Response to RC2

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

Philipp Sebastian Arndt[1] and Helen Amanda Fricker[1]

[1] Scripps Polar Center, University of California San Diego, 8885 Biological Grade, La Jolla, CA 92037, USA

Correspondence:
Philipp Sebastian Arndt (parndt@ucsd.edu)

Discussion: https://doi.org/10.5194/egusphere-2024-1156

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 2 (Ian Brown)

RC2: 'Comment on egusphere-2024-1156', Ian Brown, 17 Jun 2024
Citation: https://doi.org/10.5194/egusphere-2024-1156-RC2

Summary

This is an important contribution to our ability to monitor the supra-glacial hydrology of the ice sheets. It is a very well executed investigation and a well written manuscript. I have some small concerns regarding validation and some suggestions for minor edits.

Thank you so much Ian for taking the time to read and review our manuscript, and for your positive, thoughtful and constructive comments. In particular, we believe that your suggestions regarding a clearer distinction between ICESat-2 lake segments and unique "real" supraglacial lakes have helped to make the manuscript more clear, especially to readers who are not already very familiar with ICESat-2 data.

Specific comments

- The first sentence sets the tone so it is a little odd to address ice shelf collapse when that is not the focus of the article. Consider refocusing the opening sentence.
  We propose adding an opening that specifically addresses the difficulty of monitoring the water depths of supraglacial lakes on the ice sheets, then continue with arguing why knowing water depths is important: "Water depths of supraglacial lakes on the ice sheets are difficult to monitor continuously due the lakes' ephemeral nature and inaccessible locations. Supraglacial lakes have been linked to ice shelf collapse in Antarctica and accelerated flow of grounded ice in Greenland. However, the impact of supraglacial lakes on ice

dynamics has not been quantified accurately enough to predict their contribution to future mass loss and sea level rise. This is largely because ice-sheet-wide assessments of meltwater volumes rely on models that are poorly constrained due to a lack of accurate depth measurements."

- Line 38. "Recently" is relative. ICESAT-2 has been in orbit for 5 years and readers may access the article in a decade meaning "recently" is not appropriate. Delete the word.
  Good point, and in fact it is now nearly 6 years. We will change this to: "Launched in 2018, NASA's Ice, Cloud and land Elevation Satellite (ICESat-2)..."

- Line 205-206. Can you describe in more detail the empirical observations: how many were used to establish the thresholds?
  We admit that the phrasing of this was confusing in the submitted manuscript. What we meant to convey is that we established these thresholds based on trial-and-error testing on a number of hand-picked granules that we judged to be likely representative of various possible environments. For clarification, we propose to change this part to the following:
  "Based on these assumptions, and using a trial-and-error approach, we defined the following thresholds on the density ratios that need to hold for a major frame to pass the flatness check: $d_0/d_1 \geq 2$, $d_0/d_2 \geq 5$, $d_0/d_3 \geq 10$ and $d_0/d_4 \geq 100$. As part of this trial-and-error approach, we manually assessed the effects of tweaking the above thresholds on a number of hand-picked granules, which we judged to be likely representative of various possible environments, to ensure adequate performance (i.e. granules without surface melt vs. pervasive surface melt, granules with smooth vs. rough background topography, granules containing ice-covered and partially ice-covered lakes, granules containing slush areas, granules containing exposed bedrock, partially cloudy granules, weak vs. strong beam data, night- vs. daytime acquisitions, etc.)."

- Line 227. Does FLUID work as well in the presence of wind roughened water surfaces: I assume it does though perhaps fewer photons penetrate the surface. Please comment (as you specifically address the impact of wind on optical estimates of water depth on line 105).
  We propose to re-write this part to include a discussion of the effects of wind, as suggested:
  "Afterpulses only become noticeable when the sensor is nearly or fully saturated, which means they often appear in ATL03 data over supraglacial lakes because smooth open water surfaces (i.e. the surface of stationary water bodies that are not affected by wind) can result in specular reflection. This suggests that the presence of wind ripples increases the likelihood of detecting a lake with a clear bathymetric signal in ATL03 data by preventing sensor saturation and afterpulsing (Lu et al., 2019; Tilling et al., 2020) and also explains why we observe afterpulsing more frequently near the (more wind-shielded) margins of melt lakes than over their (more wind-exposed) interior."

- Line 251. c is presumably the speed of light in a vacuum or freshwater (line 434)? Please clarify.
  Thanks for catching this! c is the speed of light in a vacuum, which is the value that is used to calculate photon elevations from each photon's time of flight. We will clarify this by adding the following to the end of this sentence: ", where c is the speed of light in a vacuum."

- Line 321. Define "a few".
  We agree that we should be more specific here. The phrase "along-track extent" was poorly chosen. The 10 in Eq. (3) is what describes this: the maximum separation between two clusters to be merged is 10 major frames, so clusters that are separated by more than 1.4-1.6 km are not merged. To clarify this we propose to replace (ii) on line 321 with:
  "(ii) a ground track rarely crosses the same lake in two distinct locations that are separated by more than about 1.5 km."
  We will further explain equations (2) and (3) in plain language after they are defined:

“Equation (2) states that neighboring clusters are only merged if their respective lake surface elevations are within 0.1 m of each other, and Eq. (3) further states that neighboring clusters are only merged if they are separated by ten major frames that did not pass the bathymetry check, or less (about 1.5 km). This means that if FLUID encounters the unlikely but possible scenario in which a ground track crosses two arms of the same lake, which are separated in along-track distance by more than ten major frames, then these two crossings are considered to be separate lake segments and returned as two separate files in the output data rather than being merged together into one lake segment. If these two conditions do not result in…”

- Line 343-345. It would be useful to estimate the real number of lakes mapped if possible. If it is not possible please discuss this in the appropriate section of the manuscript.
  This is a great suggestion. We will add a row to Table 1 that shows the estimated number of unique, contiguous melt lakes that are sampled by our ICESat-2 lake segments:

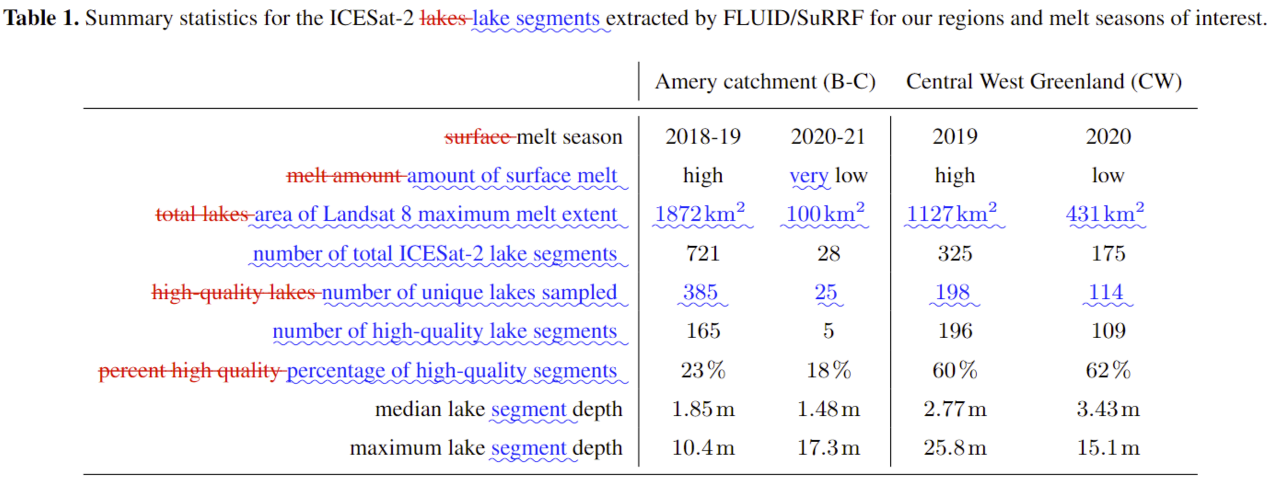


Table 1. Summary statistics for the ICESat-2 ~~lakes~~ lake segments extracted by FLUID/SuRRF for our regions and melt seasons of interest.

	Amery catchment (B-C)		Central West Greenland (CW)	
~~surface~~ melt season	2018-19	2020-21	2019	2020
~~melt amount~~ amount of surface melt	high	very low	high	low
~~total lakes~~ area of Landsat 8 maximum melt extent	1872 km^2	100 km^2	1127 km^2	431 km^2
number of total ICESat-2 lake segments	721	28	325	175
~~high-quality lakes~~ number of unique lakes sampled	385	25	198	114
number of high-quality lake segments	165	5	196	109
~~percent high quality~~ percentage of high-quality segments	23 %	18 %	60 %	62 %
median lake segment depth	1.85 m	1.48 m	2.77 m	3.43 m
maximum lake segment depth	10.4 m	17.3 m	25.8 m	15.1 m

We describe this in the text at the end of the first paragraph of section 4.1.1 (Line 612-):
“To estimate how many unique supraglacial lakes were sampled by these detected ICESat-2 lake segments during each melt season, we calculated the maximum surface meltwater extent for each of the melt seasons independently using Landsat 8 imagery, based on the methods detailed in Tuckett et al. (2021) (blue regions in Fig. 9 and 10). We then matched each detected ICESat-2 lake segment to a lake basin in these imagery-based melt extents and counted the number of total basins that were sampled by at least one ICESat-2 lake segment (see supplemental maps; Arndt and Fricker 2024c). Over Central West Greenland, this resulted in 196 unique supraglacial lakes being sampled by our data in 2019, and 109 lakes in 2020. Over the Amery Catchment, FLUID-SuRRF segments sampled 165 unique melt lakes in 2018-19 and 25 lakes in 2020-21.”

We further explain the difference between ICESat-2 lake segments and the individual “real” lakes that they sample in Section 3.2.5 (FLUID step 5: along-track aggregation of lake segments), see our comment about this section further below

- Figure 8., Line 483. Consider moving figure 8 to the front of the manuscript, for example, at the end of the Introduction where you cite the study areas.
  We will move the figure to the end of the introduction, as suggested. We will change the sentence in the introduction that refers to the study regions to include a reference to the figure, and to the detailed “Study regions and time span” section: “Here, we present this algorithm, demonstrate its performance over two drainage basins in Greenland and Antarctica (Sect. 3.5, Fig. 2), and provide a framework for its large-scale implementation using distributed high-throughput computing.”

- Section 4.1.1 (line 529-). The number of lakes detected over West Greenland is very small compared with other studies. Especially considering you measure over a season. Also, it is odd that so few lakes are detected in 2020-21 over the Amery ice shelf. The number of false negatives is presumably very high (i.e. your detection rate is low). Presumably this is a function of the ground track spacing of ICESAT-2. I think it is important to discuss this and the impact it would have on operational implementation of your algorithm (or the limits to that).

It seems like there is some confusion about ICESat-2 data coverage here, likely because we have not made it clear enough in our writing that ICESat-2 can by no means sample all of the supraglacial lakes – or even close to all of them. There are other (image-based) methods out there that are much better-suited at finding the locations of lakes and determining their horizontal extents. What makes ICESat-2 unique is its capability to make direct and accurate measurements of water depth from space. So we cannot find all supraglacial lakes with ICESat-2, but for the (comparatively few, but many more than we could measure in-sit) that we do find with ICESat-2 we now have depth measurements.

The reason that there were so few lakes detected in 2020-21 over the Amery Ice Shelf is that there was barely any surface melt in this region during that melt season (as shown in Fig. 10). We also included the total area of Landsat 8-based melt entents to Table 1 (see above) to make this more clear, and will change the description in the row titled "amount of surface melt" to "very low" for this melt season.

- We propose to rewrite part of the introduction, to make it clear that a data set based on ICESat-2 alone cannot find all the supraglacial lakes, and that we don't intend to claim that it can: "While ICESat-2 has the unique capability to make direct and accurate measurements of water depth from space, the coverage of the mission's photon-level data product (ATL03) is limited to discrete, one-dimensional ground tracks that are coarsely spaced on the Earth's surface (~9.9 km between neighboring reference tracks and ~3.3 km between all neighboring beam pair tracks at 70°N/S) and have a relatively long repeat period of three months. This means that no supraglacial lake depth data product derived from ICESat-2 alone is able to provide samples of all (or even nearly all) supraglacial lakes on the ice sheets: ICESat-2's track spacing means that the majority of lakes form in locations that ICESat-2 ground tracks never sample, and the three-month return period means that for a significant number of tracks ICESat-2 never passes over at the time at which melt lakes are visible. ICESat-2 is also unable to penetrate optically thick clouds, thus further limiting the amount of data available for water depth measurements. While ICESat-2 data alone cannot be used to continuously monitor melt lake volumes,..."

- We will replace **"lake"** with "lake segment" or similar, in all instances where we simply refer to a single-ground-track segment of ATL03 data with visible supraglacial lake bathymetry. In particular, we further clarify this in Sect. 3.2.5 (FLUID step 5: along-track aggregation of lake segments): "The resulting final clustering is now considered the set of ICESat-2 supraglacial lake segments that have been found on each ground track. Note that for simplicity we here use the term "ICESat-2 lake segment" (or simply "lake segment") to refer to any single-ground-track segment of ATL03 data with visible bathymetry from one supraglacial lake. If multiple ICESat-2 ground tracks contain data from the same supraglacial lake, the distinct ground track segments are still considered different "ICESat-2 lake segments" for the purpose of this algorithm. For example, the two ATL03 profiles acquired by the two neighboring ground tracks of the center beam pair shown in Fig. 1 would be considered two distinct "lake segments" despite ICESat-2 having acquired their underlying data during the same overpass and from the same supraglacial lake. Since multiple ICESat-2 lake segments can be associated with the same supraglacial lake, this means that the total number of unique supraglacial lakes sampled by ICESat-2 is smaller than the total number of supraglacial lake segments reported by FLUID-SuRRF (Sect. 4.1, Table 1)."

- In line 529, we will also replace **"Out of the 1249 supraglacial lakes that we detected in total,"** with "Out of the 1249 supraglacial lake segments that we detected in the ICESat-2 data analyzed in this study,..." to emphasize that our results are valid only for lakes that are visible to ICESat-2.

  - We will further emphasize track spacing in Sect. 3.5 (Study regions and time span) by adding the following: "Our two study areas cover latitudes from 68.2°N to 72.1°N in Greenland and latitudes from 68.4°S to 74.0°S in Antarctica, meaning that ICESat-2 track spacing is similar over the two regions: in Central West Greenland RGT spacing varies from ~8.8 km in the north to ~10.8 km in the south; over the Amery Catchment RGT spacing varies from ~7.9 km in the south to ~10.7 km in the north."

- Line 550-551. Did you consider identifying lakes that have emptied. Johansson et al., (2013; J. Hydrol. 476) show that many lakes are transient and will empty late in season. This would allow you to evaluate the accuracy of the estimate from filled-emptied conditions.
  We did consider this, but came to the conclusion that due to the many complexities involved in comparing repeat tracks before and after lake drainage this is outside the scope of this study. We propose adding a short paragraph explaining this after L630 to the end of Sect. 4.2.2 ("Accuracy of SuRRF depth retrievals"):

  "Since many lakes on the Greenland Ice Sheet are transient and drain late in season (Johansson et al., 2013), it could be possible to obtain independent ICESat-2-based meltwater depth estimates by comparing "full vs empty" repeat-track measurements along ICESat-2 lake segments before and after the drainage. However, this approach would suffer from many of the same drawbacks that affect depth estimation from DEMs of a lake's bed topography that were acquired after it drained (Sect. 2.2), for example: effects of lake-bottom ablation, surface elevation change from precipitation and blowing snow deposits, as well as across-track advection of surface topographical features. Furthermore, this approach would not be feasible in Antarctica, where lake drainage is very rare, in particular on grounded ice. In cases where melt lake drainage is observed on the floating ice shelves, obtaining water depth from repeat-track elevation change is not possible due to the advection of surface topography with the ice flow and post-drainage flexural rebound (Warner et al., 2021). Due to these complexities, we do not attempt to validate ICESat-2 lake depth measurements using this method."

- Line 657. I think you need to mention there is a bias towards over-estimation.
  This is a good call. We propose adding the following caveat to the end of this section, combined with noting that ground truth observations are desperately needed to validate depth estimates and quantify potential biases in the data:
  "Since in the absence of ground truth validation data our depth validation efforts were based on manual annotation of the data, we acknowledge that there may be a small but potentially significant bias towards overestimating water depths with FLUID-SuRRF. This highlights an urgent need for ground truth *in situ* water depth measurements of supraglacial lakes that coincide with ICESat-2 overpasses, to enable calibration and validation of depth estimates."
  In addition, we add a description of a correction that can be applied to SuRRF depth estimates to attempt correcting for the effects of multiple scattering in the water column (Sect. 3.3.3 "SuRRF step 2: lakebed fit", line 418):
  "Previous studies have hypothesized that ICESat-2-based depth retrieval algorithms placing the lakebed fit at the along-track elevation of highest subsurface photon density may be biased towards slightly overestimating total water depths due to multiple scattering within the water column (Fricker et al., 2021; Xiao et al., 2023). To address this, we provide an optional correction, which places the lakebed fit at a higher elevation where the initial SuRRF lakebed fit included photons further below the initial lakebed fit than would be expected from bathymetric signal photons. To achieve this, we remove any photons located at a vertical distance below the initial SuRRF lakebed fit by more than the sum of (1) ICESat-2's single-photon time-of-flight precision (~ 12 cm in ATL03 photon heights or 800 ps; Markus et al., 2017), and (2) the elevation range within ICESat-2's footprint diameter (~ 11 m Magruder et al., 2021a) obtained by projecting the footprint onto the along-track lakebed topography estimated by the initial SuRRF lakebed fit. We then reapply the lakebed fit to the remaining photons as described

above, while supplying the SuRRF Robust Fit (Sect. 3.3.1) with the uncorrected SuRRF lakebed fit as the initial guess. Since the presence or magnitude of this hypothesized overestimation of water depths cannot be established without any ground truth in situ data available along any ICESat-2 lake segments, we provide this scattering correction for reference only, and do not apply it to the water depths presented in this study. If such validation data becomes available in the future, our scattering correction can be tuned to better match observations, and can be readily applied to FLUID-SuRRF output data."

We then further discuss how applying this correction would change water depth estimates, and how they compare to the manually annotated baseline estimates for validation (4.2.2 Accuracy of SuRRF depth retrievals and comparison with alternative methods, line 598):

"When applying the correction for multiple scattering (Sect. 3.3.3) to SuRRF depth estimates, the average bias is reduced to 0.07 m deeper than the manually picked values, with a mean absolute error (MAE) of 0.15 m and a Pearson's correlation coefficient of R = 0.993. This results in the scattering-corrected version of720 SuRRF reporting a total amount of water that is 3 % larger than the estimate given by the manual baseline."

We then refer back to the scattering correction later in this section when discussion the disparity between manual altimetry expert picks and algorithmic fits to the ICESat-2 data (line 611):

"We therefore believe that the true water depth falls somewhere in between our (deeper) SuRRF estimates and the (more shallow) manual baseline estimates from Fricker et al. (2021) and Melling et al. (2024). "Our scattering correction to SuRRF depth estimates is an attempt to reconcile this disparity between depth estimates. However, in the absence of ground truth *in situ* validation data for ICESat-2 lake segments, the correct magnitude of this correction remains unknown." **This demonstrates an urgent need for in situ meltwater depth data that can be used to reliably validate the accuracy of ICESat-2 estimates."**

- Line 660. I do not think this is demonstrated given the very low numbers of detections and the fact that you can't identify whether multiple measurement lines are from the same lake.

  Given that past empirical models (e.g., Pope et al., 2016) were based on in-situ measurements of a small portion of a single supraglacial lake, and that Datta et al. (2021) were quite successful at empirically estimating lake depths from imagery using a much smaller amount of ICESat-2 data, we believe that the general sentiment of this statement is justified. However, we acknowledge that our claim was phrased quite strongly. In particular, we propose to replace **"imply"** with "suggest" to acknowledge that we have not directly demonstrated this. In addition, we propose changing **"...that the results presented here could be used to…"** with "...that ICESat-2-based depth measurements obtained from applying FLUID-SuRRF at ice-sheet-wide scale could be used to…".

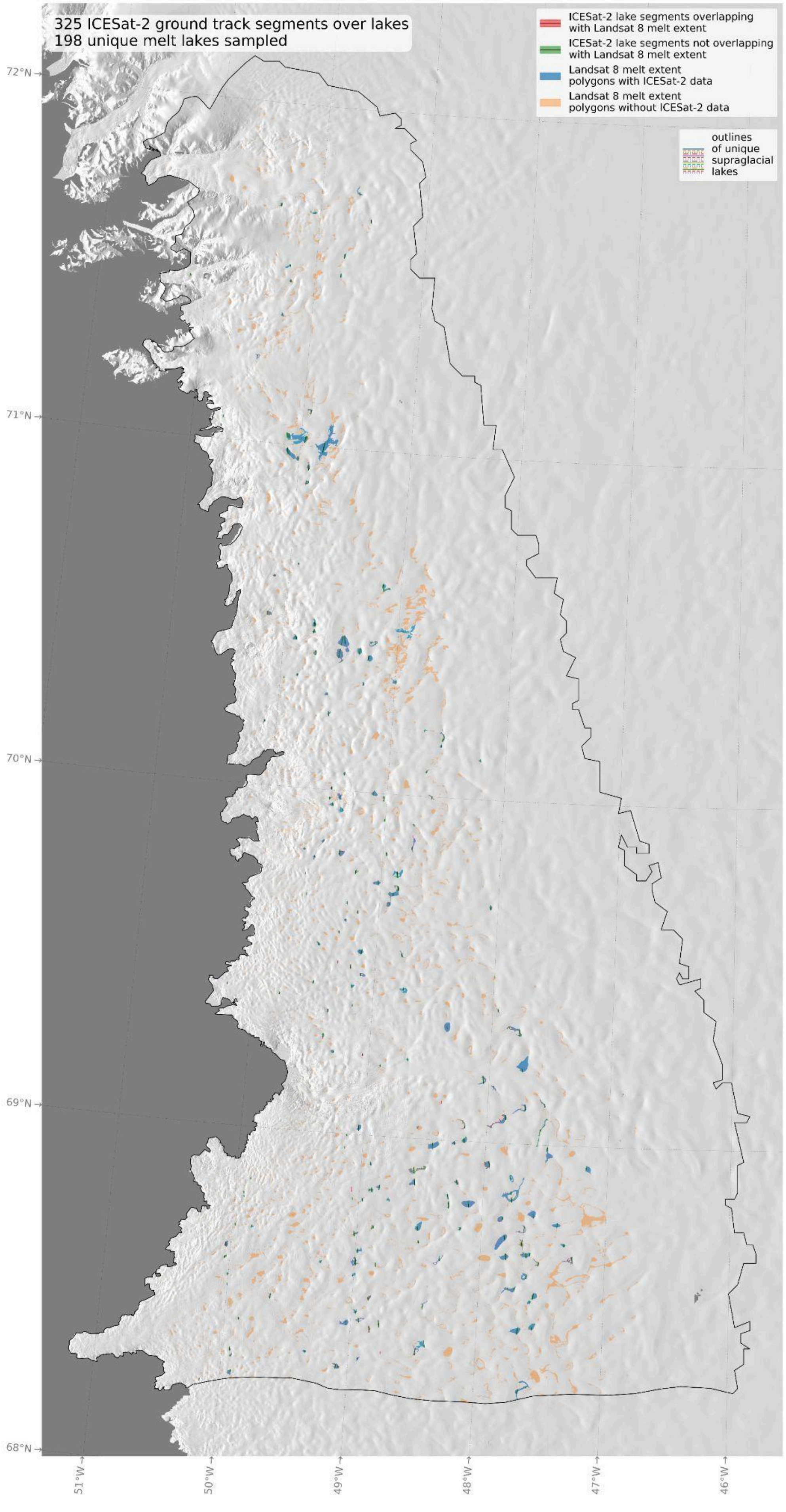
References

- Johansson, A. M., Jansson, P., & Brown, I. A. (2013). Spatial and temporal variations in lakes on the Greenland Ice Sheet. Journal of hydrology, 476, 314-320.

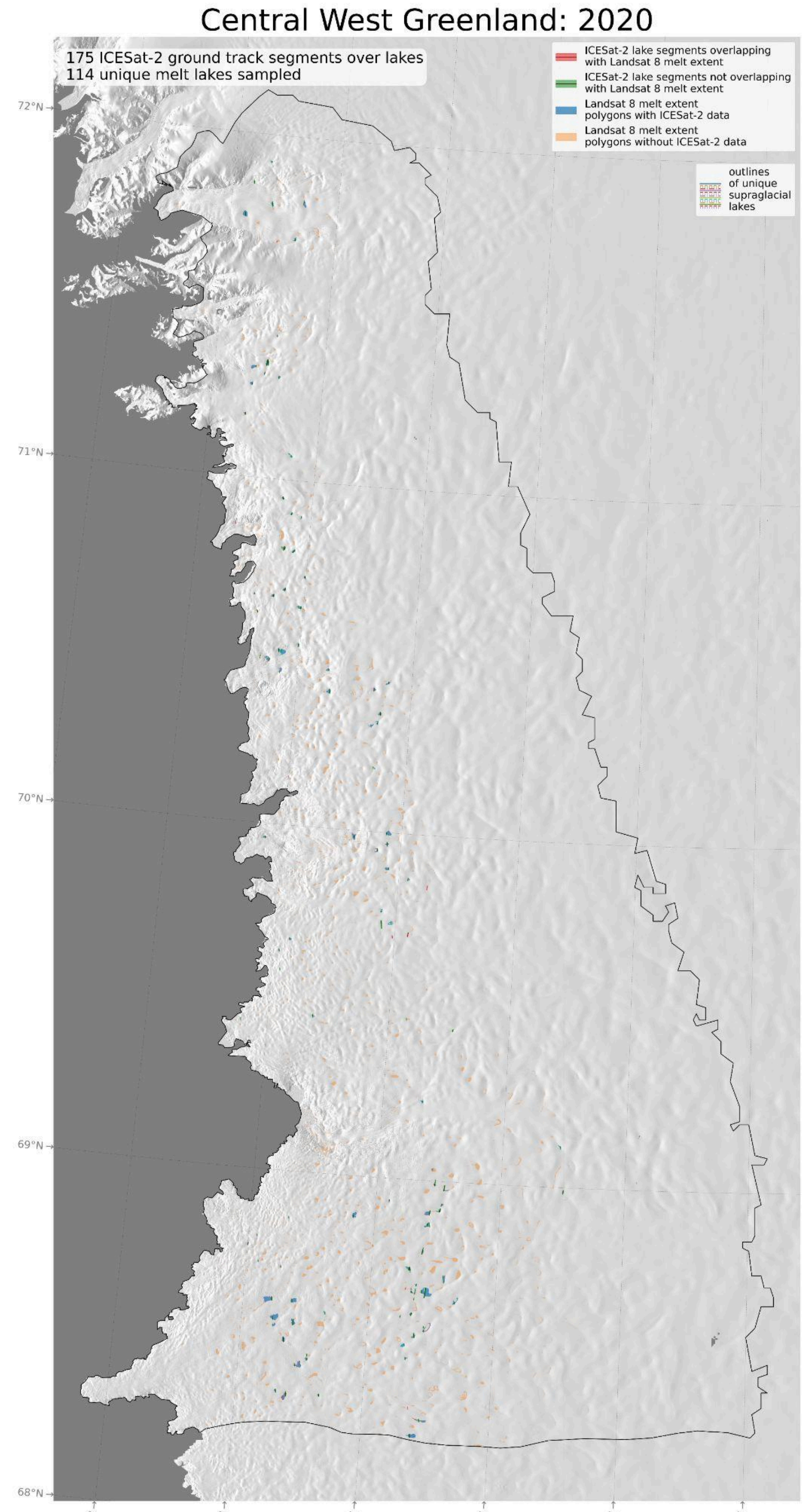
- Lu, X., Hu, Y., & Yang, Y. (2019, December). Ocean subsurface study from ICESat-2 mission. In 2019 photonics & electromagnetics research symposium-fall (PIERS-fall) (pp. 910-918). IEEE.

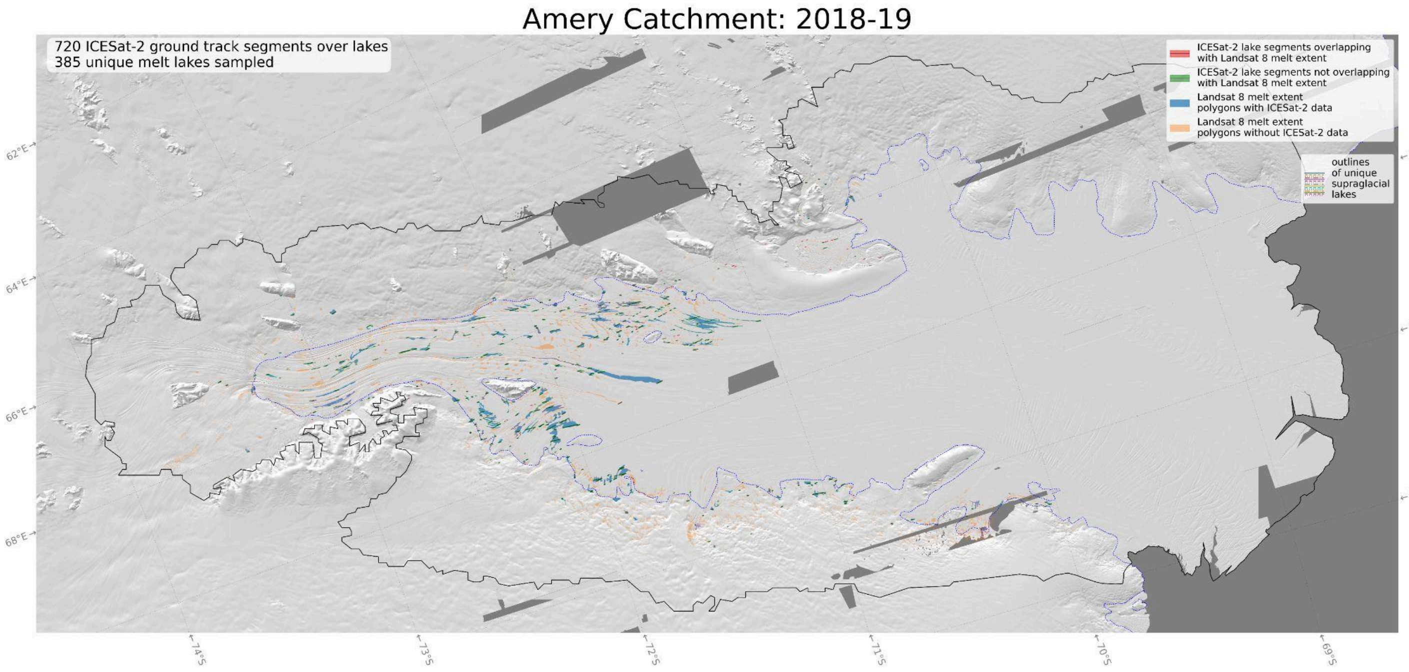
Maps of ICESat-2 lake segments and unique supraglacial lake extents

Reviewer comments about distinguishing "unique supraglacial lakes" from distinct "ICESat-2 melt lake segments" prompted us to estimate which distinct melt lakes are sampled by FLUID lake segments more than once. We report the number of unique supraglacial lakes in the text of the manuscript and Table 1, and explain how we estimated the given numbers. In a new version of the supplement at https://doi.org/10.5281/zenodo.10901826 (Arndt and Fricker, 2024c), we will additionally provide high-resolution maps of the ground tracks of FLUID lake segments over Landsat 8 maximum melt extents, with unique lakes identified by their borders. These maps can be used to better understand the spatial distribution of FLUID melt lake segments and how they relate to the overall distribution of pooled meltwater over our study regions. Due to their large scale, these maps cannot be reasonably included in the main manuscript. Lower-resolution reproductions of these maps are shown on the following pages.

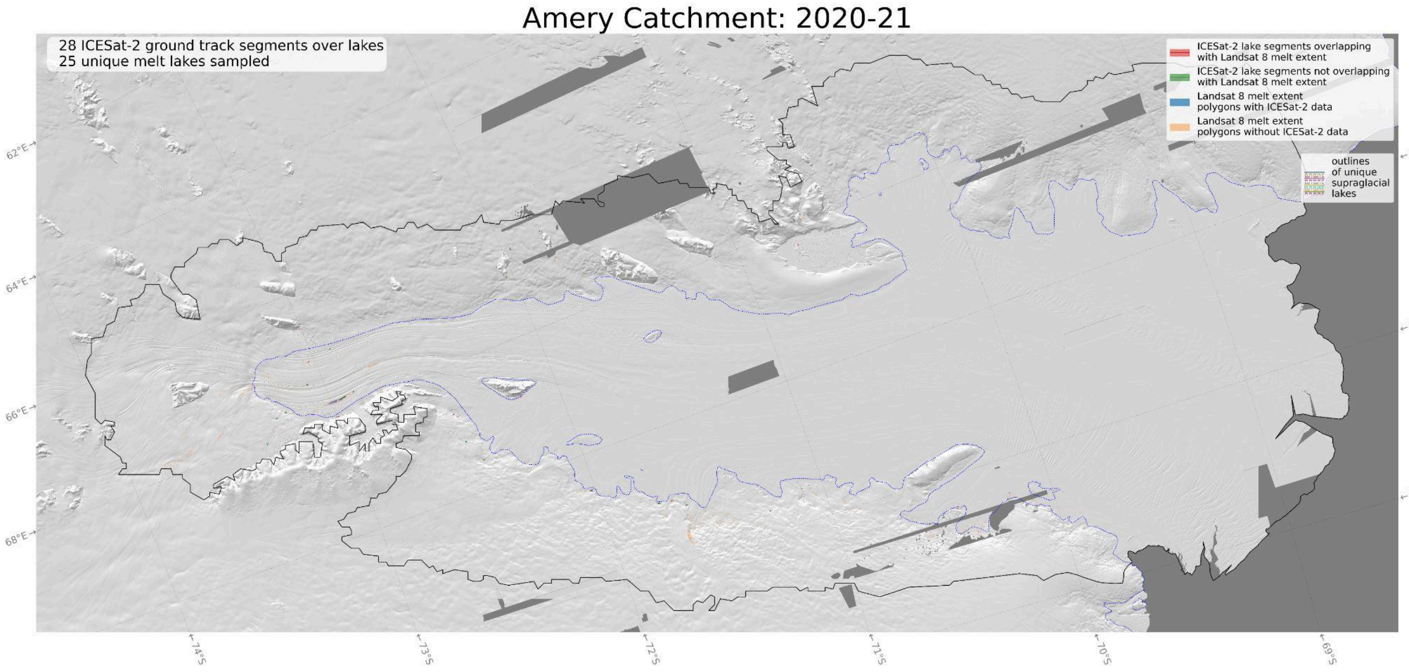


Central West Greenland: 2019


Central West Greenland: 2020
175 ICESat-2 ground track segments over lakes
114 unique melt lakes sampled
ICESat-2 lake segments overlapping with Landsat 8 melt extent
ICESat-2 lake segments not overlapping with Landsat 8 melt extent
Landsat 8 melt extent polygons with ICESat-2 data
Landsat 8 melt extent polygons without ICESat-2 data
outlines of unique supraglacial lakes
72°N
71°N
70°N
69°N
68°N
51°W
50°W
49°W
48°W
47°W
46°W



Amery Catchment: 2018-19



Amery Catchment: 2020-21