Dear Editor

We thank both reviewers for their comments on our paper. Their suggestions are both on point and have helped to improve the paper substantially. In particular, we made changes in response to all major comments, including modifying the title to better reflect the outcomes of the study; analysed velocity data using feature tracking of Sentinel 1a radar imagery and included sections on the ice dynamic response to the 2015 subglacial lake drainage event (we believe we show for the first time that subglacial lake drainage can cause a net slowdown, which we believe is a response to the glaciological context of the lakes); extended the methods, which have now been moved to a supplementary section (Appendix A); and included more background on subglacial lakes in Greenland, which we then return to in the discussion.

Our responses can be found below. Reviewer comments are in black and replies in blue.

On behalf of all co-authors,

Kind Regards,

Stephen Livingstone

Reviewer 1

This paper presents three new observations of subglacial lakes identified from satellite surface elevation data near the margin of a land-terminating section of the western Greenland Ice Sheet. The lakes are small in size, but their location near the ice margin makes them easy study objects for future investigations, compared to subglacial lakes in the interior of the ice sheet. Subglacial lakes have only recently been identified in Greenland, compared to in Antarctica, and therefore there is a potential to study these features in more detail to understand how they interact spatially and temporarily with the subglacial and proglacial hydrological systems. The paper is well structured and the language is fluent. I recommend publication after minor revision taking into account my general and detailed comments below. I apologize for any misunderstandings and look forward to seeing a revised version of the paper. My main comments and suggestions for improvements are:

1. I find the title does not reflect the paper content in a proper way; it refers to "outbursts floods". There is only one such event documented in Fig. 3. Are similar outburst floods observed for the other two lake drainage events? How common are these kind of flooding observations in satellite data from Isunnguata Sermia? Could the observed event coincide with supraglacial lake drainage events upglacier? Also, there are no drainage data presented to verify the qualitative observations from the satellite image. I would like to see some description of these caveats in the discussion section.

We agree this is misleading and have modified the title to "Brief Communication: Subglacial lake drainage beneath Isunguata Sermia, West Greenland: geomorphic and ice-dynamic effects", which we think better reflects the key findings of the paper, and takes into account the new data included in the revised paper. We tried to identify outburst floods associated with the other two subglacial lake drainage events, but could not find any conclusive evidence. The satellite and DEM archive is patchier for these two earlier events (particularly in-front of Isunguata Sermia), making it more difficult to discern any outburst events (either from NDWI or elevation change). The 2015 event also seems to have been the largest of the three, which may be one reason why we were able to clearly identify its downstream response.

2. Since subglacial lakes are relatively new findings in Greenland, it would be nice with some more review of previous studies in the introduction linked to the discussion. Are the lakes in this study a new type of subglacial lake in Greenland or have they been observed elsewhere?

Good points, thanks. We have expanded the introduction section to include more detail on how subglacial lakes in Greenland have been identified to date (see also comment below). We have also expanded the discussion section, adding in a new paragraph where we link back to the introduction, including the three main subglacial lake types from the Bowling et al. (2019) paper and the potential for water storage to delay transfer to the margin and influence downstream ice dynamics.

3. The methods are described shortly at the end of the introduction. I believe not all readers are familiar with these data and methods. Therefore, a methods description could be added in supplements. In this description, a short review on how subglacial lakes have been found in previous studies could be included.

We have expanded the methods, which we have now moved to an Appendix as also suggested, to include more details of the NDWI method (as also recommended in the specific comments). We have also added information on how subglacial lakes in previous studies were identified in the introduction where we review previous subglacial lake research.

SPECIFIC COMMENTS

Title:

The usage of plural of “outbursts floods” needs to be reflected in the paper. Only one observation of an outburst flood is presented for Lake 2 in Fig. 3. Are there additional satellite images showing outbursts floods for lake 1 and 3? If there is not room for additional figures in the paper, they could be included in supplements. Or the title could be changed to reflect the content of the paper.

Done. See reply to major comment above re. title.

Introduction:

L28: “Shallow hydraulic gradients” sounds confusing to me when referring to water,

maybe write “low hydraulic gradients”?

Done.

L37: I suggest replacing the word “significant” since it is a statistical term.

Changed to “important”.

L37-39: This sentence holds a lot of information and is a bit unclear to me, e.g. please clarify what you mean with “surface imprints”. Do they not often coincide with subglacial depressions and potential subglacial lakes?

By ‘surface inputs’, we refer to the input of surface meltwater to the bed, which is a key component of the subglacial drainage system in Greenland, relative to Antarctica. We have clarified this to “surface meltwater inputs”.

L40-44: Could you add some more review on these findings? Also, you mentioned three types of lakes here. Are the ones described in this paper a new type of lake (marginal lakes that fill over several years)? Please mention in the discussion.

Please see reply to major comment above.

L46: Do you have a reference for the statement "..is thought unlikely: : :" or is it from the references above? If so, please move the references to the end of the sentence.

We have added a reference (Bowling et al. 2019) to support this finding.

L47: Add a reference for the Landsat data.

We have added the following in brackets "(distributed by the U.S. Geological Survey - https://earthexplorer.usgs.gov/)"

L51: Vertical accuracy?

This is the horizontal accuracy of the ArcticDEM DSMs, and we have corrected to make this clear.

L52: How were the DSMs corrected against filtered IceSAT data? Did you do this? This sentence is a bit unclear.

The mean offset between ArcticDEM swaths and coincident IceSAT elevations is provided in the ArcticDEM metadata, and so this correction when available could just be applied directly to the ArcticDEM tile. This is specified in our new Appendix A. Datasets and Methods.

L53: Please describe in more detail how NDWI is used. Is there a reference to this method?

We have expanded the section on NDWI to explain its use and pre-processing steps, and also now include a reference – Zhao et al. (2018) – although to stay within the limit of a brief communication we have had to delete a reference elsewhere to accommodate this.

Zhao, H., Chen, F., and Zhang, M. A systematic extraction approach for mapping glacial lakes in high mountain regions of Asia. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 11(8), 2788-2799. doi: 10.1109/JSTARS.2018.2846551, 2018.

L50-55: These sentences describe methods and do not fit very well in the introduction. I suggest to move them to the next section and rename it to "Methods and Observations" or similar. Also, it would be clarifying with a last sentence in the introduction describing the objective and aim of the study.

To also account for the ice velocity methods and additional information on NDWI and uncertainties we have we have moved the last few sentences to a new, expanded - Appendix A. Datasets and Methods.

Discussion:

L91-93: Leverett and Russell Glacier have another subglacial drainage catchment than Isunnguata Sermia, so these two are not necessarily connected. Have you checked with other potential sources of subglacial water upglacier, such as supraglacial lake drainage events?

Certainly, during the period of late August and early September, when these subglacial lakes drained, there will also have been a number of supraglacial lake drainage events, and this is evident from checking the available satellite imagery. However, we do not think a supraglacial lake drainage event a likely cause of our proglacial observations given that the outburst flood coincides with the timing of ice-surface elevation anomaly 2. In addition, supraglacial lake drainages are relatively common along this western margin of Greenland, but major outburst floods characterised by rapid aggradation of up to 8 m of sediment are not.

L95: Wrong reference, please correct. The subglacial hydrological analysis was made in the Lindbäck et al. (2015) GRL paper (doi:10.1002/2015GL065393).

Good point. However, we are at the limit of the number of references allowed and so we have chosen to delete the wrong reference and just use Chu et al. (2016) as an example, given this is also used elsewhere in the manuscript.

L98: ": : :one drainage event _each_ over: : :"

Done

L100: How were the uncertainties (±) of each lake volume change determined?

The uncertainties of each lake volume change were determined by multiplying the internal error of the ArcticDEM by the surface area both before and after drainage and adding the errors together in quadrature. We have added a sentence to this effect in the Appendix.

L106: "largest and best-constrained _lake_: : :"?

Done

L112-114: I don't follow this statement "recharge were similar over winter and summer". February is a winter month, please rephrase the comparison periods. Also, the plot in Fig. 2 for Lake 2 looks steeper in summer 2016 than in winter, suggesting a faster refill in summer. The other two plots do not have high enough temporal resolution in summer to support the statement.

We agree that we have little data supporting this statement and discussion and so have deleted this section on lake recharge between summer and winter.

L118: What do you mean with "in close proximity"? Are you referring to other lakes than these three? Please clarify the sentence.

We have clarified our meaning here by adding "…the three subglacial lakes are…"

L120: Do you have a reference for this modelling work?

This is poorly phrased – we are actually referring to the hydrological routing analysis (Shreve equation, assuming ice overburden = water pressure) here, which is shown in Fig. 3a, and have rephrased accordingly.

L121: As mentioned earlier. How about supraglacial drainage events upglacier? Can these be ruled out?

See comment above, we believe a supraglacial lake drainage event causing our proglacial observations is unlikely.

L133: One difficulty with future studies of these lakes, is that it is hard to predict when the lakes will drain in the data (almost no observed filling/elevation change before the drainage events in Fig, 2). Any recommendations regarding this?

This is currently a challenge as we only have one drainage event per lake and so we cannot calculate the recurrence interval. In addition, the lakes seem to fill and then remain stable for some time before then draining again and so we cannot estimate based on how full the lake is (i.e. they do not seem to reach a drainage threshold). Hopefully, as the 2018 and then 2019 ArcticDEM timestamped data are released we will capture repeat drainage events that will help us to begin to answer that question.

Conclusions:

L154: As mentioned earlier, I would avoid using the term "significant" for qualitative data.

We have deleted the word "significant" here.

Figure 1:

North arrow and spatial reference are missing. I find it difficult to see the color differences, eg. 1 m compared to 10 m change. Also, is it possible to provide exact date for the images used in the subtraction? Makes it easier to reproduce the results.

We have added both a north arrow and spatial reference. The images do not have exact dates, as they are actually down-sampled (to 50 m) composites produced by merging (using median values where there is overlap) all the DSMs available in that particular year. This was done to produce a more consistent DSM of larger spatial extent to better identify large-scale changes, and was needed as the timestamped DSMs are rather patchy. We have now added some brief details to the caption detailing how the DSMs were produced and making this clear.

Figure 2:

Nice figure.

Thanks

Figure 3:

North arrow and spatial reference are missing. Fig. A: Define IS in the caption. Fig C: Why is the ice green? Fig. D: Why are the lakes blue? Are they masked out or have they lowered 10 m in elevation? Seems unlikely.

We have added a north arrow and graticule. IS is defined in the caption in the fourth sentence. There are two possible reasons why the ice is green (-ve) in the NDWI plot of Figure 3C. The ice might be drier in the second image, thus reducing the NDWI value and therefore on the change in NDWI figure, indicate a reduction in water content; and/or a change in sun angle can influence the brightness of the ice and therefore have a slight impact on the NDWI values. The lakes are blue because in one of the DSMs there are NoData values (-9999). This has now been rectified, with these values turned to Null.

Reviewer 2

General Comments

The manuscript is well written and reports on some very interesting observations. The main shortcoming is a complete lack of the investigation and discussion of ice dynamical effects. While a numerical study is clearly outside the scope of this paper, the DEM and satellite velocity data products could be easily investigated to answer some important questions.

A subglacial lake of a lateral extent of twice the ice thickness will strongly affect the surface topography and the ice flow field. Is there any evidence of a flat surface over the lake (this should be readily visible form the DEM)? Is the surface structure changing after the drainage events, e.g. a downstream bulge, or crevasse zones?

In terms of a surface expression of lake drainages, unlike in other examples of Greenland subglacial lake drainages, we do not see any evidence of a compressional zone or increased lateral crevassing at the downstream end of the lake (see Figure 1 below which shows hillshaded surface topography before and after the 2015 drainage event). The only evidence seems to be lowering of the surface above the lake, which you can see by the shadow at the downstream (left-hand) end of the lake. The ice surface above the lakes is also not flat (Figure 1). We suggest a number of reasons why this could be the case: (1) the relatively modest thickness of ice (approx. 400 m beneath lake 2) and small predicted size of lakes (<1 km2), which are likely maximum estimates given the influence of bridging stresses and the viscosity of the ice on the transmission of the effects of lake drainage to the surface; (2) unlike subglacial lakes observed elsewhere (e.g. Antarctica and further from the margin beneath the Greenland Ice Sheet) these are in a relatively confined outlet lobe and close to an ice-dammed lake. Due to the relatively deep depressions and lakes at the lateral ice margins, the ice flow in part 'peels' off to either side of the main glacier trunk. This creates a complex pattern of crevassing that may hide the (relatively subtle for the reasons outlined above) influence of the lake; (3) if the bed was relatively rough, coupled with the small sizes of the lakes, the bed would have a large effect relative to the lake, whereas in Antarctica where lakes are often an order of magnitude larger, the lake 'slippery spot' may dominate; and (4) complex surface hydrology, emergence of debris-rich layers at the surface and localised meteorological factors (katabatic winds moving emergent dust around, and strong solar insolation with resulting albedo variations) results in a complex ice surface topography with almost ubiquitous 4-5 m relief that is independent of crevasse formation.

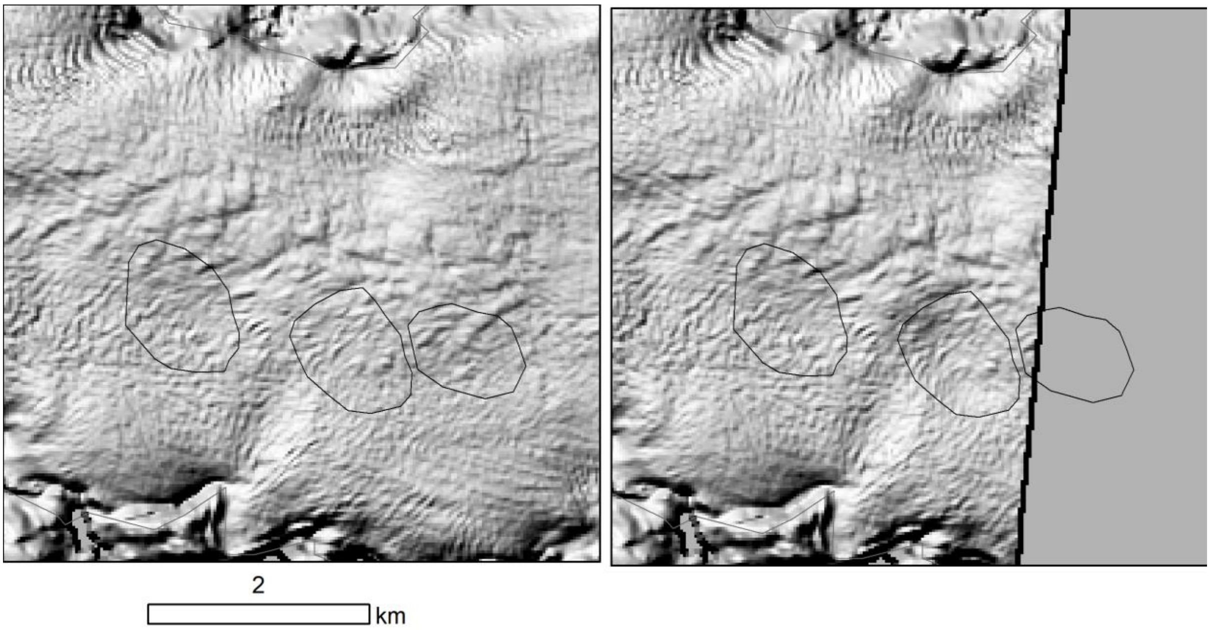

Figure 1: ArcticDEM hillshaded DSMs before (2nd August) and after (21st September) the 2015 subglacial lake drainage event. The lake that drained during this period is the middle of the polygons. The drainage is picked out by a drop in ice-surface elevation. Note how the surface is not completely flat.

The ice flow field would also be greatly affected by uncoupling from the bed of such a big area. Is there indication of increased lateral crevassing, or a compressional zone including a surface bulge at the downstream end of the lake? Are ice velocities higher over the area of the subglacial lake? Are velocities changing during drainage and refilling?

Good point. Although we could not identify an increase in lateral crevassing, compression (e.g. a surface bulge) or locally higher velocities over the subglacial lakes, we did identify an ice-dynamic response during the 2015 drainage event, although this is complicated by a regional slowdown that occurred during the same time. We used Sentinel 1a radar data (12-day repeat image pairs) to calculate ice velocity from feature and speckle tracking (adopting the same method published in Tuckett et al., (2019)). Anomalies were calculated relative to the 2015 winter mean, and revealed a distinctive and abrupt slowdown to winter values immediately downstream of the lake (relative to upstream, where values were positive) over the period during which it drained. We believe this is the first evidence for a net slowdown in ice flow following a subglacial lake drainage and have therefore added in a new methods section as an Appendix to detail the ice velocity methods; combined figures 1 and 2 (which focus on ice-surface elevation change) and added a new figure 2 where we show the ice velocity anomalies; and expanded both the Observation and Discussion sections to include a description of the ice velocity response and then some discussion on why a net slowdown is possible in the context of these lakes. We think this has added substantially to the paper, so thank the reviewer for his suggestion.

Tuckett, P.A., Ely, J.C., Sole, A.J., Livingstone, S.J., Davison, B.J., Melchior van Wessem, J., Howard, J. Large and rapid accelerations of Antarctic Peninsula outlet glaciers driven by surface melt. Nature Communications, 2019.

Minor comments

26 "channel melt rates" (it is important to distinguish this from surface melt).

Done

33 "surface melt water"

Not all water in subglacial lakes will be from surface melting (e.g. basal frictional and geothermal melting) and we therefore prefer to leave this as just meltwater.

41 This is somewhat problematic, as the lakes are at the ice bottom, which is not above the ELA. Their locations are at positions in the accumulation area, where the *surface* is above the ELA, or simply, above the EL.

Good point. We have rephrased as per the reviewers last suggestion, EL.

62 Were these anomalies stable in space, or moving with the ice?

Yes, good point, these anomalies are stable in space, i.e. they do not migrate down ice through time. We have added this point to the methods and observation section – "Timeseries of relative elevation change for each anomaly, which are not advected towards the margin, were calculated from sub-annual ArcticDEM DSMs by subtracting the mean ice-surface elevation of the anomaly from the mean elevation of a 500 m buffer around it (Fig. 1b)."

72 An indication of the ice thickness above these features is needed.

Rough ice thicknesses for each anomaly have been added to the descriptions.

115 The change in surface elevation is only discussed in terms of subglacial water storage. Another cause could be ice compression by horizontally convergent ice flow. Can this be ruled out by the surface velocity field?

If we understand you correctly, we do not think this likely for a number of reasons. (1) the anomalies are all circular to ovoid in form, which is consistent with a ponded water body rather than horizontally convergent ice flow, which we might expect to produce a more flow-parallel, linear feature; (2) horizontally convergent ice flow would produce the rise in ice surface but does not account for the drop in elevation; (3) the drop in elevation in the 2015 example coincides with an outburst flood and proglacial sediment accumulation, which we suggest must have been caused by a rapid drainage event; and (4) the anomalies are stable in space (i.e. they do not migrate down ice).

Figure 1: Years are barely readable. Better underlay the numbers by white background. Also describe in the caption that the "ice dammed lake (white background)" is visible on the surface.

We have extended the caption to mention the ice-dammed lake. We have added a white background to all the numbers and text.

Figure 2: The black line should be broken at 2011, as the anomaly might have been much lower than suggested by the line.

We have made the line dashed at 2011 to indicate that the anomaly could have been much greater, and also added a comment in the caption. Note this is now Figure 1b to account for the new ice dynamic work and figure.

~~Brief Communication: Outburst floods triggered by periodic drainage of subglacial lakes, Isunguata Sermia, West Greenland~~ Brief Communication: Subglacial lake drainage beneath Isunguata Sermia, West Greenland: geomorphic and ice-dynamic effects

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Abstract (100 words)

We report three active subglacial lakes within 2~~-~~-km of the lateral margin of Isunguata Sermia, West Greenland, identified by differencing time-stamped ArcticDEM strips. Each lake underwent one drainage-refill event between 2009 and 2017, with two lakes draining in <1 month ~~during between~~in August 2014 and August 2015~~, and all three characterised by 2-3-year refill periods~~. The 2015 drainage caused a ~~net~~ ~1-month down-glacier slowdown in ice-flow and flooded the foreland, aggrading ~~8 m of~~ the proglacial channel by 8 m~~, confirming~~. Thise proglacial flooding confirms the ice-surface elevation anomalies as subglacial water bodies and ~~demonstrating~~ demonstrates how ~~subglacial lake~~ their drainage~~s~~ can significantly modify proglacial environments. These subglacial lakes offer accessible targets for ~~future~~ geophysical investigations and exploration.

1. Introduction

Meltwater beneath the Greenland Ice Sheet is sourced from geothermal and frictional melting, and via the input of surface meltwater through englacial pathways. This meltwater drains towards the ice sheet margin through a complex network of inefficient and efficient drainage routes~~ (Davison et al., 2019)~~. Spatial and temporal variations in drainage structure are controlled by the hydraulic gradient and meltwater flux. Steeper hydraulic gradients and higher meltwater fluxes close to the ice margin lead to greater ~~ice~~ channel melt rates and promote the formation of efficient channels, which can extend up to 40 km inland and evolve on seasonal timescales in response to surface meltwater inputs (Chandler et al., 2013). ~~Shallow~~ Low hydraulic gradients and ~~lower~~ smaller meltwater fluxes dominated by subglacial meltwater sources tend to be associated with more inefficient drainage configurations further inland (Doyle et al., 2014).

Storage of water in firn (Forster et al., 2013), damaged englacial ice (Kendrick et al., 2018) and both supraglacial (Selmes et al., 2011) and subglacial lakes (Palmer et al., 2013~~; Oswald et al., 2018~~; Bowling et al., 2019) can delay the drainage of meltwater through the ice sheet to the ocean, while the rapid drainage of stored water can overwhelm the drainage system and perturb ice flow (e.g. Das et al., 2008). Storage and drainage of supraglacial lakes have been well-documented (e.g. Selmes et al., 2011), but the volume of water stored subglacially, ~~and~~ the ~~lakes'~~ residence times of the lakes, and the wider influence on the subglacial hydrological system and ice flow is poorly understood. Although subglacial lakes are expected to be a less ~~significant~~important component of the hydrological system compared with Antarctica (e.g. Siegfried & Fricker, 2018) due to steeper hydraulic gradients, dominance of surface meltwater inputs and more efficient subglacial water routing, 1000s of subglacial lakes have been predicted and over 50 identified beneath the Greenland Ice Sheet (Livingstone et al., 2013; Bowling et al., 2019). This includes stable lakes above the Equilibrium Line ~~Altitude~~ (EL~~A~~) but away from the interior identified from airborne radio-echo sounding (Palmer et al., 2013~~;~~ ~~Oswald et al. 2018~~; Bowling et al., 2019)~~;~~, hydrologically active lakes recharged by surface meltwater near the EL, determined from surface elevation change measurements derived from repeat high-resolution Digital Surface Models (DSMs) and ICESat elevation data (Palmer et al., 2015; Willis et al., 2015; Bowling et al., 2019)~~near the ELA recharged by surface meltwater;~~, and small seasonally active ~~lakes~~ subglacial water bodies below the EL~~A~~ which form during winter and drain during the melt season identified from repeat airborne radio-echo sounding (~~Palmer et al., 2013, 2015; Howat et al., 2013; Willis et al., 2015;~~ Chu et al., 2016~~; Oswald et al., 2018; Bowling et al., 2019~~).

Whilst seasonal water storage is thought to be common below the EL~~A~~ (e.g. Chu et al., 2016; Kendrick et al., 2018), longer term subglacial lake storage is thought unlikely due to the development of efficient channels and the associated increase in hydrological connectivity each melt season (Bowling et al., 2019). In this paper we acquired multi-temporal ArcticDEM ~~Digital Surface Models (~~DSMs~~)~~ (Noh & Howat, 2015) and Landsat 7 and 8 satellite imagery between 2009 and 2017 (distributed by the U.S. Geological Survey - https://earthexplorer.usgs.gov/) to identify three active subglacial lakes on a reverse bed-slope beneath Isunguata Sermia, West Greenland (67°10' N, 50°12'W) (Fig. 1). ~~The ArcticDEM DSMs were generated from high-resolution satellite imagery and have a spatial resolution of 2 m and internal accuracy of 0.2 m. Each of the 52 DSMs acquired over the time period were corrected against filtered IceSAT altimetry data using the metadata provided (Dai & Howat, 2017). Change in Normalised Difference Water Index (NDWI) to identify flooding of the proglacial zone was calculated using top-of-atmosphere corrected Landsat green (band 3) and near-infrared (band 5) bands and the formula: NDWI = (band 3 – band 5)/(band 3 + band 5).~~

2. Observations

Yearly ice-surface elevation change was determined from 2009 to 2017 by differencing the ~~multi-temporal~~annually-averaged ArcticDEM DSMs. This revealed three distinctive quasi-circular ~~regions~~features, hereafter referred to as 'anomalies', all within 2 km of the lateral margin of Isunguata Sermia, that were characterised by periods of subsidence followed by uplift (Fig. 1a). T~~T~~imeseries of relative elevation change for each anomaly, which are ~~stable in space~~ not advected towards the margin, were calculated from ~~the higher frequency~~sub-annual ArcticDEM DSMs by subtracting the mean ice-surface elevation of the anomaly from the mean elevation of a 500 m buffer around it (Fig. ~~2~~1b). This approach was used to isolate the dynamic effect and to remove the influence of systematic vertical and horizontal offsets (of up to 3-5 m) between DSMs. Anomaly 1, located <5 km from the terminus of Isunguata Sermia where the ice is ~325 m thick (Lindbäck et al., 2014), formed a 0.93 km^2 depression between 19th August 2010 and 3rd August 2011 with a mean depth of 5 m and maximum depth of 17 m. The ice-surface then rose 1 m by November 2011 before recovering back to its 2010 elevation by February 2013. Anomaly 2 (~370 m ice thickness), about 1 km further up ice ~~(~370 m ice thickness)~~, formed a 0.88 km^2 depression between 2nd August 2015 and 21st September 2015, with a mean depth of 13 m and maximum depth of 30 m. It then rose~~has since risen~~ 9 m between 2015 and 2017. Anomaly 3 (~450 m ice thickness), ~~which is just~~ immediately up-ice ~~from~~ of anomaly 2 and ~9 km from the terminus ~~(~450 m ice thickness)~~, formed a 0.67 km^2 depression between 17th August 2014 and 19th September 2014, with a mean depth of 4 m and maximum depth of 14 m, before the surface rose 3 m between 2014 and 2017. Surface structural features indicative of localised ice fracture during subsidence, such as crescentic crevasses, are not apparent in any of the depressions.

Ice velocities derived from feature tracking of Sentinel-1 radar data (SI methods) do not show a consistent area of fast flow over any of the anomalies. However, during the subsidence of anomaly 2 in late July to early August 2015 (Fig. 2), ice flow immediately downstream of the anomaly experience~~s~~d a net slowdown to roughly winter values (Fig. 2b-c), coincident with an overall regional slowdown in ice flow. This ~~i~~was followed by a return to pre-subsidence flow speeds by 19th – 31st August 2015 (Fig. 2d). During the period of subsidence ice flow also converge~~s~~d into the depression, leading to localised rapid '~~backwards~~up-glacier' flow against the regional ~~east~~westerly flow direction, which manifests as a strong positive ice flow change immediately above the anomaly (Fig. 2c).

Landsat 8 OLI satellite images acquired before and after the 2015 ice-surface subsidence (anomaly 2) reveal a major change in the 1.8 km wide proglacial braided river system (Fig. 3). On 15th July 2015 the river plain is characterised by a single channel emanating from the front of Isunguata Sermia, that then bifurcates down-river into multiple braids and intervening bars (Fig. 3a). Dry areas above the water level are demarcated by a sharp change in colour, with wetted areas darker and dry areas lighter. Using this demarcation, a major flood plain directly in-front of the main portal, which causes the river emanating from the glacier to divert northwards and then westwards, is identified. On the basis of a qualitative change from light to dark, on the 25th August 2015, and a quantified positive change in Normalised Difference Water Index (NDWI) (SI methods) of up to +0.23 (mean: +0.09) between July and August, the dry areas (bars and floodplain) became inundated by water and the braided river system re-organised (Fig. 3b-c). Differencing ArcticDEM DSMs of the proglacial area before (4th May 2015) and after (21st September 2015) the ice-surface elevation change of August-September 2015 associated with anomaly 2 reveals 3 m of mean net sediment aggradation across a 5 km stretch of the main proglacial channel (Fig. 3d). Aggradation was up to 8 m close to the outlet and declined to <1 m 5 km from the glacier terminus.

3. Discussion

We identify three ice surface elevation anomalies on Isunguata Sermia ~~characterised by localised ice-surface elevation changes~~, which we interpret as subglacial lake drainage and filling (Fig. 1). From this point onwards we therefore refer to these anomalies as 'Subglacial Lakes 1-3'. Confirmation of a subglacial lake origin is provided by flooding of the proglacial outwash plain in August 2015, which coincided with the timing of ice-surface elevation anomaly 2, evidencing the release of meltwater (Fig. 3). This inundation (wetting) of the flood plain is not replicated at the nearby Leverett-Russell Glacier (Fig. 3b), ruling out a common external forcing (e.g. heavy rainfall). All three subglacial lakes are located under 325-~~400~~ 450 m thick (Lindbäck et al., 2014), warm-based ice on a reverse gradient bed slope (15 m per km); the reverse slope may be trapping the water causing the lakes to form. Although subglacial hydrological analysis (e.g. ~~Lindbäck et al., 2014;~~ Chu et al., 2016) does not produce hydraulic minima in the locations where we identify lakes, this is likely to be ~~may be~~ ~~a~~the result of the limited and relatively poor-quality airborne radar ice-thickness measurements across the thin, near-marginal area of Isunguata Sermia, and the resolution of the bed DEMs.

The three subglacial lakes ~~each~~ underwent one drainage event each over the 8-year data period (Fig. 2). Differencing of the DSMs either side of the drainage events, over the area of the ice-surface anomalies, gives total lake volume changes of 6.5 ± 0.52 × ~~x~~ 10^6 m^3, 1.3 ± 0.05 × ~~x~~ 10^7 m^3 and 3.5 ± 0.38 × ~~x~~ 10^6 m^3 for anomalies 1-3 respectively. Drainage of Subglacial Lake 2 in 2015 and Lake 3 in 2014 were both triggered in August and drained in <1 month, which is consistent with other larger subglacial lake drainage events identified in Greenland (~~Howat et al., 2014;~~ Palmer et al., 2015; Willis et al., 2015; Bowling et al., 2019), but contrasts with the longer (months to years) drainage period of those in Antarctica (e.g. Siegfried & Fricker, 2018). If the vertical displacement of the ice-surface is ~~assumed to be~~ equivalent to the depth of the subglacial lake, this gives a mean minimum discharge of 6.5 m^3 s^{-1} for Subglacial Lake 2, which is the largest and best-constrained lake, by available DSM and satellite imagery, in this study. This is, however, well below the likely maximum discharge given the enormous mobilisation of sediment that resulted from the drainage and the unknown period of drainage within the ~~50 day~~ observational window.

Lake recharge is on the scale of a few years, and it is noticeable that the largest subglacial lake drainage event (Lake 2) subsequently refilled at the fastest rate (~5 m ~~uplift~~ yr^{-1} uplift), while the smallest drainage event (Lake 3) ~~is filling~~filled at the slowest rate (~1 m ~~uplift~~ yr^{-1} uplift). The lakes are at the lower end of the ablation zone and therefore would be expected~~likely~~ to be dominated by upstream surface meltwater inputs and the seasonal melt signal ~~(Davison et al., 2019)~~. Despite this, lake drainage is not associated with high-melt years (e.g. the 2011 drainage event coincided with a low melt year) ~~and recharge rates were similar over winter and summer. For example, the ice surface above Lake 2 rose ~3 m over a 5-month period between September 2015 and February 2016 immediately following drainage, but then rose an equivalent height over the next 6-month period between February and August 2016. This may be partially due to faster initial recovery, but also implies that the lake is able to capture significant volumes of water over winter~~. All three lakes exhibited quiescent periods of extended high-stand, which might occur when water flow into the lake is balanced by outflow, and suggests an external threshold controlling lake drainage initiation.

Although the three subglacial lakes are in close proximity, drainage of an upstream lake does not trigger a cascade of drainage in downstream lakes. In addition, the filling of Lake 3 did not limit recharge of Lake 2 just downstream (Fig. ~~2~~1b). This suggests that the lakes are not hydraulically well connected, consistent with subglacial hydraulic ~~modelling~~ routing analysis, ~~indicating~~ which indicates that the main subglacial drainage axis is just to the north of the two upstream subglacial lakes (Fig. 3a). Both the 2014 and 2015 drainage events were initiated in August at a time when drainage system connectivity is envisaged to be high and water preferentially drains towards efficient channels along a hydraulic gradient ~~(Davison et al., 2019)~~. Thus, rapid drainage could be a response to lakes infrequently connecting with the main subglacial channel.

Drainage of Subglacial Lake 2 in August 2015 resulted in a net slowdown in downstream ice flow of Isunguata Sermia over a short period of about one month, before ice flow subsequently returnin~~g~~ed to pre-drainage ice-flow speeds in late August (Fig. 2). This slowdown occurs abruptly at the location of lake 2 suggesting its drainage has impacted ice flow (Fig. 2b-c), but is also coincident with a broader regional slowdown that must at least partly overprint the dynamic signal of the subglacial lake. Although we cannot rule out a short-term speed-up in response to initial drainage, any acceleration must have been extremely rapid (< the twelve-day repeat period imagery used to calculate the velocities), and of smaller overall magnitude and/or duration than the subsequent slowdown in ice flow. This response to subglacial lake drainage is the opposite of temporary ice accelerations observed in Antarctica (e.g. Scambos et al. 2011), and is likely because any initial speed-up would have been dampened by efficient drainage of the lake through existing large subglacial channel(s) near the ice margin. Melting of the channel sides and erosion of ~~its~~the channel bed caused by ~~the~~ turbulent water flow would have enlarged the channel's cross-sectional area leading to reduced water pressure, ~~which~~ likely caus~~ed~~ing ~~the~~ deceleration of overlying ice. This is based on the timing of the event at the end of the melt season, the ~~lakes'~~ position of the lake near to the ice-margin (Fig. 1) and the large subglacial drainage catchment of Isunguata Sermia (Chu et al., 2016), all of which would act to promote the development of large and efficient channels (e.g. Chandler et al., 2013). This inference is supported by the ~~restricted~~ pattern of thickest sediment deposition at the southern end of the glacier terminus (Fig. 3), which suggests that the subglacial drainage event was at least partially focused into a channel rather than an unconstrained sheet flood.

The August 2015 subglacial lake drainage event flooded the foreland and resulted in substantial net ice-proximal sediment aggradation (7.5 ×~~x~~ 10^6 m^3) of the outwash plain (Fig. 3). Deposition was greatest in the main channel, with up to 8 m of net aggradation close to the outlet ~~diminishing~~ reducing to <1 m 5 km from the terminus. This near-margin pattern of aggradation is consistent with the geomorphic impact of jökulhlaups observed in Iceland (e.g. Dunning et al., 2013) and demonstrates the potential of episodic subglacial lake drainage events to erode the subglacial bed and modify the proglacial environment. Given the subglacial lake is located just 8 km from the glacier terminus the subglacial erosion necessary to produce the sediment volume deposited on the foreland is equivalent to a 10 m deep and 100 m wide channel cut into the bed. ~~The restricted pattern of deposition at the southern end of the glacier terminus suggests that the subglacial drainage event was at least partially focused into a channel rather than an unconstrained sheet flood.~~

The three subglacial lakes beneath Isunguata Sermia do not exhibit the seasonal pattern of winter storage and summer drainage that was previously thought to dominate in the ablation zone (Chu et al., 2016; Bowling et al., 2019). Instead, they share many of the drainage characteristics of the hydrologically active subglacial lakes identified near the EL of the Greenland Ice Sheet (e.g. Palmer et al., 2015; Willis et al., 2015; Bowling et al., 2019). This indicates the potential for multi-year storage of subglacial water towards the margin of the ice sheet in regions dominated by surface meltwater inputs to the bed. This storage could delay the delivery of meltwater to the margin and influence the ice dynamic response to surface meltwater downstream.

Although the presence or absence of sediments in these lakes or the thickness of any water column has yet to be tested, these three subglacial lakes present an extremely accessible target for future geophysical characterisation and active lake exploration. Ice-surface elevation changes suggest the lakes are at least 14-30 m deep and have minimum volumes of 3.5-13 ×~~x~~ 10^6 m^3. Ice cover is relatively thin (325-450 m), and the lakes are clustered and in close proximity to the ice margin (<2 km), road (<5 km) and key logistical support including a major airport (Kangerlussuaq). Key questions that could be addressed through detailed investigation of these lakes include: what triggers subglacial lake drainage and how does drainage evolve downstream? How do the lakes interact with other components of the subglacial drainage system? What geomorphological and sedimentological signatures of similar drainage events might be recorded in the proglacial area?

4. Conclusions

Using multi-temporal ArcticDEM DSMs and satellite imagery, we identify three active subglacial lakes <10 km from the terminus of Isunguata Sermia. The lakes are characterised by periods of relative inactivity punctuated by rapid drainage (<1 month) and then slow recharge (a few years). The most recent drainage event in 2015 flooded the outwash plain resulting in net ice-flow slowdown over a ~1 month period and net ice-marginal sediment aggradation that was greatest closest to the outflow portal and thinned downstream. This work demonstrates the potential for subglacial lakes to exist in the lower ablation zone close to the ice margin, where subglacial hydrology is dominated by ~~surface~~ seasonal surface meltwater inputs and efficient channelized drainage. The lakes appear to be only weakly connected to the main subglacial channel axis and drainage may be controlled by the ability of this channel to occasionally capture water from its surroundings. The 2015 subglacial lake drainage event had a ~~significant~~ subglacial and proglacial geomorphic impact, including substantial erosion of sediment from beneath Isunguata Sermia and ~~substantial~~ extensive aggradation of sediment in the proglacial outwash plain close to the terminus. Net slowdown in ice flow due to subglacial lake drainage is likely due to antecedent subglacial channelized drainage close to the margin towards the end of the melt season that at least partially accommodated the lake outburst flood and therefore dampened any initial acceleration.- Melting of the channel sides and erosion of its bed caused by the turbulent water flow would have enlarged the channel's cross-sectional area leading to reduced water pressure which likely caused the deceleration of overlying ice. This suggests that the ice-dynamic response to subglacial lake drainage may vary depending on their subglacial and englacial context ~~beneath ice sheets.~~ Detailed geophysical studies across and downstream of these lakes would provide insight into the conditions causing the lakes to form and drain, the resultant geomorphic imprint and the depositional archive of these lake environments. Crucially, these subglacial lakes may be the most accessible in the world due to their setting beneath thin ice close to the lateral margin of the glacier and the existing infrastructure and logistical set-up of the region.

__Author contributions.__ A. Sole and R. Storrar initially identified the subglacial lakes. S. Livingstone, A. Sole and D. Harrison processed and analysed the data. S. Livingstone wrote the paper with input and ideas from all co-authors.

Appendix A. Datasets and Methods.

The ArcticDEM DSMs were generated from high-resolution satellite imagery and have a horizontal spatial resolution of 2 m and internal accuracy of 0.2 m. Each of the 52 DSMs acquired over the time period were corrected against filtered IceSAT altimetry data using the metadata provided (Dai & Howat, 2017). Minimum subglacial lake volumes were calculated by differencing DSMs either side of the drainage events, over the area of the ice-surface anomalies, with uncertainties derived by multiplying the internal error of the ArcticDEM by the lake area both before and after drainage and adding together in quadrature.

Normalised Difference Water Index (NDWI) analysis is an effective method for highlighting water bodies and saturated environments whilst subduing background information. Before NDWI calculations were undertaken Landsat 8 OLI images were pre-processed to convert raw pixel digital number (DN) values into top of atmosphere (TOA) reflectance (Zhao et al., 2018). Change in NDWI to identify flooding of the proglacial zone was calculated using the TOA corrected Landsat 8 green (band 3) and near-infrared (band 5) bands and the formula: NDWI = (band 3 – band 5)/(band 3 + band 5) (Zhao et al., 2018).

Ice velocity was calculated from feature and speckle tracking of Sentinel 1a Interferometric Wide Swath mode Single-Look Complex Synthetic Aperture Radar amplitude images following the approach outlined in Tuckett et al. (2019). This included cross-correlation between repeat-pass image pairs to determine the offset of features (e.g. crevasses) over time and processing involved co-location of image pairs using precise satellite orbit ephemerids, conversion of images to amplitude in GMTSAR, a Butterworth high-pass filter to remove image brightness variations with a wavelength greater ~1 km and tracking of images in MATLAB using PIVSuite (https://uk.mathworks.com/matlabcentral/fileexchange/45028-pivsuite) adapted for quantifying ice flow. These data cover one swath and include 12 twelve-day repeat image pears between 3rd January and 31st August 2015. Anomalies were calculated relative to the period 3rd January – 5th April.

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References

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

Chandler, D.M., Wadham, J.L., Lis, G.P., Cowton, T., Sole, A., Bartholomew, I., Telling, J., Nienow, P., Bagshaw, E.B., Mair, D. and Vinen, S. Evolution of the subglacial drainage system beneath the Greenland Ice Sheet revealed by tracers. Nature Geoscience, 6, 195. doi.10.1038/ngeo1737, 2013.

Chu, W., Schroeder, D.M., Seroussi, H., Creyts, T.T., Palmer, S.J. and Bell, R.E. Extensive winter subglacial water storage beneath the Greenland Ice Sheet. Geophysical Research Letters, 43, doi.10.1002/2016gl071538, 2016.

Dai, C. and Howat, I.M. Measuring lava flows with ArcticDEM: Application to the 2012–2013 eruption of Tolbachik, Kamchatka. Geophysical Research Letters, 44, doi.10.1002/2017gl075920, 2017.

Das, S.B., Joughin, I., Behn, M.D., Howat, I.M., King, M.A., Lizarralde, D. and Bhatia, M.P. Fracture propagation to the base of the Greenland Ice Sheet during supraglacial lake drainage. Science, 320, 778-781, doi.10.1126/science.1153360, 2008.

~~Davison, B.J., Sole, A.J., Livingstone, S.J., Cowton, T.R. and Nienow, P.W. The influence of hydrology on the dynamics of land-terminating sectors of the Greenland Ice Sheet. Frontiers in Earth Science, 7, doi.10.3389/feart.2019.00010, 2019.~~

Doyle, S.H., Hubbard, A., Fitzpatrick, A.A., Van As, D., Mikkelsen, A.B., Pettersson, R. and Hubbard, B. Persistent flow acceleration within the interior of the Greenland ice sheet. Geophysical Research Letters, 41, 899-905, doi.10.1002/2013gl058933, 2014.

Dunning, S.A., Large, A.R., Russell, A.J., Roberts, M.J., Duller, R., Woodward, J., Mériaux, A.S., Tweed, F.S. and Lim, M. The role of multiple glacier outburst floods in proglacial landscape evolution: The 2010 Eyjafjallajökull eruption, Iceland. Geology, 41, 1123-1126, doi.10.1130/g34665.1, 2013

Forster, R.R., Box, J.E., Van Den Broeke, M.R., Miège, C., Burgess, E.W., Van Angelen, J.H., Lenaerts, J.T., Koenig, L.S., Paden, J., Lewis, C. and Gogineni, S.P. Extensive liquid meltwater storage in firn within the Greenland ice sheet. Nature Geoscience, 7, 95, doi.org/10.1038/ngeo2043, 2014.

~~Howat, I.M., Porter, C., Noh, M.J., Smith, B.E. and Jeong, S. Brief Communication: Sudden drainage of a subglacial lake beneath the Greenland Ice Sheet. The Cryosphere, 9, 103-108, doi.10.5194/tc-9-103-2015, 2015.~~

Kendrick, A.K., Schroeder, D.M., Chu, W., Young, T.J., Christoffersen, P., Todd, J., Doyle, S.H., Box, J.E., Hubbard, A., Hubbard, B. and Brennan, P.V. Surface meltwater impounded by seasonal englacial storage in West Greenland. Geophysical Research Letters, 45, 10-474, doi.10.1029/2018gl079787, 2018.

Lindbäck, K., Pettersson, R., Doyle, S.H., Helanow, C., Jansson, P., Kristensen, S.S., Stenseng, L., Forsberg, R. and Hubbard, A.L. High-resolution ice thickness and bed topography of a land-terminating section of the Greenland Ice Sheet. Earth System Science Data, 6, 331-338, doi.10.5194/essdd-7-129-2014, 2014.

Livingstone, S., Clark, C., Woodward, J. and Kingslake, J. Potential subglacial lake locations and meltwater drainage pathways beneath the Antarctic and Greenland ice sheets. Cryosphere, 7, 1721-1740, doi.10.5194/tc-7-1721-2013, 2013

Noh, M.J. and Howat, I.M. Automated stereo-photogrammetric DEM generation at high latitudes: Surface Extraction with TIN-based Search-space Minimization (SETSM) validation and demonstration over glaciated regions. GIScience & Remote Sensing, 52, 198-217, doi.10.1080/15481603.2015.1008621, 2015.

~~Oswald, G.K., Rezvanbehbahani, S. and Stearns, L.A. Radar evidence of ponded subglacial water in Greenland. Journal of Glaciology, 64, 711-729, doi.10.1017/jog.2018.60, 2018.~~

Palmer, S.J., Dowdeswell, J.A., Christoffersen, P., Young, D.A., Blankenship, D.D., Greenbaum, J.S., Benham, T., Bamber, J. and Siegert, M.J. Greenland subglacial lakes detected by radar. Geophysical Research Letters, 40, 6154-6159, doi.10.1002/2013gl058383, 2013.

Palmer, S., McMillan, M. and Morlighem, M. Subglacial lake drainage detected beneath the Greenland ice sheet. Nature communications, 6, 8408, doi.10.1038/ncomms9408, 2015

Selmes, N., Murray, T. and James, T.D. Fast draining lakes on the Greenland Ice Sheet. Geophysical Research Letters, 38, doi.10.1029/2011gl047872, 2011.

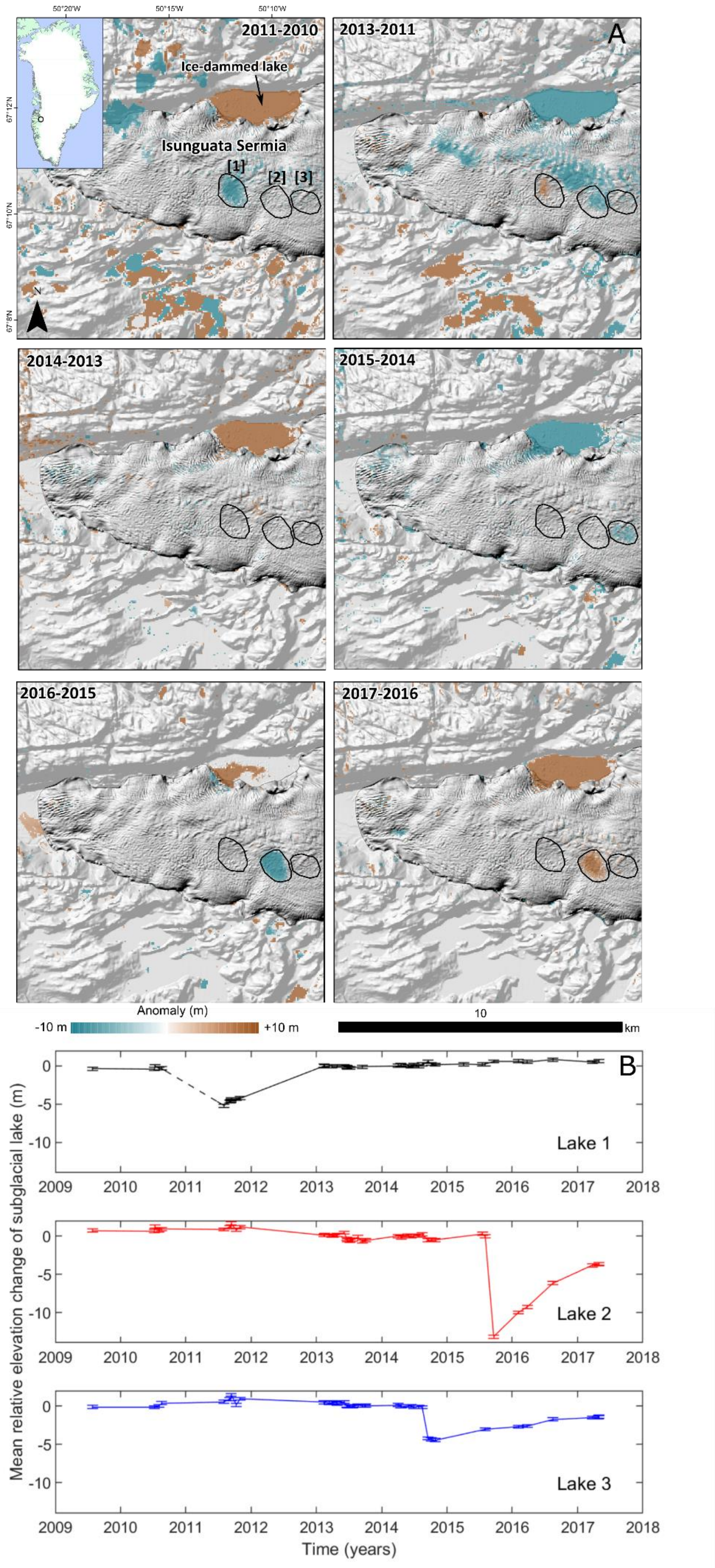
Scambos, T.A., Berthier, E. and Shuman, C.A. The triggering of subglacial lake drainage during rapid glacier drawdown: Crane Glacier, Antarctic Peninsula. Annals of Glaciology, 52, 74-82, doi.10.3189/172756411799096204, 2011.

Siegfried, M.R. and Fricker, H.A. Thirteen years of subglacial lake activity in Antarctica from multi-mission satellite altimetry. Annals of Glaciology, 59, 42-55, doi.10.1017/aog.2017.36, 2018.

Tuckett, P.A., Ely, J.C., Sole, A.J., Livingstone, S.J., Davison, B.J., Melchior van Wessem, J., Howard, J. Large and rapid accelerations of Antarctic Peninsula outlet glaciers driven by surface melt. Nature Communications, 10: 4311, doi. 10.1038/s41467-019-12039-2, 2019.

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

Zhao, H., Chen, F., and Zhang, M. A systematic extraction approach for mapping glacial lakes in high mountain regions of Asia. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 11(8), 2788-2799. doi: 10.1109/JSTARS.2018.2846551, 2018.



50°20'W
50°15'W
50°10'W
67°12'N
67°10'N
67°8'N
2011-2010
Ice-dammed lake
Isunguata Sermia
[1]
[2]
[3]
2013-2011
A
2014-2013
2015-2014
2016-2015
2017-2016
Anomaly (m)
-10 m
+10 m
10
km
B
Mean relative elevation change of subglacial lake (m)
Lake 1
Lake 2
Lake 3
Time (years)

Figure 1: Ice surface elevation change. A. Yearly anomaly plots of ice-surface elevation change from 2010-2017 ~~based on~~ annually averaged ~~the timestamped ArcticDEM~~DSMs~~. Yearly DSMs are~~, calculated as the median of all available timestamped ArcticDEM tiles in that particular year down-sampled to 50 m. Black outlines and numbers (1-3) reference the location of three identified subglacial lakes. Elevation anomalies have also picked out the filling and drainage of an ice-dammed lake at the northern margin of Isunguata Sermia. Anomalies <5 m have been removed. The background image is an ArcticDEM DSM hillshade from 2017. Note there were no data available in 2012. B. Timeseries of mean relative elevation change from 2009-2017 for the three subglacial lakes identified in Figure 1 (lake numbers are the same). Relative elevation change is calculated by taking the mean subglacial lake elevation anomaly from the mean elevation of a 500 m buffer surrounding the lake. Error bars represent the internal accuracy of the ArcticDEM (±0.2 m). Observation of the Landsat archive indicates that surface meltwater does not pond in the collapse basins following lake drainage, likely because of the heavily crevassed ice surface. Calculated mean relative elevation change is therefore a measure of ice-surface elevation change alone. Note, that the 2011 elevation anomaly is poorly constrained (dashed black line) and could therefore have been larger than suggested by the line.

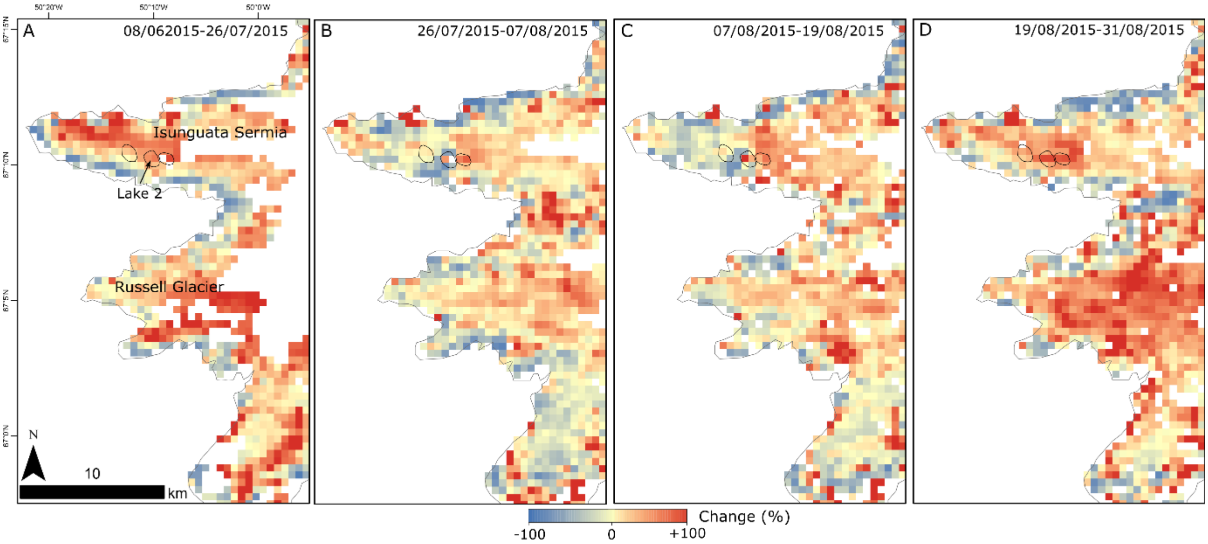


Figure 2: Ice dynamic response to subglacial lake drainage. Ice velocity anomalies (% change) are relative to Winter 2015 (3rd January – 5th April). Note in B and C the abrupt shift from positive to negative anomalies at the location of and downstream of Subglacial Lake 2, with the negative anomalies indicating a return to roughly winter average values during the period that it drained (between 26th July and 19th August). This coincided with a regional slowdown in ice flow. This was followed by recovery to pre-drainage ice flow velocities by 19th to 31stAugust (D). The strong positive anomaly over the lake in C is caused by ice flow convergence into the depression, leading to localised '~~backwards~~up-glacier' flow against the regional easterly flow direction.

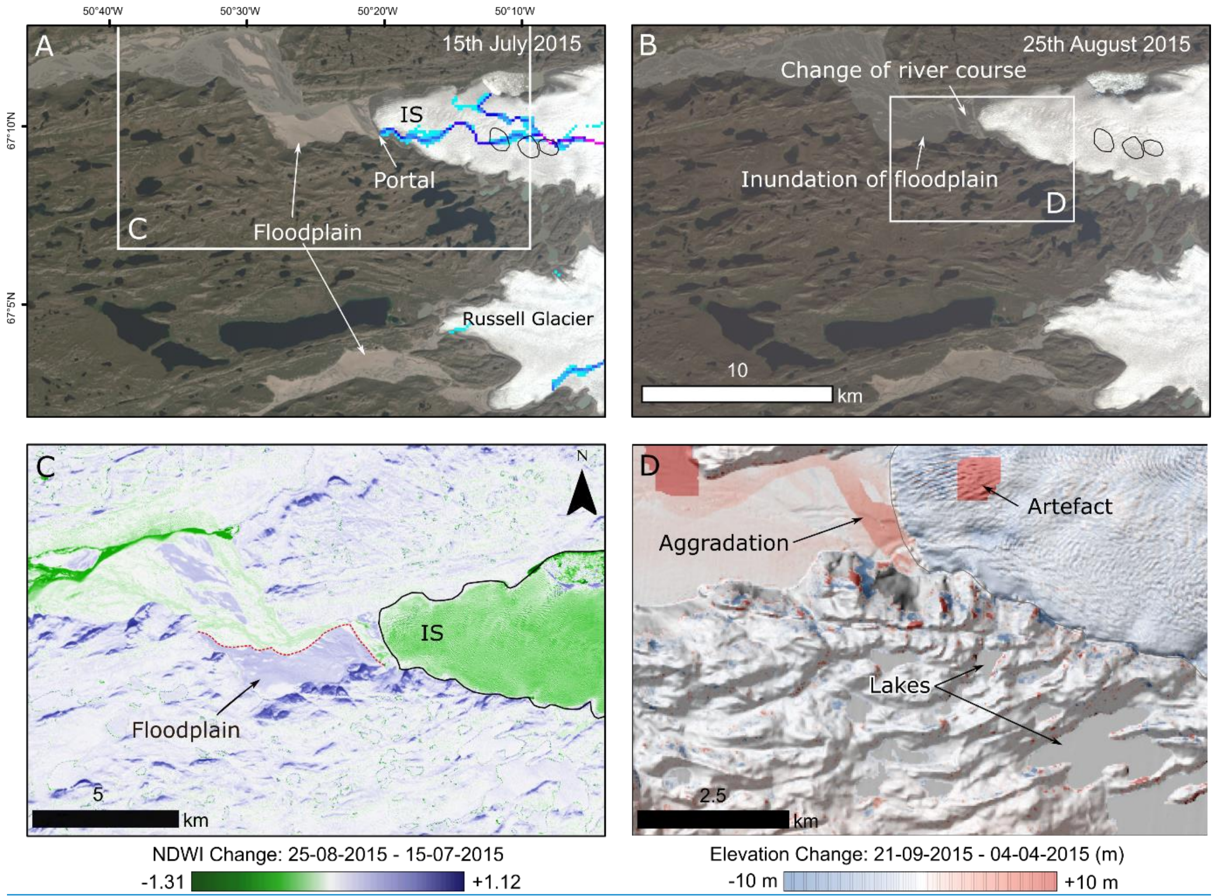


Figure 3: Proglacial signature of the 2015 subglacial lake drainage event. A and B are True Colour Landsat 8 images of Isunguata Sermia and the foreland before (15th July 2015) and after (25th August 2015) the drainage event. The blue/purple coloured line in A represents the predicted subglacial drainage routeway. IS = Isunguata Sermia. Note how the proglacial river changes its course and the whole floodplain becomes inundated resulting in a change of colour. This is not replicated at Leverett-Russell Glacier, ruling out a common external forcing (e.g. heavy rainfall). C is change in Normalised Difference Water Index (NDWI) between 7th July and 25th August 2015. Note the wetting (positive values) of the previous dry regions (bars and floodplain). D reveals the change in elevation from two ArcticDEM DSM tiles (co-registered to remove systematic vertical offsets using the mean vertical difference between common bedrock surfaces). There is up to 8 m of aggradation close to the glacier portal which declines with distance from the outlet. The dotted line demarcates the mapped wetted area in panel A.