

1 Wintertime storage of water in buried supraglacial lakes 2 across the Greenland Ice Sheet

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17

18 **Abstract**

19 Increased surface melt over the Greenland Ice Sheet (GrIS) is now estimated to account for half
20 or more of the ice sheet's total mass loss. Here, we show that some meltwater is stored, over
21 winter, in buried supraglacial lakes. We use airborne radar from Operation IceBridge between
22 2009 and 2012 to detect buried supraglacial lakes, and find that they were distributed
23 extensively around the GrIS margin through that period. Buried supraglacial lakes can persist
24 through multiple winters and are, on average, $\sim 1.9 + 0.2$ m below the surface. Most buried
25 supraglacial lakes exist with no surface expression of their occurrence in visible imagery. The
26 few buried supraglacial lakes that do exhibit surface expression have a unique visible signature
27 associated with a darker blue color where subsurface water is located. The volume of retained
28 water in the buried supraglacial lakes is likely insignificant compared to the total mass loss

1 from the GrIS, but the water may have important implications locally for the development of
2 the englacial hydrologic system and ice temperatures. Buried supraglacial lakes represent a
3 small but year-round source of meltwater in the GrIS hydrologic system.

4 **1 Introduction**

5 Annual mass loss from the Greenland Ice Sheet (GrIS) has increased substantially, quadrupling
6 in the last two decades (Shepherd et al., 2012). Warming Arctic temperatures (e.g. Comiso,
7 2003; Hall et al., 2013) and a decrease in ice-sheet albedo (e.g. Angelen et al., 2014; Box et al.,
8 2012; Tedesco et al., 2011) have increased surface melt which now accounts for half or more
9 of the total mass loss, outpacing ice dynamics in recent years (van den Broeke et al., 2009;
10 Enderlin et al., 2014; Khan et al., 2014). Even with the increasing GrIS surface melt,
11 highlighted by a record melt and runoff event in 2012 (Nghiem et al., 2012; Hall et al., 2013;
12 Hanna et al., 2014), the meltwater mass fluxing through and retained within the supra-, en- and
13 subglacial hydrologic networks is relatively unquantified making ice-sheet wide water budgets
14 difficult to balance (Rennermalm et al., 2013; Forster et al., 2013).

15 While regional climate models agree relatively well on precipitation amounts across the GrIS
16 (~20% variance), they still have large discrepancies in melt production, refreezing, and runoff
17 (from 38-83% variance, Vernon et al., 2013). This is due not only to differences in the models,
18 but also insufficient field observations for quantifying meltwater retention, transport and runoff
19 (Rennermalm et al., 2013). Field observations have only recently discovered large amounts of
20 water retention (Forster et al., 2013; Koenig et al., 2014) and latent heating from refreezing
21 (Harper et al., 2012; Humphreys et al., 2012) on the perimeter of the GrIS, and model
22 improvements to account for the water retention are still in their initial stages (Kuipers Munneke
23 et al., 2014). These recent discoveries punctuate that more observations are needed of the GrIS
24 hydrologic system, especially at and just below the ice-sheet surface, to fully understand
25 meltwater transport and eventual runoff.

26 This paper presents an initial study and mapping of over-winter surface-melt retention in buried
27 supraglacial lakes (Figure 1) within the GrIS. We define a “buried supraglacial lake,” hereafter
28 for brevity a “buried lake,” as water retained through a winter season at shallow depths within
29 the ice sheet that originally formed, during a previous melt season, as a (subaerial) supraglacial
30 lake. Thus, a buried lake is a specific type of supraglacial lake that spans the boundary between
31 the supra- and englacial hydrologic system, exists under lake ice and snow/firn layers in some

1 seasons, and can re-emerge as a supraglacial lake in others. Near-surface, high-resolution radar
2 data, collected during the Arctic spring campaigns of Operation IceBridge (OIB), clearly show
3 water retention in buried lakes through the winter season. In this paper, we use OIB radar data
4 to map the extent and depth of buried lakes across the GrIS. This effort is the first to
5 characterize wintertime meltwater storage in buried lakes over the GrIS and provide an
6 assessment of its impact on the hydrologic system.

7 **2 Background**

8 Several researchers have studied supraglacial lakes that are easily distinguishable by visible and
9 radar satellites when they form seasonally in the ablation and percolation zones across the GrIS
10 (Echelmeyer et al., 1991; Box and Ski, 2007; McMillan et al., 2007; Sneed and Hamilton,
11 2007; Sundal et al., 2009; Lampkin, 2011; Selmes et al., 2011; Tedesco and Steiner, 2011;
12 Howat et al., 2013). Supraglacial lakes form in local topographic lows formed by bedrock
13 depressions, which are not advected by the ice, and often reform in the same locations
14 (Echelmeyer et al., 1991; Box and Ski, 2007; Selmes et al., 2011). Das et al., (2008) observed
15 the rapid (< 2 hours) drainage of a supraglacial lake through fractures, delivering surface
16 meltwater to the bedrock-ice interface causing local uplift and glacier acceleration. Further
17 studies have expanded the links between supraglacial lakes, and water-filled crevasses, to the
18 en- and subglacial hydrologic system, clearly showing that surface meltwater can be routed to
19 the bed of the GrIS affecting ice dynamics. (Zwally et al., 2002; Joughin et al., 2008; Catania
20 et al., 2008; Bartholomew et al., 2011; Palmer et al., 2011; Sundal et al., 2011; Hoffman et al.,
21 2011; Tedstone et al., 2013).

22 Most studies assume that supraglacial lakes either drain during the summer, through the
23 supraglacial or englacial hydrologic system, or refreeze during the winter. Few studies have
24 investigated the behavior of supraglacial lakes during the winter season. Ohmura et al. (1991)
25 attributed the presence of ice plates they observed on the snow surface at West Lake near Swiss
26 Camp, Western Greenland, to the persistence of water late into winter, which formed a frozen
27 ice layer and then drained. Additionally, they detected a deep lake (~10 m) to the east of Swiss
28 Camp that likely remained water-filled through the winter, and developed lake ice up to 1.5 m
29 thick, before it drained in spring or early summer. Rennermalm et al. (2013) also reported
30 evidence of water retention somewhere within the GrIS hydrologic system, from peaks in
31 stream discharge that occur in the fall and spring, up to 6 months after surface melt. The buried

1 lakes that we identify and map, using radar data, in this paper represent a hitherto understudied
2 proportion of wintertime storage of water.

3

4 **3 Data**

5 **3.1 Radar data**

6 To identify and map subsurface water we use data acquired by the CReSIS ultra-wideband
7 Snow Radar during OIB Arctic Campaigns from 2009 through 2012 (Leuschen, 2014). The
8 radar operates over the frequency range from ~2 to 6.5 GHz where water has a high absorption
9 coefficient resulting in the attenuation of radar waves and a strong reflection of the wave at the
10 ice-water interface due to the large difference between the dielectric constant of ice and water
11 (Figure 2) (Ulaby et al., 1981). The Snow Radar uses a Frequency Modulated Continuous
12 Wave (FMCW) design which provides a vertical resolution of ~4 cm in snow/firn to a depth of
13 tens of meters. Radar backscatter along a transect is often displayed as an echogram (Figure 2)
14 which provides a visual image of the subsurface returns. For additional details on the Snow
15 Radar performance see Panzer et al. (2013) and Rodriguez-Morales et al. (2014).

16 **3.2 Visible and thermal imagery**

17 Visible imagery from several imaging platforms is used to support the analysis of buried lakes.
18 OIB Digital Mapping System (DMS) imagery, acquired coincident with Snow Radar data, is
19 used to examine surface features indicative of the presence of subsurface water. Cloud-free
20 Moderate Resolution Imaging Spectroradiometer (MODIS) Rapid Response Arctic Subset true
21 color imagery (250 m resolution) is used to determine whether (subaerial) supraglacial lakes
22 formed previously at the locations of the radar-located buried lakes. Additionally, at a sample
23 lake site, MODIS Land Surface Temperature (LST) data are used to corroborate melt onset and
24 surface thermal conditions and Landsat Enhanced Thematic Mapper (ETM+) panchromatic
25 imagery, with a resolution of ~15 m, is used to evaluate the summertime evolution of the lake.

26 DMS acquires imagery in the visible part of the electromagnetic spectrum at a nominal
27 resolution of 10 cm (at 1500 feet AGL, the nominal OIB flight altitude). DMS collects data
28 over three multispectral and panchromatic bands using a 21 megapixel Canon EOS 5D Mark II
29 digital camera. Data are orthorectified and corrected for camera orientation using the Applanix
30 POS/AV navigation system. For additional details see Dominguez (2014).

1 MODIS LST (MOD11A1, version 5.1) swath data at 1 km resolution are accurate to within \pm
2 1°C (Wan et al., 2002) for snow and ice surface temperatures between -15 to 0°C (Hall et al.,
3 2008). MODIS LSTs acquired over the GrIS, however, can be ~ 1 to 3 degrees colder than the
4 actual surface temperatures (Hall et al. 2013; Koenig and Hall, 2010).

5 **4 Methods**

6 **4.1 Detection of buried lakes from airborne radar**

7 All Snow Radar echograms over the GrIS from 2009-2012 (e.g. Figure 2B) were inspected
8 manually for subsurface attenuations of the radar backscatter, which could be attributed to a
9 buried lake. To ensure the radar response was associated with englacial water, and not some
10 other density or dielectric change, all 2011 detections from Snow Radar data were compared to
11 either the Accumulation Radar (~ 600 - 900 MHz) or MCoRDS Radar (~ 140 - 260 MHz), flown
12 simultaneously with the Snow Radar onboard the OIB aircraft (Figure 2). Water attenuates
13 across radar frequencies. If at least one additional radar showed attenuated backscatter the
14 detection remained in the dataset. Additionally, all detections were compared to summertime
15 cloud-free MODIS imagery to evaluate whether a subaerial supraglacial lake formed at a given
16 radar-located buried lake's location during a preceding melt season (Figure 3). The 2011 Snow
17 Radar data were chosen for this initial analysis because it was the first year in which the OIB
18 radar operators discovered the unique return over supraglacial lake regions.

19 The analysis of the 2011 Snow Radar data led to two characteristic echogram patterns for
20 englacial water retention: buried lakes (e.g. Figure 2B) and water-filled crevasse fields. The
21 water-filled crevasse fields were not included in the analysis presented here because, though it
22 is likely they contain englacial water, it is also possible that the crevasses themselves, or hoar
23 crystals formed within them, scatter the radar signal in a manner that cannot be distinguished
24 from scatter caused directly by reflections off subsurface water. Additional field verification,
25 beyond the scope of this study, would be needed to interpret radar backscatter over crevassed
26 regions.

27 The detected buried lakes from 2011 were mapped using approximately each lake's center
28 point, and were compared to high resolution (cm-scale) DMS imagery of the GrIS surface
29 coincident with the radar collection (Figure 4) (Dominguez, 2014). DMS imagery was used to
30 characterize visually the surface roughness, detect crevasses and look for any distinct surface
31 expression of the buried lakes.

1 Finally, to construct time series of buried lakes, the characteristic buried-lake radar returns
2 (Figure 2B), determined as we have outlined from the 2011 data, was used to map buried lakes
3 in OIB Snow Radar data from the 2009, 2010 and 2012. Buried lakes that formed within 1 km
4 of each other from year-to-year were considered the same feature. This is justified considering
5 Selmes et al. (2011), who reported a median area of 0.56 km² and a mean area of 0.80 km² for
6 lakes across the GrIS. Because the buried lakes are mapped using an approximate center point,
7 a 1 km radius is a reasonable distance to be considered the same feature along the changing
8 OIB flight lines.

9 **4.2 Depth retrieval of the water surface**

10 The 2009-2012 Snow Radar echograms of the buried lakes were digitized manually to
11 determine the depth from the snow surface to the water surface. If distinguishable in the
12 echogram, as shown in Figure 2B, both the snow/lake-ice interface and the lake-ice/water
13 interface were digitized. When a snow layer was digitized, a reasonable near-surface snow
14 density of 320 kg/m³ (Benson, 1962), was assumed to convert radar travel time to depth using
15 equations developed by Wiesmann and Matzler (1999). When a lake ice layer was digitized or
16 if only the snow surface and the water layer were digitized, the dielectric properties of ice were
17 assumed to convert radar travel time to depth (relative permittivity, $\epsilon' = 3.2$, Dowdeswell and
18 Evans, 2004). In the absence of field data providing a stratigraphic density profile, the adoption
19 of ice density values biases the depth measurements to shallower depths. Uncertainties in the
20 depth were estimated by taking the subset of radar echograms where a snow layer was detected
21 and calculating the depth with both the snow layer and ice assumptions. The average percent
22 difference defines the uncertainty at 9% (range of 2% to 24%) shallow.

23 **5 Results**

24 **5.1 Spatial and temporal distribution of buried lakes**

25 The wintertime storage of meltwater in buried lakes is extensive around the margin of the GrIS
26 (Figure 5). All buried lakes identified from 2009-2012 were below the 2000 m contour with
27 the majority detected between 1000 m and 2000 m on the west coast of the ice sheet (Figure 5).
28 Table 1 provides the number of buried lakes detected each year, the mean and standard
29 deviation of buried lake elevation, the number of buried lakes below 1000 m and the number
30 of lakes detected per 1000 km of OIB flight lines flown below 2000 m. Because OIB is an

1 airborne mission with a changing set of flight lines leading to an inconsistent spatial sampling,
2 and thus regionally biased sampling, these results must be analysed with caution and in full
3 appreciation of the characteristics of the survey campaigns. Thus, for example, while in Table
4 1 it appears that more lakes were detected in 2011 there were also more flightlines in 2011
5 below 2000 m and many of these were along the west coast.

6 Clusters of buried lakes are concentrated along the west coast of Greenland and near 79 N
7 Glacier where OIB gridded flight lines are flown repeatedly in multiple years (Figure 5). It is
8 also in these regions where we detect buried lakes that persist for multiple years (Figure 5).
9 Again, these multi-year detections must be taken in the context that they are detected in areas
10 with high concentrations of supraglacial lakes where OIB flightlines are repeated in multiple
11 years. It is very likely that other buried lakes are present through multiple winters yet were not
12 detected in more than one year due to the limited OIB spatial and repeat sampling. In total, 53
13 lakes were detected in two of the four years and 7 lakes were detected in three of the four years
14 (Figure 5). All lakes detected over three seasons are located on the OIB grid near Jakobshavn
15 Isbræ that is repeated annually.

16 **5.2 Surface expression of buried lakes and lake evolution**

17 DMS imagery rarely shows any surface expression of buried lakes. Only at five locations was
18 a unique surface expression found when the buried lake's ice covered surface was exposed.
19 Two examples are shown in Figures 4 and 6. These figures show a surface expression of the
20 darker blue ice adjacent to a region of lighter colored ice that corresponds with the transitional
21 zone from water detection (attenuation) to no water detection (penetration) in the radar
22 echograms (Figures 4 and 6). The darker blue color associated with the retained water can be
23 explained by the vibrational transitions as well as the higher density and temperature of water
24 molecules in the buried lake resulting in stronger hydrogen-oxygen bond absorption feature
25 near 600 nm (Grenfell and Perovich, 1981; Warren, 1984). The hydrogen bonds in water cause
26 a shift to lower energy, over that of ice, which can produce the darker blue color (Luck, 1980;
27 Langford et al., 2001). Unfortunately the DMS data used here cannot directly quantify the
28 spectral signature.

29 Figure 6 shows a radar echogram and DMS image of a lake detected on May 2, 2011,
30 approximately 100 km inland from the terminus of 79 N Glacier in Northern Greenland. Radar
31 backscatter clearly shows melt on the surface (Figure 6 between locations 3 and 4) likely driven

1 by radiative heating. The rest of the frozen lake (Figure 6 between locations 1 and 2) and buried
2 lake (Figure 6 between locations 2 and 3) has persistent accumulated snow insulating the ice
3 underneath and preventing the onset of melt. Landsat ETM+ images during the peak of the
4 2011 melt season (Figure 7) demonstrate that lake extent corresponds to regions in the radar
5 echogram where melt was initiated (Figure 7 between locations 3 to 4) and that the region of
6 the buried lake (Figure 7 between locations 2 and 3) maintained a floating ice cap into the melt
7 season. MODIS LST data, the only temperature data available for this site and date, show a
8 peak temperature of -10.7 C during the 1640 GMT overpass. The Snow Radar and DMS data
9 were acquired at 1609 GMT when OIB overflew the site very close to the peak temperature and
10 solar input. The MODIS LST, however, is rather low for the production of water observed in
11 the echogram over this site which is probably the result of the relatively coarse spatial resolution
12 (1 km) of MODIS such that the very small patch of surface melt, or melt from a few cm below
13 the surface, at the edge of the lake, was not resolved. The evolution of this particular buried
14 lake into the melt season is concentrated melting around the perimeter of the lake while the
15 deeper center of the lake remains insulated with a floating cap, likely increasing the probability
16 it will persist throughout the next winter season barring some supra- or englacial drainage event.
17 These data also indicate that the early onset of melt is spatially heterogeneous, primarily
18 occurring at locations where darker ice is exposed, and that some of the first melt of the season
19 is associated with exposed buried lakes.

20 **5.3 Depth distribution of buried lakes**

21 Figure 8 shows a histogram of the digitized water layer depths from every radar return over a
22 buried lake. The average depth to the retained water during the April and May OIB flights from
23 2009 to 2012 is 1.88 ± 0.16 m with a total range of 0.05 ± 0.01 m to 9.43 ± 0.85 m and a standard
24 deviation of 1.30 m. There is not a distinctive pattern in buried lake depths along the margins
25 of the GrIS. 38% of radar returns delineated a snow layer above the lake ice with an average
26 snow layer thickness over the buried lakes of 0.65 m (range of 0.15 m to 2.93 m) and an average
27 ice layer thickness below the snow of 1.40 m (range of 0.4 m to 4.58 m). Uncertainties
28 associated with estimates of density stratigraphy across the GrIS, which is used to convert radar
29 travel time to depth, likely cause a shallow bias in these depth measurements of on average 9%
30 and up to 24%.

31

1 **6 Discussion**

2 **6.1 Buried lakes and surface mass budget**

3 Though the water stored in buried lakes is spatially extensive, it represents only a very small
4 amount of mass likely of little consequence to mass loss projections for Greenland. Assuming
5 all the buried lakes detected in 2011, the year with the maximum number of lakes, were the size
6 of the mean supraglacial lake detected by Selmes et al. (2011), with a large water depth of 10
7 m, the volume of water retained in the lakes would amount to ~1.5 Gt of water over an area of
8 ~ 140 km². For comparison it is estimated that the firm aquifer covering ~70,000 km² of
9 southeast Greenland holds ~140 Gt of water (Forster et al., 2013; Koenig et al., 2014) while
10 recent models put GrIS runoff at between 100 and 300 Gt annually (Vernon et al., 2013). The
11 importance of buried lakes does not, therefore, lie so much in mass-loss contributions; rather
12 the spatial distribution of the retained water is locally important for the development of the
13 hydrologic system and ice temperatures.

14 **6.2 Lake evolution and implications for the hydrologic cycle**

15 The buried lakes identified and mapped in this study represent a newly documented class, or
16 subset, of supraglacial lake. We emplace their formation with the following conceptual model.
17 Once formed, a supraglacial lake can 1) drain through the englacial or supraglacial hydrologic
18 system at some time throughout the year, most often during the melt season 2) refreeze
19 completely during the winter season or 3) partially freeze during the winter season, form lake
20 ice, and retain water at depth, becoming a buried lake. Buried lakes can resurface in the
21 following melt season or remain buried for multiple seasons before re-emerging at the surface.
22 As shown in Figure 7, many of the re-emerging lakes have a characteristic crescent or toroid
23 shape and maintain a floating cap of ice into the melt season. The formation of buried lakes on
24 the GrIS follows the natural wintertime evolution of lake-ice formation observed over Arctic
25 lakes on land, with similar ice thicknesses ranging between 1 and 2 m (e.g. Surdu et al., 2014).
26 GrIS buried-lake formation also parallels meltpond refreezing on sea ice, wherein trapped
27 ponds are created and persist until complete refreezing is accomplished (Flocco et al., 2015).
28 Satellite images of the summertime extent of the supraglacial lakes paired with the subsurface
29 radar data shown here suggest that at elevations above 1000 m all three types of supraglacial
30 lakes coexist in the same region, all experiencing the same meteorological forcings. How and

1 which supraglacial lakes become buried lakes, is still unanswered but a discussion of possible
2 formation mechanisms and evolution is warranted.

3 The initial formation of a buried lake is likely dependent on two factors 1) the degree of
4 connectivity of the lake to the supra- and englacial hydrologic system responsible for the
5 transport of water out of the lake and 2) the water volume stored in the lake at the end of the
6 melt season, particularly the depth, which determines the energy balance required to freeze.
7 Without further research and modeling it is unclear if either connectivity or depth is the more
8 predominate factor in predicting buried-lake formation but, with increasing melt extent across
9 the GrIS (Mote et al, 2007; Nghiem et al., 2012; Hall et al., 2013), both may increase over time.

10 When a buried lake reaches the surface, and thaws, it will initially contain a larger amount of
11 water in the lake basin than a neighboring drained basin at the start of the melt season. As the
12 season progresses less meltwater will be needed to fill the already partially-filled basin. A more
13 efficient filling of the lake basin would lead to more efficient overtopping and surface overflow,
14 eventually leading to the development of supraglacial channels. Buried lakes tend to be
15 prevalent at elevations coincident with the occurrence of lakes associated with more than one
16 outflow channel (Lampkin et al., 2013). It is, therefore, possible buried lakes, over time,
17 promote supraglacial channel development leading to a more connected lake basin and
18 diminishing the chances of a buried lake forming in subsequent seasons. More research is
19 needed but if this scenario is true, a buried lake may be a transient process in the development
20 of a more efficient hydrologic system.

21 The retained water in buried lakes will also warm ice locally at the surface of the ice sheet as
22 measured and modeled by Humphreys et al. (2012) and Kuipers Munneke et al. (2014). If the
23 buried-lake water infiltrates cracks at the base of the lake it is capable of delivering meltwater,
24 and its associated latent heating, deeper into the ice sheet. The resultant heating and softening
25 of the ice could affect ice-flow dynamics, especially if concentrations of buried lakes are located
26 at lateral margins of outlet glaciers. The rise in ice temperatures around conduits would also
27 make it easier to activate the conduit in the spring/summer, supporting the hypothesis that
28 buried lakes are part of the evolutionary cycle towards a more efficient drainage system.
29 Considering this mechanism, buried lakes provide a possible water source for the peaks in
30 stream discharge observed by Rennermalm et al. (2013) when no surface melt was present.
31 Buried lakes represent a mechanism to extend surface meltwater infiltration deeper into the
32 GrIS at any time during the year.

1 **7 Conclusions**

2 Buried supraglacial lakes are extensively distributed around the margins of the GrIS. A few
3 previous studies suggested that water remained in the supraglacial lakes late into the winter
4 season; however, these data are the first to confirm and map extensively the distribution of the
5 retained water. Though the water retained in buried supraglacial lakes is insignificant compared
6 to total mass loss, it has important implications for the local temperature profile, development
7 of the englacial hydrologic network and ice dynamics. This research presents a new
8 understanding of meltwater routing through and within the GrIS and emphasizes the need to
9 better understand the hydrologic pathways through which meltwater drains toward the ocean.

10 **Acknowledgements**

11 The authors thank L. Brucker and T. Neumann for their insightful discussions. This work was
12 supported by the NASA's New Investigator and Cryospheric Sciences Programs. Data
13 collection and instrument development were made possible by The University of Kansas'
14 Center for Remote Sensing of Ice Sheets (CReSIS) supported by the National Science
15 Foundation and Operation IceBridge. S.E.M supported by NASA's Earth and Space Science
16 Fellowship Program grant NNX12AN98H.

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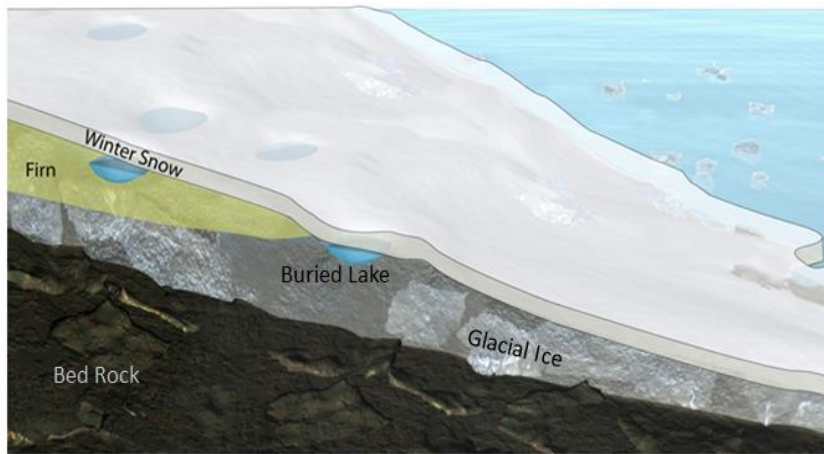
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24 Table 1. Number of buried lakes detected in each year along with the number of lakes detected
25 per km of flightlines below 2000 m , the mean elevation and standard deviation of buried lake
26 elevations and the percentage of buried lake below 1000 m in elevation. See Figure 6 for spatial
27 distribution.

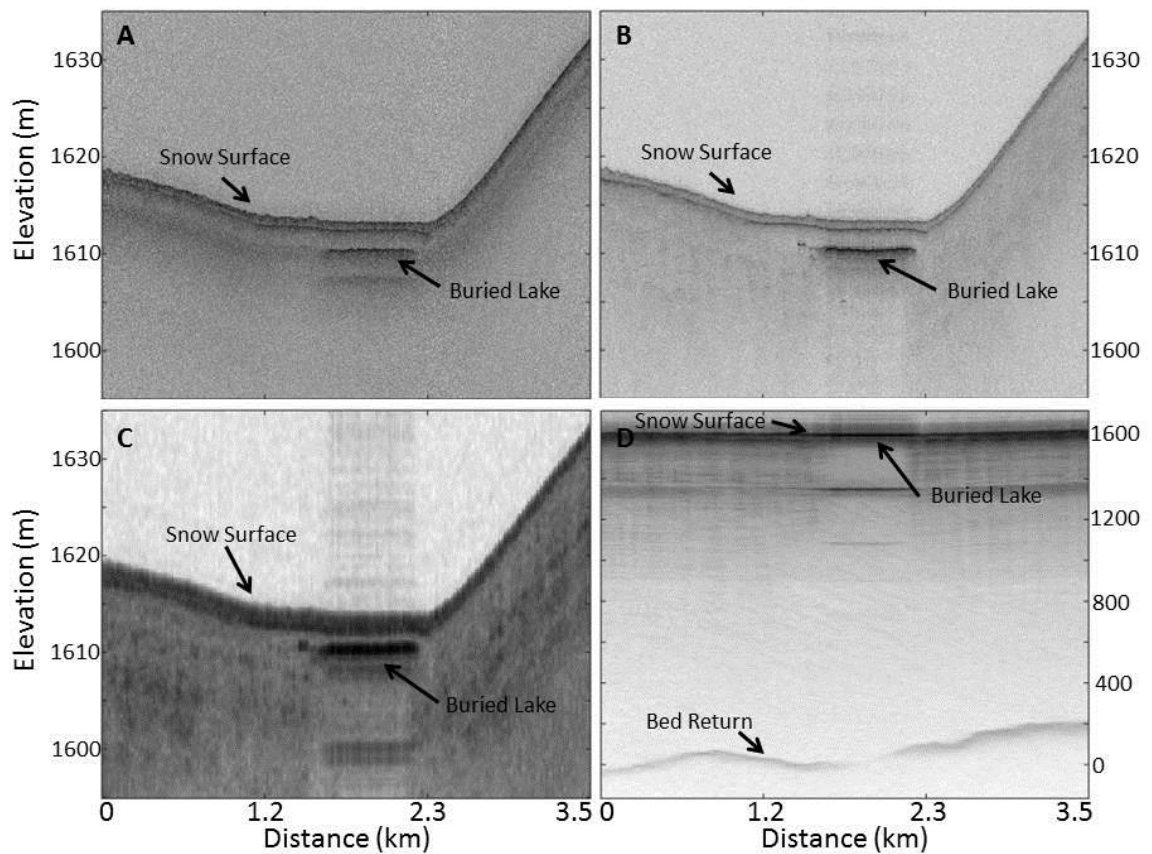
Year Collected	Buried Lakes Detected	Buried Lakes per 1000 km of	Mean Elevation (m)	Std Elevation	% of Buried Lakes
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		flightlines below 2000 m			Below 1000 m
2009	57	2.1	1268	290	14
2010	85	2.2	1180	399	33
2011	174	3.9	1415	295	10
2012	127	3.1	1371	332	15

1

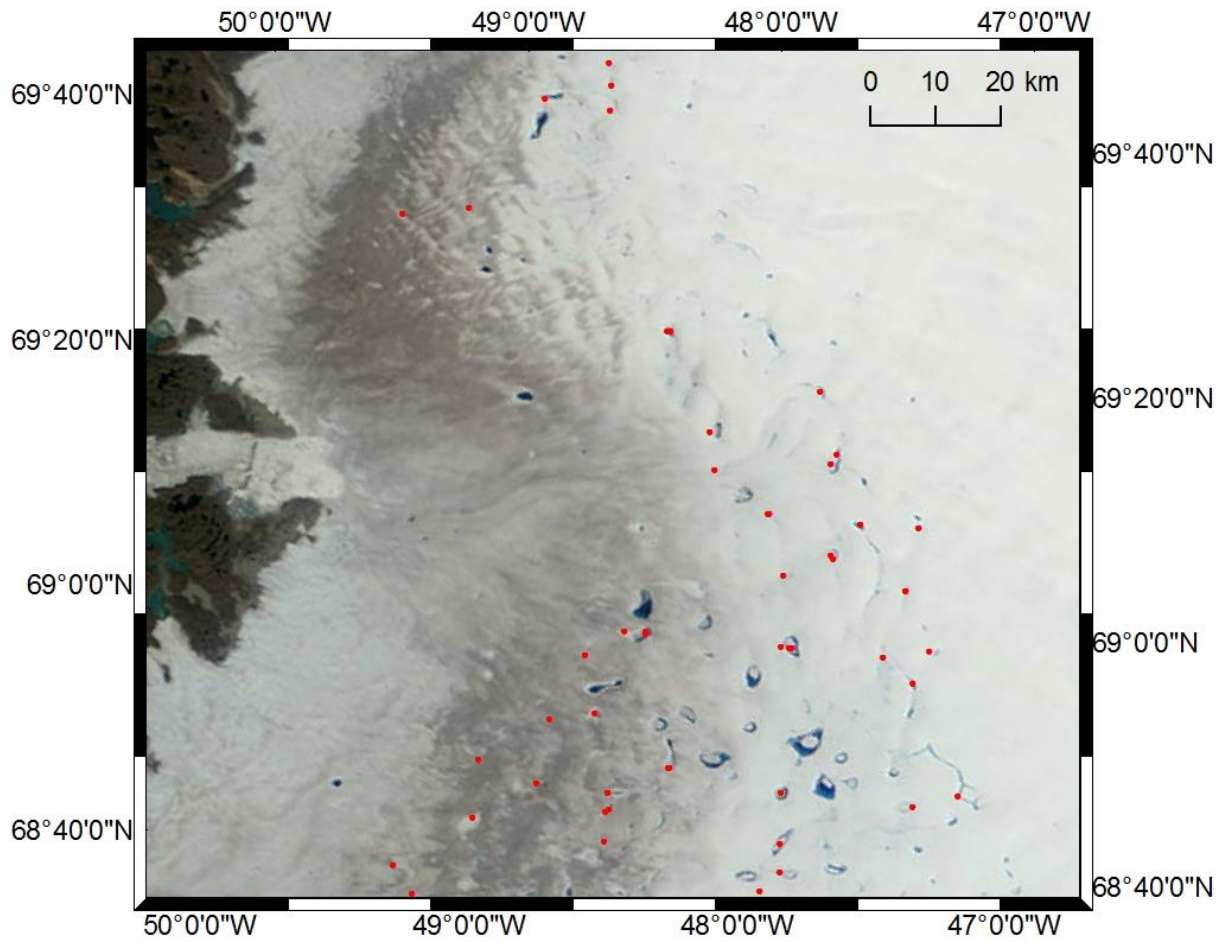


1
 2 Figure 1. An illustration showing an early spring cross sectional and perspective view of buried
 3 supraglacial lakes (blue), existing under the seasonal snow layer, still filled with water after the
 4 winter season.



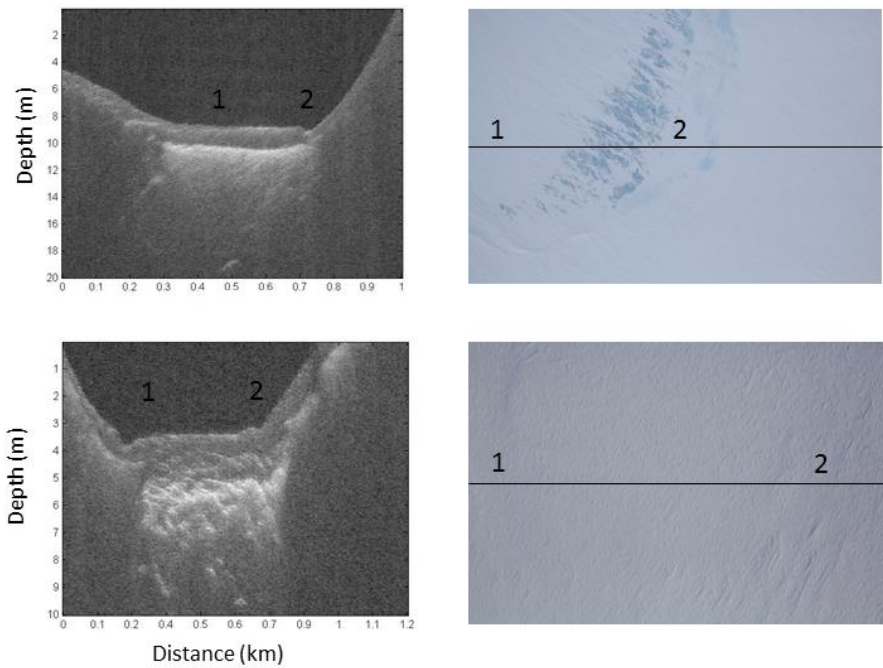
5
 6 Figure 2. Radar echograms from Western Greenland (~90 km inland of Jakobshavn's terminus)
 7 showing radar signal attenuation at multiple frequencies over a buried lake from the A) Ku-
 8 band Radar (~13-17 GHz) B) Snow Radar (~2-6.5 GHz) C) Accumulation Radar (~600-900
 9 MHz) and D) MCoRDS Radar (~140-260 MHz).

1

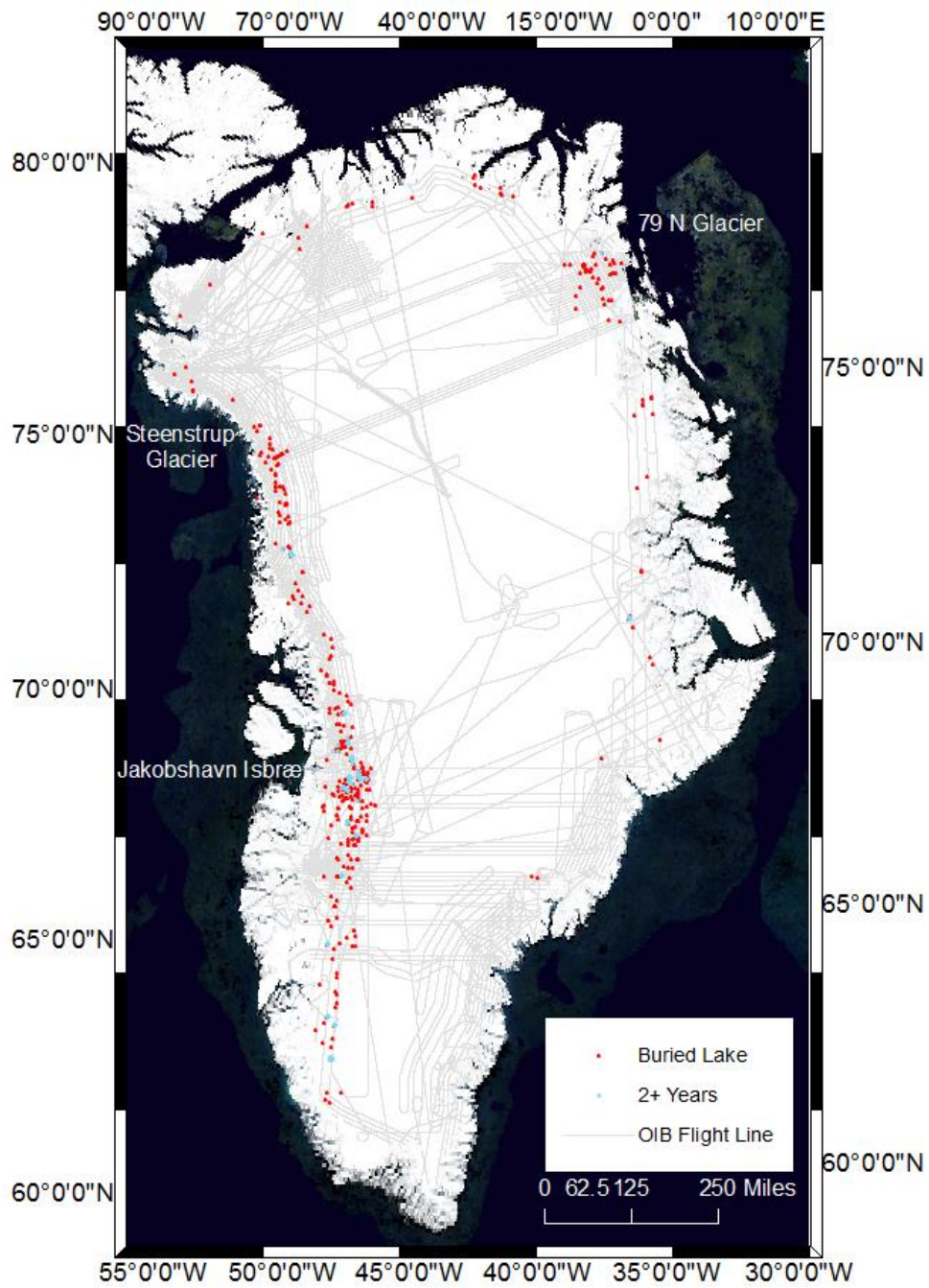


2

3 Figure 3. Radar-detected buried lake locations (red dots) overlain on MODIS Rapid Response
4 image from August 7, 2010. Note clear correspondence of radar-detected lake locations with
5 many supraglacial lakes clearly visible in this image; all the buried lakes in the dataset were
6 associated with visible supraglacial lakes captured in at least one MODIS image over the
7 analysis period.



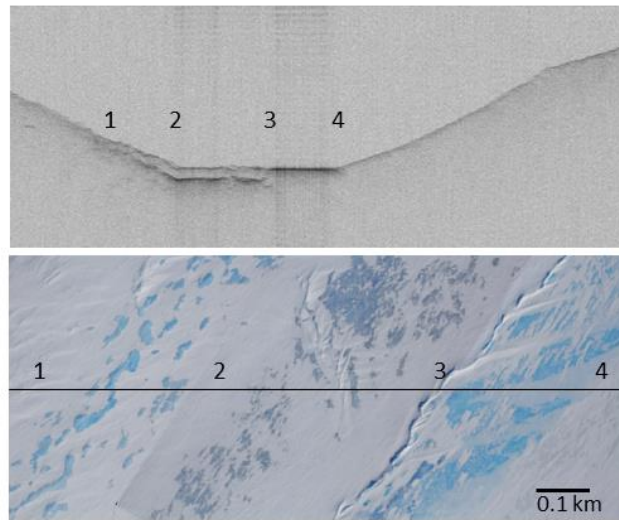
1
 2 Figure 4. Snow Radar echograms of buried lakes (left) with DMS imagery of the GrIS surface
 3 (right) from: (top) a rare buried lake in Northwest Greenland (~45 km inland from the terminus
 4 of Steenstrup Glacier) with a surface expression showing darker blue where there is buried
 5 liquid water and a more turquoise, lighter blue where the lake is frozen through and (bottom) a
 6 typical buried lake in Western Greenland (~60 km inland from the terminus of Jakobshavn
 7 Isbræ) showing surface sastrugi and no detectable lake surface expression.



1

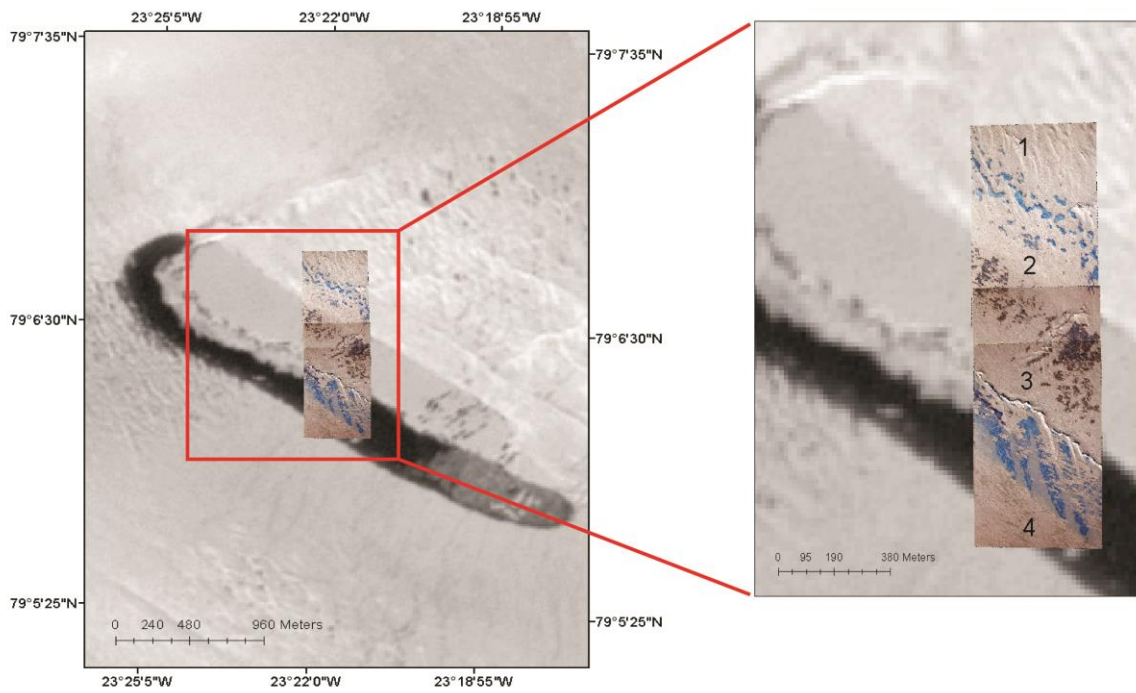
2 Figure 5. Locations of buried lakes (red circles) and multi-year buried lakes (blue circles) from
 3 2009-2012 with OIB flight lines (gray lines).

4



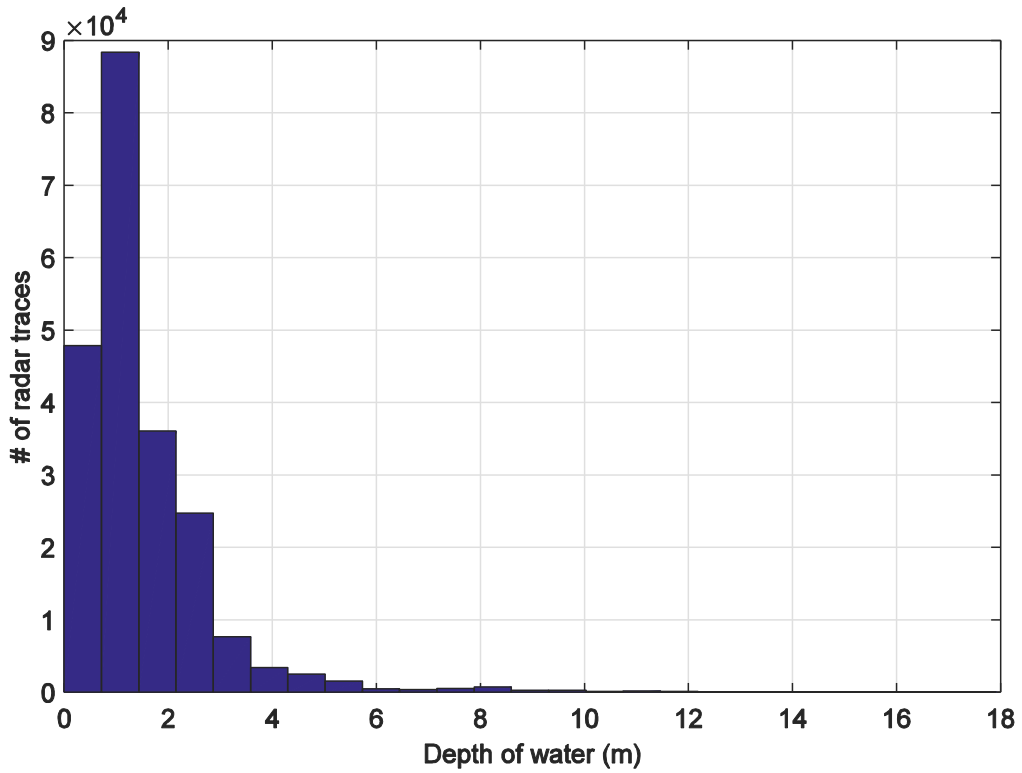
1

2 Figure 6. Snow Radar echogram (top) with DMS image of GrIS snow surface (bottom) taken
3 on May 2, 2011 for a buried lake in North Greenland (~100 km inland from the terminus 79 N
4 Glacier) showing from location 1 to 2 the turquoise blue refrozen lake, from 2 to 3 the darker
5 blue retained water, a pressure ridge at 3, and from 3 to 4 surface melt caused by radiative
6 heating at the surface of the refrozen lake edge.



1

2 Figure 7. Image comparison of May 2, 2011 DMS image for the buried lake in Figure 6
 3 superimposed over a Landsat ETM+ image acquired on July 19, 2011, well into the melt season,
 4 when a supraglacial lake had formed. Expanded images are of the same location over the section
 5 of the lake where the early season radar data showed initial surface melt. The lake extent
 6 correlates with the early season melt area (between locations 3 and 4) and the area of stored
 7 water maintained a floating ice cap into the melt season (between locations 2 and 3).



1
 2 Figure 8. Histogram showing the depth of the water surface from every radar return over a
 3 buried lake from 2009-2012. Error estimates on the depth are on average 9% shallower due to
 4 uncertainties associated with the stratigraphy of density across the GrIS, which is used to
 5 convert radar travel time to depth.