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Brief Communication: Outburst floods triggered by periodic drainage of subglacial lakes, Isunguata Sermia, West Greenland

Stephen J. Livingstone[1], Andrew J. Sole[1], Robert D. Storrar[2], Devin Harrison[3], Neil Ross[3], Jade Bowling[4]

[1]Department of Geography, University of Sheffield, Sheffield, UK

[2]Department of the Natural and Built Environment, Sheffield Hallam University, UK

[3]School of Geography, Politics and Sociology, Newcastle University, Newcastle upon Tyne, UK

[4]Lancaster Environment Centre, Lancaster University, Lancaster, UK

Correspondence to: Stephen J. Livingstone (s.j.livingstone@sheffield.ac.uk)

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 August 2014 and August 2015, and all three characterised by 2-3-year refill periods. The 2015 drainage flooded the foreland aggrading 8 m of the proglacial channel, confirming the ice-surface elevation anomalies as subglacial water bodies and demonstrating how subglacial lake drainages 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 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 hydraulic gradients and lower 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 and wider influence on the subglacial hydrological system and ice flow is poorly understood. Although expected to be a less significant component of the hydrological system compared with Antarctica (e.g. Siegfried & Fricker, 2018) due to steeper hydraulic gradients, dominance of surface 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 (ELA) but away from the interior, hydrologically active lakes near the ELA recharged by surface meltwater, and small seasonally active lakes below the ELA which form during winter and drain during the melt season (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 ELA (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 associated increase in hydrological connectivity each melt season. 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 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 ArcticDEM DSMs. This revealed three distinctive quasi-circular regions, 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. 1). Timeseries of relative elevation change for each anomaly were calculated from the DSMs by subtracting the mean ice-surface elevation of the anomaly from the mean elevation of a 500 m buffer around it (Fig. 2). 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, 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, about 1 km further up ice, 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 has since risen 9 m between 2015 and 2017. Anomaly 3, which is just up-ice from anomaly 2 and ~9 km from the terminus, 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 such as crescentic crevasses are not apparent in any of the depressions.

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 NDWI 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 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 anomalies on Isunguata Sermia characterised by localised ice-surface elevation changes, which we interpret as subglacial lake drainage and filling (Fig. 1). 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 m thick (Lindbäck et al., 2014), warm-based ice on a reverse gradient 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

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minima in the locations where we identify lakes, this may be a result of the limited and relatively poor-quality airborne radar ice-thickness measurements across the thin, near-marginal area of Isunguata Sermia.

The three subglacial lakes each underwent one drainage event 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), 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 by available DSM and satellite imagery in this study.

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}), while the smallest drainage event (Lake 3) is filling at the slowest rate (~1 m uplift yr^{-1}). The lakes are at the lower end of the ablation zone and therefore 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 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). This suggests that the lakes are not hydraulically well connected, consistent with subglacial hydraulic modelling indicating 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.

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 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.

Although the presence or absence of sediments in these lakes 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 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 DSM 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-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 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 aggradation of sediment in the proglacial outwash plain close to the terminus. 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.*

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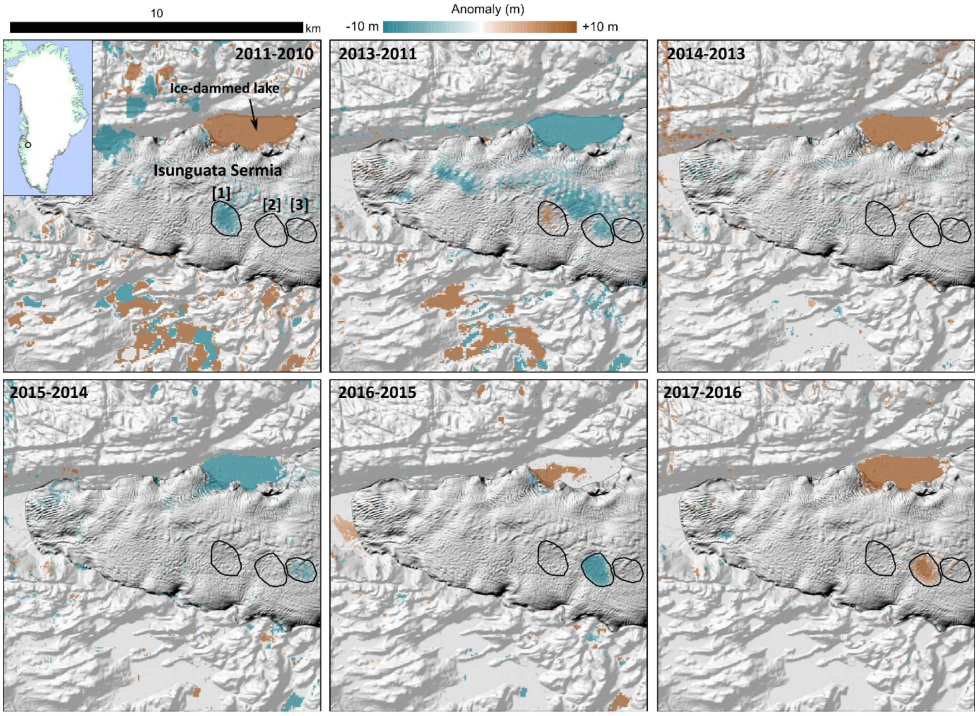

230 **Figure 1:** Yearly anomaly plots of ice-surface elevation change from 2010-2017 based on the timestamped ArcticDEM. Black outlines and numbers (1-3) reference the location of three identified subglacial lakes. Anomalies <5 m have been removed. The background image is an ArcticDEM DSM hillshade from 2017. Note there were no data available in 2012.

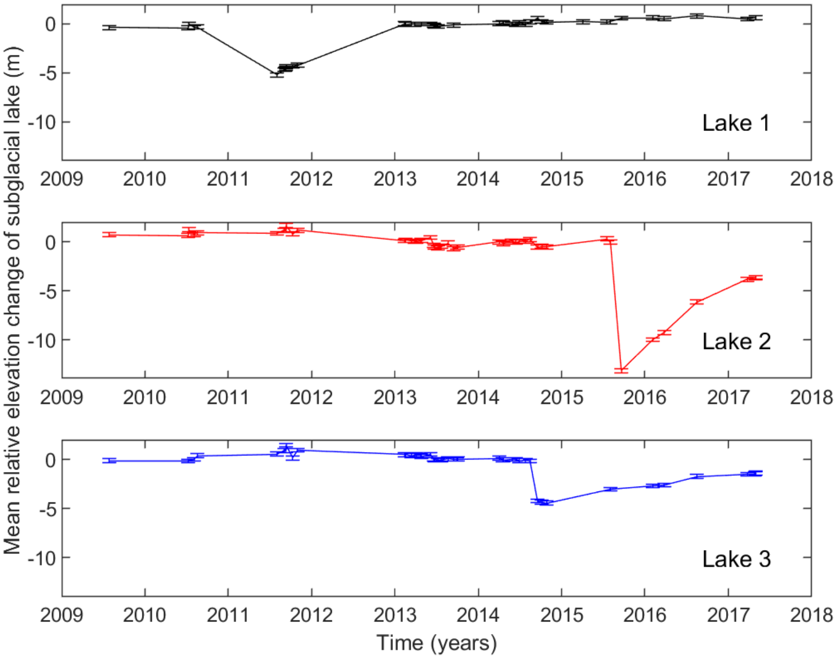

Figure 2: Timeseries of mean relative elevation change from 2009-2017 for the three subglacial lakes identified 235 in Figure 1 (lake numbers are the same). Relative elevation change is calculated by taking the mean subglacial lake elevation anomaly from the mean elevation of a 500 m buffer surrounding 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.

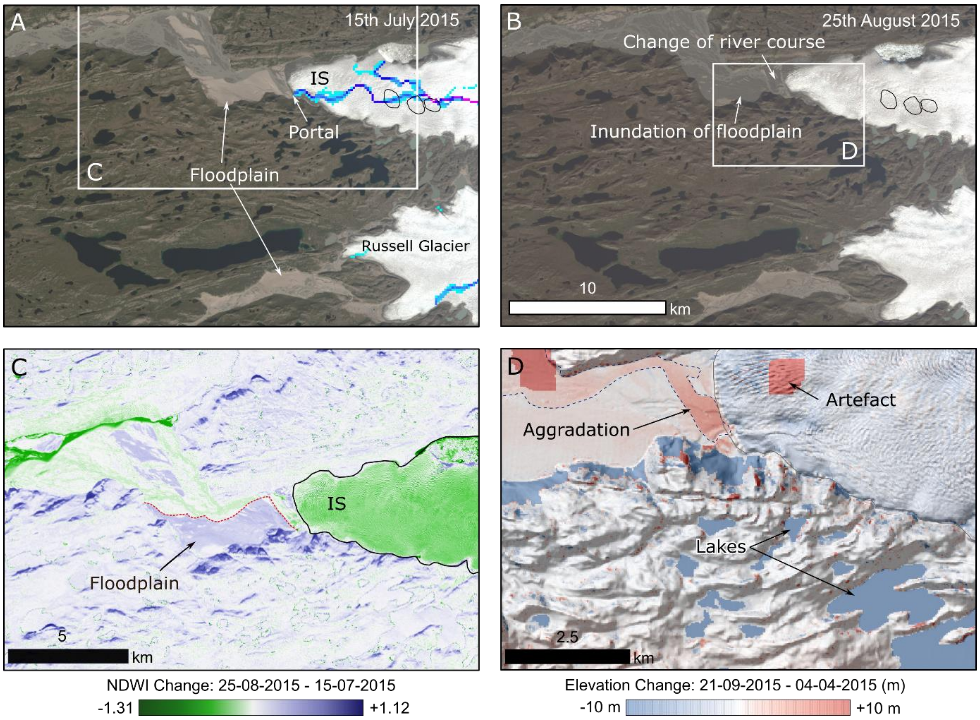

Figure 3: Proglacial signature of the 2015 subglacial lake drainage event. A and B are True Colour Landsat 8 images of Isunguata Sermia and the foreland before (15th July 2015) and after (25th August 2015) the drainage event. The blue/purple coloured line in A represents the predicted subglacial drainage 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.