Response to Reviewer #2 on the manuscript:

Using ICESat-2 and Operation IceBridge altimetry for supraglacial lake depth retrievals by Fair et al.

We thank the reviewer for their comments and suggestions to improve the clarity and structure of the manuscript. In this response, the original comment is given in black, the authors' response in blue, and the proposed changes in orange.

Scope comment: "The paper limits itself to central strong beam (GT2R), but then also includes lower confidence photos from this band which 'decreases measurement precision but gives better agreement with ground-based data.' Because of this, I am wondering why other beams were not used, or at least their potential use discussed in the paper?"

The central strong beam was initially selected for the number of lakes observed over the Amery Ice Shelf. However, we recognize that the other strong beams (GT1L and GT3L) could also be used for depth retrievals. The weak beams (GT1R, GT2R, and GT3R for these ground tracks) are less effective at detecting beds for deeper lakes, so they were omitted from this study. We added the following to Section 2.1 to address these questions:

Our study focused on the central strong beam, as the number of lakes was deemed sufficient for our purposes. While we recognize that the other strong beams could be useful for depth retrievals we did not consider them here. We speculate that the weak beams may avoid issues with multiple scattering and specular reflection, but their power is too low to reliably detect lakes deeper than 4 m.

Page 6 Line 14: "Do you have any estimate for just how widely applicable these methods will be / how easy it is to get good coverage? I understand you have to put limits on this paper somewhere, for sure, so this is mostly out of curiosity and might be of interest in a discussion/ conclusion?"

We agree that these points would be useful to readers, so we added more information in Section 5.1.

The success of this method for lake depth retrievals is governed by spatial and temporal sampling of the instruments across the lakes when they are full. The methods presented here are most effective when the altimeter passes directly over the deep part of a lake rather than at its edge. This provides a lake depth profile that is more representative of the complete lake, allowing for improved estimates of lake depth and extent. A complete lake profile also provides sufficient information to the LSBS algorithm, reducing the risk of false negatives that occur with small lakes or incomplete profiles. The temporal sampling of ICESat-2 and ATM is infrequent (every 91-days for ICESat-2 and random for ATM), and so the same lakes will not always be present every time these data are required. Therefore, coincident satellite imagery is desirable to simplify the lake-finding process.

Data & Code Citation/Sharing (1) “The Cryosphere’s data policy states that ‘Authors are required to provide a statement on how their underlying research data can be accessed. This must be placed as the section ‘Data availability’ at the end of the manuscript.’ I did not see such a section. Clarity in citing the exact subsets of the large datasets that you cite would be ideal (which I know is also in your Table 1, but not presented in one place).”

The full information for the ICESat-2 and ATM data is given in Section 3.4, including date, ground track number, and coordinates. However, we acknowledge the lack of a Data Availability section, and we included one in the revised manuscript.

Code and data availability: ICESat-2 ATL03 V002 and ATM L1B V002 data may be accessed from https://doi.org/10.5067/ATLAS/ATL03.002 and https://doi.org/10.5067/19SIM5TXKPGT, respectively. Depth data for the supraglacial lakes given in Figure 4 are available at https://doi.org/10.5281/zenodo.3838274. Depth data for lakes in Figure 3 are available upon request from Zachary Fair. The LSBS algorithm and its subroutines may also be accessed from https://doi.org/10.5281/zenodo.3838274.

Data & Code Citation/Sharing (2) “The Cryosphere guidelines also state that "Data do not comprise the only information which is important in the context of reproducibility. Therefore, Copernicus Publications encourages authors to also deposit software, algorithms, model code, video supplements, video abstracts, International Geo Sample Numbers, and other underlying material on suitable FAIR-aligned repositories/archives whenever possible. These materials should be referenced in the article and cited via a persistent identifier such as a DOI." There is clearly a lot of important code developed and used by the authors, and it would be in line with this journal’s goals that it be documented, shared, and cited. This would allow for reproducibility, further application of these methods, and further refinement, as well. I very much hope that the reviewers document, share, and cite the final version of their code to make their methods as open as the data they use and the publication they have chosen to publish in. (Of course, if you have another code/methods paper in prep, then please do cite that and I apologize for jumping the gun!)”

The lake detection algorithms are available under the Assets section through the following link: https://doi.org/10.5281/zenodo.3838274. This is noted in the “*Code and data availability*” section.

The LSBS algorithm and its subroutines may also be accessed from the DOI given above.

Data & Code Citation/Sharing (3) “And since I’m talking about data and code sharing - at the risk of inviting my own citation - you cited Pope at al 2016 on Page 2 Line 23/24. I wonder whether you might (also) want to cite Pope (2016), which I bring up here because if more fully describes, documents, and shares the code developed and used in the Pope et al paper. https://doi.org/10.1002/2015EA000125”

We agree that the given paper would be a useful citation. We therefore added the following to Page 2, Line 17:

The normalized water difference index (NWDI) and dynamics thresholding techniques have also been considered for lake detection (Fitzpatrick et al., 2014; Liang et al., 2012; Moussavi et al., 2016; Pope, 2016; Williamson et al., 2017; Moussavi et al., 2020).

Page 1 Line 8-9 (Abstract): “Can you quickly mention where the uncertainties are derived from here? It might just be me, but if quickly reading, it makes it sounds like there is comparison to some in situ data…”

The uncertainty was derived from the standard deviation of acceptable lake bed photons. In other terms, the depth uncertainty is equal to the spread of lake bed photons. We reworded the given lines to be clearer:

Lake bed uncertainties for these retrievals…

Page 4 Line 10: “about how long is each data granule, in ground distance, to include10ˆ4 - 10ˆ5 photos per window? I think this will help people understand the next assumptions.”

Each flight track for ATM is 13-15 km in length, whereas each ICESat-2 ground track is ~10^3 km in total distance. We indirectly addressed this comment in response to Reviewer #1:

We divided each data granule into discrete along-track windows to reduce the data volume to ~10^4-10^5 photons per window. This photon count is equivalent to ~1-10 km in along-track distance for ICESat-2 and ~0.15-1.5 km for ATM.

Page 4 line 14: “How were these ranges selected / chosen? This would seem to be an important part of method development.”

These thresholds were selected by comparing the flatness of lake surfaces to that of surrounding ice topography. We also note here that the ATM threshold of 0.002 m was a typo, and it is supposed to be 0.02 m. We added the following to provide more clarity:

We define a "flat" surface for regions where $\sigma \leq 0.05$ m for ATL03 data, and ≤ 0.02 m for ILATM1B data. We selected these values by comparing the "flatness" of lake surfaces to that of surrounding ice topography.

Page 4 Line 14: "I'm sorry if I missed it, but can you define sigma in the text upon first usage?"

Sigma is previously defined as the standard deviation of high-confidence photons in Lines 12-13. To avoid confusion for future readers, we edited these lines slightly:

We check the flatness of the window by computing the standard deviation (σ) of high-confidence signal photons…

Page 4 Line 17: "Consider replacing "lake surface" with 'height of the lake surface' and underlining the letters h, s, f, and, c in order to make the abbreviation very clear?"

We changed as requested:

…we assigned the data to a new array for the height of the lake surface ($\underline{h_{sfc}}$).

Page 4 Line 20: "How were these ranges selected / chosen? This would seem to be an important part of method development."

The ranges for acceptable bed photons were selected through trial-and-error. The given bounds were selected to minimize the impacts of multiple scattering and specular reflection. To make this clear in the text, and to address comments from Reviewer #1, we reworded Lines 19-22 to be:

Within these horizontal bounds, we defined photons as a lake bottom if they satisfied the condition: $h_{sfc} - a\sigma_{sfc} \leq h \leq h_{sfc} - b\sigma_{sfc}$, where σ_{sfc} is the standard deviation of lake surface photons. The constraints a and b were derived through trial-and-error, such that a = 1.0 (1.8) and b = 0.5 (0.75) for ICESat-2 (ATM). We set these constraints to reduce the impacts of multiple scattering and specular reflection on depth estimates.

Page 4 Line 22: "Consider replacing 'lake surface' with 'height of the lake bottom' and underlining the letters h, b, t, and, m in order to make the abbreviation very clear?"

We assume this is a typo and that the reviewer is actually requesting a rewording of the term "lake bottom" (rather than "lake surface"). With this assumption, we applied the following change:

…the data were placed in an array for the height of the lake bottom ($\underline{h_{btm}}$).

Page 4 Line 27: "How were these filters chosen? This would seem to be an important part of method development."

We expand upon these issues in Section 5.2. However, we acknowledge that justification is needed here, so we applied the following change:

For ICESat-2, lakes shallower than 1.3 m or less than 200 m in horizontal extent were found to be too noisy or ill-defined for further analysis (see Section 5.2 for more details).

Page 4 / Section 3.1 in general: "It would be even clearer to present these methods if there were agreement between the steps here and in Figure 2 (e.g. one box / arrow per bullet point)."

We contemplated this suggestion, and we decided that one box or arrow per bullet point was unnecessary. However, we added labels to Figure 2 (now Figure 1 in response to another suggestion) to improve consistency with Section 3. The modified figure is shown below, and the bullet points in Section 3.1 were changed for consistency:

i. We divided each data granule into discrete along-track windows…

ii. Each data window was binned into elevation-based histograms…

iii. If the satellite image(s) confirmed the presence of a lake, the data were assigned to a new array for the lake surface (h_{sfc}). The horizontal extent of the lake surface served as a constraint for where the lake bottom data could be defined…

iv. A series of filters were applied to improve surface/bed estimates…

v. If the data were obtained from ICESat-2, then we followed a photon refinement routine that is described in more detail in Section 3.2. Calculations for lake depth were then performed for both ATM and ICESat-2 retrievals and corrected for refraction (Section 3.3).

Page 6 Line 18: "I could be wrong, but it is possible that Figure 1 and 2 are cited in backwards order? You might consider flipping their numbers?"

You are correct. For better consistency, we changed the numbering for the relevant figures.

(From Page 4, Line 7) For both instruments, the procedure for separation was identical, and is as follows (see Fig. 1 for a schematic view)…

(From Page 6, Lines 16-18) We present cases over the Amery Ice Shelf […], the western Greenland ablation zone […], and Hiawatha Glacier […] (Fig. 2).

Page 5 Line 27: "You mention a refraction correction but then there is no further detail. I know it is pretty basic, but for full clarity perhaps describe slightly more / provide a citation for the method you use for refraction correction?"

The refraction correction mentioned in Line 27 is briefly described in Lines 23-25. Line 24 includes a citation to Parrish et al. (2019), who outline a refraction correction algorithm based on beam angle and water depth. For quick reference, the passage is given below:

As a final adjustment to the lake photons, we applied a refraction correction algorithm to account for slowing down of the light as it enters water. The correction follows the methods utilized by Parrish et al. (2019) by approximating refractive biases as a function of depth and beam elevation angle.

Page 6 Line 29: "I wonder if you this it is important to re-emphasize the filtering of which lake depths were kept in presenting average lake depths? e.g. lots of shallow lakes aren't being included?"

The lake statistics given in Table 2 reflect quantities calculated from the lakes included in Figure 3. Therefore, the excluded lakes were not considered for the average depth given in Line 29. To emphasize this, we reworded Line 29 to be:

The average lake depth estimate for the lakes in Fig. 3 was 1.95 m…

Figure 1: "Consider using dots to indicate location, rather than ovals, which are much larger than the image are?"

This is a good suggestion. We replaced ovals with stars centered on the regions of interest. The stars appeared small if the full continental image was used, so we cropped the images to center on the markers. The new figure may be seen below:

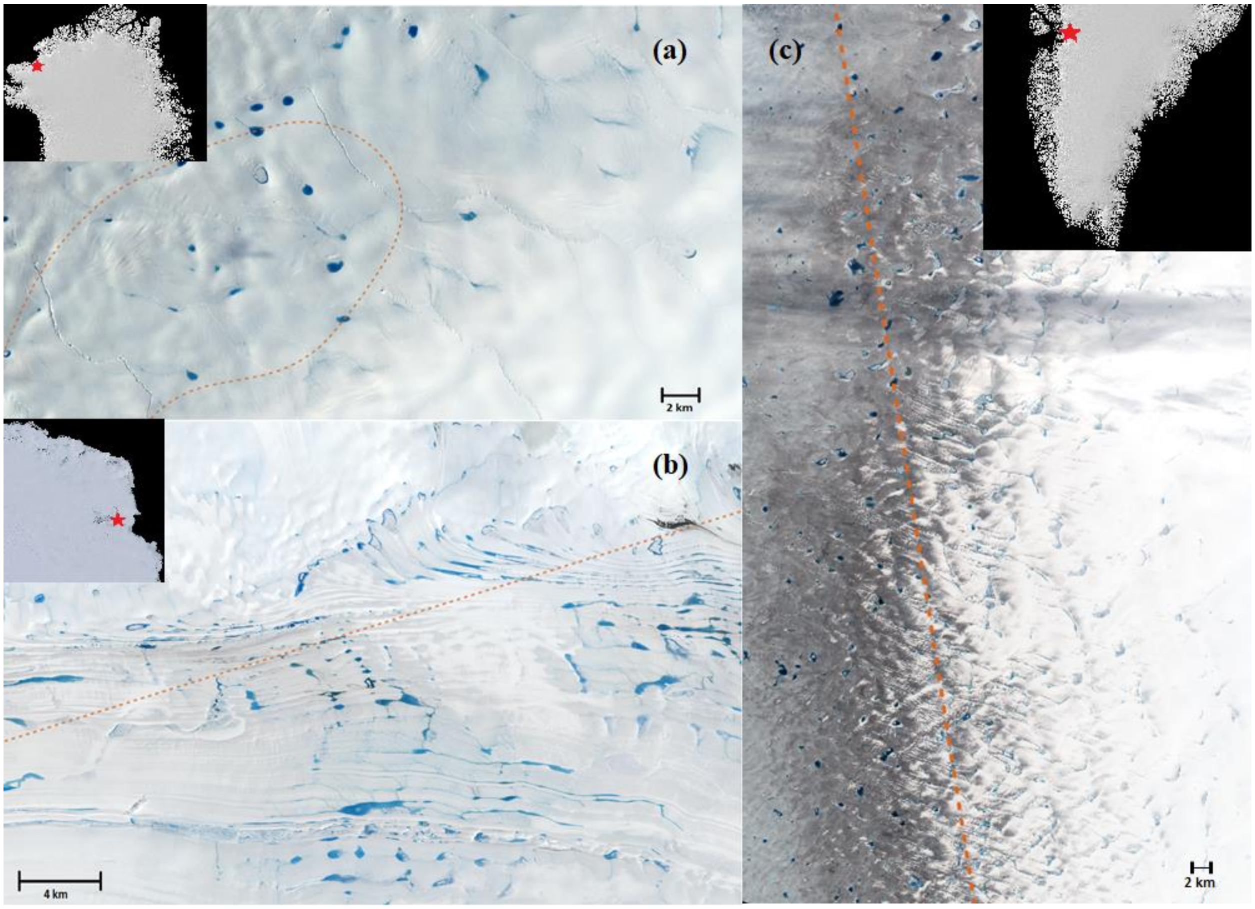

Figure 2: "It is slightly confusing that you use the same blue boxes for both data and processes (e.g. Landsat 8 imagery vs verify lake detection), consider using different shapes / colors / some design choice to indicate the difference?"

We changed the color of the "ATL03/ILATM1B granule" and "Landsat-8 imagery" boxes to green to differentiate data inputs from algorithm steps. We also grouped the steps into sections to create better consistency between the figure and Section 3, as suggested above. The new figure and caption are shown below:

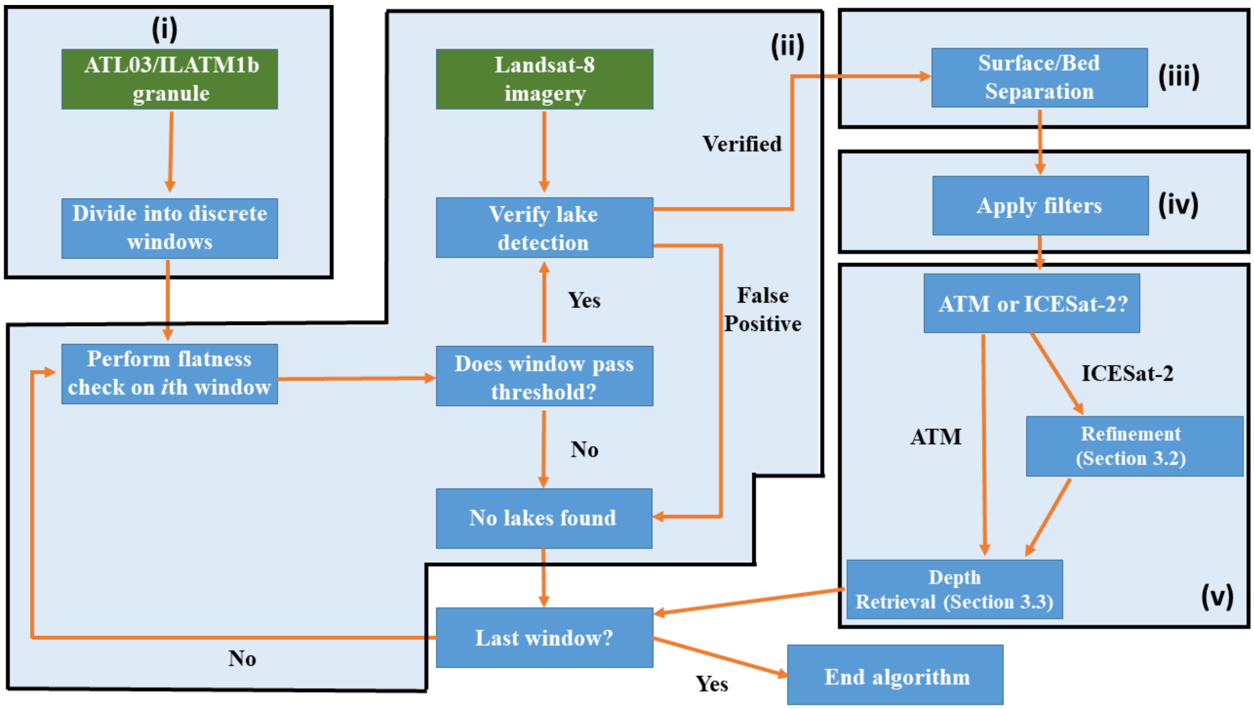

Figure 2. Schematic for the workflow of the lake surface-bed separation algorithm, where green boxes indicate data inputs and blue boxes are steps in the algorithm. Roman numerals match the steps given in Section 3.1.

Table 2: “Please also define d_s, d_p, and L in the table caption”

We changed as requested:

Cumulative statistics for ATM supraglacial lakes explored in this study, including mean and maximum signal-based depth (d_s) and polynomial-based depth (d_p), along-track extent L, mean lake depth uncertainty…