We thank both reviewers for their thorough and thoughtful comments. We have made significant changes to the structure of the paper in response. Replies to the reviewers' comments are shown in blue below. The revisions to the manuscript have resulted in changes to line numbers and equivalent new line numbers are provided with each response.

# Reviewer 1: J. H. Bondzio

# **1** General Comments

# 1.1 Summary

S. Cook et al. use three numerical models (HiDEM, Elmer/Ice, and a KPZ-model) to study the formation of crevasses on the Totten Ice Shelf (TIS). The TIS exhibits a complex crevasse pattern near the calving front of both along and across-flow crevasses. The authors find that the across-flow crevasses are not reproducible in the observed amount in a HiDEM simulation that includes the calving front region only. Priming the model through artificial introduction of across-flow crevasses into the model yields a good match of the observed iceberg size distribution, however. The authors argue that across-flow basal crevasses therefore are necessary to create the observed crevasse pattern, and have to be advected into the calving front region from upstream. In a second experiment using HiDEM, they find that basal across-flow crevasses form predominantly at regrounding points in the grounding zone. The authors argue consequently, using an implicit front tracking scheme (KPZ-model) and a continuum mechanics based model (Elmer/Ice), that initial narrow cracks created at the grounding zone are widened to observed widths as the ice shelf melts from beneath and spreads under its own weight.

# **1.2 Result Novelty**

The model study presents novel and interesting results which should be published.

# 1.3 Lack of a Sensitivity Study

The authors use the numerical models to create a logical argumentation chain, which makes it plausible that basal across-flow crevasses are created at the grounding line, advected and widened toward the calving front, where they are key for the calving process of this ice shelf. For my understanding, however, this model study lacks a solid sensitivity study of its model input parameters and parametrizations, i.o. to exclude other plausible explanations for the creation and role of across-flow crevasses. It is necessary to perform a sensitivity study w.r.t.:

• The yield stress parameter.

You mention it is hard to reproduce the amount of across-flow crevasses, and therefore you argue that across-flow crevasses have to be created upstream at the grounding line. However, Figure 2b clearly shows the creation of across-flow crevasses upstream and even near the calving front in the model. For your argument, you need to rule out that this model "failure" to reproduce the amount of cracks is not due to e.g. the choice of a model parameter (e.g. the critical yield stress of 1 MPa (cf. p3, l24)), or other model simplifications (e.g. the lateral stress boundary condition, which excludes the driving stress). A lower critical yield stress might for example potentially result in more brittle failure of the ice upstream, increasing the number of across-flow crevasses created near the calving front. In my opinion, you need to test a range of yield stress parameters

# before you can infer from your results that the across-flow crevasses have to be created upstream.

We understand the reviewer's desire to see more thorough sensitivity testing. However, each model run requires approximately 100,000 CPU hours to complete, making a suite of sensitivity tests unfeasible for this model geometry. The model has been tested extensively in other investigations to find best-fit parameters for glacier ice (see references below). For the model to produce plausible results there is not much room to vary the yield stress. If the yield stress is too low the ice shelf simply disintegrates.

Some variations can be allowed and the reviewer is correct that more crevasses would appear as yield stress is lowered. However, the effect is to increase the frequency of the cracks appearing but without changing the underlying orientations of the fractures. We would not be able to create the observed across-flow fractures in this way.

A discussion of this issue has now been added to the text (p4 l22 – p5 l1).

Åström, J. A., Riikilä, T. I., Tallinen, T., Zwinger, T., Benn, D., Moore, J. C. and Timonen, J.: A particle based simulation model for glacier dynamics, Cryosphere, 7(5), 1591–1602, doi:10.5194/tc-7-1591-2013, 2013.

Åström, J. A., Vallot, D., Schäfer, M., Welty, E. Z., O'Neel, S., Bartholomaus, T. C., Liu, Y., Riikilä, T. I., Zwinger, T., Timonen, J. and Moore, J. C.: Termini of calving glaciers as self-organized critical systems, Nat. Geosci., 7(12), 874–878, doi:10.1038/ngeo2290, 2014.

Benn, D. I., Åström, J. A., Zwinger, T., Todd, J., Nick, F. M., Cook, S., Hulton, N. R. J. and Luckman, A.: Melt-under-cutting and buoyancy-driven calving from tidewater glaciers: new insights from discrete element and continuum model simulations, J. Glaciol., 1–12, doi:10.1017/jog.2017.41, 2017.

Riikilä, T. I., Tallinen, T., Åström, J. and Timonen, J.: A discrete-element model for viscoelastic deformation and fracture of glacial ice, Comput. Phys. Commun., (APRIL), 13–22, doi:10.1016/j.cpc.2015.04.009, 2014.

Vallot, D., Åström, J., Zwinger, T., Pettersson, R., Everett, A., Benn, D. I., Luckman, A., Pelt, W. J. J. Van and Nick, F.: Effects of undercutting and sliding on calving : a coupled approach applied to Kronebreen , Svalbard, Cryosph. Discuss., doi:doi.org/10.5194/tc-2017-166, 2017.

• The basal friction law.

You state you use a constant basal friction law. Using this law, a sharp stress gradient occurs at the grounding line, which is suitable to create basal crevasses. There is a lot of uncertainty regarding the basal conditions at the grounding line, however. Other basal sliding laws include the basal effective pressure (e.g. Budd et al., 1984), which would not create this basal stress gradient. You'd need to test different basal sliding laws before you can be certain to attribute the basal crevasses to the regrounding points.

It is not currently possible to include complex sliding laws such as that of Budd et al. in the HiDEM model. Instead, the constant basal drag coefficient we use is very low (we use a value of 10<sup>7</sup> kg m<sup>-2</sup> s<sup>-1</sup>, as compared to typical flow model inversion values ~10<sup>11</sup> kg m<sup>-2</sup> s<sup>-1</sup> e.g. Morlighem et al., 2013; Arthern et al., 2015). This choice of basal friction is successful in reducing the effects of a steep gradient in basal drag at the grounding line, as demonstrated by the fact that crevasses do not appear at a grounding line. Instead, basal crevasses are concentrated at re-grounding islands, where the glacier experiences compression and an upwards push as the ice hits the island, while on top and lee side of the island there is

tension. These will create fractures near the base independent of the basal friction parameter chosen. This is now discussed in the text (p10 l24 – p11 l5).

Morlighem, M., et al. "Inversion of basal friction in Antarctica using exact and incomplete adjoints of a higher-order model." Journal of Geophysical Research: Earth Surface 118.3 (2013): 1746-1753. Arthern, Robert J., Richard CA Hindmarsh, and C. Rosie Williams. "Flow speed within the Antarctic ice sheet and its controls inferred from satellite observations." Journal of Geophysical Research: Earth Surface 120.7 (2015): 1171-1188.

• The choice of model domain extent.

For the reason of limited resources, you cannot model the entire ice shelf. The inset of your model domain, however, shows that you do not include the eastern, grounded part of the TIS in your model domain. Certainly, this grounded area will have a significant impact on the momentum balance of the ice shelf, and possibly contribute to the creation of across-flow basal crevasses? From my understanding of the text, this region has also not been accounted for by imposing suitable boundary conditions. What are the implications of this?

In the data set we use there is a larger grounded section of the shelf on the west side and a smaller one on the east side, a little upstream from the terminus (as shown in the figure below with floating ice in red and grounded ice in green). We have used an isostatic condition on the boundaries of the domain (Equation 2, p5) which is a simplification of the driving stress, as it cannot account for longitudinal stresses, which can be an important factor in the stress balance around the grounding line and transition zone. The limited domain is therefore a weakness of our model. We do not have the resources to rerun results for a larger region, but have now included this limitation in the discussion section (p10 l17-21).



# **1.4 Model Setup Description**

For reproducibility it is important to include a comprehensive description of all the used models. All boundary conditions and used model input data sets need to be described. For the HiDEM model, please state the geometry and ice velocity data sets used for setup. For

the KPZ-model, please describe in detail the choice of parameters v,  $\lambda$ , and forcing F (p5, l6). How do you vary  $\eta$ ? How is the steady state (I'm assuming it is a steady state) shown in Figure 4 reached? A table listing all variables and model parameter values would be helpful. Some of this information was missing in the text and has now been added as follows:

- HiDEM geometry: The geometry of the HiDEM model is taken from surface elevation and ice thickness data collected by the ICECAP program. These are interpolated using TELVIS (Thickness Estimation by a Lagrangian Validated Interpolation Scheme) see Sect. 2.1.
- Ice velocity: The ice velocity is not used as model input. Instead, the boundary conditions are set using isostatic/hydrostatic pressure (Equation 2, p5).
- KPZ parameters: The parameters  $\nu = 1 a^{-1}$ ,  $\lambda = 1 ma^{-1}$  and  $F = 1x 10^{-3} x' ma^{-1}$  are now included in the text (p7 l9&11).
- Choice of  $\eta$ :  $\eta$  is used in this experiment to initialise the basal fractures in the model, after which time  $\eta(t>0) = 0$  (p7 l8-10). The initial fractures are chosen to most closely match the observed geometry, and can be seen in Figure 4.
- The KPZ model output is not shown in steady state. Instead, we stopped the experiment after 100 years, which is roughly the transit time from grounding line to calving front for the flight path shown in Figure 1. This is now explicitly stated in the text (p9 l10).

# 1.5 Paper Structure and Figure Clarity

The paper loosely follows a Introduction-Methods&Data-Results-Discussion-Conclusions structure, without a separate discussion section, however. Parts of the discussion are found in the results and the conclusion section. This makes it at times hard to distinguish between the respective two. Moreover, it renders the conclusion part lengthy. I would suggest creating a separate discussion section, where the interesting model results are discussed at full length. The conclusion could then be shortened by summarizing the findings, and present a perspective for where future work should be performed. See specific comments below. The clarity of some figures could be enhanced, cf. specific comments below.

The structure of the paper has been altered as suggested, to include an explicit discussion section and to improve the clarity of discussion of different models.

# **2** Specific Comments

**2.1**: p3, l7: The introduction speaks about three models, HiDEM, Elmer/Ice and the KPZ equation. Which one is referred to here? Please be specific and describe for each model which data set is being used.

This has now been clarified (p4 I2) and each model description now states whether it uses the observed or an idealised geometry (p6 I1, p7 I8, p7 I25).

**2.2**: p3, l14: "Model performance": Please specify, which model performance is evaluated. That of HiDEM?

This has now been clarified (p4 l11).

**2.3**: p3, l18: Title: The text speaks about discrete element models only. I suggest to change the section title to just that.

The section title has been changed as suggested (p4 l17).

**2.4**: p4, l6: What are the reasons that you omitted the driving stress from the lateral stress boundary condition? Especially in the 2nd HiDEM model, the inclusion of the driving stress on grounded ice might make a significant difference for the stress regime.

The lateral boundaries of the model are forced using isostatic pressure from the surrounding ice (Equation 2). This is a simplification of the driving stress, as it cannot account for longitudinal stresses, which can be an important factor in the stress balance around the grounding line and transition zone (e.g. Pattyn et al. 2006, Schoof 2007). Were these stresses to be included it is possible that the fracture pattern would change, and this is now acknowledged within the text (p5 l17-18 & p10 l17-21).

Ref: Pattyn, Frank, et al. "Role of transition zones in marine ice sheet dynamics." Journal of Geophysical Research: Earth Surface 111.F2 (2006).

**2.5**: p4, l17-19: Please state the type of basal friction law used, and add the unit of c.

# This has been altered in the text (p5 l18-22).

**2.6**: p5, l2: With this KPZ-model, you assume uniform melt along the surface of the basal crack. Are there observations that support this assumption? Some of the work you cited (Jordan et al., 2014) finds that the melting pattern inside a basal crevasse can be highly inhomogeneous, with melting at lower sections of the crevasse, and refreezing at higher ones. Therefore, it should be discussed whether the initial crack distribution  $\eta$  is realistic, or whether perhaps deeper-penetrating cracks are possibly more realistic.

The melting assumed in the KPZ is highly simplistic, and we have now expanded the text to discuss in more detail the implications of this for the development in shape of the basal crevasses (p7 I13-18 & p12 I7-10).

**2.7**: p6, l8 and elsewhere: The ice front geometry is complex. It is therefore difficult for me to distinguish between crevasses running parallel and perpendicular to the calving front: a crack can be perpendicular to one segment of the calving front and parallel to the other. Please specify how you define your terminology.

We have updated Figure 2 to show results from a later timestep, which should make it easier for the reader to observe the overall trend of fracture orientation. Not all fractures are perpendicular to the calving front, and the text has been amended to make this clearer (p8 l11-15). What can easily be observed in the figure is the lack of across-flow fractures, particularly upstream of the calving front. This is also analysed in the new supplementary material using the observed fracture orientations.

**2.8**: p6, l10-13: This is discussion material, please move to separate discussion section.

This now appears in a new Discussion section (p10 l22-23).

**2.9**: p6, l21-24: This is discussion material, please move to separate discussion section.

This now appears in a new Discussion section (p11 l6-11).

**2.10**: p7, l1-6: This is motivation, and should be in the introduction section.

This has been moved to the Introduction (p2 | 25 - p3 | 2).

**2.11**: p7, I7-12: This is model setup description, and should be in section 2.3.

This has been moved to Sect 2.3 (p7 I7-12).

**2.12**: p7, l14-17: This is discussion material, please move to separate discussion section.

This now appears in a new Discussion section (p12 I3-10).

**2.13**: p7, l20,21: Parts of the experiment description have been given earlier already in section 2.4.

Areas of repetition have been removed.

**2.14**: p7, l22: Please add the duration it takes for this widening to take place. Figure 5 suggests 52 weeks?

This has been added to the text (p9 l16).

**2.15**: p7, I23-p8, I4: Please move this discussion material to the discussion section.

This now appears in a new Discussion section (p11 l13-16).

**2.16**: p8, I7: Please add the spacing and length of the artificial across-flow basal crevasses that have been inserted. Ideally, this information would already be given in section 2.

We used trigonometric functions to mimic depth, width and spacing of crevasses in Fig.4. The equation is now given in the text (Equation 4) and has been moved to Sect. 2.2 (model setup).

**2.17**: p8, I5-13: Please move the model setup and discussion material to the respective sections.

This section has been rewritten, and relevant text has been moved to Sect. 2.2 and the Discussion.

**2.18**: p8, l10-13: Usage of many relative terms: "break apart easily", "fractures develop slowly". Please show the results for both cases so that the reader is able to compare.

We have rewritten the text to make our statements more robust, and limited them to the data shown in Figure 7 (p9 I20-23).

**2.19**: p8, I13: Figure 7 does not show that the experiment without the insertion of basal crevasses produces the observed iceberg distribution. It only shows the case for where the basal crevasses have been inserted. I'd suggest to add the power spectrum of the earlier case to Figure 7.

The figure has been amended as suggested.

**2.20**: p8, l19: Without a suitable sensitivity study, we cannot conclude that the across-flow crevasses have really to be advected from upstream.

See above discussion.

**2.21**: p8, l24: You say that basal crevasses are created at the grounding line. With the HiDEM at hand, what can you say about the process that creates these basal crevasses? Is it - as I assume - the jump in basal shear stress?

The basal crevasses are primarily produced not at the initial grounding line, but at regrounding points downstream. The fractures are caused by the upward gradient in the bedrock, which causes compression of the ice on the upstream face of the island, and conversely extension on the top and lees-side of the island. It is this extension that leads to the across-flow basal crevasses. The along-flow crevasses are caused by shear.

# This is now discussed in more detail in the text (p10 l24 – p11 l5).

**2.22**: p9, I9: Please list and discuss the implications of the "significant oversimplifications" at an earlier point.

These are now discussed earlier in the text (p7 l13-18).

**2.23**: p9, l13: "speed with which they form": This is new discussion material. Moreover, in the current manuscript, you do not show how fast the icebergs form in time, you only mention that they form "more quickly" once across-flow crevasses are introduced to the model (p8-l13). Videos in a supplementary material could be helpful to illustrate your point.

Due to the large storage requirement of the model's output files, we have stored only a limited amount of output data and we are not able to produce a video or similar as recommended. Instead, we have restricted our discussion of the results to the data that can be seen in Figures 6 & 7 (p9 I20-23).

**2.24**: p9, l17: "which are likely produced at the grounding line": Again, you'd need to show first through a sensitivity study that the underproduction of across-flow crevasses in your calving-front-HiDEM setup is not due to the choice in model parameters.

See discussion above regarding sensitivity testing. In addition to this, our models cannot discount that basal crevasses may also be formed on the ice shelf downstream of the grounding line. This is now acknowledged in the text (p11 l23-25).

**2.25**: Sect.4: Much of section 4 (p8, l20 to p9, l12-21) is discussion material, and would deserve a separate, earlier section. I suggest to then create the conclusions from a condensed version of the discussion and the outlook.

We have altered the paper's structure as suggested by the reviewer.

**2.26**: Figure 1: I suggest to add a scale ruler, a North arrow/grid lines, and an Antarctica location inset for orientation.

We have added an Antarctic location inset and grid lines for clarity. The Eastings/Northings grid used provides information equivalent to a north arrow and scale so we have not added these for simplicity.

**2.27**: Figure 2: Only little information is gained by showing two times the same satellite image. The reader will still get a feel for the crevassing pattern if image a was to be left out. Even more so, as the remaining image would be printed larger, and the crevassing pattern would be visible in more detail.

In response to other reviewer's comments, we have updated this figure to include model output from a later timestep, making the perpendicular-to –front fractures clearer to the reader. The format has also been updated to be consistent with Figure 6 to assist the reader with interpretation.

**2.28**: Figure 3: The main information of this figure should be the basal crevasses, which occupy only the bottom part of the plot. The most visible information is the colorful ice thickness, which stems from a data set not presented here. I'd therefore suggest to use a less dominating color map for the ice thickness (e.g. a gray scale). The crevasses (black) and the grounding line (dark gray) are hard to distinguish. I'd suggest using a brighter color for the crevasses.

# Changes have been made to the figure as suggested.

**2.29**: Figure 4: Just a comment: The blue color of the vertical lines at the bottom associates them with the observed blue profile. I suggest changing their color to red, i.o. to associate them with the modeled profile. Please elaborate: does this figure show a steady state geometry?

The vertical lines at the bottom indicate the initial fractures used in the model set-up, which were directed by the observed geometry so we maintain this colour in order to make that clear to the reader. The figure does not show a steady state geometry, and we have altered the caption and relevant results section to make this clear (p9 I10).

**2.30**: Figure 5: The clarity of the figure could be enhanced by a) cropping the x and y axis so that the floating slab of ice is in the respective center of the subplot, b) dropping the 6-digit precision of the time which is superfluous, c) using a uniform format for the tick-labels of the colorbar, and d) including a y-axis.

## We have updated the figure to include the requested changes.

**2.31**: Figure 6: This figure was confusing to me at first due to its grainy appearance. The meaning of the discontinuous horizontal black lines is not clear. The broken bonds between the ice bergs are hard to distinguish from only slightly damaged or undamaged ice. The Cartesian three-arrow orientation guide has no labels and could be left out. Additionally, x and y-labels, a scaleruler, gridlines and/or a north arrow would be helpful for orientation for the reader. Why are some of the areas up to the calving front white (and I assume not damaged?). I think it would be useful - for comparison of the crevasse pattern - to include the same figure next to it for the case without the added basal across-flow crevasses. Why not use the same layout at Figure 2b?

This figure is plotted so that, on a dark background representing water, all particle locations are marked by a white dot, smaller than the actual particle in the model. Since the glacier is modelled by discrete layers of particles the more shallow ice at the calving front turns grey as some water 'shines through', while the thicker ice is white. The boundary is distinct because the model is discrete. Where crevasses have formed, particles have moved away from each other, and they therefore show up as narrow black bands.

We have updated to figure caption to help the reader with interpretation of the figure, and added a north arrow and scale bar for context. We have also adapted Figure 2 to be compatible with this figure, which will also help to provide the reader with context.

**2.32**: Figure 7: The plot includes a fit to the iceberg size distribution. Are you trying to fit the observations or the model results? Are you able say anything about the exponent chosen for the fit, or conclude anything from it? Please discuss.

The theoretical distribution (area<sup>-3/2</sup>) has not been fitted to the data, simply placed roughly overlaying them for comparison. From previous studies in fracture formation e.g. Åström (2006), the exponent of the distribution is the key variable in understanding the fracture processes involved, an exponent of -3/2 indicates brittle fracture while a higher exponent would indicate that grinding or crushing is occuring. The figure caption now makes this clearer, and the text has been expanded to include additional discussion of the topic (p10 l1-10).

## Ref: Åström, J. A. Statistical models of brittle fragmentation. Adv. Phys. 55, 247–278 (2006).

## **3 Minor Corrections**

3.1: p5, l9: This sentence is incomplete. Add "it"? This has been altered (p6 l14)

**3.2**: p6, l4: 2000 km<sup>2</sup>: For consistency, please use side lengths like for the second model domain. Model dimensions are now given in the model setup (p5 l21).

**3.3**: p9, l17: "This implies..": The sentence does not flow. Please rephrase. The sentence has been rewritten (p13 I3-5)

# Reviewer 2: J. Bassis

## **General Appreciation.**

This manuscript describes a suite of models used to describe the fracture patterns observed around Totten Ice Shelf, East Antarctica. The authors apply a discrete element models (HiDEM) a full Stokes model (Elmer/Ice) and a model meant to describe basal melt (the KPZ equation) to describe the formation and evolution of basal crevasses. The authors use the suite of models to infer that basal crevasses that initiate near the grounding zone advect to the calving front and are responsible for the checker board pattern of fractures observed near the calving front of the ice shelf. That basal crevasses that initiate upstream play an important role in calving closer to the calving front is not that surprising and is consistent with several prior studies. However, this is an interesting hypothesis—especially in light of the argument that the channel geometry is related to submarine melt—because it provides a direct connection between fractures/calving and ocean forcing and this study provides the first direct numerical simulation of some of the fundamental processes that remain poorly understood.

Organizationally, I found the manuscript a bit confusing to follow. I think it would help readers significantly if the authors presented their hypotheses or questions earlier on in the manuscript. On my first reading, it seemed as though the authors were merely throwing a couple of unrelated models at a problem without any underlying reason or rational. It wasn't until near the end of the manuscript that I realized that the authors were testing the hypothesis that crevasses near the grounding line control the fracture pattern near the calving front. That the authors need the basal crevasses is interesting and should be emphasized to readers earlier on. Here, I think the authors could significantly improve the impact of the manuscript by adding section subtitles and sketching out the logical flow. In other words, it would be helpful to see that the authors are trying to explain the fracture distribution near the calving front of the ice shelf. This could either be presented as a fundamental question early on (i.e., basal crevasses are needed to explain the fracture pattern), or complexity could be introduced into the suite of models expressly to match this fracture pattern (i.e., the HiDEM simulation without basal crevasses could not represent the fracture pattern). Without this additional text, some of the models appear unmotivated. I do also have some questions about the models and assumptions, described in more detail below.

We have attempted to improve the clarity of the manuscript in reference to comments from both reviewers by:

- Explaining the hierarchy of models more clearly in the abstract.
- Expanding the motivation for the different models in the introduction (p3 l12-23).
- Increasing the discussion of model runs performed in the model setup (p5 l25 p6 l14)
- Separating results and discussion into different sections.

# Questions about models.

Overall, I think that the hierarchy of models is interesting. I do have a few questions about the models. For example:

-How many particles are used in the HiDEM model runs. What is the vertical number of particles? More details on the numerical setup would be helpful to readers.

Approximately 2.5 million particles are used for the grounding line model and 5 million for the calving front model. This corresponds to a minimum of 15 particles vertically for the grounding line model and 5 for the calving front model. This information has now been included in the text (p6 I3-6).

-How are the basal crevasses/channels used in the last simulation specified in HiDEM? Are these based on observations? Providing this data is critical.

To mimic the ice-base shape in Fig. 4, we cut-out a set of ~100 m deep and 0.5-1km wide embayments at the ice-base at ~0-2km intervals using trigonometric functions to positive power (e.g.  $sin(cx)^8cos(bx)^2$ ). This is now described in the text (p6 l6-13).

-What ice temperature is used in the ELMER/ICE simulations? This should be important in determining the rate of crevasse widening. I'm also curious about the effect of the strain rate on widening. The strain rate is sufficient to allow crevasses to widen, but I would expect crevasses to actually close if the strain rate is smaller. This would be interesting to check.

The temperature of the ice is -9°C (p8 l6). We only consider strain thinning in this manuscript, as those are the conditions observed on the floating portion of the Totten Ice Shelf. The reviewer is correct that if the thinning were less then the basal crevasses would be likely to close, and this may be considered in future simulations on different ice shelves. This has now been acknowledged in the discussion of the results (p12 l1-2).

-Similarly, I would have liked to see some more quantitative comparisons between observations and data if feasible. For instance, how wide are the fractures predicted by HiDEM and do they penetrate the entire ice thickness? It is difficult to detect if fractures penetrate the entire ice thickness using surface observations, but one could estimate the width of fractures (based on pixels) and compare this to the predicted width of fractures from HiDEM. In fact, it would be really nice to have a statistical comparison between length, width and orientation of fractures predicted by HiDEM and those observed in the images. This would significantly bolster the authors claims and avoid the need to rely on qualitative inspection of figures to determine how well the model is performing. This is important for a range of reasons, but it is important to recognize that the iceberg size distribution is modified by interaction with the ocean (bergs melt, erode, tip over, etc.) and hence the comparison between berg sizes is not necessarily a one-to-one comparison with bergs that detach. Fracture distributions should be more straightforward to map and compare. We have struggled to find a robust way to quantitatively compare the modelled and observed fractures for a number of reasons. Firstly, the dimensions of observed fractures are hard to determine accurately because of the thick snow and firn layer on the ice shelf – this snow blurs the edges of fractures, making robust measurements of length and width extremely difficult. For full thickness rifts at the edges of the ice shelf, the evolution of their width will also be affected by an ice mélange (of frozen ice debris and sea ice) which we cannot adequately represent in the model, meaning that the modelled rifts will likely develop further than in the observed shelf.

The orientation of fractures is the most promising method for comparing the two sets of fractures. We have digitized both the observed and modelled fractures, and created a dataset of orientations of each line segment. The results have now been included in Supplementary material, and the two orientation distributions are shown in Supp. Fig. 2. The highest frequency in the observed fractures is in the across-flow direction, while this orientation is much less frequent in the modelled fractures supporting our conclusion that these fractures are not produced locally.

We have retained our discussion of the iceberg size distributions observed and produced by the model. The reviewer is correct that a number of processes will affect the size of icebergs after they detach form the shelf, but previous work has shown that the observed iceberg size distribution around Antarctica is actually very close to that expected from pure brittle fracture (Tournadre et al, 2016). The iceberg size distribution is useful because it provides information on the fracture processes occurring in the model, which cannot be extracted as easily from the fracture distribution alone. We have expanded our discussion around this point in the text (p10 l1-10).

# Ref: Tournadre, J., Bouhier, N., Girard-Ardhuin, F. and Remy, F.: Antarctic icebergs distributions 1992–2014, J. Geophys. Res. Ocean., 121, 327–349, doi:10.1002/2015JC010969, 2016.

A few other quantitative questions I had about data included: How many total icebergs were detached in 2009, 2010 and 2011 respectively and how many icebergs in each size class were detected? What time of year are these images? Is there a bias associated with the time of year? Furthermore, it is possible that the distribution of icebergs/ calving rate is not stationary stochastic. If this is the case, then the distribution of icebergs would not be stationary stochastic, as the authors assume.

To obtain the current iceberg size distribution for Totten Ice Shelf, icebergs were manually digitised from three Landsat 7 images from 23/11/2009, 26/11/2010 and 29/11/2011. The dataset consists of 370 icebergs, broken down by year: 83 (2009), 148 (2010), 139 (2011). These years cover a wide range of average calving rate, as measured by Dr. Yan Liu of Beijing Normal University, leading us to consider that we have sampled the full range of calving behaviour of the ice shelf. Broken down by year, the three iceberg size distributions look similar therefore we consider this to be a robust test of the model. Our distribution is also consistent with pan-Antarctic icebergs distributions 1992–2014, measured by Tournadre et al. (2016). This is now discussed in detail in the new addition of supplementary material to the paper.

**KPZ equation** The use of the KPZ equation in this context is interesting and novel. I have played around with it a few times for various things. My understanding of the usage of the KPZ equation here is the v,  $\lambda$  and F (which includes two terms to allow for a linearly varying profile) are all adjusted to match observations. This means that the authors have 4 free

parameters to adjust. From looking at Figure 4, it also looks like the position, width and initial depth of the crevasses are all also determined as part of the solution. There is an old saying that given three parameters you can fit an elephant. Given 5, you can make its trunk wiggle. Although, I find this a bit extreme, I do think it is worth discussion the robustness of the results in the face of 7 unconstrained parameters. This should start by listing the numerical values of parameters used. Are results sensitive to order of magnitude changes in parameters? Factors of two changes? I also have questions about the fact that, as far as I can tell the melt rate (F) is not related to ocean forcing at all. I guess this is just an empirical constant, but the KPZ model is of limited utility if we cannot relate it to ocean forcing. At the very least, we have observations of the melt rate and hence, can constrain the average value of the melt forcing term. Similarly, the time at which the simulation result is obtained is not given. How long does it take for these channels to evolve and how different do the channels look at different instances of time. This is crucial because the KPZ equation does not necessarily admit a steady-state—similarity solutions exist that allow for continuous variation. If the solution is steady-state, then this should be declared along with how long it takes the simulation to arrive at steady-state.

## General comment on the KPZ approach:

The use of the KPZ-equation in this context is, at best, a crude phenomenological description of the way basal crevasses are formed and developed on the Totten Ice Shelf. In our opinion the interesting question related to this approach is whether a simple and straightforward implementation of the KPZ-equation can largely reproduce the basal shape or not. The model is much too crude to learn new information from detailed exploration of the model details.

As I mentioned, I think the use of the KPZ equation here is interesting and novel. However, it appears as though the KPZ equation as listed in Equation (4) has an error. The actual equation should read:

$$\frac{\partial h}{\partial t} + u. \nabla h = v \nabla^2 h + \frac{\lambda}{2} [\nabla h]^2 + F + \eta,$$

where u is the velocity along the interface. There is no physical reason to omit the advection term. Typically, the KPZ equation is used for materials where the interface does not have a background velocity (as in the refs cited) and hence, one can replace the material derivative with the partial derivative with respect to time, as the authors seem to have done. In this case, however, the interface is moving with the background velocity of the ice and there is a gradient in the velocity. If the "fractures" are indeed enlarged by a constant melt rate, then including the advection term should allow the authors to reproduce the spatial pattern of fractures using a constant melt rate F instead of a linearly varying melt rate. Now, because velocity is not Galilean invariant one need only specify the difference in velocity across the domain. One could do this in a consistent manner with the Elmer/Ice model by using the same strain rate across the domain.

We have chosen to treat the x-coordinate in KPZ equation as a Lagrangian coordinate (x'), such that it is attached to the ice moving at ~1 km a<sup>-1</sup>. This is a rough simplification of the region covered by the flight path shown in Fig. 4, where the velocities range from roughly 1500 m a<sup>-1</sup> upstream to 1700 m a<sup>-1</sup> downstream. With the coordinate transformation between our coordinate system (x') and the one suggest by the reviewer (x), x' = x- u\*t, the

advection vanishes (dx/dt = dx'/dt - u = 0). What needs to be taken into account then is that the ice further downstream has been exposed to melt for a longer time period. With a constant melt rate of approximately 2 m a<sup>-1</sup> and ice speed of 1 km a<sup>-1</sup>, we get an interface slope of ~10<sup>-3</sup>. This is now laid out more clearly in the text, with our justification for treating the front as stationary (p6 I20-25) and a description of the Lagrangian coordinate system used (p7 I1-3).

Given the number of simplifications made by using the KPZ equation (particularly the homogeneous melt rate), we consider the order of magnitude to be the important factor in interpreting the results. It is largely meaningless to try to fit exact values for a crude phenomenological model like this one. The free parameters *F*,  $\lambda$  and *v* are melt rates and should be of order 1 m a<sup>-1</sup> according to ocean modelling (Gwyther et al., 2014). The only adjustable input in the model is therefore the initial line-fracture configurations. The figure below demonstrates the effect of varying the melt rate used for *F*,  $\lambda$  and *v* – the size (both horizontally and vertically) of the features produced and the slope of the shelf are affected by the choice of melt rate, while their location and relative magnitude are fixed by the choice of initial line fractures (η).



What the exercise leading to Fig.4 shows is that it is possible to choose a suitable starting configuration of line-cracks, apply KPZ-dynamics with reasonable parameter values and arrive at an ice-surface and ice-base that match observations. We have tested the KPZ equation with different setups to test the robustness of the result in Fig.4. For example we tested Eq. (5) (previously Eq. 4 in the old manuscript) with and without random fluctuations. In both cases it is possible to arrive at results similar to Fig.4 with minor (i.e. within a factor  $\sim$ 2) adjustments of F,  $\lambda$  and v.

There are other, subtle, issues associated with the use of the KPZ equation in this context. One prominent assumption of the KPZ equation is that the erosion of the interface does not depend on the absolute elevation of the interface. This is the reason why only scalar powers of rh appear in the expansion. In the case of submarine melt, however, this assumption is violated because of the pressure dependence of the melting point. Erosion of ice should occur more rapidly deep beneath the surface of the ocean and erosion (or even marine ice deposition) should occur closer to the ocean surface. As a consequence, I'm not even sure that the sign of the  $[\nabla h]^2$  term is right. Expanding on this point, the KPZ equation is useful for describing interface evolution because it represents a large universality class of processes that, irrespective to process details, ultimately behave like the KPZ equation. The universality class, however, is not infinitely large. Here, I think the authors should attempt to establish whether submarine melt actually resides in the broader universality class exemplified by the KPZ equation. Failing this, I would really like more detail on \*\*why\*\* the authors think the KPZ equation is an adequate description of the submarine melting process and the role of the pressure dependence of the melt point in this argument. It would indeed be nice to establish whether the interface created by basal melt actually belongs to the KPZ universality class. To do this properly it would demand enough data to perform a scaling analysis and compute scaling exponents. We do not currently have enough data to do this. The only thing we attempt in this paper is to test the hypothesis that KPZ actually can describe the interface, and it can as evidenced by Fig.4. One can, of course, speculate slightly about what would eventually be the outcome of the melt-pressure dependence with a melt-freeze boundary. For long time periods (compared to glacier thickness/melt-rate) the entire interface should then asymptotically reach the equilibrium line between melt and freeze. Assuming melt-rate only has a simple height dependence, it would induce a flat interface. This is obviously not case, indicating that the ocean water is warm enough to drive the interface. As long as this happens, the KPZ analysis seems to capture the dynamics reasonably well. This is not very surprising if the phase-diagram for (fresh) water and ice is investigated. The phase-transition between ice and water: It is practically a constant (0°C) up to pressures of 10MPa, which corresponds to a water depth of about 1000 m. Only for deeper water does the melting point decrease significantly, making this dependence largely irrelevant for this particular case.

Finally, I was confused about the role of the Elmer/Ice and KPZ simulations of basal channel evolution. Why not incorporate the KPZ equation into the ELMER/ICE simulations so that the authors can self-consistently simulate the strain induced widening and erosion? If this isn't feasible, then what are we supposed to learn from the two simulations? As far as I can tell, the Elmer/Ice simulation tells us that crevasses widen and become shallower over time, but the Elmer/Ice simulations omit ocean forcing. In contrast, the KPZ simulations tell us that crevasses become wider and deeper over time, but this simulation omits any ice dynamics (included advection!). Do these effects cancel out? Does one dominate? Do we need both or can we omit one of them? I do wonder if the widening by ice dynamics alone is sufficient to explain the width of observed basal crevasses. If it is not sufficient, then this argues that erosion by submarine melt is necessary.

We do not quite understand what the reviewer means by incorporating the KPZ into Elmer/Ice. We guess he means introducing thermodynamics and thereby melting at the interface. These would be very interesting, but rather demanding computations and we do

not currently have the resources to perform them. What we can say is that, as the reviewer points out, both KPZ and Elmer predicts widening of the crevasses. This is consistent with our hypothesis that the crevasses originate from thin fractures in the grounding zone.

The reviewer points out that flow will make the crevasses shallower, while melt will make them deeper. Unfortunately, we cannot use the models presented here to make any conclusions from this about the relative importance of the two processes. The KPZ has assumed a homogeneous melt rate, while previous modelling work has suggested that melt will be highest along the walls of basal fractures while refreezing may occur at the peak (Jordan et al., 2014; Khazendar and Jenkins, 2003). Meanwhile, while our simulation suggests that longitudinal stretching may make basal crevasses shallower, other modelling work has suggested that the concentration of tensile stresses in the thin ice above the crevasse may enhance further brittle fragmentation allowing the basal crevasse to grow (Bassis and Ma, 2015). To properly assess how these processes would interact would require a combined ocean, ice flow and fracture model. We have extended our discussion in the text to include these topics (p11 l17 – p12 l10).

## **Detailed comments:**

Page 3: "We also use a continuum ice flow model and a stochastic equation describing fracture development" This is unclear. It seems as though the KPZ equation is used to model the evolution of the interface in response to melt. The KPZ equation is indeed stochastic. However, the authors omit the stochastic terms, at which point version of the KPZ that they use is entirely deterministic . . . Also, the authors claim  $\eta$  is a stochastic term, but then they set it equal to the initial width/length of basal crevasses. This seems to confuse initial conditions with the stochastic forcing. Typically, the stochastic term in the KPZ emerges as a white noise Gaussian process, which is quite different from the assumptions made here. It might be less confusing to separate this into an initial condition and noise term with the noise term set to zero.

This is a minor point given the fact that the stochastic term is set to zero, but stochastic partial differential equations fall into two categories the so-called Ito and Stratonovich interpretations. These two interpretations are subtly different in important ways, but necessary to place stochastic differential equations on firm mathematical footing. What interpretation is assumed here?

This is not really a topic for a publication in the Cryosphere, and with a stochastic term set to zero, the division into Ito and Stratonovich become irrelevant. Where we used a non-zero  $\eta$ , we used the Ito formulation. It seems to be the consensus that for climate/ocean/etc models Stratonovich would be preferable. However, in our case, we cannot even make a proper interpretation of what would be the right form of  $\eta$ , and the question is superceded by the other simplifications used in setting up the model. We have rewritten the original sentence to make its meaning clearer (p3 I19).

# Page 4: How big of a difference does it make to results if a different percentage of bonds is broken? Say 0.1% or 10%?

The proportion of bonds broken has little effect on the results, so long as it is below the percolation limit (see Fracture Mechanics: With an Introduction to Micromechanics by

Dietmar Gross and Thomas Seelig for a discussion of the application of percolation theory to fracture propagation and material failure). The value we have chosen is well below the percolation limit.

Page 4 last sentence after equation 3. The constant "c" is apparently dimensionless (at least no units are given) and thus friction does not have the correct units. Either "c" should have units or units of friction needs to be more carefully explained (have the equations themselves been non-dimensionalized)?

The units were overlooked and have now been added (p5 l22).

Figure 2: Am I missing something? Fractures look like the run both parallel and perpendicular to the front?

We have updated the figure to use fracture data from later timestep, which we believe makes the pattern clearer to the reader. We have also addressed the reviewer's underlying concern about the fracture orientation by further analysis described above.

Figure 3 is hard to decipher. Is it possible to show Figure 3 in the same style of as Figure 2 so that we can see where the crevasses are located on an image?

High snowfall in this region of the ice shelf means that the surface has very few features visible in satellite imagery. We have retained the ice thickness as background, but plotted in grayscale as suggested by reviewer #1 to improve clarity.

Figure 6 is very pixelated (maybe a conversion issue?) and hard to interpret.

The figure file will be provided in highest possible resolution for paper production to solve any pixilation issues. We have also updated to figure caption to help the reader with interpretation of the figure.

Figure 7. It doesn't look like the simulation obeys a -3/2 scaling law. According to the red curve, the computation predicts more icebergs at low iceberg area and not enough at large iceberg area. The observations are really only power-law over about an order of magnitude. Fitting power-laws to such a limited data range is fraught with peril. This maybe an example where it is better to avoid a logarithmic plot AND to include error bars in the observations. How many icebergs are there with sizes close to  $10^6 \text{ m}^2$ ? Is this actually statistically significant?

For this figure we did not fit a power law (hence the lack of error bars). Instead, we overlaid a theoretical distribution based on brittle fragmentation. The reviewer is correct that the simulation does not obey the -3/2 scaling law perfectly. The origin of this behaviour originates in two different mechanisms of fracture: pure tensile fracture, and crushing small debris in shear-bands. This is an extensive topic which we will address in more detail in a separate paper. The discussion of this was lacking in both the text and the figure caption, and has now been expanded (see revised figure caption and p10 l1-10 in updated text).

## Modelled fracture and calving on the Totten Ice Shelf

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Abstract. The Totten Ice Shelf (IS) has a large drainage basin, much of which is grounded below sea level, leaving the glacier vulnerable to retreat through the Marine Ice Shelf Instability mechanism. The ice shelf has also been shown to be sensitive to changes in calving rate, as a very small retreat of the calving front from its current position is predicted to cause a change in flow at the grounding line. Therefore understanding the processes behind calving on the Totten IS is key to predicting its future

- 15 sea level rise contribution. Here we use the Helsinki Discrete Element Model (HiDEM) to show that ealving onnot all of the fractures visible at the front of the Totten IS is controlled not only by locally are produced fractures at the calving front\_locally, but is also influenced bythat the across-flow basal fracturescrevasses, which are likely produced atpart of the distinctive crosscutting fracture pattern, are advected into the calving front area from upstream. A separate simulation of the grounding line.-Our model results show\_shows that regroundingre-grounding points may be key areas of basal crevasse production, and
- 20 can produce basal crevasses in both an along and across flow orientation. As well as affecting calving, The along flow basal crevasses at the grounding line may be a possible precursor to basal channels. while we suggest the across-flow grounding line fractures are the source of the across-flow features observed at the calving front. We use two additional models to examinesimulate the evolution of basal fractures as they advect downstream, demonstrating that both strain and ocean melt have the potential to deform narrow fractures into the broad basal features observed near the calving front. The wide range of the across flow fractures into the broad basal features observed near the calving front. The wide range of the across flow fractures into the broad basal features observed near the calving front. The wide range of the across flow fractures into the broad basal features observed near the calving front. The wide range of the across flow fractures into the broad basal features observed near the calving front. The wide range of the across flow fractures is the potential to deform harrow fractures into the broad basal features observed near the calving front. The wide range of the across flow fractures is the potential to deform harrow fractures into the broad basal features observed near the calving front. The wide range of the across flow fractures is the potential to deform harrow fractures into the broad basal features observed near the calving front.
- 25 factors which influence fracture patterns and calving on this glacier will be a challenge for predicting its future mass loss.

## **1** Introduction

The calving of icebergs is responsible for around half of the mass lost from the Antarctic ice sheet (Depoorter et al., 2013; Liu et al., 2015; Rignot et al., 2013). Despite this, it is not currently well represented in the large seale ice sheet models, with different calving approaches producing widely varying predictions of Antarctica's future sea level rise contribution (e.g. Deconto and Pollard, 2016; Levermann et al., 2014). Calving is ultimately controlled by how fractures develop on a glacier, 5 and the key process involved can range from lateral rift propagation in the case of large icebergs, or the vertical penetration of a dense crevasse field in ice shelf disintegration (Benn et al., 2007). Fractures involved in calving may form in situ, or be advected into the ealving front region from upstream. Basal crevasses have been observed near the grounding line of ice shelves (e.g. Bindschadler et al., 2011b; Jacobel et al., 2014) and may evolve in shape and size as they advect downstream (Jordan et 10 al., 2014). To fully understand the calving behaviour of an ice shelf, we must therefore understand how fractures form and propagate on it. In this paper we applying(Depoorter et al., 2013; Liu et al., 2015; Rignot et al., 2013). Despite this, the calving process is not currently well represented in the large scale ice sheet models, with different calving approaches producing widely varying predictions of Antarctica's future sea level rise contribution (e.g. Deconto and Pollard, 2016; Levermann et al., 2014). Calving is ultimately controlled by how fractures develop on a glacier, and the key processes involved can range from lateral 15 rift propagation in the case of large icebergs, or the vertical penetration of a dense crevasse field in ice shelf disintegration (Benn et al., 2007). Fractures involved in calving may form in situ, or be advected into the calving front region from upstream. Basal crevasses have been observed near the grounding line of ice shelves (e.g. Bindschadler et al., 2011b; Jacobel et al., 2014) and may evolve in shape and size as they advect downstream (Jordan et al., 2014). To fully understand the calving behaviour of an ice shelf, we must therefore understand how fractures form and propagate on it. In this paper we apply fracture modelling

20 to the Totten Ice Shelf (IS) to investigate these processes.

25

The Totten IS is fed by a large drainage basin, containing at least 3.5 m global sea level equivalent (Greenbaum et al., 2015). This region of the Antarctic Ice Sheet is grounded largely below sea level (Greenbaum et al., 2015), and has shown signs of significant grounding line fluctuation in the past (Aitken et al., 2016), leading to speculation that it may be vulnerable to Marine Ice Sheet Instability (Greenbaum et al., 2015; Pollard et al., 2015; Weertman, 1974). There have been some indications that the Totten IS may already have been thinning (Khazendar et al., 2013), although it is unclear if this represents a long term

trend (Paolo et al., 2015). Crucially, the Totten IS has been identified as having one of the lowest proportions of "passive" ice in Antarctica (Fürst et al., 2016), i.e. the proportion of the ice shelf which can be lost without a resulting dynamic change in the grounded ice upstream. This means that any change in calving rate on the Totten IS could quickly cause an increased flux of ice across its grounding line and hence an increased contribution to global sea level rise.

5 The first stage to predicting future calving rates from Totten IS is to be able to reproduce current fracture patterns and calving rates. One tool which we can use to improve our understanding of the processes behind fracture and calving on ice shelves is a discrete element model (DEM). A DEM discretises the ice shelf geometry into a lattice of bonded particles. By allowing the bonds between particles to break, the model is able to explicitly develop fractures, rather than representing fracturing by a parameterisation as in continuum approaches. Discrete element models have been used successfully to simulate calving
10 behaviour at marine terminating glaciers (Bassis and Jacobs, 2013; Vallot et al., 2017), to examine causes behind changes in calving behaviour (Åström et al., 2014) and to investigate how fracture propagation is affected by other elements of the ervospheric system (Benn et al., 2017; Vallot et al., 2017).

In this paper we present the first application of a discrete element model to an Antarctic ice shelf, and use it to examine fracture and calving on the Totten IS. We apply HiDEM to regions at both the calving front and the grounding zone to examine different 15 areas of fracture formation. We also use a continuum ice flow model and a stochastic equation describing fracture development to examine how those fractures may evolve as they are advected downstream.

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- 20 Ice Sheet Instability (Greenbaum et al., 2015; Pollard et al., 2015; Weertman, 1974). There have been some indications that the Totten IS may already have been thinning (Khazendar et al., 2013), although it is unclear if this represents a long term trend (Paolo et al., 2015). Crucially, the Totten IS has been identified as having one of the lowest proportions of "passive" ice in Antarctica (Fürst et al., 2016), i.e. the proportion of the ice shelf which can be lost without a resulting dynamic change in the grounded ice upstream. This means that any change in calving rate on the Totten IS could quickly cause an increased flux
- 25 of ice across its grounding line and hence an increased contribution to global sea level rise.

The Totten IS has a dense pattern of both longitudinal and transversal fractures near the calving front, typical of fast flowing ice shelves in Antarctica (Wesche et al., 2013). Little is currently known about what fractures exist upstream of the calving front, as these are highly challenging to observe from satellite imagery. High rates of snowfall on the Totten IS act to quickly fill any surface crevasses, while the thickness of the ice shelf means that basal crevasses would need to be extremely large to

5 have an observable surface expression. However, the water in the ocean cavity underneath the Totten IS is known to be warm enough to drive melt of the ice (Gwyther et al., 2014; Rintoul et al., 2016; Roberts et al., 2018). Therefore any basal crevasses exposed to seawater are likely to be affected by melting.

The first stage to predicting future calving rates from the Totten IS is to be able to reproduce current fracture patterns and calving rates. One tool which we can use to improve our understanding of the processes behind fracture and calving on ice

10 shelves is a discrete element model (DEM). A DEM discretises the ice shelf geometry into a lattice of bonded particles. By allowing the bonds between particles to break, the model is able to explicitly develop fractures, rather than representing fracturing by a homogenized variable as in continuum approaches. Discrete element models have been used successfully to simulate calving behaviour at marine terminating glaciers (Bassis and Jacobs, 2013; Vallot et al., 2017), to examine causes behind changes in calving behaviour (Åström et al., 2014) and to investigate how fracture propagation is affected by other 15 elements of the cryospheric system (Benn et al., 2017; Vallot et al., 2017).

In this paper we present the first application of a discrete element model to an Antarctic ice shelf, and use it to examine fracture and calving on the Totten IS. The DEM can only be used to simulate small regions of an ice shelf due to its high computational cost. We choose to apply the model to two sections of the ice shelf most likely to experience fracture development: the calving front, and the grounding line. The DEM results at the calving front demonstrate that the observed transverse fractures cannot

- 20 be reproduced locally, and therefore must advect into the region from upstream. The grounding line model demonstrates that across-flow fractures can be produced at pinning points near the grounding line. We then use two additional models to investigate how fractures produced at the grounding line might be modified as they advect downstream: a continuum ice flow model to simulate the effects of internal strain, and the Kardar-Parisi-Zhang (KPZ) equation to simulate fracture development under a constant marine melting. These results are used to demonstrate that the observed fracture pattern at the calving front
- 25 can plausibly be explained by a combination of both locally produced fractures and basal features produced initially at the

grounding line. In combination, the three models produce a description of the key areas of fracture production on the Totten IS.

### 2 Data and Methods

#### 2.1 Glaciological Data

- 5 The geometry of the model is taken from aerogeophysical data collected by the International Collaboration for Exploration of the Cryosphere through Aerogeophysical Profiling (ICECAP) project which has flown a dense network of flights of the Totten IS. The surface elevation (Blankenship et al., 2015) and ice thickness (Blankenship et al., 2012) data are interpolated using TELVIS (Thickness Estimation by a Lagrangian Validated Interpolation Scheme) (Roberts et al., 2011), to produce a geometry which is glaciologically self-consistent and has previously been used to infer basal melt rates on the glacier
- 10 (Roberts et al., 2017). The bedrock elevation, which is used to distinguish zones of grounded/floating ice, is taken from gravity inversions (Greenbaum et al., 2015).

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- 20 information on the types of basal fractures observed on the ice shelf.

The performance of the discrete element model is evaluated by comparing the size and frequency of simulated icebergs with those observed in satellite images. The observed iceberg size distribution is calculated from three separate Landsat 7 images from 2009, 2010 and 2011, with each iceberg within 20 km of the calving front mapped and its area measured. The distance is chosen to ensure that only icebergs originating from the Totten IS are included. The three images produce a sample of 370

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#### 2.2 Discrete ParticleElement Model

We model fracture formation on Totten IS using the Helsinki Discrete Element Model (HiDEM) which is described in detail

- 5 in Åström et al. (2013) and Riikilä et al. (2014). The model geometry is constructed with interconnected inelastic blocks, each representing a discrete volume of ice. The blocks are connected to their neighbours by breakable elastic beams whose energy dissipation depends on the deformation rate. As the ice deforms under its own weight, stresses on the beams increase; if stress reaches a failure threshold, the beam breaks creating a fracture in the modelled ice shelf. We have chosen a critical stress of approximately 1 MPa, governed by previous applications of the model to glacier ice (Åström et al., 2013, 2014).
- 10 We model fracture formation on the Totten IS using the Helsinki Discrete Element Model (HiDEM) which is described in detail in Åström et al. (2013) and Riikilä et al. (2014). The model geometry is constructed with interconnected inelastic blocks, each representing a discrete volume of ice. The blocks are connected to their neighbours by breakable elastic beams whose energy dissipation depends on the deformation rate. As the ice deforms under its own weight, stresses on the beams increase; if stress reaches a failure threshold, the beam breaks creating a fracture in the modelled ice shelf. We have chosen a
- 15 critical stress of approximately 1 MPa, governed by previous applications of the model to glacier ice (Åström et al., 2013, 2014). The range of possible yield stresses that produce plausible results is not large, and previous results indicate that changing yield stress has the effect of changing the number of fractures but not their underlying orientation. Therefore the assessment of our results is restricted to orientation of fractures rather than their density.

The movement of each block of ice is calculated using a discrete version of Newton's equation of motion and is iterated with a timestep of 0.0001 s length. For computational reasons, we use a densely packed, face-centred cubic (fcc) lattice of spherical blocks-50 m in size. The shape of the lattice introduces a weak directional bias in the elastic and fracture properties of the ice. The symmetry of the underlying fcc-lattice is however easily broken by the propagating cracks, as evidenced by the results. At the beginning of a fracture simulation, the ice is assumed to contain a small<u>low</u> density of randomly scattered small pre-existing cracks. For these experiments, approximately 1% of the bonds are broken at the beginning of the simulation.

The effect of the surrounding ocean is simulated by applying a buoyancy force  $(F_b)$  to each block of ice forming the model domain:

$$F_b = (\rho_w - \rho_i)gV_p \,, \tag{1}$$

5 where  $\rho_w$  and  $\rho_i$  are the densities of ocean water and ice <u>respectively</u>, *g* is the gravitational constant and  $V_p$  is the volume of a block. Since the model <u>domain</u> cannot cover the whole of the ice shelf due to computational cost, some of the boundaries of the domain are necessarily not simply floating passively, but are being pushed by the up-stream pressure from the landbased flowing part of the glacier. This pressure was modelled by applying <u>hydrostatie isostatic</u> pressure,  $P_{sc}$ , at the lateral boundaries of the simulated area where required.

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$$P_{sc} = \begin{cases} \rho_i g z & z > 0\\ (\rho_i - \rho_w) g z & z < 0 \end{cases}$$
 (2)

where z is the elevation above sea level. This is a simplification of the driving stress, as it neglects longitudinal stresses which can be significant around the grounding line (Schoof, 2007). Where the model domain is grounded a constant-basal frictionshear stress  $F_f$  is applied:

(3)

$$F_f = -c \frac{dx}{dt},$$

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15 where  $\frac{dx}{dt}$  is the sliding velocity and c is a drag coefficient set at  $10^{\frac{7}{7}}$  kg m<sup>-2</sup> s<sup>-1</sup>.

The model is applied to two regions of the ice shelf, one at the calving front and one around the southern tip of the grounding line. Each model setup uses the observed geometry described above. Our first model domain is 55 x 40 km covering roughly 2000 km<sup>2</sup> of the Totten IS calving front (Fig. 1,2). The area of the ice shelf covered in the calving front domain is almost entirely floating. A particle size of 50 m was chosen, creating a model domain of approximately 5 million individual particles and a minimum stack of 5 particles vertically. Our second model domain covers a 45 x 45 km<sup>2</sup> section of ice at the Formatted: Font: 10 pt, English (United Kingdom)
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southern-most point of the Totten IS (Fig. 1, 3). For this model a 150 m particle size was used, creating a model set up with 2.5 million particles and a stack of between 7 and 19 particles vertically. Lastly, the model is run again using the calving

front domain, but this time a series of basal crevasses are artificially introduced into the geometry mimicking the observed basal profile with straight, across-flow basal features with a height *h* given by a trigonometric function:

 $h = 250 \sin(0.005x)^8 \cos(0.015x)^2$ (4)

This produces regular basal features with a spacing and width which roughly mimics the observed basal crevasses. Since the model domain was chosen to align with the dominant flow direction to improve computational efficiency, the introduced features also align with the model grid. This model run is used to simulate the effect of fractures which were advected into the domain rather than produced locally.

## 2.3 Kardar-Parisi-Zhang (KPZ) Equation

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where the vertical front location  $h_x$  varies with horizontal location Lagrangian coordinate  $x'_x$  and time  $t_x$  assuming a constant along flow velocity of 1 km a<sup>-1</sup>. This is a simplification, as the ice shelf does experience along flow acceleration, but the method provides a first order estimate of the effects of melting excluding strain thinning. The first term on the r.h.s. can be thought of

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as a 'bending stiffness' that keeps the front from fluctuating too much, the second term drives the front perpendicular to its normal, F is the driving force (melting) and  $\eta$  is a stochastic term which can be used to introduce noise, but in this case we use it to represent a series of initial basal crevasses to which the front propagation of the front is applied.

To investigate the role of ocean melting we use the KPZ equation applied to a set of line cracks in an idealised and

- 5 homogeneous 1 km thick glacier (Fig. 4). The vertical blue line segments at the bottom of the figure represent initial line cracks, represented by <u>n</u> in Equation 4. The melting front is then propagated forward in time with  $v = 1 a^{-1}$ ,  $\lambda = 1 m a^{-1}$  and  $\eta(t>0) = 0$ . To represent the longer exposure to melt for downstream ice we linearly increase the driving force F along the flowline:  $F = 1x10^{-3}x'm a^{-1}$ . The initial crack configuration is varied until a solution is found that approximates the measured base along the flight path. The surface elevation is thereafter calculated by assuming neutral buoyancy locally.
- 10 The KPZ approach used here makes a number of significant simplifications in modelling basal melt. The approach neglects spatial variations in melt rate across the ice shelf, which can be significant (e. g. Gwyther et al., 2014; Roberts et al., 2018). More importantly, the constant melt rate used neglects variations in melt rate which have been predicted to occur within basal features, where melt rates at the peak of a basal crevasse are typically found to be lower than on the walls (Jordan et al., 2014; Khazendar and Jenkins, 2003; Millgate et al., 2013). This internal difference in melt rates would change the shape of the basal
- 15 crevasses as they evolve.

## 2.4 Elmer/Ice

 
 The effects of internal ice deformation will also change the shape of a basal fracture as it advects along with the ice shelf. To simulate how this may work we use the finite element model Elmer/Ice (Gagliardini et al., 2013) to simulate the changing shape of an idealised basal crevasse in two dimensions (2D). The model uses an idealised domain with an initial narrow basal crevasse in a linear slab of ice, similar to the geometry used for the KPZ equation but this time with a single crack. 2.4 Elmer/Ice

The effects of internal ice deformation will also change the shape of a basal fracture as it advects along with the ice shelf. To simulate how this may work we use the finite element model Elmer/Iee (Gagliardini et al., 2013) to simulate the changing shape of an idealised basal crevasse in two dimensions (2D).

25 The shelf is represented by a slab of ice initially 680 m thick and 4 km long, floating with neutral buoyancy, with an imposed basal crevasse 200 m wide at the base which penetrates 300 m vertically into the shelf (Fig. 5). Longitudinal stretching is

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simulated by fixing the left hand boundary of the domain, while moving the right hand side at 500 m/a. This is roughly equivalent to the maximum rate of stretching experienced on the Totten IS at the grounding line. The domain is iterated forward in time with timesteps of 12 hr, with the 2D velocity field solved at each time step using the Stokes equation together with Glen's flow law with an exponent of n=3 (see Gagliardini et al. (2013) for more detail). We choose a constant temperature within the ice of -9°C and no enhancement factor. The geometry of the domain is evolved with a kinematic condition for the free surface at the top and bottom boundaries, and is automatically adjusted to remain in hydrostatic equilibrium by maintaining the lower boundary at seawater pressure.

- 10 The shelf is represented by a slab of ice initially 680 m thick and 4 km long, floating with neutral buoyancy, with an imposed basal crevasse 200 m wide at the base which penetrates 300 m vertically into the shelf (Fig. 5). Longitudinal stretching is simulated by fixing the left hand boundary of the domain, while moving the right hand side at 500 m a<sup>-1</sup>. This is roughly equivalent to the maximum rate of stretching experienced on the Totten IS at the grounding line. The domain is iterated forward in time with timesteps of 12 hr, with the 2D velocity field solved at each time step using the Stokes equation
- 15 together with Glen's flow law with an exponent of n=3 (see Gagliardini et al. (2013) for more detail). We choose a constant temperature within the ice of -9°C and an enhancement factor of one. The geometry of the domain is evolved with a kinematic condition for the free surface at the top and bottom boundaries, and the model is automatically adjusted to remain in hydrostatic equilibrium by maintaining the lower boundary at seawater pressure.

#### **3 Results**

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## 20 3.1 Sources of fracture

The HiDEM model was run on two domains, one at the calving front and one near the grounding line. Our first model setup covers roughly 2000 km<sup>2</sup> of the Totten IS calving front (Fig. 1, 2). The area, with almost all of the ice shelf covered in the calving front domain is almost entirely consisting of floating, ice (Fig. 1, 2). The modelled fracture pattern shows tensile cracks, with the majority running roughly perpendicular to the calving front (Fig. or parallel to ice flow and cutting through the

<u>full ice thickness (Fig. 2b)</u>. These cracks appear where the calving front begins to spread laterally, as it is pushed towards the open sea by the upstream pressure. ObservationsOther modelled fractures at the eastern edge of the domain are caused by shear around a pinning point and form at an angle to the flow direction. Satellite observations of fracture patterns are hampered by thick snow cover on the Totten IS, however near the calving front similar cracks perpendicular to the calving front are clearly

5 visible in satellite imagery (Fig. 2a). However, the large-The satellite imagery also shows a number of eracks visible perpendicular to the flow direction are not reproduced by the model. These across-flow features-appear to, which can be advected into the calving area fromobserved tens of kilometres upstream of the calving front (Fig. 2a). We hypothesise that these These features originate at the grounding line, as basal crevassing at the grounding line has previously been are similar in form to those observed on other ice shelves (e.g. Jacobel et al., 2014). These basal features would only become visible atLarsen C, which have been shown to be the surface as they move downstream, where high melt rates and tensile acceleration.

of the ice cause the basal features to widen sufficiently to have a surface expression-

To test the hypothesis that the of large basal crevasses (Luckman et al., 2012). Since these across-flow fractures develop at the grounding line, basal features are not reproduced by the HiDEM model we use ainfer that they are advected into the calving front region from further upstream.

15 Our second modelHiDEM domain eovering a 45x45 km<sup>2</sup> section of ice atcovers the southern-most point of the Totten IS (Fig. 1, 3). The observed geometry in this region shows a grounding zone rather than a distinct grounding line, where the ice re-grounds on many small islands (Fig. 3). In this region, the HiDEM simulation produces a number of fractures at the base of the ice shelf, which cluster around the re-grounding islands (Fig. 3). The formed cracksbasal crevasses have a tendency to form either in the along-flow direction as shear cracks or in the crossacross-flow direction as tensile cracks. The crackscrevasses typically reach 200 m above the base of the ice.

The fractures ariseproduced by the HiDEM model at the grounding line are narrow (less than 100 m wide at the base). Examining geometry data from the ICECAP survey, the across-flow basal crevasses causing a visible surface expression are much larger with a width of 1 – 3 km and height of 150 – 300 m (Fig. 4). To investigate whether the narrow basal crevasses Formatted: Font: 10 pt, English (United Kingdom)
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formed at the grounding line might evolve into these broad features as they move downstream, we use two models to simulate the effects of basal melting and internal strain separately.

The first experiment uses the KPZ equation to apply constant basal melting to a set of narrow basal fractures, selected with positions and heights specifically designed to match the observed geometry along a single ICECAP flightline (Fig. 4). The

5 model was run forward over a period of 100 years, which is approximately equal to the transit time from grounding line to calving front. In this way it is possible to reproduce both the surface and basal features of the Totten IS on an along-flow flight path (Fig. 4). changes This demonstrates that basal melting is a plausible mechanism for turning narrow basal crevasses at the grounding line into the broader basal features observed near the calving front.

We separately investigate how internal ice deformation may affect the shape of basal crevasses using an idealised simulation
 of a single basal crevasse in Elmer/Ice. As the model runs forward over time, longitudinal strain causes the initial crack to widen from 200 to 350 m after 52 weeks (Fig. 5). At the same time the height of the crevasse decreases from 300 m to 180 m. This simple pair of model experiments demonstrate that narrow fractures produced at the grounding line are a possible source for the wider basal features observed near the calving front. Both basal melting and internal strain can act to widen an initially narrow basal crevasse, although only the basal melt experiment is able to maintain a large vertical extent.

- 15 Lastly, to investigate the importance of these advected, across-flow features in the calving front region we perform an additional HiDEM simulation of the calving front, with across-flow basal crevasses artificially introduced into the geometry. In this model realization, the Totten IS begins to form visible full-thickness fractures in both the along- and across-flow directions (Fig. 6).
- An additional method for examining the model output is to compare the fragment size distribution (FSD) of the icebergs produced. The form of the FSD is controlled by the type of fracture mechanism occurring in the model. An FSD with the form "area<sup>-3/2</sup>" indicates a dominant mechanism of brittle fragmentation, while distributions with a higher slope indicate that grinding and crushing of fragments is occurring (Åström, 2006). A slope of -3/2 has previously been observed for Antarctic icebergs (Tournadre et al., 2016), and is also observed for icebergs produced by Totten IS, although smaller icebergs are underrepresented due to systematic difficulties in optically resolving small icebergs and distinguishing smaller icebergs from sea ice

(see Supplementary Material). Both HiDEM simulations (with and without introduced basal crevasses) reproduce the observed distribution of "area<sup>-3/2</sup>" at large iceberg sizes, which indicates that the models accurately reproduce the brittle fragmentation process driving large iceberg production. At smaller iceberg sizes, the simulations show a higher slope, indicating that grinding of smaller fragments occurs in the simulations (Fig.7).

## 5 <u>4 Discussion</u>

The initial HiDEM simulation of fracture development at the calving front of the Totten IS replicates the observed pattern of full thickness fractures produced roughly perpendicular to the calving front, but cannot reproduce the observed basal crevasses running across-flow behind the calving front. These features appear to advect into the calving front area from further upstream, a conclusion which is supported by their wide and rounded shape (Fig. 4). Recently produced fractures would be more likely

- 10 to have a narrower and sharper shape, so the broad and round shapes observed indicate that other processes such as strain deformation or melting have modified the crevasse's shape over time. We cannot completely rule out the possibility of across-flow fractures being produced in the calving front area, since our model uses a simplified boundary condition where the driving stress is approximated by the isostatic pressure. This neglects longitudinal stresses, which can be significant around grounding lines and transition zones (Schoof, 2007). Were these stresses to be included in the model boundary conditions, it is possible
- 15 that the fracture pattern would be altered.

We hypothesise that the across-flow basal features originate at the grounding line, as basal crevassing at the grounding line has previously been observed on other ice shelves (e.g. Jacobel et al., 2014). A second HiDEM experiment around the southernmost grounding zone shows that high levels of basal crevassing occur particularly near to pinning points. at the baseHere the upward gradient in the bedrock causes compression of the ice, and conversely extension on the top and lee-side of the island.

20 It is this process that causes the basal fractures. If these fractures were caused by a sharp gradient in basal shear stress as the ice transitions from grounded to floating, then fractures would be expected to occur at the first point of ungrounding as well as at pinning points. Instead, we see fractures occurring primarily not at the initial point of floatation, but at re-grounding islands. If the drag coefficient were increased then basal crevasses might begin to appear at the initial grounding line also, and basal crevasse production may thus depend on the subglacial environment at the grounding line.

The model predicts the formation of both across- and along-flow basal crevasses in the grounding zone, with the along-flow crevasses caused by shear between the freely floating toice and that grounded conditions on the pinning points. The across-flow features are hypothesised to be the source of across-flow surface features observed downstream on the Totten IS. It is possible that along-flow basal crevasses could be a nucleus for the formation of basal channels, which subsequently grow by enhanced melting (Drews, 2015). (Drews, 2015). This is a potential mechanism for the development of grounding-line sourced channels, the cause of which can be unclear in the absence of obvious subglacial hydrology (Alley et al., 2016).

#### **3.2 Fracture advection**

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The basal crevasses formed in the grounding zone will undergo significant changes in shape as they advect downstream to the calving front. The glacier flow rate accelerates downstream of the grounding area, meaning the ice will stretch and thin, causing the basal cracks to widen as they move downstream. The water in the ocean cavity underneath the Totten IS is also known to be warm enough to drive melt of the ice (Gwyther et al., 2014; Rintoul et al., 2016; Roberts et al., 2017). As basal crevasses are exposed to sea water one might also expect that the cracks will become wider and deeper by melting.

To investigate the role of ocean melting we use the KPZ equation applied to a set of line cracks in a homogeneous 1 km thick glacier (Fig. (Alley et al., 2016).

15 As the across-flow basal crevasses advect downstream, ocean-driven melt and lateral spreading of the ice are likely to widen them, until they are large enough near the calving front to produce a visible surface expression. 4). The vertical blue line segments at the bottom of the figure represent initial line cracks, represented by *η* in Equation 4. The melting front is then propagated forward in time with *η*(t>0)=0, and a driving force *F* that increases linearly along the flowline to represent the longer exposure to melt for downstream ice. The initial crack configuration (*η*(x,0)) is varied until a solution is found that approximates the measured base along the flight path. The surface elevation is thereafter calculated by assuming neutral buoyaney locally-Basal melt rates are highest at the southern end of the Totten Ice Shelf (Gwyther et al., 2014) where the thicker ice shelf means that the pressure dependent melting point is reduced at the base. Nearer the calving front, accelerating velocities and lateral spreading of the ice means internal deformation is more likely to be a dominant factor in basal crevasse evolution (e.g. Li et al., 2016).

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-In this way it is possible to reproduce both the surface and basal features of the Totten IS on an along-flow flight path (Fig. 4).

The evolution of basal fractures predicted here by the KPZ equation neglects spatial variations in melt rate across the ice shelf (e. g. Gwyther et al., 2014; Roberts et al., 2017), as well as variations in melt rate which have been predicted to occur within basal features (Jordan et al., 2014; Millgate et al., 2013). It also does not include the effects of internal ice deformation and strain thinning, which are particularly significant near the calving front where the ice shelf is unconfined and spreads laterally. We separately investigate how internal ice deformation may affect the shape of basal crevasses using an idealised simulation in Elmer/Ice. The model uses an idealised domain with an initial narrow basal crevasse in a linear slab of ice, similar to the geometry used for the KPZ equation but this time with a single creak. Longitudinal stretching is imposed on the idealised ice
10 shelf, by fixing the left hand boundary, while moving the right hand boundary horizontally. As the model runs forward over time, the longitudinal strain causes the initial creak to widen from 200 to 350 m (Fig. 5).

These experiments show that both longitudinal stretching and ocean melt within crevasses could lead narrow basal crevasses at the grounding line to evolve into broader features observed near the calving front of the Totten Glacier, as has previously been suggested by Bassis and Ma (2015). Basal melt rates are highest at the southern end of the Totten Ice Shelf (Gwyther et 15 al., 2014) where the thicker ice shelf means that the pressure dependent melting point is reduced at the base. Nearer the calving front, accelerating velocities and lateral spreading of the ice means internal deformation is more likely to be a dominant factor in basal crevasse evolution (e.g. Li et al., 2016).

With these results in mind, we introduce artificial basal features into the geometry of the original calving front model, to test if they can induce cracks perpendicular to the flow direction as observed in the terminus region. We mimic the observed
 features in Fig. 4 with straight, across-flow Gaussian shaped basal features. We have modelled the two effects separately, using the KPZ to simulate a spatially constant basal melt rate and a full-Stokes ice flow model (Elmer/Ice) to examine the effect of longitudinal stretching on basal crevasse shape. Using the KPZ equation to model the development of fractures under ocean melting, we demonstrate that broad across-flow basal features observed in aerogeophysical data can be reproduced by applying a spatially constant melt rate. Likewise, our Elmer/Ice simulation was able to produce a broadening of an initial narrow basal

crevasse through longitudinal stretching. Both models make significant oversimplifications, but demonstrate that narrow features at the grounding line are a plausible source for the broader features observed near the calving front of the Totten Glacier, as has previously been suggested by Bassis and Ma (2015). It should also be stated that basal crevasses have also been observed to form downstream of the grounding line (Luckman et al., 2012) and we cannot rule out the possibility that

5 further basal fractures form between the grounding line and the calving front. The widening of basal crevasses by longitudinal stretching also depends on the strain rate, and for ice shelves with a lower strain rate basal crevasses could in fact close as they advect downstream.

The simulation of longitudinal stretching was able to widen the initial crevasse, but the height of the feature was also reduced. This might lead to the assumption that basal melting is required to produce the height of basal crevasses observed

- 10 near the calving front. However, previous modelling has shown that concentration of tensile stresses in the ice above a basal fracture can encourage further brittle fracture, providing a mechanism for basal crevasses to penetrate an increasing fraction of the ice thickness as they advect downstream (Bassis and Ma, 2015). In fact this may be a more likely mechanism for maintaining basal crevasses height, as other modelling work has shown that melt rates are likely to be highest on the walls of basal crevasses, while the peak of basal crevasses may be filled in by marine ice formation (Jordan et al., 2014; Khazendar)
- 15 and Jenkins, 2003).

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-Since the model domain was chosen to align with the dominant flow direction to improve computational efficiency, the introduced features also align with the model grid. The results of a HiDEM simulation are shown in Fig. 6. In this model realization, the Totten IS begins to form icebergs from fractures forming both parallel and perpendicular to the flow direction, as observed in satellite imagery (Fig. 2a). Without the introduction of across flow basal features the terminus does not break apart easily, and fractures develop only slowly to form icebergs. Once the across-flow basal features are introduced into the model geometry, the HiDEM model produces icebergs much more quickly, although both simulations eventually reproduce the observed iceberg size distribution (Fig.7).

## 4 Conclusions

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Our results represent the first application of a discrete element model, HiDEM, to an Antarctic ice shelf. We use the model to simulate fracture formation in two separate areas of the Totten IS. At the calving front, our results show that HiDEM reproduces fractures perpendicular to the calving front which <u>drivecontribute to</u> the small, disintegration type calving events observed in satellite imagery. The model set-up at the calving front is not fully able to reproduce the fracture observed from satellite imagery, as it is missing many across-flow features which advect into the model domain from further upstream.

We suggest that these across-flow fractures develop at the grounding line, where the longitudinal stress caused by the transition from grounded to floating ice is likely to cause basal crevassing. A second HiDEM experiment around the southern-most grounding zone shows that high levels of basal crevassing occur particularly near to pinning points. Basal crevasses have previously been found at the grounding line around Antarctica (e.g. Jacobel et al., 2014) and our results suggest that pinning points are extremely important in determining where these fractures occur. The model predicts the formation of both across- and along-flow basal crevasses at the grounding line, and it is possible that along-flow fractures may be a potential precursor for the basal channels observed on many ice shelves, the source of which is currently unclear (Alley et al., 2016).

As the across flow basal crevasses advect downstream, ocean driven melt and lateral spreading of the ice are likely to widen them, until they are large enough near the calving front to produce a visible surface expression. We have modelled the two effects separately, using the KPZ to simulate a spatially constant basal melt rate and a full-Stokes ice flow model (Elmer/Ice) to examine the effect of longitudinal stretching on basal crevasse shape. Using the KPZ equation to model the development of fractures under ocean melting, we demonstrate that broad across flow basal features observed in acrogeophysical data can be reproduced by applying a spatially constant melt rate. Likewise, our Elmer/Ice simulation was able to produce a broadening of an initial narrow basal crevasse through longitudinal stretching. Both models make significant oversimplifications, but demonstrate that narrow features at the grounding line are a plausible source for the broader basal features advected into the calving zone.

A second HiDEM simulation at the grounding line of the Totten IS demonstrates that this region is a likely source of basal fractures, particularly forming around pinning points. Simulations of crevasse evolution under homogeneous basal melting and

25 longitudinal stretching demonstrate that narrow basal crevasses at the grounding line can plausibly evolve into the broader

features observed near the calving front. However, coupled ocean/ice/fracture models would give a more thorough representation of the different processes involved in the evolution of basal crevasse shapes, and would provide a more robust comparison of the relative importance of ice shelf processes such as internal strain and basal melt.

Our results show that it is the interaction between the advected and locally produced fractures at the ice shelf calving front 5 which controls the shape of icebergs produced, and the speed with which they form. The development of fractures both at the grounding line and the calving front will be important in considering how calving rates may evolve in future. fracture pattern on the Totten IS, and thus controls the formation of icebergs. This presents a significant complication for accurately modelling calving at the Totten Glacier. The fracture pattern at the ice shelf front depends not only on the local lateral spreading which creates along-flow rifts. It is also strongly affected by across-flow features which are likely-produced upstream, likely at the 10 grounding line. This implies that the conditions at the grounding line decades prior, as well as calving behaviour of the ice shelf is affected not only by stresses at the calving front, but also the cumulative ocean melt history acting on a section of ice shelf, will also have a significant impact on calving behaviour and the conditions at the grounding line when the ice reached the shelf decades or centuries prior to calving. The combination of multiple different effects fracture sources is a significant challenge for calving models. One way to address this problem may be to combine modelling methods which allow local fractures to be accurately reproduced (e.g. HiDEM), in conjunction with traditional ice sheet modelling software which can 15 track the history and advection of fractures over longer periods of time. Additionally, observations from satellite altimeters, such as CryoSat2, over ice shelf regions (Lacroix et al., 2007; Skourup et al., 2017) can also help give an improved

understanding of surface crevasse characteristics, leading to improved modelling of fractures and calving.

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**Figure 1: Locations of model domains**. Blue line shows the grounding line as defined by ASAID (Bindschadler et al., 2011a). Red box shows extent of HiDEM calving front model. Yellow box shows extent of HiDEM grounding line model. Pink line shows flight path used to tune the KPZ model. Background image: Sentinel 1, December 2016.



Figure 2: Observed and modelled fractures. a. Location of calving front domain (yellow box). Back groundBackground image from Sentinel 1 (December 2016) shows the dense pattern of fractures at the calving front (yellow box shows model
domain) b. Model output fromModelled crevasses in HiDEM atoccur most densely near the calving front. Red dots show modelled crevasses. Crevasses largely, and typically run roughly parallel to flow<sup>2</sup>, or perpendicular to calving front. In this projection thick ice appears white, thin ice appears grey and water appears black. The dark fractures on the shelf are full thickness rifts exposing the black water underneath.

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Figure 3: <u>Model output</u><u>Modelled fractures</u> from HiDEM at the grounding zone. <u>BlackRed</u> dots show modelled crevasses. <u>GreyBlue</u> line shows grounding line from HiDEM model geometry. Background <u>colourgreyscale</u> shows ice thickness. Crevasses are <u>largely</u> clustered around pinning points where the ice <u>regroundsre-grounds</u>.



Figure 4: <u>DevelopmentEvolution</u> of basal fracture geometry under ocean melt. <u>Measured (dark blue) and computed (red)</u>
ice surface and base along flight line. <u>VerticalThe KPZ equation is used to evolve an initial set of narrow fractures (vertical</u> lines at the bottom of the figure represent relative position and height of original) under constant basal fractures.<u>melt. The</u> computed surface and base after 100 years (red) can be made to match the measured geometry along a flight path (dark blue).





Figure 5: Evolution of basal crevasse geometry in Elmer/Ice. Top panel shows initial geometry of basal crevasse experiment. Bottom panel shows evolved geometry under longitudinal stretching after one year. The effect of longitudinal stretching on the shelf widens the basal crevasse.



Figure 6: Fracture pattern produced by HiDEM with additionalartificial basal features. Example output from the HiDEM model on the Totten IS, showing modelled fracture pattern. Light scattering within the<u>crevasses</u>. In this projection thick ice appears white, thin ice appears grey and fractures are computed to show internal structure visible as dark lines on the ice shelf. The introduced basal features are a source of additional across flow fracture, producing a checkerboard fracture 5 pattern similar to observation.

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5 Figure 7. Evaluation of HiDEM results.iceberg size distributions. Frequency distribution of simulated and observed iceberg sizes. The model is able to reproduce the Dark blue circles show observed size distribution. The disparity at smaller iceberg sizes is caused, red crosses show icebergs produced by difficulty of detection in satellite imagery the original model geometry.

pale blue circles show icebergs produced by the modified geometry with additional basal crevasses. Overlaid are the theoretical distributions for brittle fragmentation: area<sup>-3/2</sup> (black line) and grinding: area<sup>-2</sup> (red line).