We thank Referee #1 for their assessment of the study and their suggestions for improving this manuscript. Below, the reviewer comments are in black, with our response following in blue.

General comments:

"I feel there is a need to include some caution about these results as they are limited to instantaneous changes in grounding line flux. It would be helpful to either include additional experiments that considered the temporal evolution of the system. Or, emphasize clearly that this assessment is limited to instantaneous changes and could be considered as a sensitivity exercise rather than predictive of any future scenario."

and

"I think it is important to emphasis to the reader that these conclusions/results are based on the instantaneous response and that it is unclear how the system will evolve temporally. (This point is mentioned at the end of the discussion, but it should be more prominent throughout.) An uninitiated reader may not realize this nuance. I think it is important that this point is addressed prior to publication."

Thank you for highlighting these important points throughout your review. We have addressed these comments in our general response to both referees.

Specific Comments:

Title: Not sure that you can claim to be considering future calving events. But you are considering a whole range of possible scenarios (thinning and ungrounding).

Possible alternative: The impact of iceberg calving and ice-shelf thinning on the Larsen C Ice Shelf

We agree with this point, thank you. The title will be amended accordingly.

Larsen C ice shelf -> Larsen C Ice Shelf. (Repeat this for Gipps Ice Rise and Bawden Ice Rise in text too)

Done

Abstract:

I like how you've been able to quantify the buttressing capacity of the ice shelf. Again I think it would be good to emphasis the caveat that this is instantaneous, or emphasis that this is a sensitivity test to the current configuration of the ice shelf.

Thank you, we will ensure this is emphasised throughout.

Lines 42 – 45: Both of these studies identify the need to simulate the temporal evolution of the system in order to accurately model the response to ice-shelf change.

That is correct, and we would also require transient experiments to simulate the mass redistribution in response to these experiments. Here, we are concerned only with the changes in buttressing (which are instantaneous) in response to perturbations in ice-shelf geometry.

Line 107: "The surface elevation was adjusted at a few points to ensure that at least 1 m of ice was present across the whole computational domain." Is this only relevant for areas of exposed bedrock (i.e. nunataks)?

Yes, we will add a statement to that effect in the text.

Lines 109 – 111: What impact does accounting for firn density have on the results? Does the minimum ice density refer to the surface firn density?

Thank you for highlighting this point, it was also raised by Referee #2. We will now include details on the sensitivity to ice density in the appendix. The minimum ice density refers to the depth integrated ice density, and we will clarify this in the text.

Lines 113 - 114: You use MEaSUREs velocities for model initialization, but Sentinel-1 SAR for ice velocity pre- and post- calving: how do these velocities compare? Could you use Sentinal for initialization?.

The Sentinel-1 derived ice velocities are slightly higher across the ice shelf when compared to the MEaSUREs data set (the difference is on the order of 10-20 m/a). The reason that the Sentinel-1 velocity data was not used for the model initialisation is that the ice velocity in the A68 region of the shelf is much higher than in the MEaSUREs data set (on the order of 100-200 m/a) during the 2014-2016 period before the final calving event. We did not want to initialise the model velocities in the A68 region of the shelf to these higher values, which are the expression of the iceberg beginning to detach from the rest of the shelf.

Equation (6): Are you considering the difference in speed or velocity components here?

We are considering the difference in ice velocity components. We will clarify this in the text.

Equation (7) first term on RHS: Do you mean that you constrain the gradient in the difference between A and \hat{A}? Or just the gradient in A? (which I think is the usual approach).

We constrain the gradient in the difference between A and \hat{A}, which is the same as constraining the gradient in A in our case, as we assume a spatially uniform A prior.

Line 126: How are prior estimates \hat{A} and \hat{C} chosen?

Both A and C priors are both chosen to be spatially uniform across the model domain. We will include their values in the main text and the explanation of how they are calculated. The A prior corresponds to ice at a temperature of -10 degC as suggested in Morland and Smith (1983). The C prior is derived from the sliding law, assuming a basal velocity of 100 m/a and a basal shear stress of 80kPa.

Line 127: Is it appropriate to use the same regularization parameters for A and C?

We determined that is appropriate to use the same regularisation parameters for both A and C but realise that this was not justified in the text. We will include further L-curves in the appendix that show the impact of varying the regularisation parameters for A whilst holding those for C constant and vice-versa.

Section 2.4 Calving experiments – good explanation of procedure.

Line 152-153: "the ice shelf became afloat without changing the ice thickness" Does this result in areas of thicker ice (that were formerly part of the ice rise) within the ice shelf that might induce flow "backwards" i.e. upstream relative to the large-scale flow?

This does occur at the Gipps ice rise, but not at the Bawden ice rise. At the Gipps ice rise, the ice thickness does increase as you move downstream across what was the grounded ice rise. However, the gradient is smaller than in other regions across the ice shelf, such as where crevasses cut across the flow, and this increase in ice thickness occurs across one or two model nodes. There is not such a change in the stresses as to induce 'backwards' flow.

Section 3 Results – I think it would be good to include an initial sentence here that states that this section is split into subsections reporting the results of each of the scenarios outlined in the methods.

Done

Line 176: "no observable, transient response to the calving of the A68" – it would be good to add that from the dataset spanning 5 years there has been not appreciable change in velocity and no long-term response to calving.

Done

Lines 185 – 188: "Therefore, Fig. 4a and b show what proportion of the total buttressing is provided by each section of the ice shelf removed in the series of calving perturbations. From this, we see that over 95% of the total buttressing is provided by ice in the first 25 km downstream of the GL, and that over 80% is generated in the first 5 km of ice immediately downstream of the GL." Statements like these are where I feel there needs to be some further note that this is just based on the instantaneous response. This could be framed in terms of a sensitivity, or the contribution to buttressing made by the current configuration of the ice shelf.

As stated in our general response to both referees, we will clarify that these are instantaneous calculations about the current configuration of the shelf. But we do think that the passage that you have quoted is correct, in that we have calculated the total buttressing provided by the shelf, and then found by how much that buttressing is reduced by moving the calving front to different locations.

Section 3.3 Ungrounding experiments: Again these results should be treated with caution. Studies such as Favier & Pattyn 2015 have demonstrated the influence of an ice rise on the temporal evolution of grounding-line flux and position.

Thank you for highlighting that study. We will emphasise that these experiments only investigate the buttressing provided by the ice rises, rather than the impact of their removal on the transient mass redistribution.

Line 202: "over 200 m of thinning is required to produce a doubling of GLF" – how does this compare in terms of areal extent to the idealized calving experiments? A doubling in GLF seems huge, how does this translate into contributions to sea level rise? I expect it would be more than a doubling in SLR contribution.

Thank you for this suggestion. We will include a line in the text that compares the ice-shelf mass removed in the calving experiments to the thinning experiments. However, we have chosen not to frame these results in terms of a SLR contribution, as transient experiments would be needed to determine the mass redistribution in response to these perturbations.

Lines 203 – 204: "The maximum ice thickness in the shelf was 1,400 m, so a thinning perturbation larger than this had to be applied to reduce the ice shelf to the minimum thickness of 1 m everywhere." I think there must be a typo here – thinning of 1,400m would lead to no ice shelf remaining?

Thank you for highlighting this, we agree that it is poorly worded and will correct this. There is an algorithm in the model code that ensures the ice thickness is never less than 1m, so by thinning the shelf by 1,500m the ice shelf is effectively set to the minimum ice thickness everywhere. But really the maximum amount of thinning applied was 1,489m the maximum value of ice-shelf thickness at any of the ice-shelf nodes.

Lines 228 – 231: “Therefore, the dynamic response to the detaching of the nascent A68 iceberg will have already taken place in this region, and this response is included in the ice velocity data used to initialise our model. Finally, in the model we essentially force the already detaching iceberg to have contact with ice upstream, inducing an artificial ‘pulling’ effect on this upstream ice, which is removed when the iceberg is calved from the domain.” This is evident in Fig 2C where the model assimulation produces speeds less than observations.

Thank you for raising this point, we will refer the reader to Fig 2c at this point.

Lines 238 – 242: Again important to emphasis that this assessment is based on instantaneous response.

Agreed, we will address this throughout the manuscript.

Lines 246 – 247: “We argue that it is this second definition, the integrated impact of changes in ice-shelf geometry on stresses at the GL and consequently on GLF, that is the key measure of the buttressing capability of ice shelves.” The buttressing capacity of the ice shelf in its current configuration. It is noted by Furst et al., 2016 that after a calving event occurs the stress field within the shelf will evolve, such that the initial assessment is no longer valid.

We will clarify that it is changes to the current configuration that we are addressing, and that questions around transient mass redistribution in response to a perturbation are not presented here.

Lines 253 – 254: “by removing the entire ice shelf and calculating the instantaneous response in GLF we are able to quantify the total amount of buttressing that the LCIS provides” Good point!

Thank you.

Lines 254 – 256: Again important to emphasis that this based on instantaneous response.

Done.

Lines 269 – 274: This seems like an artifact of the modelling rather than something that would occur in the real world - surely the 1m (and even more so with 0.001m) thick ice shelf would break or buckle when trying to resist the flow of 1000+m ice streams. I think it is important to acknowledge this.

Yes, we will clarify that this was just a technical exercise to ensure that the chosen minimum ice shelf thickness (which is used for numerical reasons) did not unduly impact the results of the experiment.

Lines 275 – 279: How does this magnitude of basal melting compare to surface accumulation? By how much is the ice shelf actually thinning?

As these experiments are instantaneous, there is no surface accumulation field applied to the model. Therefore, the amount of thinning stated is the actual amount by which the ice-shelf thickness is reduced.

Lines 286 – 288: "This suggests that, whilst these two ice rises may exert a significant control on the flow of the shelf upstream of the pinning points, they do not exert a strong mechanical control on the ice flux at the GL, and only contribute a small amount to the total buttressing capability of the shelf." This statement is again based on the instantaneous response. In a temporal sense removing the ice rise would have a massive effect on the flow of the shelf, changing its geometry and thickness, and later impacting the flow at the grounding line.

We are happy to reiterate that the results presented here are instantaneous and that transient evolution is not explored. But from our early transient experiments, we find that on losing basal contact at the ice rises the instantaneous change in GLF is maximal, and that the GLF decays towards its initial value through time.

Lines 293 – 299: This is a very important point, which should be highlighted much earlier.

It is good that you have acknowledged this point, but I think you need to explore this point more or at least note that these results are not complete.

Someone reading this may easier assume that the large parts of the shelf can be removed without increasing discharge, which is not the case! Instantaneously maybe, but once the geometry/thickness of the shelf has adjusted to the imposed change the GLF will change too. You have only explored the buttressing generated by the current configuration of the LCIS.

We hope that the new manuscript will be clear on this point throughout. But as stated in our general response to both reviewers, we do want to emphasise that the buttressing effect is necessarily 'instantaneous' as it relates to the stress state in the ice. We think that our statements about which parts of the ice shelf generate the buttressing are correct, but that does not necessarily relate to the transient evolution. Again, our initial transient experiments suggest that the instantaneous change in GLF is maximal, and it decays towards its initial value, as the tributaries thin in response to the acceleration.

Lines 311 – 313: "Here, again, we found that large changes to the geometry of the ice shelf are required to produce significant changes in GLF, with 30 m of thinning across the shelf inducing a 10% increase in GLF and over 200 m of thinning required to produce a doubling of GLF." It may be good to put these changes in GLF into context in terms of the total mass balance of the catchment, i.e. total accumulation - GLF. What does a 10% increase in GLF mean for sea-level contributions?

We can certainly include a further statement here on the mass balance of the catchment. The reference GLF is stated earlier in the manuscript, but we can restate that here as well. As stated in a response above, we do not use a surface mass balance field in these instantaneous experiments, and do not want to discuss the results in terms of SLR contribution, as transient experiments would be needed to do so.

Lines 315 – 317: "This suggests that whilst these pinning points control the local ice-shelf dynamics, they only provide a small amount of the total buttressing of the LCIS." I don't think this is a good sentence to end on. The statement is based on the instantaneous response. And it's probably not the most significant finding from the study.

Thank you for highlighting this, we agree that it is not the most significant finding from the study and therefore should not be the final sentence of the text. But we do think that it is correct to say that the ice rises only provide a small amount of the total buttressing of the LCIS in its current configuration; that is what our experiments are designed to elicit. We agree though that this should not be interpreted as a comment on the potential transient mass redistribution following a perturbation.

Appendix B: Linearity of GLF response to thinning: It would be good to compare this with theoretical results such as Pegler 2018 and Haseloff & Sergienko 2018 as the buttressing force in these cases features an integral along the length of the ice shelf with an integrand containing the vertical integrated (i.e. thickness) longitudinal stress.

Thank you for highlighting this work, we will investigate the links to these theoretical results, and include that in this appendix.

References:

Favier, L., & Pattyn, F. (2015). Antarctic ice rise formation, evolution, and stability. Geophysical Research Letters, 42(11), 4456–4463. https://doi.org/10.1002/2015GL064195

Haseloff, M., & Sergienko, O. V. (2018). The effect of buttressing on grounding line dynamics. Journal of Glaciology, 64(245), 417–431. https://doi.org/10.1017/jog.2018.30

Pegler, S. S. (2018). Marine ice sheet dynamics: The impacts of ice-shelf buttressing. Journal of Fluid Mechanics (Vol. 857). https://doi.org/10.1017/jfm.2018.741