Point-by-point Reply to Review Comments

by J.J. Fürst, G. Durand, F. Gillet-Chaulet, L. Tavard, J. Mouginot, N. Gourmelen & O. Gagliardini

First of all we want to thank the two reviewers for the critical and useful comments they gave on the manuscript. All comments are considered and helped to improve the quality of our work. In the following the responses to the reviewers comments are indented and denoted in italic.

REFEREE #2

Interactive comment on Assimilation of Antarctic velocity observations provides evidence for uncharted pinning points by J. J. Furst et al.

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This study is about finding pinning points on Antarctic ice shelves from a modelling inversion of ice geometry and speed. The authors use a shallow shelf approximation version of Elmer/Ice to simultaneously invert for basal friction and ice viscosity. The concept is novel and interesting. The manuscript is well written and provides informations in great details. This study is an interesting modelling exercice highlighting the need for a better sub-ice shelf bathymetry in order to accurately model ice shelf flow. I am not sure however that this methodology is the most effective way of mapping pinning points in Antarctica as measurements from satellite altimetry (ICESat, CryoSat), interferometry (InSAR) or imagery (Landsat, RADARSAT) would be more straightforward and comprehensive. My comments are directed towards the datasets part of the study. I believe this study would make a nice contribution to the ice shelves modelling community after addressing a few minor issues.

1. General comments

P1468, l 22. This point is about Section 2.4.1 Ice sheet geometry: - It should be stated more clearly why the authors take a multiple approach for assuring floatation. I believe it is because Bedmap2 (Fretwell et al., 2013) ice thickness can be in contradiction with its own mask around the grounding line. - For ice shelves, inverting the thickness from the surface or the basal topography of Bedmap2 does not make sense. Indeed, Bedmap2 ice shelf thickness and basal elevation both stem form an elevation inversion taking into account firn air content and geoid corrections (Griggs and Bamber 2011). - There will however be a positive bias in elevation around the grounding line as Bedmap2 elevation 5 km around the grounding line is an interpolation of two different products, the ice sheet DEM, and the ice shelf DEM (Fretwell et al., 2012). See Griggs and Bamber (2011) to understand the positive bias. The grounding line position of the Bedmap2 mask is a potential source of error here.

The reviewer rightly points out issues in the underlying geometric data set. Griggs and Bamber (2011) describe a strong positive bias near the grounding *line where the applied flotation criterion is likely violated. For continuity reasons with the grounded geometry, the Bedmap2 shelf thickness near the grounding line is an interpolation product (certainly within the first 5 km) (Fretwell et al., 2013). For the ice shelf geometry, additional uncertainty arises from the sparse information on firn density and thickness. Therefore, authors agree with the reviewer that ice thicknesses near the grounding line in Bedmap2 have to be taken with a pinch of salt. In our manuscript we show that the data assimilation is rather insensitive to different shelf geometries (prescribing upper and lower shelf surfaces, ice thickness or ice densities). In addition, the focus of this manuscript is certainly not on the grounding line but on pinning points near the ice front. Therefore the authors argue that though there are certainly unresolved issues in the input geometry, they have secondary influence on the presented results.*

Added comment *on Bedmap2 geometry product as discussed here.*

P1470, L2-4. The meaning of this sentence is unclear to me: Therefore, details in this generic density field should not be interpreted in terms of snow/ice transformation.

Removed sentence *as it contained double information.*

P1470, L4-8. The value of 15 meters is typical for firn-air content on ice shelves. As the authors make no mention of it, I wander if a firn correction has been applied for thickness inversions U or L. This is substantial correction to make for the thickness inversion from elevation as 15 meters of firn air content translates into roughly 150 meters of ice thickness.

As discussed in response to one comment from reviewer #1, no firn correction has been applied for any of the presented options to impose flotation. This is certainly a small shortcoming of the manuscript but we now refer to other inversion studies that did so. For this work, the authors refrain from repeating the computationally expensive inversion with a firn-corrected shelf geometry because of three main reasons. First the observational record on firn densities and layer thicknesses is sparse. Sole source could be a regional climate model, limited by its very coarse resolution over Antarctica. Second, our results show that three different input geometries result in a comparable velocity mismatches. A firn correction approach would be a compromise between the extreme options we suggested to guarantee flotation. Third, we rely on the Bedamp2 product which has known deficiencies around the grounding line which are not removable without going back to the original raw geometry data.

No firn correction applied *but we refer to relevant data-assimilation literature on this topic.*

P1473, L1. This point is about Section 3.2 Geometry at flotation: Again this discussion seems to indicate that firn air content hasnt been taken into account. Thickness U or L should not be considered, see earlier comment.

See reply to above comment.

P1473, L7-9. How can case T have thicker ice thicknesses than Bedmap2 thicknesses when there are the same?

The reviewer refers here to a passage which actually does not compare ice thicknesses but ice volume below sea-level. Here, the full citation:

'In case $\mathbb{T}$, the ice shelf volume beneath sea-level is higher than in the original Bedmap2 geometry, resulting in an increased hydrostatic back pressure, compensated by lowering B.'

The ice volume beneath sea-level increases from the direct Bedmap2 geometry to the $\mathbb{T}$ geometry, as the ice-flow model uses a rather high constant ice density which causes a general lowering of the ice surface by 15 m. The reviewer is right that the ice has the same thickness for both cases, but the upper and lower ice surface is at a different position.

No correction necessary.

P1474, L25-28. It is unclear to me how you use the observed velocity in the optimisation in terms of grid and how this affects the shear margins of channelized flow.

A similar comment was posted by reviewer #1 *and the authors adjusted the passage.*

***Reformulated passage for clarity** as follows:*

'The velocity observations are not interpolated onto the model grid, because the underlying finite element approach intrinsically allows to compute the velocity solution at any location. During the minimisation of the cost function, differences between modelled and observed flow speeds are calculated at the data locations in the velocity mosaic.'

P1479, L25-27. I dont understand this statement <Almost half of the newly identified grounded shelf positions are located within 2 km of grounded parts of the ice sheet>. What is the newly identified grounded shelf?

This section was entirely rewritten in response to comments from the reviewer #1. *The authors hope that the passages are clearer now and that the terminology is more consistently used.*

***Reformulated section 3.3.2 (old 3.5)** for clarity.*

P1480, L4. How can a large radius include less points? Also, I am not sure I exactly understand the intended purpose of PIN1, PIN5 and PIN10. It is presumably to deal with multiple grounding lines as provided in Rignot et al. (2011) dataset.

Actions undertaken *see above reply.*

P1480, L2-9. The fact that including pinning points does not improve the mismatch might be a sign of over-fitting. Indeed, if the modelled velocities are too much forced to resemble the observed velocities, then there is no reason to have differences between the runs with and without pinning points. Could you elaborate on this?

The reviewer is right that over-fitting the velocity field cannot be excluded as a source for no improvement after introducing complementary information on pinning points. Yet it is impossible for the model to reduce ice velocities along a flow line by simple adjustment of the ice viscosity parameter B. This is only becomes possible by allowing an optimisation of the basal friction coefficient. ***Added over-fitting*** *as a potential source for no improvement.*

P1481, L22. Figure 7 is really too zoomed out. I would zoom in onto individual ice shelves. From this figure, it is very difficult to retrieve anything else that the approximate position of the un-charted pinning points. Figure 8. Location of PPP1-7 should be marked in here so that it is clear where you place the pinning points.

As both reviewers had difficulties to see details on the ice shelves for Figure 7, we now present zoomed in versions around the respective pinning points. Their respective positions are indicated in Figure 1. In addition, streamlines and pink rectangles were increased in sizes.

Figure adjusted *as requested.*

P1482, L11-12. Jugging from the RAMP images in Figure 8, satellite imagery alone seems to be quite effective at spotting pinning points. I believe altimetry data would as well, see also Table 2.

The authors agree with the reviewer that pinning points could directly be inferred from the velocity observations Rignot et al. (2011b) or from surface features seen in RAMP images. This is now expressed by the following passage in the Summary & Conclusions (P1484, ines 14-16):

'Though the identification could be done on the sole basis of the velocities observations or even directly from RADARSAT imagery, our approach implicitly quantifies the effect of these pinning points on ice dynamics.'

No action necessary *as a similar statement was already included in the manuscript.*

2. Specific comments
P1465, L8. give rise to biases.

Corrected *as suggested.*

P1473, L25. I am not aware of a Griggs ice rise in LC.

Thank you. ***Corrected.***

P1482, L9. Venable ice shelf

Thank you. ***Corrected*** *as suggested.*

P1484, L21. ice shelf front

Corrected *everywhere in the manuscript.*

P1485, L9. Operation IceBridge

Corrected.

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