Review of Holmes et al.: Modelled 3D calving at Kronebreen, Svalbard, driven by tidal fluctuations and frontal melt

This study investigates the controls on calving at Kronebreen, a tidewater glacier in Svalbard. The paper has a modelling component and an observational component. The modelling component employs the full-Stokes finite-element model Elmer/Ice with a crevasse-depth calving law, with a ten-minute timestep. The observational element consists of ice-front profiles determined by side-looking multi-beam surveys, and demonstrate the presence of undercuts beneath the waterline. The two components are linked via a discussion of model forcing, but otherwise observations and model results are not strongly integrated.

I focus here mainly on the modelling component of the paper, particularly potential mismatches between model formulation and calving processes on the glacier.

First, I agree with the point made by Jason Amundson about the basal friction law used in the model. Indeed, a detailed study by Vallot et al. 2017 (J. Glac. *63*,1012-1024) demonstrated that a linear friction law is inappropriate for Kronebreen, and indicates that a regularised Coulomb or similar would be a better approximation. Basal slip may well mediate glacier response to tidal fluctuations, with the implication that the model is missing an important process.

Second, on tidal timescales pressure fluctuations on the front will be propagated via elastic strain, not viscous deformation. This means that the decision not to implement the elastic stress solver in Elmer/Ice has potentially serious implications. It would be far better to conduct shorter runs with elasticity on than long runs with elasticity off.

Third, Elmer/Ice respresents ice as a homogeneous, continuous medium, whereas Kronebreen is deeply crevassed in the terminal zone. Taken together with the point about elastic response, this means that ice response to tidal cycles will likely be dominated by brittle-elastic processes, such that the model will be incapable of representing processes likely key in triggering calving.

Fourth, calving is implemented in the model when crevasses penetrate (a) from the surface to the waterline or (b) the full thickness of the glacier, with crevasse depth calculated using a 'zero-stress criterion'. This is, of course, a great simplification of how crevasse penetration and calving actually works. Although Elmer/Ice predicts individual calving events, there is no reason to believe that it can be trusted to deliver reliable results at that scale. I believe that the CD law implemented in Elmer/Ice is the best method for modelling calving in a continuum model (by a long way), but I am also very aware of its limitations. CD in Elmer/Ice performs well in modelling overall ice-front position (such as the seasonal fluctuations Store Glacier modelled by Todd et al.), but it was not designed to predict individual calving events (HiDEM is much better suited to this).

Fifth, there is the issue of the ice temperature derived from model spin-up. Does this include firn warming by refreezing of meltwater? Firn warming is a very important process on larger Svalbard glaciers, making them some degrees warmer than they would otherwise be. Indeed, large Svalbard glaciers are often near-temperate, with only thin cold surface zones in their ablation areas and lower accumulation areas. This probably does not affect the model results in any material way, but it is worth reflecting on.

The above questions about model formulation highlight an issue that runs through the paper. That is, the model results are taken at face value and discussed as though they provide insights into calving behaviour on the glacier, whereas there is no indication that calving does occur in the ways predicted by the model. If the paper also included a detailed time-series of calving observations (such as that presented by How et al. for Tunabreen), it would be possible to determine whether the modelled patterns mirror the real world. But as it stands, the paper shows us how the model behaves, not how the glacier behaves.

For both 'full-penetration' and 'waterline' criteria, calving depends on the stresses in the ice near the front; for the 'waterline' criterion, it additionally depends on the distance to the waterline. The considerations discussed above imply that the model will be rather insensitive to back-pressure fluctuations on tidal timescales, in turn suggesting that the modelled calving is mainly responding to (a) varying freeboard height (potentially encouraging calving at high tide, because crevasses do not have to penetrate as far before calving is implemented); and (b) undercut development, which modifies the tensile stresses at the surface. These effects may be sufficient to explain the observed patterns in the model output.

Despite these shortcomings, the paper contains much of potential interest about the behaviour of the Elmer/Ice calving model, and could be developed into a valuable contribution if it is reconfigured to emphasise that it is an exploration of model behaviour, with more circumspect discussion of it applicability to real glacier calving. In addition, considerable value could be added if model output was compared with bulk frontal ablation rates at Kronebreen, which are available for summer 2016 (Adrian Luckman has data covering this period). This would provide much-needed ground truthing against which model results could be evaluated.

The data on the submerged part of the Kronebreen glacier front are an important element of the paper. I understand there are good reasons why the shallowest 20m are not imaged, though unfortunately this is perhaps the most significant part of the submarine ice cliff. As noted in the review by Amundson, the form of the front just below the waterline has big implications for the stresses in the ice, and the style of calving (see Slater et al., 2020), so it is to be hoped that future technical developments will allow this portion to be visualised. The authors may wish to discuss the prospects of this.

Finally, I have two comments on the Figures in the paper.

Figures 4 and 5: the rose diagrams contain a great deal of information, but I find them very difficult to read. This is because the top of the roses indicate both extreme highs and extreme lows, and one has to mentally 'unwrap' the diagram to grasp the patterns in the data. I think it would be better to present these data with a single vertical axis running from extreme highs (top) to extreme lows (bottom), and events during rising and falling tides shown as bars to the left and right of the axis, respectively.

Figure 6 is puzzling. The caption tells us that calving events are indicated by dots and that the blue-shaded area represents a period of lower calving frequency. But the blue-shaded area contains a large number of dots, far more than in the pink-shaded area. This discrepancy needs to be resolved.