# Responses to Reviewer 1

## General comments

This manuscript presents the first quantification of the drainage of supraglacial lakes in Greenland during winter. Such events have previously only been described qualitatively, or their occurrence inferred from proglacial river data. As such, the authors make a worthwhile contribution to help fill in some gaps in our understanding of ice sheet hydrology. The paper is on the whole clearly written and the data analysis is valid and suitable (barring a few inconsistencies – see specific comments below). The main conclusions are justified, although there are some overly speculative comments made at the very end of the manuscript.

**Thank you to the reviewer for his thorough and very helpful review of our manuscript and for these positive comments. We are pleased the reviewer recognises the 'worthwhile contribution' and 'filling in of gaps' our paper makes and are glad to hear he thinks it is generally 'clearly written' with 'valid' and 'suitable' data analysis with the main conclusions 'justified'. We will clear up the 'inconsistencies' and remove 'overly speculative comments' as detailed below.**

My main comment is that the temporal coverage of the radar data used is limited. Sentinel-1b only started consistently retrieving data from west Greenland in October 2016, so a 6-day period for the same relative orbit is only possible from then. This raises the question of why the authors did not look for winter lake drainages over more recent years (i.e. after 2016/17). Doing so might improve the temporal resolution of the data and thus avoid some of the limitations.

**The temporal coverage we include in our analysis spans 3 years. While, of course, time span can always be increased (as can spatial coverage) we note that many published papers investigating lake drainages or other phenomena on ice masses only cover 1 or 2 years. We are keen for The Cryosphere to publish what we believe is the first documentation of winter lake drainage on the GrIS. It will be up to others to adapt and extend this analysis to cover other time periods and other parts of the ice sheet, and other ice masses.**

**However, following the reviewer's comment we did investigate imagery from later years from the same relative orbit as we'd used in our analysis and unfortunately the temporal resolution is not significantly improved. We wish to examine just one relative orbit to remove ambiguity of backscatter associated with using different relative orbits. As a way of background, we first started this work in 2017 [Note Corinne Benedek has taken Maternity Leave since this time]. We chose an area of the ice sheet where others had worked and where we knew there were plenty of lake drainages. We chose a relative orbit where temporal resolution was good over the previous 3 winters, and that is how we arrived at the data set we have.**

## Specific comments

L2: 'immediately' seems to contradict the 'hours to days' later in the sentence. I suggest removing it.

**We will replace 'immediately' with 'rapidly'.**
**Updated: deleted 'immediately' rather than replacing as 'rapidly' already appears in the same sentence.**

L3 & L26: Is meltwater access always sustained for the rest of the summer? If the ice is thick (so that creep closure rates at the base of the moulin are rapid) and surface meltwater input following lake drainage is low (i.e. the lake and moulin are at high elevation), the moulin might close and the lake refill.

**Recognizing this point, we will change line 3 to "and then can allow melt water. . ." and change line 26 to "may permit meltwater"**
**Updated: as above**

L26: 'This' should be 'Drainage' otherwise it is somewhat vague what is being referred to.

**We will change "This" to "This drainage"**
**Updated: as above**

L27: Not necessarily the 'down-glacier direction'. The direction of subglacial water flow is determined by the subglacial hydropotential surface, the slope and aspect of which will vary from that of the ice surface (due to the bed topography) and may be different from the broad definition of 'down-glacier'.

**We will change to "down-hydraulic-potential direction"**
**Updated: as above**

L32: It might be worth adding that the ice speed often decelerates below the pre drainage value because of the temporary increases in basal hydraulic efficiency.

**We will add this suggestion**
**Updated: added this note to the same line.**

L36: Although lakes contribute to total runoff from the ice sheet, they do not 'control' it. If you look at a seasonal hydrograph (e.g. Bartholomew et al. (2011, doi:10.1029/2011GL047063)), the overall shape is determined by atmospheric temperatures and ice surface melt rates. Because the highest melt rates are closer to the margins at lower elevations where there are fewer lakes, most meltwater enters the subglacial drainage system via crevasses and moulins not associated with lakes (Koziol et al. 2017). Lake drainages are typically superimposed on this seasonal pattern.

**We agree. Thank you. We will rewrite our text to make these exact points**
**Updated 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". As noted in Reviewer 2 Responses**

L48 - 49: This last part of the sentence doesn't quite make sense to me.

**Sorry this 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).**
**Updated: above plus removed "that" near start of sentence.**

L52: You should use the final TC reference which is 2013 (also in the reference list).

**Yes, we will change this - The Cryosphere, 7, 1433–1445, 2013**
**Updated: as above**

L64: More recent data acquisitions from Sentinel-1 a and b are more consistent and regular. Did you look over the 2017-2018 and later winters and not find any lakes? Or have you not looked at these data? Doing so might remove some of the temporal frequency limitations you mention later in the manuscript.

**Please see our response to this point in the General Comments section above**
**No updates made.**

L90: I wonder if it is worth mentioning somewhere that subglacial lake drainage (and the resulting formation of so-called 'collapse basins') might lead to a similar change in radar backscatter. The fact that you used a supraglacial lake mask to search for the backscatter changes suggests that the changes you identified were supraglacial lake drainages, but it might be worth a mention nonetheless.

**We think the place to make this point is not here in the Methods but perhaps in the conclusions / suggestions for future work and so we will add it there.**
**Updated: in Section 3.4.2 optical lake mask, added "Other surface changes, such as the drainage of a subglacial lake, could result in changes in SAR backscatter as well. The aim of restricting the analysis to summertime optically-identifiable lakes is to reduce the likelihood that the changes identified in this study are due to the incidence of these events."**

L105. The 'therefore' does not quite follow as written, but needs more explanation in the previous sentence justifying why you'd expect gradual freezing to lead to an increase in backscatter. Also, you should provide more details about why you think that a lake drainage would lead to a sudden, significant and sustained increase in backscatter. Is it because the collapsed lid of the lake would create chaotic relief and therefore be bright, or is it just the change from the radar 'seeing' through the frozen to the lake surface, to the radar instead seeing the ice of the drained lake bed?

**We will remove the word "therefore". We will also explain more fully why we'd expect a slow lake freezethrough to be associated with a gradual backscatter increase. This is explained in the paper we were both involved with (Miles et al, 2017) but we will**

**summarise things here and refer to that earlier paper. Briefly, liquid water absorbs HV backscatter, whereas frozen water reflects more of the signal as bubbles entrained within frozen lake ice increase the relative backscatter compared to liquid water . The backscatter signal of unfrozen and frozen lakes is therefore sufficiently distinct to allow freeze-through identification.**

**Similarly, we will add a sentence or two with reference to previous literature about why a lake drainage would lead to a sudden, significant and sustained increase in backscatter. We agree with the referee that both of his suggested processes are relevant. The former would produce a very high backscatter that is greater than the surrounding whereas the latter would produce an increase in backscatter to around the background values. We saw examples of both associated with summer lake drainages, which we reported in Miles et al 2017.**

**Updated: Added the following text in the same location: "Water presents in C-Band SAR imagery with low backscatter. As the lake surface begins to freeze, scattering due to bubbles trapped in the ice increases. C-Band waves continue to reach the underlying water until the ice becomes thick enough to obscure it. Summer lake drainage events have been observed to follow a pattern of low to high backscatter (Johansson2012, Miles2017). A winter lake drainage would result in the same process of low to high backscatter due to the removal of water and the exposure of the ice underneath in addition to roughness added above by the collapse of the ice lid."**

L106: I think the comparison with a summer lake drainage is probably valid but requires a bit more explanation. In the summer case, the backscatter values change because the surface changes from water to ice. It is likely the same change that is seen in winter (even though the lake might be partially frozen over) because C-band SAR can penetrate a few m of ice - likely thicker than the frozen lake surface, at least in the early part of the winter.

**Yes we agree. We think this point is implicit in what we have said but we will make it more explicit.**
**Updated: as in previous comment**

L121: It would be useful to also state the actual area in metres squared

**We agree and will add this, i.e. 8000 $m^2$. [Note the resolution of GRD scenes used is 40 x 40 m].**
**Updated: as above**

L125: Should it not be the latest rather than the greatest? Otherwise the estimated volume might be significantly greater than it was at the time the lake drained. Later in the manuscript you do refer to the volume estimates being for the last Landsat image of the season, so I think there is a mistake somewhere here.

**Sorry there was an error made here in the description and in the calculation of area, depths and volumes. We agree that the calculations presented should be from the latest**

**unfrozen Landsat-8 image prior to freeze over. We have recalculated areas, depths and volumes and will change the table values to those shown below. We will also add a listing in the appendix of the image scenes used for these calculations. Compared to previously the lake areas have all decreased. The exception is Lake 5, which has increased slightly, as a result of us accidentally excluding some peripheral pixels in the previous calculation that are now included. Compared to previously the mean lake depths have all increased and are now closer to the estimates derived from the photoclinometry method.**

| 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 $km^3$ |

**Updated: as above**

L133: Did the image tiles include any seawater? If so, was this used as the darkest pixel? Might the darkest pixel not be from a lake with sediment at its base and thus not truly representative of the spectral signal of deep water?

**Yes, the tile included seawater; and yes, seawater was always the darkest pixel. We will amend the text to make this more explicit: "Reflectance of deep water was determined per image by selecting the darkest pixel (which was always a seawater pixel) in each image."**
**Updated: as above**

L157 – 160: Understanding of this process would be greatly aided by the addition of an explanatory diagram.

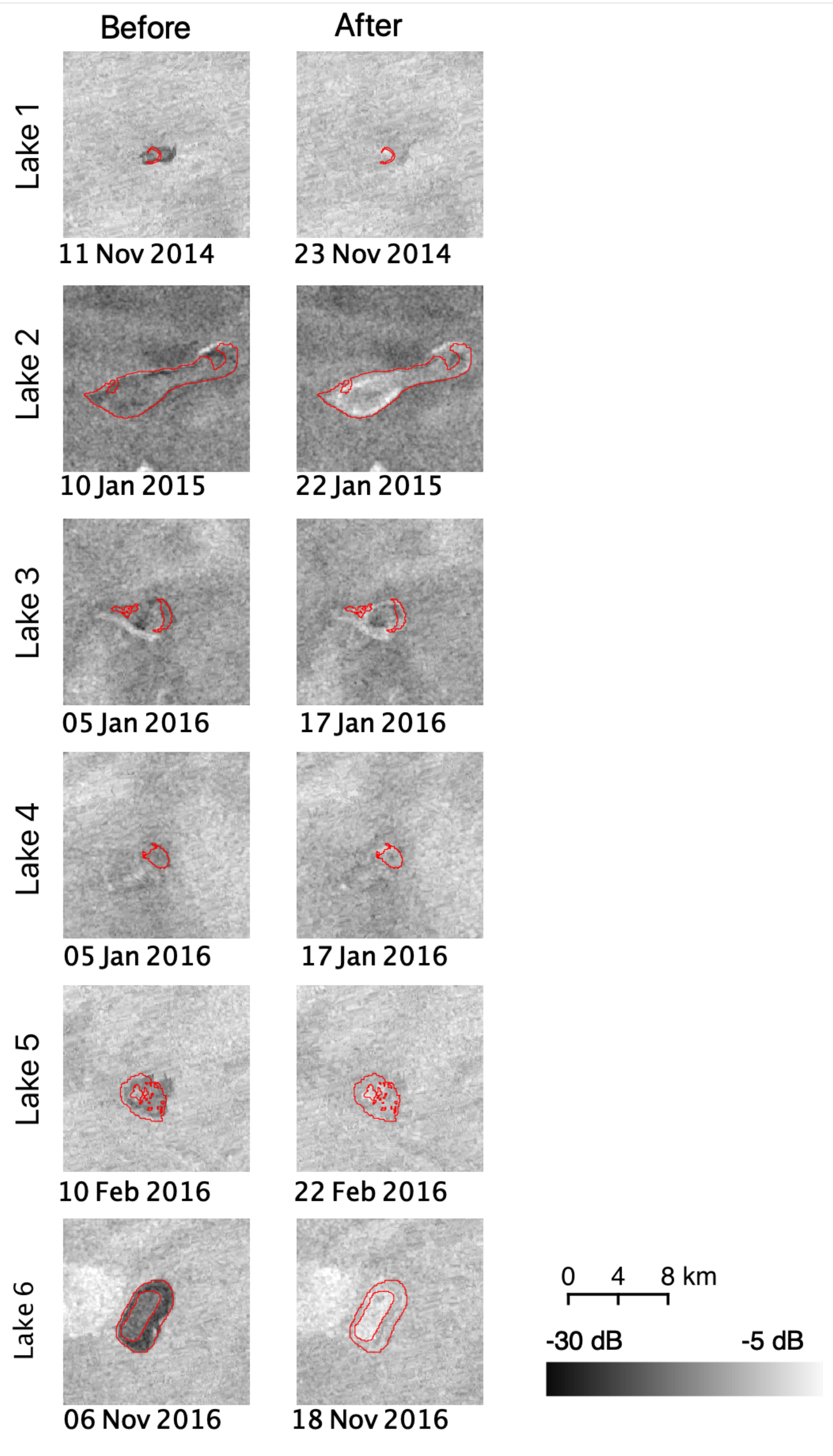
**We plan to tighten up the explanation of this method in the text. We mention that the method was used by Pope et al 2013 and described there (without ref to a diagram). But we can also add a simple 2D cartoon of a cross section along one of the transects shown in the Supp Mat Figure A2, first showing the offset and then showing closure of the offset and therefore the final surface . So Supp Mat Figure A2 would then have three components: a b and c.**
**Updated: as above**

L172 – 174: But you used the Landsat image with the greatest area for the lake depth rather than the latest one (L125). It is also possible that the lake volume reduced following your Landsat-derived volume calculation.

**Please see our response to the L125 comment above. Lake volumes have been recalculated based on the last available Landsat-8 image for each lake prior to freeze-over. The dates / filenames of these images will be included in the Appendix and referenced here as well. The text will be changed to reflect the volume calculation and to note that though they were based on the last available image before freeze over, this does not rule out the possibility that lake volume changed between the image acquisition date and freeze-over.**
**No updates made**

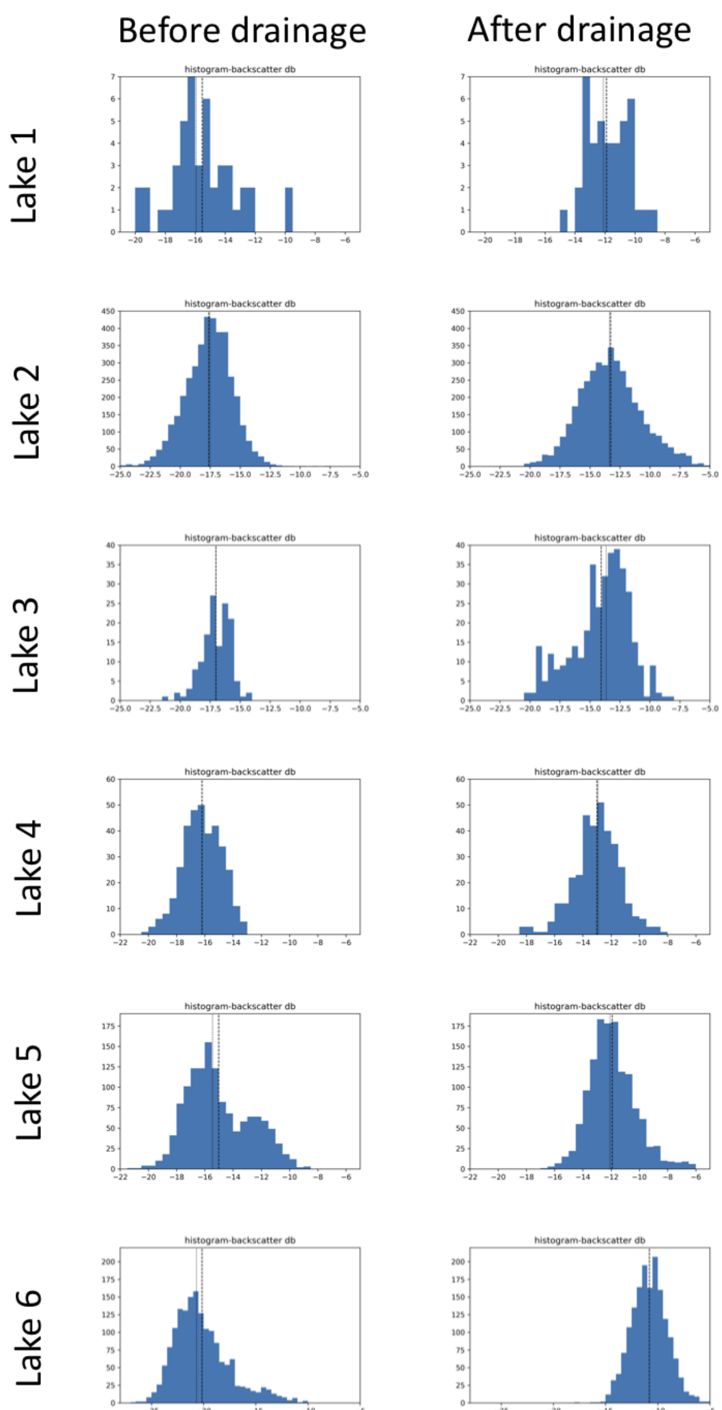
L179: It would be useful to show the extent of the optical lake masks on the Sentinel-1 backscatter images to see over what area the mean change in dB is calculated. Also, might a median value be less prone to the influence of outliers?

**We agree that it would be useful to include the lake mask boundaries on Figure 3 and will add them. A draft edit of this figure is here and also included in the responses to Reviewer 2.**




**Regarding using the mean vs median dB. We have checked the frequency distributions of dB for several lakes and they are normally distributed, with the mean and medians being the same value or only very slightly different. Please see distributions for the drained lakes below, showing the mean (dashed line) and the median (dotted line). We propose,**

**therefore, to stick with our use of the mean and can justify this by summarising the above in the text.**



**Updated: changed figure to show outlines and added the following to Methods text in section 2.3 Isolating drainage events: "Backscatter distribution of the final lakes was examined and determined to be very close to normally distributed and thus lake medians and means were close in value."**

L186: 'identified' would be better than 'filtered out' (otherwise it seems like you are removing them from the time series)

**We will remove this sentence in response to the next comment**
**Updated: as above**

L186 – 187: This repeats some of the methods section really. Is it needed here again? 'All other lakes. . .' could follow logically straight on from the previous paragraph.

**We will remove this sentence as the reviewer suggests**
**Updated: as above**

Figure 3 caption: Does the last sentence definitely apply to this figure? It does not seem to make sense.

**Thank you for spotting this. The sentence does not belong here and will be removed.**
**Updated: as above.**

L198 (subtitle 3.2): It would be useful to state in the section title what you are confirming - 'Confirmation of winter lake drainage. . .'

**Thank you. We agree. The section title will be changed to 'Confirmation of winter lake drainage by optical imagery'.**
**Updated: as above**

L219: Average depth for Lake 2 after drainage is more than double that calculated when the lake was present. Why do you think the differences are so large? Do you only calculate the depth of the depression to the lake shoreline using photoclinometry? Apologies if I've misunderstood the method, but I found it difficult to follow.

**Yes, using photoclinometry we only calculate the elevation change within the lake - so upto its shoreline. We will clarify this in the text. See also our reply to comment L157-160 above - we hope the method will be clearer with the addition of the extra diagram. Note also that the recalculations of the lake depths using the optical imagery with the last available image from the previous summer have resulted in slightly deeper mean lake depths (see our new Table 1 above) which bring them slightly closer to the mean depths calculated using the photoclinometry. However, it is still the case that the photoclinometry method of lake depth calculation produces lake depths that are bigger than those produced using the optical band method , > 2X for Lake 2, around 1.5 X for Lake 5 and nearly 2.5X for Lake 6.**

**We mention likely reasons for the discrepancies in lines 172-175 and also lines 294-303. These are all to do with errors in the two techniques of course. We propose to remove lines 172-175. Around L219 in the results we propose to say that possible reasons for the discrepancies will be discussed below in the Discussion. Then we will ensure that the errors in both the optical band method and the photoclinometry method and the likely reasons for the differences in lake depth calculations are discussed fully in the Discussion around what is now lines 294-303. We will quantify the depth errors in the two techniques with reference to previous literature. From Pope et al (2016) we estimate error using the optical band method is 0.46 m and from Pope et al (2012) we estimate error using the photoclinometry method is 1.61. Please see our responses to Reviewer 2's comments for 'Table 1' and 'L 218' for derivation of these errors.**

**Finally, please note that these calculations of lake depth are subsidiary to the main point of the paper, which is to document winter lake drainages (rather than quantify precisely the volumes of water drained). These two additional 'tests' support the SAR backscatter changes by showing: i) that water depths were shallower in the subsequent summer than the previous summer; and ii) that surface elevation dropped over the winter.**
**Updated: Deleted lines 172-175. The following line is added in the results section on Photoclinometry: "Possible reasons for the discrepancy between attenuation-based depth estimates and photoclinometry-based collapse depths will be addressed in the Discussion." Error discussion added in section 3.4.4.**

L227: 'calculated using' might be better than 'expressed through'

**Agreed. We will change the text as suggested.**
**Updated: as above.**

Figure 7 caption: The second and third sentences are a bit convoluted. I suggest changing to: 'The first column of images shows the collapse vertical distance of each pixel calculated by interpolating and differencing the pre- and post-drainage topography.'

**Thank you. We agree and will alter the text as suggested.**
**Updated: as above.**

L232: I think it would be worth briefly reiterating how you used the z-score – i.e. the z-score of backscatter change for each lake is calculated relative to the backscatter change of all lakes across the scene

**This is a good idea and we will reiterate briefly what we mean here and how we used the z-score to identify <u>large</u>, <u>anomalous</u> and <u>sudden</u> changes. The point here, of course, is that we also need to ensure the changes are also <u>sustained</u> to identify lake drainages correctly.**
**Updated: changed sentence to "If lakes are identified as anomalous based on z-score with no additional filtration done to confirm sustained change, the three seasons analyzed would result in 188. . ."**

L250: C-band SAR penetrates a few m of ice (Rignot et al. 2001), so likely sees through the nascent ice lid. I think this needs to be stated more clearly early on. You discuss the low backscatter values in a somewhat vague manner initially before offering an explanation in Section 3.3.3. Perhaps it would make more sense to swap the order of Sections 3.3.2 and 3.3.3?

**We would like to keep the order of sections 3.3.2 and 3.3.3 as this is the order in which the methods are done and the images are processed (equivalent to methods sections 2.1 and 2.2). and the method proceeds.**

**We will add a bit more to the end of the methods section (2.2), when we talk about using HV polarisation data to image shallow subsurface lakes, that HV data penetrates several metres through the surface, including snow, firn and any nascent lake ice lid. We will add the Rignot et al reference there. We will also add to the sentence on L250 to reiterate that we're using HV polarisation data, which is sensitive to volume scattering and therefore may be detecting water below the surface not seen in optical imagery. See also our response to comment L105 and L106, where we propose to clarify that HV backscatter changes are due to shallow subsurface processes.**
**Updated: Added the following to section 2.2: "The presence of water may be observed even when the lake surface begins to freeze and is covered by snow as the HV polarisation of C-band SAR can penetrate up to a few metres of ice (Rignot, 2001)."**
**Edited sentence on L250 to now read "but HV backscatter measurements, which are sensitive to volumetric scattering, remain low in this portion and both photoclinometry and ArcticDEM changes show a caving-in of ice in this area (Figure 5 and Figure 8 )"**

L257 – 258: Based on Figure 5 you might have more luck using Otsu thresholding on the Sentinel-1 images, as this would 'fill in' the interior of many of the lakes that are doughnut shaped in the NDWI composite.

**We thought of this but decided not to make the assumption that doughnut-shaped or other irregularly-shaped lakes necessarily contained water beneath a snow/ice lid. We wanted to focus the analysis of backscatter change solely on those areas which irrefutably showed evidence for deep water in the optical images. Using the Otsu thresholding method to 'fill in' lake interiors would have dampened the backscatter change signals we found if, in fact, those areas were not actually part of a lake. We would then have had 'less luck' in finding lake drainage events.**
**No updated made**

L266: The value of 9 m is for dry cold firn. It will be less for the ice lids on the lakes (a few m or less I expect based on Rignot 2001).

**Yes we will change the text accordingly and refer to "a few metres"**
**Updated: as above**

L272: Be clear that this is temporal frequency

**Thank you, yes, we will add the word "temporal" to refer to "temporal frequency" here.**

**Updated: as above**

L273: Both satellites were only recording image consistently from c. October 2016

**Agreed.**
**Updated: added "(only available since late 2016)"**

L282 – 283: Here you state that the depth estimates were based on the last available image, but on L125 you state that the depth measurement was based on the image when the lake was largest.

**As per the earlier comments, we have corrected the area, depth, and volume calculations presented in Table 1 to show quantities based on the <u>last</u> available Landsat-8 image before freeze-over.**
**No updates made**

L285 – 287: Based on the above discrepancy in how you measured the lake depth, your estimate might very well be an overestimate rather than an underestimate. This needs to be cleared up and the justification of why the lake depth and the photoclinometry depth are so different amended accordingly.

**Please see our response to comment for L219. We will add error estimates to our calculations of water depths based on both the optical band and the photoclinometry methods. We will clarify why the optical band method may underestimate water depths (crucially there is a depth threshold beyond which light attenuation is unaltered - Pope et al 2016; Williamson et al, 2018) and why the photoclinometry method may overestimate water depths (differences in the date of the DEM and the dates of the imagery used to calculate the slope-reflectance relationships; and shadowing in the lake basin not seen outside of the lake basin introducing error in slope calculations inside the lake basin when using an empirical relationship defined for areas outside the lake basin).**

**Updated: Added the following text to Section 3.4.4**
**"The depth estimation differences may be the result of a combination of factors. First, the attenuation-based algorithm is known to underestimate lake depths as the depths increase beyond a certain threshold(Pope2016, Williamson2018). Photoclinometry-based depths may be overestimating collapse depths due to topography differences in dates between the DEM used as a basis and the optical imagery used to create the shape/shading relationship. Shadows within the lake basin that do not appear in the ambient image may also introduce error into the calculation."**

L290 – 291: In terms of determining whether water was transported into the basin from higher elevations, could you not compare the dB values with the maximum achieved over the winter to detect surface melt at higher elevations? You could also use the runoff output of a regional climate model like RACMO.

**Both of these things could be done but we think they are not relevant to and would therefore detract from the main purpose of our paper. The main point of our paper is to**

**provide what we believe to be the first method for identifying automatically lake drainages using changes in SAR backscatter within lake basins. This has not previously been reported in the literature. Furthermore, we have applied the method and identified winter lake draianges. This phenomenon has not previously been reported in the literature either. We wanted to verify our method using other remote sensing techniques, which we have done using available optical imagery in two different ways. First, we have shown that water depths in the lakes prior to winter drainage in the previous fall are greater than those after drainage in the subsequent spring. Second we have used photoclinometry to show that there is a collapse in the lake surface elevation over the winter. In response to a comment by both referees, we have also used 2m resolution ArcticDEM strips to verify elevation change associated with the drainage of Lake 6 (see below). So providing a new method, applying it, and verifying it is the purpose of our paper.**

**The calculations of water depth and volume are very much a subsidiary part of the paper, but we provide these for general interest.**

**We think the referee is implying that dB values of SAR imagery (presumably imagery collected at the same time as the first available optical imagery the following spring) could be used to determine whether there's been any lake filling between the time of the winter lake drainage and the time of the 1st available optical image in the spring. This could be done but it would still not allow us to adjust the optically derived lake depth to allow us to get a better estimate of drained lake volume. The same procedure would have to be applied between the last available optical satellite image the previous autumn/fall, and the time of the lake drainage to determine whether water entered the lake (or froze in the lake) over the intervening period. Again, we would not be able to quantify the volume of water involved.**

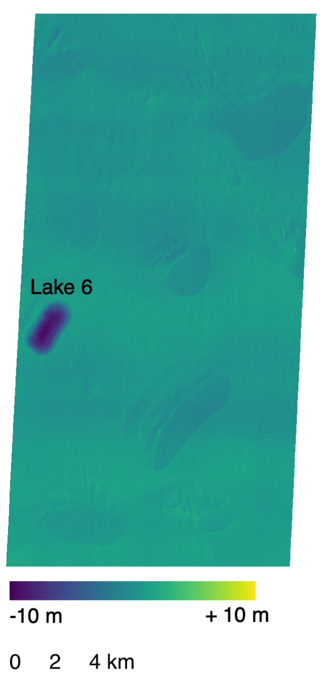
**The referee also talks about using RACMO to adjust the lake volumes determined from optical imagery. What we assume he's thinking about here is that runoff into the lake basin between the time of the lake drainage and the time of the first available optical image could be used to adjust the lake volume derived from the optical image according to how much extra water may have flowed into the lake during the spring. Again, presumably the same would need to be done between the time of the last available optical image the previous autumn/fall and the time of the lake drainage in order to adjust the lake volume derived from the autumn/fall optical image according to how much extra water may have flowed into the lake. What would be required here, is actually a surface hydrology routing model driven by the runoff output from RACMO. This, we believe, is way beyond the scope of this paper. All we are trying to do in the final section of our paper is use independent evidence to verify that a winter lake drainage occurred. We could leave it there but we thought it would be useful to obtain first order approximate values for the volume of the lake drainage event, which we do. And we discuss the errors associated with the derived volumes.**

**No updates made**

L293 – 294: Have you considered using the ArcticDEM time-stamped data strips? There may be some that would help to further constrain the volume of the drained lakes. See e.g. Livingstone et al. (2019) https://doi.org/10.5194/tc-13-2789-2019

**Thank you for this suggestion. We have examined the ArcticDEM time-stamped 2 m data strips and a satisfactory pair of 'before' and 'after' images exists only for Lake 6. In this case, a marked difference is shown in Lake 6 surface elevation before and after drainage. Using ArcticDEM 2 m strips from 21 September 2016 (before drainage) and 12 March 2017 (after drainage), we calculate the elevation difference (after minus before) seen in the figure below. If we mask this by the lake mask for Lake 6, we get a mean before/after depth difference of 2.17 m. Note this compares with the mean depth derived from the optical band method of 1.41 m (new Table 1 - see above) and that from the photoclinometry method of 3.38 m (Fig 7 and stated on L219). Note also that this photoclinometry-derived value is less than that quoted in our original manuscript (4.04 m) where we had not masked the lake according to our optically-derived maximum composite lake mask. For Lakes 2 and 5, the optically-derived lake masks are the same as those over which we apply the photoclinometry method. For Lake 6, the optically-derived lake mask is smaller than than over which we apply the photoclinometry. To compare with the optically-derived mean depth estimate, we must crop the photoclinometry-derived and the ArcticDEM-derived depth estimates. We will adjust our manuscript in the relevant places to explain this and make the correct comparisons.**

**The Figure below is a draft. We propose to add a figure to our paper for Lake 6 which is similar to the current Fig 7. So it will have 3 panels, elevation change and hillshades of the before and after ArcticDEMs for lake 6 and surrounding area. We will adjust the colour bar to be the same as that in Fig 7.**



**Updated: Text added to Methods, Results and Discussion and Figure as described regarding the ArcticDEM differencing of Lake 6.**

L301: Maybe remind the reader that this refers to the 5 m mosaicked product so is made up of data from many different times.

**Will will change the line to read ". . . in the ArcticDEM 5 m mosaics."**
**Updated: as above**

L303: Changes in backscatter are 'caused by' lake drainage events

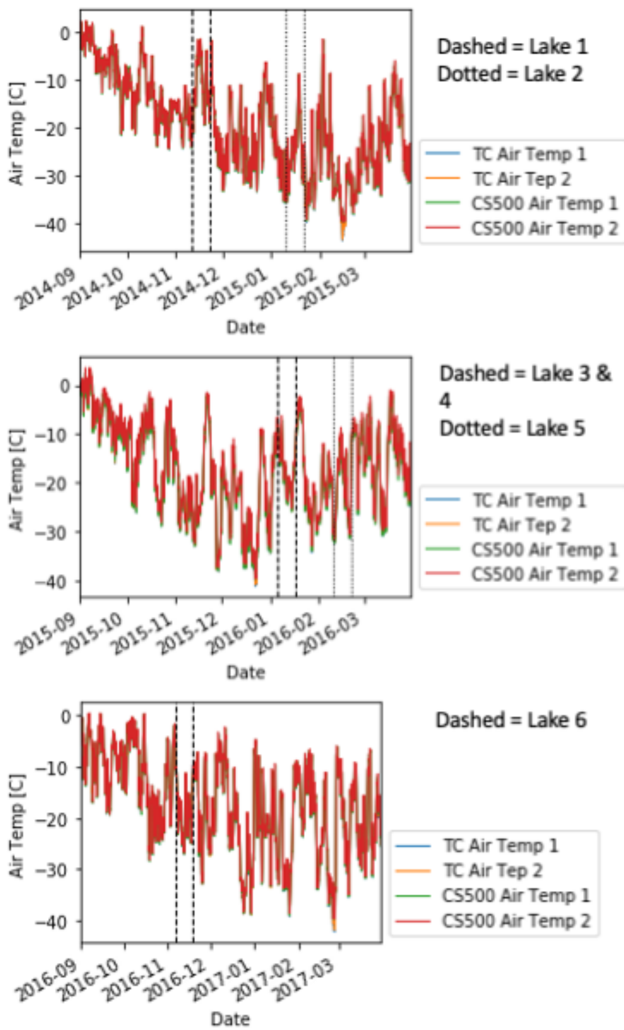
**Agreed. We will add 'caused by' lake drainage events.**
**Updated: as above**

L313: What about short sharp melt events over winter? Have you looked at any available meteorological data? Also do you detect a reduction in backscatter for the non lake surface at the same time the lake backscatter increases? This might indicate a small amount of surface melting that might have an effect on the (presumably relatively inefficient) subglacial drainage system if it got to the ice bed.

**We had not looked at meteorological data to see if there's evidence for short melt events coinciding with lake drainage events during the winter. But following the referee's suggestion, we have examined the Swiss Camp air temperature record for the 6 month (Oct-March) periods 2014/15, 2015/16, and 2016/17 covering our 3 winters (see the Figure below, where the 12 day periods during which lakes drain are indicated by the vertical lines).**

**As you can see, there is no clear evidence that the 6 lake drainage events are associated with especially large increases in air temperatures to above zero that would be indicative of melt events. The only exception might be Lake 1 where there is a large rise in temperature from -21 to near zero and the highest temperatures since early-mid Oct. But for the rest, air temperatures are either rising but not to above freezing, falling, or fluctuating. Furthermore there are other larger rises in air temperature sometimes rising to zero at other times of the year that are not associated with lake drainage events.**

**Given this, we do not propose to include this analysis in our paper, but we can in Supp. Mat. if the referee or editor thinks it would be helpful.**




**No updates made.**

L316: The transient nature of any speed-up probably means that there would be no discernible signal in a winter average velocity estimate.

**We think the referee has misunderstood what we're trying to say here, which we agree is not very well articulated. We are not suggesting that we might see the effect of a single lake drainage triggered speed up in the MEaSUREs data set. We are using the MEaSUREs velocity field to see if the locations of lakes are in particularly fast flowing areas of the ice sheet or areas of high strain rates which they do not seem to be. We propose to rewrite this section to make it clearer.**

**Updated: edited sentences to say "No pattern of lake locations and speeds seems to be visible, although our sample size is small and more evidence is needed to examine the possibility of speed triggers on lake drainage events further" and "These concurrent drainage events may be related with one drainage triggering another by creating localised**

**ice acceleration transferred via stress gradients to the second lake site (Christoffersen2018). Alternatively, they may indicate a larger scale ice movement that triggered both events simultaneously."**

L317 – 318: I'm not sure your sample size is big enough to be able to say this definitively, so it may be worth including this caveat.

**We will change the text to read "No pattern of lake locations and speeds seems to be visible, although our sample size is small and more evidence is needed to examine this possible association further".**
**Updated: as above.**

L322 – 325: Without actually doing a rough calculation (basin or lake diameter, velocity and time) this seems overly speculative.

**We agree, and given the referees previous comment about small sample size we do not think it worth performing these calculations and so we propose to delete these sentences.**
**Updated: as above.**

L319: the term 'cascade draining' is a little misleading (although I realise it is used in the title of the Christoffersen paper). Perhaps add a very brief explanation of the process – i.e. drainage of one lake creates ice acceleration and a tensile shock that is transferred through the ice and can trigger other lakes to drain etc.

**We will change the text to: "These concurrent drainages support the observations and modelling of Christoffersen et al. (2018) where the drainage of one lake creates localised ice acceleration, which is transferred via stress gradients to other areas triggering other lakes to drain". Alternatively, they may indicate a larger scale ice movement that triggered both events simultaneously."**
**Updated: as above**

L329: I don't think it is necessary to repeat 'large, sudden, anomalous and sustained' here.

**Agreed. We will change the text to: " We find six winter lake drainage events across a study site containing approximately 300 supraglacial lakes".**
**Updated but also edited with Lake3-4 changes based on Reviewer 2's comments**

L329 & 332: I think it is worth specifying that you are talking about supraglacial lakes here (for anyone who might just read the conclusion).

**Agreed. We will add 'supraglacial' after '300'.**
**Updated: as above.**

Technical corrections: Figure 2: Lines need to be thicker and symbols larger (and C is very difficult to see)

**Agreed. We will make these changes to make the graph clearer.**
**Updated: line widths, marker sizes, and colors adjusted**

L148: missing space between value and units

**Agreed. And we will check the entire document for this.**
**Updated: as above**

L151: Do you mean Appendix A? Appendix B appears to show ice velocity data.

**Agreed, we will correct this to read Appendix A3**
**Updated: referencing appendix A**

L230: 'event' should be 'events'

**Agreed. We will edit the text to 'events'.**
**Updated: as above. Also deleted 'a' from earlier in the sentence**

L242: 'false negative ones' should be 'false negatives'

**Agreed. We will edit the text to 'false negatives'.**
**Updated: as above.**

L243: 'false positive' should be 'false positives'

**Agreed. We will edit the text to 'false positives'.**
**Updated: as above**

## 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.**

<u>Specific comments</u>

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 . . ."**
**Updated: as above**

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".**
**Updated: as above**

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), . . ."**
**Updated: as above**

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.**
**Updated: as above**

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

**Agreed. We will combine the sentences.**
**Updated: as above**

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).**
**Updated: as above**

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)."**
**Updated: as above**

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

**Agreed. We will remove these words.**
**Updated: as above**

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.**
**Updated: image list included in Appendix E**

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.**
**No updates made**

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.**

Updated: as above

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.**
Updated: as above

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 $km^3$ |

Updated: as above

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.**
**Updated: as above**

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.**

**Updated: as above.**

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**
**No updates made**

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.**

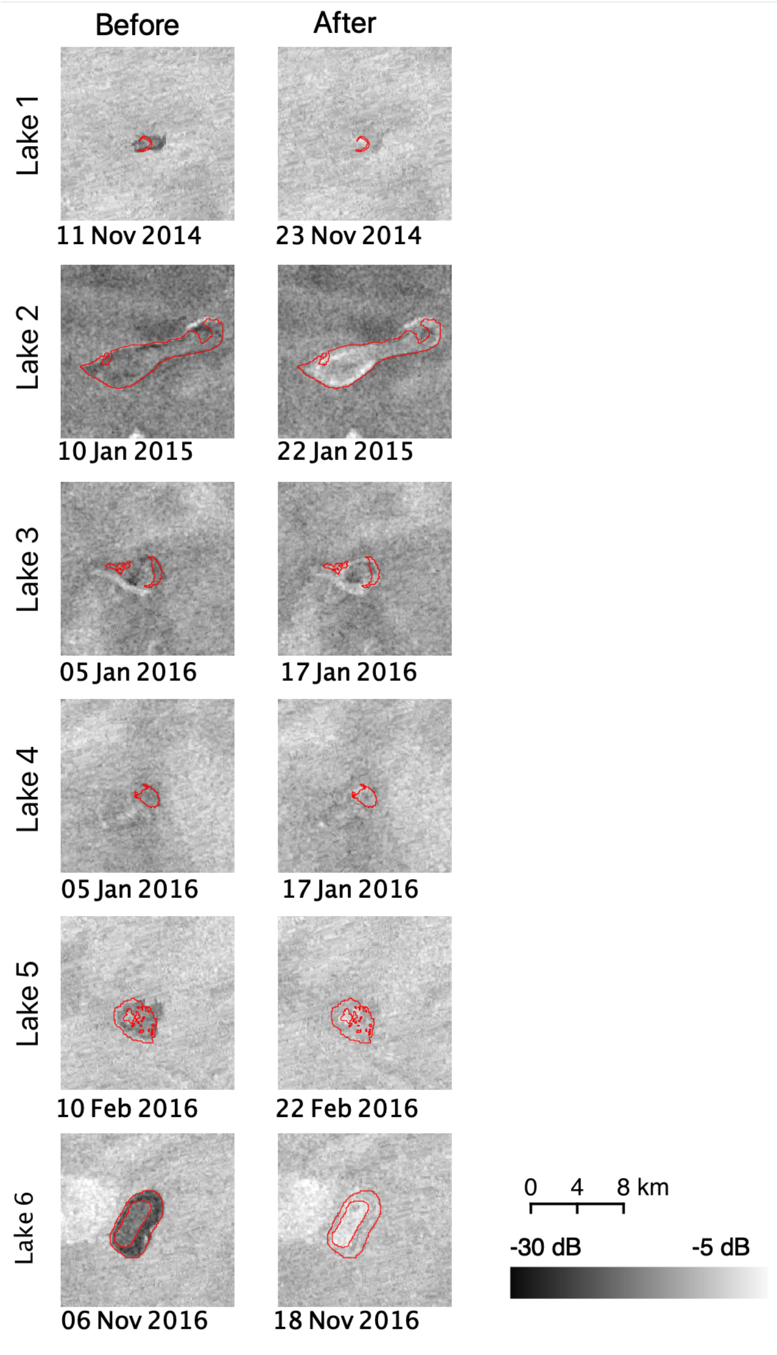



Figure 4 – Do lakes 3 and 4 have enough backscatter data before the jump to indicate "sustained backscatter"?

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

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).

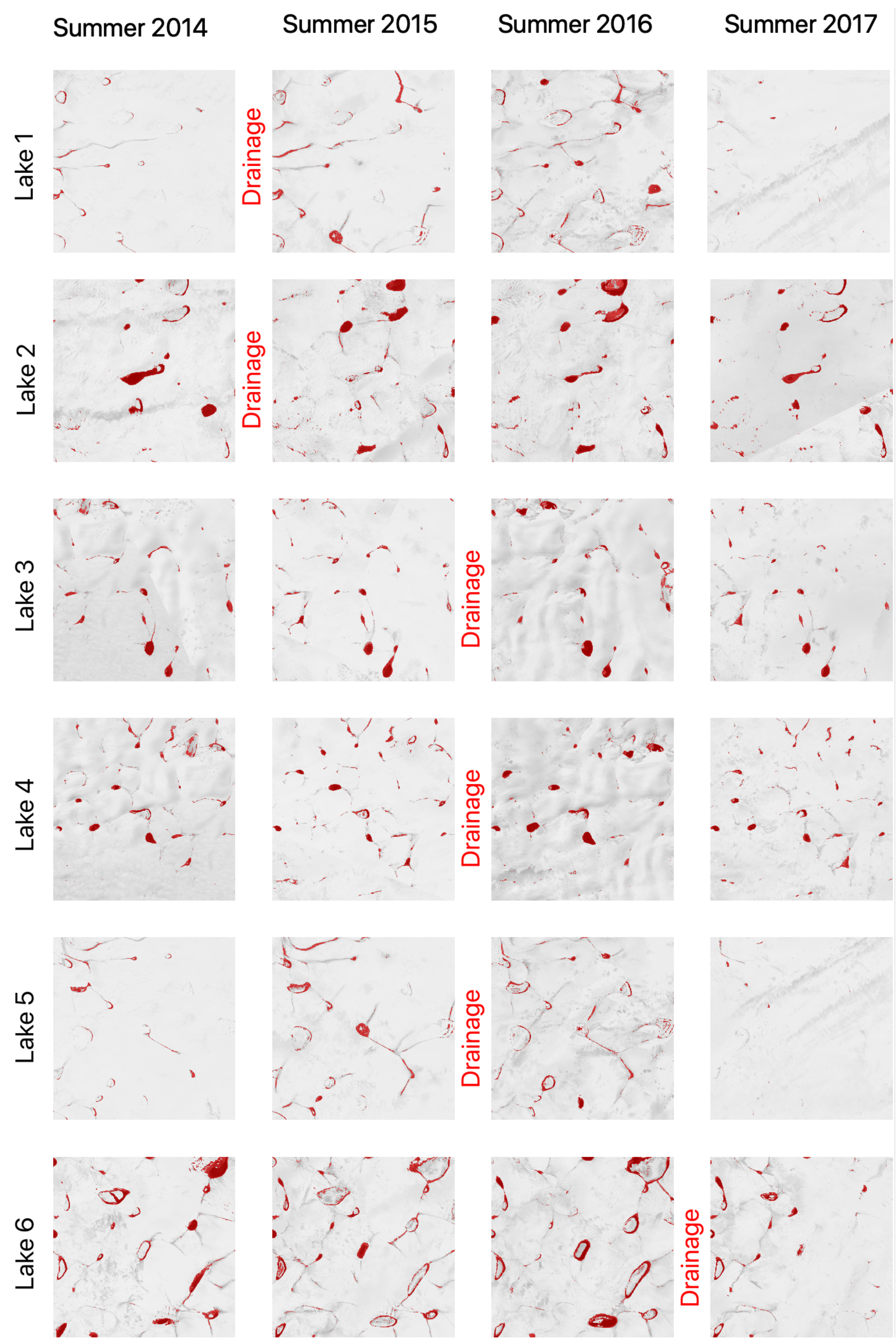
**We agree that these figures would be useful and will plan to include them in the supplementary material for the other lakes.**

**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.**
**Updated: edits made to Methods 2.2 and L250 regarding penetration of HV through floating ice lid.**

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.**

**Updated: as above**




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.**

**Updated: as above**

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.**
**Updated: as above**

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

**Agreed. We will add "elevation" in the caption.**
**Updated: as above**

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.”**

**Updated: as above**

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.**
**No updates made**

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.**

**Updated: we have added sections on DEM differencing following this suggestion after the discussions of photoclinometry within Methods, Results, and Discussion.**

L337 – “other hydrological phenomena” such as?

**we will add “such as onset of melt, rapid filling, or rate of freezing”**
**Updated: as above**

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

**We will delete this sentence.**
**Updated: as above**

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.**
**Updated: as above**

Technical corrections:

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

**Will change to "This lake drainage and subsequent water input generates…"**
**Updated: as above**

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

**Will make this change.**
**Updated: as above**

L58 – there is an extra space in "changes"

**Will remove space.**
**Updated: as above**

L93 – change "files" to "images"

**Will make the change.**
**Updated: as above**

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

**Will change.**
**Updated: as above**

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

**Will edit to say "This finding..."**
**Updated: sentence removed per response to Reviewer 1**

Figure A2 – Two periods at the end of caption

**Will edit.**
**Updated: as above**

# Winter drainage of surface lakes on the Greenland Ice Sheet from Sentinel-1 SAR Imagery

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**Abstract.** Surface lakes on the Greenland Ice Sheet play a key role in its surface mass balance, hydrology, and biogeochemistry. They often drain rapidly in the summer via hydrofracture, which ~~immediately~~ delivers lake water to the ice sheet base over timescales of hours to days and then ~~allows~~ can allow melt water to reach the base for the rest of the summer. Rapid lake drainage, therefore, influences subglacial drainage evolution, water pressures, ice flow, biogeochemical activity, and ultimately the delivery of water, sediments and nutrients to the ocean. It is assumed that rapid lake drainage events are confined to the summer, as this is when all observations to date have been made. Here we develop a method to quantify backscatter changes in satellite radar imagery, which we use to document the drainage of six different lakes during three winters (2014/15, 2015/16 and 2016/17) in fast flowing parts of the Greenland Ice Sheet. Analysis of optical imagery from before and after the three winters supports the radar-based evidence for winter lake drainage events and also provides estimates of lake drainage volumes, which range between 0.000046 ~~and 0.0202~~ $\pm$ 0.000017 km$^3$ and 0.0200 $\pm$ 0.002817 km$^3$. For three of the events, optical imagery allows repeat photoclinometry (shape from shading) calculations to be made showing mean vertical collapse of the lake surfaces ranging between ~~4.04~~ 1.21 $\pm$ 1.61 m and 7.25 $\pm$ 1.61 m, and drainage volumes of ~~0.004~~ 0.002 $\pm$ 0.002968 km$^3$ to ~~0.049~~ 0.044 $\pm$ 0.009858 km$^3$. For one of these three, time-stamped ArcticDEM strips allow for DEM differencing demonstrating a mean collapse depth of 2.17 $\pm$ 0.08 m across the lake area. The findings show that background winter ice motion can trigger rapid lake drainage, which may have important implications for subglacial hydrology and biogeochemical processes.

## 1 Introduction

Lakes form each summer on the surface of the Greenland Ice Sheet (GrIS), particularly in the upper ablation and lower accumulation areas (McMillan et al., 2007; Selmes et al., 2011; Liang et al., 2012; Pope et al., 2016; Williamson et al., 2017). They enhance melt rates via their effects on albedo (Lüthje et al., 2006; Tedesco et al., 2012), store water and delay its delivery to the ocean (Banwell et al., 2012; Leeson et al., 2012; Arnold et al., 2014), and collect nutrients - the products of surface inorganic and organic chemical processes (Musilova et al., 2017; Lamarche-Gagnon et al., 2019). Many lakes drain over the summer (Selmes et al., 2013; Williamson et al., 2017), sometimes slowly by overtopping their basins and incising a channel (Hoffman et al., 2011; Tedesco et al., 2013; Koziol et al., 2017) but often rapidly by hydrofracturing from the surface to the base of the ice sheet (Das et al., 2008; Doyle et al., 2013; Tedesco et al., 2013; Stevens et al., 2015; Chudley et al., 2019). The rapid drainage of a lake may trigger the opening of crevasses and the generation of moulins (Hoffman et al., 2018) or the drainage of other lakes (Christoffersen et al., 2018) through ice dynamic coupling. Rapid lake drainage provides a major shock to the ice sheet as millions of cubic metres of water are delivered to the bed in a few hours, and the resultant fracture permits may permit meltwater to reach the bed for the rest of the summer. This lake drainage and subsequent water input generates a radiating subglacial water 'blister' beneath the draining lake, which evolves into a conduit in the down-glacier down-hydraulic-potential direction allowing the lake water and subsequent melt water to be evacuated (Pimentel and Flowers, 2010; Tsai and Rice, 2010; Dow et al., 2015). High water pressures are generated transiently during lake drainage (Banwell et al., 2016), lifting the ice sheet off the bed and increasing temporarily its sliding velocity (Das et al., 2008; Doyle et al., 2013; Tedesco et al., 2013; Stevens et al., 2015; Chudley et al., 2019). The subsequent evolution of the subglacial conduit may lower water pressures (Schoof, 2010; Hewitt, 2013; Werder et al., 2013; Banwell et al., 2016) and reduce sliding speeds, often below pre-drainage values as a result of temporary increases in basal hydraulic efficiency (Bartholomew et al., 2010).

Rapid lake drainage and subsequent meltwater influx also alter subglacial biogeochemistry as large volumes of oxygenated water containing surface microbial taxa and inorganic and organic nutrients replace wintertime anoxic waters and associated microbes, shifting subglacial redox potential and associated biogeochemical pathways (Wadham et al., 2010; Shade et al., 2012). Lake drainage events , therefore, ultimately control 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. They can produce small floods that flush out sediments (Bartholomew et al., 2011), raise levels of phosphorus, nitrogen and sulphate in proglacial streams (Hawkings et al., 2016; Wadham et al., 2016), and mark a transition from net subglacial methane production and proglacial export during winter to consumption with little or no export in the summer (Dieser et al., 2014).

Much of what we know about the locations, timings and magnitudes of rapid lake drainage events comes from the analysis of optical satellite imagery (Box and Ski, 2007; McMillan et al., 2007; Sneed and Hamilton, 2007; Leeson et al., 2013; Moussavi et al., 2016; Pope et al., 2016; Williamson et al., 2018) although studies have recently begun using optical imagery from drones (Chudley et al., 2019), and airborne and satellite radar data (Koenig et al., 2015; Miles et al., 2017)(Miles et al., 2017). Conventional understanding is that rapid lake drainages are confined to the summer . They and may be driven by active in-situ hydrofracture through the lake bottom triggered by rising water levels in the lake increased lake volume (Alley et al., 2005; van der Veen, 2007; Krawczynski et al., 2009; Arnold et al., 2014; Clason et al., 2015) and/or by passive fracture in response to perturbations in ice sheet flow induced by surface meltwater initially tapping the bed via nearby moulins (Stevens et al., 2015; Chudley et al., 2019). Conventional understanding is that lakes that completely or partially drain during the summer then freeze during the winter, opening of crevasses and the generation of moulins 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).High proglacial stream discharge anomalies outside of the summer melt season have been attributed to the release of stored water from the ice sheet. Evidence In another study, proglacial stream evidence from one study showed suggested that water was released from englacial or subglacial water stores (Rennermalm et al., 2012) although the formation stores (Rennermalm et al., 2013). Proglacial stream evidence together with the appearance of surface collapse features reported in another, suggested water has the potential to be on the ice sheet suggested that water may have been released from surface lakes during the winter (Russell, 1993).

Here we develop an algorithm to carefully examine spatial and temporal variations in microwave backscatter in from Sentinel-1 satellite synthetic aperture radar (SAR) imagery to and document the location and timing of six separate lake drainage events over three different winters. We confirm the winter lake drainages and provide estimates of draining lake volumes through calculation of water areas and depths in Landsat-8 optical imagery from the previous and subsequent melt seasons. For three of the events, the optical imagery allows us to calculate surface elevation change s changes associated with the lake drainages using the technique of photoclinometry. For one of those three events an independent calculation of surface elevation change is available through the comparison of time-stamped ArcticDEM strips before and after the event.

## 2 Methods

The study was conducted over a 30,452 km$^2$ area of the GrIS (Figure 1). The site spans elevations from 300 meters m to 2038 meters m above sea level and includes approximately 300 lakes over 5 pixels in size (0.0045 km$^2$). The study period spans imagery from July 2014 to May 2017 and includes, therefore, three fall-winter-spring periods from October through May, hereafter "winter periods": 2014/15, 2015/16 and 2016/17.

There are five six components to our analysis. First, a lake mask is established from optical imagery. Second, for each lake, trends in mean backscatter change during the winter are calculated. Third, the backscatter changes are used to identify large anomalous, sudden and sustained increases in backscatter that are indicative of winter lake drainage events. Fourth, optical images from before the winter periods are used to provide estimates of lake volumes prior to drainage. Fifth, for three of the events, optical imagery and the technique of photoclinometry are used to calculate patterns of surface elevation change associated with the lake drainage events, providing independent estimates of lake drainage volumes. Sixth, for one of those three events, time-stamped ArcticDEM differencing is used to confirm the patterns of elevation change and provide another independent measure of lake drainage volume. These components to our analysis are described more fully in the six sections below.

### 2.1 Establishing lake outlines using optical imagery

Prior to each winter, lake boundaries were delineated based on a calculation of maximum $NDWI_{ice}$ per pixel from optical imagery during the preceding late melt season (late July through August, image IDs listed in Appendix E). Landsat-8 Tier 1 TOA images were chosen based on minimal cloudiness (filtered using the Landsat-8 QA band) and images were removed from the set manually where cloudiness interfered with $NDWI_{ice}$ calculations. Late season images were chosen so that lakes that had already drained prior to the end of summer freeze-over period were not included in the calculations. For each late summer period, multiple images were needed to cover the entire region and to obtain at least one cloud-free pre-freeze-over image for all areas of the study site.

Normalized Difference Water Index $NDWI_{ice}$ was calculated for each pixel in each of the images in the Landsat-8 set (Yang and Smith, 2012) (Equation 1).

$$NDWI_{\text{ice}} = (Blue\text{–}Red)/(Blue + Red) \quad (1)$$

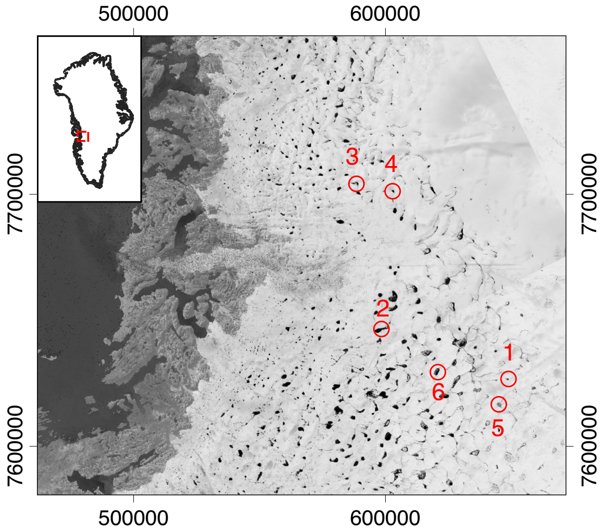



**Figure 1.** Study area within the context of the Greenland Ice Sheet (inset). Distribution of all surface lakes detected from optical imagery, with the six winter draining lakes highlighted (red numbers, in chronological order of drainage), which are shown in more detail in Figure 6. The base map is a composite image showing the maximum $NDWI_{ice}$ observed for each pixel in Landsat-8 optical images over the course of all summers from 2014 through 2017. The outline of Greenland is from OpenStreetMap (© OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License.)

where Blue and Red refer to band reflectance.

For each late summer, a mask was created from the set of Landsat-8 images by recording the maximum $NDWI_{ice}$ value observed in each pixel over the set and setting an $NDWI_{ice}$ threshold of 0.25 following Yang and Smith (2012) and Miles et al. (2017) indicating the presence of deep water. These lake masks, one for each summer, were then used as the basis for defining lake boundaries for the analysis of backscatter changes in SAR imagery during the subsequent winter periods.

### 2.2 Calculating time series of mean lake backscatter from SAR imagery

For each winter period, lake masks delineated from the previous late summer's Landsat-8 images were applied to Sentinel-1 SAR images in order to calculate trends in mean backscatter for each lake over time. Analysis was restricted to lakes identified in the optical data, as the delineation of lakes from SAR imagery alone is not trivial. Low backscatter values in C-Band SAR could be indicative of surface characteristics other than the expression of water. Changes in mean backscatter of each lake were tracked over each winter period and these changes were used to identify wintertime lake drainages as described further below.

Google Earth Engine (Gorelick et al., 2017) was used to select a series of Sentinel-1 images over the study site. Sentinel-1 ~~files~~ images on the Google Earth Engine repository have been pre-processed using the following steps: i) Apply Orbit File; ii) Thermal Noise Removal; iii) Radiometric Calibration (to Gamma Nought); iv) Terrain Correction (using SRTM, to UTM 22 projection). We restricted our selection to ascending relative orbits to reduce backscatter variation from image to image due to look angle alone. While Sentinel-1 has a repeat pass time of 12 days per satellite (6 days when both 1A and 1B satellites are combined), not all images are collected, sometimes leaving lengthy data gaps over the study site. For the purposes of this study, images from ascending Relative Orbit 17 were used as this orbit provided the greatest number of images over the study site within the study period. Three images were removed as outliers as they exhibited significant scene-wide departures from the backscatter of images adjacent in time. Both HH and HV polarizations are available for our study site, but we include only the data from the HV polarization as it more clearly shows buried shallow near-surface lakes (Miles et al., 2017). The presence of water may be observed even when the lake surface is frozen and covered by snow as the HV polarisation of C-band SAR can penetrate up to a few metres of ice (Rignot et al., 2001).

### 2.3 Isolating drainage events

For each winter, the mean backscatter of each lake was calculated for each Sentinel-1 image to create a time series of mean backscatter for each lake. Lakes over the winter undergo a slow freeze-through process (Selmes et al., 2013; Law et al., 2020). Water in C-Band SAR imagery presents as low backscatter. As the lake surface begins to freeze, scattering due to bubbles trapped in the ice increases. C-Band waves continue to reach the underlying water until the ice becomes thick enough to obscure it. Summer lake drainage events have been observed to follow a pattern of low to high backscatter (Johansson and Brown, 2012; Miles et al., 2017). A winter lake drainage would result in the same trend of low to high backscatter due to the removal of water and the exposure of the ice underneath, in addition to roughness added above by the collapse of the ice lid. We hypothesize, therefore, that a winter lake drainage event would appear as a large sudden increase in backscatter between two images, which is then ~~maintained~~ sustained over a long period of time, in much the same way as it does for a summer lake drainage (Miles et al., 2017).

To be certain that a large sudden increase in mean backscatter is an expression of a change in a particular lake, rather than an artifact of the sensing process, an anomalous ~~large~~ increase in lake backscatter is identified by comparing the mean backscatter change of each lake to that for all the other lakes in the scene in the same consecutive image pair. For a selection of lakes, the backscatter frequency distributions were examined and shown to be close to normally distributed and thus lake medians and means were close in value. For each consecutive image pair, the z-score of backscatter change for each lake is calculated relative to the backscatter change of all lakes ~~across the scene~~ within the study site and a threshold of +1.5 is used to isolate those lakes that experience a greater than average increase in backscatter between images. ~~Change events were then filtered based on the time between consecutive images.~~

To be sure that a large anomalous and sudden increase in backscatter was sustained rather than just an isolated ~~variance~~occurrence, filters were employed to check for reversal in the subsequent three images, where those images occurred within 48 days of the ~~originals~~last of the original pair. In each timestep, lakes were removed from consideration if the reversed backscatter change was greater than 25% of the magnitude of the original anomalous increase (see 'A' in Figure 2). Lakes were also checked to be sure that there was no preceding dip that was being reversed by the anomalous increase itself (see 'C' in Figure 2). The aim of this processing was to identify lakes that showed a sustained backscatter step change increase between two relatively stable levels (see also 'B' and 'D' in Figure 2). Given that there are some large gaps in Sentinel-1 data collection within each relative

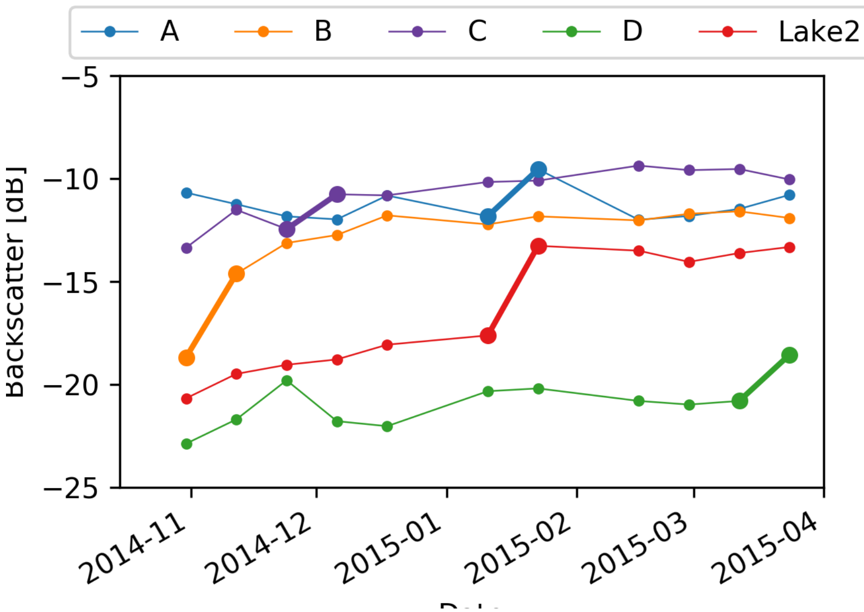



**Figure 2.** This figure illustrates the filtering criteria for identifying drained lakes. (A) Anomalous sustained step change but one that is not sustained. (B) Anomalous increase but with insufficient history to determine if the change was an adjustment from a previous dip or step increase from a previous low. (C) Anomalous sustained change but with a prior dip such that this change was a return to prior values rather than a sustained change. (D) Anomalous change without sufficient information to confirm a sustained change. Lake 2 shows anomalous sudden and sustained backscatter change depicting lake drainage. All the time series shown are results from actual lakes in the 2014-2015 season. Bold line segments are the transitions that met the z-score threshold.

orbit, specifying that a change event had to occur within 12 days and be sustained for up to 48 days, reduced the number of events compared to those originally detected. Finally, only lakes greater than 5 pixels in size (8000 $m^2$) were considered.

### 2.4 Lake volume

Lake depths were calculated from Landsat 8 imagery using physical principles based on the Bouguer-Lambert-Beer law as outlined elsewhere (Sneed and Hamilton, 2007; Pope et al., 2016; Williamson et al., 2018). For the six lakes we found that drained in the winter, the latest Landsat-8 images showing the ~~greatest lake area from the melt season prior to the lake drainage event~~ lake prior to freezing over were selected manually. Lake depth, z, was calculated on a per-pixel basis from:

$$z = [ln(Ad - Rinf)–ln(Rpix - Rinf)]/g \quad (2)$$

where $A_d$ is the lake bottom albedo, Rinf is the reflectance of a deep water pixel, Rpix is the reflectance of the pixel being assessed, and g is based on calibrated values for Landsat 8 (Pope et al., 2016). For this analysis, calculations were performed for both the red and panchromatic bands with the final depths ~~averaged between the~~ taken as the mean of the two results

(Pope et al., 2016; Williamson et al., 2018). For each band, the outline of each lake was established using a mask based on an $NDWI_{ice}$ threshold of 0.25. The reflectance values of all pixels immediately exterior (30m) to this outline were averaged to obtain a value for $A_d$. Reflectance of deep water Rinf was determined per image by selecting the darkest pixel in each image(which was always a seawater pixel). For each lake, the depths of all lake pixels were added to calculate lake volume. Error in the depth calculation follows from Pope et al. (2016). We take the average of the documented error for the Landsat-8 red band (0.28 m) and that for the panchromatic band (0.63 m) to give an error of 0.46 m. Uncertainty in lake volume follows from this uncertainty in the depth calculation. In line with previous work, we do not define errors for lake areas, which instead are fixed according to our threshold $NDWI_{ice}$ value of 0.25.

### 2.5 Photoclinometry and elevation change

This technique is also known as 'shape-from-shading' and uses a single surface DEM , and a series of optical satellite images to calculate surface slopes, elevations, and therefore elevation changesand a Landsat-8 image to develop a relationship between reflectance and slope in a baseline location to then extrapolate the topography in another. We used the this technique to reconstruct the topography of the lake surface using winter Landsat-8 images before and after the drainage event and then produced a differencing image.

The ArcticDEM (5m resolution mosaic) for the part of the ice sheet encompassing the draining lakes, which we (Porter et al., 2018) served as the base DEM for area surrounding the lake, and was resampled using bilinear interpolation to match the 30m 30 m Landsat-8 resolution. We used Landsat-8 images from before and after each of the six winter lake drainage events. Image image pairs were chosen to be as close to the timing of each lake drainage as possible , but also to be both before and after, as well as cloud free over the lake, and to be from the same Path and Row across each pair to reduce any incidence angle error. It was also important to find image pairs that contained snow cover in order to produce clear relationships between reflectance and slope angle that could be used to determine slopes and therefore elevations across the lakesAll images used were taken when the surface was snow covered to ensure that reflectance variation was due to surface slope. The calculations follow the methods outlined by Pope et al. (2013) and were completed for three of the six drained lakes as suitable Landsat-8 image pairs did not exist for the other three.

For each Landsat-8 image (six in total, two per lake) the following procedure was adopted. Band 4 was extracted and used as the basis for calculation. Transects were drawn across the lake parallel with the solar azimuth at the time of the image. Transects were 10 km in length, to achieve sufficient coverage of both the lake and ambient area, and were spaced 250 m apart across the width of the lake. The lake was outlined manually based on the Band 4 image, and a 100m 100 m buffer external to the lake boundary was added to ensure that the changing lake topography was not included in the production of a baseline relationship between topography and reflectance. Each transect was sampled every 30m 30 m along its length for Band 4 reflectance , for topography and for elevation in the ArcticDEM, and for the binary delineation of buffered lake area or ambient area. Sample lake imagery is shown in Appendix BA. Surface slope was calculated between each pair of sample points outside the buffer region along each transectfrom the elevation difference between adjacent nodes. A linear relationship was established between slope and Band 4 reflectance for all pixels sampled points outside the buffered lake area.

For each image processed, the linear slope-reflectance relationship established for non-lake pixels was then applied to the buffered lake pixels to calculate slope for each of the nodes on each transect across the buffered lake area. Elevation for each node on each transect across the buffered lake was reconstructed by integrating the slope values, starting from the known elevation of the node at the edge of the buffered lake on the north side of the lake and progressing to the south side. This resulted in small offset errors on each transect at the nodes on the south side of the buffered lake, where elevations did not match the known elevations from the DEM. These offsets were closed by linearly tilting each transect across the buffered lake, adjusting all elevations accordingly (Appendix A4). Elevation values were then interpolated (IDW method) using a 250 m x 30 m grid to create a digital elevation model of each lake before and after drainage. These grids were then differenced to calculate the patterns of lake surface elevation change due to winter lake drainage.

Error in the photoclinometry depth calculation is derived from Pope et al. (2013), who compared elevations derived using the photoclinometry method applied to Landsat imagery with airborne LiDAR elevation data. In areas where the photoclinometry assumptions were met (no shading) the median error was just 0.03 m, so the height difference error is 0.04 m. In areas where the photoclinometry assumptions were not always met (e.g. shaded areas), the median error was 1.44, so the 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 spacings of the sample points between the Iceland and Greenland studies, we use the larger of the two errors, i.e. 1.61 m. As for the attenuation-based depth calculations, we do not define errors for lake areas, which are fixed according to our threshold NDWIice value of 0.25.

### 2.6 ArcticDEM Differencing

We used 2 m time-stamped ArcticDEM strips (Porter et al., 2018) from dates prior to and after each drainage but within the winter season to avoid changes due to surface melt. Relevant DEMs could only be found for Lake 6 dated 21 Sept 2016 and 12 March 2017. We calculated the difference between these two DEMs in the region of Lake 6 to determine changes in surface elevation over this time period and an independent measure of drained lake volume.

Error in the ArcticDEM depth differential follows from Noh and Howat (2015). Error in the calculation of the DEM is approximately 0.2 m so the height difference error is 0.08 m.

## 3 Results

### 3.1 Winter lake drainage from Sentinel-1 imagery

We found six lakes that experienced large, anomalous, sudden and sustained backscatter increases that we interpret as lake drainage events over the three winter seasons analyzed. ~~The lake locations~~ Three of these events (Lakes 2, 5 and 6) appear clear in the Sentinel-1 imagery and are supported by optical imagery and photoclinometry evidence with one of them (Lake 6) also supported by ArcticDEM differencing. The remaining three lakes exhibit a time series of mean backscatter change that is in line with our expectations of drained lake behaviour but have insufficient evidence from other datasets to confirm drainage.

The locations of the drained lakes are shown in Figure 1 and the drainage characteristics are summarized in Table 1. Although one of the criteria for lake selection was having a z-score of backscatter increase greater than 1.5, results show that all six lakes that met all of the criteria had a z-score of backscatter increase greater than 2.0 (Table 1). The size of the drained lakes varied widely (between 0.18 $km^2$ and 6.84 $km^2$) as did the timing of drainage within the winter season, ranging between early November and late February (Table 1). During the 2015-2016 winter, Lakes 3 and 4 towards the north of the study area, and separated by a straight-line distance of 14.9 km, drained within the same 12 day time period (Figure 1 and Table 1). Lake volumes vary between 0.000046 $km^3$ and 0.0202 $km^3$. These may be underestimations of drained volume as physically based depth calculations can underestimate the depth of deep water (Pope et al., 2016; Williamson et al., 2018) and as the lake may have continued to fill after the last available Landsat-8 image. Conversely, they may be slight overestimations of drained volume if some water froze prior to drainage.

For each lake, the backscatter changes signifying a drainage are shown in Figure 3. All lakes generally undergo a large, anomalous, sudden change from predominantly dark (low backscatter) to light (higher backscatter) when compared to their surroundings. This transition is visually more obvious for the larger lakes (Lakes 1, 2, 5, and 6) and less clear for the smaller lakes (Lakes 3 and 4) (Figure 3) although the mean backscatter change for Lake 3 is actually slightly greater than that for Lake 5 (Table 1).

The mean backscatter time series for each lake is shown in Figure 4. Each series shows at least two dates of similar backscatter values prior to the step change from low to high backscatter. Each series maintains its higher backscatter after the initial jump. The backscatter changes of Lakes 3 and 4 are smaller in dB than the change that occurs in Lake 6 but the z-scores signifying how unusual anomalous the jumps are when compared to those in other lakes, are significantly higher in Lakes 3 and 4 (Table 1).

Drained lakes are filtered out based on their large anomalous increases in backscatter in comparison with other lakes, that occur within 12 days, and that are sustained for at least 48 days. All other lakes undergo changes in backscatter that are comparable with those in nearby lakes, or they experience large anomalous sudden backscatter changes but that are not sustained. Figure 5 shows the mean backscatter of Lake 6 over time together with that for the 10 largest lakes in its immediate vicinity (within a 20 km x 20 km square, centered on Lake 6). The sudden increase in mean backscatter of Lake 6 is far greater than that for the surrounding lakes. Lake 6 initially has low backscatter that is comparable with that for some of the surrounding lakes. Optical imagery from the end of the previous summer shows Lake 6 and these other 'low backscatter lakes' were water filled. Over a single image transition, Lake 6 experiences a backscatter increase to levels that are comparable with other surrounding lakes that optical imagery from the end of the previous summer showed were drained. The lakes surrounding Lake 6 experience much slower backscatter increases over time, which we interpret to be slow freezing of the water in the filled lakes or the ice surface in the bottom of the drained lakes. Figure 5 also illustrates what the backscatter changes look like within the Sentinel-1 imagery. Small changes are observable within the surrounding lakes but a much bigger change is seen in Lake 6.

**Table 1.** Details of the lake drainage events. Location refers to longitude, latitude (WGS84). The drainage dates are the Sentinel-1 image dates over which the anomalous change was identified. The delta dB is the mean change in backscatter (measured in decibels) within the lake boundary from one image to the next. The z-score is the measure of the magnitude of this backscatter change compared to the backscatter change of other lakes in the study site across the same image pair. Lake area is the size of the lake delineated by the $NDWI_{ice}$-based mask. Lake volume was calculated as described in Methods.

| 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 | ~~0.18~~ 0.04 km$^2$ | ~~0.50 m~~ 0.57 ± 0.46 m | ~~0.000046 km$^3$~~ 0.000021±0.000017 km$^3$ |
| Lake 2 | -48.52, 68.91 | 10 Jan 2015 to 22 Jan 2015 | -4.4 | 3.4 | ~~6.84~~ 6.12 km$^2$ | ~~3.20 m~~ 3.26 ± 0.46 m | ~~0.0202 km$^3$~~ 0.0200±0.002817 km$^3$ |
| Lake 3 | -48.75, 69.43 | 05 Jan 2016 to 17 Jan 2016 | -3.8 | 2.7 | ~~0.93~~ 0.43 km$^2$ | ~~1.43 m~~ 1.89 ± 0.46 m | ~~0.0011 km$^3$~~ 0.0008±0.000197 km$^3$ |
| Lake 4 | -48.38, 69.40 | 05 Jan 2016 to 17 Jan 2016 | -2.3 | 2.6 | ~~0.71~~ 0.51 km$^2$ | ~~2.32 m~~ 2.56 ± 0.46 m | ~~0.0014 km$^3$~~ 0.0013±0.000237 km$^3$ |
| Lake 5 | -47.43, 68.62 | 10 Feb 2016 to 22 Feb 2016 | -3.2 | 2.8 | ~~1.43~~ 1.84 km$^2$ | ~~0.82 m~~ 0.86 ± 0.46 m | ~~0.0017 km$^3$~~ 0.0016 ±0.000848 km$^3$ |
| Lake 6 | -48.03, 68.75 | 06 Nov 2016 to 18 Nov 2016 | -9.3 | 2.2 | ~~2.86~~ 2.27 km$^2$ | ~~1.33 m~~ 1.41 ± 0.46 m | 0.0032 ~~km$^3$~~ ±0.001043 km$^3$ |

### 3.2 Confirmation of winter lake drainage by optical imagery

Analysis of Landsat-8 imagery from the summers prior and subsequent to the six inferred winter drainage events supports the interpretation that the changing SAR backscatter represents lake drainage. Using the same method described above for creating composite $NDWI_{ice}$ masks for late summer (from late July and August images), here we create similar $NDWI_{ice}$ masks for each summer but using all cloud-free Landsat-8 images between May and August from 2014 to 2017. The purpose of this is to calculate maximum lake areas for all lakes, including the six lakes inferred to drain during the winter, in the summers prior and subsequent to the winter lake drainages. Maximum summer water coverages for the six winter draining lakes are shown in Table 2. The corresponding composite $NDWI_{ice}$ images for each summer are shown in Figure 6.

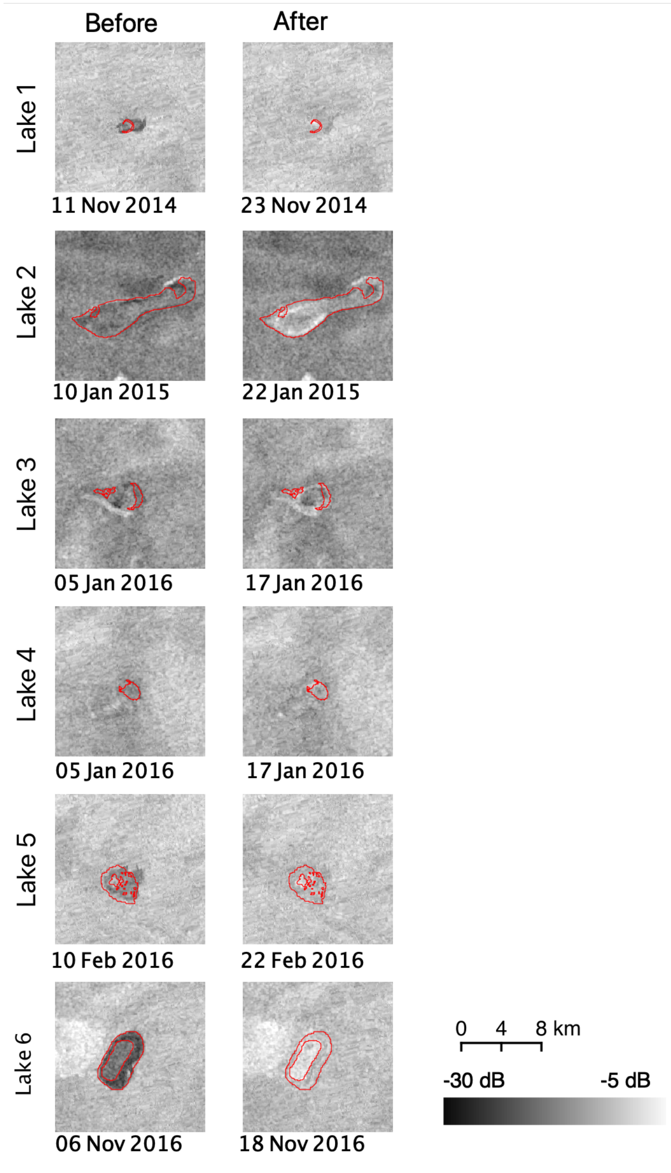



**Figure 3.** Sentinel-1 backscatter for each lake immediately before and after drainage. Before and after drainage dates are listed in Table 1. Note the lakes before drainage have a lower backscatter that changes to a higher backscatter across the image pair.~~Connective lines are omitted from the graph when the time between images is greater than 12 days.~~

The maximum lake extents for Lakes 1, 2, 5 and 6, appear larger in the summers prior to drainage than after drainage. This suggests that the winter lake drainages were associated with fractures / moulins that remained open, allowing the following summers' meltwater reaching the basin to drain directly into the ice sheet. These reductions in maximum lake extents contrast

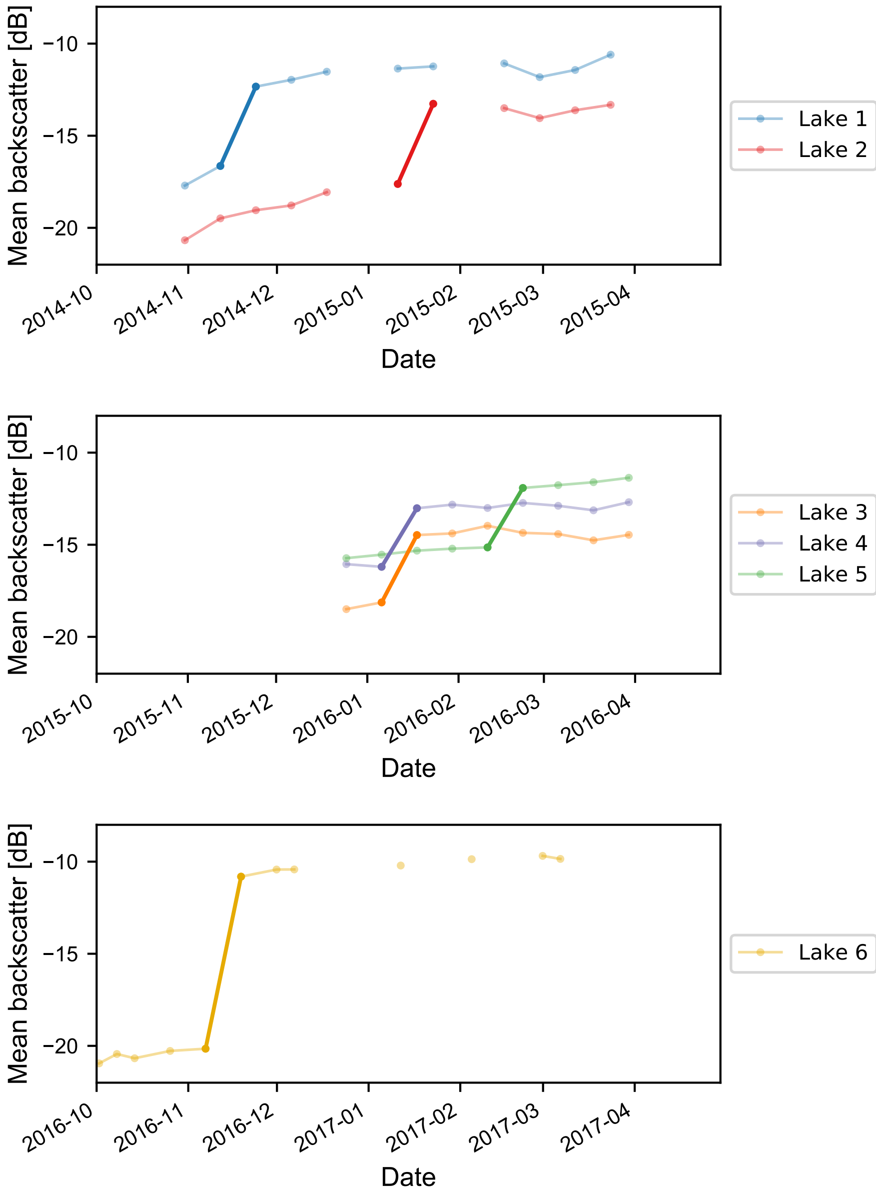



**Figure 4.** ~~This figure shows the backscatter~~ Backscatter time series for the lakes with identified drainage events. Connecting lines are only included when the time between images is 12 days or less. Each series represents one lake and each point represents the mean backscatter of all of the lake's pixels in a particular Sentinel-1 image. Bold lines indicate the transition determined to be the drainage event.

with those observed for the many surrounding lakes, which fill to around the same size in the adjacent summers. Lakes 3 and 4 show little difference in area before and after drainage, but the lakes do change shape (Figure 6). This suggests that the fractures / moulins associated with the winter drainage of these lakes closed shut or were advected out of the lake basins, allowing the

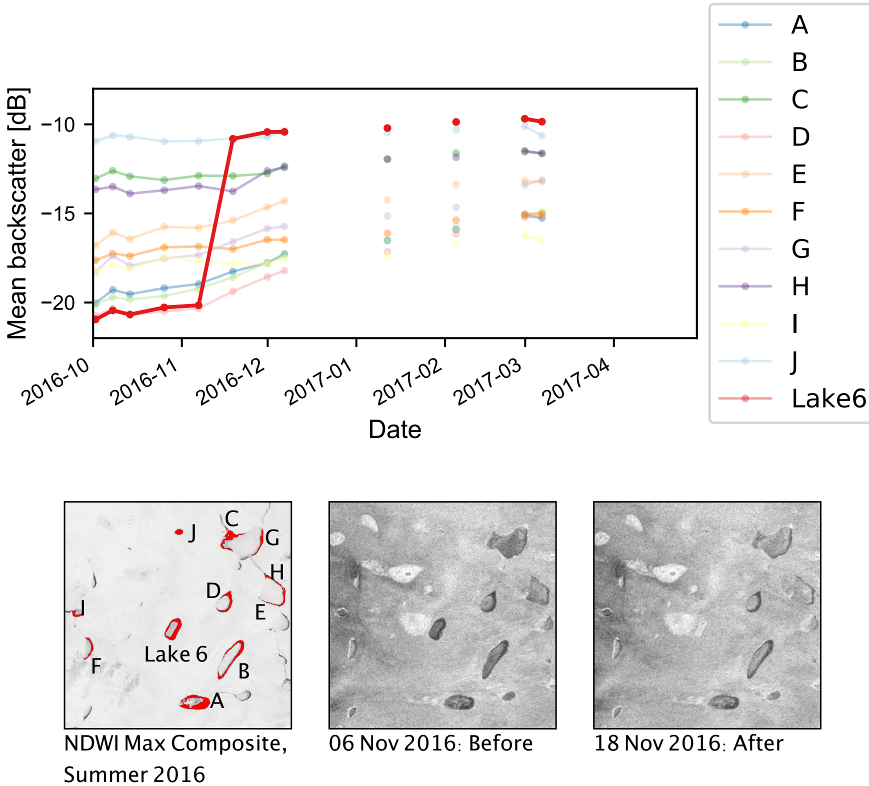



**Figure 5.** Sentinel-1 backscatter time series for the largest 10 lakes within ~~20~~ 10 km of Lake 6. Connective lines are omitted from the time series graph when the time between images is greater than 12 days. Image (a) is a composite maximum $NDWI_{ice}$ image for late summer 2016, prior to lake drainage showing the lakes included in the graph above. Images (b) and (c) are Sentinel-1 backscatter images for 06 November 2016 and 18 November 2016 across which the drainage of Lake 6 is observed. ~~Connective lines are omitted from the time series graph when the time between images is greater than 12 days.~~ While the backscatter of the surrounding lakes undergoes ~~some~~ a small gradual increase over time, the backscatter increase of Lake 6 is much greater than that seen in the other lakes.

lakes to form again in the subsequent summer. Lakes that experience large area changes recover their area over time, but not necessarily within the first summer following drainage.

### 3.3 Confirmation of lake drainage by photoclinometry and the ArcticDEM

Finally, we ~~use the technique of~~ used two additional techniques to support the conclusion that the observed changes in Sentinel-1 backscatter are lake drainages. First, we used photoclinometry based on the 5 m ArcticDEM mosaic and Landsat-8 imagery ~~(Table S2)~~ before and after the winter drainage events (see Methods) to calculate surface elevation changes across three of the lakes (Figure 7). Landsat-8 images suggest a smooth flat surface to each lake prior to drainage and a rough topography following drainage, suggesting the caving in of a frozen, snow-covered lake surface during drainage. Mean elevation

**Table 2.** Maximum lake area for each summer generated by calculating maximum $NDWI_{ice}$ per pixel from May through August each year. The lake $NDWI_{ice}$ threshold is set at 0.25 and area is calculated based on all pixels in the lake above this value.

| | Lake Areas ($km^2$) | | | |
|---|---|---|---|---|
| Lake | Summer 2014 | Summer 2015 | Summer 2016 | Summer 2017 |
| Lake 1 | 0.0936* | 0.0189 | 0.4734 | 0 (cloud cover) |
| Lake 2 | 6.498* | 0.936 | 2.774 | 3.595 |
| Lake 3 | 0.967 | 0.934* | 1.532 | 0.698 |
| Lake 4 | 0.699 | 0.639* | 0.658 | 0.495 |
| Lake 5 | 0.166 | 2.201* | 0.471 | 0 (cloud cover) |
| Lake 6 | 1.001 | 1.987 | 2.757* | 0.614 |

* indicates pre-drainage area.

changes calculated from photoclinometry using these images are 7.25 $\pm$ 1.61 m for Lake 2, 1.21 $\pm$ 1.61 m for Lake 5, and 4.04 3.38 $\pm$ 1.61 m for Lake 6. These depths are greater than those calculated based on the last available optical image, seen in Table 1 but are internally consistent in their rank from smallest to largest. The per-pixel elevation changes provide independent estimates of drainage volumes for Lakes 2, 5 and 6 of 0.049 $km^3$, 0.004 $km^3$ and 0.018 $km^3$ respectively. In relative terms, these compare well with the volume changes estimated from $NDWI_{ice}$ areas and pixel depths, but are 2 – 3 times larger for Lakes 2 and 5 and over 5 times larger for Lake 6. Possible reasons for the discrepancy between attenuation-based depth estimates and photoclinometry-based collapse depths are addressed in the Discussion.

Second, we examined differences in ArcticDEMs from dates during the winter on either side of the Lake 6 drainage event. Elevation change between time-stamped ArcticDEM strips from 21 September 2016 and 12 March 2017 is shown in Figure 8. Elevation change is greater within the lake area than surrounding it. The use of an $NDWI_{ice}$ -based mask to delineate lake area does not identify possible subsurface water. It appears from the Sentinel-1 imagery (Figure 5 and Figure 3) that Lake 6 contains a floating ice island obscuring water beneath. The mean of the differenced ArcticDEM within the $NDWI_{ice}$-based mask outline of Lake 6, is 2.17 $\pm$ 0.08 m. Note this compares with the mean depth derived from the optically-based depth calculations of 1.41 $\pm$ 0.46 m and that from the photoclinometry method of 3.38 $\pm$ 1.61 m (Figure 7). If the entire closed volume of Lake 6 is considered and the data for the entire area included in the analysis, the mean elevation difference from the ArcticDEM strips is 3.66 m and that from the photoclinometry is 4.04 $\pm$ 1.61 m.

### 3.4 Discussion

## 4 Discussion

We have developed a novel algorithm for analysis of Sentinel-1 SAR imagery and used it to identify six winter lake drainage events on the GrIS, the first such events to be reported in full. Because SAR backscatter is often difficult to interpret (White

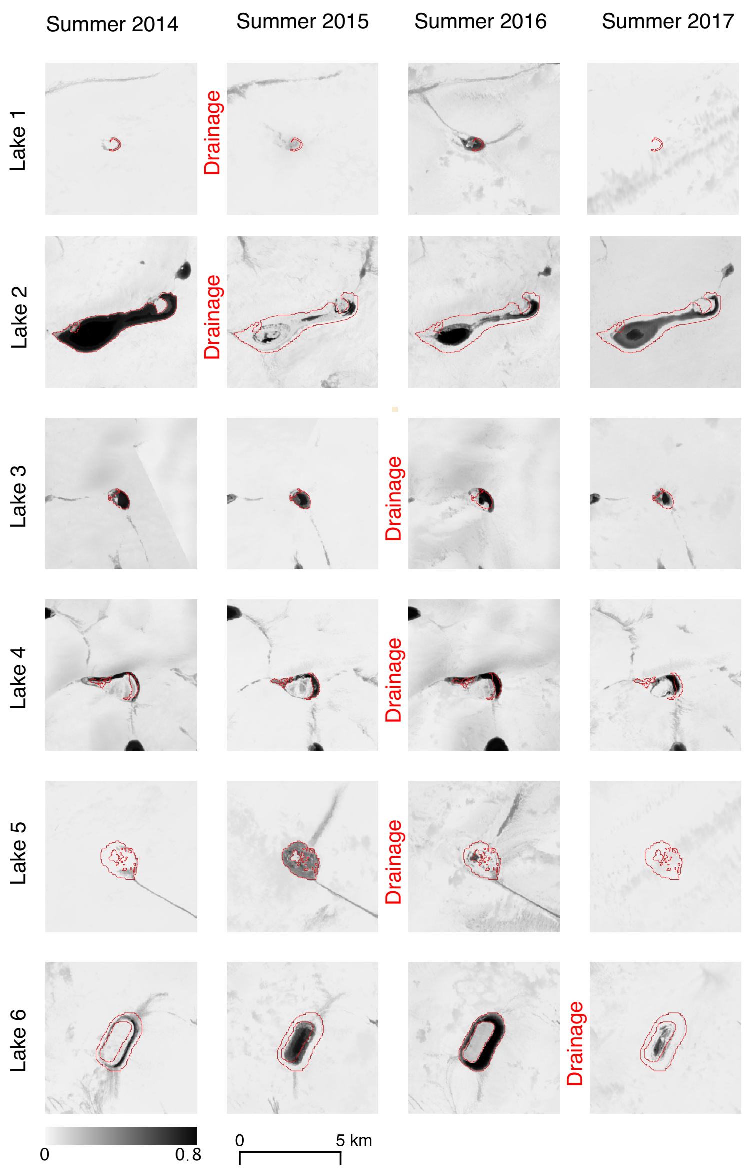
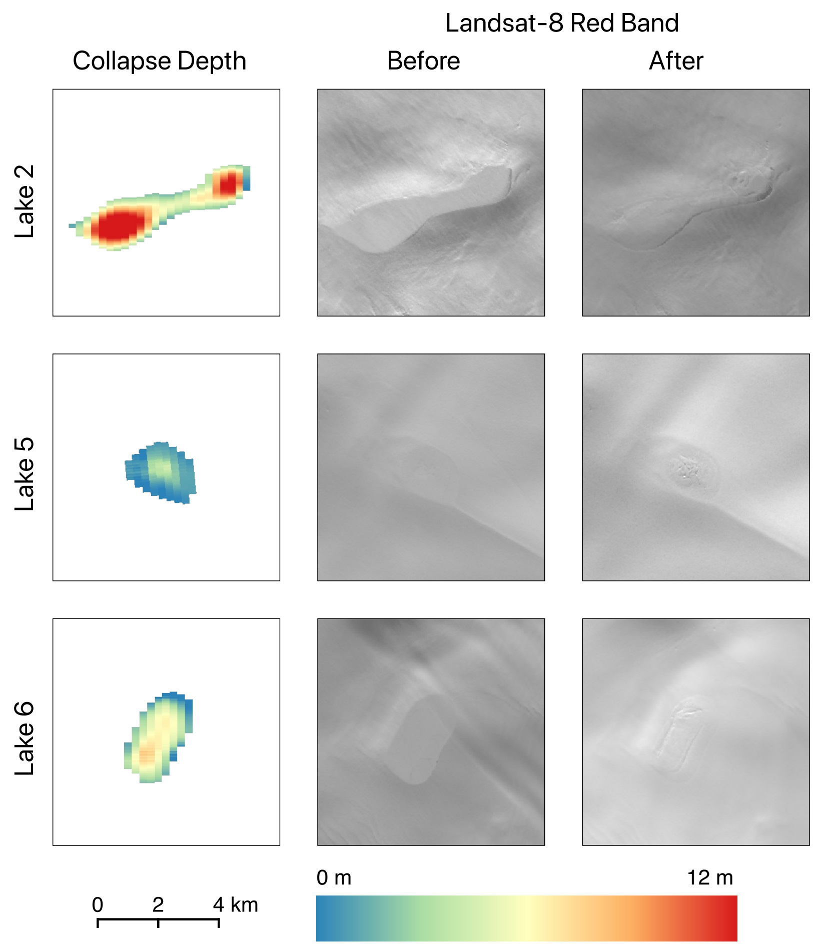



**Figure 6.** $NDWI_{ice}$ for each identified drained lake at the peak of each summer within the study. Note that most lakes take more than a single summer season to recover from their winter drainage.

et al., 2015) we have validated our technique by examining Landsat-8 optical imagery from the previous and subsequent summers. Changes in lake area and volume as well as topographic changes ~~expressed through~~ calculated using photoclinometry support the inference that these large, anomalous, sudden and sustained backscatter increases are lake drainage events. We have also been able to validate the winter drainage of one of these lakes by differencing available ArcticDEM strips.




~~This figure shows~~

**Figure 7.** Elevation difference results of the photoclinometry analysis beside the before and after images (Landsat-8 Red Band, B4) to illustrate the visible physical changes to the lake lid before and after drainage. The first column of images shows the vertical elevation drop of each pixel calculated by interpolating and differencing the pre- and post-drainage topography.

#### 4.0.1 ~~Identifying lake drainage events~~

~~Identification of a~~

### 4.1 Identifying lake drainage events

Identification of winter lake drainage ~~event~~ events using Sentinel-1 data required multiple steps to isolate drainage events from other changes in backscatter. The drainage events identified occurred in lakes of various sizes and locations. If lakes are ~~filtered based only~~ identified as anomalous based on z-score with no additional filtration done to confirm sustained change,

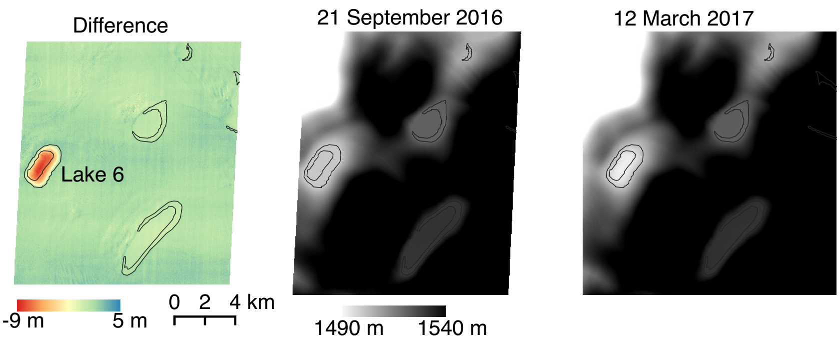



**Figure 8.** Elevation difference results of the ~~photoclinometry~~ ArcticDEM analysis ~~beside the before and after images (Landsat-8 Red Band, B4)~~ to ~~illustrate~~ confirm the ~~visible physical~~ changes ~~to~~ observed in the ~~lake lid before~~ Sentinel-1 imagery and ~~after drainage. The first column of images shows the collapse vertical distance of each pixel. It is the result of interpolating and differencing the pre- and post-drainage topography as mapped out by~~ photoclinometry analyses.

the three seasons analyzed would result in 188, 160, and 221 anomalous lakes for the 2014-2015, 2015-2016, and 2016-2107 winter seasons respectively. For each of these years, retaining only lakes that met the 1.5 z-score threshold and demonstrated no reversal of trend in the first timestep would result in 75, 60, and 85 lakes, respectively. Reversal was considered to be any change greater than 25% of the magnitude of the anomalous transition occurring either in the previous timestep or in the following three timesteps. Raising this threshold to 30% ~~results~~ would result in 4 anomalous lakes for each season. Raising the same threshold to 40% ~~results~~ would result in 10, 7, and 10 lakes for the three seasons~~. Raising the same threshold~~ , respectively. Raising it again to 50% ~~results~~ would result in 25, 19, and 21 lakes for the three seasons~~measured~~.

Extending the requirement for stability by requiring more consecutive images without reversal would be difficult in most years due to the limited image acquisition over this site. Overall the filtration proved not to be overly sensitive to z-score threshold, as all drained lakes had z-scores over 2 even though the threshold ~~set was~~ was set to 1.5. The criteria used to determine lake drainage events is thought to be conservative and is more likely to have missed drainage events (~~including false negative ones~~included false negatives) than to have found drainage events that were not real (~~false-positive~~incorporated false-positives).

#### 4.1.1 ~~Optical lake mask~~

### 4.2 Optical lake mask

As lake delineation using Sentinel-1 backscatter alone is not trivial (Miles et al., 2017; Wangchuk et al., 2019), all change tracking in this study is based on pixels within lake outlines generated from Landsat-8 optical imagery. However, in comparing the ~~optically generated~~ optically-generated masks to the Sentinel-1 backscatter images, the two are often different, typically with the SAR images showing larger lake areas than those ~~from~~ seen in the optical data. This discrepancy may be due to water depths insufficient to meet the $NDWI_{ice}$ threshold set, or ~~may be due~~ to shallow subsurface water below a snow or ice lid. This is most apparent in Lake 6 (Figures 5 and 6), where a low-$NDWI_{ice}$ island appears in the center of the lake, but ~~backscatter measurements~~ HV backscatter measurements, which are sensitive to volumetric scattering, remain low in this portion and ~~photoclinometry~~ both photoclinometry and ArcticDEM changes show a caving-in of ice in this area (Figure 5 ~~), possibly pointing to this as a floating island of snow with water concealed beneath~~and Figure 8). Beginning with the $NDWI_{ice}$ mask also results in the splitting of some lakes into multiple disconnected water bodies where parts of the lake are below the threshold. As such, some larger lakes may be filtered out of the study as they appear to be a collection of smaller lakes, and some backscatter tracking is only occurring on partial lakes, where only deeper portions with higher $NDWI_{ice}$ values are included in the lake delineation. Other surface changes, such as the drainage of a subglacial lake, could result in changes in SAR backscatter as well. The aim of restricting the analysis to lakes that are optically-identifiable in the summer is to reduce the likelihood that the changes identified in this study are due to such events.

We have used masks ~~in this study~~ created from just a few ~~late-season~~ summer images to reduce the likelihood of incorporating lakes that drained ~~within~~ in the summer into our wintertime lake tracking algorithm. Creating lake masks using a longer time span of images might allow for more complete lake boundaries to be included. By including more summer images, these masks might account for areas of water that are only occasionally seen at the surface but are more often under snow or ice, so especially those at higher elevations. Lake 1, for example, often appears below the 0.25 $NDWI_{ice}$ threshold due to the absence of cloud-free and unfrozen images within a given summer, although the lower backscatter in this area seems to indicate ~~water below~~shallow subsurface water.

#### 4.2.1 ~~Sentinel-1 backscatter~~

### 4.3 Sentinel-1 backscatter

While Sentinel-1 backscatter allows for the tracking of lakes that are obscured by ~~the cover of cloud~~ cloud cover and darkness, it is also limited in what it can observe. ~~Winter lakes are buried beneath an ice lid, generally below snow.~~ The penetration depth of C-band radar producing backscatter varies based on the physical properties of the medium through which it passes, especially ~~dependent on moisture~~ moisture content, but reaches a maximum of ~~approximately 9 m~~ a few metres of depth (Rignot et al., 2001). ~~It is~~ However, it is also possible that winter lakes exist below this depth and are ~~missed by the Sentinel-1 backscatter used in this study~~not detected. This penetration depth is also likely to be insufficient to reach the buried firn aquifers identified in the Greenland Ice Sheet (Forster et al., 2014; Koenig et al., 2014).

~~Occasionally,~~ In our study, three images showed large, scene-wide departures from typical backscatter values ~~. These images~~ and were omitted from further analysis (dated: 03 Feb 2015, 10 Apr 2016, and 16 May 2016)~~were omitted in this study as they were anomalous although if~~. If it were known what caused this phenomenon then perhaps the images could be corrected and used.

Sentinel-1 is also limited in its temporal frequency of available imagery for the same site. While the repeat pass time of Sentinel-1 is at most 6 days when both satellites are included (only available since late 2016), it is ~~necessary~~ advisable to use imagery from the same relative orbit for greater consistency from image to image, and not all images within each path are acquired. A shorter repeat pass could help more accurately assess the rate of backscatter change and thus gain a better understanding of the ~~nature~~ speed and timing of these drainage events. For example, no image in Relative Orbit 17 exists between 06 Nov 2016 and 18 Nov 2016, ~~the dates across which we assess~~ a 12 day gap in sensing, the dates between which Lake 6 ~~to be draining, a 12-day gap in sensing~~drained. If additional orbits ~~are~~ had been included in this analysis, the gap ~~can be~~ could have been reduced to 10 days, but no further.

### 4.3.1 ~~Drainage water volume~~

## 4.4 Drainage water volume

Sentinel-1 backscatter alone does not allow for the ~~estimation~~ calculation of water volumes and therefore water volume changes. ~~The~~ Available optical satellite data ~~available~~ can be used to estimate ~~the~~ water volume, but the optical measurements are limited in their capability to calculate accurately the drained volume. In this study, physically based depth measurements are made on a per pixel basis for each lake ~~per pixel based on~~ using the last available image in the summer before the lake is covered by a frozen lid (Table 1). ~~This calculation provides an estimate of the drained lake volume, assuming that no more water can be drained than is present at the formation of the ice lid.~~ However, ~~these~~ there are several sources of error associated with these measurements. First, the measurements have been shown to underestimate the depth of deep water (Pope et al., 2016; Williamson et al., 2018). ~~Additionally, these measurements occur~~ Second, the measurements made months prior to the drainage events, and the lake volumes derived from them could be impacted by additional melt filling the lake or freezing of water prior to the drainage event. ~~This study has also set~~ Third, the lake boundary is set using an $NDWI_{ice}$ threshold of 0.25, which may underestimate the full extent of the lake area. ~~There is also~~ Fourth, the calculation assumes all the lake water from the previous autumn drains. There is no reliable method of using optical data to measure whether any water remains at the start of the subsequent melt season. Images showing the first water visible in the ~~summer~~ spring after drainage could be showing water remaining in the lake or water transported into the basin from higher elevations that year. Often cloud-free images are not available until well into the melt season and thus cannot reliably be used as a lower bound ~~to~~ in a calculation of water volume difference from the previous autumn.

Photoclinometry results show, for each lake, a topographical change in the surface shape between the pre- and ~~post- drainage~~ post-drainage images indicating an elevation drop. However, the depth of caving is greater than the deepest ~~measurement estimated by attenuation-based depth calculations prior to winter. There are also some areas (for example,~~ water depth determined from the light attenuation based method using optical imagery from the previous autumn. The depth estimation differences may be the result of a combination of factors. As mentioned above, the attenuation-based algorithm is known to underestimate lake depths as the depths increase beyond a certain threshold (Pope et al., 2016; Williamson et al., 2018). Furthermore, photoclinometry-based depths may overestimate collapse depths due to topography changes between the date of the ~~northern portion of Lake 2) where shadows exist in the Landsat-8 imagery that would invalidate the reflectance to slope relationshipand introduce error into the calculations of the topography for the shaded pixels.~~ DEM and the date of the optical imagery used to create the shape/shading relationship. Finally, shadows within the lake basin that do not appear parts of the image surrounding the lake may also introduce errors into the calculation of shape from shading within the basin.

While the depth estimation using this ~~technique~~ photoclinometry may be inaccurate in places for the reasons outlined above, the technique confirms that a change in surface topography ~~has occurred. Additionally, the smaller volume estimates for the area-depth technique may be due to the lake depth algorithm underestimating depths beyond a certain threshold (Pope et al, 2016; Williamson et al, 2018) as well as error resulting from differences between the actual surface topography at the time the Landsat-8 image was taken compared to that in the ArcticDEM.~~ occurred. Photoclinometry is potentially a useful method for detecting surface or shallow subsurface lake drainages on ice sheets and ice shelves.

The optical data ~~supports~~ support the assertion that the changes in winter SAR backscatter observed are caused by lake drainage events. The larger lakes in the study, Lakes 2, 5, and 6 all show a significant reduction in lake area in the summer following the winter drainage compared to the previous summer with more than a single summer season needed to regain pre-drainage lake area (Figure 7). This may be due to the opening of a fracture that continues to allow water to drain through the lake bed for some time, similar to that found by Chudley et al. (2019). ~~The smaller lakes~~ Lake 1 shows a similar slow re-filling over time but the effect is less clear in Lakes 3 and 4.

Compared to Lakes 1, 2, 5, and 6, Lakes 3 and 4 did re-fill to their former size in the summer following drainage ~~but changed shape, indicating that the fracture closed up or was~~ (Figure 6). While these two lakes did show a large, anomalous sudden and sustained backscatter increase suggesting winter lake drainage according to our criteria, they were small in area and the subsequent filling makes it less clear that drainage events actually occurred. These lakes also lack the additional support of photoclinometry or ArcticDEM differencing that the lakes definitively drained. The SAR backscatter changes suggest that the lakes did drain, and if this is the case, the available optical data suggest that any fracture created during drainage may have been subsequently squeezed shut or advected out of the ~~lake basin prior to the subsequent~~ small lake basin allowing the lakes to fill again the following summer.

#### 4.4.1 ~~Causes and implications of lake drainage~~

The drainage of Lake 6 is further confirmed by the analysis of the ArcticDEM differential (Figure 8), which shows a collapse across the entire lake area, including the central area that did not appear as deep water in any preceding-summer Landsat-8 images. The collapse is greatest at the center and decreases toward the edges of the lake boundary. The magnitude of the collapse as measured by the DEM differential is similar to that measured by the photoclinometry method. Furthermore, the nearby lakes show no significant elevation change across the same period.

### 4.5 Causes and implications of lake drainage

The causes of lake drainage events have been studied extensively (Williamson et al., 2018; Christoffersen et al., 2018). However the observation of ~~winter isolated~~ isolated winter lake drainages points to the possibility that drainages can occur without increases to lake volume to actively cause hydrofracture or to connect to a nearby moulin to trigger sliding or uplift and passively open a crack. Instead, it shows that ice dynamics unrelated to surface hydrology can trigger drainage. The evidence available in this study is insufficient to identify conclusively the cause of these winter lake drainages. Appendix Figure B1 shows the locations of the winter lake drainage events compared to ice speeds derived from MEaSUREs data (Howat, 2017) for the winter periods containing each drainage event. ~~No pattern of lake locations and speeds seems to be visible~~There is no obvious correlation between ice speed patterns and the location of winter lake drainage events suggesting that patterns of ice flow are not necessarily a trigger for drainage. Our sample size is small, however, and more evidence is needed to examine further the possibility. In this study, most of the lake drainages occur in isolation - with the exception of the drainages of Lakes 3 and 4, which occur in the same 12-day period. These lakes are separated by a linear distance of 14.9 km. These concurrent ~~drainages support the observations of Christoffersen et al. (2018) of cascade draining or~~ drainage events may be related, with one drainage triggering the other by creating localised ice acceleration transferred via stress gradients (Christoffersen et al., 2018). Alternatively, they may indicate a larger scale ice movement that triggered both events simultaneously. ~~In the summer after drainage, these small lakes fill to pre-drainage levels, though the footprint of the lake changes, whereas the larger lakes (Lakes 2, 5, and 6) do not reach pre-drainage levels for at least 1-2 years. It is possible that this difference is simply because the larger lakes require more runoff to fill and thus it takes more time to fill them. However, another possible explanation is that the fracture that drained the small lakes was advected out of the lake basin more quickly both because of the smaller basin size and the relatively fast ice velocity in this area (see Appendix Figure B1) and that the larger lakes remain connected to the fractures that drained them for a longer period of time.~~

## 5 Conclusions

We have developed an automated method for identifying large, ~~sudden, anomalous~~anomalous, sudden and sustained backscatter changes in Sentinel-1 SAR imagery, which we apply to ~~"winter"~~ images collected between October and May spanning three winter seasons. We find ~~six such large, sudden, anomalous and sustained backscatter changes, which are indicative of~~ four winter lake drainage events across a study site containing approximately 300 ~~lakes. The events are validated using~~ supraglacial lakes that are supported by optical data and two other possible drainage events that meet our backscatter change criteria but lack the optical data support to unequivocally confirm drainage.

The optical imagery from before ~~and after~~ the winter seasons ~~, which~~ are used to provide estimates of lake volumes associated with the drainages. While ~~these~~ the events are rare, they provide conclusive evidence for the first time that lake drainages over winter occur. They are likely triggered simply by crevasse opening across the lake due to high surface strain rates associated with background winter ice movement. This shows that rapid lake drainage events do not have to be triggered during lake water filling, as has been observed previously for summer events. A full picture of the hydrology of the Greenland Ice Sheet requires observation of surface water on a multi-year and multi-season basis. Identification of the drainage events was achieved by developing a time-series filtering algorithm that may be adapted to identify other hydrological phenomena ~~and behaviour in~~ such as the onset of melt, or the rate of filling or freezing of surface or shallow subsurface water bodies on ice sheets and ice shelves. The algorithm is based on a set of thresholds that were set conservatively to capture only the most obvious incidences of large, anomalous, sudden and sustained backscatter changes and therefore our study is more likely to have underestimated rather than overestimated the number of winter lake drainages (included false negatives rather than false positives). Further ~~study would be required to identify the full range of lake backscatter behaviour through time and what other types of behaviour may indicate. Further~~ work is required to examine whether winter lake drainage occurs in other parts of the ice sheet ~~,~~ and in other years, ~~to examine more precisely~~ what the triggering mechanisms are, how basal hydrology and biogeochemistry are affected, and whether winter lake drainage will become more prevalent under future climate warming scenarios.

*Data availability.* All data used in this study are available publicly through ESA, USGS, and Google Earth Engine.

## Appendix A: Appendix A: Photoclinometry process

### A1 List of Landsat-8 images used for Photoclinometry

~~Table **??** of Landsat-8 images were used for the photoclinometry portion of the study (see 2)~~

~~Landsat-8 images used for photoclinometry process.~~

| Lake | Landsat-8 Scene |
|---|---|
| Lake 2 Before | LC08 _008012 _20141101 |
| Lake 2 After | LC08 _008012 _20150221 |
| Lake 5 Before | LC08 _008011 _20151104 |
| Lake 5 After | LC08 _008011 _20160428 |
| Lake 6 Before | LC08 _009011 _20161028 |
| Lake 6 After | LC08 _009011 _20170217 |

### A2 Slope vs. Reflectance

Figure A1 ~~show~~ shows the correlation of slope with reflectance for the non-lake areas of each of the Landsat-8 images used in the photoclinometry section of this study. For each image, a new relationship was established and used to infer the slope of the lake area within that image.

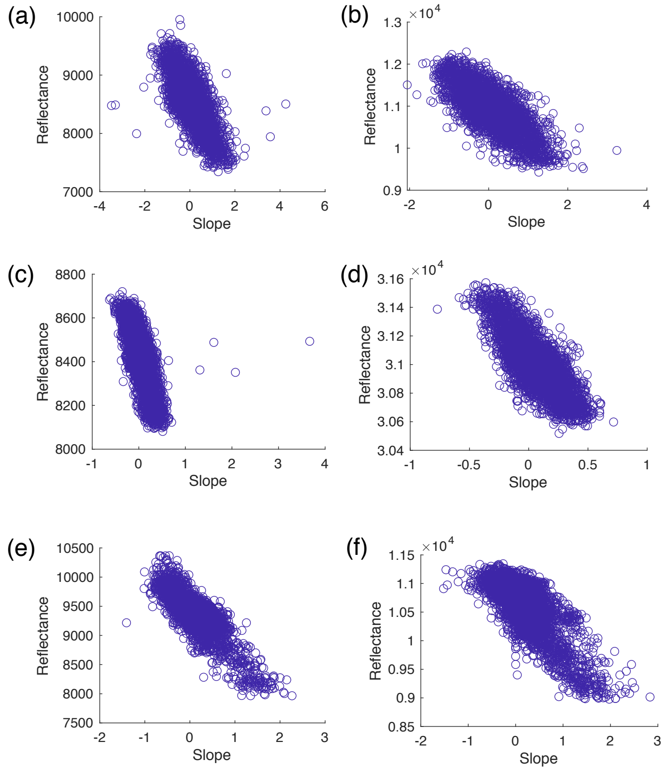



**Figure A1.** Plots of slope vs. Landsat-8 red band reflectance for areas outside of the lake and buffer zone for each of the Landsat-8 images analyzed for the photoclinometry portion of this study. The plots are laid out as follows: (a) Lake 2 Before, (b) Lake 2 After, (c) Lake 5 Before, (d) Lake 5 after, (e) Lake 6 Before, and (f) Lake 6 After. ~~Images are the same as those in A2~~

## A3 Lake sampling

Figure A2 shows the ~~typical arrangement of~~ set up for the photoclinometry portion of the study. The lake was manually outlined ~~,~~ and buffered, and transects were spaced every 250 m and sampled every 30m along transect for each 10 km long transect.

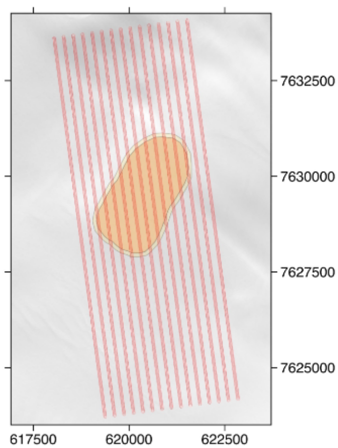



**Figure A2.** Lake 6 transects for photoclinometry calculations for image on 28 Oct 2016 prior to drainage (red), lake extent (orange) and buffer (yellow). For description of how these features are used in the photoclinometry calculations, see Methods..

## A4 Process

Figure A3 shows the correction of a transect across the lake. Transect 'A' in the graph was the original transect calculated following the photoclinometry process. Transect 'B' is the result of correction by calculating the elevation difference between the end of the lake transect and the elevation at that lake edge in the ArcticDEM and then distributing that elevation difference evenly across the lake transect.

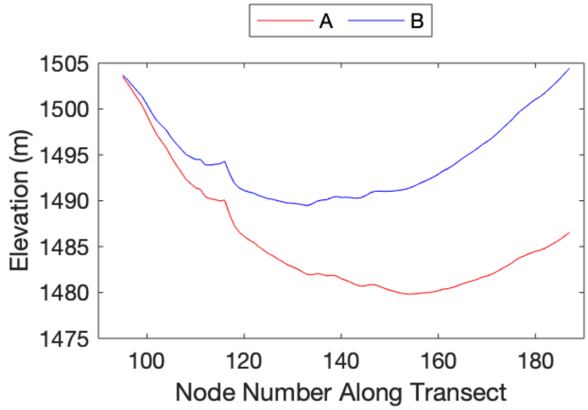



**Figure A3.** An example Lake 6 transect pair for photoclinometry calculations before (red), and after (blue) correction.

## Appendix B: Appendix B

Figure B1 presents pixel by pixel ice speeds based on MEaSUREs velocity data (Howat, 2017) for the ~~quarters nearest~~ winters surrounding each of the drainage events.

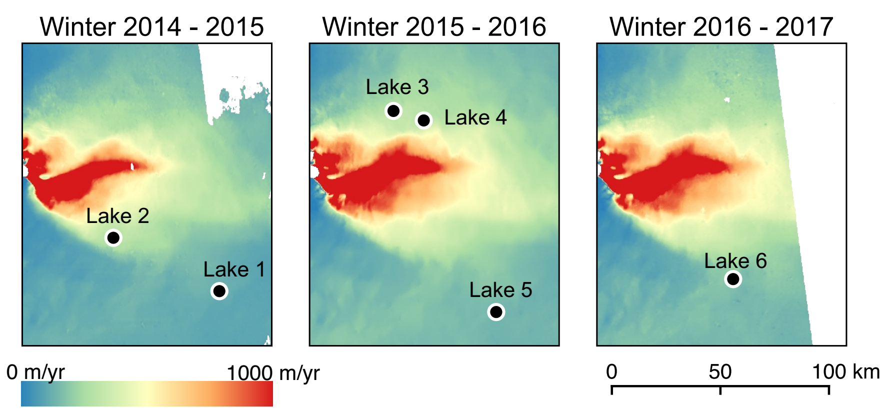



**Figure B1.** ~~This figure shows the ice~~ Ice speeds for the winter quarter proximate to each of the lake drainages.

## Appendix C: Appendix C

This figure shows the behaviour of lakes surrounding the identified drained lakes for the summers included in this study. The images shown are peak values of $NDWI_{ice}$ for each pixel, creating a maximum composite image. Red shading covers the extent of the lake mask for each year.

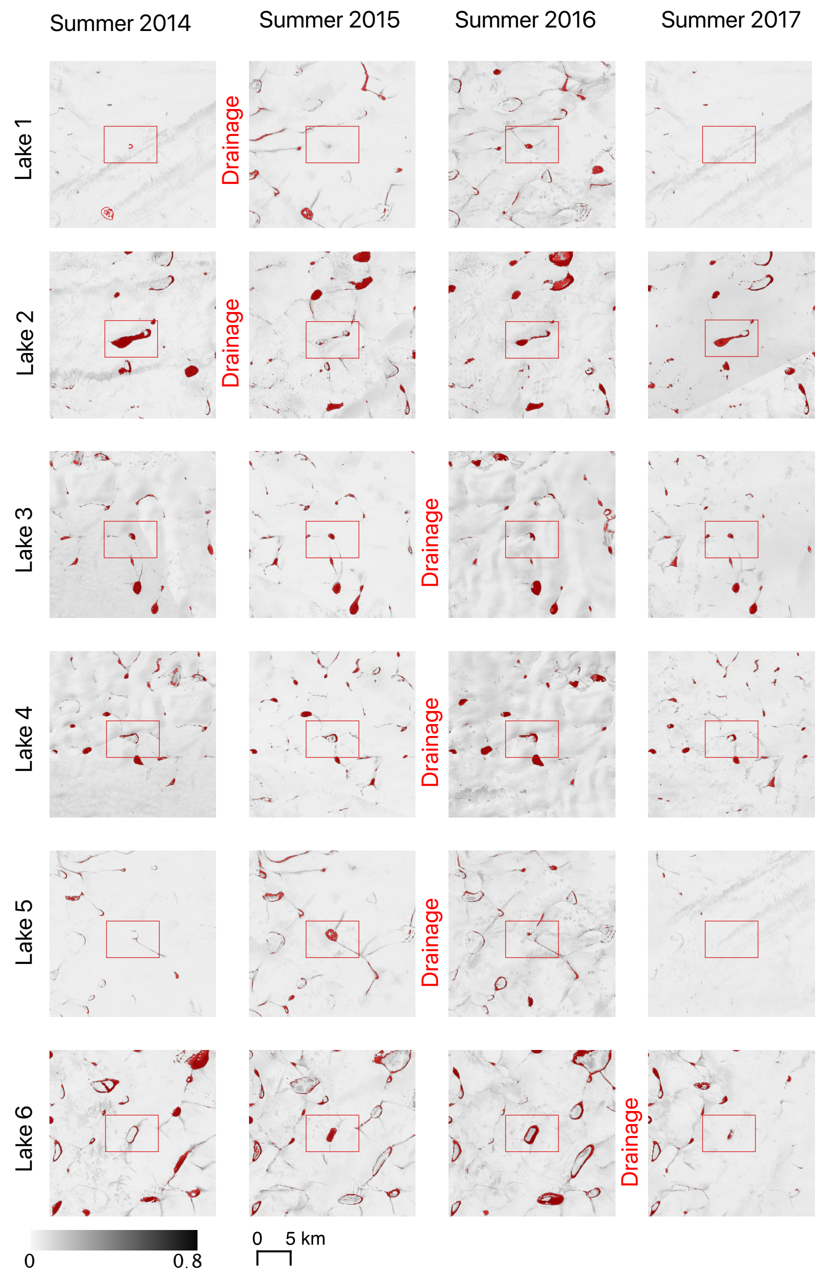



**Figure C1.** Composite maximum $NDWI_{ice}$ images for each summer. Each pixel shows the highest $NDWI_{ice}$ reached for that pixel for the season. The red outlines show the lake outline as delineated by a threshold exceeding 0.25 in the maximum $NDWI_{ice}$ composite for the pre-drainage summer.

**Appendix D: Appendix D**

The figures in this appendix show the backscatter time series for the lakes proximate to each of the identified drainage events. These are the equivalent of Figure 5 for all the lakes apart from Lake 6, which is shown in the body of the paper. For each figure, the top panels shows the backscatter time series. In the bottom row, (a) shows the lakes captured by the $NDWI_{ice}$ mask, (b) shows the backscatter prior to the drainage event and (c) shows the backscatter after the drainage event.

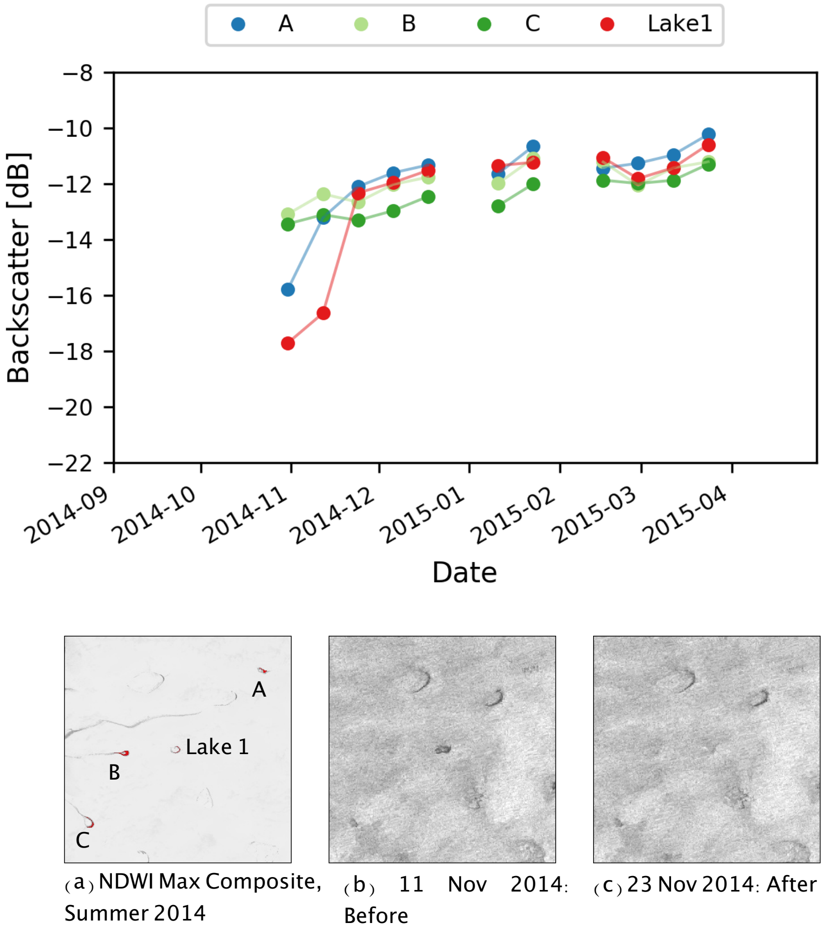
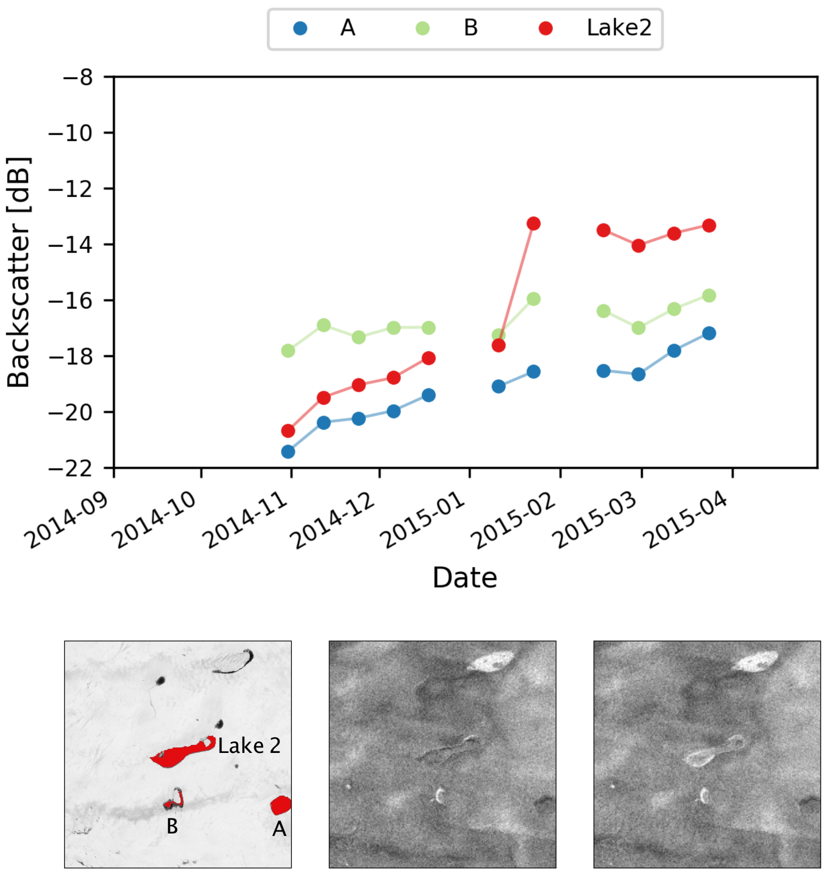



**Figure D1.** Lake 1 Surrounding Lakes

485

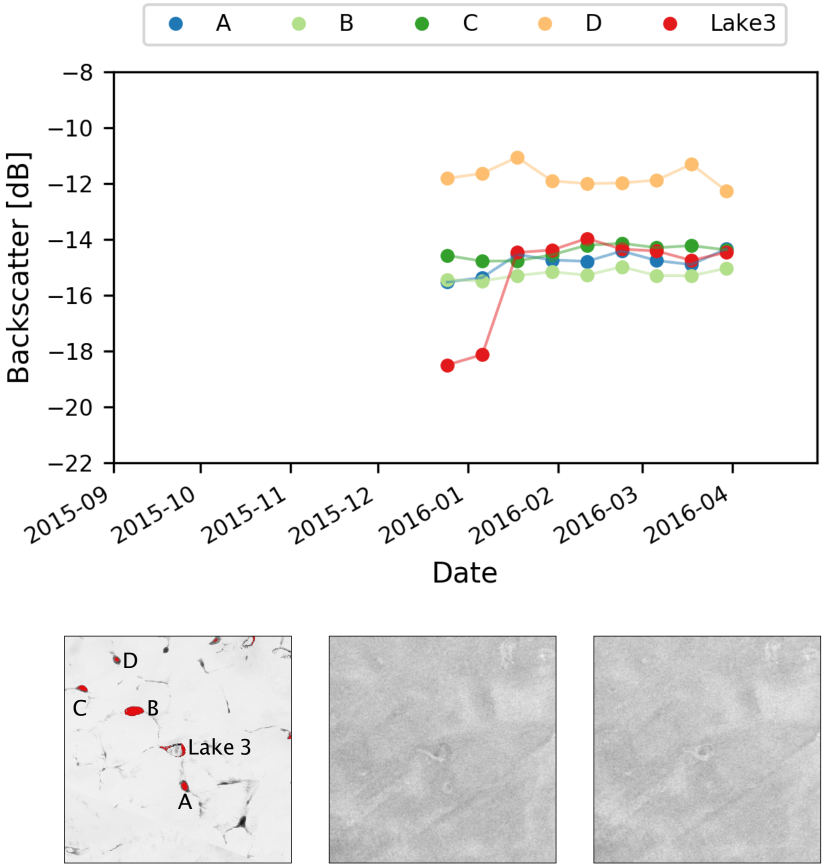



(a) NDWI Max Composite, Summer 2014

(b) 10 Jan 2015: Before

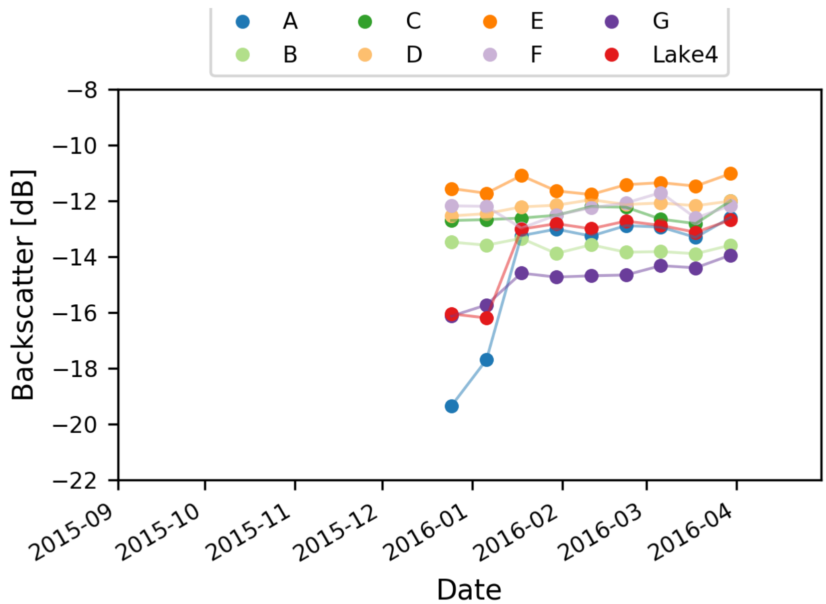
(c) 23 Jan 2015: After

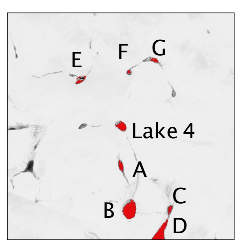
**Figure D2.** Lake 2 Surrounding Lakes



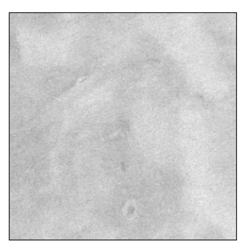

(a) NDWI Max Composite, Summer 2015 (b) 05 Jan 2016: Before (c) 17 Jan 2016: After

**Figure D3.** Lake 3 Surrounding Lakes

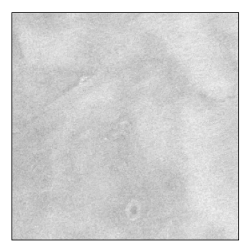



(a) NDWI Max Composite, Summer 2015

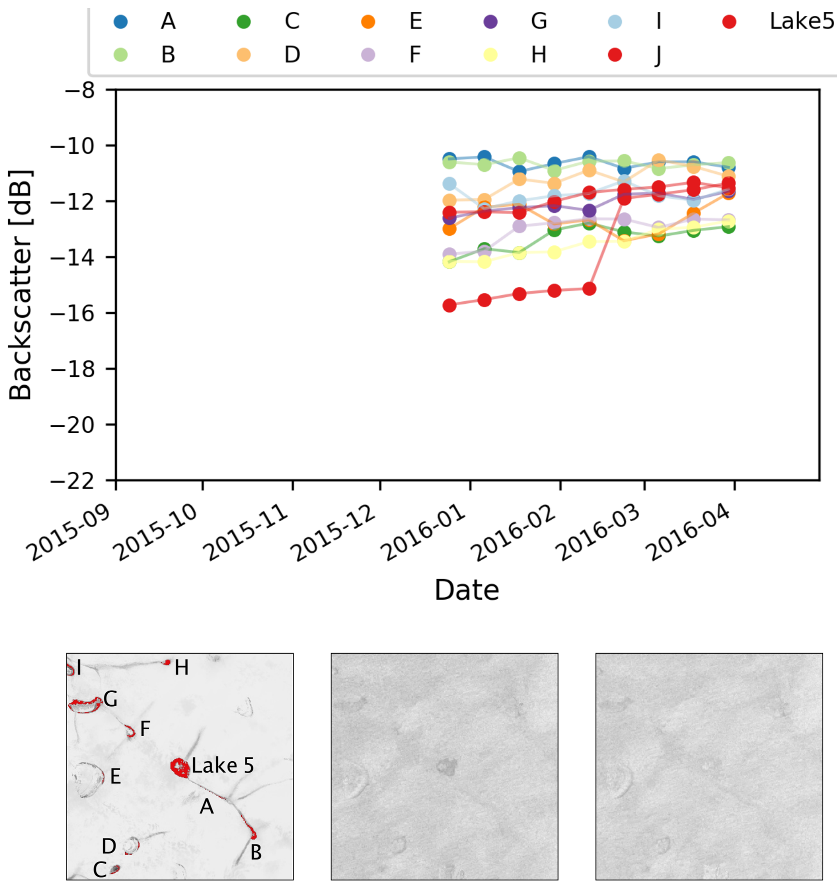


(b) 05 Jan 2016: Before



(c) 17 Jan 2016: After

**Figure D4.** Lake 4 Surrounding Lakes




(a) NDWI Max Composite, Summer 2015 (b) 10 Feb 2016: Before (c) 22 Feb 2016: After

**Figure D5.** Lake 5 Surrounding Lakes

**Appendix E: Appendix E**

The following is a list of Landsat-8 image IDs included in the late-summer $NDWI_{ice}$ max composite images used to delineate the lake boundaries for backscatter analysis.

Late Summer 2014 Max Composite

LC08_006013_20140815

LC08_007012_20140806

LC08_007013_20140806

LC08_007013_20140822

LC08_008011_20140829

LC08_008012_20140829

LC08_008013_20140813

LC08_008013_20140829

LC08_009010_20140804

LC08_009011_20140804

LC08_009012_20140804

LC08_009013_20140804

LC08_010010_20140811

LC08_010010_20140827

LC08_010011_20140811

LC08_010011_20140827

LC08_010012_20140811

LC08_010012_20140827

LC08_010013_20140811

LC08_010013_20140827

LC08_011009_20140802

LC08_011010_20140802

LC08_011010_20140818

LC08_011011_20140802

LC08_011011_20140818

LC08_011012_20140802

LC08_011012_20140818

LC08_012009_20140825

LC08_012010_20140825

LC08_012011_20140825

LC08_014009_20140807
LC08_014009_20140823
LC08_014010_20140807
LC08_014010_20140823
LC08_016009_20140805
LC08_016009_20140821
LC08_082234_20140804
LC08_082235_20140804
LC08_084234_20140802

Late Summer 2015 Max Composite
LC08_006013_20150802
LC08_006013_20150818
LC08_008011_20150731
LC08_008011_20150816
LC08_008012_20150731
LC08_008012_20150816
LC08_008013_20150731
LC08_008013_20150816
LC08_009011_20150807
LC08_009013_20150807
LC08_010010_20150729
LC08_010010_20150814
LC08_010011_20150729
LC08_010011_20150814
LC08_010012_20150729
LC08_010012_20150814
LC08_010013_20150729
LC08_010013_20150814
LC08_011009_20150805
LC08_011010_20150805
LC08_011011_20150805
LC08_011012_20150805
LC08_012009_20150727
LC08_012010_20150727

LC08_012011_20150727
LC08_012011_20150812
LC08_013009_20150803
LC08_013009_20150819
LC08_013010_20150803
LC08_013010_20150819
LC08_013011_20150803
LC08_013011_20150819
LC08_014009_20150725
LC08_014009_20150810
LC08_014010_20150810
LC08_015009_20150801
LC08_015009_20150817
LC08_015010_20150801

Late Summer 2016 Max Composite
LC08_006013_20160804
LC08_006013_20160820
LC08_008011_20160802
LC08_008011_20160818
LC08_008012_20160802
LC08_008012_20160818
LC08_008013_20160802
LC08_008013_20160818
LC08_009010_20160809
LC08_009011_20160809
LC08_009012_20160809
LC08_009013_20160809
LC08_010010_20160816
LC08_010011_20160816
LC08_010012_20160816
LC08_010013_20160816
LC08_011009_20160807
LC08_011010_20160807
LC08_011011_20160807

LC08_011012_20160807
LC08_012009_20160814
LC08_012010_20160814
LC08_012011_20160814
LC08_013009_20160805
LC08_013009_20160821
LC08_013010_20160805
LC08_013010_20160821
LC08_013011_20160805
LC08_013011_20160821
LC08_014009_20160812
LC08_014010_20160812
LC08_015009_20160803
LC08_015010_20160803
LC08_016009_20160810
LC08_081235_20160801
LC08_082235_20160809

Late Summer 2017 Max Composite
LC08_006013_20170722
LC08_006013_20170823
LC08_007012_20170814
LC08_007013_20170814
LC08_008011_20170805
LC08_008011_20170821
LC08_008012_20170805
LC08_008012_20170821
LC08_008013_20170720
LC08_008013_20170805
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LC08_011012_20170725
LC08_011012_20170826
LC08_012009_20170716
LC08_012009_20170801
LC08_012010_20170716
LC08_012010_20170801
LC08_012011_20170801
LC08_013009_20170723
LC08_013009_20170808
LC08_013009_20170824
LC08_013010_20170723
LC08_013010_20170808
LC08_013010_20170824
LC08_013011_20170723
LC08_013011_20170808
LC08_014009_20170730
LC08_014010_20170730
LC08_014010_20170815
LC08_015009_20170721
LC08_015010_20170721
LC08_016009_20170813

LC08_084233_20170725
LC08_084234_20170725
LC08_085231_20170716
LC08_085234_20170801
LC08_086233_20170723

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