Reviewer 1

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 Comments:

An important point to clarify is the definition of damage. Initially, damage is defined in modeling as a variable of the enhancement factor, which modulates the ice's fluidity. This modeling variable is defined between 0 and 1 and can be adjusted to best fit the observed ice flow. Here, the authors completely recalculate this damage variable from satellite observations, independently of a model or flow velocities. It is not entirely clear how these products could be directly used in a flow model. Some studies have suggested that the crevasses derived by NerD do not match the damage modeled in an ice flow model (Gerli et al., 2024). Therefore, to avoid confusion between the terminology used by modelers and that of this paper, I suggest using the term "satellite-derived damage" or something similar throughout the manuscript.

Indeed, as the reviewer states, our use of 'damage' is different from the definition in damage mechanics models. It is also not a parameterisation that can directly be used in flow models since there is no quantified translation from damage signal to fracture depth (as is explained in Izeboud and Lhermitte (2023)). We will more explicitly define 'damage' in the manuscript as 'visible features of damage at the ice shelf surface' as an umbrella for crevasses, rifts and fractures.

We also appreciate the suggested term, and will adjust the manuscript to use 'satellite-derived damage' or "damage signal" when discussing our observations.

Regarding the calculation of damage, why didn't the authors use the same optical images as for lake detection? It seems that NerD also works with this type of image. The paper lacks details on the time coverage of Sentinel-1 vs. Sentinel-2 images. Do the dates align perfectly? What is the time delay? There are also unclear areas regarding damage calculation: only one map is presented —is it a mosaic? Over what period was it calculated? Why don't the authors present a time series of damage alongside the time series of lake drainage? This would better specify the exact timing of events, particularly concerning tidal cycles: for instance, does damage increase with tides? Does this increase precede drainage events?

While NeRD is compatible with both optical and radar imagery, we opted for Sentinel-1 radar data for damage detection. This choice was driven by the fact that optical images, including those from Sentinel-2, are affected by cloud cover, limiting their usability for consistent monitoring. In contrast, Sentinel-1 provides reliable coverage over short time periods, ensuring a more complete dataset for our analysis.

Regarding the damage map, we acknowledge that our methods section could have been more explicit. We created a single damage map by selecting individual Sentinel-1 images from September to November of each year that cover the Shackleton Ice Shelf. Each image was processed using NeRD, and we calculated the median damage value from the image stack. However, due to variations in satellite coverage, not all areas of the ice shelf were imaged with the same frequency.

The time period for damage assessment does not specifically overlap with the lake drainage events. This is because NeRD detects linear features based on grayscale contrasts and is sensitive to edges between water and snow. To minimize potential interference from surface meltwater, we used images from before the melt season, which also reinforces the use of Sentinel-1 over Sentinel-2 for this purpose.

In terms of damage characterization, NeRD is designed to detect large-scale damage features (>100 m) and assess the spatial extent and growth of damaged areas. However, it is not suited for tracking fine-scale crevasse development or deepening. While investigating potential correlations between crevasse changes, tidal phases, and drainage events would be highly valuable, it is not feasible given the resolution and capabilities of our current dataset.
To enhance transparency and provide additional insights, we will include damage maps for each season in the supplementary materials. We hope these additions, along with the clarifications above, address your concerns.

A second point concerns the features detectable via the NerD algorithm. Looking at Figure 1A, it seems the algorithm effectively detects dislocation zones with wide surface crevasses, as observed near Denman's grounding line or north of Denman Ice Shelf. However, examination of a Landsat image (see below) reveals that almost the entire Denman Ice Shelf is heavily fractured by basal crevasses, unlike the Shackleton Ice Shelf. Yet, damage maps show very similar low damage values, suggesting an underestimation of basal fracturing. Given this limitation, I think the interpretation of results should be revisited, and this should be mentioned in the discussion, specifically in the sense that ice shelf can still be damaged from below, if it is not detected by your method. Additionally, a significant portion of the Denman Ice Shelf's front appears to be detached from Shackleton, more so than shown in Figures 1 and 2. Thus, some of the damage signal may no longer belong to the ice shelf and could merely represent calving icebergs. Analyzing lake evolution in this sector is therefore limited. The Shackleton Ice Shelf's frontal boundaries are also ambiguous (see image below), with a border region between sea ice and mixed ice that could bias the damage analysis. How are you dealing with these regions?

We acknowledge the limitation that NeRD tends to underestimate basal fracturing, as basal crevasses are often represented as low damage values or may not be detected at all. We will explicitly clarify this in the discussion to ensure a more nuanced interpretation of the results, emphasizing that ice shelves can still experience significant damage from below, even if it is not captured by our method.

Regarding the Denman Ice Shelf front, we appreciate this important consideration. The damage maps were clipped to ice shelf fronts that were manually delineated based on Sentinel-1 observations from September to November. However, the impact of any inaccuracies in the ice shelf front positioning is limited due to the following factors:
(a) The velocity maps were masked more strictly than the damage maps, effectively removing the outermost portion of the Denman ice front, as seen in Figure 2.
(b) Only one drainage event (event F) was identified in that region, and all detected drainage events were manually verified to exclude false positives.
We also recognize the ambiguity in the Shackleton Ice Shelf's frontal boundaries and the potential influence of mixed sea ice in these regions. We will clarify how these areas were handled in our analysis and ensure that any potential biases in the damage assessment are acknowledged.
We appreciate your detailed feedback and will incorporate these points into the revised manuscript.

L200-215: How does the coarser resolution affect your interpretation? Drainage is a highly localized phenomenon. When downsampling, you might "leak" damage values located far from drainage events, especially with a factor of 10. Why was a factor of 10 used? Were smaller downsampling values tested unsuccessfully? If so, this could indicate that the correlation between damage and lake drainage events is not as strong as suggested, and tuning the data by downsampling may not be the correct approach? Furthermore, most figures shown in this paper are very general and synthetic, for the sake of the "brief communication" format. This significantly limits the analysis of results. For example, it is important to include a zoomed-in or more detailed figure focusing on a lake drainage event that clearly shows the relationship with damage/crevassed regions (or a new panel of Fig 2). Similarly, it would be important to include a Sentinel-1 image with the retrieved damage (at least in an appendix) and the visually observed fracturing. I am unsure of the best solution: either move the paper to the regular format of The Cryosphere or add one or two figures to the appendix.

We will add a zoomed-in figure of a lake drainage event and its relationship with damage/crevassed regions, either as an additional panel in Figure 2 or as a supplementary figure. Additionally, a Sentinel-1 image with the retrieved damage and visually observed fracturing will be included in the supplementary material.

Regarding downsampling, NeRD detects broader damaged areas rather than individual crevasses, meaning even at 300 m resolution, the damage maps do not pinpoint exact crevasse locations. We hypothesize that overall ice weakness, rather than specific crevasse presence, is the key factor influencing lake drainage. The activeness parameter is designed to capture this broader structural weakness.
We tested different downsampling approaches and found that correlating lake drainages with damage remains difficult due to the widespread nature of damage and the limited number of observed drainage events. This challenge persists regardless of resolution, indicating that while a relationship likely exists, it is not strongly defined.

Concerning the tidal analysis, the authors argue that drainage events always occur during the ascending phase of tides. Looking at Figure 3, I would argue this is a bit of a stretch. Indeed, 6/11 drainage events in 2019 (more than half) started during the lowest (or even descending) phase of the tidal cycle (drainages M, L, F, H, J, E). The same applies to 2020, which saw only one drainage event. This does not undermine the paper's conclusions, as it remains plausible that changes in stress on the ice shelf with tidal cycle, and thus damage, favour these drainage events. For example, could the authors argue that the descending phase of the tidal cycle might be even more prone to crevasse opening due to flexure, whereas the ascending phase might favor crevasse closure?

We understand the concern. We would like to clarify that indeed drainage events M, E and K 'start' in the descending phase (3/13) and 4/13 in the lowest phase. However, with this, it is important to realise that the drainage events shown in figure 3 occur between the detected dates t1 and t2, since we only detect 'lake is present' at t1 and 'lake has drained' at t2 – it is not a draining that starts at t1 and ends at t3. Therefore, Figure 3 does (in our opinion) clearly suggest that drainage does not occur in the descending phase (even though, indeed, crevasse might be more prone to opening in that phase!). We do acknowledge that we cannot differentiate if the drainage occurs in the lowest part of the cycle or the ascending part, so will adjust the text accordingly.

Specific Comments:

L46: Does lake advection with ice flow affect your mosaic calculation in any way?

No, this effect is negligible. The mosaics are calculated on a very short period of time (8-10 days) and thus the only area where advection would be significant is at the fast flowing Denman Glacier (max speeds of ~1500 m/yr (Miles et al. 2020[1]), ~4.6 m/day, just enough to have 1 pixel of advection in the 30 m Sentinel-2 images in the selected period) -- ice flow speed quickly drops to <= 500 m/year to the sides of the ice

[1] https://doi.org/10.5194/tc-15-663-2021

tongue. Moreover, in this short period of time the amount of repeat satellite overpasses is very limited, and we get just the minimum amount of image to stitch them together for a domain-covering mosaic, thus having almost no impact of advection on the mosaic calculation). We'll include a supplementary figure in the next manuscript to show the overlap of the used satellite images to construct each mosaic.

L65: Can you justify the choice of 80% loss of area?

This is in line with other literature, following Doyle et al.(2013), Fitzpatrick et al. (2014), Miles et al. (2017), Williamson et al. (2017). These references will be specified in the text.

- *Doyle, S. H., Hubbard, A. L., Dow, C. F., Jones, G. A., Fitzpatrick, A., Gusmeroli, A., Kulessa, 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*

L67-70: Can you justify the threshold choices? Why 54,000 m²? Why a median lake depth greater than 0.65 m?

Similarly as previous comment, these threshold choices for lake area and depth were based on previous studies that utilized similar criteria to define lakes of significant size and impact.Specifically, an area of 54,000 m² was chosen as it corresponds to 60 pixels in Landsat 8 imagery, providing sufficient resolution to capture lake characteristics. This area threshold is consistent with previous research (Williamson et al. (2018a), which considered lakes of this size to be relevant in terms of water volume and potential impact on ice shelves.*Williamson, A. G.; Banwell, A. F.; Willis, I. C.; Arnold, N. S. Dual-Satellite (Sentinel-2 and Landsat 8) Remote Sensing of Supraglacial Lakes in Greenland. The Cryosphere* ***2018****, 12 (9), 3045–3065. https://doi.org/10.5194/tc-12-3045-2018 a.*

Regarding the median lake depth threshold of 0.65 m, this value was selected to filter out large but shallow areas that do not have a well-defined depth profile. The standard deviation of 0.3 m helps ensure that only lakes with substantial depth variations are included. These values are comparable to those used in other studies, such as those by Williamson et al. (2018b) on supraglacial lakes in Greenland.

Williamson, A. G.; Willis, I. C.; Arnold, N. S.; Banwell, A. F. Controls on Rapid Supraglacial Lake Drainage in West Greenland: An Exploratory Data Analysis Approach. Journal of Glaciology ***2018****, 64 (244), 208–226. https://doi.org/10.1017/jog.2018.8 b*

L84: Why don't you consider rifting? Rifts could also be an important source of lake drainage.

We acknowledge that rifts can indeed be a source of meltwater drainage.

However, rifts typically form towards the front of the ice shelf and (by definition) extend through the entire thickness of the ice, which makes (nearby) water accumulation less likely. Instead, rifts are primarily locations of severe damage where water is more likely to run off directly rather than accumulate and form lakes. This aligns with our conclusions that while rifts can contribute to drainage, they are not conducive to lake formation. Nevertheless, indeed the widening or propagation of existing rifts could lead to lake drainages. This process, however, is not captured by the produced damage maps, since the NeRD algorithm does not detect individual fracture features.

Although distinguishing between rifts and crevasses can be challenging, our focus remains on understanding the broader dynamics of damage and its impact on lake drainage, without specifically isolating rifts as a separate category.

L115: Same as before, better justify the threshold used to classify damage.

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.

L127: If the activeness value mainly reflects shearing, why not directly use shear strain rates? What is the added value of activeness?

While shear strain rates provide valuable information about the stress environment within an ice shelf, they do not capture the behaviour of observed damage features. Damage development (crevasse or fracture opening) is strongly linked to strain rates, but they advect and rotate with the ice as well. As a result, observed damage features might be found in areas downstream of where they formed, and might have become 'passive'. The activeness parameter is aimed to account for this, using the observed orientation (angle with respect to flow) to infer if the detected features are in a position that favors crevasse opening.

We will add a clarification in the text where the activeness parameter is introduced:

As detected damage features might have advected downstream of the area where they formed, we infer a measure of local 'activeness' of the features. The obtained damage orientation is used to identify areas with a likelihood of active damage development, by comparing the damage orientation to local ice flow angle to infer if the feature is in a position that favors crevasse opening

L137: What do you mean by "more pronounced"?

To clarify the term "more pronounced," we are referring to regions within glacier zones where ice flow velocities are particularly high. These areas are predominantly influenced by the strain and shear forces generated by the flowing ice. This dynamic environment is characterized by significant stress from adjacent slower-moving or stationary ice masses, which enhances the activeness of these regions.

New sentence. This pattern occurs where the moving ice experiences shear stress from adjacent slower-moving or stationary ice masses, leading to mix-mode crevasse opening (Colgan et al. 2016). Glacier zones, where ice flow is most pronounced, serve as the clearest examples of areas exhibiting high activeness Glacier zones, characterized by high ice flow velocities, serve as the most illustrative examples of areas exhibiting high activeness.

L150-155: Can you clarify how you can have low damage but high activeness?
In essence, high activeness indicates the potential for further damage development due to the local stress environment, while low damage simply reflects the current state of structural integrity. You can find small yet opening crevasses as well as large but stationary rifts. This distinction highlights that activeness is more about the dynamics and stress patterns in the ice shelf rather than the extent of existing damage.

L195: Do we really need more data and satellites? With Sentinel-2 providing data every 5 days, Sentinel-1 every 6–12 days, and Landsat-8-9 every 15 days, what is your temporal sampling of drainage events when combining these data? What is the finest temporal scale you could achieve?
The reviewer makes a good point, as more is not always better, and we might instead focus on a smarter use of the data that is available. In any case, hydrofracturing or rapid lake drainages occur on very short time scales (some even under 24 h) and being able to sample with an interval of 2 to 6 days would greatly benefit studying hydrofracturing processes. In our case, we utilized mosaics with a period of 8 to 10 days, which represents the finest possible temporal resolution we could achieve due to the relatively high cloud coverage during the Antarctic summer. For other regions with less cloud cover a finer temporal resolution can probably already be achieved, or by integrating radar (Sentinel-1) in the detection approach: e.g. in West Greenland, Miles et al. (2017) achieved a 3 day interval by combining Sentinel-1 and Landsat-8.

We'll adjust the text to give more context: "..., rapid filling and drainage events that occur entirely between image acquisitions may go undetected completely; cloud cover and other atmospheric disturbances can obscure satellite imagery and potentially mask drainage events that occur on timescales of 2-6 days (Miles et al., 2017). The limitation of using 8-10 day mosaics underscores the need for higher temporal resolution in satellite data or the integration of complementary observational methods to accurately identify and attribute rapid drainage events and hydrofracture mechanisms."

Fig1: Meltwater extent appears highly correlated with Denman's shear margins. Has any analysis been conducted in this regard?
Figure 1 displays the extent of meltwater lakes, which is different than the total meltwater extent on the ice shelf. On the Shackleton ice shelf it is not uncommon that the whole domain experiences melt at some point in season (see also De Roda Husman et al., 2024 and Saunderson et al., 2022). The meltwater lakes accumulate in areas depending on surface topography, firn air content and the amount of melt, and it is not strange to see this in the shear margins (i.e. lots of available surface depressions for water accumulation due to ice deformation). Our observations are consistent with the observed lakes by Arthur et al. (2020) on the eastern half of the Denman glacier, included below for clarity.

- *de Roda Husman, S., Lhermitte, S., Bolibar, J., Izeboud, M., Hu, Z., Shukla, S., van der Meer, M., Long, D., and Wouters, B.: A high-resolution record of surface melt on Antarctic ice shelves using multi-source remote sensing data and deep learning, Remote Sensing of Environment, 301, 113 950, https://doi.org/https://doi.org/10.1016/j.rse.2023.113950, 2024.*
- *Saunderson, D., Mackintosh, A., McCormack, F., Jones, R. S., and Picard, G.: Surface melt on the Shackleton Ice Shelf, East Antarctica (2003–2021), The Cryosphere, 16, 4553–4569, https://doi.org/10.5194/tc-16-4553-2022, 2022*

- *Arthur, J. F., Stokes, C. R., Jamieson, S. S. R., Carr, J. R., and Leeson, A. A.: Distribution and Seasonal Evolution of Supraglacial Lakes on* Shackleton Ice Shelf, East Antarctica, The Cryosphere, 14, 4103–4120, https://doi.org/10.5194/tc-14-4103-2020, 2020

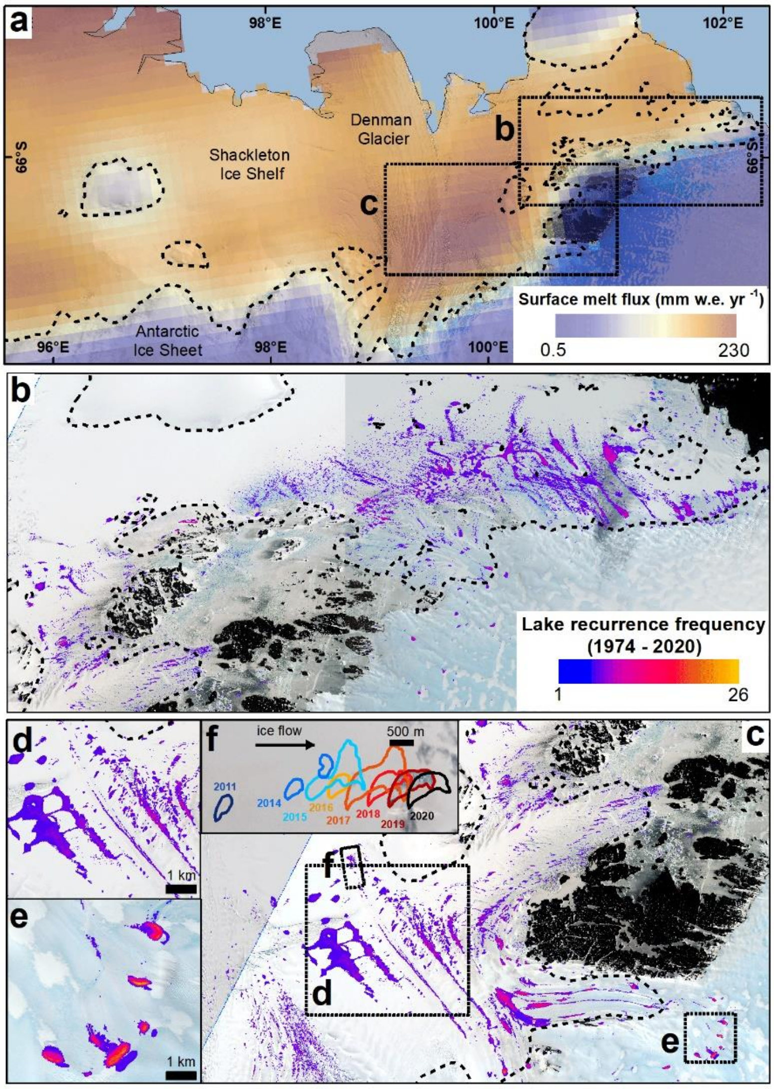

Figure from Arthur et al. (2020) of detected surface meltwater lakes on a subset area of the Shackleton Ice Shelf.

Fig2: What do you mean by pixel quality? Be more specific. This figure also needs a close-up on an actual drainage event, showing the related fracturing observed in the raw data (see earlier comment).
We will rephrase the 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).

And indeed, we will provide close ups of the drainage events. An example is shown below. The figure below shows the S2 timeseries of a detected lake (E as in figure 2) that is detected to be draining between 2020-01-30 and 2020-02-13. We will also add S1 and L8 in supplementary, based on which we have narrowed down the draining window.

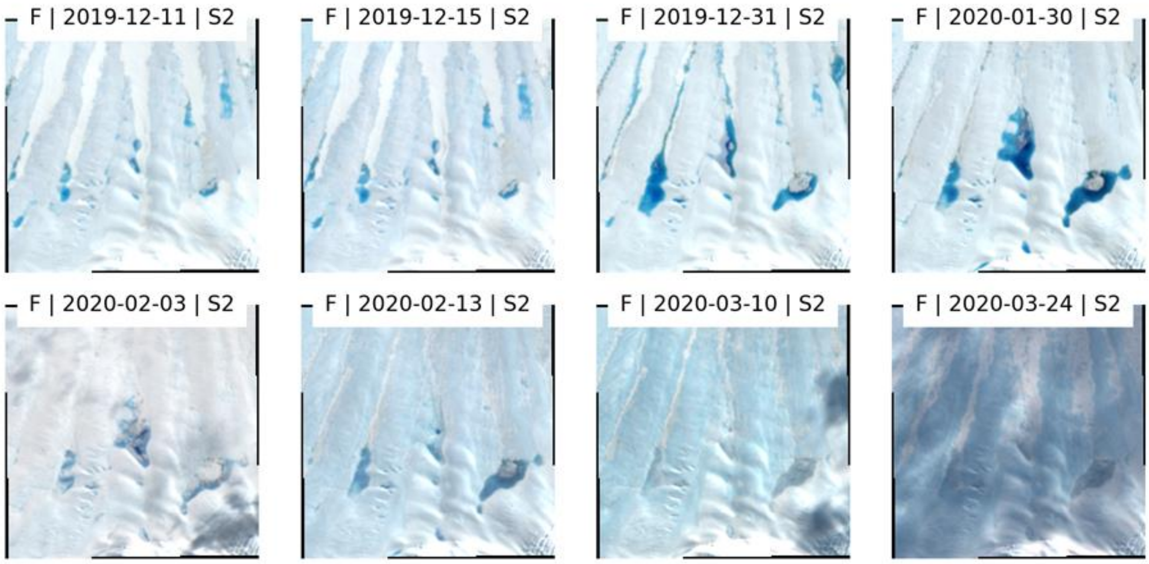

Fig3: Include damage evolution with the tidal cycle (see earlier comment).

Thank you, we do agree that studying the damage evolution with the tidal movement would be a valuable addition. As also stated in the earlier comment, it is not straightforward to include the desired damage evolution from NeRD in this way. To mitigate potential misinterpretation of meltwater as damage by NeRD, we have assessed damage before each melt season (in September). Moreover, given Nerd's nature of utilizing a 10-pixel window size and subsequent loss of spatial resolution, it is questionable whether NeRD is the appropriate tool for finding meaningful temporal changes in damage with a temporal resolution that matches tidal movements. Instead, NeRD is better suited for investigating damage patterns.