

## Reviewer 1 revisions

### General comments

This manuscript presents a novel winter supraglacial lake drainage detection methodology using a combination of two SAR data sources. This advanced methodology normalizes for differences in acquisition geometry and satellite missions, allowing for a cohesive output with a high temporal resolution. A thorough literature review was conducted and presented in a logical manner, relating the works of other groups effectively to the topic analyzed in this manuscript. The methodology seems well thought-out and incorporates many data sources and processing chains to provide meaningful context to the drainages, in particular the volume estimation using ArcticDEM strips, subglacial water pathways mapping, and the integration of ASCAT data for surface melt estimation. The results are overall well presented and the integration of the summer drainage dataset with their winter dataset provides a novel insight into how the drainage behaviors in each season influence each other. The writing style is elevated yet easy to read; however, some restructuring and concision is needed for the final discussion sections and conclusion. Overall, I find this manuscript to be of a high quality in both methodology and presentation, with some minor work needed to clarify the details of some processes and bring the work to a succinct conclusion.

### Specific comments

**L16:** "...exhibiting substantial interannual variability, *ranging from* a maximum..."

This was included in the revised manuscript.

**L54:** Adjust the phrase "ice layers" to more clearly reference upper ice layers

Phrasing was updated to make it clear we were referring to the upper ice layers.

**L70:** There are several instances of the British spelling of some words being used, while the majority of the manuscript is written with American English spelling. Please adjust the spellings so that they are consistent (specific examples include behaviour, analysed, favourable).

The manuscript was reviewed and made to be consistent with British spelling.

**L104-109:** An important fact about 79NG is that it has an extensive floating tongue. This fact should be mentioned in this paragraph and related to the study area you define in Fig. 1 (mentioning the fact that lakes that form on the floating tongue are not analyzed). The terminology used to describe your study area must also be changed to reflect the difference between the terminus and the grounding line. There are several instances throughout the manuscript where 79NG's terminus is referenced but the grounding line is meant – these two are not interchangeable for a glacier with a floating tongue and could lead to confusion by the reader.

We noted that 79NG has a floating tongue and that lakes on it were not included in the analysis. Instances of saying "terminus" in regard to 79NG were changed to grounding line.

**L109:** I believe where Fig. 2.1 is mentioned, you are actually referring to Fig. 1b.

This error was corrected.

**Figure 2:** I would consider adding a legend to the figure to describe the red and yellow polygons. Additionally, the distance scale could be shortened as it really only needs to be up to 3km long since the image subsets are roughly 4 x 4 km.

A legend was added for the red and yellow polygons and the scale bar size was adjusted.

**L214-215:** The flow of this sentence could be improved for ease of understanding. Rephrasing the sentence so that the main clause (“we applied...”) starts the sentence with the rest of the information following could help. Putting some of the information into a second sentence would help as well.

The flow was improved and changed to: “We applied a multi-slope normalisation method to account for the influence of surface geophysical changes on regression-modelled incidence angle–backscatter relationships before and after drainage events.”

**L231:** You could add some information about how the threshold was defined as four times the monthly median absolute deviation.

Details were added on how arrived at a threshold of 4 MAD.

**L278:** This paragraph starts similarly to the last one (place context and provide context). Rephrase one of them to help it sound less repetitive.

To address this, we rephrased the opening sentence of both the paragraphs to read:

“Subglacial hydraulic potential gradients and associated flow routing were calculated to situate winter lake drainage observations within the framework of potential subglacial meltwater pathways.”

And

“Daily ASCAT C-band normalised radar backscatter ( $\sigma^0$ ) data were used to characterise the intensity and spatial extent of surface melt during each melt season across the 79NG and ZI basins.”

**L278:** Make the distinction of surface melt and supraglacial lakes clearer. Describe what exactly is meant by surface melt (i.e., wetness of the entire surface vs. the pooling of meltwater into lakes).

This was clarified in the revised version by stating:

“Here, surface melt refers to the presence of near-surface liquid water expressed as wet snow or a wetted ice surface across the broader glacier surface, rather than meltwater ponding within supraglacial lakes”

**L278:** I believe this is the first mention of the ASCAT C-band data. Either give the description of the acronym or briefly summarize what this data is. Also include a citation/website reference for the data.

We provided the description of the acronym.

**L287-289:** Here, it is not extremely clear what the annual melt index consists of. It sounds like you are just adding up the total melt area. Is the melt intensity involved in this index? If it is just the sum of the area, how is that different than what is described in the next sentence?

We edited the sentences where melt index and intensity are described.

**L298:** I would add "...90 winter lake drainage events" to make it clear this is not including summer drainages. Even though you say "between the 2014/2015 and 2023/2024 winter seasons", it could be interpreted that the entire years between those two seasons are included.

Agreed. We will include this in the revised version.

**L322:** One of the instances of saying "terminus of 79NG" that is incorrect. These lakes are near the grounding line, whereas the terminus is the edge of the floating tongue. The use of terminus with ZI is correct, since it lost its floating tongue, resulting in the terminus being roughly along the grounding line.

Terminology was changed to use "grounding line" for ZI and 79NG to avoid confusion.

**L322-324:** I would be curious to know if the lakes fully drained both times. Or did they partially drain the first time and then finish the drainage months later? If you're able to tell that from your data, that could be interesting to include.

No edits were made as they were not addressed by our methodology or study scope.

**L326-327:** Clarify if that means that each pixel depth across all lakes was averaged together or if the maximum or average depth of each lake was calculated and then averaged over all lakes.

No edits were made. We refer to our original response:

"We think this is clear as we make no mention of maximum depth and refer only to mean depths. Whether we take the mean of all pixel depths across all lakes, or whether we take the mean depths of each lake and then take the mean of those, the result will be the same."

**L339:** Just wanted to comment that this is a very nice display of a lot data in one figure!

**Figure 5:** Make sure the cube in km<sup>3</sup> is raised instead of using a ^ symbol.

This was corrected.

**Figure 7:** I don't find the second subfigure (b) to be the easiest to draw information from. Consider if there is a better way to display this information. However, if you keep it as is, move the numbers to the side of the circle in cases where the circle is the same size or smaller than the number (i.e., 1, 2 and 3), to improve readability of the numbers.

We chose to keep the figure. We moved the numbers and changed the colour of the circles to improve readability of the numbers.

**L405:** I would add "... for individual lakes *over all seven years*" to make the total amount of possible drainages clearer.

This was included.

**L442:** Perhaps you could add more information about how the lakes are subglacially connected. Are they all along the major meltwater channel? Are some on smaller branched leading to the main channel?

Details were added in regard to whether lakes were located along tributaries or the main channel.

**L444-459:** For Events 2-6, there is no mention on the hydrological connections of the lake clusters. Looking at the map, it does not seem that they are always connected on descending channels. Some details to that would be nice to have described here.

Details on hydrologic connections were added for Events 2-6.

**L445:** Make it clear that the numbers in brackets for all following events (e.g. (~740-660m)) are referencing elevation. Upon quick glance, it could be mistaken to be the distance between them or the diameter of the lakes.

We clarified that these numbers were referencing elevation by including m a.s.l.

**L550:** I would make this paragraph part of the previous one.

This edit was included in the revised version.

**L551-552:** Expand on this phrase to fully address why this leads to more drainages in the winter of cool years and not in the summer, when the drainage system is presumably also inefficient.

We expanded on this in the revised version and included an additional reference.

Gjerde, G., Behn, M. D., Stevens, L. A., Das, S. B., and Joughin, I.: Seasonal drainage-system evolution beneath the Greenland Ice Sheet inferred from transient speed-up events, *The Cryosphere*, 19, 6149–6169, <https://doi.org/10.5194/tc-19-6149-2025>, 2025.

**L572:** “...increasing the probability that meltwater reaches the *grounding line, thus driving basal melting.*”

This edit was included in the revised version.

**L575:** Is the Zheng et al. (2023) study also in Northeast Greenland? If so, there could be a better way to combine this sentence with the previous one more fluidly.

This sentence and previous sentence were combined.

**L594-569:** This information feels repetitive to the information at the beginning of the previous paragraph. Condense all of the information together in the previous paragraph.

We did not condense the information with the previous paragraph. We felt that the information is unique. We did change how it was worded to clarify the point being made.

**L604:** “Instead” does not feel like the right transition word here. Perhaps just saying “These near synchronous drainages...” would help it flow better.

This was incorporated.

**L615:** “...pathway *and* are...”

This was fixed.

**L640:** Would it create a better structure for this section to begin the section with this paragraph? This way, the different mechanisms are described clearly first and then can be referenced as you go through the

different event descriptions. You could even label each mechanism as Mechanism 1, Mechanism 2, etc. and to make the description within each event description more concise. The way it is now, the event description paragraphs feel a little repetitive and scrambled.

We agree that moving this paragraph to the beginning of Section 5.2 will improve the overall structure. We will consider labelling the mechanisms to reduce repetitiveness throughout the paragraphs.

**L674-684:** The flow feels a little disconnected in these two paragraphs. I would suggest reordering the sentences to something like this: First L679-682, second L674-678, third L682-684. Bringing L679-682 to the beginning gives more context to what will then be described.

This was done as suggested.

**Section 5.4:** This section needs significant editing/restructuring. The first and last paragraph of this section do not provide new information; instead, they summarize information already presented in the manuscript. The first paragraph gives a nice overview of the novel method developed and implemented in this manuscript. This, however, does not belong in the discussion, but would be a nice addition at the beginning of the conclusion section. Similarly, the last paragraph addresses challenges in the presented methods. This would be more suitable to include near the end of the conclusion section. The remaining two middle paragraphs discuss the use of  $\sigma^{\circ}$ HV35 in 10-year composite imagery. The title of this section should be renamed to more specifically address the discussion of this particular part of the methodology instead of a general overview of overarching methodology of the manuscript.

**Section 5.5:** This section is also in need of restructuring in order to make the focus more precisely on future work. A majority of the sentences are used to summarize your findings or the findings and downfalls of other researchers. Much of this information has already been stated elsewhere in your manuscript and does not need to be repeated here in order to address gaps for future work. My suggestion would be to take out the few lines which describe actionable future work ideas and bring them together in a short paragraph in the conclusion section, eliminating this section entirely. In the first paragraph, this would be L721-722 about extending winter lake drainage investigations to other regions. In the second paragraph, it is the last sentence about data fusion. In the third paragraph, I do not see a clear future research statement. From the fourth paragraph, you could write a sentence about needing better or more specific data to study how winter lake drainages affect ice dynamics and how that can affect the behavior of supraglacial lakes in the melt season. In the last paragraph, you could more or less use the final sentence by exchanging “these measurements” in L751 with “SAR observations with high frequency in situ GPS measurements”.

**Conclusions:** As mentioned in the last two comments, I would exchange the first paragraph here with the first paragraph from section 5.4. Then, I would put the last paragraph from section 5.4 as the second to last paragraph, leading in to the future work sentences pulled from section 5.5. The last paragraph in the conclusions section as it is can be condensed to summarize less. The sentence in L780-782 was already said at the beginning of the section and can be removed. Figure A1 caption: Are the first few words in a different font?

Edits for Section 5.4, 5.5 and the conclusion were done as suggested.

The font for Figure A1 caption was corrected.

## Reviewer 2 revisions

In their TCD manuscript “A decade of winter supraglacial lake drainage across Northeast Greenland using C-band SAR”, Dean et al. present a database of winter supraglacial lake drainage events in Northeast Greenland derived from SAR observations. They combine data from both Sentinel-1 and the Radarsat Constellation Mission, providing a 10-year record of winter lake drainage activity. To improve temporal coverage, the authors apply a normalization approach that enables the joint use of multiple sensors and acquisition geometries. Using this merged dataset, they identify between four and eighteen drainage events per winter.

### General Comments

Overall, the manuscript is very well written, and I enjoyed reading it. The authors successfully integrate multiple datasets and present their interpretations in a clear and well-structured way. I did not identify any fundamental flaws in the methods. However, the velocity analysis could be improved. I suggest calculating velocity anomaly fields relative to a seasonal or annual baseline velocity map. This approach would allow for a more spatially consistent analysis of velocity changes compared to interpreting arbitrarily chosen profiles.

Below, I list some specific comments that should be addressed before publication.

### Specific Comments

#### Abstract

**L18:** Please explain what cascading events are, as not all readers may be familiar with the term.

An explanation of cascading events was included in the abstract.

**L20:** You mention that there are more winter drainages when there are fewer summer drainages. Could this imply that drainage events are largely independent of the season, and instead controlled by a threshold pressure condition?

This was explained in 545-553 of the original manuscript. Details we included in response RC1 for the same section further clarify our explanation.

#### Introduction

**L37:** Although you defined that “lakes” refer to supraglacial lakes earlier (L25), the phrasing reads awkwardly here. Consider using supraglacial lakes and lakes interchangeably throughout.

We revised the definition at L26 to read “Supraglacial lakes – hereafter often referred to simply as lakes – ...” to allow more flexible wording, and we adjusted the sentence around L37 for improved flow.

**L45:** WorldView imagery has a much higher resolution than 10 m, but access is limited, making it less suitable for time series analysis—perhaps better for case studies.

We added details briefly describing the use of very high resolution sensors.

**L58:** Note that Sentinel-1C is now operational.

We rephrased to reflect this.

**L121:** A short paragraph describing seasonal ice dynamics in the study region would improve context.

We added a short paragraph describing the seasonal ice dynamics.

## Methods and Data

**Figure 1:** Please clarify what the sampling points (yellow triangles?) represent. Also, is the 10-year melt season mask derived from Landsat?

The caption was revised to clarify that the yellow sampling points were used for ice velocity sampling, and that the 10-year melt season mask was derived using Landsat.

**L166:** You mention that all data were acquired in HH and HV polarization but only HV was used. Why? Schröder et al. (2020) demonstrated reduced ambiguity when combining HH and HV.

Based on our initial response, we did not make any edits:

Schröder et al. (2020) indeed demonstrated that the inclusion of HH polarization can aid in the detection of supraglacial lakes. However, a primary objective of Schröder et al. (2020) was the mapping of lake area, which differs from the focus of our study. We do not attempt to delineate lake extent but instead analyze backscatter time series to detect lake drainage behaviour. We therefore chose to follow previous studies in which both HH and HV polarizations were available (e.g, Benedek & Willis, 2021; Hossain et al., 2024) and use only HV. In the context of our time-series-based approach, HH is unlikely to provide additional information, whereas HV offers superior penetration and greater sensitivity to volume scattering, making it particularly well suited for detecting winter drainage events. We do not rule out the potential usefulness of HH polarization in future methodological developments like ours, and this remains an interesting avenue for further investigation.

**Figure 2:** Does column 4 show the backscatter mean within the summer lake polygon? Please clarify. It would also help to indicate which SAR satellite (S1 or RCM) is used in panels (ii) and (iii).

We clarified that column four shows backscatter extracted within the mean 10-year landsat derived lake mask. We included the abbreviation of “S1” as Sentinel-1 in the revised Figure 2 caption and note that S1 is already included in the panel titles.

**L204:** Would using the non-terrain-corrected  $\sigma^0$  values change your results?

No edits were made.

**L222:** In Figure 2 (iv), consider including side-by-side imagery from S1 and RCM for the same lake and approximate date, both before and after normalization. This could serve as a clear visual validation of your correction approach.

For the revised version we chose not to incorporate this suggested edit based on our original response:

“In the revised version we will consider including S1 and RCM imagery in the Figure, though this will be challenging as it is already quite large. We are also unsure of how useful including a comparison of both sensors would be as they were never used together in the same time series.”

**L230:** See previous comment.

**L233–L234:** Please elaborate on the cause (e.g., lids?).

We were a bit confused about what was meant by the reviewer. We did include an added sentence to clarify the purpose of the 14-day pre post filter.

**L237:** Please define how the end of a drainage event is determined; this is not obvious from Figure 2 (iv).

In the revised version we clarified how the end of the drainage event is determined.

**L254:** Why was manual delineation required? Couldn't the Landsat lake masks be used here?

An explanation of why manual delineation was used was included in the revised version.

## **Results and Discussion**

**L365–L377:** This section is particularly interesting -- do you have a hypothesis or possible explanation for this observed behavior?

No edits were made as we already discuss it in section 5.1.

**L398:** The statement seems self-evident, since summer drainages are far more numerous than winter ones.

Based on our initial response, no edits were made:

“We disagree with this point. Just because summer drainages are more numerous than winter drainages, a positive correlation between summer drainages and melt index does not necessarily mean there has to be a positive correlation between annual drainage and melt index. A negative correlation with winter drainages could offset it. The observed increase in annual drainage frequency therefore reflects a net seasonal redistribution rather than a trivial consequence of summer dominance.”

**Figures 9 & 10:** These velocity plots are difficult to interpret. I suggest showing relative velocity anomalies compared to monthly or annual baselines. Importantly, note that apparent velocity increases coinciding with lake drainage (e.g., Fig. 10b ii at ~12 km) could reflect vertical displacement rather than

true horizontal acceleration. SAR offset tracking cannot separate vertical and horizontal motion, and these velocity fields are not corrected for vertical effects. See for example Joughin et al. (2016) on this issue.

In the revised version we followed the suggestion to replace the profile based analyses with velocity anomaly maps relative to an annual baseline. Both Figure 9 and 10 were updated. A description of the approach was added to methods 3.6. We also noted potential implication of vertical motion of horizontal ice velocity in offset tracking derived products.

**L600:** The reference to L1C is confusing; please clarify this and adjust the velocity plots accordingly.

This was a typo and was corrected in the revised version.

**L605:** If lake L5B drained first, this event would not qualify as cascading. Please clarify your terminology. You mention “basal uplift” — this may indeed be visible in the velocity fields, but again, vertical motion needs to be treated carefully (see comment above).

Given these issues, I recommend replacing profile-based analyses with velocity anomaly maps relative to an annual baseline. Such maps would better reveal spatial patterns in velocity changes and/or uplift events.

Based on our initial response, we did not make edits in regard to the comment on L5B:

“We disagree that drainage of L5B occurring first would preclude this event from being considered cascading. We use the term “cascading” to describe a chain-reaction drainage sequence, consistent with the framework of Christoffersen et al. (2018), in which drainage events may propagate upstream and/or downstream depending on stress transmission and hydrological routing. See our definition on L85 which, as we state above, we will also add to L8, the first time we refer to cascading events in the Abstract. Accordingly, if an upstream lake (L5A) subsequently drained in response to the drainage of a downstream lake (L5B), we interpret this as a coupled, chain-reaction sequence. Regarding our mention of basal uplift, this is intended as a hypothesis based on interpretation rather than a reference to the velocity fields shown in Figure 10, which, as we mention above, are horizontal velocities.”

**L730–L732:** I fully agree with the statements here and the following paragraph.

Additional Reference

Joughin, I., Shean, D. E., Smith, B. E., & Dutrieux, P. (2016). Grounding line variability and subglacial lake drainage on Pine Island Glacier, Antarctica. *Geophysical Research Letters*, 43, 9093–9102.  
<https://doi.org/10.1002/2016GL070259>