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Interactive comment on "Effects of undercutting and sliding on calving: a coupled approach applied to Kronebreen, Svalbard" *by* Dorothée Vallot et al.

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We first want to thank the referee for the constructive comments. Our answered answers to the questions are detailed below.

General comment:

One of the main conclusions of the paper is that calving rate is controlled by basal sliding. I can see two problems in the methodology that question the validity of this conclusion. First, the friction coefficient inferred using inverse methods with Elmer/Ice has to be scaled down by "some" orders of magnitude when

used with HiDEM. I didn't understand the justification regarding the different time scales of calving and sliding processes to justify this scaling. The "some orders of magnitude" should be quantified. Is it a constant for the whole domain? Is it the same value (give it) for all simulations? This should be explained much more precisely.

This is a good point and our original text was not well formulated to explain this properly: There is a clear separation of timescales between the velocities of sliding ($\sim$ m/day) and calving ice ($\sim$ m/sec). This means that as long as sliding is slow enough to be negligible during a single calving event, we can change it without much effect on any single calving event. As an approximation we can assume that fast processes are at equilibrium when we consider slower timescales. However, a rescaling speeds up the frequency of calving, and we can thus 'speed up', within reason, the few minutes of HiDEM simulation to effectively model calving which would otherwise take tens of hours or days, and thus be practically impossible to simulate with HiDEM. By applying scaling, the calving events modelled during the simulation of HiDEM (few minutes) correspond to the sum of calving events that would happen during the time scale of sliding. The scaling factor that we use is the same for the whole domain and for all simulations. We use a friction scaling factor for β equal to 10^{-2} (or sliding velocity scaled up by 10^{2}), and simulations run until calving stops and a new quasi-static equilibrium is reached.

This is now explained in the text (p. 12, lines 10–18): "This means that as long as sliding is slow enough to be negligible during a single calving event, we can change it without much effect on any single calving event. As an approximation we can assume that fast processes are at equilibrium when we consider slower timescales. However, a rescaling speeds up the frequency of calving, and we can thus 'speed up', within reason, the few minutes of HiDEM simulation to effectively model calving which would otherwise take tens of hours or days, and thus be practically impossible to simulate with HiDEM. By applying scaling, the calving events modelled during the simulation of HiDEM (few minutes) correspond to the sum of calving events that would happen during the time scale of sliding. The scaling factor that we use is the same for the whole domain and for all simulations. We use a friction scaling factor for β equal to 10^{-2} (or sliding velocity scaled up by 10^{2}), and simulations run until calving stops and a new quasi-static equilibrium is reached."

Second, calving rate is a continuous view of calving, as calving is discrete and a calving rate can only be inferred when averaging a number of calving events during a given time. Here, it seems that calving rate is inferred from one simulation of HiDEM and I then suppose that it is inferred from one calving event? Or a limited number of calving events arising during a very short time? Can we deduce a calving rate from that, and then conclude that calving rate is very sensitive to basal sliding?

This is another good point: During one simulation with HiDEM, several calving events are triggered. Calving rate is then inferred from the difference between the initial and final position of the front, after calving has stopped and the glacier has come to rest. This approach is, as the referee points out, dependent on several assumptions, and the error is not easy to estimate. Therefore, the comparison with observed calving rate is very important in order to estimate the validity of this approach. To be clearer, we use "mean volumetric calving rate" instead of just "calving rate". The discussion on basal sliding is based on the comparison between two time steps with the assumptions made in the simulations. Of course, the fact that it is a one-way coupling and that the advance is step-wise and not continuous (due to observation time resolution and modelling limitations) makes the conclusion dependent on these assumptions. We have now changed the text to better explain that the model results regarding basal sliding and calving are valid only under the specific model assumptions.

In Methods/Frontal ablation calculation:

"For the modelled case, during one simulation with HiDEM, several calving events are triggered. Volumetric calving rate is then inferred from the difference between the initial,

F_i^{elmer}, and final position, F_i^{hidem}, of the front, after calving has stopped."

Also, it should be worth verifying that the results are not too strongly dependent on the time step in between two HiDEM simulations. How different are the calving rates obtained by running the HiDEM model every dt, dt/2, dt/4 time step of the Elmer/Ice model?

This is yet another good point that would need further investigation in a fully coupled version. Here we only have observations every 11 days and do not know what happens at dt/2 or dt/4 so it would not be possible to compare. However, we did early test with gradually vanishing sliding and vanishing under-cut. When sliding vanishes, the under-cut determines calving (compare with Benn et al., 2017), and when both vanish, there is typically no calving at all. When comparing HiDEM calving for specified undercuts of different sizes in Benn et al (2017), the results shows that the magnitude of calving increases with undercut size: for small undercuts calving just removes part of the overhang, but for large undercuts calving removes all of the overhang plus additional ice. The mechanisms are different in each case - low-magnitude calving for small undercuts just involves collapse of part of the unsupported overhang, whereas high-magnitude calving for large undercuts involves forward rotation of the whole front around a pivot point located at the base of the undercut cliff. When the time step is changed as the referee suggest above, there are differences, but the overall rate changes stays roughly within $\pm$50%.

We have now changed the following text to better explain this. In Methods/ Calving with first-principles ice fracture model HiDEM

"If the time step is changed, the overall rate change stays roughly within $\pm 50\%$"

In the discussion:

"Because the imposed undercuts are the product of melt during the whole interval between observations, the model results should be treated with caution. Benn et al.

(2017) compared HiDEM calving for specified undercuts of different sizes and showed that calving magnitude increases with undercut size. For small undercuts, calving simply removes part of the overhang, but for large undercuts calving removes all of the overhang plus additional ice. The mechanisms are different in each case: low-magnitude calving for small undercuts occurs through collapse of part of the unsupported overhang, whereas high-magnitude calving for large undercuts involves forward rotation of the whole front around a pivot point located at the base of the undercut cliff. The long time-step intervals (11 or 18 days) between the starting geometry and the HiDEM simulation in the present study might therefore bias the results towards higher calving events. Testing this possibility is beyond the scope of the present paper, but remains an important goal for future research. Despite this caveat, our results compare remarkably well with observations, and yield valuable insights into the calving process."

<u>Minor remarks:</u>

page 2, lines 12-15: The fact that it is untested against observations certainly also apply to the particle models (or you should give a reference in which the particle model is validated against data).

This is true but this is also the subject of the paper: to test HiDEM results against observations. However, the sentence "These are largely untested against observations, and may fail to adequately represent key processes." was not well placed and broke the transition between the former and the next sentence. Therefore we removed it.

page 2, lines 12-15: The distinction between continuous and discrete approaches could be a bit more rigorous and objective. There are also some drawbacks in the particle model that will anyway render its use very difficult for large or long applications.

We gave more details on the discrete models and drawbacks to transition to the next paragraph:

"These problems can be circumvented using discrete particle models, which represent ice as assemblages of particles linked by breakable elastic bonds. Ice is considered as a granular material and each particle obeys Newton's equations of motion. Above a certain stress threshold, the bond is broken, which allows the ice to fracture. Åström et al. (2013, 2014) showed that complex crevasse patterns and calving processes observed in nature can be modelled using a particle model, the Helsinki Discrete Element Model (HiDEM). Bassis and Jacobs (2013) used a similar particle model and suggested that glacier geometry provides the first-order control on calving regime. However, the drawback of these models is that due to their high computer resource demand, they only can be applied to a few minutes of physical time. A compromise should be found by coupling a continuum model, such as Elmer/Ice, to a discrete model, such as HiDEM, to successively describe the ice as a fluid and as a brittle solid."

page 2, line 22: with the discrete element model HiDEM

Done!

Figure 1: what are the different colours? Especially the white versus grey?

We added more details in the caption:

"Ocean is in blue, bare rock is in red and glacier ice is in white. The grey area represents the Kronebreen glacier system."

page 3, line 10: as shown by Nahrgang et al. (2014) presenting (there are similar problems with the use of brackets for the references all along the manuscript. Please, check this).

We changed it there and at other places.

Figure 2: should be Elmer/Ice not Elmer/ICE to be consistent with the text.

We changed it.

Table 1: give in the first column the number of day = 11d, etc...

Done!

page 6, lines 1-2: here you are mentioning the one-way coupling between HiDEM and Elmer/Ice, and then saying that a completely coupled model would also couple the hydrology and the ice flow. But to be completely coupled, you should add the coupling with the plume model? I would suggest to modify the transition: Also, an improvement could be to calculate the friction...

We add more information as suggested:

"We call this approach a one-way coupling because inputs to the HiDEM are output results from Elmer/Ice and undercutting model but not vice versa. In Elmer/Ice, we use the observed frontal positions. A completely coupled physical model would use the output of the HiDEM, the modelled front position, as input to the ice flow model Elmer/Ice and the undercutting model. It would also calculate the basal friction from a sliding law rather than an inversion. In principle, such an implementation is possible using the same model components as this study."

page 6, line 20: in this part it should be clearly mentioned what is making the front position advance or retreat. Which equation is solved for the front position? Is it a similar to equation (2) and therefore the front is moving as a balance of ice flow and front melting?

The front is advanced by imposing a Lagrangian scheme over a distance equal to the ice velocity multiplied by the time step. We do not account for the melting during the advance because we only have observations at the beginning and the end of each timespan. Instead, we lump frontal melting by applying an undercut after the advance as explained hereafter.

We add this information.

"The front is advanced by imposing a Lagrangian scheme over a distance equal to the ice velocity multiplied by the time step. We do not account for the melting during the

advance because we only have observations at the beginning and the end of each timespan. Instead, we lump frontal melting by applying an undercut after the advance as explained hereafter."

page 7, line 15: on which Grid? The finite element one? Why not solving equation (3) using the finite element method?

It is possible to solve equation (3) using the finite element method but not the D-infinity flow method. Of course, we could have used another subglacial hydrology model but this was not the case for this study. It is the surface runoff grid (100×100 m).

We add this information in the description of the surface runoff and of the flow path calculation:

"Surface runoff is modelled on a 100×100 grid."

"We use the surface runoff grid."

page 7, line 19: I cannot understand what you mean by this last sentence... what is flow accumulation?

A matlab routine is calculating the flow direction from Equation (3) and given D-infinity flow method. The accumulated flow is the sum of all water flowing in a cell from adjacent cells given this flow direction. Each cell is weighted by the surface runoff calculated for the cell.

page 8, line 10: that sea level corresponds to z = 0 is already mentioned above.

We remove the sentence.

page 9, line 5 and after: this part is not clear. What are the reasons for these 3 different treatments should be explained.

The three different treatments depend on the relative position between the observed and modelled front. To explain it better, we added more details before explaining the cases:

"When the first discharge occurs, the melt rate calculated with the plume model in 2D is summed for the period of time between t_0 and t_1 and projected to the advanced front $F_1^{elmer}(z=0)$ (advanced from $F_0^{obs}(z=0)$) at the location of the subglacial outlets and ice is removed normal to the front. This yields a new position of the front at depth z below sea level called $F_1^{elmer}(z)$. At the second iteration, t_2, we know where the front would be if there had not been any calving between t_1 and t_2: $F_2^{elmer}(z=0)$, which is the advanced front from the observed position at t_1, $F_1^{obs}(z=0)$. So we can transfer the whole undercut from previous iteration to $F_2^{elmer}(z)$ if $F_1^{obs}(z=0)$ is situated in front of $F_1^{elmer}(z)$ (see Fig. 4b–c). Otherwise, the undercut would have been fully or partly calved away (see Fig. 4b–c). We then apply the new undercut on this new geometry given the melt rates between t_1 and t_2.

At time t_i, the modelled front position at depth z (advanced by Elmer/Ice from the observed front position at t_{i-1}) is $F_i^{elmer}(z)$ and the observed front position is $F_i^{obs}(z=0)$. We advance this observed front with Elmer/Ice during $\Delta t = t_{i+1} - t_i$ to obtain the front position $F_{i+1}^{elmer}(z=0)$ at t_{i+1}. We want to determine $F_{i+1}^{elmer}(z)$ and depth z given the melt rate calculated between t_i and t_{i+1} and the state of the undercut from the previous front $F_i^{elmer}(z)$ updated by the observed front $F_i^{obs}(z=0)$."

page 9, line 11: again, same remark as above: which method? Are you solving a free surface evolution equation for the front? Is the Elmer/Ice model time step also 11 days? This should be specified somewhere.

We do not use Elmer/Ice for the undercutting model and we do not use a free surface evolution equation. We use the front position evolved with Elmer/Ice, $F_i^{elmer}(z=0)$ and apply the undercut on it. We first determine the melt rate during the time period between t_i and t_{i+1} given the accumulated discharge calculated by the hydrology model and using the plume model. Second, we project this melt rate onto the calving front using the method described above.

page 9, line 27: that varies spatially according to the inversion done using Elmer/Ice? Yes, we use the coefficient of friction calculated by the inversion with Elmer/Ice but scaled down as explained after.

page 9, line 32: see my main point. It clearly questions the fact that a calving rate can be inferred from this approach? What does it change if you run HiDEM every two (or half) timestep?

Please, refer to the general comment answer.

page 10, line 4: which complication? As for the "some orders of magnitude", the explanation should be more precise.

The complications induced come from the construction of the ice in HiDEM. It reads an input file with surface, bed and basal ice coordinates. The basal ice different from the bed where there is undercutting. It is not possible to add more ice under this basal ice and create an ice foot. We give more details:

"HiDEM reads a file with surface and bed coordinates on a grid and a file with surface and basal ice (to take into account the undercut) coordinates. When simulating with an undercut at a discharge location and in order to avoid complication in the HiDEM (position of the basal ice), we remove particles below the maximum melt (no ice foot)."

Table 2, last line first column : $C($ ***instead of*** $C_($

Done!

Figure 5: Downstream the front, one would expect zero friction? Are the value on this plot extrapolated? Should be mentioned.

We added more details in the HiDEM description: "In the ocean, the basal friction coefficient is extrapolated downstream of the front and taken equal to the mean of the values further from the terminus in case the ice advances."

Figure 6: I would expect that the discharge increase along the water path and I

don't see this from the plot. On (b), the axis for SD should also start a 0 (and with a continuous curve going to 0 for no discharge).

It does increase but it is maybe not so obvious with the logarithmic color scale. We use this colorscale to highlight the path. We changed the figure according to the comment (Fig. 1 from the answer).

Table 3: how the sum of SD and ND volume compare to the integrated runoff over the basin?

The sum of SD and ND should be actually equal to the integrated runoff over the basin.

Figure 8; what represent the horizontal thin lines in the ocean?

Do you mean in (d) and (e)? It represents the sea level. We add this information in the figure caption. "Horizontal lines in (d, e) represent the sea level for each time step."

page 15, line 6: To my understanding, $a_c^o bs$ doesn't include only calving but also melt at the front? So, it should also be mentioned.

The melt at the front is not included in the calculation of $a_c^o bs$ (see Eq. 4) but shown in am because it is modelled.

Table 4: it should be am and not $a_m^o bs$ in the table? In the legend, I am a bit confused by what you call the tangential ice velocity (tangent to the front?). Isn't it the velocity normal to the front that you mean here? Same in the legend of Fig.9.

This is true, we change to a_m.

We understand the confusion. It is actually normal to the front and tangent to the flow. It depends in which domain we are. Better clarification is given: "[. . .] difference between the tangential (ice flow direction) ice velocity at the front [. . .]"

Figure 11: As you mention in the text that Fig. 11 shows strain rates that ressem-

ble crevasses pattern, would be nice to have an aerial image of the real crevasse pattern? How do you explain the very similar patterns for all simulations inside the domain? What drive these features? And why choosing to plot strain-rates when you could directly plot places where bounds are broken?

We add a crevasse map in Figure 1 (Fig. 2 from the answer. The crevasses form as a result of increasing strain-rate towards the terminus, and as a result of shear strain near margins, which is rather similar in all cases. Strain-rate is better than broken bonds, since strain-rate differentiates between very narrow cracks and wide crevasses.

page 20, line 1: regarding the key role of basal friction, see my main comment

Please, refer to the general comment answer. We also change the whole section 5.2 to:

"Because the imposed undercuts are the product of melt during the whole interval between observations, the model results should be treated with caution. Benn et al. (2017) compared HiDEM calving for specified undercuts of different sizes and showed that calving magnitude increases with undercut size. For small undercuts, calving simply removes part of the overhang, but for large undercuts calving removes all of the overhang plus additional ice. The mechanisms are different in each case: low-magnitude calving for small undercuts occurs through collapse of part of the unsupported overhang, whereas high-magnitude calving for large undercuts involves forward rotation of the whole front around a pivot point located at the base of the undercut cliff. The long time-step intervals (11 or 18 days) between the starting geometry and the HiDEM simulation in the present study might therefore bias the results towards higher calving events. Testing this possibility is beyond the scope of the present paper, but remains an important goal for future research. Despite this caveat, our results compare remarkably well with observations, and yield valuable insights into the calving process.

Firstly, the HiDEM results show that undercutting associated with meltwater plumes is an essential factor for calving during the melt season (t_4 and t_6). Surface melt leads to the formation of a subglacial drainage system that ultimately releases the water into the ocean from discharge points at the front of the glacier. Simulations without frontal undercutting at these subglacial discharge locations do not agree well with observed frontal positions and mean volumetric calving rates. In contrast, simulations with frontal undercutting reproduce the retreat reasonably well at these locations, particularly where the discharge is high such as at ND. The largest discrepancy between modelled and observed calving is in the region south of SD at t_4. Here, the model predicts calving of a large block, whereas the observed front underwent little change. This largely reflects the rules used for calving in HiDEM: any block that is completely detached from the main ice body is considered as calved, even if only separated by a narrow crack from the rest of the glacier and still sitting at its original position. This is the case for the large 'calved' region south of SD at t4, where the block was completely detached but remained grounded and in situ. If this were to occur in nature, it would not register as a calving event on satellite images. The discrepancy between model results and observations at this locality therefore may be more apparent than real.

Secondly, the model results replicate the observed high calving rates at t_{11}, after the end of the melt season when there is no undercutting. At this time, the observed mean volumetric calving rate is 24.99×10^5 m^3 d^{-1}, which compares well with the HiDEM rate of 28.50×10^5 m^3 d^{-1}. These values are much higher than those at the start of the melt season, when there is also zero undercutting. This contrast can be attributed to the high strain rates in the vicinity of the ice front at t_{11}, which would encourage opening of tensile fractures (Fig. 11). In turn, the high strain rates result from low basal friction (Fig. 5d), likely reflecting stored water at the glacier bed after the end of the melt season. It is possible that geometric factors also play a role in the high calving rates at t_{11}, because the mean ice front height is greater at that time than at t_0, reflecting sustained calving retreat during the summer months, which would have increased longitudinal stress gradients at the front (Benn et al., 2017). This interpretation is supported by experiments $C(g_0, \beta_6, 0)$ and $C(g_6, \beta_0, 0)$, in which the basal friction values are transposed for non-undercut ice geometries at t_0 and t_6. Imposing low friction (β_6) at t_0

produces mean volumetric calving rates similar to (but smaller than) those observed at t_6, whereas imposing high basal friction (β_0) at t_6 produces low volumetric calving rates similar to those observed at t_0. The influence of basal friction on calving rates is consistent with the results of Luckman et al. (2015), who found that a strong correlation exists between frontal ablation rates and ice velocity at Kronebreen when velocity is high. Low basal friction is associated with both high near-terminus strain rates and high velocities, facilitating fracturing and high rates of ice delivery to the front. Our experiments do not include varying fjord water temperature, so we cannot corroborate the strong correlation between frontal ablation and fjord temperature observed by Luckman et al. (2015). However, our results are consistent with their finding that melt-undercutting is a primary control on calving rates, with an additional role played by ice dynamics at times of high velocity."

And a paragraph of the conclusion to:

"Two factors impacting glacier calving are studied here using HiDEM: i) melt-undercutting associated with buoyant plumes; and ii) basal friction, which influences strain rates and velocity near the terminus. The performance of the calving model is evaluated quantitatively by comparing observed and modelled mean volumetric: calving rate and qualitatively by comparing calved regions. Results show that modelled calving rates are smaller than observed values during the melt season in the absence of melt-undercutting, and that there is a closer match with observations if undercutting is included. Additionally, there is good agreement between modelled and observed calving before (t_0) and after (t_{11}) the melt season, when there is no undercutting. Both modelled and observed calving rates are much greater after the melt season than before, which we attribute to lower basal friction and higher strain rates in the near-terminus region at t_{11}. The influence of basal friction on calving rates is corroborated by model experiments that transposed early and late-season friction values, which had a large effect on modelled calving. These results are consistent with the conclusions of Luckman et al. (2015), that melt-undercutting is the primary control on calving at

Kronebreen at the seasonal scale, whereas dynamic factors are important at times of high velocity (i.e. low basal friction)."

page 22, line 7: Elmer/Ice.

Done!

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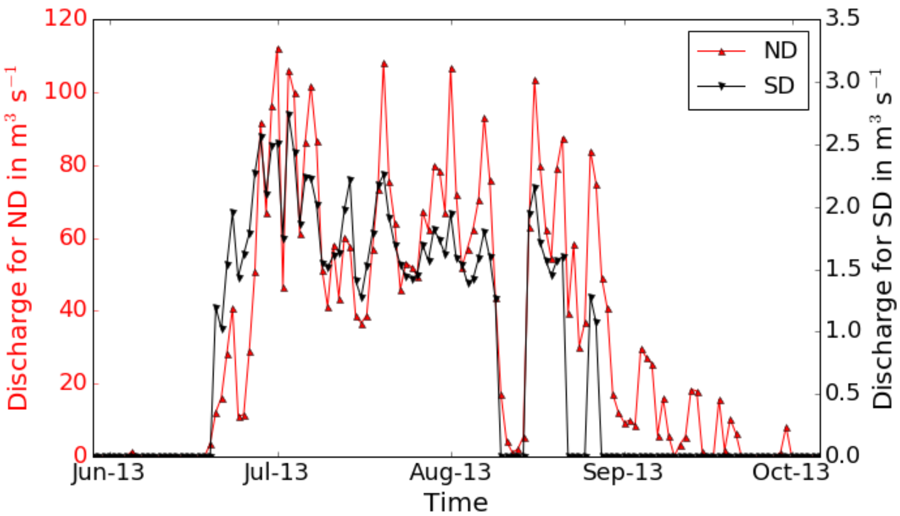

Fig. 1.

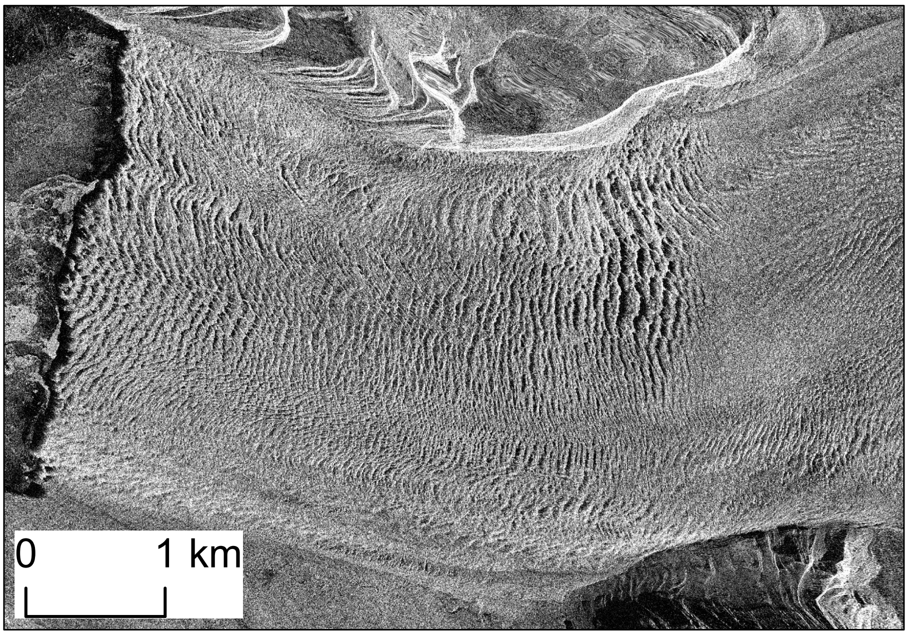

Fig. 2.