Response to RC1

A Framework for Automated Supraglacial Lake Detection and Depth Retrieval in ICESat-2 Photon Data Across the Greenland and Antarctic Ice Sheets

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Comments from the reviewers are given in black.
Our responses are given in red.
Quotes from the submitted manuscript are given in bold red.
Proposed amendments or additions to the revised manuscript are given in blue in the Times New Roman font.

References that were already included in the original manuscript are cited in-text only, in the same format as in the submitted manuscript. New references are added to the end of this document in full.

Referee Comment 1 (Jennifer Arthur)

RC1: 'Comment on egusphere-2024-1156', Jennifer Arthur (jennifer.arthur@npolar.no), 11 Jun 2024
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Summary

This manuscript uses ICESat-2's ATL03 altimetry product to develop two new algorithms which together provide a scalable framework for supraglacial lake detection and depth determination from ATL03 data. Surface melt is an important, yet poorly constrained, component of ice-sheet surface mass balance, leading to surface meltwater accumulating as lakes on ice-shelf surfaces and on grounded ice. In Antarctica, this has been linked to the process of meltwater-driven hydrofracture, which can trigger rapid ice-shelf collapse. Accurately measuring supraglacial lake meltwater depths from satellite data is important due to the challenges in obtaining in situ measurements and is needed for modelling meltwater interactions with ice sheet dynamics. However, few studies have developed automated lake depth estimation methods that are scalable beyond small data subsets, and previous studies rely on methods with poorly constrained parameters and a lack of in situ measurements.
The authors apply their algorithm framework to two regions that experience high surface melt (central west Greenland and the Amery Ice Shelf) and are able to reliably detect lakes where lake bathymetry is visible. The methodology appears robust, and the algorithm performs well even for more complex lakes (especially in Antarctica), including thin, elongated lakes and those with patchy ice cover. The authors found 1249 lakes with their algorithm during four melt seasons and conclude that lake depths agree well with manually-picked lakebeds in ICESat-2 along-track segments.
Overall, it is my view that this study is of broad interest to the cryospheric community as it builds upon previous work focused on supraglacial lake depths on both ice sheets, especially in the context of ice-shelf surface

hydrology and dynamics, by paving the way for developing pan-ice sheet supraglacial lake depth and volume products. I think the surface hydrology and ice shelf communities would be very interested to see this algorithm applied at an ice-sheet scale in future.
In general, this is a very well-written manuscript with detailed methods, clear figures and most of my comments are relatively minor. Once the authors address these, I can therefore recommend that this manuscript is suitable for publication in The Cryosphere.
Please see the attached for specific comments.

Thank you so much Jenny for taking the time to read and review our manuscript, and for your positive, thoughtful and constructive comments. In particular, we believe that your comments were instrumental in better presenting this manuscript within the context of the broader research community's efforts to characterize surface hydrological processes and quantify meltwater on the ice sheets.

General points

1. The manuscript could elaborate in a bit more depth about how this algorithm framework approach differs from previous algorithms that have been developed for supraglacial lake depth/bed detection with the same ICESat-2 product (e.g. Datta and Wouters, 2021, who use ICESat-2 ATL03 to derive lake depths and constrain empirically-derived depths from Landsat 8, Sentinel-2, PlanetScope and SkySat imagery). It is clear to me that previous approaches have been tested on small subsets and so are not as scalable as the approach presented here, but I think more detail could be provided for readers.

   For a detailed discussion of this, as well as various explicit proposed changes, please see our response to CC1. We will make it clear in the introduction that:
   - The main "selling point" of our study is that we present a method allowing users to implement supraglacial lake depth estimation from ICESat-2 at scale, and that we took on the task to demonstrate that this works in practice.
   - The motivation behind large-scale implementation are promising case study results (e.g., Datta and Wouters, 2021; Leeuwen, 2023) suggesting that statistically learning the relationship between reflectance in imagery and water depth using ICESat-2 data has great potential to improve imagery-based approaches for continuously monitoring meltwater depths and volumes. For such statistical models to be able to perform well and generalize, we need as much ICESat-2-labeled training data (from a variety of locations, times and environmental conditions) as possible.
   - The fact that FLUID-SuRRF is automated and scalable is not a unique selling point for our study. Other algorithms that claim automation and scalability have been published (e.g. Datta and Wouters, 2021; Xiao et al., 2023). What makes our study unique is the fact that we actually scale it up across two large domains.

   We will also add a comparison of actual depth retrievals between SuRRF, Watta, RTE and a DEM-based method to Section 4.2.2 by including them in Fig. 12 and giving a short description/explanation in the text. We will, however, not go into much detail about this, and instead refer the reader to the method comparison studies of Fricker et al. (2021) and Melling et al. (2024). Fricker et al. includes an earlier version of SuRRF, and all other depth estimates shown in Fig. 12 are reproduced from the two studies mentioned above. For more details on this, see our response to general point 3.

2. 'Lakes with a bathymetric signal' is referred to often throughout the manuscript, and I suggest perhaps the first time this is mentioned adding for clarity: 'lakes with a bathymetric signal, i.e lakes with a visible

or partly-visible lakebed'.

Thank you for the suggestion. We agree that adding this phrase will make it easier for the reader to understand what is meant. We will make the following clarifying changes: (1) change **"a bathymetric signal is discernible"** to "the lakebed is visible or partially visible" in the abstract, (2) change **"signal"** to "return from the lakebed" in the caption of Fig. 1, and (3) add ", i.e. for lakes with a visible or partly visible lakebed" to the last sentence of section 3.1.

3. Performance of the SuRRF algorithm is compared to manual baseline estimates in Section 4.2.2, but I think this could be interesting to elaborate briefly on how the depth estimates are different from results that derive depths using the Radiative Transfer Equation (given that this is a commonly-applied method). For example, does SuRRF tend to detect deeper lakes, implying previous methods underestimate lake depths?

   This is a good point, and we should have made this more clear. We will clarify in Sect. 2.2 (where the RTE approach is introduced) by changing the last sentence from **"As a result, it has been found that the RTE approach can significantly over- or underestimate lake depths (Fricker et al, 2021; Melling et. al, 2024)."** to "As a result, it has been shown that the RTE approach can significantly over- or underestimate lake depths in different environments: in Fricker et al. (2021) the method underestimated depths by 30 to 70 % on Amery Ice Shelf in East Antarctica, while in Melling et al. (2024) it overestimated depths by up to 153 % in Southwest Greenland."
   As suggested, we will further add a comparison of actual depth retrievals between SuRRF, Watta, RTE methods and a DEM-based method to Section 4.2.2 by including them in Fig. 12 (see below) and giving a short description/explanation in the text. To reflect this, we will rename Section 4.2.2 to "Accuracy of SuRRF depth retrievals and comparison with alternative methods"

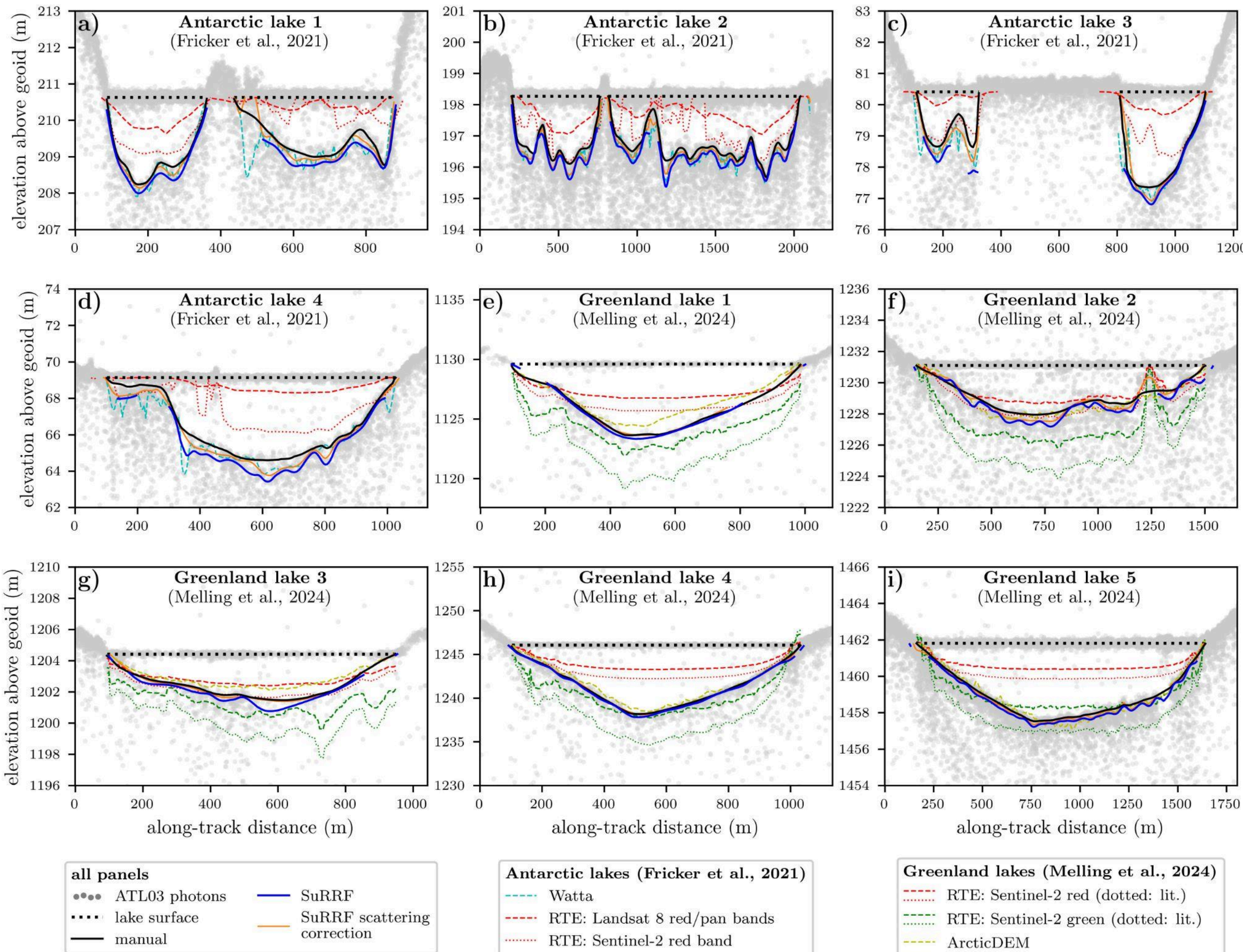


Figure 12. Comparison between SuRRF water depth estimates, manually annotated ICESat-2 depths and results from other methods for meltwater depth estimation. a)-d): ICESat-2 melt lake segments on the Amery Ice Shelf with manual annotations from Fricker et al. (2021). Other meltwater depth estimates that were reported by Fricker et al. are shown for the Watta algorithm (based on ICESat-2; Datta and Wouters, 2021), for the RTE method applied to the average of Landsat 8's red and panchromatic bands (Spergel et al., 2021) and to Sentinel-2's red band (Moussavi et al., 2020). e)-i): ICESat-2 melt lake segments in Southwest Greenland with manual annotations from Melling et al. (2024). Other meltwater depth estimates that were reported by Melling et al. are shown for the RTE method individually applied to both Sentinel-2's red and green bands, as well as estimates from post-drainage lakebed topography in ArcticDEM (based on Bowling et al., 2019).

We will, however, not go into much detail in the text beyond briefly describing what is shown on the figure, and instead refer the reader to the method comparison studies of Fricker et al. (2021), Melling et al. (2024) and Lutz et al. (2024). Fricker et al. includes an earlier version of SuRRF, and all other depth estimates shown in Fig. 12 are reproduced from either Fricker et al. or Melling et al.

On line 592, we will specify that we are showing results from other methods, but that for in-depth comparisons, we refer the reader to the relevant studies:

"We here use the manual annotations from both of these method comparison studies to evaluate SuRRF's depth estimation performance for all nine lake segments, and to briefly compare SuRRF to other methods whose results were included in previous comparisons (Fig. 12). For a detailed comparison between various ICESat-2 lake depth algorithms (including an earlier version of SuRRF) and RTE-methods, we refer the reader to Fricker et al. (2021). For in-depth discussions comparing manually picked ICESat-2 depths to RTE methods, DEM-based approaches as well as empirical methods using in-situ data, we refer the reader to Melling et al. (2024) and Lutz et al. (2024)."

We will add the following comparison between SuRRF and alternative methods to the end of section 4.2.2 (line 612):

In addition to SuRRF and manual depth estimates, panels a)-d) of Fig. 12 show depth estimates for Antarctic lakes that were reported in Fricker et al. (2021), for the Watta algorithm (based on ICESat-2; Datta and Wouters, 2021) and for the RTE method applied to the average of Landsat 8's red and panchromatic bands (Spergel et al., 2021) and to Sentinel-2's red band (Moussavi et al., 2020). Both SuRRF and Watta track the general shape of lakebed returns in the ATL03 photon clouds well (Pearson's correlation coefficients of R = 0.99 and 0.94, respectively), and and largely agree with manually determined along-track water depths (MAEs of 0.29 m and 0.30 m, respectively). In contrast to SuRRF, Watta appears to have a tendency to overfit where photon density near the lakebed is high with a large elevation spread, resulting in an unreasonably "wiggly" lakebed fit (e.g., Antarctic lake 1, 500-800 m). SuRRF's smoother fit under these conditions is likely due to the fact that it utilizes an adaptive kernel for its robust fit, whose width increases as the number of photons that narrowly cluster around the previous iteration's fit decreases (Sect. 3.3.1). In contrast to SuRRF, Watta also attempts to fit the lakebed across the entire lake basin, even where the lakebed is not visible or indistinguishable from noise, which can sometimes result in arbitrary, unrealistic depth estimates (e.g., Antarctic lake 1, around 450 m). Under such conditions SuRRF assigns a low confidence score to the lakebed fit and discards associated depth estimates to prevent arbitrary results. However, in some cases this results in SuRRF discarding depth estimates where Watta appears to fit the lakebed reasonably well (e.g., Antarctic lake 3, 250-300 m). The RTE approach based on Landsat 8's red/panchromatic band average consistently underestimates water depths, reporting a total amount of water that is ~ 73 % lower than the manual baseline. The RTE approach based on Sentinel-2's red band also underestimates water depths, and reports a total amount of water that is 34 % lower than the manual baseline.

Panels e)-i) of Fig. 12 also show non-ICESat-2 depth estimates for Greenland lakes that were reported in Melling et al. (2024), for the RTE method individually applied to both Sentinel-2's red and green bands, as well as estimates from post-drainage lakebed topography in ArcticDEM (based on Bowling et al. 2019). The RTE approach based on Sentinel-2's red band generally underestimates depths and reports a total amount of water that is 42 % lower than the manual baseline (similar to this method's performance over Antarctic lakes). In contrast, the RTE approach based on Sentinel-2's green band generally overestimates depths and reports a total amount of water that is 34 % larger than the manual baseline. However, Melling et al. also note that when using values of tuneable parameters that have been commonly used in the literature (Sneed and Hamilton, 2007; Georgiou et al., 2009; Pope et al., 2016), the RTE approach for Sentinel-2's green band overestimates lake depths even more, which results in reporting a total amount of water that is 84 % larger the manual baseline, with individual depths being overestimated by up to 153 %. This implies that RTE-based methods, while being popular for their simplicity, can potentially result in highly inaccurate meltwater volume estimates. The depth estimates derived from DEMs of emptied lake basins match the ICESat-2 manual baseline reasonably well, and when compared with it underestimate the total amount of water by 6 % with a MAE of 0.34 m. Since this method's performance is comparable to that of ICESat-2-based methods, this implies that DEM-based methods could be used supplement ICESat-2 depth measurements for labeling reflectance in passive optical imagery with supraglacial water depths, at least on the Greenland Ice Sheet where melt lakes on grounded ice drain regularly (Johansson et al., 2013).

4. For those who are less familiar with distributed High-Throughput Computing, how widely useable is this algorithm for others to whom the OSG Open Science Pool is not accessible, aka. non-US-based researchers?

   Our Python code works without the need for using any OSG services: it can be run on a local computer or on any computing cluster (locally or in the cloud) in the provided singularity container. We used the OSG Open Science Pool because it provided us with free computational infrastructure. We do not have the resources to scale this method up to ice-sheet-wide implementation on commercial cloud computing platforms at a feasible price point, and during initial development PA had no access to NASA-provided computational resources due to the COVID19 pandemic preventing in-person fingerprinting of non-US citizens. We believe that the OSG Open Science Pool is the most accessible option for large-scale implementation, but there are unfortunately some limitations to who can use it. As a non US-based researcher, one could gain access to the OSG Open Science Pool if collaborating with a US-based researcher or an institution that operates its own access point. Since we want our methods and data to be accessible and encourage others to use it in their own research, we will explain this in more detail in the Code and data availability section:

"The FLUID/SuRRF source code is freely available at https://doi.org/10.5281/zenodo.10905941 (Arndt and Fricker, 2024a). To execute this code, users need to create a free NASA Earthdata login for ICESat-2 data access. The source code contains a singularity container in which this version of FLUID/SuRRF can be executed. The main Python script detect_lakes.py can be run either locally on any individual ATL03 granule, or on many granules in parallel on any computing cluster that supports the specified computing environment or the use of singularity containers. In this study we present our implementation of FLUID/SuRRF on the OSG Open Science Pool because it provided us with free computational infrastructure. Due to funding mandates, free access to the OSG Open Science Pool is limited to researchers contributing to a US-based project at an academic, government, or non-profit organization, or researchers affiliated with any project or institution that operates its own local access point. This means that to implement FLUID/SuRRF on the OSG Open Science Pool as described here, you need to have at least one collaborator on your team to whom the above criteria apply. This collaborator can register your project with OSG on the Open Science Pool. Then, anyone contributing to the project can register for an account on OSG Connect to gain access to the Open Science Pool. For more information, see https://osg-htc.org/services/open_science_pool.html and https://osg-htc.org/about/organization. More information is also included in the README file."

Specific comments

- L30: I would cite something more relevant than this EGU abstract here, e.g. Gilbert and Kittel (2024), https://doi.org/10.1029/2020GL091733.
  We will replace the citation with the suggested one.

- L34: Perhaps add a sentence or two here about what direct observations of supraglacial lake depths do exist, particularly in Antarctica (to highlight the paucity of observations).
  This is a good suggestion, and we will briefly mention this here:
  "However, there are few direct in-situ observations of supraglacial lake depths (none in Antarctica, and ten lakes up to 11.5 m deep in Greenland), which leads to errors in total water volume estimates."
  We will elaborate on this further in Sect. 2.2, where we introduce empirical models derived from regression of in-situ depth measurements with optical imagery (L109, see comment below).

- L109: add where these in situ measurements were collected (west Greenland).
  We include a description of where the in-situ measurements were collected, as suggested. This does not only include West Greenland, but also South-East and North-East Greenland. Based on the previous comment, we also reiterate that no observations are available for Antarctica. See the updated paragraph below:
  "Another approach to estimating lake depths is using **empirical models** derived from regression of in-situ depth measurements with optical imagery (Tedesco and Steiner, 2011; Legleiter et al., 2014; Pope et al., 2016; Lutz et al., 2024). However, in-situ measurements of supraglacial lake depths are very sparse, with – to the best of our knowledge and at the time of writing – no such data is available for Antarctica, and data available for only ten lakes up to 11.5 m deep on the Greenland Ice Sheet between 2005 and 2024: Box and Ski (2007) sampled two

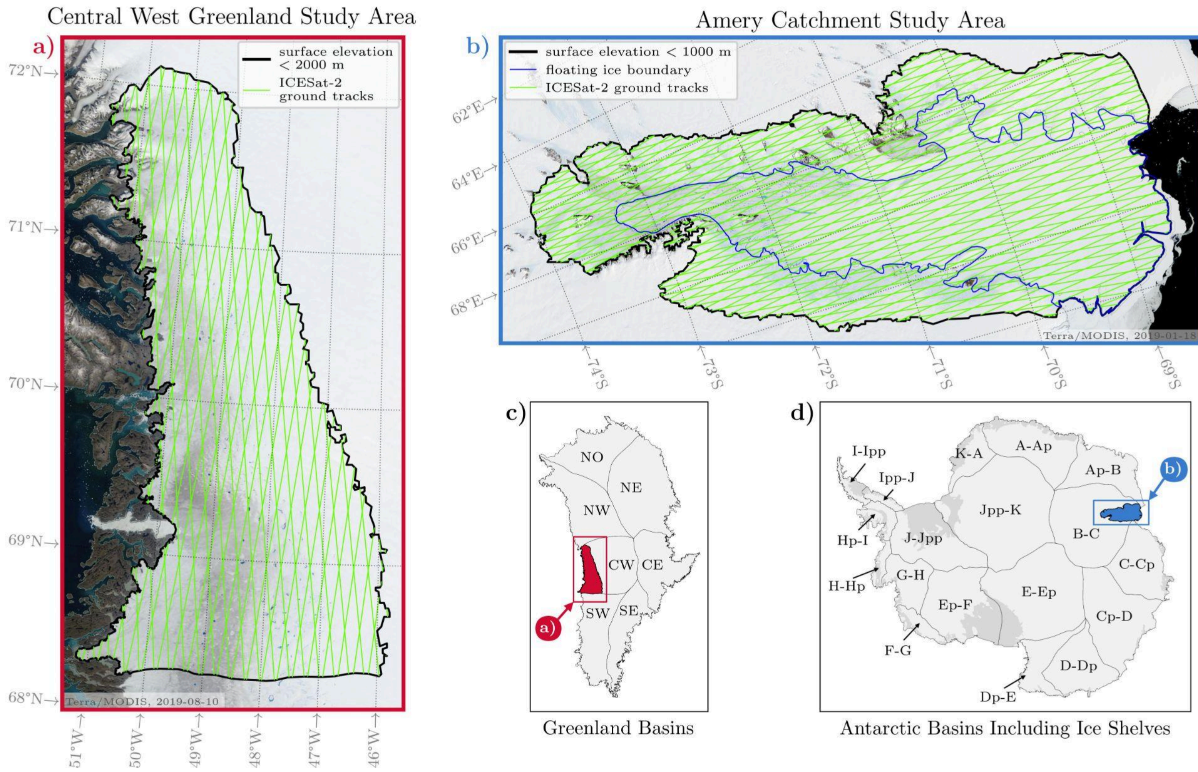
lakes on Jakobshavn Isbræ and Sermeq Avannarleq in 2005, Sneed and Hamilton (2007) sampled one lake on Helheim Glacier in 2008, Tedesco and Steiner (2011) sampled one lake in Central West Greenland in 2010, Legleiter et al. (2014) sampled three supraglacial water bodies on Isunnguata Sermia and Russell Glacier in 2012 and Lutz et al. (2024) sampled three lakes on Zachariæ Isstrøm in 2022. This makes the observations provided by Lutz et al. the only in-situ depth data of supraglacial lakes that overlap with the Landsat 8 and Sentinel-2 missions. Further, it has been shown that the relationship between water depth and reflectance values in optical imagery can vary significantly by geographical region (Lutz et al., 2024). Thus, the regression coefficients of these empirical models are limited to the spatial area of the original in-situ measurements, making them impractical for application on a larger, ice-sheet-wide scale."

For reference, for a full list of in-situ measurements of supraglacial lake depth available in the literature, see the table below:

source	lon	lat	date	IMBIE_basin	IMBIE_name	depth_min	depth_max	n_obs	accuracy_m	instrument
Box and Ski (2007)	-49.1254	69.5345	2005-08-14	CW	JAKOBSHAVN_ISBRAE	1.05	11.5	335	0.1	Garmin Fish Finder 100
Box and Ski (2007)	-49.5345	69.4891	2005-08-15	CW	SERMEQ_AVANNARLEQ	1.25	10	338	0.1	Garmin Fish Finder 100
Sneed and Hamilton (2011)	-38.45	66.46145	2008-07-11	SE	HELHEIMGLETSCHER	0.7	3	21	0.03	Satlantic Profiler II
Tedesco and Steiner (2011)	-49.4944	69.60972	2010-07-02 to 05	CW	CW_NONAME1	n/a	4.5	6000	0.25	HDS-5 Lowrance
Legleiter et al. (2014)	-48.322	67.11825	2012-07-20	SW	ISUNNGUATA-RUSSELL	n/a	3.16	3264	0.025	Ohmex SonarMite 235KHz
Legleiter et al. (2014)	-48.1008	66.9025	2012-07-21	SW	SAQQAP-MAJORQAQ-SOUTHTERRUSSEL_SOUTHQUARUSSEL	n/a	10.45	4383	0.025	Ohmex SonarMite 235KHz
Legleiter et al. (2014)	-48.7649	67.18042	2012-07-23	SW	ISUNNGUATA-RUSSELL	n/a	1.66	1164	0.025	Ohmex SonarMite 235KHz
Lutz et al. (2024)	-21.8182	78.92271	2022-07-09	NE	ZACHARIAE_ISSTROM	0.41	8.21	2129	0.2	Lawrence Elite 7 FS
Lutz et al. (2024)	-21.9217	78.90026	2022-07-03	NE	ZACHARIAE_ISSTROM	0.46	6.78	981	0.2	Lawrence Elite 7 FS
Lutz et al. (2024)	-21.9373	78.87014	2022-07-09	NE	ZACHARIAE_ISSTROM	0.39	7.32	2991	0.2	Lawrence Elite 7 FS

(some of the information for Lutz et al. is from private communication, but we were told that their dataset should be up on PANGAEA soon)

- L484: I would rename the labels ‘CW < 200 m’ and ‘B-C < 1000 m’ to ‘Surface Elevation < 200 m’ and ‘Surface Elevation < 1000 m’ for clarity, or else clarify this in the figure caption.
  We will follow this suggestion. See the updated figure below.



- L543: could also add here that lakes typically are advected downstream year-on-year (e.g. Arthur et al., 2020).
  We will follow this suggestion and add the following at the end of the sentence on L543: "', with existing basins typically being advected to locations significantly further downstream from one melt season to the next (Arthur et al., 2020)."

- L579-585: This explanation for differences in lake elevation-depth relationships could be better cited. For example, Banwell and MacAyeal (2015) highlight lake deepening by lake-bottom ablation.
  We agree that this section should have been better supported by existing literature. We will reference Lampkin and VanderBerg (2011) and Tedesco et al., (2012) to support the claim that fixed lakebed locations controlled by bedrock topography and lake bottom ablation cause deep lakes in Greenland. We will reference Bell et al. (2018) as a reference for arguing that lakes on grounded ice in Antarctica are more prevalent under warmer conditions and behave similarly to lakes on grounded ice in Greenland. We will also add two new references:
  - Glen et al. (2024) as a reference supporting that there are more small, shallow and slushy lakes in Greenland in warm summers than in cooler summers.
  - Banwell et al. (2014) as a reference supporting the claim that lakes which form on the fairly flat topography of Antarctic ice shelves tend to be more shallow than those on grounded ice on the Greenland Ice Sheet.

- L613: I'm not sure about the overall relevance of Section 4.3 and don't think it adds substantially to the manuscript, because the algorithm application to ocean bathymetry, inland waters or sea ice melt ponds is less relevant in the context of this manuscript. I would suggest removing this section and moving the content from 'The ephemeral nature of supraglacial lakes…' to further up in the introduction as justification for your algorithm.
  ICESat-2 is an interdisciplinary instrument where scientists from different fields have worked together to improve algorithms that apply to 'cross-cutting' themes, such as bathymetry. In that spirit, we consider the section to be highly relevant in the context of this largely methods-focused manuscript, because

method development for ICESat-2 water depth estimation benefits from cross-discipline collaboration between scientists who work on using the satellite's bathymetric capabilities in different environments (Parrish et al., 2022). As such, Section 4.3 is meant to (1) give credit to some of the work that is not directly concerned with supraglacial lakes but has inspired our own work and (2) encourage readers with an interest in ICESat-2-specific methods for supraglacial lake depth estimation to draw inspiration from the broader related literature themselves.

However, this comment has made us realize that we did not justify this well in Section 4.3, and therefore suggest the following change:
"Beyond estimating the depth of supraglacial lakes, ICESat-2's bathymetric capabilities have been used for various other applications. Many algorithms employed for depth retrieval from ATL03 share significant similarities, enabling method development for ICESat-2-derived bathymetry to benefit from broader cross-discipline collaboration (Parrish et al., 2022). Methods similar to FLUID-SuRRF have been used for [...]. However, there are also notable differences between bathymetric applications of ICESat-2 in different environments that have led to the development of specialized approaches, in particular for their large-scale implementation. For nearshore and inland bathymetry applications [...]"

- L630: I don't entirely agree with the part of this sentence that states the calculated water depths prevent the calculation of lake volumes. Surely it would be possible to calculate lake volumes by combining the ICESat-2 derived depths with lake extents derived from optical imagery (Landsat 8) as an initial estimate? I do understand though that with the small dataset you present here it is not enough to track the meltwater through the melt season.

  Thank you for catching this! We meant to say that the ICESat-2 observations by themselves are not enough to calculate lake volumes and therefore need to be combined with other types of data such as imagery to achieve this goal. We will change the sentence to "Our ICESat-2-derived water depths are the first comprehensive dataset of supraglacial lake depths that were directly measured from a satellite; however, these along-track observations alone are too sparsely spaced…". We will also add a reference to ICESat-2 in the next sentence to make this more clear: "However, the large volume and wide variety of data that our method provides implies that the ICESat-2 based depth measurements presented here could be used to…"

Technical/minor corrections

- In some places the Surface Removal and Robust Fit algorithm is referred to as SuRRF and in others as SuRFF, so check throughout for consistency.
  Thank you for catching that! We will replace 14 instances where we accidentally used the abbreviation **"SuRFF"** with "SuRRF".

- L178: delete 'each' (same on L653).
  We will delete **"each"** in both instances, as suggested.

- L611: Is a word missing here? '.. in between our (deeper) SuRRF estimates and the (more shallow) manual baseline estimates'.
  Yes, thanks for catching that. We will add "and", as suggested.

- L640: don't hyphenate 'well-enough'.
  We will remove the hyphen, as suggested.

- L710: it’s origin → its origin
  We will remove the apostrophe.

References:

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