Response to Reviewer3:

Weak relationship between remotely detected crevasses and inferred ice rheological parameters on Antarctic ice shelves; C., Gerli, S., Rosier, H., Gudmundsson, S., Sun

Adrien Gilbert, 9th Feb 2024

This study examines whether the surface crevasse field observed from remote sensing is related to the flow rate factor derived from inverse methods constrained by surface velocity. A poor relationship is found, suggesting that surface crevasse observations may not be a good proxy for quantifying ice damage affecting ice rheology over a thickness relevant to ice flow dynamics.

The study addresses an important topic, as observational constraints on ice damage are critical for assessing ice shelf dynamics and stability in ice sheet models. The methodology is rigorous and clearly described, and the results are convincing and well presented. I recommend the paper for publication in The Cryosphere after major revisions.

General Comments

My main concern is that the inferred flow rate factor from surface velocity is consistently presented in the manuscript as the truth that the observed crevasse field should match. I think this way of presenting the study is not fair as it could be turn differently. For example, the crevasse field could be presented as the truth that the inferred flow rate should match, and one could conclude that the model does not capture the effective viscosity and stress field well due to its simplification, inappropriate physics or inaccurate ice shelf three dimensional geometry. The manuscript clearly lacks of a discussion about the model assumption and the reliability of the inferred flow rate factor. Even if the model is strongly constrained by surface velocity observations, it does not sound right to question the utility of crevasse field observations without even mentioning that the weak relationship could be due to the model lacking the relevant physics. Are we sure that the inferred flow rate factor is not affected by neglecting the elastic stress field or the depth-dependent variation of the flow rate factor or other things? The whole study could also conclude that the SSA does not capture the stress field of the ice shelf well, because the inferred value of the flow rate factor is weakly related to the observed damaged areas. This would give the opposite message to the community ...

I suggest that the authors should also consider the case where the SSA approximation is the cause of the discrepancy and provide strong arguments if they think this cannot be the case.

Response:

The reviewer argues that surface crevasses must impact ice rheology, as estimated by state-of-the-art ice flow models. The main research question addressed in this study is whether this is indeed the case and whether satellite-derived “damage” maps can be used to constrain inverse problems in ice-flow models that infer the ice viscosity from surface velocities. Here, we used classification analyses and found a limited match between modelled and satellite-derived damage. The reviewer questions whether the discrepancy found between these two products is due to the model lacking physics, either by the use of a depth-integrated approximation or by neglecting the elastic component of deformation.

Since we are studying ice shelves, it is conventional in ice flow modelling to employ the SSA (Shallow Shelf Approximation) equations. This approximation stems from the relatively thin nature of ice shelves compared to their horizontal extents and it assumes that horizontal stresses within the ice shelf are primarily controlled by the horizontal velocity gradients, neglecting vertical shear stresses and variations in ice thickness. There are certain regions where indeed the SSA may not behave well / break down, i.e., in areas close to the grounding line, in regions where there's a drastic change in slope or topography, close to pinning points and ice rises, due to the presence of high vertical shear. In this work, we have investigated the depth-integrated ice viscosity for the Filchner Ronne and Pine Island Ice Shelves and have ignored for the ROC analysis all regions of "A" that were within 5 km of the grounding line.

The advantage of adopting the SSA equations is that they provide a depth-integrated solution, so whenever we invert for "A", by fitting horizontal surface velocities, we obtain a depth-integrated ice rate factor that depicts the depth-integrated properties of the ice for that moment in time. This allows us to identify weakened ice throughout the ice shelf thickness, even where there is no surface expression of ice damage or weakening. In this work, we showed that most of the surface crevasses mapped by satellite imagery are shallow features that do not have an impact on the depth-integrated ice viscosity and ice flow.

The reviewer questions the ability of the model to accurately depict areas of damage due to a lack of physics and the use of SSA. In response, we direct the reviewer to a study by DeRydt et al., 2019, where the same model effectively identified Chasm 1 and Halloween crack on the Brunt ice shelf. In that study, the model adopted the same setup as this work, employing the SSA approximation and inversion methods to estimate the spatial distribution of "A". They examined nine different configurations of the ice shelf between 1999 and 2017, based on snapshot observations of surface velocity, ice thickness, and ice shelf extent, investigated the timing and location of rift formation and looked at mechanical changes in the ice shelf by analyzing spatial maps of principal stress magnitude and direction. Figure A2 in the Appendix of the article illustrates the distribution of "A" before and after rift formation, showing higher values of "A" (weakening of the ice) along the trajectory of active rifts, Chasm 1 and Halloween crack, and at the hinge zone immediately downstream of the grounding line. These areas of soft ice accommodate the high strain rates or discontinuities in flow speed in those locations. Bands of stiffer (colder) ice are also seen along flow lines from the grounding line to the ice front and have previously been identified via ground penetrating radar as bands of meteoric ice originated upstream of the GL, in contrast to the surrounding areas that predominantly consist of (warmer) marine ice (King et al., 2018). These results overall suggested not only that the model accurately represented active rifts as areas of weakness but also that the distribution of "A" was meaningful and further supported by other independent work.

A similar weakening is visible in our study when analyzing the "A" distribution for Pine Island Ice Shelf fitting velocities of November 2019, a moment in time preceding the calving event that took place on February 11th, 2020. We will refer the reviewer to an additional figure in the Supplementary Material which will display the inverted ice rate factor and observed speed for Pine Island Ice Shelf, in 2019 and 2020.

In summary, by properly fitting surface velocities, the model can correctly represent the stress distributions and deformation across the shelf and accurately identify rifts and weakened ice regions. As argued by the reviewer, improvements can always be made by accounting for the full stress tensor; such measures are nevertheless unnecessary given the model's already precise representation of ice weakening.

The second point of the reviewer was the disregard of the elastic stresses. Here, we refrain from investigating these effects, since most of the ice behaves as a viscous fluid, and instances of elastic behavior may arise in limited settings: when a rift propagates in rapid episodic bursts in very short timescales, or at the bending zone region downstream of the grounding line, due to the impact of tides and tidal flexure. In the current context, we find these effects to be irrelevant to the outcomes of our study. In fact, elastic effects can be safely ignored at stresses and strain rates typical of ice shelf flow. We refer the reviewer to Gudmundsson et al., 2007, Figure A1. For very short loading times, the response of the ice is indeed elastic with a modulus equal to the instantaneous Young's modulus of ice. For very long loading times, the ice behaves as a viscous material with an effective viscosity related to englacial temperature and effective stress. Between these two limits, there is a range of loading periods for which the ice behaves elastically but with a Young's modulus related to delayed elastic response (primary creep). Loading periods/strain rates in ice shelves are about 5 orders of magnitude too small for elastic effects to be of relevance. For this reason, we disregard any effects of elastic deformation.

To satisfy this comment, we will add a section in the discussion of the manuscript.

Specific comments

Line 31: what is fracture data? You could clarify.

Response: We use the same terminology as Surawy-Stepney et al., (2023), who state this hypothesis. We will refer to this article for their definition.

Line 72: You could elaborate here about why a classification problem rather than a simple correlation coefficient.

Response: Classification analyses such as ROC provide a more comprehensive assessment of model performance, as they can handle imbalanced datasets more effectively than correlation coefficients, which might be biased towards the dominant class. Moreover, the ROC analysis provides model performance across various threshold levels, giving insights into how changes in the threshold affect the trade-off between true positive rate and false positive rate. These advantages are extensively detailed throughout the manuscript, particularly in the methodology and in the Classification Techniques section. We decided to refrain from further elaborating on this aspect in the Introduction section since our focus there regards addressing the research question and defining the concept of damage.

Line 72: Why not opposite ? I though it would be more logical to treat the damage as a predictor for ice rate factor since the damage map are the observations. Does it change something ?

Response: This paragraph adopts the terminology frequently used in ROC analyses.
The text says:

"We treat our model inverted ice rate factor as a predictor for damage and quantify how often it corresponds to crevassed areas (true positives) as against to how often crevasses are incorrectly predicted from areas of damage (false positive)."

This paragraph refers to the ROC plot analysis. The crevasse products obtained by remote sensing/machine learning techniques represent the true observations to be classified (that is, to match). Since the ROC analysis requires two binary maps, it varies the classification threshold of the "A" field, to generate a binary "A" map for each threshold. The predictor variable (the "A" field) is the variable used to make a prediction. We will make it clear in the text.

Line 156: The meaning of "classify areas of damage" is not clear to me. Is there different type of damage expected from remote sensing observations ? Or do you mean classify between damaged and not damaged area ?

Response: The text reads:

"If there is a strong link between the inverted ice rate factor A and the damage maps obtained from remote sensing methods, we would expect to be able to use the inverted A field to classify areas of damage as identified through the remote sensing methods."

Here again we use the classification terminology: "classify" referring to the ability to predict crevasses where satellite maps detected crevasses (True Positive).

Line 215: Increase font size of legends in the two crevasse maps

Response: We will do it.

Line 215: why not using recommended value from Cuffey and Paterson (2010) rather than value coming from one specific study?

Response: It corresponds to the same value. We will add Cuffey and Paterson (2010) as a citation.

Line 332: how ? Using recommended Arrhenius law from Cuffey and Paterson 2010 ?

Response: We adopt the same approach of Spring and Morland, 1983. We will add it as a citation.