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Title: A basin-scale mapping method for crevasse depth using ICESat-2: a case study on Greenland's Sermeq Kujalleq (Jakobshavn Isbræ)

Response to Reviewer #1:

Thank you very much for your careful review and constructive comments. We greatly appreciate your suggestions, which have helped us improve the clarity and rigor of the manuscript and, importantly, better highlight the methodological originality and novelty of the proposed method. In response, we have carefully addressed all the comments and will revise the manuscript accordingly. Specifically, we clarified the methodological differences between the proposed method and DDA-ice and added direct comparisons at several stages. We also quantitatively evaluated the computational efficiency of the proposed method, added comparisons with existing crevasse depth studies based on OIB lidar and ArcticDEM, revised the discussion on crevasse depth interpretation, and improved the related figures and descriptions. The detailed responses and corresponding revisions are provided below.

Major Comments

1. The research gap identified by the paper is that “efficiently extracting crevasses and estimating their depths from the ATL03 product remains a non-trivial challenge”. There is, however, an established literature of extracting crevasse products from ATL03 data, of which the study identifies a couple (Herzfeld et al 2021; Chang et al 2023). Given this method represents an evolution of the method of Chang et al. (2023), the work of Herzfeld et al. (2021; and the uncited Herzfeld et al. 2017 <https://doi.org/10.1109/TGRS.2016.2617323>) is probably the most important comparator, as the dda-ice algorithm is now established across a number of studies. The implication in this study is that the new method is “automated and rapid” (e.g. L548) and represents a step-change in processing capability that allows it to be applied across a large spatial scale (L100-105). However, given no information is provided about the actual processing times involved, nor how this compares to prior methods, I find that these statements are hard to justify and perhaps unfair to the prior work that has been done in this space. If these statements regarding the efficiency and prior processing limitations were to remain, I think it would be necessary to provide some sort of quantitative evidence regarding the improvement in processing capability

cf. dda-ice. Certainly, given this method exists, it seems a little unusual to compare instead against ATL06 data in section 5.1, as ATL06 is **not** the null alternative given the existence of alternative ATL03 processing techniques. At the very least, the manuscript should spend longer comparing the new method to the dda-ice algorithm (and indeed, there are strong parallels between the two methods), identifying the differences in methodological choices between the two, and potential advantages/disadvantages of each.

Response:

We sincerely thank the reviewer for this important and constructive comment. We agree that the research gap stated in the original manuscript, namely that “efficiently extracting crevasses and estimating their depths from the ATL03 product remains a non-trivial challenge,” was not sufficiently explained in relation to existing ATL03-based crevasse studies, particularly DDA-ice. We also acknowledge that the statements regarding the method being “automated and rapid” required stronger quantitative support. We would also like to clarify that the comparison with ATL06 in the original manuscript was intended to illustrate the limitations of the standard land-ice elevation product for crevasse characterization, thereby highlighting the need for direct processing of ATL03 photon data. At the same time, we agree with the reviewer that a direct comparison with DDA-ice is also necessary to better position the proposed method relative to existing ATL03-based approaches. In response, we have substantially revised this part of the manuscript from three aspects.

(1) Relationship and methodological differences between DDA-ice and the proposed method

We first clarify the relationship between the proposed method and the DDA-ice framework. Previous studies, including Herzfeld et al. (2017), Herzfeld et al. (2021), and Chang et al. (2023), have established important approaches for photon classification, denoising, and surface reconstruction from photon-counting laser altimetry data. Herzfeld et al. (2017) developed and validated the original DDA framework using simulated ICESat-2 data, and Herzfeld et al. (2021) subsequently applied DDA-ice to actual ICESat-2 observations for glacier surface reconstruction and crevasse characterization. Chang et al. (2023) further improved the photon-processing strategy by adopting a different photon density estimation approach, which was designed to better preserve photons associated with complex surface structures. Building on these previous advances, the present study further

introduces a roughness-based candidate crevassed region screening strategy to reduce the amount of ATL03 data requiring detailed processing, thereby improving the efficiency of large-scale analysis. In addition, the method extends the processing from photon denoising and surface reconstruction to the automated extraction of individual crevasses and their geometric attributes, including crevasse location, width, and depth. Therefore, the main methodological developments of the present study lie in the candidate region screening strategy for efficient large-scale processing and the subsequent automated extraction of individual crevasse geometry. We will revise the Introduction accordingly to better describe the relationship between the proposed method and previous ATL03-based approaches and to highlight the methodological developments introduced in this study.

(2) Computational efficiency improved by the roughness-based pre-screening

To support our description of the proposed method as “rapid,” we quantified the computational benefit of the roughness-based pre-screening strategy. In this study, “rapid” refers specifically to the reduction in computational cost achieved by identifying potential crevassed regions before the computationally intensive photon filtering, surface reconstruction, and crevasse extraction steps, thereby reducing the amount of ATL03 data requiring detailed processing and improving the efficiency of large-scale ICESat-2 analysis. We conducted an additional runtime experiment using 18 ICESat-2 ATL03 beams acquired over the SKJI on 12 July 2019 (RGT 0224) and 16 July 2019 (RGT 0277 and RGT 0285), with their spatial distribution shown in Figure R1(a). All experiments were performed under the same computational environment.

Two processing strategies were compared:

1) Roughness-guided workflow (the proposed method):

ATL03 photon data were first evaluated using the proposed roughness index to identify potential crevassed regions. Only the selected high-roughness regions were subsequently processed using the density-based filtering, surface reconstruction, and crevasse-depth extraction procedures.

2) Full-track processing workflow (without roughness screening):

The same downstream processing procedures, including the density-based filtering, surface reconstruction, and crevasse-depth extraction procedures, were directly applied to the complete ATL03 beam, but without roughness-based pre-screening.

The detailed beam comparison is provided in Table R1, and the cumulative processing time comparison is shown in Figure R1 (b). The results demonstrate a substantial reduction in computational cost when roughness-based pre-screening is used. For the 18 tested beams, the full-track processing workflow required 4941.6 s in total, whereas the proposed method with roughness-based pre-screening required only 68.9 s, with an overall speed-up by 71.7 times. The average processing time was reduced from 274.5 s beam⁻¹ to 3.8 s beam⁻¹.

The efficiency improvement is mainly attributed to the removal of photon regions without crevasses by roughness-based pre-screening. For example, the RGT 0277 beams contain extensive non-crevassed regions. After roughness-based pre-screening, only 1.06–5.15% of the original photons were retained for subsequent processing, resulting in a speed-up of 189.5–558.7 times. In contrast, for RGT 0285 beams where a larger proportion of the track corresponds to rough/crevassed surfaces, the retained photon ratios were much higher (52.4–99.1%) and the computational improvement was correspondingly smaller (speed up of 1.0–2.1 times). These results suggest that the computational benefit of roughness-based pre-screening is expected to become increasingly pronounced as the scale of ATL03 track length increases, because extensive non-crevasses regions can be excluded before subsequent steps, including photon denoising, surface reconstruction, and crevasse extraction. Following the reviewer's suggestion, we will add this computational efficiency assessment in the supplementary material.

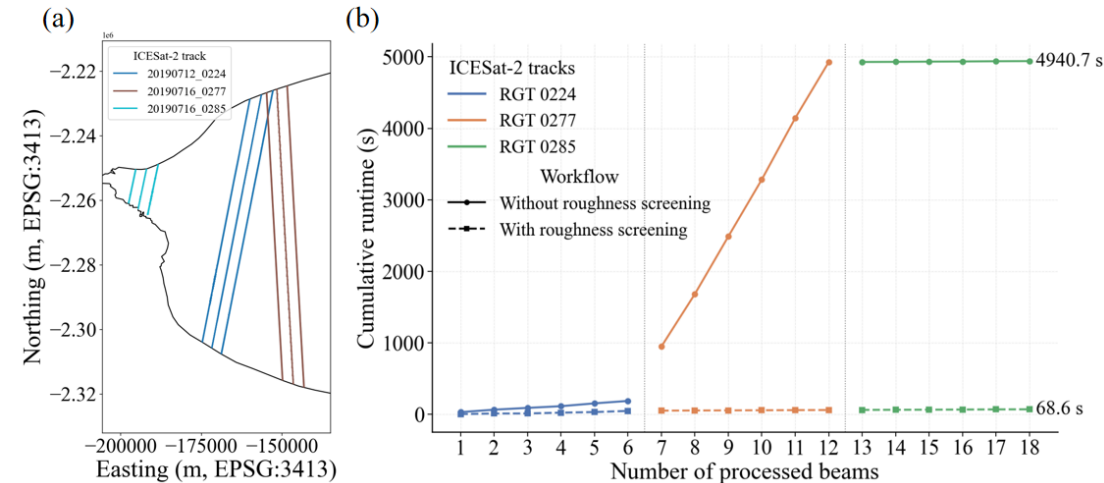


Figure R1. Spatial distribution of tested ICESat-2 data and cumulative runtime comparison with and without roughness-based pre-screening.

127 **Table R1.** Computational efficiency comparison with and without roughness-based pre-screening.

Track	Beam	Raw photons	Retained photons	Retention (%)	runtime without roughness screening (s)	runtime with roughness-based screening (s)	Speed-up (times)
20190712_0224	gt1l	449,500	2,464	0.55	29.30	1.18	24.9
	gt1r	165,642	63,405	38.28	34.23	8.92	3.8
	gt2l	321,773	2,144	0.67	25.05	0.56	44.9
	gt2r	136,440	73,195	53.65	23.99	11.41	2.1
	gt3l	526,383	146,026	27.74	39.32	8.19	4.8
	gt3r	169,719	102,016	60.11	34.13	15.84	2.2
20190716_0277	gt1l	824,407	42,449	5.15	760.25	4.01	189.5
	gt1r	205,114	7,732	3.77	734.57	1.95	376.6
	gt2l	675,047	12,858	1.90	805.06	1.57	512.8
	gt2r	212,408	7,842	3.69	796.39	1.68	474.1
	gt3l	842,380	8,920	1.06	860.37	2.00	430.7
	gt3r	216,063	3,913	1.81	782.48	1.40	558.7
20190716_0285	gt1l	78,817	45,903	58.24	3.28	1.62	2.0
	gt1r	23,701	20,291	85.61	1.93	1.61	1.2
	gt2l	67,177	35,223	52.43	2.93	1.40	2.1
	gt2r	28,851	28,589	99.09	2.09	2.00	1.0
	gt3l	93,731	52,591	56.11	3.41	1.87	1.8
	gt3r	28,818	22,640	78.56	1.95	1.43	1.4

(3) Comparison with DDA-ice

We further conducted a direct comparison with DDA-ice by evaluating photon denoising performance and, for the final crevasse results, coupling the DDA-based reconstruction with the same crevasse extraction procedure used in our method to enable a consistent comparison of individual crevasse extraction, spacing, and depth estimates.

1) Comparison of photon denoising performance

To ensure a direct and reproducible comparison, we selected the same ICESat-2 dataset used by Herzfeld et al. (2021) to demonstrate surface-height determination over the crevassed region of SKJI. Specifically, the comparison used ATL03 granule ATL03_20190511210825_06660305_002_02.h5, acquired along RGT 666 on 11 May 2019, and focused on the gt3l strong beam. As shown in Figure R2 and Table R2, both DDA-ice and the proposed method effectively preserve the dominant glacier surface signals and the bottom signals of most crevasses. Quantitative evaluation shows that the two methods achieve comparable precision values, with DDA-ice and the proposed method reaching precision values of 0.968–0.983 and 0.954–0.974, respectively. However, the proposed method achieves substantially higher recall values (0.855–0.886) compared with DDA-ice (0.508–0.548) across the three test segments. This indicates that, while both methods can effectively suppress noise photons, DDA-ice tends to remove more valid signal photons during denoising, particularly those associated with complex crevasse structures. As highlighted by the red boxes in Figure R2, noticeable differences occur along several steep crevasse walls. The proposed method generally preserves a more continuous distribution of sidewall photons, while DDA-ice shows partial loss or discontinuity of photons along some steeply inclined walls. This difference is mainly associated with the neighborhood configuration used in the photon density estimation. In our method, the orientation of the elliptical neighborhood is adaptively adjusted according to the local distribution direction of the photons, allowing the neighborhood to better follow inclined or near vertical crevasse wall structures. Consequently, photons distributed along these structures receive a higher and more representative local density response and are more likely to be retained during denoising.

The effect of the neighborhood geometry on photon density estimation was examined in greater detail in our previous study (Chang et al., 2023), which is partly used in the denoising step of this study. In particular, Figure 12 in Chang et al., 2023

compared photon densities obtained using horizontal elliptical neighborhoods with different major-axis lengths and a direction adaptive elliptical neighborhood, while Figure 13 in Chang et al., 2023 further compared the proposed weighted-density formulation with DDA-based density estimates. These experiments showed that adapting the neighborhood orientation to the local photon distribution can improve the separation between signal and noise photons, particularly for inclined surface structures. The more continuous preservation of crevasse wall photons observed in the present comparison is therefore consistent with our previous analysis. This direction adaptive neighborhood represents an important methodological difference from the DDA-based density estimation and appears to facilitate more continuous preservation of steep crevasse wall signals in our method.

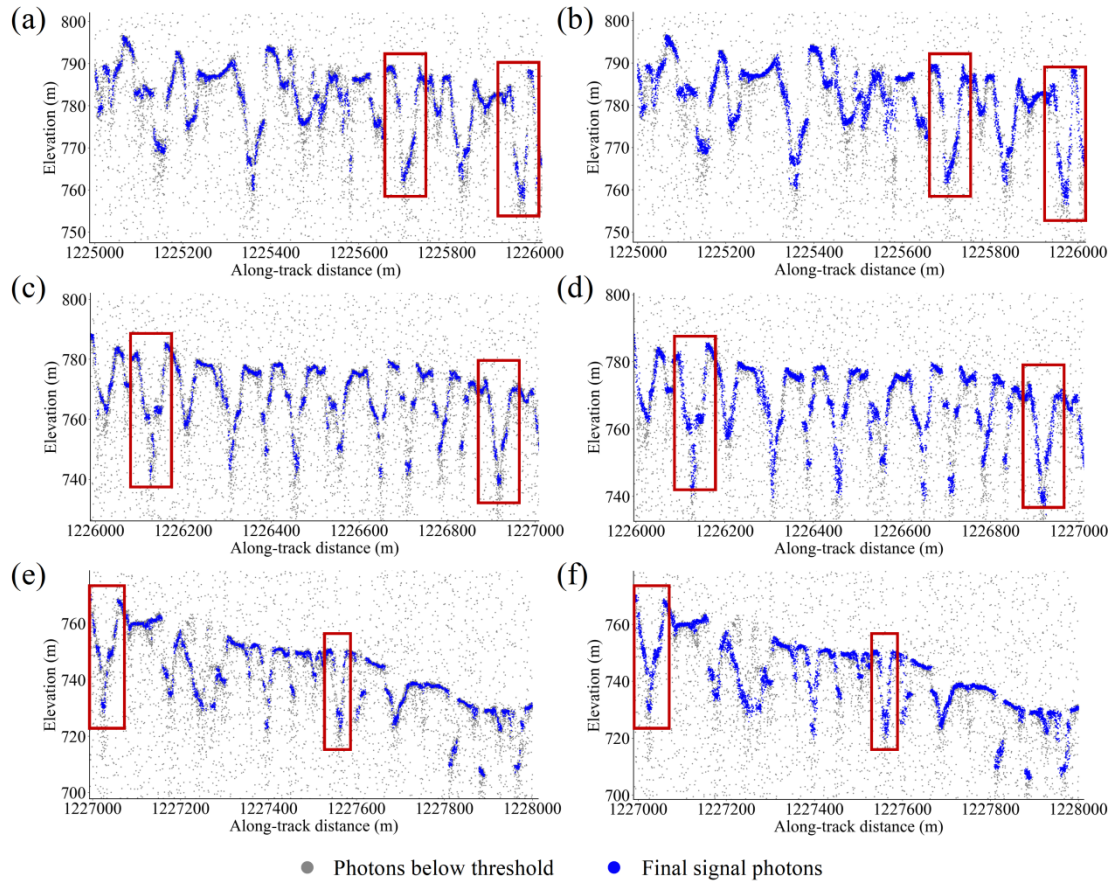


Figure R2. Comparison of photon denoising results between DDA-ice and the proposed method. Panels (a) and (b), (c) and (d), and (e) and (f) present three corresponding examples, where panels (a), (c), and (e) show the denoising results from DDA-ice, and panels (b), (d), and (f) show the corresponding results from the proposed method.

Table R2. Quantitative comparison of photon denoising performance between DDA-ice and the proposed method across three test segments.

Test segment	Method	Precision	Recall	F1-score
Segment 1	DDA-ice	0.976	0.548	0.702
(Figure R2 (a) and (b))	Proposed method	0.964	0.886	0.924
Segment 2	DDA-ice	0.983	0.508	0.670
(Figure R2 (c) and (d))	Proposed method	0.974	0.855	0.911
Segment 3	DDA-ice	0.968	0.519	0.676
(Figure R2 (e) and (f))	Proposed method	0.954	0.884	0.918

2) Comparison of crevasse spacing

We further evaluated the performance of the automated extraction of individual crevasses by comparing the extracted crevasse locations and spacing with the manual measurement results reported by Herzfeld et al. (2021) for the same ICESat-2 segment. In their study, crevasses deeper than 20 m derived from the DDA-ice surface reconstruction were marked along the ICESat-2 track and matched with corresponding crevasse features in a SkySat image. Crevasse spacing was then calculated from these identified features, yielding a mean spacing of 81.37 m from DDA-ice and 81.25 m from SkySat imagery.

Using the same ATL03 segment, our workflow automatically reconstructed the surface profile and extracted individual crevasses without manually specifying their locations. To make the comparison consistent with Herzfeld et al. (2021), the crevasses used for the spacing calculation were selected according to the same correspondence shown in their Figure 8. In particular, the two adjacent depressions highlighted by the yellow box in Figure R3 (b) were treated as a single crevasse feature in the spacing calculation, consistent with the interpretation adopted by Herzfeld et al. (2021). The resulting mean crevasse spacing from our automated extraction was 78.28 m. Although the mean spacing derived from our method is slightly smaller, the overall spacing pattern along the track is consistent with those obtained from DDA-ice and SkySat. Differences in individual spacing values are expected because the identification of a crevasse edge can vary slightly with the reconstructed surface morphology. In addition, as noted by Herzfeld et al. (2021), the

SkySat and ICESat-2 observations were separated by approximately five months, during which glacier flow and crevasse evolution may have altered the positions and geometry of individual features. Therefore, exact agreement in spacing is not expected.

More importantly, this comparison demonstrates that the proposed method can automatically identify individual crevasses and provide their locations and geometric attributes directly from ATL03 photon data. The close agreement in the overall crevasse-spacing pattern with the DDA-ice and SkySat results provides additional support for the reliability of the automated individual-crevasse extraction in our study. This automated extraction step represents a key extension of our method beyond photon denoising and surface reconstruction and enables the generation of individual-crevasse products for subsequent large-scale analysis.

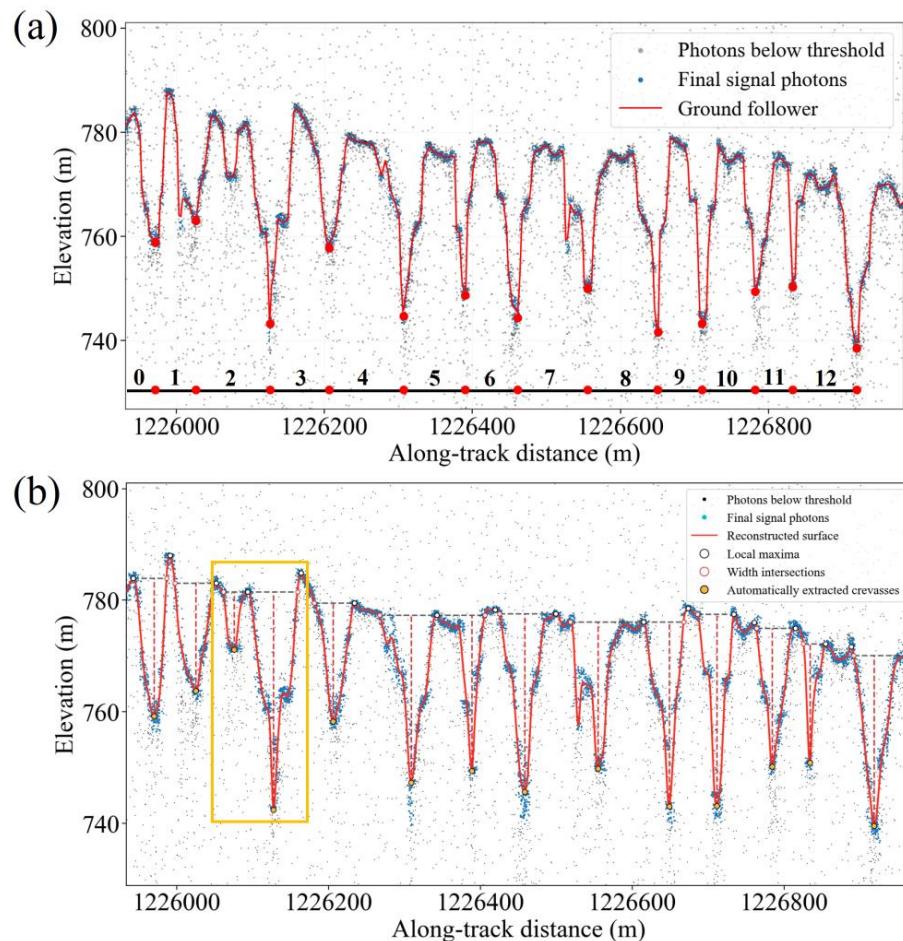


Figure R3. Comparison of crevasse extraction results between the proposed automated method and manually extracted DDA-ice results for the same ICESat-2 segment used in Herzfeld et al. (2021).

Table R3. Jakobshavn Isbræ crevasse spacing estimates from the proposed method, DDA-ice results (manually extracted), and SkySat imagery.

Segment	Ours (m)	DDA-ice (m)	Skysat (m)
1	60.4	59	58
2	109.6	106	108
3	70.7	82	83
4	108.4	106	120
5	81	82	83
6	79.6	76	79
7	98.8	100	100
8	96	94	113
9	61.8	65	71
10	56.3	71	58
11	41.2	53	42
12	75.5	82	58
Mean Spacing	78.28	81.37	81.25

3) Comparison of individual crevasse extraction and depth estimation

To enable a further comparison with DDA-ice at the level of final crevasse extraction results, we coupled the DDA-ice photon processing and ground follower reconstruction with our automated crevasse identification and depth retrieval procedure. These results were then compared with those from our complete workflow for the same ATL03 segment. Figure R4 compares the resulting crevasse extractions from the DDA-ice reconstructed surface and from our reconstructed surface. Both workflows identified the same 14 major crevasses within the selected section, with very similar locations and depth estimates. As summarized in Table R4, the mean crevasse depth was 26.34 m for the DDA-based reconstruction and 26.81 m for our method, corresponding to a mean difference of only 0.47 m. The individual depth differences were generally small, indicating that both surface reconstruction approaches can provide consistent estimates of major crevasse depth when followed by the same extraction procedure.

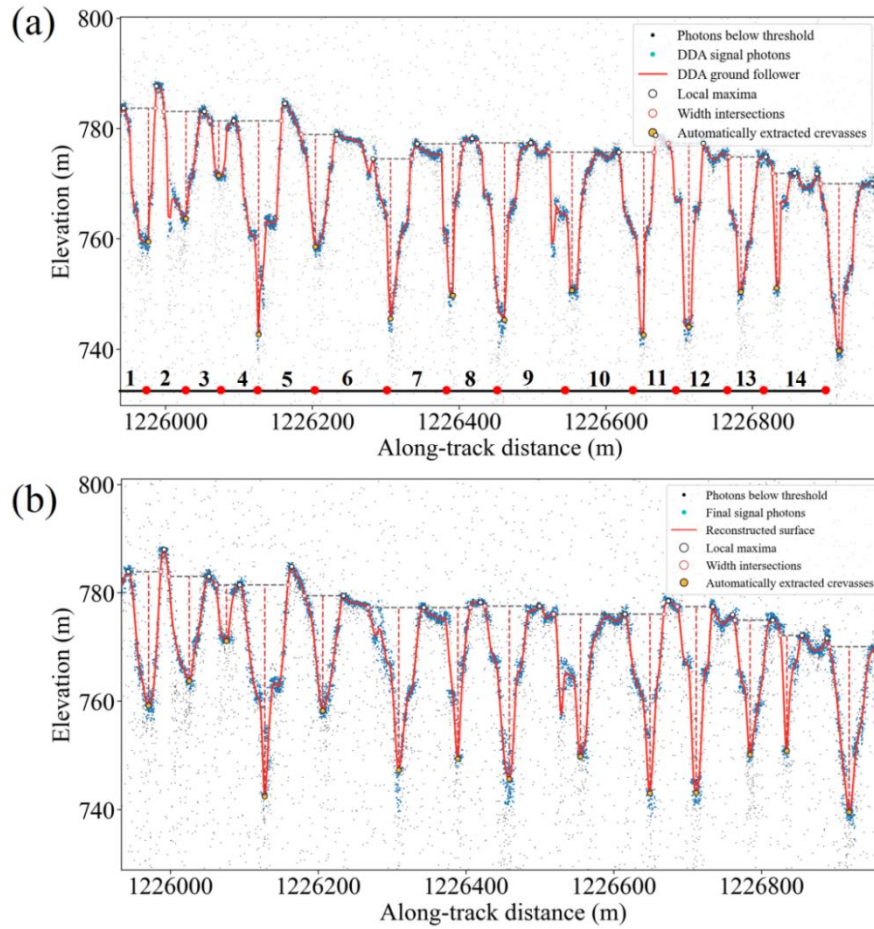


Figure R4. Comparison of individual crevasse extraction results from (a) the DDA-based reconstruction coupled with our crevasse extraction procedure and (b) the proposed method.

Table R4. Comparison of crevasse depth estimates derived from DDA-based surface reconstruction coupled with the proposed crevasse extraction procedure and those derived from the proposed method.

Crevasse	DDA depth (m)	Ours depth (m)	Absolute depth difference (m)
1	24.16	24.73	0.57
2	19.48	19.32	0.16
3	9.96	10.43	0.47
4	38.70	39.10	0.40
5	20.41	21.23	0.82
6	28.97	30.04	1.07

Crevasse	DDA depth (m)	Ours depth (m)	Absolute depth difference (m)
7	27.54	27.98	0.44
8	32.18	31.99	0.19
9	25.06	26.31	1.25
10	33.19	33.12	0.07
11	33.32	34.41	1.09
12	24.53	24.79	0.26
13	20.85	21.38	0.53
14	30.39	30.55	0.16
Mean depth	26.34	26.81	0.47

To further examine the consistency of the two processing strategies under different acquisition conditions, we selected two representative ATL03 datasets: a winter weak-beam case acquired on 17 February 2019 (RGT 0780, gt1r) and a summer strong-beam case acquired on 10 August 2019 (RGT 0666, gt1l). For consistency with the preceding comparison, the DDA-ice photon processing and ground-follower reconstruction were coupled with our automated crevasse extraction procedure, and the resulting outputs were compared with those from our complete workflow. Because DDA-ice does not include the roughness-based candidate-region pre-screening used in our workflow, applying the full DDA processing chain to all ATL03 observations would require substantially greater computational effort. We therefore limited this additional comparison to these two representative cases.

Figure R5 compares the results obtained by coupling DDA-ice photon processing and ground follower reconstruction with our automated crevasse extraction procedure (left panels) and those obtained from our complete workflow (right panels). Panels (a) and (b) correspond to the winter weak beam case, whereas panels (c) and (d) show the summer strong beam case. Despite differences in season, beam strength, surface morphology, and photon distribution, the two processing strategies reconstruct similar overall surface structures and identify broadly consistent crevasse features.

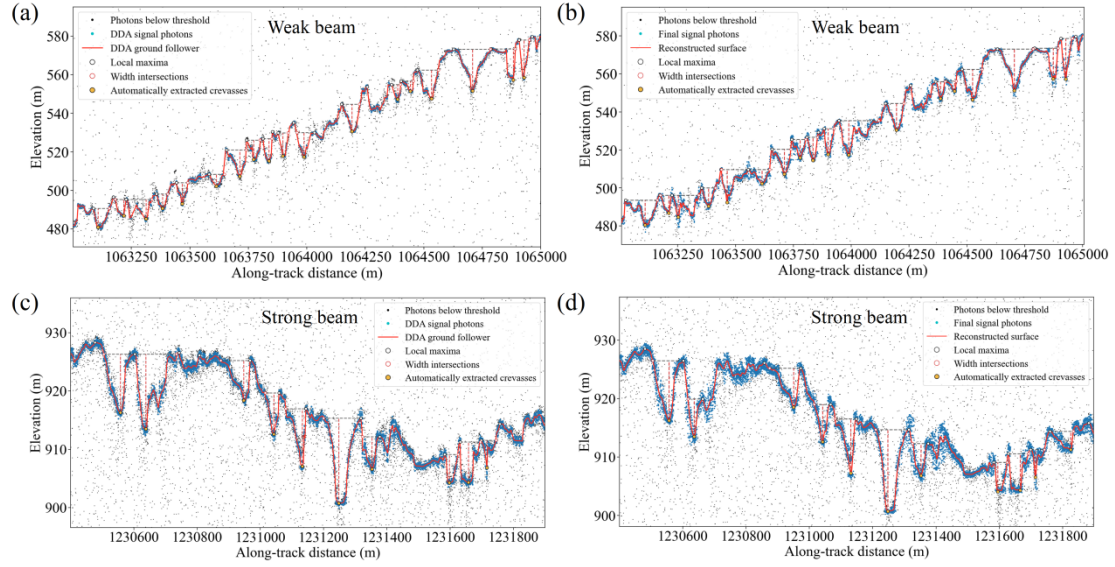


Figure R5. Comparison of crevasse extraction results under different seasonal and beam conditions. Panels (a) and (c) show the crevasse extraction results obtained by applying the proposed crevasse extraction procedure to the surface reconstructed by the DDA-based method, whereas panels (b) and (d) show the results obtained using the proposed method.

Overall, the comparison indicates that both DDA-ice and our method are capable of reconstructing crevassed glacier surfaces and providing consistent estimates of major crevasse geometry. The main contributions of our method relative to DDA-ice can be summarized in the following three aspects:

1) The roughness-based candidate region pre-screening limits the computationally intensive photon denoising and surface reconstruction procedures to areas with a high likelihood of containing crevasses, thereby reducing unnecessary processing over relatively smooth regions and improving the feasibility of basin-scale implementation.

2) The direction-adaptive elliptical neighborhood used in our photon density estimation better follows locally inclined photon structures and appears to facilitate more continuous preservation of signal photons along steep crevasse walls.

3) Most importantly, the reconstructed surface is further coupled with an automated individual crevasse extraction procedure, enabling the direct retrieval of crevasse locations, depths, widths, and other geometric attributes. DDA-ice provides a robust framework for photon classification and surface height reconstruction in crevasse regions, and not for automatically extracting crevasses, whereas the proposed method extends these capabilities toward automated generation of individual crevasse

products over large spatial scales.

2. A second claim is “this is the first study to map crevasse depths from ICESat-2 over the GrIS” (L528-529). Whilst this is true, there are two alternative studies that mapped crevasse depth at large scales, and more that map other crevasse components. The first is the study of Enderlin and Bartholomaus (2020; <https://doi.org/10.5194/tc-14-4121-2020>), who process OIB lidar processing to map >50,000 crevasses across 19 Greenlandic outlet glaciers. This study is likely worth discussing and contrasting, given the processing chain for OIB lidar displays strong parallels with processing for ATL03 data (i.e. extracting depths from a flight line of point returns). It provides alternative observations at Jakobshavn that should be compared directly. It also makes different assumptions about how to infer crevasse depth (discussed below). The second is the study of Chudley et al. (2025), which extracts crevasse depths from ArcticDEM data. This is mentioned in the text (L501), but in section 5.2 the compared crevasse depths are only identified manually. This seems a shame considering (i) using a prior automated method could provide a much larger sample size than the 16 in this study; and (ii) given an automated method likely performs worse than manual picks, the proposed method could actually be even better than comparator methods. There are also alternative methods/studies that map the *presence* of crevasses, including Van Wyk de Vries et al. (2021; <https://doi.org/10.1017/jog.2023.3>), and Khan et al. (2025, <https://doi.org/10.31223/X5HM9P>).

Response:

We thank the reviewer for this important comment. Firstly, we would like to clarify the scope of the statement that this is the first study to map crevasse depths from ICESat-2 over the GrIS. This statement does not imply that our study is the first to investigate crevasses, as previous studies have explored crevasse geometry and depth using other remote sensing datasets. Rather, it specifically refers to the first automated Greenland-wide crevasse depth mapping framework based on ICESat-2 ATL03 photon data. We will revise the wording in the manuscript accordingly to avoid overstatement. Nevertheless, we agree that the original manuscript did not

sufficiently compare the proposed ICESat-2-based crevasse depth retrieval framework with existing large-scale crevasse depth studies. Following the reviewer's suggestion, we have added a more comprehensive discussion of previous large scale crevasse depth mapping studies, including the OIB lidar-based analysis of Enderlin and Bartholomaus (2020) and the ArcticDEM-based approach of Chudley et al. (2025). Detailed comparisons with these studies are provided below.

(1) Comparison with airborne lidar crevasse depths from Enderlin and Bartholomaus (2020)

Enderlin and Bartholomaus (2020) assessed crevasse depths over Greenland outlet glaciers using airborne lidar observations from Operation IceBridge (OIB). Based on dense airborne laser altimetry measurements, they extracted crevasse depths for more than 50,000 crevasses across 19 outlet glaciers in Greenland. For SKJI, the OIB lidar observations used in their analysis were collected between 2013 and 2017. Since the OIB and ICESat-2 observations were acquired during different periods, the observed crevasses may have evolved due to glacier dynamics and surface processes over time. Consequently, direct matching of individual crevasses may introduce additional uncertainties.

To minimize the influence of these spatial and temporal differences, we performed the statistical comparison based on the along flow distribution of crevasse depths rather than individual crevasse matching. The OIB datasets provided by Enderlin and Bartholomaus (2020) include the parameter *location_along_centerline_relative_terminus*, which represents the distance of each crevasse from the glacier terminus along the glacier flow direction. Since the original centerline data were not available, we reconstructed a representative centerline from the OIB crevasse locations and projected the ICESat 2 derived crevasses onto this reference centerline to obtain comparable along flow distances. The crevasse depths from all datasets were then aggregated using the same distance intervals. This strategy allows comparison of the large scale spatial variation of crevasse depths along the glacier flow direction while avoiding uncertainties associated with direct matching of individual crevasses observed by different platforms.

The spatial distribution of the crevasses used for comparison is shown in Figure R6 (a). To establish a consistent spatial reference for the comparison, a representative flowline was reconstructed from the OIB crevasse locations using a 200 m along flow bin size, followed by spline smoothing. The reconstructed flowline was sampled at 10

m intervals and used to determine the along flow position of ICESat 2 derived crevasses. Only ICESat 2 crevasses located within 1 km of the reconstructed flowline were retained for subsequent comparison, ensuring that the selected satellite observations represented the same glacier branch as the OIB observations. The along flow depth variations were calculated using 2.5 km distance intervals from 5 to 22.5 km upstream of the terminus, and only bins containing at least three crevasse observations were retained. The comparison results between ICESat 2 and OIB observations are presented in Figure R6 (b). Despite the differences in acquisition time and observation geometry, the two datasets show a consistent along flow variation pattern. The median crevasse depths increase from the upstream region, reach relatively high values at approximately 8 to 14 km from the terminus, and decrease toward the downstream region. **The Pearson correlation coefficient between the ICESat 2 and OIB derived depth variations reaches 0.82, indicating a good agreement in the spatial distribution of crevasse depth changes.** The depths derived from ICESat-2 are generally smaller than those obtained from the OIB lidar observations. This difference is likely related to both the different depth retrieval strategies and observation geometries. In the OIB-based approach, crevasse depths were inferred from dense airborne lidar measurements of the crevasse walls, and the depth estimation involved geometric interpretation and extrapolation of the observed surface structure to estimate the crevasse depth. Therefore, the retrieved values tend to represent the potential maximum depth of individual crevasses. In contrast, the ICESat-2-derived crevasse depths in this study are calculated directly from the observed elevation difference between the reconstructed glacier surface and the detected crevasse bottom, without geometric extrapolation based on crevasse shape. When the ground track does not intersect the deepest part of a crevasse, the derived depth may be smaller than the maximum geometric depth. Consequently, the difference between the two datasets is expected and mainly reflects the different measurement strategies rather than inconsistencies in the spatial distribution of crevasse depths.

Overall, the comparison with independent OIB lidar observations demonstrates that the proposed ICESat 2 based approach can effectively capture the large scale spatial variation of crevasse depths over SKJI. Although ATL03 derived depths may not represent the maximum depth of individual crevasses due to the discrete sampling geometry of satellite photon observations, the method provides a new opportunity for

retrieving crevasse depth information over large glacier regions where airborne measurements and detailed surface models are unavailable.

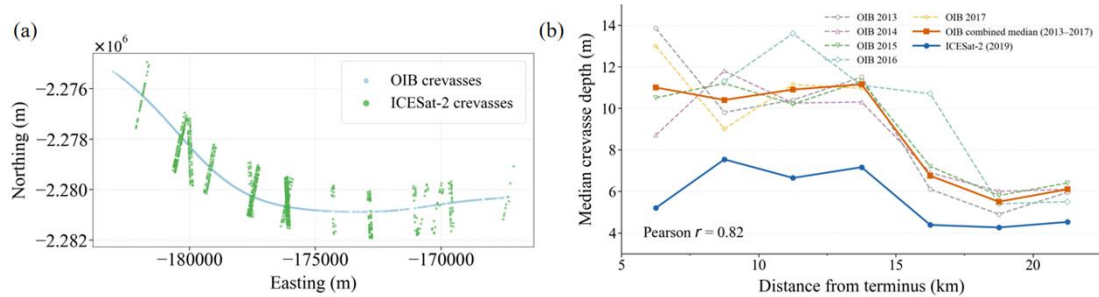


Figure R6. Comparison of crevasse distributions and depths between ICESat-2 and OIB observations at SKJI. (a) Spatial distribution of OIB-derived and ICESat-2-derived crevasses. (b) Comparison of median crevasse depths along the distance from the glacier terminus.

(2) Comparison with ArcticDEM-derived crevasse depths using CrevDEM (Chudley et al., 2025)

Chudley et al. (2025) developed an automated ArcticDEM-based framework for extracting crevasse depths at large spatial scales, providing an important alternative approach for Greenland-wide crevasse characterization from satellite-derived elevation data. Compared with photon-based observations from ICESat-2 ATL03, ArcticDEM provides spatially continuous surface elevation information, but the retrieval of crevasse depths from DEMs may be affected by spatial resolution, surface interpolation, and narrow and steep-sided crevasses. In contrast, ICESat-2 ATL03 directly records along track photon returns, offering an independent observation of surface depressions. Therefore, we compared our ICESat-2 ATL03-derived crevasse depths with the ArcticDEM-derived results from Chudley et al. (2025).

To investigate the consistency and differences between these two approaches, we first performed a detailed comparison for a representative overlapping dataset (Figure R7). The selected ArcticDEM strip was acquired on 10 April 2019, while the corresponding ICESat-2 ATL03 observations were acquired on 20 April 2019, resulting in a temporal separation of 10 days. The elevation profiles derived from ICESat-2 ATL03 and ArcticDEM show consistent surface variations along the same track, and both datasets capture the corresponding crevasse depressions. For the representative case, 90 matched crevasses were identified, resulting in an MAE of

3.72 m, an RMSE of 5.93 m, and a bias of -3.33 m in depth (ArcticDEM minus ICESat-2). Although most shallow crevasses showed comparable depth estimates, larger discrepancies occurred for several deep crevasses. Examination of the original ATL03 photon profiles indicates that these deep features contain distinct photon returns extending into the crevasse bottoms (Figure R7 (d)). The relatively smaller ArcticDEM depths for these features may be related to the limits in narrow and steep-sided crevasse geometries in ArcticDEM.

We then extended the comparison from individual examples to a larger scale by applying the automated CrevDEM framework to multiple temporally matched ICESat-2-ArcticDEM data pairs. Compared with the original manual comparison of 16 crevasses, the expanded analysis identified 2,598 automatically matched crevasses across 11 ICESat-2-ArcticDEM datasets (Figure R8 and Table R5). The overall comparison yielded an MAE of 4.10 m, an RMSE of 5.64 m, and a bias of -3.16 m in depth. The consistently negative bias indicates that ArcticDEM-derived crevasse depths were generally shallower than those derived from ATL03. This difference was more evident for deeper crevasses, highlighting the complementary nature of the two observation strategies: ArcticDEM enables spatially continuous mapping of surface crevasse features, whereas ATL03 provides direct along-track photon observations that can better resolve vertical structures within deep crevasses.

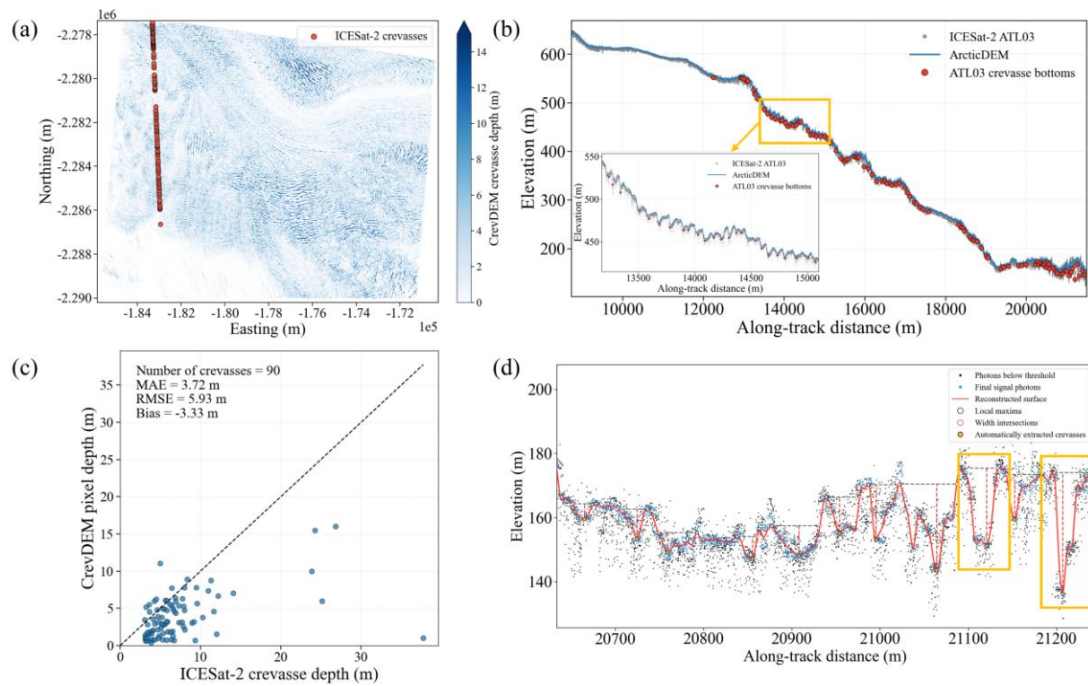


Figure R7. Representative case of automated crevasse detection and depth retrieval using ICESat-2 ATL03 and ArcticDEM. (a) Spatial distributions of crevasses

extracted from ICESat-2 ATL03 and ArcticDEM. (b) Comparison of ICESat-2 ATL03 and ArcticDEM elevation profiles. (c) Comparison of crevasse depths for a representative dataset. (d) Detailed ATL03 photon profiles for representative deep crevasses.

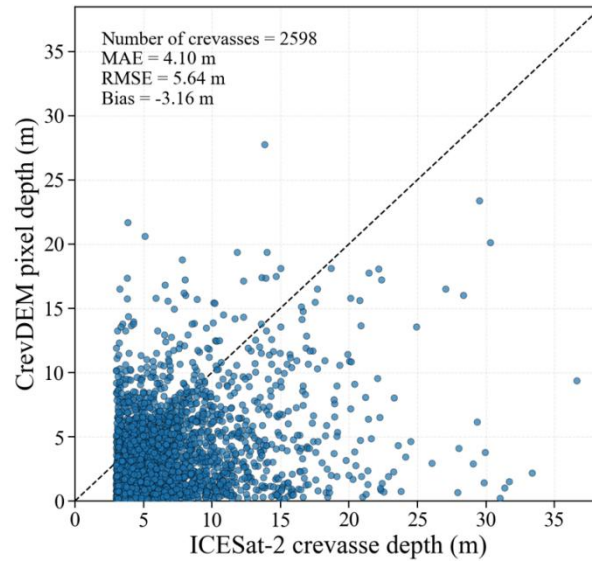


Figure R8. Comparison of crevasse depths derived from ICESat-2 ATL03 and ArcticDEM.

444 **Table R5.** Statistical comparison of crevasse depths for selected ICESat-2-ArcticDEM data pairs.

ICESat-2 data	ArcticDEM data	Time difference (d)	Matched crevasses	MAE (m)	RMSE (m)	Bias (m)
ATL03_20190314235626_11 SETSM_s2s041_WV01_20190321_102001008062F100_690205_006_02.h5	102001008316C000_2m_lsf_seg1_dem.tif	7	371	4.68	6.40	-4.00
ATL03_20190420093051_03 SETSM_s2s041_WV03_20190410_1040010049CC9200_380303_006_02.h5	104001004C8E3900_2m_lsf_seg1_dem.tif	10	294	3.73	5.08	-3.26
ATL03_20190515210004_07 SETSM_s2s041_WV03_20190522_104001004A3D8A00_270305_006_02.h5	104001004BA65400_2m_lsf_seg1_dem.tif	7	45	2.93	3.99	-1.82
ATL03_20190519080649_07 SETSM_s2s041_WV01_20190502_1020010085D49300_800303_006_02.h5	1020010083E1A300_2m_lsf_seg1_dem.tif	17	324	3.90	5.12	-2.50
ATL03_20190613193602_11 SETSM_s2s041_WV02_20190608_103001009258F900_690305_006_02.h5	10300100933BDE00_2m_lsf_seg1_dem.tif	5	724	3.90	5.43	-2.73
ATL03_20190617064249_12 SETSM_s2s041_WV03_20190616_104001004D5B7500_220303_006_02.h5	104001004D8CF800_2m_lsf_seg1_dem.tif	1	521	3.99	5.52	-3.13
ATL03_20190712181153_02 SETSM_s2s041_WV02_20190727_1030010096D5C800_240405_006_02.h5	10300100965C7900_2m_lsf_seg1_dem.tif	15	159	5.20	6.96	-4.43
ATL03_20190814163946_07 SETSM_s2s041_WV03_20190811_104001004F39CA00_270405_006_02.h5	1040010050BAD800_2m_lsf_seg1_dem.tif	3	8	4.88	5.72	-4.88
ATL03_20190818034635_07 SETSM_s2s041_WV03_20190811_104001004F39CA00_800403_006_02.h5	1040010050BAD800_2m_lsf_seg1_dem.tif	7	7	2.57	3.30	-2.15
ATL03_20191113121942_07 SETSM_s2s041_WV02_20191024_103001009A4C0300_270505_006_01.h5	103001009BB01900_2m_lsf_seg1_dem.tif	20	12	3.27	3.92	-2.86
ATL03_20191116232629_07 SETSM_s2s041_WV02_20191024_103001009A4C0300_800503_006_01.h5	103001009BB01900_2m_lsf_seg1_dem.tif	23	133	4.40	6.20	-3.48
Overall	—	—	2598	4.10	5.64	-3.16

3. Given the data of Chudley et al. (2025) is public, and the methods of Chudley, Van Wyk de Vries, and Khan are all publicly available (<https://github.com/trchudley/crevdem>, <https://github.com/MaxVWDV/Gabor-crevasse-detector>, <https://theithub.org/resources/crevassedetect/about>), it is unusual to have no comparisons to any existing methods, which could help highlight the benefits of the method.

Response:

We thank the reviewer for this important suggestion. We agree that comparison with existing automated approaches is necessary to better place the proposed method in the context of previous crevasse-mapping studies and to clarify its relative strengths. In the revised manuscript, we have therefore expanded the comparison with existing methods. In particular, we added quantitative comparisons with Enderlin and Bartholomaus (2020) and Chudley et al. (2025), because both studies provide crevasse depth estimates and are therefore directly relevant to the primary output of our method. We have also added a direct comparison with DDA-ice, including photon filtering, surface reconstruction, individual crevasse extraction, and depth retrieval, as described in our response to Comment 1.

We also carefully considered the methods of Van Wyk de Vries et al. (2023) and Khan et al. (2025). Van Wyk de Vries et al. (2023) developed a Gabor-filter-based approach using Sentinel-2 imagery to automatically identify individual crevasses and characterize their spatial density and orientation, while Khan et al. (2025) developed the MimiNet deep learning framework using Sentinel-1 SAR imagery to map the distribution and temporal variability of crevasse fields. These studies make important contributions to automated crevasse mapping, particularly in characterizing the horizontal occurrence and spatial organization of crevassing. However, their principal outputs differ from the individual crevasse depth estimates that are the main focus of the present study, and therefore they do not provide directly comparable depth products for quantitative evaluation. In the revised manuscript, we will expand the Introduction to acknowledge these image-based crevasse mapping approaches and clarify their contributions. In addition, the horizontal locations of crevasses extracted from ATL03 in our study have already been independently validated using 3 m Planet optical imagery, which provides a higher resolution reference for assessing crevasse

locations, with a mean positional residual of 2.66 m. For these reasons, we did not include the methods of Van Wyk de Vries et al. (2023) and Khan et al. (2025) in the quantitative comparison.

4. If the method is indeed better or more efficient than comparator methods, is it disappointing there has been no effort to share any easily reusable code via a GitHub repository or similar. Given that other approaches have shared their approach (see above), it is worth doing - especially as it would give the approach a clear advantage over dda-ice method, which is currently not shared.

Response:

Many thanks. We also agree with the reviewer that public release of the processing code would improve the reproducibility and reuse of the method. The code is currently being organized, and we intend to make the core processing workflow available through a GitHub repository upon acceptance of the manuscript. A corresponding code availability statement will be included in the revised manuscript.

5. A further note about the Section 5.3. The text claims that difference in depths are to do with photogrammetric error, but studies using high-resolution data have asserted that the apparent shallow depths of large (>10 m) crevasses are likely not an error but a real observation of infilled ice debris (Enderline and Bartholomaus, 2020; Chudley et al. 2021). Indeed, the comparator profiles presented in Fig 13 appear, to me, broadly ‘within error’, and the average difference in depth of 1.40m seems reasonable considering the two datasets do not appear to be coregistered – or else probably explained by the higher resolution of the ATL03 (0.7 m cf. 2 m) rather than any photogrammetric error. (Elsewhere in the text it is instead said that ICESat-2 depths are “30% deeper” (L40;L560), but I cannot see where this figure comes from). Enderlin and Bartholomaus (2020) explicitly account for the debris infill in lidar data by making an assumption that crevasses follow V-shaped geometries, and estimating the ‘true depth’ of the crevasse by linearly projecting crevasse walls to an extrapolated intersection. Of course, any extrapolated intersection assumes that any linear data is

exactly orthogonal to crevasse depth (which will be violated for ATL03 data) - but either way, it is likely best to acknowledge that the true crevasse depth – on the scale observed at Jakobshavn and similar fast-flowing outlets – cannot be determined in any optically-derived dataset.

Response:

Many thanks for this insightful comment. We agree that the previous discussion of the depth differences may have been overly simplified by mainly attributing them to photogrammetric errors. The reported ~30% difference was calculated from the additional comparison between ATL03-derived and ArcticDEM-derived crevasse depths. Specifically, the mean depth derived from ATL03 was 6.20 m, whereas the corresponding mean depth derived from ArcticDEM was 4.77 m. The relative difference was calculated as $(6.20 - 4.77) / 4.77$, resulting in an increase of approximately 29.9% in ATL03-derived depths compared with ArcticDEM-derived depths. Following this comment and previous studies on crevasse depth interpretation (Enderlin and Bartholomaus, 2020; Chudley et al., 2021), we have re-evaluated the interpretation of the observed depth differences and revised the corresponding discussion in the manuscript. We now clarify that the discrepancy between ATL03-derived and ArcticDEM-derived depths may be affected by multiple factors, including differences in spatial resolution, crevasse geometry, and potential ice-debris infilling within crevasses, rather than solely measurement errors.

We have therefore revised Section 5.3 to provide a more cautious interpretation of the retrieved depths. The depths obtained from ATL03 represent observed photon-derived depths rather than the absolute geometric depths of crevasses. Following previous studies (Enderlin and Bartholomaus, 2020; Chudley et al., 2021), we also acknowledge that the true crevasse depth cannot be directly determined from optical or photon-based observations alone.

Conclusion

Given my comments above regarding comparator papers from both the ICESat-2 and Greenlandic crevasse literature, I believe that this paper does not, in its current state, sufficiently communicate the “originality” not “significance” components of the Cryosphere review criteria. However, I think a clear pathway to this does exist, with a better focus on novelty either as a (i) a method paper or (ii) a science paper. If (i), it

would be necessary to see a robust comparison to alternative approaches (especially dda-ice), which would help identify this as a quantitatively better method, either in terms of processing speed or accuracy. The existence of publicly available code (e.g. in a GitHub repository) would present a step-change from the dda-ice comparator method and help this method be distributed through the community. Through this route, I can see real impact in wider community use. If (ii), the dataset presented here should probably be paired with some aspect of scientific interrogation, either through some investigation of e.g. the relationship between depth and conventional predictors of crevasse propagation (following e.g. Enderlin and Bartholomaeus, 2020), or by expanding the dataset to compare changes through time to prove the utility of the method (following e.g. Van Wyk de Vries et al. 2021). With the latter, there is real value in being able to ‘fill in’ the sparse observations by Chudley et al. (2025), or demonstrate temporal changes following the Enderlin and Bartholomaeus (2020) statistics. This would evidence that the proposed method can provide invaluable temporal coverage to balance the spatial coverage of other datasets.

Response:

Many thanks for this constructive summary and for clearly outlining two possible directions to strengthen the manuscript. In the revision, we followed the first pathway suggested by the reviewer and further positioned the study as a methodological contribution. Specifically, we substantially expanded the comparison with existing approaches, with particular emphasis on DDA-ice, which is the most directly comparable ATL03-based framework. We added quantitative comparisons at several levels, including photon denoising performance, individual crevasse extraction, crevasse spacing, and crevasse depth estimation. We also quantified the computational efficiency gained from the roughness-based pre-screening strategy and demonstrated the reduction in processing time relative to full-track processing. In addition, we expanded the comparison with other existing crevasse depth datasets and approaches, including OIB lidar observations and ArcticDEM-based crevasse depth retrievals, to better clarify the applicability and limitations of the proposed method. Following the reviewer’s suggestion regarding reproducibility, we have also added a statement on code availability and are preparing the core processing workflow for public release through a GitHub repository. Based on these revisions, we have refocused the manuscript to more clearly emphasize the methodological novelty of the proposed method, particularly its combination of efficient candidate-region screening and

576 automated extraction of individual crevasse depths over large spatial scales. We
577 believe these additions substantially improve the communication of both the
578 originality and significance of the study.