 8–11 seems to undergo a non-monotonic evolution, where it first jumps to a high value, then decreases for a bit, before it recovers to a value similar to the original one. Can the authors comment on that? Maybe a further analysis of the stresses as suggested above may help with this interpretation as well?

Give it a title “Experiment A” and similarly for the panels of Figure **8** (to facilitate an easy comparison with the text/ captions)

caption: “… b) Details”

Additional References

Weiss, J. "Subcritical crack propagation as a mechanism of crevasse formation and iceberg calving." Journal of Glaciology 50.168 (2004): 109-115.

Nath, P. C., and D. G. Vaughan. "Subsurface crevasse formation in glaciers and ice sheets." Journal of Geophysical Research: Solid Earth 108.B1 (2003).