

Assessing supraglacial lake depth using ICESat-2, Sentinel-2, TanDEM-X, and in situ sonar measurements over Northeast Greenland

Lutz et al.

In this manuscript, the authors compare 4 different methods for calculating lake depth. The first two methods empirically fit optical reflectance values to depth measurements obtained from ICESat-2 and in-situ sonar measurements. The third method (RTM) relies solely on optical observations, using a physically based radiative transfer equation to estimate lake depth. The final method uses DEM differencing. The authors demonstrate and discuss the limitations of using each method to estimate supraglacial lake depths. Overall, this work is useful and will be a valuable addition to the scientific community. I have no major concerns with the methodology. While my list of comments may appear long, I believe most of them are relatively minor and I applaud the authors with their efforts on this work.

General comments

I think that the writing can be improved throughout. Generally, there are places where many words can be replaced with a few words to improve readability and flow. For example:

- L20: remove "able to be" from "were able to be procured"
- L48: "research has been conducted to fit empirical functions..." can be replaced with "empirical functions have been fit..."
- L51: remove "in their analysis"
- L60: "began to be" can be replaced with "been".
- L84: Replace "the monitoring of such a dynamic hydrologic process" with "monitoring dynamic hydrologic processes".
- L88: Replace "the presence of atmosphere in an image" with "the atmosphere".
- L105: Replace: "due to the fact that" with "as"
- L108: "the values of g are" can be changed to "g is"
- L121: Replace "in order to allow" with "To obtain"
- L139: "lake crossings of SGLs" is redundant.
- L261: Replace "across the reflectance values" to "with reflectance".

These are just a few examples where the writing is redundant. Please check the rest of the manuscript for sentences where the writing can be similarly condensed.

I also find some phrases and sentences to be vague. For example:

- L65 – Which "several other algorithms"?
- L69 – "within a certain margin" – what is this margin? Can this be quantified?
- L150 – "preprocessed by converting the digital numbers to reflectance values" – what is meant by this?
- L200 – "configurable high resolution spaceborne radar..." What is meant by 'configurable'? What is the resolution?

- L244 – “data points for the green band only start stacking...” What is meant by ‘stacking’ here?
- L382 – “The ocean itself also inherently has a relatively wide spread of reflectance values” How wide?

Keep an eye on consistency. Sometimes ‘SGL’ is used, and other times ‘supraglacial lake’ is used. Sometimes radiative transfer model is used and other times it is ‘algorithm’. Sometimes ‘RGB’ is used and other times this is spelt out. There are also places in the methods where the tense switches between present and past (L120-125, L170-172, L215-220, L340-343). I would recommend writing the methods section in past tense, although this may just be a personal preference. Finally, most of the manuscript is written in a passive voice however a few sentences use first person pronouns (L121, L205, L334, L339). Personally, I think writing in an active, first-person voice is clearer and more concise. I would encourage the authors to use active voice more frequently, especially throughout the methods section, or to remove the few instances with first-person pronouns.

Finally, be careful of sentences that begin with “this”, without specifically stating what “this” refers to. Some examples include L194, L238, L263, L319, L422.

Abstract

The tense changes from past to present and back again several times in the abstract.

L14 – change ‘regression’ to ‘empirical’

L14-18: “The first empirical... to create empirical relations”. I think that these sentences should be simplified to something like: “The empirical methods are developed to relate Sentinel-2 reflectance values to supraglacial lake depth obtained from 1) ICESat-2 crossings over 19 lakes in Northeast and Southwest Greenland, and 2) in-situ sonar tracks from four lakes on Zachariæ Isstrøm in Northeast Greenland.”

L20: remove “able to be”

L21: Add “empirical” between “sonar-based” and “equation”

L22: “Through the evaluation... lake bed sediment could be seen”. This sentence is a bit vague and feels out of place in the abstract. Please either expand a bit (e.g. what is the influence of the lake bed sediment?), or remove.

L23: Replace “appropriately adapted equation” with “ICESat-2 empirically derived depth equation”

L27: Add "to explore lake volume interannual variability" or something to the end of this sentence to elaborate on why this was done from 2016-2022.

L28: Consider replacing "pitfalls" with "limitations"

The last sentence of the abstract is a bit weak, specifically "while retaining sufficient accuracy under certain conditions". What does "sufficient accuracy" mean? Under what conditions? I have the same issue with the final sentence of the manuscript.

Introduction

L34 – replace "variations" with "variability".

L35 – replace "developmental rate of the lakes" with "timing of lake development".

L35 – I think that "topographical depression" is a more commonly used phrase than "surface sink". For the term "sink" I usually think of something that takes up some resource (e.g. carbon sink). Consider replacing this phrase elsewhere as well (L176).

L36 – I think the comma after "locations" can be removed.

L37 – Remove "allowing for lake development to be easily tracked."

L38 – Here, it may be better to specifically cite Greenland-based work. Now mostly Antarctica-based work is cited (Arthur et al 2020, Dirscherl et al 2020, Dell et al 2021, Corr et al 2022). There is a lot more Greenland-based work that could be cited here (e.g. Williamson et al 2017, Miles et al 2018, Hu et al 2022, Dunmire et al 2022, Zhang et al 2023, ...).

Paragraph 1 – In this paragraph there is a missing the link between the surface and subglacial hydrologic networks. I.e: how does water get from the surface to the bed? I would recommend adding a sentence or two on hydrofracture, moulins, etc, and how the water gets from supraglacial lakes to the subglacial hydrologic system.

L43 – Maybe change "presented" to "explored" or "commonly utilized"?

L43 – Change "This method" to "The radiative transfer model"

L45 – Add "water" before "depth".

L46 – Replace "implemented on SGLs by many research groups on various data sources and areas of interest" with "commonly used to estimate SGL volume across the GrIS". And again, I would focus your citations on Greenland-based work (could add Glen et al 2024, MacDonald et al 2018).

L55 – I would recommend combining the last two sentences of this paragraph. For example: “Furthermore, these methods are limited by ...”. Also does “these methods” specifically refer to the empirical methods or to all methods which utilize optical imagery? Please specify for clarification.

L67 – Replace “physically based algorithm” with “radiative transfer model” for consistency and please check other places as well.

Somewhere in the introduction I think sonar data should be introduced (e.g. what it is and how it can obtain lake depths).

L75 – How are the errors and uncertainties quantified? What “truth” are the methods compared against? After reading the full manuscript I don’t think the errors of the methods are truly quantified so I would consider rewording this sentence.

The introduction is missing a citation and discussion of Melling et al 2024. How does this work complement and expand upon what was done in that work?

Data and Methods

In general, I think the organization of this section should be re-worked. The subsections switch between data, methods, and study region. Maybe it would make sense to break up the Data and Methods into separate sections? I think a more organized approach would start by introducing all the data used and then move on to the 4 different methods.

How are the lakes in this study delineated? Is this done manually, or have you used a pre-existing algorithm?

L78-80: I would consider removing these lines. They feel out of place considering they introduce the four methods and then the next subsection immediately covers the data.

L85: Change “rendering” to “which renders”

L86: “which is valuable for a detailed analysis of the lakes”. This depends a bit on the context... the 10m resolution of S2 is certainly an improvement compared to Landsat but is still not fine enough to resolve some features such as smaller fractures which can be resolved in WorldView imagery, for example.

L91: Replace “cloudy days” with “cloudy images”.

L91: “solely or in combination with other data sources” is unnecessary.

L93: "other data acquisitions" is a bit vague since the other data sources have not been described yet. I would add in parenthesis (e.g. ICESat-2 and in-situ sonar data)

L95: Please specify the maximum date offset for S2 imagery, compared with the other data sources.

L106: remove "here" before R_{inf}

L107: remove "empirically" and add "the reflectance of" before "optically deep water".

L110: Other work has combined the red and green bands for lake-depth estimation. Can you elaborate why only the green band is used here? I know this comes a bit later on in the discussion, but it may also be helpful reasoning here in the methods section.

L115: Consider adding a brief description of the ATL03 product.

L116: Replace "close" with "intraseasonal"

L117: The wording of the last two sentences in this paragraph is a bit awkward, especially "such a monitoring task is enabled".

L120: Surely these lakes are not the only lakes where an ICESat-2 path crossed a filled SGL? Did you look at all GrIS regions or just NE and SW?

L149: Replace "significant" with "substantial", as I assume there was no actual significance test for this?

L149: The sentences beginning with "Figure 2(b)..." seem out of place in this ICESat-2 lake cross tracking retrieval section, as these sentences refer only to Sentinel-2 data.

L163 – I would consider modifying this sentence: "Then, the corrected depths and..." to something like: "The corrected ICESat-2 depths are then compared with RGB reflectance values for all 19 lakes. An exponential function is fitted to each band and the R^2 values are used to determine which optical band best correlates with lake depth.", or something of the sort.

L167: Replace "One of the depth algorithms" with "The second empirically-derived depth algorithm"

L175 – How is this error estimated? Is this from a different paper?

L175 – The naming convention is unclear to me. How is it based on the location of the topographical depressions? As there are only 19 lakes in the manuscript here,

perhaps it would be clearer to rename the lakes to something simpler (thus also removing the need for both numbers and letters in the naming).

L186 – Please include which lakes these tracks are for.

L191 – Perhaps it is helpful to say here that this process (the creation of the depth-reflectance relationship) was done similar to how it was with ICESat-2. In L191, I think it is important to mention that this is done for each S2 band.

L208 – Why are the DEMs used from after lake drainage? Would it make more sense to use DEMs from before lake-filling as this would more accurately represent the non-lake surface? After drainage, the DEM surface may also include ice fractures or ridges that result from the drainage, which would therefore provide an inaccurate representation of the actual lake depth.

L218 – How is the surface elevation RMSE calculated? Is it compared with the Copernicus DEM? Or is this really the standard deviation of the lake edge pixel elevation?

Results

L235 – Replace “reference” with “represent”.

L236 – I think it should be specifically said that the ice in SW Greenland has a “lower albedo”.

L257 – Remove “gathered”

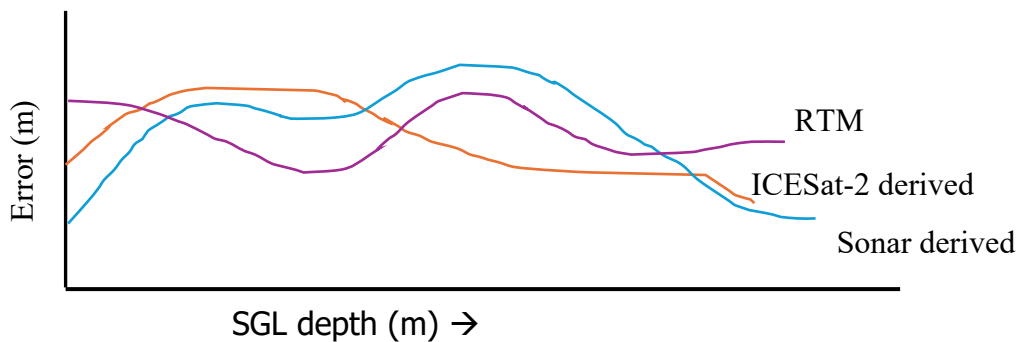
L258 – Specify that this is RMSE of the exponential fit.

L260-265 – I don't fully follow this section. For example: “while the data points in the Southwest function...”. Are these ‘data points’ from actual ICESat-2 data? The use of ‘in the Southwest function’ confuses me a bit.

L271 – Out of curiosity, if Lake 469 was included in the analysis, would it still reasonably fit the same curve in Fig. 5d?

L280 – It is mentioned that the RMSE ranges from 0.27 to 0.94 m, but for which reflectance values is the RMSE relatively low or high?

Section 3.3 – A figure that shows depth error (compared with DEM) with lake depth for each non-DEM method would be helpful to reference throughout this section. For example, I'm thinking of something like this below:



L286 – What are the errors associated with using the DEM results as a reference? How accurate are the DEM results?

L288 – In comparison, what is the maximum depth determined from the DEM method?

L288 – The sentence: “The sonar equation produces the largest errors in the shallower regions”, reads to me as: compared to the other methods, sonar is the worst in shallow water. Instead, I guess it is meant that sonar does worse in shallow water compared to its performance in deeper water. Consider rewording this for clarity.

L303 – What does ‘significantly’ mean here? 1m? 5m?

L312, Figure 7 – How are these uncertainties determined?

L314 – Could also cite Dunmire et al 2021 here.

L322 – add “to” after “comparing”.

Discussion

Again, a reference to Melling et al 2024 and a discussion of the results in the context of this previous work is missing here.

L339 – Specify that the ‘this’ in “this limits the scope of such a method” refers to the saturation of the red band at higher lake depths.

L341 – “depths between 10 and 25 m.” Are these maximum depths?

L341 – “Moreover, in the interannual comparison...” Which method are these statistics based on?

L343 – replace “in the lakes where average depths are larger” with “in lakes with deeper average depths”.

L345 – “However, an analysis...” This sentence reads awkwardly and should be reworded for clarity.

L352 – What we care about at the end of the day is the actual volume of water stored in SGLs. The red band underestimates deep depths and the green band overestimates shallow depths; but, we can't truly know which method is better suited without a similar comparison between red-band derived depths and DEM-derived depths. I'm not fully convinced that the question of which band is better suited can be answered with this work as it only includes 5 lakes in NE Greenland. How do we know that these 5 lakes are generally representative of GrIS SGLs?

L358 – Can you quantify how many (or what %) of points used in the regression are deep (> 7m) or shallow (< 0.5m).

L359 – It is not immediately clear to me why not having many very deep or shallow points for the regression would lead the ICESat-2 equation to overestimate depths.

L362 – Change “where the edges of the lake are never estimated to be as shallow as they are in the DEM estimates.” to “where lake depth at the lake edge is overestimated compared to the DEM method.”

L364 – “... the sonar equation regression never reaching a value below 0.5 m...” Can you place a boundary condition on the regression equation such that the line has to reach 0m in this range of reflectance values? From Figure 5 it appears that there are several points that are near 0m depth. Can you force your regression to cross the y-axis somewhere between these reflection values so that the equation is physically bound?

L387 – “... imperfect lake masks...” Did you consider remasking the lakes to be sure that no water pixels were included in your calculation of Ad?

L390 – Change “could improperly reflect the situation in reality” to “may not be realistic”.

L393 – This is a long paragraph and I would recommend starting a new paragraph at the sentence that begins with “Thus...”

L394 – Since you discuss % changes in volume of the lake, I think it would be helpful to provide the parameter changes as % changes as well. E.g: what % change is a 0.01 m⁻¹ change in *g*?

I would like to see a slightly expanded sensitivity analysis. Fig. B3 only has 3 points per panel. I think this analysis would be improved if there were more values tested. Also, in L394, it is mentioned that a 0.01 m^{-1} change in g results in a 7.4% change in the lake volume, but none of the points in Figure B3 represent a 0.01 m^{-1} change in g .

L400 – "... ice surface is more dynamic, e.g. with sediment dispersion." With the word 'dynamic' here, I think of the ice surface as physically moving. I think changing to 'variable' would be helpful.

L405 – Remove the words "there are" and "which" from this line.

L409 – I prefer the terms "overestimated" and "underestimated" than "deeper/shallower than in actuality" (see L417 as well)

L410 – "Due to the insights gained from the ICESat-2 analysis..." I recommend specifying these insights here.

L415 – Replace "noticeable" with "obvious".

L444 – Please comment on the applicability of the regression methods to a larger area or for continent/basin wide lake volume estimation.

Figures

Figure 1 – It would be helpful to also plot the lake locations in 1b. Also, in the caption header the future tense "will be" is used. Please change this to "was". Finally, the titles for the different lakes are not intuitive. I assume the date is in the form dd-mm-yy. I think it would be better to label the images with the date of the optical image (in a more intuitive format), as the beam information is already located in Table A1.

Figure 2 – Include the Sentinel-2 image date explicitly either on the image or in the caption (assuming 18 August 2019 is for the ICESat-2 data?). Remove "plotted" in L154 and "the" before "Sentinel-2 image" in L155.

Figure 3 – Is it necessary to note who took the photos? In panel c, it would be helpful to see this area in relation to the study area in 1b. Also, the borders in panel c seem blurry. In d, I would replace "in situ" with "sonar" in the legend and caption.

Figure 4 – Please include the image acquisition dates either on the image or in the caption.

Figure 5 – I think it would make more sense to order the plots by band wavelength : R (a), B (b), G (c). The legend for the NE and SW Greenland points should be in panel (a). Did you use the Red and Blue bands with Sonar? If so, it may be interesting to see

these bands as panels as well. In the caption, please specify *SGL* depth (L247). How does the fitted curve in d compare with the fitted curve in c?

Figure 6 – Should mention the image date for each lake, either in the image or the caption. A separate (maybe in Appendix) figure showing the depth difference between each method and the DEM method would be helpful to more clearly visualize the differences, specifically as this is discussed in section 3.3.

Figure 8 – Include a map of where these lakes are located.

Figure B1 – Include panel labels (a), (b), (c). I think it would also be helpful to plot these scatter plots on a square grid (with the same limits for x and y-axis).

Figure B2 – The colors for > 10 and 0-2 appear very similar to me.

Figure B3 - Include panel labels (a), (b), (c). It may be better to represent the axis as % changes. So, % change in the parameter values and corresponding % change in calculated lake volume.

References used in this review

Dunmire, D., Banwell, A. F., Lenaerts, J., & Datta, R. T. (2021). Contrasting regional variability of buried meltwater extent over two years across the Greenland Ice Sheet. *The Cryosphere Discussions*. doi: 10.5194/tc-2021-3

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Hu, J., Huang, H., Chi, Z., Cheng, X., Wei, Z., Chen, P., Xu, X., Qi, S., Xu, Y., and Zheng, Y.: Distribution and Evolution of Supraglacial Lakes in Greenland during the 2016–2018 Melt Seasons, *Remote Sens.-Basel*, 14, 55, <https://doi.org/10.3390/rs14010055>, 2022.

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Zhang, W., Yang, K., Smith, L. C., Wang, Y., van As, D., Noël, B., . . . Liu, J. (2023, 11). Pan-Greenland mapping of supraglacial rivers, lakes, and water-filled crevasses in a cool summer (2018) and a warm summer (2019). *Remote Sensing of Environment*, 297, 113781. doi: 10.1016/j.rse.2023.113781