Reviewer 2

We thank the reviewer for their time and feedback on the manuscript. The valuable comments and questions are carefully considered, and we discuss below how we intent to incorporate their suggestions in the next version of the manuscript.

In short (also considering comments from the other reviewers), we will focus on (a) extending our temporal analysis to increase our sample size of observed lake drainages, (b) extend analysis of our activeness parameter by comparing to the vulnerability map of Lai et al. (2020) and to the strain rates (c) provide more details on methods, specifically the NeRD algorithm and the definition of thresholds and (d) will implement major textual changes to better clarify and align our conclusions to our observations.

For some (minor) edits we have already started implementing changes, and for some comments we can already provide some provisional additional figures in this document. We thank you for understanding this was not feasible yet for all comments.

General Points

One issue is that the study is quite limited in scope, both in terms of space and time. The generalizability of the conclusions is very limited by the fact that this study only covers three years and one relatively small ice shelf. Given the computing platform the authors used (google earth engine), it seems like it could have been relatively simple to extend the work to other locations and, within the restrictions of the datasets used, to more melt seasons.

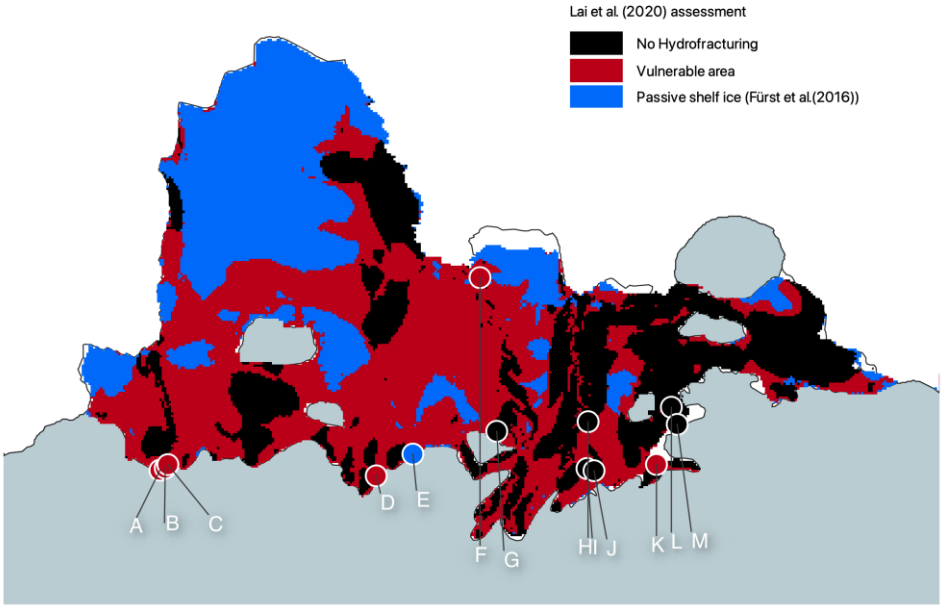
The main novelty of the paper is the consideration of 'activeness' (i.e. how perpendicular is ice flow to the predominant fracture orientation). And one could imagine a paper on this topic (1) proposing activeness as an important factor and (1) thoroughly test if this is the case. However, without an extension in the temporal and spatial coverage of the analysis, I think it is difficult to conclude much about the importance or otherwise of activeness for lake drainage. For example, as I note below, the authors state "…it is clear that at least one of these factors, damage or activeness, must be present for lake drainage to occur." (albeit with a caveat that the exact relationship needs further investigation). I think, given the results presented here, this is a much too strong conclusion to draw at this stage. That leaves the main contribution of the paper as (1) proposing activeness as an important factor. It is worth making it clearer that this is the main contribution of the paper. Or alternatively extending the analysis so that it can achieve (2) as well. This would involve extending to other ice shelves and/or other time periods.

We recognize the limitations of our study, and understand the concerns of the reviewer as a result of that. As the reviewer describes clearly below, the main aim of this study was to assess when/where the combination of melt lakes and damage would (not) lead to hydrofracturing, and we propose activeness as an important factor. We concur that some conclusions might be worded too strong and will rephrase the manuscript to focus on that contribution and bring more nuance to the conclusions; more specifics are explained below. Our intent was, and remains, to present a case study to address the factors contributing to hydrofracturing/lake drainages, which is also why we chose a Brief Communication format. We think that the Shackleton ice shelf presents an ideal case study with multiple 'types' of lakes and lake drainages, as well as various damage features. We agree that a larger scale application would be very valuable and will extent our analysis to the time period 2015-2024 (adding 6 more years, and hopefully many more drainage events).

Other important potential extensions that are missing include between lake drainage locations and ice-shelf stresses and/or vulnerability to hydrofracture as proposed by Lai et al. (2020). These are obliquely discussed in the context of introducing the idea that how close fractures are to perpendicular to ice flow (activeness) is an important factor. However, no comparisons are made to them directly. This would seem like a more direct way (or at the least a complementary way) of testing the ideas that lie behind the activeness proposal.

This is a valuable suggestion, and we'll incorporate a comparison to the vulnerable regions as detected by Lai et al. (2020) in the next version of our manuscript. A preliminary comparison can be seen in the (draft) figure below, showing their assessment at Shackleton, indicating the (non-)vulnerability to hydrofracturing of the ice shelf areas, i.e. if observed fractures are unstable if inundated with water. Our detected hydrofracturing events are superimposed on the map, with the color indicating the assessment of Lai et al. (2020) at their location, showing that 7 of the 13 events are in an area that they assessed as resistive to hydrofracturing; compared to all events occuring in areas of the ice shelf we identified as medium to highly active (seven and

six lake draining events respectively, Figure 2). We will expand on our results and discussion including this figure and provide similar comparison to strain rates.



Specific comments

L14: "only some of these lakes drain." This needs citations

We will add two references to support that statement:

Stokes, C. R.; Sanderson, J. E.; Miles, B. W. J.; Jamieson, S. S. R.; Leeson, A. A. Widespread Distribution of Supraglacial Lakes around the Margin of the East Antarctic Ice Sheet. *Sci Rep* 2019, *9* (1), 13823. https://doi.org/10.1038/s41598-019-50343-5.
Arthur, J. F.; Stokes, C. R.; Jamieson, S. S. R.; Rachel Carr, J.; Leeson, A. A.; Verjans, V. Large Interannual Variability in Supraglacial Lakes around East Antarctica. *Nat Commun* 2022, *13* (1), 1711. https://doi.org/10.1038/s41467-022-29385-3.

L17: missing "an"

Agreed and implemented.

L44: reference should not be in parentheses

Agreed and implemented.

L44: explain what "Median image mosaics" are in more detail

Thank you for your suggestion. We construct median image mosaics by selecting satellite images within the respective time period (10 or 8 days), filtering for cloud cover (<30%) and taking the pixel-wise median value of the image stack. In practice this means that for some parts of the ice shelf there's only a single overpass in the short time period and the "median" value of 1 sample is calculated. This short description will be added to L44.

L46: comma before 'which'

Agreed and implemented.

Section 2.1: Inconsistent tense. Are and was are both used. Change to be consistent.

Checked and Corrected.

L48: not clear what grid is being referred to here. Is this a spatial reference grid? If so, give its name. Or maybe it is not needed here, unless it's important for the analysis that it was this grid for some reason.

The grid mentioned here is a simple processing approach to tile the data in smaller files to streamline the processing of mosaics. It is not strictly necessary and will be removed for clarity.

L52: rephrase "Antarctic ice flow velocity observations of 2019"

We have changed the wording to:
Annual ice flow velocity data are sourced from the ITS_LIVE campaign (Gardner et al., 2020).

L53: delete "and kept constant during the studied period."

Agreed and implemented.

Figure 1 caption: add 'the' before MEASURES.

Agreed and implemented.

L62: rephrase "combining all lake masks of a season."

We hope with the following we can clarify the lake extent creation.
L55: The location and depth of supraglacial lakes are determined using a threshold-based method on the collected mosaics.
L62: For each melt season, the maximum lake extent is derived by aggregating all lake masks per mosaic generated during that period.

L78: "damage maps of 300 m" should be "300m-resolution damage maps"

Agreed and implemented.

L83: I am unclear what "(tolerating a deviation of 15◦)" means.

We have precised our answer and revised the text for clarity:

L83: Then, an area was considered likely to be 'active' if the difference between the damage orientation and the flow angle falls within 45° ± 15°, which occurs mainly in the shear zones of the ice shelf or in regions exhibiting mixed-mode opening fractures."

L98: delete "under-"

Agreed and implemented.

Figure 2 caption: rephrase "show NeRD damage and activeness of summer 2019/20" and "pixel quality" (I am not sure what quality refers to here).

Below is our revised caption:

Figure 2. Spatial occurrence of lake drainages on Shackleton ice shelf. a) and b) present NeRD-derived damage and activeness metrics for the 2019/20 melt season, as derived in subsection 2.4 respectively. The bottom row shows a zoomed section around the glaciers on the ice shelf, with c) NeRD damage d) maximum lake extent, and e) activeness for the melt season 2019/20. Coloured dots with blue labels: Drainage events detected during the Antarctic melt seasons of 2018/19, 2019/20 and 2020/21. The colour of each dot represents either activeness or damage at its location for the respective melt season in which it occurred. Thick black line: Grounding line. Thin black line: Shelf coastline. Both from from MEaSURES data set by Gerrish et al. (2022).

L103: explain what "record summer" means explicitly. I am guessing it means record high temperatures and/or melt volume/extent. But which of these, I am not sure.

You are right, the term "record summer" refers to the 2019-2020 season being notable for its unprecedented melt extent and duration, record surface meltwater ponding, and anomalously high air temperatures (Banwell et al., 2021). This will be edited in the manuscript.

L104: delete ‘such as those by’ and put the citations in parentheses
Agreed and implemented.

L105: replace ‘the’ with ‘our’
Agreed and implemented.

L100: should this reference figure 3 as well as or instead of figure 2?
In the sentence in L100, “However, our findings indicate minimal lake formations in this region, suggesting immediate drainage of meltwater into the ocean in highly damaged areas” we mean the drainage/runoff of meltwater without first forming a meltwater lake. Therefore this is not included in Figure 3 (lake drainage events). We have added “..., without meltwater lake formation” to the sentence

L105-107: “However, the findings indicate minimal lake formations in this region, suggesting immediate drainage of meltwater into the ocean in highly damaged areas (Figure 1 and 2).” This is not clear. Which part are you referring to as the north of the ice shelf? The north-west-most part is not covered by the damage map and the region to the south of that is not ubiquitously highly damaged, so I am not sure this is a fair conclusion to reach from these two maps (damage and meltwater).
Our apologies, this was indeed unclear. In this statement, we meant the area north of Masson Island, we’ll clarify in the text. Also, we will add the north tip of West Shackleton to complete our (damage) map in the next version of the manuscript.

L116: how did you decide on these values for the categories no, medium and high?

Understood, and we’ll further clarify in the text. Different than the melt lake thresholds, there is limited previous research using similar damage detection approaches. As the damage signal is a measure of feature contrast in the satellite image, there is unfortunately not a quantitative translation to physical properties (such as crevasse depth or density). We have therefore discretized the damage signal values to obtain a data-based estimate of what our ‘low’, ‘medium’ and ‘high’ values were. Due to the strongly skewed data distribution (supplementary Figure B1), we discretized the damage signal values in bins of unequal width, containing progressively less data samples (damaged pixels) to favor the representation of high values: the ‘low’, ‘medium’ and ‘high’ classes contain respectively 62.5%, 25% and 12.5% of the samples. The widths of the bins were obtained by initially applying a quantile-based discretization with 8 equal-sized buckets, and then grouping the first buckets into one to yield a reasonable bin-range: the first 5 buckets together contain damage signals between [0, 0.01) (classified as ‘low’) - which is still quite a small range, compared to the ‘medium’ [0.01, 0.2) and ‘high’ [>0.2] classes.
A similar approach was done to discretize the Activeness parameter. As this parameter has a normal distributed data, we divided the buckets to favor both the low and high ends of the curve, yielding the class ‘low’ activeness with 12.5% of samples, ‘medium’ activeness with 75% of samples, and high activeness with 12.5% of samples.
The thresholds in the submitted script deviate a bit from the here mentioned (no effect on the classification). The here presented approach represents our initial though process. We will adjust the thresholds in the manuscript accordingly.

Figure B2: I think this would be useful to have in the main paper.
Thank you for the suggestion. We agree that Figure B2 provides valuable detail; however the Brief Communications format only allows for three display items (tables/figures) so we are very limited in our flexibility here, unfortunately.

L118: replace “a detailed listing” with “a list”
Agreed and implemented.

L127: this is not an indication of where the ice is deforming, only of where it is flowing perpendicular to fractures. The ice is actively deforming essentially everywhere.

You are indeed correct, deformation occurs everywhere on the ice shelf. This activeness metric specifically targets areas where the relative orientation between flow and fractures indicates dynamic activity with respect to the fracture only. We rephrased:

L127: The activeness parameter provides insights into the dynamic behavior of the ice shelf, with high values indicating areas where the local fractures have a high likelihood to be under active development due to the flow of the ice.

L128: replace "distributed in a bell-shaped curve" with "normally distributed"

Agreed and implemented.

L131: clarify what "the glaciers," refers to here.

We referred here to the main glaciers of Shackleton Ice Shelf. We refined the text by mentioning them:

L131: Regions with high activeness are observed around the glaciers Northcliffe, Denman, Scott and Apfel, as well as around the northern tip of West Shackleton, and along the grounding lines of both West and East Shackleton, refer to Figure 1 and 2b.

L132: delete 'this'

Agreed and implemented.

L133: "tends to concentrate inland, away from the ice shelf edge" I do not see this spatial distribution in the figure. Can you explain this in more detail? What exactly do you mean by concentrate?

L136: would "fast flowing areas' be more precise than "glacier zones"?

Thank you for pointing that out, we agree and clarified our text with:

L136: Areas of fast flowing ice originated from the glaciers Northcliffe, Denman, Scott and Apfel, serve as the clearest examples of areas exhibiting high activeness on Shackleton ice shelf.

L138-139: "Unlike damage values, the activeness parameter does not appear to be directly related to the distribution of accumulated meltwater" This implies that the distribution of meltwater is directly related to damage. This is mentioned briefly at the start of section 3, but is this what is being referred to here? This should be made a little clearer and perhaps this statement softened somewhat, given that the distributions of damage and meltwater accumulation have not been explored in detail and it has not been established that there is a close connection (see my comment on L105-107).

The reviewer is right, this statement is a bit strong. We will produce an additional figure of the distribution of meltwater lakes compared to the observed damage values, to get an indication of their relation.

L145: In what sense is the ice shelf a prototypical example? This paper provides no comparison to other ice shelves, so if it is typical, this needs to be discussed. And I think prototypical refers to this example in some way being the originator, or the original version of something, which, unless I am missing something, it is not.

This was not meant to discuss the whole ice shelf: L145 referred to drainages A-E as 'example' where both high damage and high activeness are detected. This might be an effect to English being our second language. We'll change the sentence to "Drainages A to E on the grounding line on West Shackleton are cases where both damage and activeness are high at the lake drainage sites"

L147: I am not sure what "the glacier tongue" is referring to. Please clarify.

The Denman Glacier. Implemented

L157-159: "Although the exact relationship between these metrics requires further investigation across different ice shelves and with more drainage events, it is clear that at least one of these factors, damage or activeness, must be present for lake drainage to occur." As mentioned in the main point above, this statement should be softened. There are examples in Greenland of fracture perpendicular to the background flow direction directly draining lakes on grounded ice. It seems likely the same is possible on ice shelves. A more precise statement restricted to what this dataset tells us about this ice shelf over these three years, given the limitations of the remote sensing datasets and your analysis, is needed here. In other words, not only does the quantification of the exact relationship require further investigation, so does establishing that activeness and damage are a requirement at all.

These are fair points and we will implement this with care, pending on the added analyses with extended time series.

L161-163: I suggest deleting this opening paragraph.

Agreed and implemented.

L166-167: I suggest deleting the opening sentence of this paragraph.

Agreed and implemented.

L171: Delete "Our data reveals a trend:" A trend implies something changing over time. Also, it is unnecessary. I suggest just describing the relationship.

Agreed and implemented.

L177: delete "not only confirms but also extends the work of" and put the citation in parentheses. It's not clear to me that this analysis confirms that work. Maybe you can say that it is broadly consistent with it.

Thank you for your suggestion. We have revised the text to clarify and simplify our findings as follows:

L177: Our observations of several drainage events support a model in which tidal forcing plays an important role in modulating supraglacial lake drainage across the ice shelf. This mechanism is broadly consistent with previous findings (Trusel et al., 2022).

L180: delete "highlight the multifaceted nature of drainage events and"

Agreed and implemented.

L182: delete "intricate"

Agreed and implemented.

L192-193: "the temporal resolution of satellite passes may not be sufficient to capture all drainage events, especially those of short duration." This is a little repetitive of earlier in the paragraph.

Thank you for noticing, we will remove this redundant phrase from the paragraph.

L108-109: "produce different results" can you be more precise with this statement. Changing the thresholds would of course change the results quantitatively, but could it change things qualitatively too?

Yes, altering the thresholds in the algorithm primarily affects the quantitative outcomes of our study, as some drainage events could then fall into a different 'low', 'medium' or 'high' category, depending on the bounds of these bin classes. However, as long as all ranges of damage and activeness are present on the studied ice shelf, their data distribution and consequently the defined classes are expected to remain relatively similar. Hence it is unlikely to change the qualitative interpretation.

We'll change the sentence to "Consequently, applying different thresholds could yield varying quantitative results, e.g. in terms of classification of damage and activeness."

L226: this sentence mentions a predictive model for the first time. It isn't clear what this is referring to. What would be the purpose of such a model? I was assuming it would be some kind of parameterization in an ice-sheet model, but the need for real-time data confusing me in that case.

Thank you for your observation. We acknowledge that the introduction of a predictive model in this context may have been unclear. Our intention was to suggest that combining damage severity, activeness, and meltwater accumulation could serve as indicators for potential drainage sites. In an extreme and ideal scenario, this could be expanded to a model that predicts hydrofracturing before it occurs (hence the near real-time data). Nevertheless, we agree this is probably a bridge to far and will keep it at 'indicator for potential drainage sites'.

L224: When expanding our study to an Antarctic-wide scale, we could assess if the link between drainage events and medium damage, high activeness, and large tidal range occurs on a larger scale. The combination of damage severity, activeness, and meltwater accumulation could serve as indicators for potential drainage sites.

The discussion: One limitation to the idea of activeness being a control is that fractures could advect into areas that are compressive, but the fractures could remain still perpendicular to flow. This scenario would yield non-zero activeness, but may not be conducive to hydrofracture. This underlines the utility of comparing lake drainage locations to ice shelf stresses and fracture orientation to principal stresses orientations.

The reviewer makes a very good point. We will include an analysis with calculated strain rates (see earlier comments above) to further analyse our activeness parameter, and will take this case into consideration as well.

Data availability: It would have been good to have access to the code and data for the review process.

For the next review process, Google Earth Engine and Python code available through the links below. Please beware those are prelimary versions. For the final submission the repositories will be revisted, cleaned and prepared with documentation.

GEE: https://code.earthengine.google.com/?accept_repo=users/juliussommer/HydrofractureShackleton

Python Github: https://github.com/js-chemE/HydrofractureShackleton_2023