Responses to Reviewer 2

General comments

This manuscript presents evidence of 6 different winter lake drainages across the Greenland Ice Sheet. The authors use a variety of methods (Sentinel-1 backscatter tracking, optical imagery analysis, photoclinometry) to provide evidence of these lake drainages and quantify drainage volumes. The findings presented in this paper are a valuable contribution to better understanding Greenland Ice Sheet hydrology. My first concern with the paper is that the writing is, at times, hard to follow. This is particularly true within the Methods section where overly wordy sentences take too long to dissect and comprehend. My second concern is that I am not convinced by the evidence for paper the 'drainages' of lakes 3 and 4 for reasons which I have further discussed below. Additionally, there is no elevation-change analysis from photoclinometry for these lakes. I understand that this may not be possible with the available Landsat-8 images; however, I don't believe that the evidence presented is convincing.

Thank you to the reviewer for spending the time so carefully looking through our manuscript. We're pleased the reviewer thinks our paper makes a 'valuable contribution' to the understanding of GrIS hydrology.

Regarding the writing. We propose to go through the manuscript very carefully clarifying all places where this referee and the other referee did not immediately grasp what we had done. We could also add a 'flow chart' type Figure to our Methods section if the reviewer/ editor felt this would be useful.

Regarding Lakes 3 and 4. We agree that the evidence for winter drainage of these lakes is more equivocal than for the other 4 lakes. However, the backscatter change for these lakes does meet what we think are quite strict rules for defining lake drainage, i.e. a <u>large</u>, <u>anomalous</u>, <u>sudden</u> and <u>sustained</u> increase in backscatter. One of our rules is that there should not have been a big reduction in backscatter immediately prior to a large increase. We look only at the time interval immediately prior to the increase to detect whether or not there has been a large previous decrease. This runs the risk of error of commission, which is *possibly* the case for Lakes 3 and 4. However, as Figure 4 shows, Lake 1 is also picked up as a draining lake using this criterion, and this lake drainage is then very well supported by the additional evidence. We *could* redefine our definition of a lake drainage to say that we need evidence from *two* prior time steps rather than just one. This would then have excluded Lake 1 from our analysis as there is only one image prior to the large jump in backscatter to look at (as there is for Lakes 3 and 4). So with this stricter definition we would have errors of omission. Given all this, we would like to propose that we keep our current definition of a lake drainage so that we can include Lake 1. This will mean we also keep and show Lakes 3 and 4. *But* we will then in the discussion and conclusions highlight even more forcefully that the extra optical band evidence in support of winter lake drainage is lacking (although lack of evidence isn't necessarily proof of course). We will articulate what we say above regarding the criteria for identifying lake drainage and errors of omission / commission and change text accordingly. For example, we will reorientate

L339-342 to suggest we may have included false positives (Lakes 3 & 4) but a stricter requirement regarding prior imagery might include false negatives (e.g. Lake 1). If people wish to use our technique in the future they can decide whether to be more or less strict by scrutinising either 2 or 1 images prior respectively. We hope that the referee / editor agree this is a good way forward.

Specific comments

L7 – specify which winters

We will change the text to the following: ". . . during the three winters (2014/15, 2015/16 and 2016/17) in fast flowing parts . . ."

L36 – Sentence beginning with "Lake drainage events, therefore,. . ." seems out of place within the rest of this paragraph.

Reviewer 1 also commented on this sentence. We will change the sentence to "Thus, lake drainage events influence the quantity and quality of water issuing from the ice sheet, although their effects are superimposed on the larger scale atmospheric controls on melt patterns and runoff".

L37 – Where do drainage events raise levels of phosphorus, nitrogen and sulfate?

We will edit this to read as follows: ". . . raise levels of phosphorus, nitrogen and sulphate in proglacial streams (Hawkings et al., 2016, Wadham et al., 2016), . . ."

L43 – I don't believe Koenig et al (2015) documented lake drainages, just the existence of winter-stored meltwater.

We will remove the reference to Koenig et al. 2015 here and keep it in line 49 in discussion of winter lake freeze-through.

L44 – Perhaps combine these two sentences so the second one doesn't start with "They".

Agreed. We will combine the sentences.

L47-49 – The sentence beginning with "conventional understanding" does not make sense

Apologies, this was a typographical error and was spotted by Reviewer 1 too. The sentence should read "Conventional understanding is that lakes that completely or partially drain during the summer then freeze during the winter, either freezing through completely or maintaining a liquid water core (Selmes et al., 2013; Koenig et al., 2015; Miles et al., 2017; Law et al., 2020).

L51-53 – This sentence is somewhat unclear to me

We will split the sentence and change the text to "Proglacial stream evidence from one study suggested that water was released from englacial or subglacial stores (Rennermalm et al., 2012). Proglacial stream evidence together with the appearance of surface collapse features on the ice sheet suggested that water may have been released from surface lakes (Russell, 1993)."

L54 - delete "carefully" and "in" in "microwave backscatter in Sentinel-1 satellite"

Agreed. We will remove these words.

L76 – what are the dates that determine a "late season" image?

We will include the dates of the images used within the Appendix. Late season images ranged from ~ July 25 through August. We began with images from the last week of August alone and added earlier images as necessary to achieve cloud-free coverage of the full site.

L86 – Would it make more sense to use the last optical image from the summer to define the lake boundaries instead of the maximum?

We think it best to use the composite image rather than just a single late summer image to define the lake areas within which to then look for SAR backscatter change. It means the lake areas are defined on the basis of a few images rather than just one, which will remove possible errors associated with relying on just one image. The date of the last image may vary due to variable cloud cover. Using just the last image does not allow for the possibility that the lake fills after the last available image. It also means we're looking at the mean dB change over a larger area and so we'll be erring on the side of caution when defining a dB change. It also allows for the possibility that the last image extent may underestimate the true water extent that can be detected in the SAR imagery if water around the lake edge is shallow subsurface and not visible in the optical image.

L111 – What does "lakes across the scene" mean? How large of an area is this?

For clarity, we propose to change this to " . . . all lakes within the study site . . .". We describe the size of the site and the number of lakes earlier on lines 61-62.

L112 – What does the last sentence mean?

Apologies for the confusion. We propose to delete this last sentence as the relevant points of the method are addressed in line 120 in the following paragraph.

L125-126 – Again, would it make more sense to use the last optical image from the summer to calculate lake volumes instead of the maximum lake area?

Sorry - the areas, volumes, and depths shown in Table 1 contained an error in the submitted manuscript and along with the error a mistaken description of the images used for calculating depth. We agree that for this calculation the last available image prior to freeze-over is the most appropriate as it most closely represents the volume of water present in the lake at the time of drainage. We will be editing Table 1 and the description of images used here and in the Table caption to reflect this correction. Table 1 values will be changed to appear as follows:

Lake	Location	Drainage Date	delta dB	z-score	Pre-drainage Lake Area	Pre-drainage Mean Lake Depth	Pre-drainage Lake Volume
Lake 1	-47.32 , 68.70	11 Nov 2014 to 23 Nov 2014	-4.3	3.5	0.04 km^2	0.57 m	0.000021 km^3
Lake 2	-48.52, 68.91	10 Jan 2015 to 22 Jan 2015	-4.4	3.4	6.12 km^2	3.26 m	0.0200 km^3
Lake 3	-48.75, 69.43	05 Jan 2016 to 17 Jan 2016	-3.8	2.7	0.43 km^2	1.89 m	0.0008 km^3
Lake 4	-48.38, 69.40	05 Jan 2016 to 17 Jan 2016	-2.3	2.6	0.51 km^2	2.56 m	0.0013 km^3
Lake 5	-47.43, 68.62	10 Feb 2016 to 22 Feb 2016	-3.2	2.8	1.84 km^2	0.86 m	0.0016 km^3
Lake 6	-48.03, 68.75	06 Nov 2016 to 18 Nov 2016	-9.3	2.2	2.27 km^2	1.41 m	0.0032 km^3

L175 – I imagine that partial re-freeze would greatly impact the lake volume. Some water must have frozen as these lakes are no longer on the surface but are buried beneath a layer of ice. Also, I am wondering how the lake area detected from optical imagery compares with lake area detected from S1 imagery immediately prior to collapse? I imagine that the outlines of lake 3 and 4 would look quite different between the optical and S1 imagery.

Regarding refreezing. We agree that a partial refreeze between the time of the last available satellite image in the previous summer and the time of the lake drainage in the winter would impact the lake volume. The depth of refreezing cannot be gleaned from satellite imagery. A model would be needed to calculate this. However the focus of our paper is not on the precise volume of water drained, but on the fact that winter lake drainages occur at all. Here we are using the optical imagery in the way we do to get simple estimates of the drained lake volumes, which we can then compare with the other estimates of drained lake volumes from photoclinometry. It is encouraging that both methods give not dissimilar results showing that L2 > L6 > L5 in terms of volume drained. We note, however, that the optical band method *underestimates* lake volumes compared to the photoclinometry method so the role of refreezing is likely less important than the fact that the optical method is biased towards measuring shallower water depths due to possible under-measurement of the deepest water because of saturation of the red band within the water column (Moussavi et al., 2016; Pope et al., 2016). As we say in reply to a comment on this section by referee 1, we're proposing to remove lines 172-5 here and discuss the reasons for the differences between the two volume estimates more fully in the Discussion.

Regarding lake area. It does appear from the images that there is a difference in lake outlines between the optical and the SAR data. Outlining the precise boundary of a supraglacial lake based on SAR imagery alone is not straightforward, and at the present time there is no published method for delineating the lake outlines from SAR imagery alone. This is the subject of ongoing work. For this work, we bound the lakes using optical imagery in line with established published methods and used these outlines to track SAR backscatter changes over time (e.g. Miles et al, 2017). It seems from the imagery that water exists under the surface where it is not evident in the optical data, but we cannot be certain this is the case. Further work is needed to establish methods to determine water presence in subsurface lakes where none is visible in optical imagery.

For clarity (and in response to a comment from the other Reviewer as well) we intend to add the optically-determined lake mask onto Figure 3 to better illustrate the area of analysis.

Table 1 – What are the uncertainties on lake depth and volume?

For the optical band method shown here in Table 1, we will use the values from the detailed error assessments undertaken for the Greenland Ice Sheet by Pope et al, 2016.

https://tc.copernicus.org/articles/10/15/2016/

They calculated errors for Landsat 8 data of 0.28 m for the red band and 0.63 m for the panchromatic band. As we're using the averages of the red and panchromatic band in our work (as recommended by Pope et al, 2016) we will assume an error of (0.28 + 0.63) / 2 = 0.46 m.

We will add these errors to the depth calculations shown in Table 1 and use them to estimate errors for our calculations of lake volumes. In line with previous work using these methods, we do not define errors for lake areas, which instead are fixed according to our threshold $NDWI_{ice}$ value of 0.25.

L190 – With regards to Lake 6: I looked briefly at this lake on GEE during this time period using the HH band. I noticed that surrounding lakes show an increase in backscatter similar to lake 6 with the HH band. Do you have an explanation for this?

HV polarised SAR accentuates volume (shallow subsurface) scattering whereas HH polarised SAR accentuates surface scattering. So an increase in HH backscatter of all lakes probably reflects an overall increase in surface roughness (formation of sastrugi for example) whereas the increase in HV backscatter picks out the reduction in volume scattering due to the drainage of water.

https://nsidc.org/sites/nsidc.org/files/files/SARTheory.pdf

Figure 3 – I believe it would be useful to include dates on these images. Also the last line of the caption seems misplaced. Finally, I am not convinced by the 'drainages' of lakes 3 and 4. Lake 3 appears more as though there was some partial freeze through of the sides of the lake. For lake 4, it is very hard to discern the lake in the Sentinel-1 image and makes me question whether there is indeed subsurface water here. What are the boundaries used for this lake?

We will edit the figure to include dates. We will also add the lake boundaries (this suggestion was also made by Reviewer 1). The figure below shows the proposed changes. Please see our detailed response to the general comment at the start of this review above regarding the issue of whether to include Lakes 3 and 4. They are highlighted by our analysis as having large, anomalous, sudden and sustained changes in backscatter, that are unlike those observed in other lakes. We propose to keep them in our paper, but be more circumspect with regards to their interpretation. Including them as "possible" lake drainages may help others who may wish to use / adapt our technique for use in other years and / or other areas of the ice sheet.

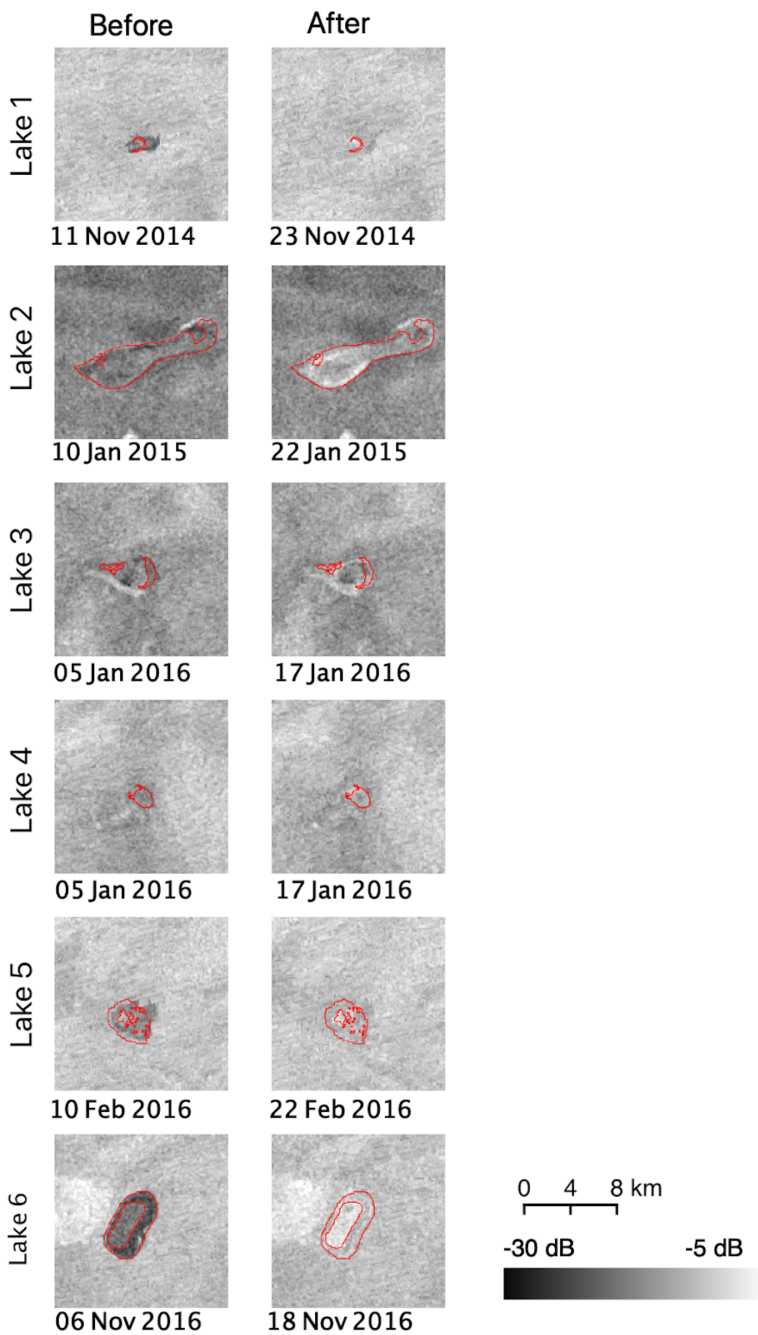


Figure 4 – Do lakes 3 and 4 have enough backscatter data before the jump to indicate "sustained backscatter"?

This is a good question. Please see our detailed response to the general comment at the start of this review.

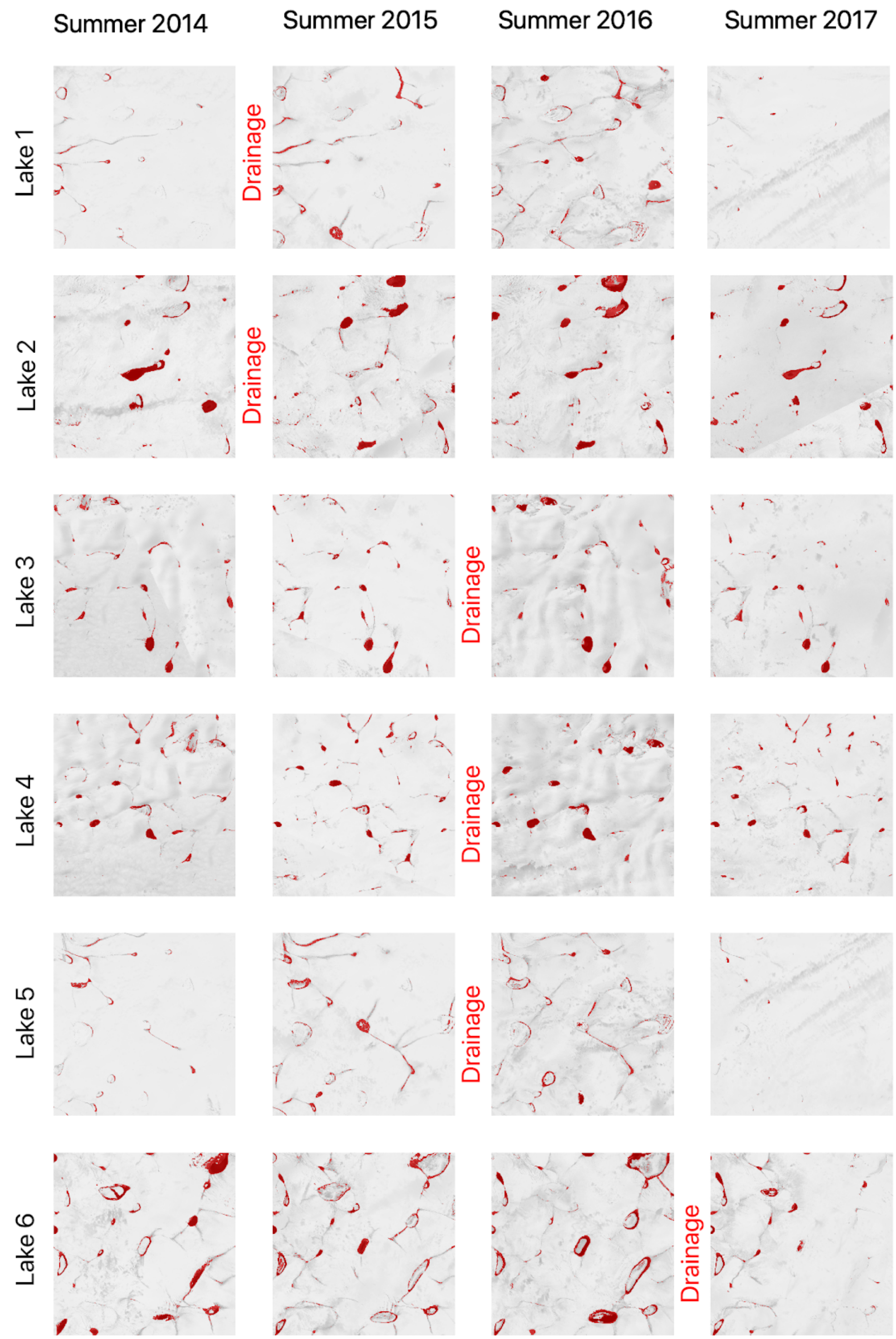
Figure 5 – This analysis is extremely beneficial and I think it would be useful to show something similar for the other lakes in this study. Also, was the area used for each lake the area outlined in red in the NDWI Max Composite? This seems to miss what appears to be subsurface water for lakes C, G, and H. In fact, it seems that the subsurface part of Lake H also increases backscatter (although not as significantly as Lake 6).

We agree that these figures would be useful and will plan to include them in the supplementary material for the other lakes.

Yes, the area used for each lake is the area outlined in red in the NDWI Max Composite. We agree that it is possible we are missing some areas of subsurface water but at the moment there is no published method for identifying whether a pixel contains subsurface water or not from Sentinel-1 imagery alone. From the optical imagery, it is not possible for us to know for certain whether 'non-water' areas are floating ice covered by snow, or genuine ice islands or peninsulas. For this reason, we opted to confine our analysis to deep water demonstrated by optical data.

L208 – "These reductions in maximum lake extent contrast with those observed for the many surrounding lakes, which fill to around the same size in adjacent summers". A figure or some evidence of this would be useful.

We will plan to include a supplementary graphic which is similar to Figure 6 but with an altered scale to include more surrounding lakes. See below for a draft of such a Figure - we will add arrows or a box to highlight the drained lakes. In this additional figure, the background image in each is the maximum NDWI composite for the given summer season and the red shaded region is the lake mask used for analysis based on an NDWIice value in the summer composite >= 0.25.



L218 – What are the uncertainties on the elevation changes from photoclinometry? Do you have any idea why these values are so much larger than the depths from optical images?

For the photoclinometry method we will use uncertainty values from the detailed error assessment undertaken for Langjökull, Iceland by Pope et al (2012, their Table 2)

https://www.tandfonline.com/doi/pdf/10.1080/01431161.2012.705446

Here they compared elevations derived using the photoclinometry method on Landsat imagery, with airborne LiDAR elevation data. In areas where the photoclinometry assumptions were met (no shading) the median error is just 0.03 m, so the height difference error is then sqrt(0.03^2 + 0.03^2) = 0.04 m. In areas where photoclinometry assumptions were not always met (e.g. shaded areas), the median error is 1.44 and the equivalent height difference error is 1.61 m. We suspect the real error for our case on the Greenland Ice Sheet lies somewhere between these two, but to account for the different locations, DEMs, solar elevations and along-track spacing of the tie points between the Iceland and Greenland studies we will use the larger of the two errors, i.e. 1.61 m. We will add these errors to our calculations of lake depths and also use these to estimate errors for our calculations of lake volumes. In line with previous work using these methods, we do not define errors for lake areas, which instead are fixed according to our threshold $NDWI_{ice}$ value of 0.25.

We do have ideas about why these values are larger than those derived from the optical band method which we discuss on lines 294-303. We plan to improve the explanation for the possible reasons for the discrepancy here - please see our response to Reviewer 1's comment for L219 and photoclinometry uncertainty.

Figure 6 – For Summer 2017 lakes 1 and 5: are these just cloudy images? If so, I would emphasize this somehow because it also looks like the lake just isn't there. Also, a scale would be nice. Once again, I do not find this analysis very convincing for lakes 3 and 4. You mention that they "change shape" but I do not see a significant shape change for lake 4.

We will add a scale to this figure. We don't know for sure whether the 2017 images for lakes 1 and 5 are cloudy or whether the lakes are largely obscured due to snow blowing and drifting or to recently settled snow. Note these lakes are in the same general area of the ice sheet and at the highest elevations of the 6 lakes. We will add a note to the figure heading to point out the possible reasons why the lakes may be obscured.

Figure 7 – "elevation" should be added before "difference" in the first line of the caption

Agreed. We will add "elevation" in the caption.

L269-271 – This is already mentioned and fits better in the methods section

We assume the reviewer is referring to:

"Occasionally, images showed large scene-wide departures from typical backscatter values. These images (dated: 03 Feb 2015, 10 Apr 2016, and 16 May 2016) were omitted in this

study as they were anomalous although if it were known what caused this phenomenon then perhaps the images could be corrected and used."

It is the last part of this sentence that is part of the discussion here and which we'd like to state as it is a 'problem' that needs to be overcome. We suggest shortening the sentence to:

"In our study, three images showed large, scene-wide departures from typical backscatter values and were omitted from further analysis. If it were known what caused this phenomenon then perhaps the images could be corrected and used."

L290 – can Sentinel-1 be used to determine if water is present in the lake at the start of the melt season? Of course it's harder to interpret than optical imagery but perhaps can give some idea of water presence?

There is no published method for determining whether a given pixel contains water from Sentinel-1 backscatter values alone. While work is being done to address this question using additional data and/or machine learning, it is not a trivial issue. For the purposes of this study, we decided to confine our work to pixels that we can verify as water through optical data. We could speculate about the behaviour of the water based on what we can see in the backscatter patterns, but without sufficient evidence we are reluctant to do that.

L298 – Did you try DEM differencing? (https://doi.org/10.1029/2020GL087970)

Reviewer 1 (his comment for L293 – 294) also suggested we try DEM differencing using individual ARCTIC DEM 2 m strips. Please see our detailed response to his comment. We were able to find before and after lake drainage strips only for Lake 6. We have performed the DEM differencing for Lake 6 and the results confirm a mean lowering of 2.17 m , adding further weight to our algorithm for detecting lake drainages from SAR imagery.

L337 – "other hydrological phenomena" such as?

we will add "such as onset of melt, rapid filling, or rate of freezing"

L343 – "what other types of behavior may indicate" is extremely vague

We will delete this sentence.

Figure B1 – Are the different colored dots significant? Also, please label the lakes in this image.

We will edit this image to replace the colored dots with lake numbers.

Technical corrections:

L26 – Needs a clarifier after 'This' to begin the sentence

Will change to "This lake drainage and subsequent water input generates…"

L45 – "rising water levels in the lake" → "increased lake volume"

Will make this change.

L58 – there is an extra space in "changes"

Will remove space.

L93 – change "files" to "images"

Will make the change.

L263 – "cover of cloud" → "cloud cover"

Will change.

L324 – Sentence that begins with "This" with no clarifier

Will edit to say "This finding..."

Figure A2 – Two periods at the end of caption

Will edit.