Supraglacial lake bathymetry automatically derived from ICESat-2 constraining lake depth estimates from multi-source satellite imagery

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General comments:

This manuscript presents a new algorithm, 'Watta', for automatically extracting supraglacial lake depth estimates using ICESat-2 geolocated photon heights (ATL03) which are then used to validate empirically-derived lake depths from Landsat 8, Sentinel-2, Planet Labs Skysat and PlanetScope imagery. The authors test the algorithm performance on 46 supraglacial lakes near Jakobshavn Glacier in West Greenland during an intense melt season (2019). Finally, they use this stacked dataset in combination with Operation IceBridge imagery to track volume, drainage mechanisms and ice cover evolution of two individual lakes in this region.

Supraglacial lakes form in the ablation zones of Greenland and Antarctica during the summer melt season and can impact ice sheet dynamics, making lake detection and depth retrieval important. However, lake volumes have been difficult to quantify due to a lack of *in-situ* measurements and uncertainties associated with image-based methods. This manuscript builds upon other recent studies by applying a novel method for lake depth extraction, which is the first application of high-resolution Planet Labs satellite imagery to calculate supraglacial lake depths in combination with other imagery sources and ICESat-2 heights. It also provides useful insight into lake dynamics and ice cover evolution, which to date have been limited by the comparatively coarse resolution of publicly-available satellite datasets (Sentinel, Landsat).

Therefore, it is my view that the findings are of broad interest to the cryospheric community and represent a promising step forward for studying supraglacial hydrology and dynamics. I look forward to seeing further development of this method and its applications elsewhere on the Greenland and Antarctic ice sheets, particularly on floating ice shelves.

In general, this is a well-written manuscript and most of my comments are relatively minor. I would like to see in places some additional detail around the discussion of lake depth retrieval methods (see specific comments).

Lastly, 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." Although the authors state at the end of the manuscript that the Matlab code will be converted and shared publicly, I would like to see this section added including statements of how Landsat, Sentinel and Planet imagery can be accessed.

Once the authors address these points and my comments below, I can therefore recommend that this manuscript is suitable for publication in *The Cryosphere*.

Specific comments:

Line 17: Specify Landsat 8 OLI, as you are specifying Sentinel-2.

Line 38: ‘a common feature on large parts of the ice sheets’ – this should be ice sheet (singular) as the paragraph has only discussed Greenland so far.

Line 40: ‘ (…) of both ice sheets’. So far, Antarctica has not been mentioned in the text. Perhaps add an additional 1-2 sentences in the previous paragraph introducing meltwater production and Antarctic-wide surface meltwater and supraglacial lakes.

Line 43: Suggest rewording to: ‘The complex links between (…) can potentially be deduced (…)’.

Line 45: Specify here that feature types are ‘supraglacial’.

Line 46-7: I think detail could be added here outlining both the physically-based and empirically-based methods, together with a slight clarification of the wording, as the physically-based approach has been applied to other optical imagery such as Aster (Sneed and Hamilton, 2007), Landsat (Banwell et al., 2014) and Sentinel. It should also be added to the text that the physically-based method assumes a minimal impact of wind-driven surface waves, low slopes of lake bottoms and a homogeneous lake-bottom albedo on lake depths, which may be particularly important in Greenland (Sneed and Hamilton, 2011). I believe the empirically-based method was first applied to WorldView2 by Legleigter et al. (2014), so I suggest citing this work too (see below for full reference).

Line 49: Can you include a specific lake depth limit here? I believe Pope et al. (2016) found that the maximum lake depth that could be derived from the empirical depth retrieval method using *in-situ* estimates was 5 m.

Line 55: Specify resolution here (e.g. ≤ 3 m, daily) to demonstrate improvements over Sentinel-2.

Line 61: Could you specify by how much the physically-based estimates tended to underestimate lake depth?

Line 65: Specify native resolution (0.7 m).

Line 68-70: This sentence is slightly hard to follow – adding ‘from’ before ‘multiple imagery sources’ may improve the clarity?

Line 72: It is not clear to me what the representative sections are that are referred to in this sentence – is this part needed?

Line 75: Can you cite any work here to support that this was an unusually intense melt season, e.g. Tedesco and Fettweis (2020)? I would also specify 2019 here too, just to clarify to the reader.

Line 78: I think this is the first place CAMBOT is used as an acronym, so include the full name (Continuous Airborne Mapping By Optical Translator).

Line 85 (Figure 1): Please make the scale bar in the top left panel bigger, and add lat-lon labels to the main panel. Perhaps also add '(A)' to the Lake Ayse label to make clearer how the Skysat image relates to the main panel. In the Figure caption, specify that RGT = repeat ground track. Finally, a small comment but maybe call SkySat boxes 'grey' rather than white in the caption so that it is clear when looking at the main panel.

Line 100: Specify ICESat-2 confidence levels (i.e. low, medium, high) in brackets.

Line 116: Are there any studies you can cite here to demonstrate the PlanetScope radiometry issues? Possibly Saunier (2020)?

Line 121: What is the vertical accuracy of the GIMP-2 DEM? Also, include the GIMP-2 dataset citation here (Howat et al.).

Line 143: Specify how lake boundaries are delineated? Discussion of NDWI does not come until Section 3.2, consider moving some of this into the Methods section.

Line 195: I wonder if you have considered what the effect is of wind-driven scattering on lake surface roughness and on the surface photon return?

Line 218: Specify that $NDWI_{ice}$ uses the blue and red bands.

Line 220: Is 'limitations' a better word here, rather than 'limits'?

Line 246: I think Banwell et al. (2019) calculate a lake-bottom ablation rate of 20.3 mm day^{-1} on McMurdo Ice Shelf. Perhaps worth adding in?

Line 315: Be explicit in the Figure 5 caption that G = green and R = red in panels c-j.

Line 330: In Fig. 6 caption, write abbreviations in full again for clarity (

Line 345: 'Liquid water (…) remains constant at around 3%' – over what period? Looking at Figure S4, the surface water extent appears to increase?

Line 346: Can you refer to a figure/results here to support this statement?

Line 355: Could you add lake outlines to Panel b of Figure 7?

Lines 360-62: Refer to Fig. 8(j-l) end of first sentence, and (m-o) in the next sentence.

Line 383: Refer to Fig. 8m-n at the end of this sentence.

Line 390: Looking at the SkySat image in Figure 9b, incised streams are also visible to the right of the image; could Lake Julian not also have drained through these?

Line 401: Should this refer to Fig. 10c here, not 10b?

Line 419: It isn't clear to me how this suggests the presence of an ice layer in the same place following drainage in the previous season? Is there evidence of this in satellite imagery?

Line 425: I suggest slightly rewording the first part for clarity: '(a) Sentinel-2 image acquired on May 14th 2019, with ICESat-2 RGT 727 (occurring on May 15th 425, 2019 and August 14th, 2019) overlapping in green (…). (b) Lake depth derived from Watta (Panel c) and Sentinel imagery (Panel a).' Please also add full stops to make it easier for the reader to separate descriptions of (a), (b), (c), (d) and (e).

Line 433: Refer to Fig. 11d here, and Fig. 11e-i in the next sentence.

Line 436: I agree that the stream is clearly incised on September 24th but think it might be difficult to conclude the same from the April 20th Skysat image.

Line 440: I think it would be helpful here to cite some work showing how surface relief preconditions the spatial distributions of lakes and surface drainage, e.g. Ignéczi et al. (2018).

Line 447: Specify again that the intense melt season was in 2019.

Line 450: Specify Landsat geolocational accuracy (5 m).

Line 460: I suggest citing some other recent studies that have quantified the seasonal evolution of surface meltwater in Antarctica: Dell et al. (2020), Moussavi et al. (2020).

Line 469: See general comment above about data availability.

Technical/minor corrections:

Line 12: 'bathymmetric' spelling error (same on Line 57 and 60).

Line 16: Italicise '*in situ'* (and please check throughout).

Line 23: Add comma after '(both publicly-available and commercial)'.

Line 30: This should be Slater *et al.* (2018) (please also check similar instances throughout – especially in places where the reference is unclear e.g. Pope, 2016 or Pope et al., 2016). Some references are also missing from the reference list (e.g. Fair et al., 2020) – please check.

Line 35: Consider rewording to 'led to unprecedented summer mass loss'.

Line 51: Change 'LandSat' to 'Landsat 7 and 8'.

Line 62: I suggest moving '(supraglacial lake depth)' to Line 57 i.e. 'empirical (supraglacial lake depth) bathymetric methods'.

Line 65: Typo, 'wen' should be 'when'.

Line 112: No need to hyphenate ‘high spatial’.

Line 119: Replace ‘is’ with ‘are’ (‘frequently captured multiple times’).

Line 120: Specify ‘spectral’ response curves and write near infrared (NIR) in full here.

Line 135: Comma should be full-stop.

Line 137: Change ‘is’ to ‘are’.

Line 176: Remove duplicate word ‘outliers’.

Line 205: New sentence after ‘lake edges’.

Line 215: ‘in order to exclude regions with moving surface water, which evolves rapidly and can be mistaken for fixed topography’.

Line 218: Remove double comma.

Line 242: Keep to past tense for consistency.

Line 292: Typo (‘there were’).

Line 435: Missing word (‘a’ substantial quantity of liquid water).

Line 438: ‘connects’ to an efficient drainage system.

References

Banwell, A.F, Caballero, M, et al. (2014) Supraglacial lakes on the Larsen B ice shelf, Antarctica, and at Paakitsoq, West Greenland: a comparative study. Annals of Glaciology 55(66), doi: 10.3189/2014AoG66A049.

Ignéczi, A, Sole, A, Livingstone, S.J., Ng, F.S, Yang, K (2018) Greenland Ice Sheet Surface Topography and Drainage Structure Controlled by the Transfer of Basal Variability. Frontiers in Earth Science, https://doi.org/10.3389/feart.2018.00101.

Legleiter, C. J., Tedesco, M., Smith, L. C., Behar, A. E., and Overstreet, B. T.: Mapping the bathymetry of supraglacial lakes and streams on the Greenland ice sheet using field measurements and high-resolution satellite images, The Cryosphere, 8, 215–228, https://doi.org/10.5194/tc-8-215-2014, 2014).

Pope, A (2016) Reproducibly estimating and evaluating supraglacial lake depth with Landsat 8 and other multispectral sensors. Earth and Space Science, 3, 176–188, doi:10.1002/2015EA000125.

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Tedesco, M and Fettweis, X (2020): Unprecedented atmospheric conditions (1948–2019) drive the 2019 exceptional melting season over the Greenland ice sheet. The Cryosphere, 14, 1209-1223, https://doi.org/10.5194/tc-14-1209-2020.

Saunier, S (2020) TN on Quality Assessment for PlanetScope (DOVE) https://earth.esa.int/eogateway/documents/20142/1305226/EDAP-REP-007-TN-on-Quality-Assessment-for-PlanetScope-DOVE-v1.2.pdf

Sneed, W.A and Hamilton, G.S (2007) Evolution of melt pond volume on the surface of the Greenland Ice Sheet. Geophysical Research Letters 34(3), L03501 (doi: 10.1029/2006GL028697).