Response to Reviewer #1

J.A. Wilner et al.

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SUMMARY

With this manuscript, the authors aim to put the applicability of four calving laws to the test for ten ice-shelf settings in Antarctica. For this purpose, they employ a state-of-the-art ice-flow model, which comprises accurate calving front tracking. For each ice shelf, the model is initialised with present-day maps of ice geometry and surface velocities. Consecutive forward simulations are undertaken for 200 years with constant climatic conditions. Assuming that present-day ice-front positions are in steady state, the authors then compare the final geometry with the observed calving-front positions. The areal mismatch serves as a quality measure. Results suggest that the performance of the von Mises laws and the eigen-calving are comparable. The former seem superior with regard to a buttressing analysis, because are larger fraction of passive shelf ice (PSI) is preserved - more comparable to observations.

The manuscript is very well written and illustrated and therefore easy to follow. The authors also formulate very concise objectives. However, I miss some important details of the experimental setup, which might well have implications for the interpretation of the result. Do not misunderstand me, I remain very positive about this manuscript and I recommend that the editor should continue to considered it for publication in The Cryosphere after my concerns have been alleviated. These concerns certainly imply a major revision.

Response: We thank the reviewer for the positive and constructive comments. The feedback in this review has improved the quality of the manuscript. Please see our responses to individual comments below.

MAJOR COMMENTS

EXPERIMENTAL SETUP

The introductory paragraph to section 2 (L102-117) serves to explain the experimental setup. Yet key information is missing here. As I understand it, your model domain only comprises the floating part of the benchmark ice shelves. I immediately wonder about upstream boundary conditions at the grounding line. I suspect observed velocities. For reproducibility, please specify the time period of the constant RACMO forcing. Finally, I wonder about your treatment of sub-shelf melting. This component is key to keep the ice-shelf geometry in balance/close to present-day. Yet the basal mass balance is unspecified. Please amend.

Response: The model domain comprises the floating part of the ice shelves under consideration and, in some cases, a small portion of the adjacent grounded ice; this will now be clarified in the manuscript. Upstream boundary conditions at the grounding line indeed utilize observed velocities with fixed ice thickness, which we will now include in the manuscript. We will also clarify that the time period of the constant RACMO2.3 forcing is averaged over 1979-2011, as well as the fact that sub-shelf melting is constrained by the dataset of Rignot et al. (2013).

INITIALISATION

I understand that inverse techniques are used to get an initial model state from observations on ice geometry and surface velocities. After such an initialisation, there is no guarantee that subsequent simulations do not strongly drift away from these initial states (spurious flux-divergence, etc.). Even if such simulations would equilibrate after 200 years, the ice-shelf settings might be very different. Unfortunately the authors show no temporal evolution or quantify the overall mismatch between observed and modelled quantities of ice velocities, thickness or grounding line positions. Did you check if the volume evolution actually equilibrated or is there still a drift or some oscillations after 200 years. An additional equilibration simulation with a stationary calving front position, prescribed from observations, could prove useful. In absence of such reference information, it is very difficult to assess your calving-law analysis.

Response: These are excellent suggestions and we thank the referee for making them. A simulation of Ross Ice Shelf with a fixed calving front position (see Fig. 1 shown below) indicates marginal drift in floating ice volume (<1%) and mean floating ice thickness (∼1%) over 200 years, with somewhat larger drift in mean floating ice velocity (∼-4.5%). The larger drift in ice velocity is likely due to the shock of initial conditions. We will include a supplementary figure showing these drifts for all benchmark ice shelves with fixed calving front position applied over the 200 year simulation period. Grounding line position is largely unchanged over the 200 year simulation for all benchmark ice shelves.

BUTTRESSING

I did enjoy reading the sections on buttressing and more specifically on the passive shelf-ice analysis. I consider it an interesting addition. Yet I am not convinced about your decision to presented it in the discussion section. Please consider transferring it to the results. Moreover, you are certainly aware that

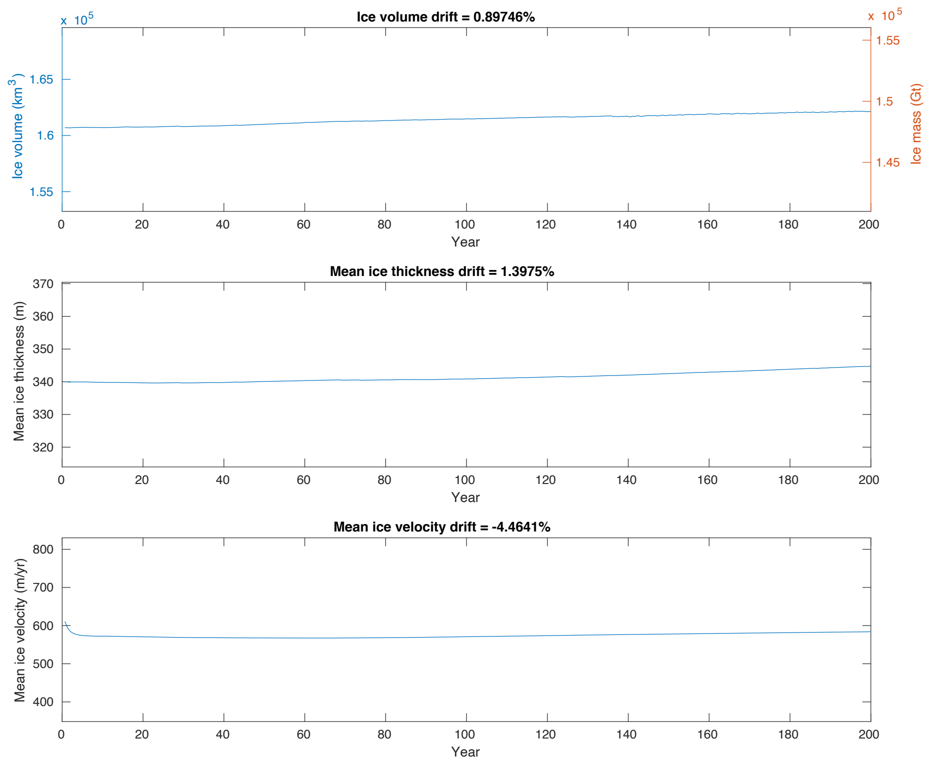

Fig. 1: Drift of various ice parameters over a 200-year simulation for Ross Ice Shelf with a fixed calving front. Only the floating portion of the domain is considered here.

this analysis stays highly qualitative. In a way, I think it mostly boils down again to your areal analysis. Admittedly, there are some differences in the butteressing fields between the various steady-state geometries (Fig. 7) - also some distance usptream of the calving front. This difference might, however, be indicative for important differences in ice geometry and/or velocity impeding a clean comparison. Please check. Finally, the locally derived buttressing number from Furst et al. (2016) has been challenged as an appropriate indicator for grounding-line buttressing (e.g., Zhang et al., 2020). You should pick this up in your discussion.

Response: We are pleased that you found the sections on buttressing, particularly the passive shelf-ice analysis, to be of interest. While we understand your suggestion to place this analysis in the results section rather than the discussion, we made a deliberate decision to include it in the discussion for reasons that we believe enhance the overall context and logical flow of the paper. Chiefly among these reasons is that we consider it prudent to cleanly distinguish between the key point of the paper (the areal mismatch analysis on a shelf-by-shelf basis) and any supplementary analyses, such as the buttressing analysis, which might derive from the areal mismatch results. We agree with the reviewer's assessment of the qualitative nature of our buttressing analysis, and deem it the most concise manner in which to present these results - future work should consider more quantitative avenues. Although the subtle differences in the buttressing fields between EC and VM in Figure 7 may be indicative of upstream influence of different frontal geometries or ice velocities, we do not consider the comparison especially problematic; first, the buttressing field differences are minor compared to the differences in frontal position and second, our intent is for the reader to mainly consider the frontal positions rather than upstream buttressing effects. We will add a reference to Zhang et al. (2020) in the discussion to clarify that Fürst et al. (2016) is one way of measuring buttressing, but it strongly depends on the direction chosen at any given point.

DISCUSSION

You start your discussion by a qualitative assessment of the EC and VM formulations and consequences on the expected frontal shapes. I am not sure if I fully follow your argument for the 'evened out' VM calving fronts (L258). In Fig. 3b and 4c, the VM law results in some elongated ice-shelf protrusions. In a latter section (L304-314), you expand this assessment to the anticipated frontal retreat under climate warming, which might less well be captured by EC. This is nicely substantiated by the results from Choi et al. (2018) on Greenland. I would transfer this section to the beginning of the discussion - just after your first explanations. I also appreciate your discussion of the computation of the areal mismatch - it is valuable. However, I completely miss any assessment of the experimental setup, involving model initialisation, calibration and equilibration. I wonder if you can compare the calibrated parameters (Table 1) to realistic ranges or values from other studies. As climatic conditions over Antarctica are not in steady state, also the assumption that the observed calving front should be reproduced in your model setup can be challenged. Please extend your discussion.

Response: We thank the reviewer for these comments. In retrospect, we agree that our argument for "evened out" calving fronts is a bit convoluted (and not always accurate) as presented in the text and will clarify accordingly, or perhaps remove entirely. Our discussion about the anticipated frontal retreat under a warming climate follows from the buttressing discussion, hence its placement towards the end of the discussion section, but we may also introduce the concept towards the beginning of the discussion section as suggested by the reviewer. Regarding the points about the experimental setup, please refer to our response to the 'Initialisation' section. The reviewer brings up a good point about comparing calibrated parameter values to those of other studies, and we will include such comparative values (as available) in our revised discussion. Admittedly, the assumption of steady state climatic conditions may indeed be challenged, and we shall extend our discussion to better account for our reasoning for this assumption.

MINOR COMMENTS

- L1 Insert 'for each ice-shelf setup' after '[...] of these calving laws'.
  Response: Changed

- L222-224 Does your model see a pinning point beneath the Eastern section of the Thwaites Ice Shelf? If not, you might want to introduce some friction there. It would be good to include a supplementary figure on how modelled and observed velocity fields (and/or geometries along a flow-line) compare right after the inversions. Best for all ice-shelves.
  Response: Thank you for bringing this to our attention; yes, a pinning point beneath the eastern section of the Thwaites Ice Shelf is evident in our model with the bathymetric data used here (BedMachineV3).

- Fig. 1 - 4 Can you specify if you show modelled or observed velocities as background field. I guess that Fig. 1 shows modelled results, while the others show observations. Which radar image (from which mission/sensor) is shown as grey shading.
  Response: We will correct the figure captions to specify whether it is the modeled or observed velocities in the background field. Radar data is from the Radarsat Antarctic Mapping Project (RAMP) Antarctic Mapping Mission (AMM-1), and we will specify this in the first relevant caption.

- Fig. 6 As it stands, this figure allows us only to compare PSI fractions for two calving laws. To me, it seems not possible to judge, which one is more reliable. I therefore suggest that you add the PSI fraction right after the model initialisation (t=0yr). This is not difficult and would give a baseline for comparison. As this plot aggregates information from all ten ice-shelves, I suggest that you further add a supplementary figure, which presents this PSI analysis for each ice-shelf. This might substantiate your argument why to prefer VM over EC.
  Response: These are valid suggestions, and we will modify Fig. 6 to also specify the PSI fraction at t=0 yr as well as include a supplementary figure showing the same PSI analysis for each ice shelf.