Point-by-point reply to Reviewer 1 – Manuscript entitled: Evaluation of satellite methods for estimating supraglacial lake depth in southwest Greenland, authored: Melling et al.

Manuscript iteration: Revision post review

Editor: Joseph MacGregor

We thank anonymous reviewer #1 for their comments on and suggested edits to our paper. These are listed below in bold type, with our response to each one given in normal type. We note that all line numbers refer to the original manuscript.

1) "First, the conclusions suggest using ICESat-2 to constrain or correct the RTE methods. Although they do not use machine learning, Datta et al., (2021) uses ICESat-2 lake depths to constrain empirically-derived depths from Landsat-8, among other imagery sources. They also do not use the RTE equation used here, but I still think it is worth elaborating on how this study builds upon theirs (or how results from both could benefit the community)."

We agree that Datta and Wouters (2021) is worth elaborating on and propose to add/change lines 364-368 to read, *"Methods which exploit regularly acquired 2-D satellite imagery - such as the application of the RTE to optical satellite imagery - are thus needed to monitor the total volume of water held within lakes on the ice sheet surface and its evolution through time. ArcticDEM and ICESat-2 data are of most value for their potential to constrain these methods. For example, Datta and Wouters (2021) used ICESat-2 to constrain empirically derived estimates of lake bathymetry from Sentinel-2 scenes in western Greenland. With a larger amount of ArcticDEM and/or ICESat-2 data, we suggest that future research could combine multiple satellite bands (Adegun et al., 2023) and data sources as inputs to a machine learning model and generate a well-constrained depth-detection product using a data-driven approach, as opposed to the model-derived approach we use here."*

We will also add the Adegun et al. (2023) citation to the reference list of the revised manuscript.

2) "On the subject of ICESat-2, its value for this study is not immediately clear to me. I assume that it serves as high-accuracy validation for the RTE and ArcticDEM methods, but this is not mentioned explicitly in the text. Also, ICESat-2 is barely discussed after Section 3.1. Between these issues and the sparse coverage over all five lakes (especially Lakes 4/5), the manuscript needs to provide more justification on why the ICESat-2 depths are useful here."

Due to its spatially limited nature, ICESat-2 can only be used in a comparison along 1-D transects. As such, we do not refer to it in sections 3.2 and 3.3 as these sections intercompare the RTE and ArcticDEM in 2-D. The main utility of using three different depth detection methods rather than two is that it increases our confidence in depths calculated at locations where there is agreement between methods. Where two methods disagree, each one is equally likely to be 'correct'. Bringing in a third method in this case helps to identify in which of the first two methods possible deficiencies lie.

We use it here in addition to ArcticDEM because it is considered to have a high level of accuracy (e.g. Markus et al., 2017).

At line 67, we will add "*Intercomparing multiple depth detection methods increases our confidence in the depths calculated at locations where there is agreement between methods. This is especially important in the absence of 'ground truth' data*."

3) "Page 2, Line 32: For a general audience, I recommend mentioning why lakes prefer draining over refreezing (or vice versa)."

In the revised manuscript, we propose to add the following text in lines 31-33, *"These lakes either drain or refreeze, with ~34 % of lakes at lower elevations draining slowly, ~14 % draining rapidly and ~50 % refreezing. At higher elevations, lakes tend to refreeze (Selmes et al., 2013)."*

4) "Page 2, Lines 33-36: Hydrofracturing is formally defined on Line 36, so I would refrain from mentioning it until then."

We propose editing lines 33-36 to read, "*This process is known as hydrofracture, and related drainage events can occur in as little as two hours (Das et al., 2008). In these events, the water is routed to the base of the ice sheet where it can cause a hydraulic pressure increase that temporarily lifts the ice off the bed. This process can enhance basal sliding and increase ice flow rates*"

5) "Page 2, Line 45: I would like to see a reference or two here demonstrating the importance of melt lakes for models, if possible."

We will add references to Christoffersen et al. (2018) (https://doi.org/10.1038/s41467-018-03420-8) and Tedesco et al. (2013) (https://doi.org/10.1088/1748-9326/8/3/034007) on line 45.

6) "Page 2, Line 51: Replace semi-colon with colon."

We will replace the semi-colon on line 51 with a colon.

7) " Figure 1: Nice figure! For panels 1-5, I would specify in the caption where the imagery is from."

In the caption for Figure 1, we will add the text, "*background images in panels (1)-(5) are the Sentinel-2 tiles detailed in Table A1*."

8) "Page 4, Lines 92-93: This sentence doesn't add much justification – the following sentence is enough."

We will edit lines 92-95 to read, "*These bands have previously been used to determine lake depth on the Greenland ice sheet (e.g. Williamson et al., 2018; Moussavi et al., 2020; Datta and Wouters, 2021)*."

9) "Page 6, first paragraph: This is overall well-written, but it is also getting a bit in the weeds. I suggest condensing it to something like: "Previous studies assumed that Ku≈ 1-2.5Kd, with Brodsky

et al., (2022) suggesting that higher Ku values (and therefore higher g values) lead to more accurate lake depths. Here, we use an average of the above range and take Ku = 1.75Kd, or g = 2.75Kd.""

We agree that this reads better when condensed and propose editing lines 124-129 to read, "*Many laboratory-derived estimates exist of K_d but very few exist of K_u (Philpot, 1989). Other studies have taken K_u to be equal to K_d, and thus g to be $2K_d$ (e.g. Maritorena et al., 1994; Sneed and Hamilton, 2007), but K_u must be larger than K_d because upwelling photons are more rapidly attenuated than the downwelling photon flux in water (Kirk, 1989). Experimental studies suggest that g could be as high as $3.5K_d$ (Kirk, 1989), with some studies suggesting a higher g value leads to more accurate lake depths (Brodský et al., 2022). Here, we therefore use an average of this range and take g = $2.75K_d$.*"

10) "Page 7, Line 183: Outdated reference. Refer instead to Markus et al., (2017) – see "New References" section below for full citation."

We will refer instead to Markus et al. (2017) on line 183. We will also remove the reference to Abdalati et al. (2010) from the reference list and add the citation for Markus et al. (2017).

11) "Section 2.4, first paragraph: I suggest noting that the spacing between ICESat-2 beam pairs is 3.3 km, which limits the coverage of individual lakes."

We propose the addition of "*The spacing between ICESat-2 beam pairs at all latitudes is ~3.3 km which limits the coverage of individual lakes*." at line 185.

12) "Page 7, Line 186: Cite Neumann et al., (2019) with the mention of ATL03 usage."

In altering line 186 to add a citation of Neumann et al. (2019), we noticed that the version number was not immediately clear to a reader unfamiliar with ICESat-2 so propose to alter the line to read, "*We estimate the lake bathymetry of the supraglacial lakes using the ICESat-2 ATLAS ATL03 (version 3) data product (Table A1) (Neumann et al., 2019)…*". We will also add the Neumann et al. (2019) citation to the reference list.

13) "Page 9, Lines 208-209: Not sure if I follow the logic here. Why not keep ICESat-2 at its native resolution, if the other datasets are resampled to 0.7 m?"

The ICESat-2 bathymetry data set is digitised manually by 10 experts based on the ICESat-2 photon cloud, and subsequently averaged to minimise observer error, and so does not have a native resolution as such. Individual experts sampled with different frequencies along the photon cloud and a final sampling of 100 equidistant points per lake was selected to accommodate differences in manual delineations. Since the obtained bathymetry is smooth, using another sampling interval would not make a big difference to Figure 2 or any results obtained from the subsequent analysis of its data.

To clarify the manual delineation procedure, we will alter lines 192-196 to read, "*We invited 10 altimetry experts to manually digitise the lake bathymetry from the refraction-corrected ATLAS ATL03 photon data plots using an online digitisation tool (https://apps.automeris.io/wpd/).*" There will be no effect on Figure 3 as the data for this figure were extracted from each dataset at the 100 equidistant ICESat-2 points along each transect. To reflect this, we will add the following text at line 226,

"…coefficient for each method pairing at each of the 100 equally spaced points along which the ICESat-2 data was sampled (Fig. 3)."

14) "Table 1: Given Figure 3, I don't think this table adds much to the paper. I think a table showcasing the maximum depth for each lake and method would be more useful."

We agree with the reviewer that this table does not currently add much to the paper. In the revised manuscript, we will alter this table to display the maximum depths for each method for each lake, and a column showing which method has achieved the maximum depth for each lake.

15) "Figure 4: This is a really nice figure, and I think it merits more discussion. In particular, I notice DEM/RTE differences that seem to be related to depth. Also, the green band has expectedly large underestimations in a few spots for Lakes 4 and 5. I would like to see some speculation in the Results or Discussion on these points."

In the revised manuscript, we propose to add the following text at line 254, "*Consistent with the findings from Fig. 2, the lakes exhibit a relationship between the green band RTE depths and the ArcticDEM depths where the green band RTE overestimates depth in the deepest portions of the lakes. This is particularly evident in Lake 5 as its bathymetry is simpler than that of the other lakes. Additionally, there are notable depth underestimations of the green band RTE in Lake 4 and Lake 5. These underestimations correspond to floating ice on the lake surface which is not present in the ArcticDEM data.*"

16) "Page 15, Lines 269-270: For visual reference, I suggest pointing out the "plateau depths" in Figure 5, using a dotted line or marker(s)."

In the revised manuscript, we will add dashed lines to Figure 5 to point out the plateau depths for visual reference. Additionally, we will edit the caption to read (at line 267), "*The diagonal long-dashed lines represent one-to-one agreements between the depth datasets. The red-band RTE plateau depths are indicated by the labelled short-dash white lines in (a).*"

17) "Figure 6 caption, first sentence: Suggest rephrasing to "Sensitivity analysis of RTE parameters, with plausible values given for each.""

We propose altering line 278 to read, "*Figure 6: Sensitivity analysis of the RTE parameters, within plausible ranges identified for each parameter (Appendix A.3).*"

18) "Lines 298-300: It might be a bit much to call this a flaw in the method. Water reflectance is very low (~0.1 in the red band) unless specular reflection is observed, so you would need a very dirty lake bottom to achieve negative lake depths. This could be a more feasible issue for the green band, but I would imagine that it is still very uncommon."

We agree that this wording was too strong and will alter lines 298-300 to read, "*Both the red and green band RTEs produce negative depths when the value of R_w is larger than the value of A_d. Physically, this* *means that the lake bottom albedo is lower than the reflectance of the pixel of interest. In practice, this only occurs in scenarios where; a) the pixel of interest represents misclassified floating ice, such as in the green band RTE plots for Lake 4 and Lake 5 (Fig. 4), or b) as a result of uncertainty in A_d.*"

19) "Page 17, Lines 318-320: Just curious, what is a saturation depth for the green band? A ballpark number is sufficient."

At line 318, we propose to add the following text, "*From Fig. 6 we can see that the saturation depth of the green band RTE is approximately 8-11 m. This depth is dependent upon the values of A_d and thus will be different for every lake*."

20) "Page 17, Lines 326-328: This sentence has redundant wording. I suggest revising to something like, "We determined that use of the green band RTE can lead to lake volume overestimations of more than 150% relative to ArcticDEM, with similar overestimations expected at larger scales.""

We will edit lines 326-328 to read, "*Use of the green band RTE can lead to lake volume overestimations of 150 % relative to ArcticDEM, with similar overestimations expected at larger scales.*" in the revised manuscript.

21) "Page 18, Line 339: "…and consistent overestimations in the green band.""

We propose to edit the text on lines 338-339 to read, *"…red band RTE depths and the green band RTE depths due to the plateauing effect observed in the red band RTE and consistent overestimations in the green band RTE.*"

22) "Page 18, Lines 344-347: Long sentence, needs to be more concise (or split into two sentences)."

In the revised manuscript, lines 344-347 will read, "*It is clear from Fig. 6 that depth is largely insensitive to the choice of R_∞. Since our calculation of A_d is the same as that which is commonly used within existing literature (Sneed and Hamilton, 2007; Moussavi et al., 2020) we suggest that there is disagreement with respect to the best-performing band, at depths lower than the saturation point of the red band RTE, because we use a different value of g*."

23) "Page 20, Lines 406-407: Given that only five lakes were observed, this is a rather strong conclusion to make."

We agree that this assertion was too strong given the limited number of observed lakes and so propose altering lines 406-407 to read, "*Interestingly, the methods currently used within the literature to determine the parameter values appear to limit the accuracy of lake depth calculation using the green band RTE within our five-lake sample*."

24) "Appendix A, Section 1: "Characteristics" ---> "Criteria""

We will change "*Characteristics*" in the section heading of Appendix A Section 1 to read, "*Criteria*". Additionally, on line 173, we will change "*characteristics*" to "*criteria*".

25) "Table A1: The ICESat-2 data used for this study is out of date – Version 006 was released in June. As a sanity check, I would see if there's any significant differences in the ICESat-2 V003/V006 data over the five lakes."

As the reviewer correctly points out, the analysis is based on an older version (version 3) of the ICESat-2 data set. This information will be added to the text (line. 186 will read, *"…using the ICESat-2 ATLAS ATL03 (version 3) data product…"*).

We further noticed that information on which ICESat-2 tracks were used for the different lakes was missing from the manuscript and we will therefore add it to Table A1 in the revised manuscript.

We have examined the two datasets over our five lakes and have determined that:

- The geolocation of the satellite track has moved by 0.6 - 1.2 m in version 6 (Fig. 1). This is within the spacing of the ArcticDEM and S2 datasets and so should not affect our comparison.

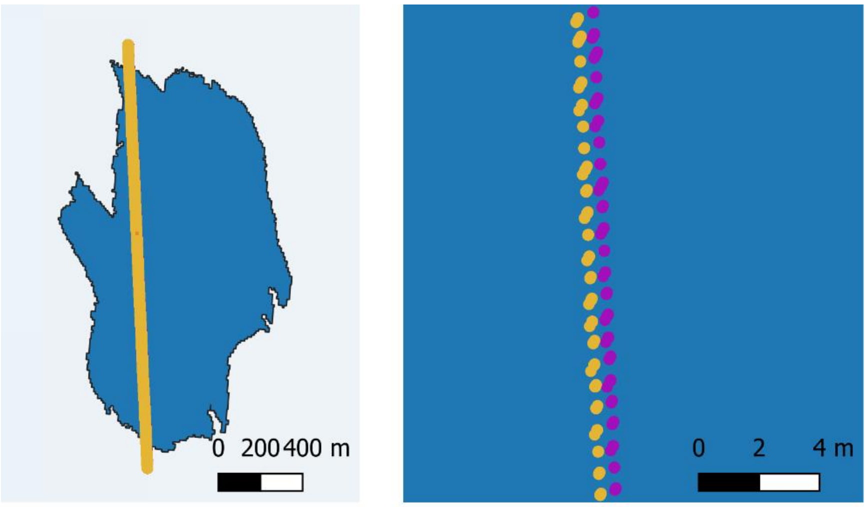

Figure 1: The geolocation difference between ICESat-2 version 3 and ICESat-2 version 6.

- The individual photon heights have changed slightly on the order of 0.2 - 0.5 m (Figs. 2 – 6). This offset is observed both for the lake surface and bed photons so this should not affect lake depth estimates (which subtract the latter from the former), especially considering the uncertainty associated with the manual delineations.

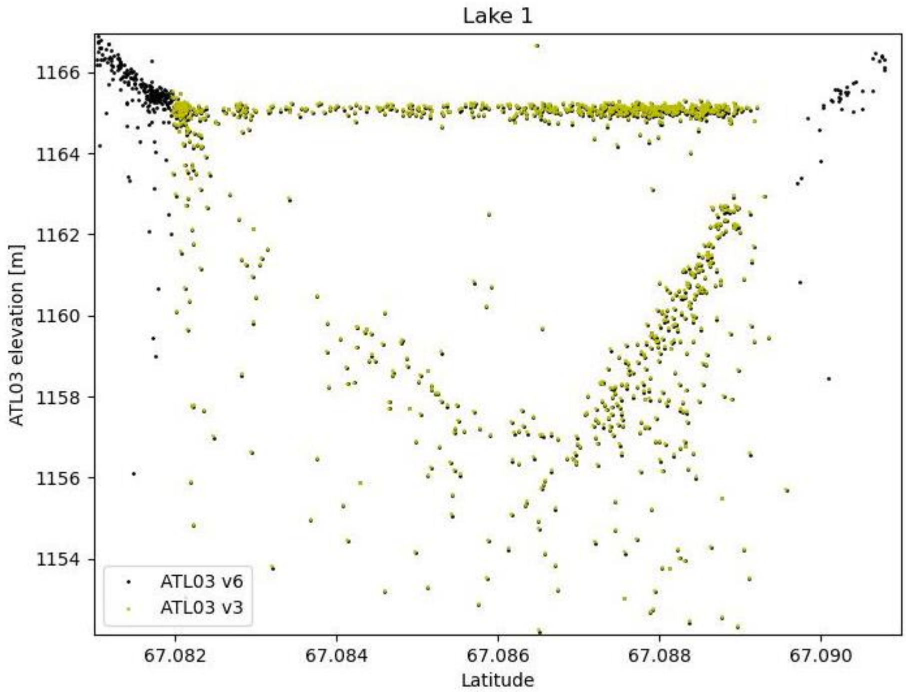

Figure 2: The photon plots of ICESat-2 version 3 (ATL03 v3) and ICESat-2 version 6 (ATL03 v6) for Lake 1.

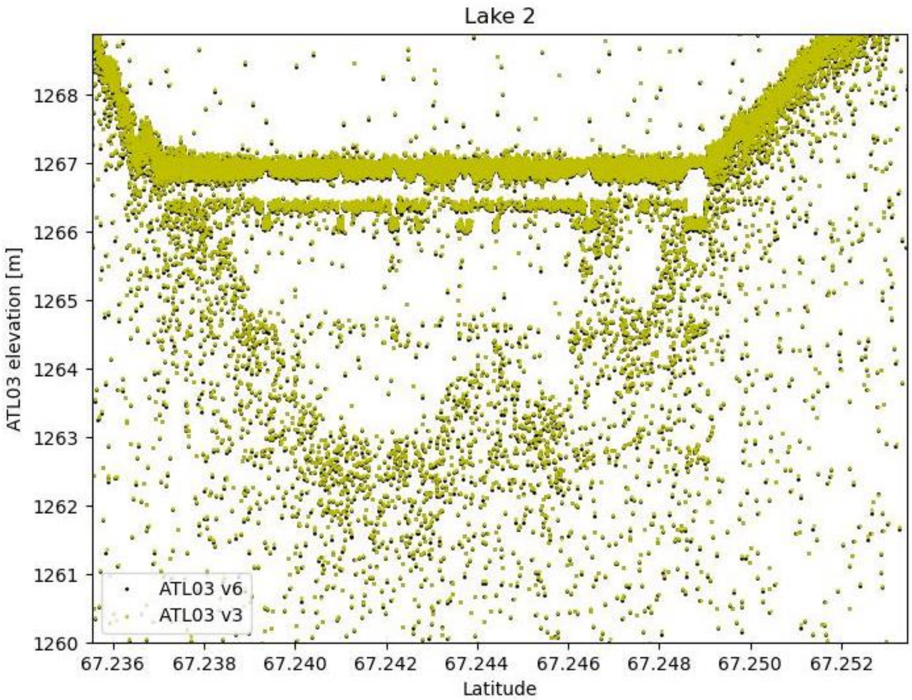

Figure 3: The photon plots of ICESat-2 version 3 (ATL03 v3) and ICESat-2 version 6 (ATL03 v6) for Lake 2.

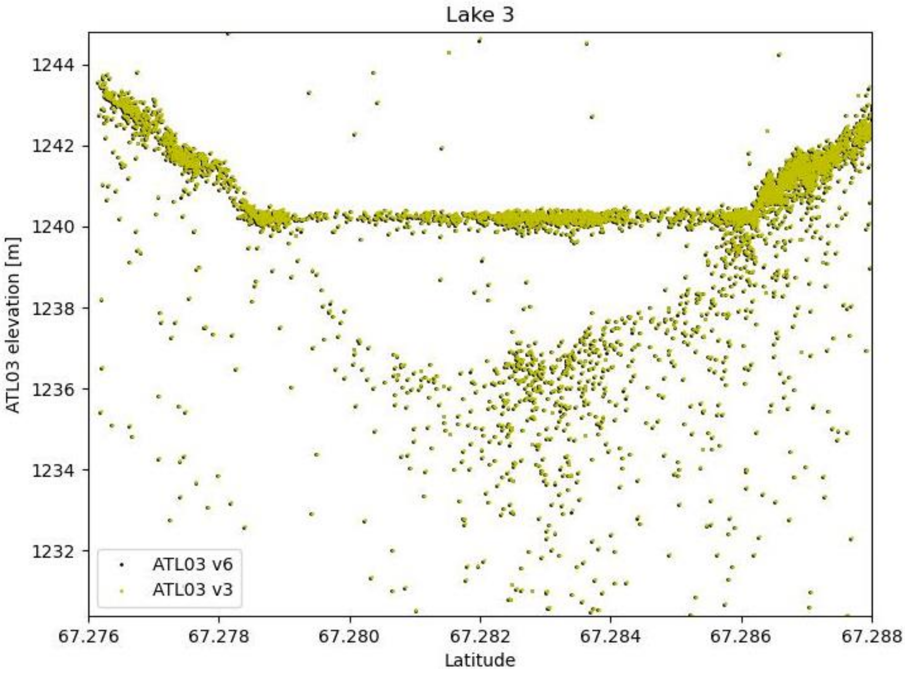

Figure 4: The photon plots of ICESat-2 version 3 (ATL03 v3) and ICESat-2 version 6 (ATL03 v6) for Lake 3.

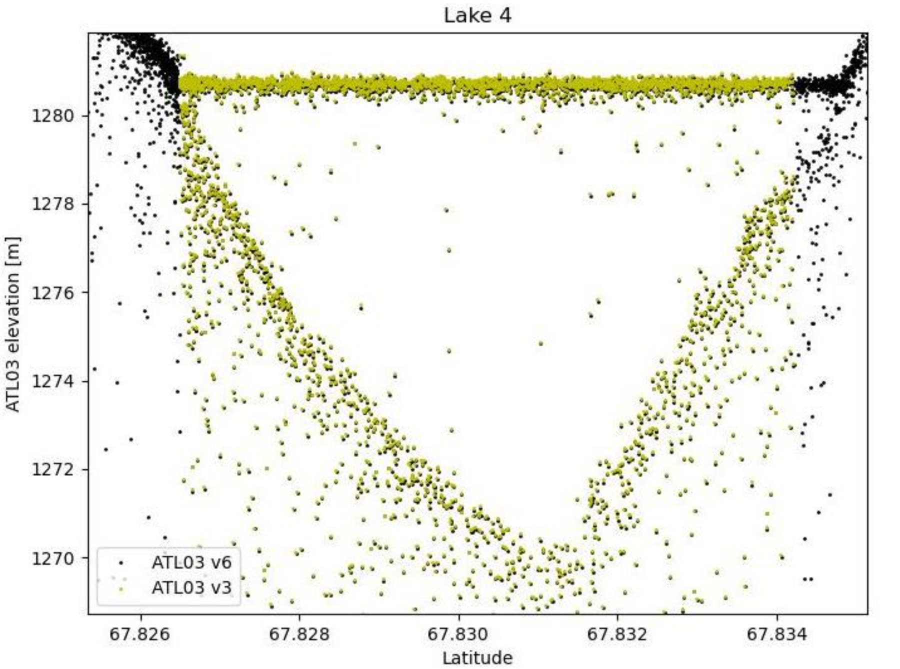

Figure 5: The photon plots of ICESat-2 version 3 (ATL03 v3) and ICESat-2 version 6 (ATL03 v6) for Lake 4.

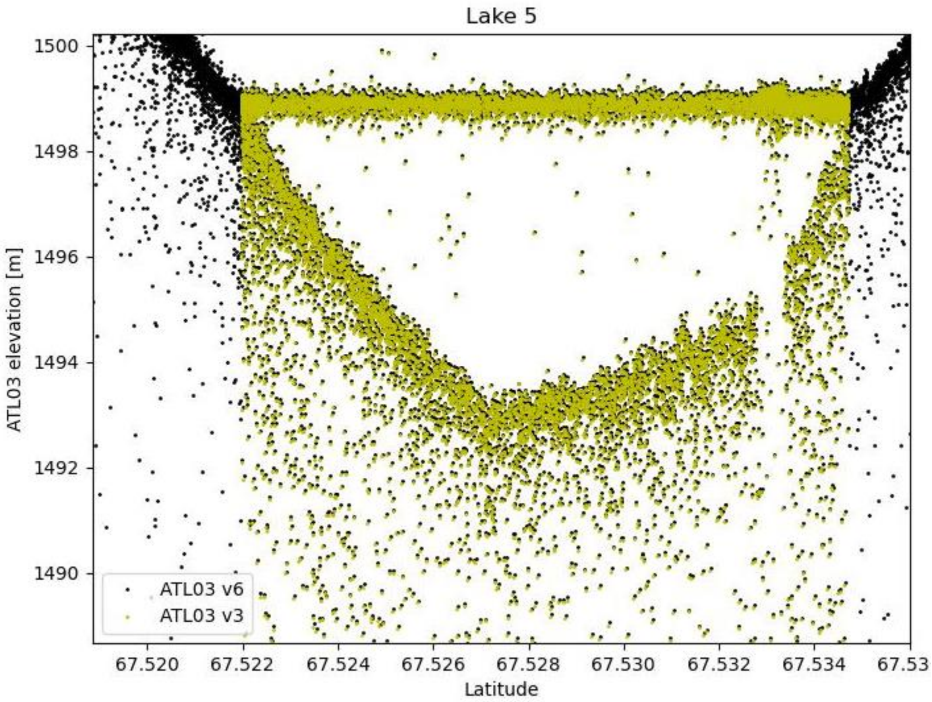

Figure 6: The photon plots of ICESat-2 version 3 (ATL03 v3) and ICESat-2 version 6 (ATL03 v6) for Lake 5.

<u>References within this response</u>

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