

Response to Review “*Brief Communications: Tides and Damage as Drivers of Lake Drainages on Shackleton Ice Shelf*”

We thank the editor and reviewer for this new round of review of our manuscript. We were happy to hear that the new version of the manuscript was received well. Remaining comments or questions are discussed and implemented as detailed below (with the reviewer's comment in blue). There are no major changes to the manuscript.

Yours sincerely,
Julius Sommer, on behalf of all co-authors.

Reviewer 1

This manuscript investigates the role of pre-existing ice shelf damage and tidal flexure in controlling supraglacial lake drainage on the Shackleton Ice Shelf. Using NeRD-derived damage and activeness maps, the authors compare the spatial distribution of fractures with lake locations and drainage events, and further analyze drainage timing relative to tidal cycles. They find that lake drainages predominantly occur in areas classified as medium to highly damaged and active, and that drainage events often coincide with the ascending tidal phase.

The authors have engaged constructively with Reviewer 1's comments. However, several methodological choices and interpretations remain unclear or potentially misleading (particularly concerning the relative nature of the damage classification). For these reasons, the manuscript still requires further clarification and refinement before it can be published.

General Comments:

First, the manuscript explains that damage values were normalized to the observed maxima and discretized based on their skewed distribution, with thresholds specific to the Shackleton Ice Shelf (Section 2.4, Table B1). This is clearly acknowledged in the discussion, where the authors note that values and thresholds would need to be adjusted for other ice shelves. However, labeling these categories as “low/medium/high damage” risks suggesting that they represent physically absolute levels of structural weakening, whereas in reality they are relative, dataset-specific bins. These binnings (low/medium/high) is based on statistical groupings derived from the Shackleton distribution, NOT on any fracture mechanics threshold. Therefore, using terminology such as “high damage” risks over-interpreting these classes as representing absolute fracture intensity, which in turn, bias the physical interpretation of drainage processes. I would suggest rephrasing throughout to avoid implying a direct physical meaning — for example, by emphasizing that the classes reflect relative signal strength within Shackleton rather than absolute damage levels.

We thank the reviewer for this valuable suggestion and fully agree that the current terminology could imply an absolute physical meaning. We have refined the wording throughout the manuscript to emphasize that the “low–medium–high” categories represent relative levels within the Shackleton Ice Shelf dataset, rather than absolute measures of structural weakening.

For simplicity and visual clarity, we have retained the existing “low–medium–high” labels in the figures and tables, but have explicitly clarified in the corresponding captions that these categories reflect relative, dataset-specific groupings based on the Shackleton distribution.

*L153: “We categorized damage levels into three distinct groups **with values specific to Shackleton ice shelf**: not/low damaged (...), medium-damaged (...), and highly damaged (...).”*

And throughout text, for example: L160 and L164 “... lake drainages in **relatively** medium-damaged regions...” , “... no lake drainages have been recorded in **relatively** low-damaged areas...”

A second methodological (also highlighted by another reviewer) issue concerns the lake mapping thresholds, that are still not properly explained. The classification of drainage events requires that lakes drain by at least 80%, citing a previous study. However, this threshold is never properly justified in terms of the present analysis. Requiring such a high threshold may exclude events where lakes partially drain (e.g. 50%), which could still be linked to hydrological connections and evolving damage, and would further strengthen the manuscript. The choice of 80% should be justified, and the potential implications of omitting partial drainage events should be discussed.

We understand the reviewer’s point, and indeed partial drainages may also be linked to the same hydrological and damage connections as 80-100%-draining lakes. It becomes, however, much more difficult to confidently distinguish true positive from false positive detected lake drainages in the observations. Already for the 80%-draining lakes, we discard significant amount of the supposedly drainages: see Table R1 below.

Tab R1: Detected drainage events for different shrink criteria in area% in comparison to the initial lake size

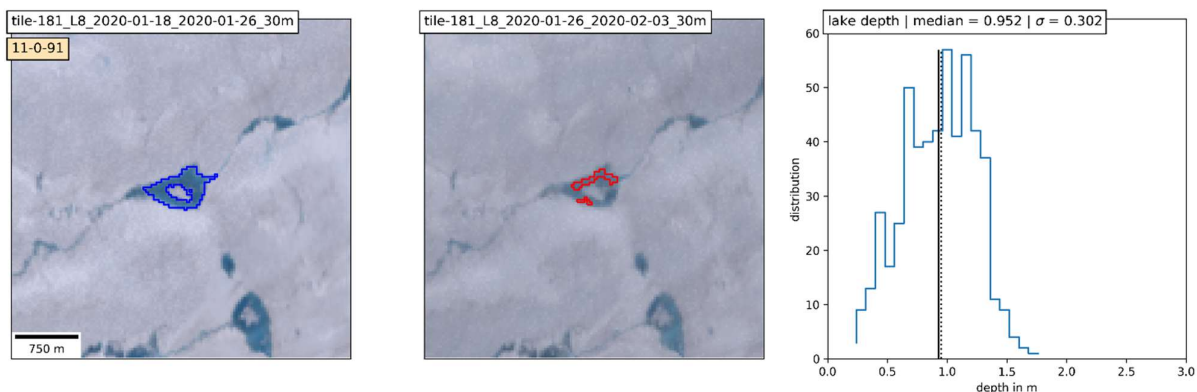
	50%	70%	80%	80% + manual
2016	72	54	49	7
2018	22	14	12	1
2019	132	96	80	15
2020	41	34	32	2

For example, in the year 2019, using a 50% threshold yields 132 initially detected events versus 80 events for the 80% drainage threshold. However, after manual inspection, we found the same number of drainages (15) for both thresholds.

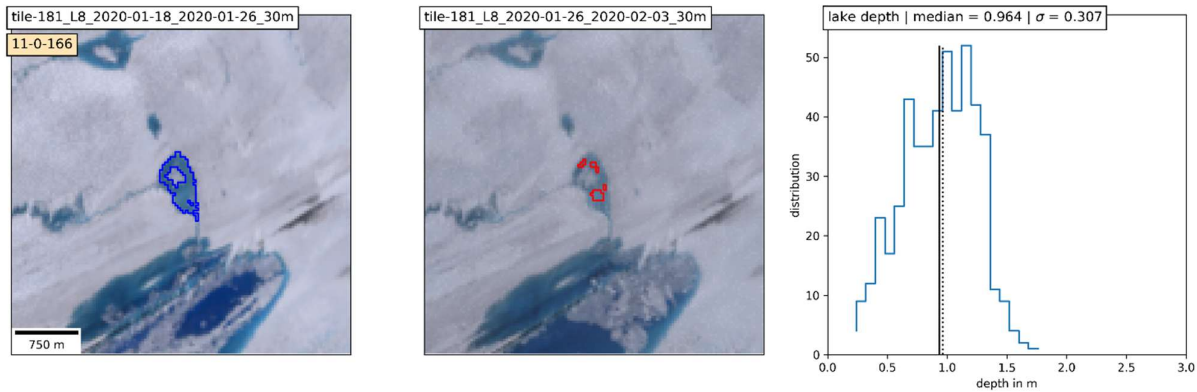
Therefore, the use of the 80% threshold is twofold: (a) we want to be confident in the detected event actually present lake drainage (versus refreezing or changes in snow cover) and (b) be consistent with respect to other literature (as was already discussed in the previous review round).

We have specified this in the text at L80: “While lower thresholds (e.g. 50–70 %) can also indicate partial drainage, our observations suggest that these cases are often ambiguous and more difficult to classify confidently as true drainage events, as surface changes may equally reflect refreezing, snow cover variations, or meltwater redistribution. Therefore, we retain the 80 % criterion as a conservative and literature-consistent threshold.”

See below two examples of lakes that lose between 50% and 80% of their surface area, but were subsequently not classified as true positive drainage event, as inspection by our team attributed both changes to refreezing/snow cover change/runoff.



Example of 50% lake drainage, discarded as True drainage, because of suspected surface runoff.



Example of 70% lake drainage, discarded as True drainage, because of suspected surface runoff and/or refreezing.

Following other literature using 80% drainage threshold: Doyle et al.(2013), Fitzpatrick et al. (2014), Miles et al. (2017), Williamson et al. (2017).

- Doyle, S. H., Hubbard, A. L., Dow, C. F., Jones, G. A., Fitzpatrick, A., Gusmeroli, A., Kulesa, B., Lindback, K., Pettersson, R., and Box, J. E.: Ice tectonic deformation during the rapid in situ drainage of a supraglacial lake on the Greenland Ice Sheet, *The Cryosphere*, 7, 129–140, <https://doi.org/10.5194/tc-7-129-2013>, 2013
- Fitzpatrick, A. A. W., Hubbard, A. L., Box, J. E., Quincey, D. J., van As, D., Mikkelsen, A. P. B., Doyle, S. H., Dow, C. F., Hasholt, B., and Jones, G. A.: A decade (2002–2012) of supraglacial lake volume estimates across Russell Glacier, West Greenland, *The Cryosphere*, 8, 107–121, <https://doi.org/10.5194/tc-8-107-2014>, 2014
- Miles, K. E., Willis, I. C., Benedek, C. L., Williamson, A. G., and Tedesco, M.: Toward monitoring surface and subsurface lakes on the Greenland Ice Sheet using Sentinel-1 SAR and Landsat 8 OLI imagery, *Front. Earth Sci.*, 5, 1–17, <https://doi.org/10.3389/feart.2017.00058>, 2017
- Williamson, A. G., Arnold, N. S., Banwell, A. F., and Willis, I. C. (2017). A Fully Automated Supraglacial lake area and volume Tracking (“FAST”) algorithm: development and application using MODIS imagery of West Greenland. *Remote Sens. Environ.* 196, 113–133. doi: 10.1016/j.rse.2017.04.032

Finally, there is a conceptual contradiction in the interpretation of drainage controls. The manuscript concludes that drainages occur during the ascending phase of the tidal cycle, when surface crevasses tend to close but basal crevasses are expected to open. This would suggest that basal fractures play an important role in enabling drainage. However, NeRD is known to be less sensitive to basal fractures (as evidenced by the low detected damage in the shelf interior, where basal fracturing is in fact widespread). It is therefore unclear how the presented NeRD-based damage fields can be used to support conclusions about processes that are likely governed by basal fracturing. This limitation should be acknowledged more directly, and the apparent tension between results (drainages linked to ascending tide) and method (surface-sensitive NeRD) discussed explicitly. Yes indeed, the results imply that basal crevassing plays a key role, whilst NeRD is not specifically suited to detect basal fractures. We agree with the reviewer that the damage fields as detected by NeRD cannot capture the full process that governs lake drainages. Nevertheless, we think the surface damage fields, and also the activeness parameter derived from them, do provide valuable insights on where hydrofracturing occurs – since basal fractures also don't explain the whole process (as they're widespread in the ice shelf interior, where almost no surface damage nor lake drainages are detected)

We have made this limitation more clear in the manuscript, and more explicitly discuss the importance of basal crevasses.

L246: “During the ascending tidal phase, tensile stresses at the base of the ice shelf promote the opening of basal crevasses, which facilitates water drainage when the base of the lake or a surface crevasse is reached. However, with the NeRD framework, we are not able to distinguish basal from surface crevasses to further study this process, and so cannot determine why basal crevasse opening would be more favorable to facilitate lake drainages. In line with this, future work should target and constrain the role of basal fracturing in lake formation and meltwater drainage”

L256 “To study individual drainage events in high detail, other fracture detection methods are advised, such as segmentation approaches (Surawy-Stepney et al., 2023, e.g.,) that can delineate individual features, or ground-penetrating radar observations to include basal crevasses.”

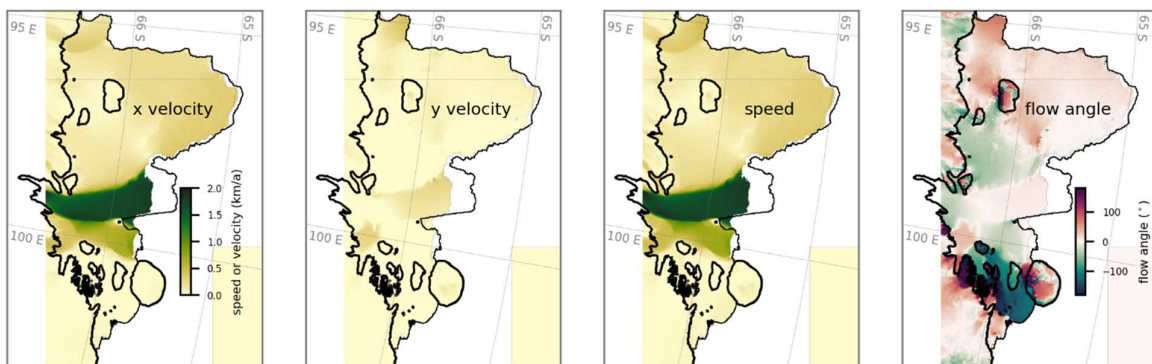
Specific Comments

• L80 (Lake drainage definition): Why was the 80% threshold chosen? Even if a lake drains partially (or does not drain fully), such an event could still indicate hydrological connections with damage evolution. Please clarify.

See also our response to the general comments above. The use of the 80% threshold is twofold: (a) we want to be confident in the detected event actually present lake drainage (versus refreezing or changes in snow cover). Lowering the drainage threshold does not yield more clear detected drainage events (after manual inspection is performed). And (b) be consistent with respect to other literature (as was already discussed in the previous review round).

• L95 (Comparison of local damage orientation with ice flow angle): Ice flow direction can be noisy due to velocity data errors. Was the velocity field filtered or smoothed before comparison? Please specify.

We thank the reviewer to point that out. The utilized ice velocity data (spatial resolution of 240 m) was down-sampled to a resolution of 300 m, using an average resampling method. No further processing of the velocity data was performed during this study. The following figure demonstrates the smooth velocity fields used for the comparison with the local damage orientation.



We have added the figure to the appendix and further specified the down-sampling in the method section:

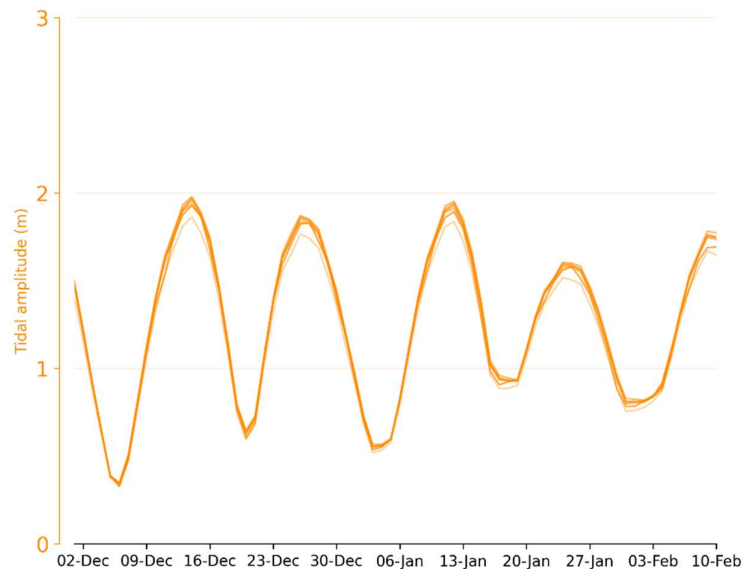
L64: “The ice flow velocity data is downsampled from its original resolution of 240 m to a resolution of 300 m using an average resampling method.”

• L107: Add “new small fracture and basal crevasses” for completeness, since basal fracturing is also mentioned later as a possible pathway.

Agreed and implemented.

• Section 2.5 (Tidal heights): Please clarify where tidal heights are calculated. Do you compute the tidal signal at a specific offshore location, or across the model grid domain? Are there spatial variations in tidal amplitude over the study region that could affect results?

We thank the reviewer for pointing that out. Initially, we computed the tidal amplitude at the location of each individual lake. The following figure presents the amplitudes at all 15 lake locations from the Antarctic summer of 2019–2020. We came to the conclusion that despite the slight variations, it is sufficient to display only one of the tidal amplitude evolution per year in Fig 03.



These results are in the line with Padman et al. (2018), in which they demonstrate a limited variability of tidal amplitude along the Shackleton ice shelf.

We include this figure to the appendix, and further specify in L123: *“Due to low tidal amplitude variations across Shackleton ice shelf (section C1, (Padman et al., 2018)), the tidal amplitudes for this study are determined at the central location of lake I (Figure 1).”*

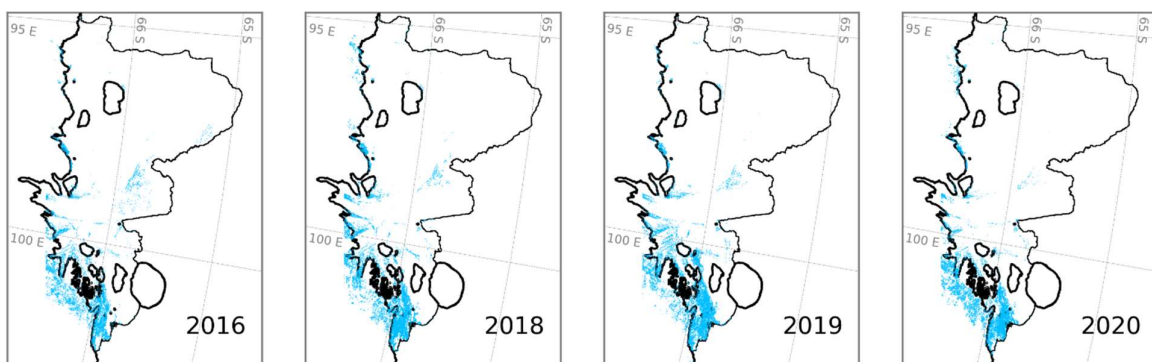
• L120: Wording issue — change *“with a total surface maxima of 234 km²”* to *“with a total surface maximum extent of 234 km²”*.

Agreed and implemented. We further recalculated the total surface maximum extents by only accounting for the detected meltwater on the ice shelf (excluding the meltwater on grounded ice).

L131: *“During the study period, extensive supraglacial lake extents were detected, with a total surface maximum extent of 150 km² for 2016-2017, 213 km² for 2018-2019, 215 km² for 2019-2020, and 152 km² for 2020-2021.”*

• L120: Consider adding a seasonal map figure (similar to Figure 1) for each melt season to help the reader visualize interannual variability.

We have added a figure of the extent of all years to the appendix:



•L135: *Since NeRD does not directly detect individual crevasses, I suggest rephrasing to match your rebuttal letter: e.g., “the damage maps represent the likely presence of large fractures (>100 m) within a 300 m region.” Please also add that the algorithm is more sensitive to surface crevasses, as evidenced by the low damage signal in the shelf interior where basal fracturing is expected.*

We’ve clarified these two points in the manuscript, where the NeRD method is introduced: L98: *“By using the NeRD method, we detect features at the ice shelf surface only – all visible crevasses, fractures and rifts – and group these under the umbrella term ‘damage’, distinguishing from the damage parameter commonly used in continuum mechanics literature (Sun et al., 2017). Basal crevasses are not explicitly included, but might be detected if their concurrent surface depression is distinct. The damage maps represent the presence of large features (roughly >100 m) within the 300 m range, rather than the delineation of the feature itself.”*

• L140: *The classification of damage into “low/medium/high” is based on the data distribution rather than physically interpretable thresholds. While I understand the need to emphasize the minority high-damage pixels, this makes the classes relative to the Shackleton Ice Shelf dataset and not absolute. To be clear, what is categorized as “high damage” here may not represent high damage elsewhere. This raises two concerns: (i) whether interpreting drainage events as occurring in “high damage” areas may be biased, since the thresholds are not physically defined, and (ii) whether results are transferable to other ice shelves without rescaling or re-normalization. Could the authors clarify explicitly that these categories are relative, not absolute, and discuss how this affects the physical interpretation of lake drainage processes?*

We understand these concerns, and refer to our response at the general comments. We’ve clarified in the manuscript that these classes are relative to Shackleton. Nevertheless, compared to damage maps in the Amundsen Sea Embayment (Izeboud and Lhermitte, 2023), the range of initial detected damage values is similar. Furthermore, we have defined that these bins are chosen to favour the ‘minority class’ and not to imply physical differences. The high damage signals will always be in the minority class, so even though the exact distributions might differ, we do not expect fundamental changes in results. But, naturally, they should be assessed with care when transferring this method to other ice shelves.

• L144: *The statement “lake drainages predominantly occur in areas classified as medium to highly damaged” is partly a result of the statistical classification rather than a physically meaningful threshold. Please clarify this.* Agreed and implemented by adding “relatively”, as discussed under the earlier comment.

• L208: *Similarly, the link between drainage and “high damage” is again an artifact of the classification scheme. Please emphasize this limitation.*

Agreed and implemented by adding “relatively”, as discussed under the earlier comment.

• L225: *If lake drainages coincide with the ascending tidal phase (when surface crevasses are expected to close), this would imply basal crevasses may play a key role. Could the authors explain in more detail how basal opening could trigger surface lake drainage?*

Yes indeed, it implies that basal crevassing plays a key role. During the ascending tidal phase, tensile stress at the base of the ice shelf promotes the opening of basal crevasses, which may connect to surface crevasses or the base of a lake, facilitating lake drainage. This is in essence the same process for surface fractures. Unfortunately, the reason why drainages would then occur more frequently for basal crevasse opening than surface crevasse opening cannot be inferred from our results as we do not distinguish basal crevasses explicitly, nor are we with certainty detecting purely surface crevasses. The NeRD method picks up on some basal crevasses due to the clear localised surface depression (Izeboud and Lhermitte, 2023). Therefore, we think other methods would be more suited to study this in more detail.

We have added this in the discussion, L246: *“During the ascending tidal phase, tensile stresses at the base of the ice shelf promote the opening of basal crevasses, which facilitates water drainage when the base of the lake or a surface crevasse is reached. However, with the NeRD framework, we are not able to distinguish basal from surface crevasses to further study this process, and so cannot determine why basal crevasse opening would be more favorable to facilitate lake drainages. In line with this, future work should target and constrain the role of basal fracturing in lake formation and meltwater drainage”*

- L230: *Please expand the discussion of NeRD limitations based on your response to previous comments. Specifically, you said that NeRD provides regional likelihoods of fracture occurrence, not delineation of individual crevasses and the method is more sensitive to surface features, missing basal fractures. Would more classical segmentation approaches (e.g., Surawy-Stepney et al., 2024) improve crevasse mapping? Since basal crevassing is suggested as a trigger, future work might target methods explicitly designed to map basal features.*

We appreciate the reviewer's suggestion to expand on the limitations of the NeRD method. We note that segmentation approaches, such as Surawy-Stepney et al. (2023), would not overcome the limitations completely. They do delineate individual fractures, but they likewise rely on surface imagery and therefore remain insensitive to basal features.

We have added the following to the discussion: L256 *"To study individual drainage events in high detail, other fracture detection methods are advised, such as segmentation approaches (Surawy-Stepney et al., 2023, e.g.,) that can delineate individual features, or ground-penetrating radar observations to include basal crevasses."*