Dear Editor and Reviewer,

We would like to thank you for your detailed feedback, and we address each of their specific comments below. However, we would like to address up-front the major criticism that the elevation anomalies we observe are surface lakes and not subglacial lakes.

The fact many of the locations are associated with surface water does not preclude a subglacial lake as the driver of elevation changes. Indeed, we would expect this as subglacial lake drainage will create an ice-surface depression that would then naturally at least partially fill with surface water. Clearly where there is no surface water, we can have more confidence in a subglacial lake origin. However, where this is not the case, we believe we can still identify subglacial lakes via the following criteria.

- Assessing the ice surface profiles (ICESat-2&ArcticDEM). We can use this approach to identify wavy (i.e. elevation profiles that could not represent surface water or surface water covered with an ice lid) profiles that are not associated with surface water (e.g., Figure 1 of the main manuscript) but nevertheless still display an elevation change. We also provided more examples below (Figure R1). Sequence of ArcticDEM images at the same location may also confirm the elevation anomaly. Where surface water is identified we can evaluate whether the extent of surface water is the same size as the areal extent of the elevation change anomaly. Where the surface water is shallow (<7 m) we can also use ICESat-2 to measure the height of the lake bottom, which would be independent of surface water.

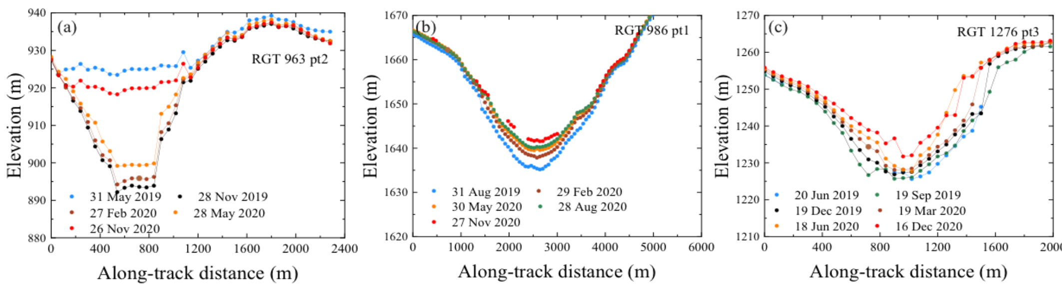

Figure R1 Elevation anomaly profiles across three subglacial lakes for RGT 963 pt2 (a), 986 pt1 (b), and 1276 pt3 (c).

- Investigating the temporal pattern and magnitude of elevation change. Surface lakes typically show a sub-seasonal pattern of filling and draining and experience elevation changes of <10 m. In contrast previously identified active subglacial lakes in Antarctica, Greenland and Iceland show multi-year fill-drain behaviours (Livingstone et al., 2022). We individually analysed each potential lake to determine the elevation change pattern. All of our medium and high confidence lakes displayed multi-year patterns, often with elevation change magnitudes of >10 m.

- Finally, we adopted a confidence level for each potential lake based on the above analysis – low, medium and high – with all low confidence lakes removed from the inventory.

Overall, we present multiple lines of evidence to support our interpretation of active subglacial lakes in the ablation zone of the Greenland Ice Sheet, and develop a method that will allow others to deal with the challenge of discriminating subglacial and surface lakes. We recognize there is some uncertainty (as captured in our medium and high confidence levels), but this study represents a major step-forward in demonstrating that these lakes do exist and are widespread.

On behalf of all the authors,
Yubin Fan

Reviewer #2

I really don't think the main premise of this study is correct. The authors have found 61 locations on Greenland where ICESat-2 and ArcticDEM strips indicate that the ice-sheet surface height has changed, and they take these changes to indicate the presence of subglacial lakes, in some cases arguing that the temporal pattern of height change is diagnostic of subglacial lake activity. I think the simplest assumption, that needs to be carefully considered, and requires strong evidence to be disproven, is that the height changes observed here are the result of supraglacial lake activity.

I did a spot check of the locations in table S2 against Google Earth, and, of the locations for which Google Earth had high-resolution imagery available (i.e. most of the west-coast lakes, and most in the far northeast), every single one had at least some sign of a supraglacial lake, although most were not identified in column I as being twinned with a supraglacial lake. In some cases, the lake was partially snow covered, and in others it was drained at the time of the Google Earth imagery, but it seems plausible that all of the observed height changes were a result of supraglacial water motion. It appears that the authors only identify lakes as being associated with a supraglacial lake when they can clearly see a double surface in the ICESat-2 data, but inspection of visible imagery is an easy way to see whether a particular location is in a lake basin, and it's often possible to see water at the surface.

Supraglacial lakes are known to be common in the ablation areas of Greenland. They can fill and drain in a single season, or can be present over multiple years, freezing partially or completely in the winter, and often have lids of frozen lake and snow that may or may not melt in the summer, and whose height can vary over time as water flows into or out of the lake (for example, the lake in figure S1 appears to be partially covered with frozen lake ice). As a result, height changes at the surface of the ice sheet may reflect changes in supraglacial lake volume, even when water is not visible at the surface. Because of this, any height-change within a lake basin should be suspected to be as a result of supraglacial processes. These can include not just changes in the level of exposed water, but also, changes in water level below a floating layer of lake ice, or enhanced ablation due to water flow or due to the presence of low-albedo sediments in the lake basin.

Response:

We believe that our premise is right (see also our general comment at the beginning of this reply). Certainly, supraglacial lakes are common within the ablation zone of the Greenland Ice Sheet. But, recent work has demonstrated that active subglacial lakes also exist in this zone (Livingstone et al., 2022 and references herein). Subglacial and supraglacial lakes are likely to be linked as whenever a subglacial lake drains it will create a surface depression (as also seen in Iceland and Antarctica) that could then fill with water creating a surface lake. We recognize this in the manuscript and have devised an approach to discriminate between the two lake types ("3.3 Impact of surface lakes on the detection of subglacial lakes") that accounts for uncertainty in our results ("3.4 Lake confidence level classification").

From analysing the elevation change data, we suggest the elevation-change pattern is demonstrably different between the two lake types. In particular, surface lakes produce a flat (or broadly horizontal with small undulations if there is a floating ice lid on top of water) surface elevation profile and typically show seasonal elevation change patterns. We used three criteria to discriminate confidence levels, (1) whether the elevation anomaly has a flat surface on the elevation profile (Table S2, Column 'Flat spot?'), (2) whether the elevation change pattern is characteristic of long-term subglacial lake drainage or filling (Table S2, Column 'Timeseries conf'), (3) Elevation anomaly profiles across the subglacial lake for each RGT and its magnitude of elevation change (Table S2, Column 'ATL conf'). The three separate confidence levels are integrated into a total confidence level (as stated in Section 3.4). Potential lake locations that were classified as low-confidence were not listed and discussed in the paper. The 15 high confidence subglacial lakes we identified typically exhibited large elevation changes over multi-year periods and with bumpy ice surfaces indicating that at least some of the elevation change was not associated with surface water.

Subglacial lakes affected by surface lakes that we identify in the table are those lakes with an obvious double-layer reflection in the ATL03 profile (the measurement time of ICESat-2). To further verify this, we checked the Landsat imagery around the acquisition time of ICESat-2 to further confirm the existence of surface water (e.g., Figure R2). In addition, surface water does not necessarily mean there is not also a subglacial lake; as we state once a subglacial lake drains it is not surprising that a surface lake occurs in the collapsed ice-surface basin (Willis et al., 2015).

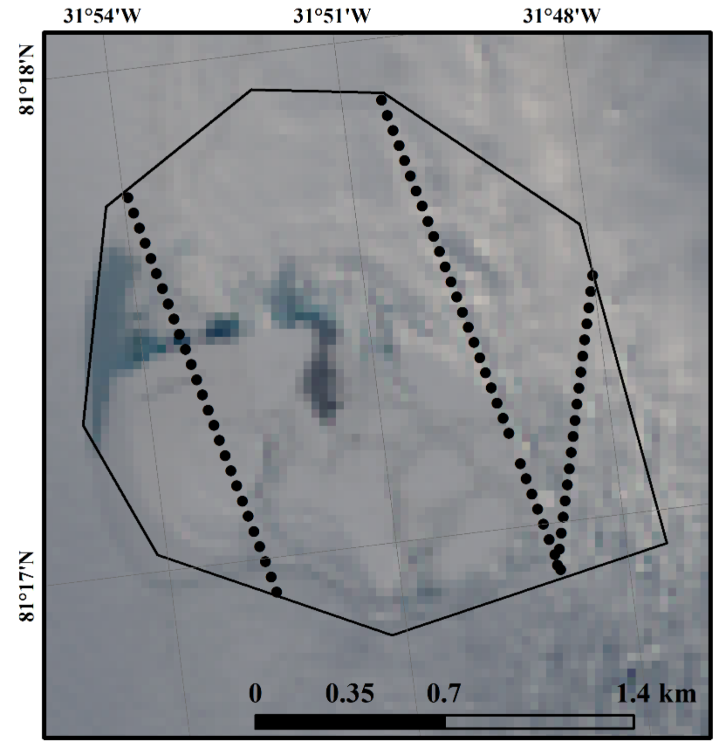

Figure R2 Manual check on surface water around the ICESat-2 acquisition time, taking Lake ACADEMY05 as an example. ICESat-2 shows an elevation anomaly in 04 September 2019, and both ATL03 data and LandSat-8 image (04 September 2019) confirm that there is very little surface water (affect only one ICESat-2 footprint) that day.

For a few of the lakes, water is obviously present in the ICESat-2 data, and the authors have attempted to use a technique based on ATL03 photon data to measure changes in the lake-bed height at times when the lakes are ice filled. This technique (the Watta algorithm) involves estimating the depth of the lake water based on the returns from the surface and bottom of the lake. There are two problems with the current study's estimates of ice-surface height (i.e. lake-bottom height) based on these results. First, the return form the bottom is typically quite diffuse, so that the photons used for measuring the lake bottom can come from a range of depths below the lake bottom itself. This leads to an uncertainty in the depth that is not quantified here; because lighting conditions, sediment load on the bottom of the lake, and the scattering characteristics of the lake bottom could all influence the diffuseness of the bottom reflector, it seems likely that uncertainty in identifying the height of the lake bottom in the ATL03 data could lead to substantial scatter in estimates of lake-bottom height and thus to apparent height and volume change where there is none. Second, the authors use the lake-bottom heights as calculated from (presumably) single ICESat-2 beams to replace the heights in the ATL11 time series (see my comment on line 124) without using the ATL11 polynomial surface to correct for the position of the measurements relative to the ATL11 reference point. This can lead to potentially large inconsistencies between the ATL11 time series and the heights from the Watta algorithm.

If the supraglacial lakes are paired with subglacial lakes, there should be a diffuse lake-like signal that extends outside the supraglacial lake boundary. It might sometimes be possible to see the water that leaves draining supraglacial lakes as it inflates the subglacial water system. However, in the few examples where this kind of behavior has been observed using GPS (see Das et al, 2008), the uplift was so brief that it would require considerable luck to observe it with ICESat-2 or with a Worldview DEM.

Response:

We acknowledge these uncertainties, but believe they have a limited effect on lake determination and its elevation/volume change estimation. First, ICESat-2 cannot identify all surface lakes because there is a depth limit (~7 m, Fair et al., 2020), and the estimated depths derived from the Watta algorithm have a high correlation with the image-based depths derived from Landsat-8/Sentinel-2 and manually-picked photon estimates (Fricker et al., 2020). Despite having an uncertainty in the depth estimation, the corrected elevation can provide information on whether there remains a residual (i.e. subglacially-derived) elevation anomaly. The spatial offset between ATL03 acquisition location and ATL11 RPT is rather small across the GrIS. The elevation derived from ATL03 and ATL11 have a mean difference of about – 0.17 m for the corrected 18 lakes, and this value is considerably smaller than the detected elevation changes (as shown in Table S3, generally >5 m). Thus, this correction does not significantly affect the change trend, and is within the calculated elevation-change uncertainty.

Reference:

Fair, Z., Flanner, M., Brunt, K. M., Fricker, H. A., and Gardner, A.: Using ICESat-2 and Operation IceBridge altimetry for supraglacial lake depth retrievals. The Cryosphere, 14, 4253–4263, https://doi.org/10.5194/tc-14-4253-2020, 2020.

Fricker, H. A., Arndt, P., Brunt, K. M., Datta., R. T., Fair, Z. and Jasinski, M. F.: ICESat-2 Meltwater Depth Estimates: Application to Surface Melt on Amery Ice Shelf, East Antarctica. Geophys. Res. Lett., 48, e2020GL090550, https://doi.org/10.1029/2020GL090550, 2020.

Comments on specific lines within the paper follow.

Line 47: "ICESat-2 has an improved footprint size (approximately 17 m with 0.7 m along-track)." The authors should be clear that the footprint size is 11 m (not 17, see Magruder et al, 2020) and the along-track pulse-to-pulse spacing is 0.7 m.

Response:

We corrected it in the revised manuscript.

Line 90: "The elevation-change anomaly associated with subglacial lake filling and/ or drainage should have a characteristic spatial pattern comprising an obvious elevation anomaly at the lake center while the outside remains stable." I don't think this is necessarily true. For a lot of subglacial lakes, the height-change signal is fairly spatially diffuse, with smooth variations in the height-change signal reflecting the flexure of the ice. It seems reasonable for subglacial-lake-driven height changes to be smooth at a scale of around one ice thickness. Truly sharp spatial patterns in height change are more likely associated with supraglacial lakes.

Response:

We respectfully disagree that there will always be a smooth transition. Where ice is thinner the elevation change signal might produce a more clearly defined boundary. This is demonstrated for some Antarctic subglacial lakes in the Antarctic Peninsula, which have produced sharp elevation changes (e.g., Hodgson et al., 2022, Figure 7). In contrast, over thicker ice (typical of subglacial lakes in Antarctica) the transition to no elevation change is more gradual. Therefore, the elevation changes associated with active subglacial lakes in Greenland may be not as smooth as those identified on the Antarctic Ice Sheet.

We have rephrased this part as follows 'The relative elevation-change anomaly associated with subglacial lake should have a characteristic spatial pattern comprising an obvious elevation anomaly at the lake center which reduces to zero (within uncertainty) outside the lake. '.

Reference: Hodgson, D. A., Jordan, T. A., Riley, T. R., and Fretwell, P. T.: Drainage and refill of an Antarctic Peninsula subglacial lake reveals an active subglacial hydrological network, The Cryosphere Discuss. [preprint], https://doi.org/10.5194/tc-2022-144, in review, 2022.

Line 100: "Subglacial lakes which also coincided with elevation anomalies during the ArcticDEM period were confirmed as subglacial lakes". Is this the definition of "confirmed" and "unconfirmed?" I don't think this is a good way to confirm that a given lake is subglacial rather than supraglacial—ArcticDEM data can show height changes associated with changes in lake ice on top of supraglacial lakes, and can show height differences between filled supraglacial lakes with frozen lake ice and drained supraglacial lakes. Similar problems can be seen in comparisons between ArcticDEM and ICESat-2 data.

Response:

ArcticDEM cross-validation is mainly used to determine whether there is an elevation anomaly. "Confirmed" in the text does not necessarily mean that this location is a subglacial lake. Instead it indicates that these locations are more likely to be subglacial lakes. However, only the long-term elevation time-series of these locations was subsequently discriminated. We have now specified that these are potential subglacial lakes in the revised manuscript (Page 4, Line 122-123).

Line 124: "The bottom height was taken as the corrected ATL11 elevation"—I take this to mean that the bottom height calculated based on the Watta algorithm was used in place of the elevation from ATL11 for that cycle. Simply replacing an ATL11 value with a single-beam elevation from ATL03 risks mixing values that have had different corrections applied. ATL11 heights are calculated relative to the ATL11 reference surface, which takes into account the local shape of the ice-sheet surface. The appropriate way to do this calculation would be to use the ATL11 polynomial coefficient fields to calculate the height of the reference surface at the location of the location of the Watta height estimate, and subtract the reference surface height from the Watta height.

Response:

The spatial offset between the ATL03 acquisition location and ATL11 RPT is small for the GrIS. The elevations derived from ATL03 and ATL11 have a mean difference of about – 0.17 m. This value is smaller than the detected elevation changes for each difference between two lake heights (as shown in Table S3, generally >5 m), so this correction does not substantially affect the change trend of this lake.

Line 125 (figure S1). As noted in my comment about line 90 (above), the surface-height changes associated with subglacial lakes in Antarctica are spatially smooth, which is expected based on the mechanics of ice deformation. Although the authors do not plot the height change they would estimate between 2019 and 2020, the difference between the lines in figure S1b indicates that it would be fairly jagged. This suggests to me that at least part of the signal visible in figure S1 is either due to errors in the bottom-height estimate from the Watta algorithm or due to melt.

Response:

Figure S1b shows the elevation profile before the Watta correction. When we plot the corrected elevation profile (Figure R3), it shows that this position still maintains the elevation anomaly (>5 m), which is rather large compared to the depth uncertainty (with a mean absolute difference of 0.33 m compared with manual-pick depths, derived from the supplement table of Fricker et al. (2020)). We have added these statements in the revised manuscript (Page 5, Line 160-161).

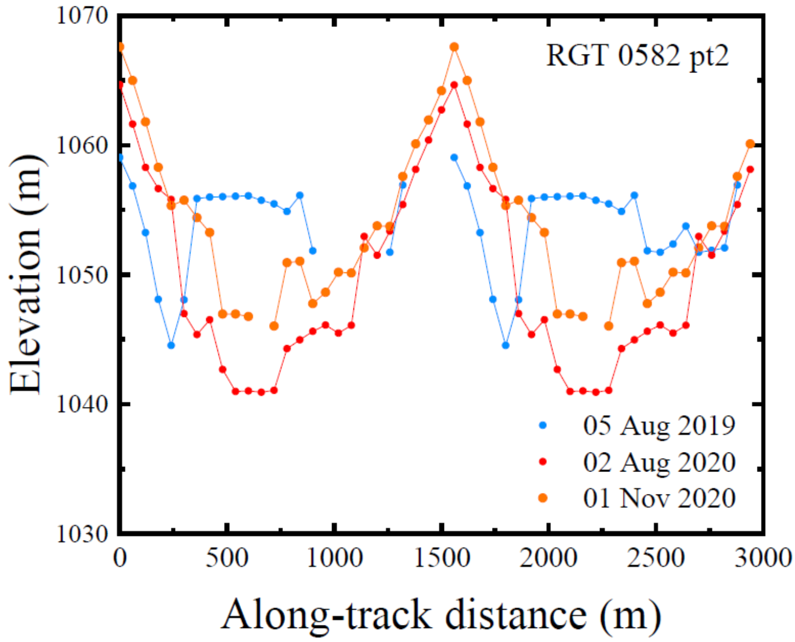

Figure R3 Elevation anomaly profile across the subglacial lake along the ICESat-2 RGT 0582 pt2 after Watta correction.

Section 3.4 (129-136): I don't see a good reason to believe that subglacial lakes on Greenland should show the "multi-year pattern of filling and then rapid drainage" that the authors take as indicative of a subglacial lake. Supraglacial water inputs to the bed of the Greenland ice sheet are large and seasonal, which could quickly fill or overfill subglacial lakes, leading to filling and drainage on subseasonal timescales.

Response:

Multi-year patterns of filling and then rapid drainage have already been identified for other active subglacial lakes in Greenland (e.g., Figure R4) (Willis et al., 2015; Bowling et al., 2019; Livingstone et al., 2019; Liang et al., 2022). This pattern suggests that despite large water inputs to the bed, subglacial lakes do not always quickly fill and then drain on sub-seasonal timescales (although the reviewer is right that this probably also happens; but such instances are then more difficult to distinguish from typical seasonal supraglacial lake behaviour). A key finding of this paper is that this multi-year style of behaviour is widespread in the ablation zone.

Reference:

Willis, M. J., Herried, B. G., Bevis, M. G., and Bell, R. E.: Recharge of a subglacial lake by surface meltwater in northeast Greenland. Nature, 518(7538), 223-U165, https://doi.org/10.1038/nature14116, 2015.

Liang, Q., Xiao, W., Howat, I., Cheng, X., Hui, F., Chen, Z., Jiang, M., and Zheng, L.: Filling and drainage of a subglacial lake beneath the Flade Isblink ice cap, northeast Greenland. The Cryosphere Discussions, pp.1-17, https://doi.org/10.5194/tc-2021-374, 2022.

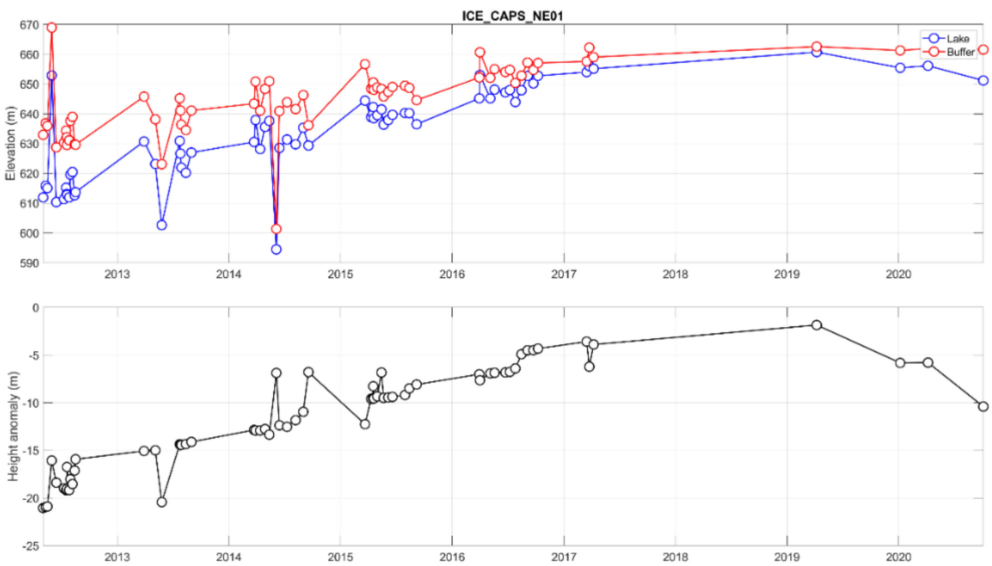

Figure R4 Elevation time-series over the combined ArcticDEM and ICESat-2 periods (2009-2020) within the lake and the lake buffer (up panel), and its corresponding elevation anomaly (down panel), taking Lake ICE_CAPS_NE01 as an example. Note the pattern of multi-year filling and then rapid drainage.

In contrast to subglacial lakes, the elevation change caused by supraglacial water tended to show a pattern of seasonal change (Figure R5); these elevation anomaly patterns are removed from the lake inventory.

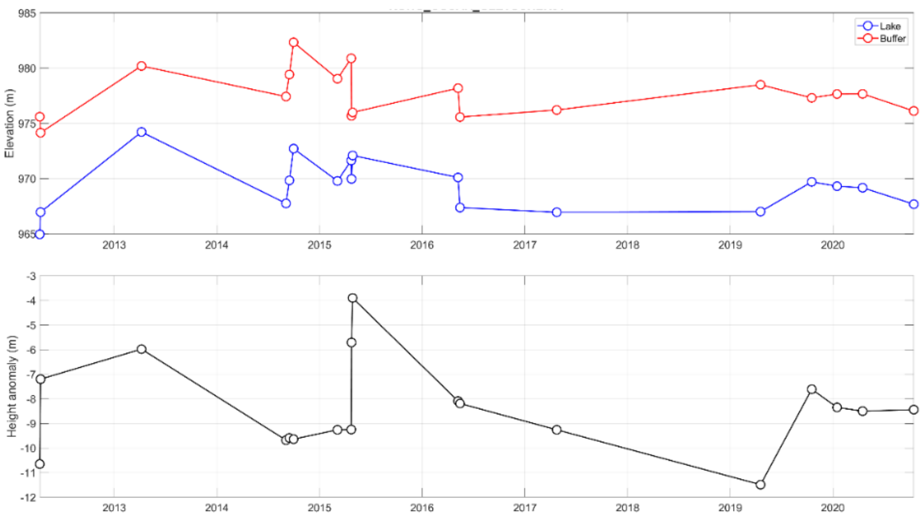

Figure R5 Elevation time-series over the combined ArcticDEM and ICESat-2 periods (2009-2020) of one surface lake, which shows a pattern (where data frequency allows) of seasonal elevation change without a significant long-term trend.

Section 3.5. I don't see a description of how height anomalies are calculated. In figure 3 and in table S4, some of the lakes have anomalies that are always negative or always positive. To what are these anomalies relative?

Response:

The elevation anomalies in table S3/S4 and Figure 2/3 are relative values, which were calculated by subtracting the median ice-surface elevation within the region overlying the subglacial lake from the buffer around it.

We rephrased this part as follows 'The elevation-change rate within the lake polygons is composed of ice-flux divergence, ice ablation and water motion (Smith et al., 2009), while the ice outside is only affected by ice-flux divergence and ablation. This 'background' elevation change needs to be subtracted to calculate the relative elevation-change caused by the subglacial lake. For each ICESat-2 overpass, we first calculated the median value of all ICESat-2 measurement points within the lake polygon, and then the median elevation of the area surrounding the lake (within the buffer-region) was subtracted to produce the elevation anomaly.'.

Reference:

Smith, B., Fricker, H., Joughin, I., and Tulaczyk, S.: An inventory of active subglacial lakes in Antarctica detected by ICESat (2003–2008). J. Glaciol., 55(192), 573–595, https://doi.org/10.3189/002214309789470879, 2009.

Section 3.6: This section should come before section 3.2, where the results of the ArcticDEM strip registration are used to try to confirm the lake locations.

Response:

We moved this to Section 3.2.

Line 145: what does it mean that "the effect of the buffer size on the elevation-change rate was neglected"? Does this mean that the authors do not account for the effect of the buffer size in their uncertainty calculations? Or does it mean something else?

Response:

What we meant here is that the effects of different buffer sizes (the radius of a circle whose area is equal to the lake and a buffer of half the radius of the standard buffer in this paper) on the elevation-change rate estimations was small (~6%). In addition, buffer selection does not affect temporal lake trends (i.e., fill or drain), so we neglect the effect of the buffer size on our lake elevation change data.

We used the radius buffer because this produced a similar footprint number to the lake region providing a more robust estimation.

Line 177: “missed by ICESat-2”—do the authors mean that the lakes locations were sampled by ICESat-2, but no height anomaly was detected? This would be typical for subglacial lakes in Antarctica, which often show episodic activity.

Response:

Two active lake locations found by Bowling et al. (2019) and a lake found by Livingstone et al. (2019) (67.178°N, 50.149°W) were all sampled by ICESat-2. Although elevation anomalies (> ±2 m) were detected, these locations have been removed (e.g., Figure R6, RGT 1169 pt2, sample Lake Isunguata Sermia 2) because they did not show a characteristic temporal pattern of subglacial lake filling and draining during the ICESat-2 period.

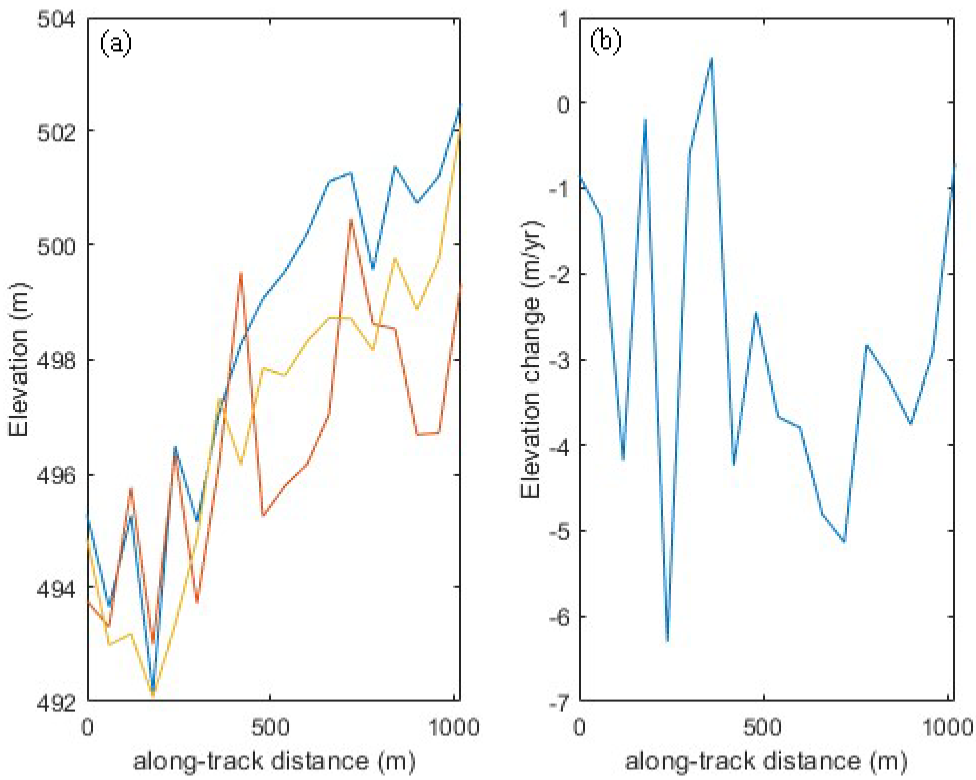

Figure R6 Elevation anomaly profiles across the subglacial lake are given for RGT 1169 pt2 (a) and the corresponding elevation-change rate (b), indicating no constant elevation change of this known subglacial lake.

Line 179: “No classic bright, flat and strong reflections were found from analysis of RES data.” How many of the lake locations were directly sampled by RES surveys?

I'd be surprised if all 61 were. Please specify which were and were not sampled.

Response:

Subglacial lakes derived from RES data during 1993-2016 have been published by Bowling et al. (2019) and Livingstone et al. (2022). These 57 stable lake locations were sampled by ICESat-2, but no height anomaly was detected (Figure R7, Lake located in Kangerlussuaq Gletsjer, tally:44 in the Livingstone inventory).

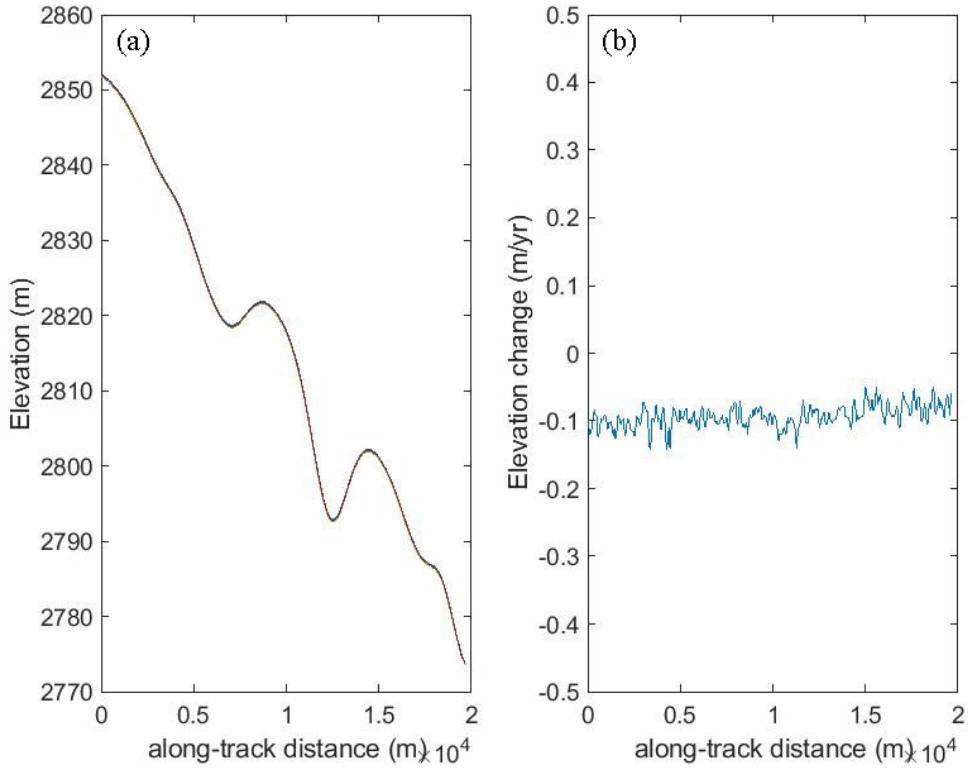

Figure R7 Elevation anomaly profiles across one stable subglacial lake are given for RGT 1169 pt2 (a) and the corresponding elevation-change rate (b), indicating this lake shows stable elevation.

We only checked the RES data from 2017-2019, and 10 of 50 confirmed lakes (for which we have a lake boundary) located in the southwestern GrIS were sampled by RES data, and no flat reflections were found (Figure R8).

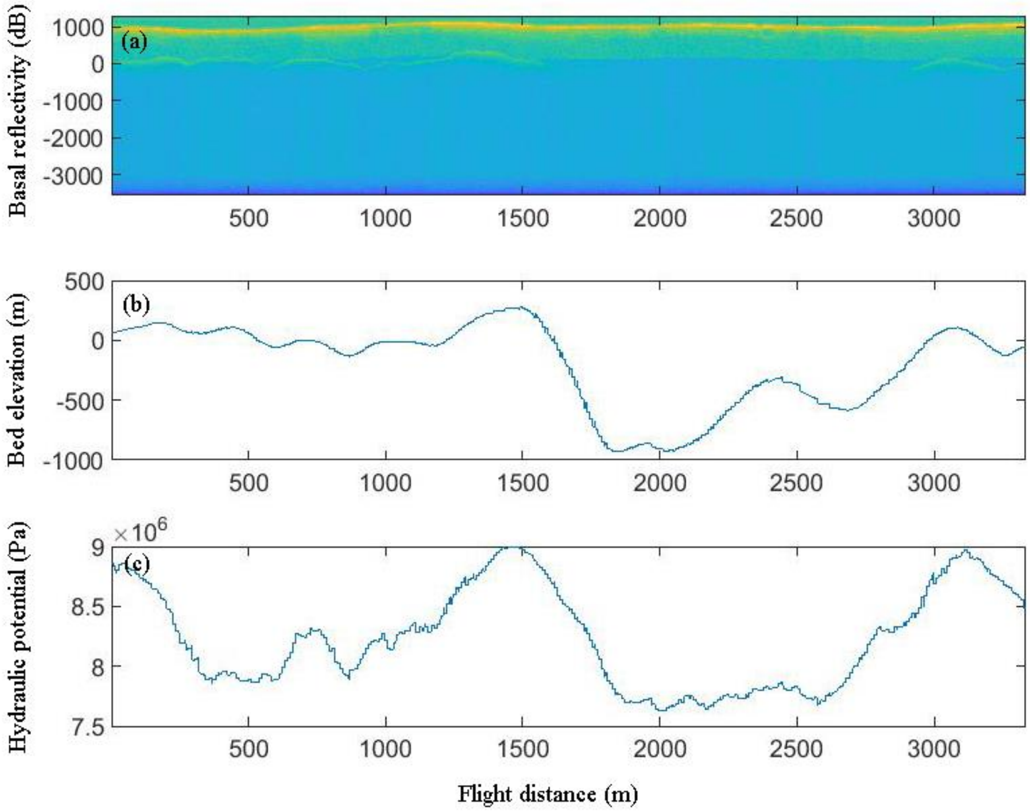

Figure R8 Relative basal reflectivity (a), the bed elevation (b), and hydraulic potential of one active subglacial lake detected by ICESat-2.

We rephrased this part as follows 'RES data during 1993-2016 were analysed by Bowling et al. (2019), revealing 57 stable lakes. Of the 57 stable lakes, 39 of them were sampled by the ICESat-2 ATL11 data (within a circular buffer using the 1/2 length provided by Livingstone et al. (2022)), but no clear elevation anomaly was found. In addition, 10 of the 61 active lakes were sampled by RES data from 2017 to 2019, but no classic flat reflections were found.'.

Line 184: " However, since lakes occur at all latitudes, we infer that their occurrence has no connection with the spatial density of ICESat-2 tracks." Obviously, the occurrence of subglacial lakes has no connection with the spatial density of ICESat-2 tracks. The detection of the lakes, on the other hand, almost certainly does, because many of the lakes are small compared to the track-to-track spacing of ICESat-2 data. It seems likely that at low latitudes, ICESat-2 misses many more lakes than it does at high latitudes.

Response:

We have removed this vague statement in the revised manuscript.

187-197—the simplest explanation for the association between the lakes in this study, negative surface mass balance, and thin snow cover, is that the lakes observed here are supraglacial, not subglacial.

Response:

We respectfully disagree (see response to major comment above). The lakes' distribution agrees with previously published data (Livingstone et al., 2022), and predictions by Bowling et al. (2019). Thick firn limits the amount of surface-derived water that reaches the ice bed in the southeastern and inland sectors of Greenland. Lakes located in these regions get limited or no surface recharge and therefore their elevation changes are small and cannot be captured by the altimetric data

198-204: the sizes of the lakes are also consistent with supraglacial, not subglacial lakes.

Response:

Steeper ice-surface slopes and thus subglacial hydrologic gradients control the morphology of subglacial lakes in Greenland (Bowling et al., 2019). Therefore, the size of the lakes underneath the Greenland Ice Sheet is typically smaller than those in Antarctica. Indeed, the lakes we identify are similar to other active lakes identified in Greenland (Bowling et al., 2019; Livingstone et al., 2019) and in Iceland (Livingstone et al., 2022), with typical areas of 0-10 km^2, and lengths mostly between 1-2 km.

Reference:

Bowling, J.S., Livingstone, S. J., Sole, A. J. and Chu, W.: Distribution and dynamics of Greenland subglacial lakes. Nature Communications, 10:2810, https://doi.org/10.1038/s41467-019-10821-w, 2019.

Livingstone, S. J., Sole, A. J., Storrar, R. D., Harrison, D., Ross, N., and Bowling, J.: Brief communication: Subglacial lake drainage beneath Isunguata Sermia,West

Greenland: geomorphic and ice dynamic effects. The Cryosphere, 13, 2789–2796, https://doi.org/10.5194/tc-13-2789-2019, 2019.

Livingstone, S. J., Li, Y., Rutishauser, A., Sanderson, R. J., Winter, K., Mikucki, J. A., Björnsson, H., Bowling, J., Chu, W., Dow, C., Fricker, H., McMillan, M., Ng, F., Ross. N., Siegert, M., Siegfried, M., and Sole, A.: Subglacial lakes and their changing role in a warming climate. Nat. Rev. Earth Environ., 19, https://doi.org/10.1038/s43017-021-00246-9, 2022.