Formation and Development of Supraglacial Lakes in the Percolation zone of the Western Greenland ice sheet

Thesis

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in the Graduate School of The Ohio State University

By

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2016

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Abstract

Supraglacial lakes have been expanding into the interior of the Greenland ice sheet under a warming climate. In recent years lakes have been forming in unprecedented regions beyond the ablation zone. The expansion of lakes well into the lower accumulation zone of the ice sheet suggests a change in the condition of the firn towards promoting meltwater runoff as opposed to infiltration and storage. We explore the relationship between lake formation and firn structure in this comparative study of two lakes in western Greenland. From remote sensing observations and regional climate model meteorological output of the two lakes over a brief period (2009-2015), we find lakes form over near-surface ice lens within the firn and the development of percolation lakes is dependent upon ice dynamics.

Acknowledgements

I'm grateful to Ian for helping me create a research project, providing advice when requested to problem solve with issues in the various datasets I've used, and promoting independence in my research project and longer term research vision. I'd like to thank the other members of his research group, Santiago de la Peña, M.J. Noh, and Seongsu Jeong, for sharing their expertise during research group meetings. I'm grateful for the shared research group meetings with Mike Durand and Doug Alsdorf, which helped me and several other graduate students develop as a researcher and scientist. I'd like to thank Joachim Moortgat and Bryan Mark for their service as committee members.

While a SES graduate student, I had the rare opportunity to attend a conference in Greenland. This opportunity would not have been possible without Ian, the NSF, and travel support from the organizers of Ilulissat Climate Days and The Ohio State Office of Energy and Environment. I was also fortunate to receive funds from the Friends of Orton Hall to attend the AGU annual meeting in 2015. These conferences were fantastic environments to immerse oneself in the latest research and I found them to be inspirational.

I’d like to extend much gratitude towards various Ohio State faculty and staff members, including Byrd Polar and Geography colleagues, friends and family who have supported me in numerous varied ways during my graduate career in Columbus. You have my sincere gratitude.

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Chapter 1. Introduction

Temperatures over the Greenland ice sheet have been increasing since the 1990s (Box 2013), leading to an expansion of the percolation zone (e.g Box 2013; de la Peña et al. 2015; Van Angelen et al. 2014), where surface meltwater seasonally infiltrates the underlying snow and firn. Observations show that meltwater can penetrate deep within the firn, suggesting that the firn pore space may sequester a substantial amount of an increase in meltwater and thus act as a buffer between increasing melt, runoff and, thus, contribution to increased sea level. Based on their observations, Harper et al. (2012) estimate that the firn layer could absorb between 322 and 1289 gigatons of meltwater, or approximately the equivalent mass of 1 to 4 years of average runoff.

The mass of meltwater that the firn layer may retain, however, is determined by the depth to which melt may penetrate. The permeability of firn, and how permeability changes with changes in firn conditions, is largely unknown. Harper et al. (2012) found that deep penetration of meltwater was facilitated by cracks in thin ice layers and narrow, vertical "pipes" along which water traveled through relatively low-density firn. Several anomalously intense melt seasons have resulted in substantial densification of the near surface firn and the formation of thick ice layers, reaching over 1m thick (de la Peña et al. 2015; Mikkelsen et al. 2015). This was concurrent with the inland expansion of surface meltwater lakes over the southwestern margin to elevations hundreds of meters above the equilibrium line and well into the percolation zone (Fitzpatrick et al. 2014; Howat et al. 2013). The expansion of lakes to higher elevations indicates increased lateral transport of meltwater, rather than vertical infiltration and storage at depth. The ability of the firn to absorb increases in meltwater may therefore be significantly limited by a concurrent increase in shallow firn density and reduction in its permeability. For example, intense melting, infiltration and refreezing one summer may create an effectively impenetrable ice layer that would act as an aquitard to meltwater generated in subsequent years.

The formation of new lakes at higher elevations in the percolation zone offers an opportunity to examine the changing hydraulic conditions of the firn under increased melt. We hypothesize that these lakes form due to a reduction in firn permeability at shallow depths, resulting in lateral transport of meltwater into topographic depressions. Therefore, the appearance of a lake indicates that the pore space at depth within the firn (i.e. below the base of the aquitard upon which the lake is perched) has become inaccessible to infiltration. If the lake is perched above the previous year's accumulation, it implies a nearly complete nullification of the firn's ability to absorb meltwater under warming at that elevation.

Here we examine repeat, airborne snow-penetrating radar and laser altimetry collected by the National Aeronautics and Space Administration's Operation Ice Bridge over two lakes that first appeared in the percolation zone of western Greenland during the summer of 2011. We use these observations to assess the conditions that caused the lakes to form and how the lakes evolved over subsequent years.

Chapter 2. Data and Methods

Our primary data sets for examining percolation zone lake evolution are surface elevation and near-surface radar transects obtained by the US National Aeronautics and Space Administration's Operation IceBridge (OIB) airborne surveys conducted each spring (March-May) between 2009 and 2015. In order to locate lakes that appear after 2009 and that were overflown annually by OIB along repeat trajectories, we created a database of sequential, melt season imagery from Landsat Enhanced Thematic Mapper Plus (ETM+), Landsat Optical Land Imagery and Advanced Spaceborne Thermal Emissivity and Reflection Radiometer (ASTER) for the margin of southwest Greenland. These images were used to locate lakes that formed above 1500 m after the year 2009, as documented in Howat et al. (2013). Following lake detection, OIB flight lines are overlain on the imagery to determine if and how often the lake was surveyed. While we identify numerous, recently-formed lakes, we identify only two that appeared for the first time in the satellite imagery after 2009 and were surveyed each season between 2009 and 2015 (Figure 1; Table 1). Lake 1 is located at 68°28’07” North, 314°49’46” East at 1780 m elevation. Lake 2 is located at 69°14’31” North, 313°08’48” East at 1722 m within the catchment of Jakobshavn Isbrae.

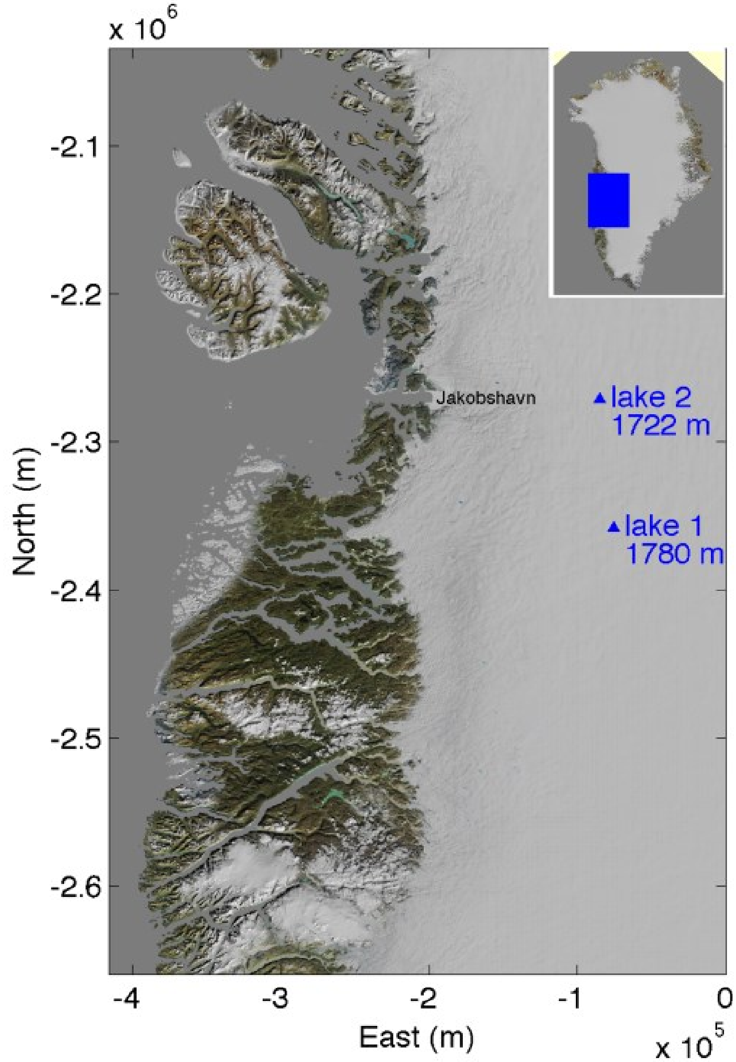

Figure 1. Newly formed lakes in the percolation zone with repeat passes from the Operation IceBridge campaign in the study area.

lake 1:			**lake 2:**		
date of survey	**segment #**	**frame #**	**date of survey**	**segment #**	**frame #**
04/06/2011	02	632-633	04/22/2011	02	025
04/29/2012	01	386-387	04/29/2012	01	190-191
04/04/2013	04	004	04/06/2013	03	043-044
04/09/2014	01	573-574	04/14/2014	02	339-340
04/21/2015	13	108-109	04/23/2015	02	337

Table 1. Snow Radar details for the two lakes.

For each lake we examine time series of snow surface elevation and near-surface firn structure obtained along the repeat OIB flight lines. Surface elevation is obtained from the Airborne Topographic Mapper (ATM) scanning lidar. We use the ATM Level 2 Elevation, Slope, and Roughness, Version 2 product distributed by the National Snow and Ice Data Center. The Level 2 data are obtained from fitting overlapping planes to subsamples of the Level 1 point cloud. These planes span the lidar swath width evenly in 3 off-nadir tracks, along with an additional nadir track. In the along-track direction, the planes are spaced approximately every 0.5 seconds with ~50% overlap (Krabill 2014). The ATM scanning lidar has a vertical accuracy of 10-20 centimeters. The nadir block, whose center is beneath the aircraft centerline, is used for all 2011-2015 ATM Level 2 elevations for lake 1 and all ATM elevations for lake 2 (2011-2013, 2015) except 2014 (Figure 1). Due to its proximity to the nadir track of previous years, an off-nadir track, track 2, is used in 2014 for lake 2.

Changes in near-surface (<20 m depth) firn structure are investigated using echograms obtained with the University of Kansas Snow Radar, an ultra-wideband Frequency Modulated Continuous Wave (FMCW) microwave (2-8 GHz) imaging radar with a range resolution of 4.0 cm in snow (Leuschen, Carl, Prasad Gogineni, Richard Hale, John Paden, Fernando Rodriguez, Ben Panzer, Daniel Gomez, n.d.). For more information on the Snow Radar, see Rodriguez-Morales et al. (2014). We use the IceBridge Snow Radar L1B Geolocated Radar Echo Strength Profiles, Version 1 and 2 products from the National Snow and Ice Data Center (2009-2013) and

CReSIS (2014 and 2015). The Snow Radar elevation was corrected to the ATM for years 2011-2013 of lakes 1 and 2. For lake 1, the elevation correction applied for years 2011, 2012 and 2013 are 2.2, 1.5 and 2.1 meters, respectively. For lake 2, the elevation correction applied for years 2011, 2012, and 2013 are 2.2, 1.8, and 2.1 meters, respectively. For years 2014 and 2015 for both lakes, a depth from surface vs. distance data matrix was extracted and aligned to the lidar measurements of surface elevation. A depth-dependent power law gain was applied to all the echograms.

Chapter 3. Results

3.1. Lake 1

Lake 1 first appeared as 0.216 km^2 of surface water in the Landsat imagery in July 2011 (Fig. 2b), before which no evidence of surface water appeared in the imagery and the altimeter and radar profiles across the lake revealed a parabolic basin with no anomalous subsurface structures (Fig. 2f). A radar profile obtained in spring 2012 following the first appearance of the lake reveals a 500-m wide, bright reflector at a depth of 3.8 m below the surface (Fig. 2g), located at the bottom of the basin and matching the aerial extent of the lake. The reflector is horizontal, rather than matching the convex surface topography. While the surface surrounding the lake lowered by up to 0.5 m between April 2011 and April 2012, the center of the new lake rose up to 0.2 m. Note that the flight line was approximately 0.253 m off-center of the lake basin, so the elevation changes in the true center of the lake may have been larger.

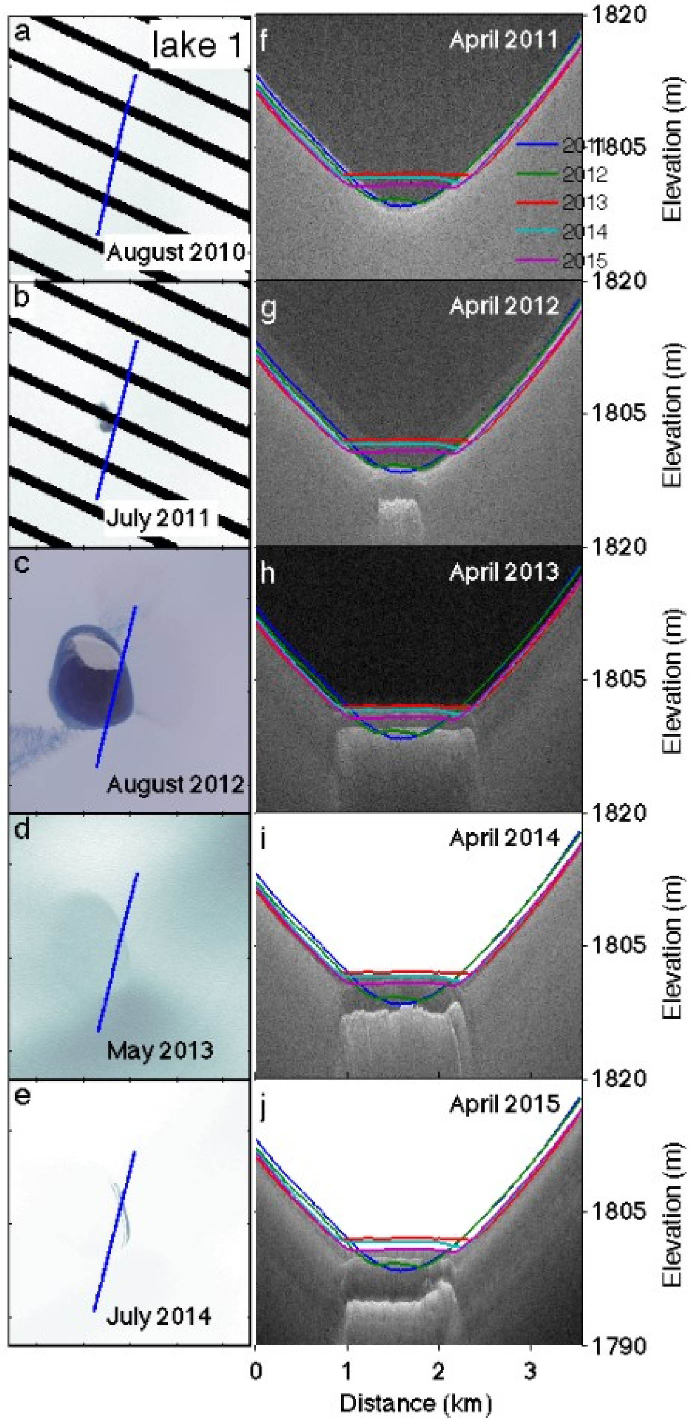

Figure 2. Lake 1 flyovers (a-e) and corresponding radar echograms and surface elevations (f-j). Flight lines are aligned in the NE direction.

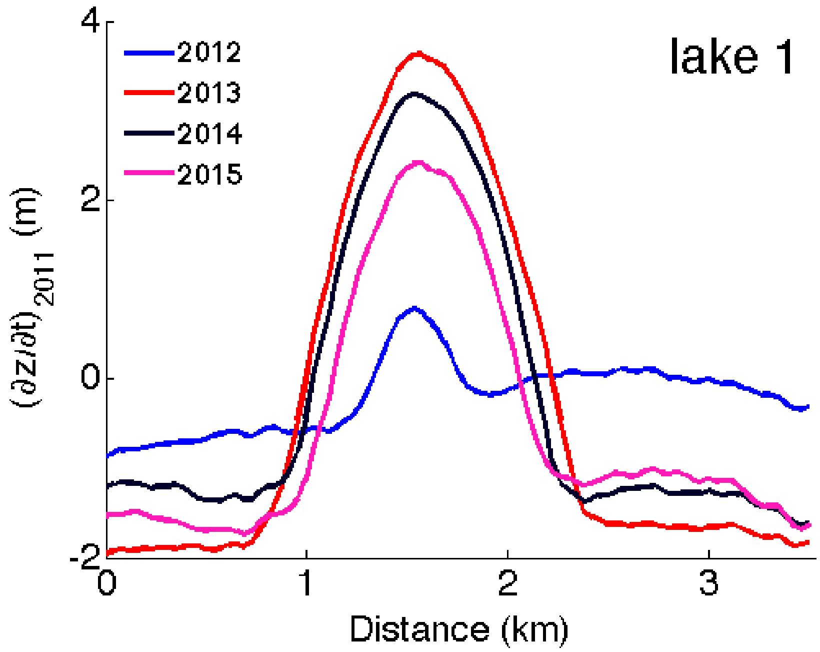

Figure 3. Surface elevation changes relative to 2011 from ATM. The flight line heads in the northeast direction.

In Landsat imagery from August 2012, an anomalously strong melt season at high elevation on the ice sheet (Nghiem et al. 2012; Tedesco et al. 2013), the lake expanded 2.60 km^2, or by 4.7 times. An "island" of snow or ice is visible on the north end of the lake that is of equal size and shape to the previous year's lake extent. The surface around the lake lowered by 1.5 m to 2 m between April 2012 and 2013 while the surface above the lake rose by 3.5 m. This spatial pattern resulted in a widening and flattening of the lake basin consistent with infilling. The April 2013 echogram records a bright, horizontal subsurface reflector four times wider than the one observed in April 2012, matching the extent of the widened basin. The reflector is 4 m higher in elevation than in 2012, located at or just above the April 2012 surface elevation, and again approximately 4 m below the new surface. No backscatter is returned below this reflector.

No clear imagery of the lake was available during the 2013 melt season and it's uncertain whether the lake re-formed that year. The spring 2014 aerial surveys recorded an increase in surface elevation around the lake, reaching 0.8 m to the North, with small changes to the south. The lake surface lowered by up to 0.5 m in the center of the basin. The bright subsurface reflector appears similar in extent and return power as in 2013, but is less smooth and has lowered in elevation by 1.5 m.

A lake edge reappears in July 2014 (Fig. 2e). From the 2015 spring aerial survey, the surface over the lake is up to 0.8 m lower than the previous year (Fig. 3). Surrounding the lake, the surface is lowered about 0.4 m to the south and a slight rise of up to 0.23 m is observed in the north. The snow radar echogram reveals a bright reflector, 6 m beneath the surface, that is similar in extent and return power to the previous year, but its north end, about 500 m in length, is bent up toward the surface in a northeastern direction, approximately parallel to the surface (Fig. 2j).

3.2. Lake 2

Lake 2 also first appeared as 0.120 km^2 of surface water in August 2011 imagery, with no prior surface or subsurface evidence of meltwater ponding (Fig. 4k-l and 4p). Regionally, the surface at the elevation of the lake lowered by ~1 m per year due to ice stretching resulting from acceleration of Jakobshavn Isbrae. Potentially associated with this acceleration, crevasses appeared 1.3 km to the southwest of the lake in August 2010 (Fig. 4m). InSAR surface velocities at lake 2 are about 184 m/yr, which are almost 2.2 times faster than at Lake 1 (Joughin et al. 2010). April 2011 and 2012 altimeter surveys record an overall surface lowering of between 0.5 and 2 m, increasing from north to south along the profile (Fig. 5). The flightline is ~20 m west of the lake edge, so that no clear change associated with lake formation was captured in the altimeter profile. However, a distinct, horizontal, subsurface reflector appears 3 m below the surface in the April 2012 echogram with several scattered reflectors ~4 m below that (Figure 4q).

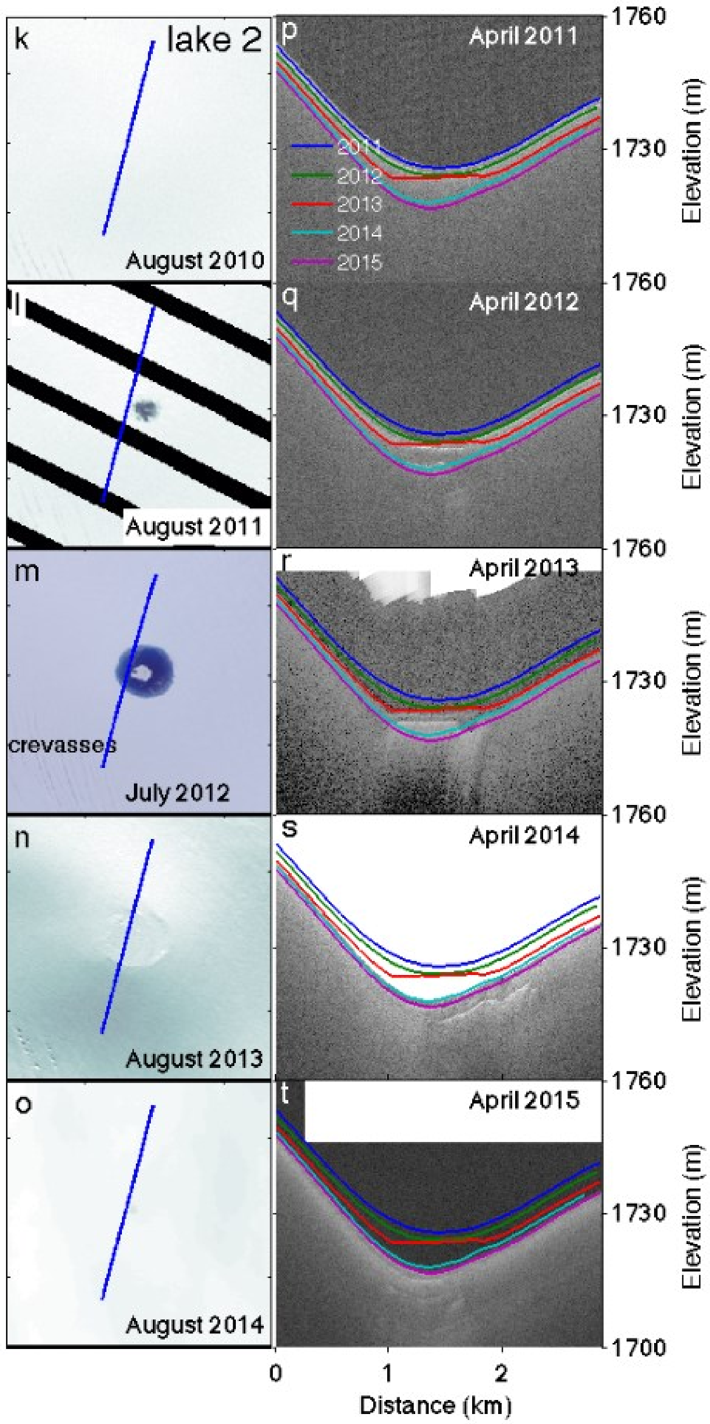

Figure 4. Lake 2 flyovers (k-o) and corresponding radar echograms and surface elevations (p-t). Flight lines are aligned in the NE direction.

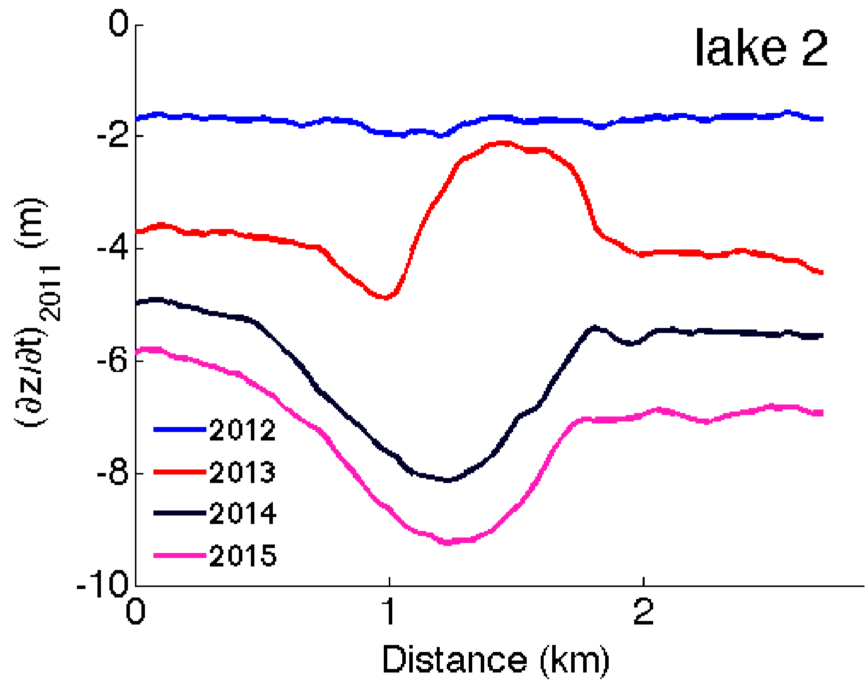

Figure 5. Surface elevation changes relative to 2011 from ATM. The flight line heads in the northeast direction.

The lake was nearly 6 times larger in area in summer 2012 during that anomalously strong melt season and, as lake 1, contained a snow/ice "island" of approximately the same size and shape as the previous year's lake. The spring 2013 flightline traversed the western edge of the lake, and recorded a surface lowering of between 2 and 2.5 m of the area surrounding the lake basin, but only 0.25 over the surveyed portion of the lake (so that part of the lake surface rose ~2m above the surrounding ice). Consistent with this pattern of infilling, the lake basin widened and flattened. The radar again observed a subsurface reflector at ~3 m depth, but substantially wider and brighter than in 2012, with no backscatter return beneath it.

Surface meltwater did not appear in the imagery during the 2013 melt season, however, the edges of the buried lake are clearly demarcated as shown in the low sun-angle Landsat 8 imagery (Fig. 2n). The April 2014 altimeter survey shows a drop in the lake surface elevation that mirrors, in magnitude and spatial pattern, the previous rise, so that the overall lowering between 2011 and 2014 is greatest in the center of the lake, reaching 8 m in the middle of the surveyed portion, decreasing outward to the regional change of 4-5 m. The bright, horizontal subsurface reflector visible the previous year is no longer present in the 2014 echogram, with the only clearly visible structure a bright, surface parallel reflector on the North side of the lake at 4.6 m depth. Also in contrast to the previous years survey, there appears to be backscatter from tens of meters below the former lake bottom.

The lake's darkened surface appears very faintly in August 2014 (Fig. 2o). The surface over and around the lake is similar in shape to the previous year with lowering throughout the area. From a spring 2015 aerial survey over the lake, there is lowering of up to 1.2 m (Fig. 5). Around the lake, there is lowering of up to 1.45 m to the north and 0.98 m to the south. A 300 m long bright reflector is observed 2 m beneath the surface (Fig. 4t). The linear reflector contrasts with the convex surface above it. Between 2-4 m beneath the flat reflector are several short scattered reflectors that are aligned to the surface.

3.3 RACMO Climatology

We use snowmelt and snowfall output from the regional atmospheric climate model (RACMO/GR, v2.1) for the period 1958-2013. Created by the Royal Netherlands Meteorological Institute (KNMI), RACMO is comprised of HIRLAM atmospheric dynamics (Undén et al., 2001) and the physical processes of ECMWF cycle 28r4 (White, 2004). For more details on the components of RACMO, v2.1, see Lenaerts et al. 2012 and van Meijgaard et al. 2008. RACMO has a horizontal resolution of 11 km and 40 atmospheric levels over Greenland (Lenaerts et al. 2012). To account for melt, percolation and refreeze processes, a multi-layer snow/firn/ice model has been incorporated into RACMO for Greenland (Ettema et al. 2010). Compared to in situ measurements, the near-surface climate of Greenland from RACMO has fared well (Ettema et al. 2010). Since the comparison with in situ measurements, RACMO improvements over Greenland include an albedo and a drifting snow scheme (Lenaerts et al. 2012 and van Angelen et al. 2014).

3.3.1 Snowmelt

The increase in snowmelt over lakes 1 and 2 since 2000 is concurrent with an increase in warming (Figure 6). For lakes 1 and 2, the five highest records of snowmelt within the 1958-2013 RACMO record are 2004, 2007, and 2010-2012 (Figure 6). Three of these are cited as high melt years in Greenland (Mote 2007; Tedesco et al. 2011; Nghiem et al. 2012). Lakes 1 and 2 form in 2011, the third highest snowmelt year within the 1958-2013 RACMO record (Figure 6). This record is surrounded by the two highest years of snowmelt, 2010 and 2012 (Figure 6).

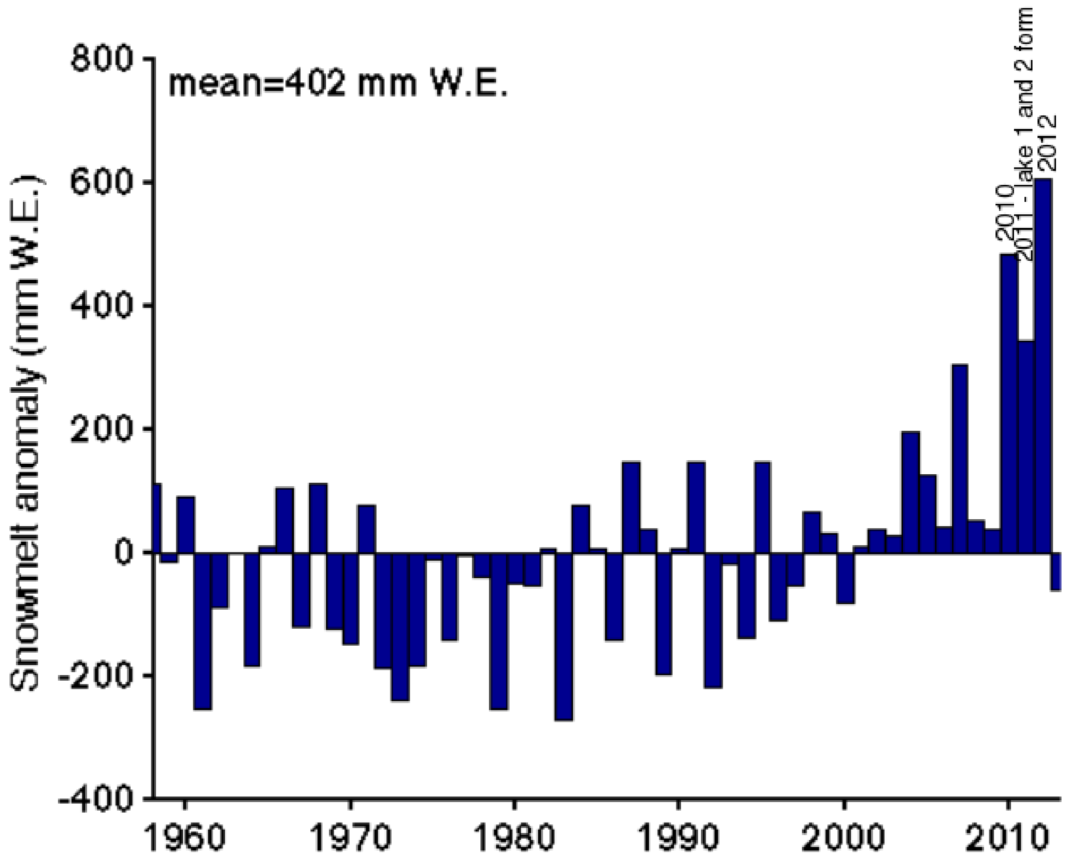

Figure 6. Annual snowmelt anomalies, the difference in value from the long-term mean, for both lakes from RACMO.

3.3.2. Snowfall

2009 and 2011 are two of the three lowest annual snowfall records within the 1958-2013 climatological record of RACMO for the two lakes (Figure 7). These record snowfall lows surround a year of moderate snowfall in 2010 (Figure 7).

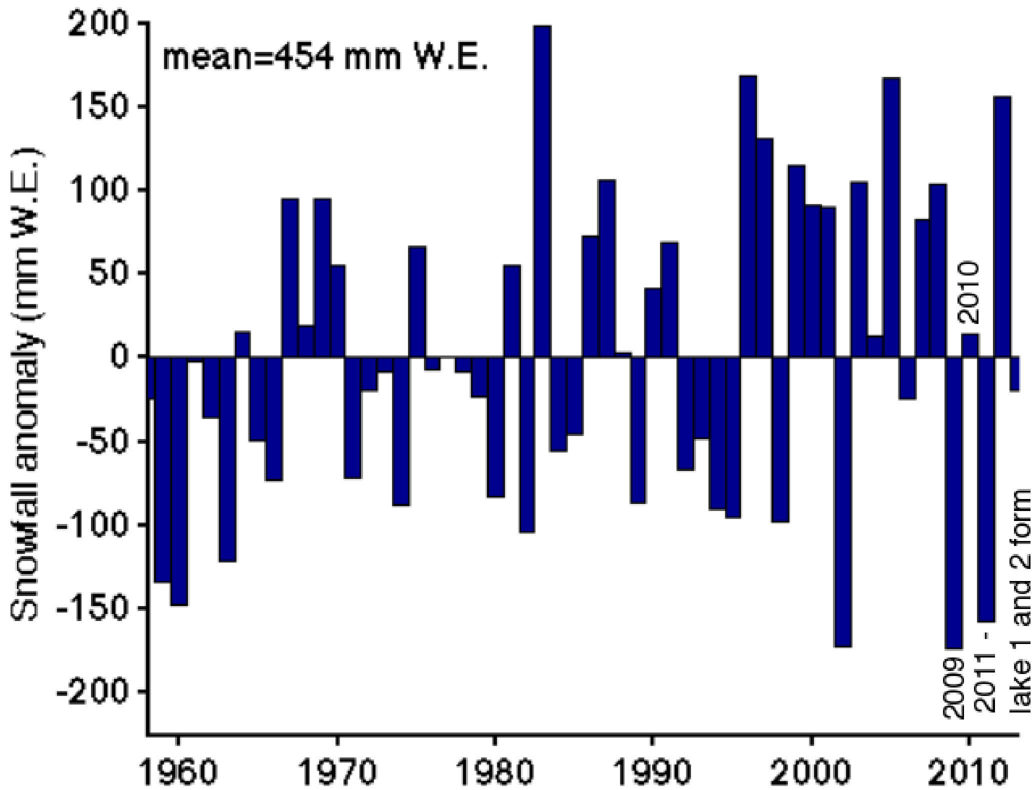

Figure 7. Annual snowfall anomalies, the difference in value from the long-term mean, for both lakes from RACMO .

Chapter 4. Discussion

Our observations capture the formation and evolution of two lakes in the percolation zone of the Greenland Ice Sheet. The observations are consistent with the hypothesis that anomalously high melt leads to reduced permeability of near-surface firn, runoff and ponding within topographic depressions. Despite similar patterns of initial formation at the two lakes, the observations reveal contrasting behaviors that yield insight into lake development and persistence. In the following sections we compare and contrast the formation and evolution of the two lakes.

4.1 Lake formation

For both lakes, melt was nearly double, and snowfall was nearly half the annual 56- year mean the year of their formation (Figures 6 and 7). Such high melt and low snowfall would enable lake formation by increasing the amount of meltwater available and reducing the amount of pore space available in the underlying new snow/firn for meltwater infiltration.

A bright, nearly level reflector appears in the spring radar echograms for both lakes following the 2011 melt season when the lakes first appeared (Figures 2f, 2g, 4p and 4r). In the 2010 (not shown) or 2011 echograms there is no visible variation in the firn structure beneath the lake basin and the surrounding regions that would provide evidence for pre-conditioning of the firn for lake formation.

Instead, these data suggest that the change in structure and hydrologic conditions that lead to lake formation were mainly the result of the summer 2011 melt season conditions.

We interpret the bright, level reflector located ~3 m below the spring surface to be the boundary between lake ice, overlain by new snow accumulation and liquid water below. The persistence of liquid water in Greenland supraglacial lakes was first discovered by Koenig et al. (2015), who based their interpretation on how water attenuates backscatter across frequencies. Koenig checks for the presence of liquid water using the OIB Snow Radar, and in addition, either the Accumulation radar (~600-900 MHz) or MCoRDS radar (~140-260 MHz). We confirm the attenuation of backscatter, indicating the presence of water, within the OIB Snow and Accumulation radar echograms for both lakes in 2013. We interpret the bright reflector as the top of liquid water because the fraction of reflected to incident power, or the amplitude reflection coefficient (R_A) (Navarro and Eisen, 2010), is about fifteen times higher at the boundary between ice and liquid water than between ice and snow. This high value would explain the very high backscatter of the layer and the radar opacity beneath.

If a lake formed above a fully saturated firn column in summer, we would expect a broadly distributed reflector with the same power intensity throughout, representative of the boundary between snow and refrozen saturated snow in the spring echogram. However, this does not appear (Figures 2g and 4r).

Our data reveal a sharp transition in firn structure at the lake edges. The bright, level, radar-opaque reflector terminates abruptly where the surface slope begins to increase, with little or no change in the echograms of the firn surrounding the lake. This contrasts with the expectation that increased meltwater throughout and refreezing would result in extensive ice layer formation, as described by de la Peña et al. (2015) and Mikklesen et al. (2015). We would then also expect a gradual increase in the quantity of ice approaching the lake, as the total throughput of meltwater increases. Either such structures cannot be resolved, or water is efficiently drained to the lake, so that little is refrozen in the surrounding firn.

While lake formation above fully saturated firn is not in agreement with our echogram observations, lake formation above an ice layer remains viable. Therefore we infer lakes form above an ice layer. Alternatively, because an ice lens is shorter in distance compared to an ice layer, and liquid water results in radar opacity beneath the bright reflector, we infer lakes may form above an ice lens within the basin low.

4.2 Multi-year lake development

The anomalously high melt of 2012 resulted in similar deepening and expansion of both lakes, with expansion of the bright, level reflector, interpreted as the lake ice/liquid water interface above (Figures 2c, 2h, 3, 4m, 4r, and 5). The melt per area of lake 2 is more than double that of lake 1, however the rise in the lake surface is much less, about seven times less. In the April 2013 echogram of lake 1, there is overlap between the lake ice/liquid water interface and the previous year's lake surface. These observations suggest in summer 2012, a new lake formed on top of the lake of the previous summer for lake 1.

In 2013, snowfall and snowmelt decrease to about average, with snowmelt anomalies surpassing snowfall anomalies by about three times (Figures 6 and 7). Despite similar trends in meteorology, lake 1 persists while lake 2 drains (Figures 2i and 4s). Evidence of the drainage of lake 2 consists of 1) a lack of features in the topographic low of the radar echogram and 2) the lowering and convex shape of the surface from the ATM (Figures 4s and 5). Evidence of lake 1 persistence consists of 1) the continued presence of a bright reflector in the near subsurface and 2) a flat surface over the lake from the ATM (Figure 2i). We interpret the bright reflector in the lake 1 echogram as the continued overwintering of liquid water within the lake (Figure 2i).

Aerial survey results of lake 1 the following year are similar. We interpret the bright reflector in the spring 2015 echogram of lake 1 as the continued persistence of liquid water (Figure 2j). In summer 2014 at lake 2, a small lake forms in the same location as the previous year's drained lake (Figure 4o). Its appearance suggests lake formation can occur over a single melt season.

Since April 2013, the rate of elevation lowering over lake 1 has been less than the rate of lowering at the lake ice/liquid water interface at its near surface.

4.3 Lake termination

Data from the April 2014 aerial survey show lake 2 drains but lake 1 does not (Figures 2i and 4s). As stated earlier, evidence of lake 2 drainage consists of 1) a lack of features in the topographic low of the radar echogram and 2) the lowering and convex shape of the surface from the ATM (Figures 4s and 5). Evidence of lake 1 persistence consists of 1) the continued presence of a bright reflector in the near subsurface and 2) a flat surface over the lake from the ATM (Figure 2i). InSAR surface velocity maps show the speed at lake 2 is more than double the speed at lake 1 (Joughin et al. 2010). We hypothesize the difference in development of the two lakes is due to a difference in ice dynamics. .We hypothesize the drainage of lake 2 is due to the fast advection of the near-surface ice lens at lake 2, which would allow the meltwater to spill out the side of the advecting lake bottom and infiltrate the immediate firn. A separate hypothesis for the contrasting behavior between the lakes is the extension of nearby crevasses (Figure 4m) into the lake resulting in fracture at the lake bottom. Fracture would cause meltwater to spill out the bottom and into the crevasse.

Chapter 5. Conclusions

From observations of supraglacial lakes in the lower accumulation zone, we infer the formation of near surface ice lens', which are significant in their ability to lower permeability and in their potential development into ice layers. We hypothesize with continued warming, there will be continued expansion of percolation zone supraglacial lakes. Modeling is needed to determine whether meltwater availability, topography, firn thickness, or ice lens thickness will be the limiting factor in the expansion of lakes and how they may vary on a regional scale.

We find the overwintering of near surface liquid water persists over multiple seasons. Modeling is needed to determine what conditions enable near surface liquid water to exist and persist. Through the modeling study, one explores the possibility of liquid water storage in areas of Greenland outside of the southeast, where an aquifer was recently found (Forster et al. 2013). High accumulation rates are found to enable liquid meltwater to persist in the southeast Greenland aquifer (Munneke et al. 2014), but lower accumulation rates are found in the southwest, the location of the lakes.

We find lake development is dependent on ice dynamics. While lakes can drain in the percolation zone, the region of lakes which do drain is likely limited to the Jakobshavn region due to the unusually high velocities present. Moreover, the effect of lake drainage is likely limited to the immediately surrounding firn.

Our findings are based on our interpretation of the echograms, so it would be useful to evaluate them using an electromagnetic model which simulates radar power returns. Our study and those suggested above are important to the understanding and proper assessment of recent changes of the Greenland firn. With continued warming in the arctic, an understanding of how and where meltwater travels and refreezes in the percolation zone is critical to obtain precise estimates of the buffering capacity within the Greenland firn, which in turn will lead to better estimates of Greenland mass balance.

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Appendix A: Supplemental Figure

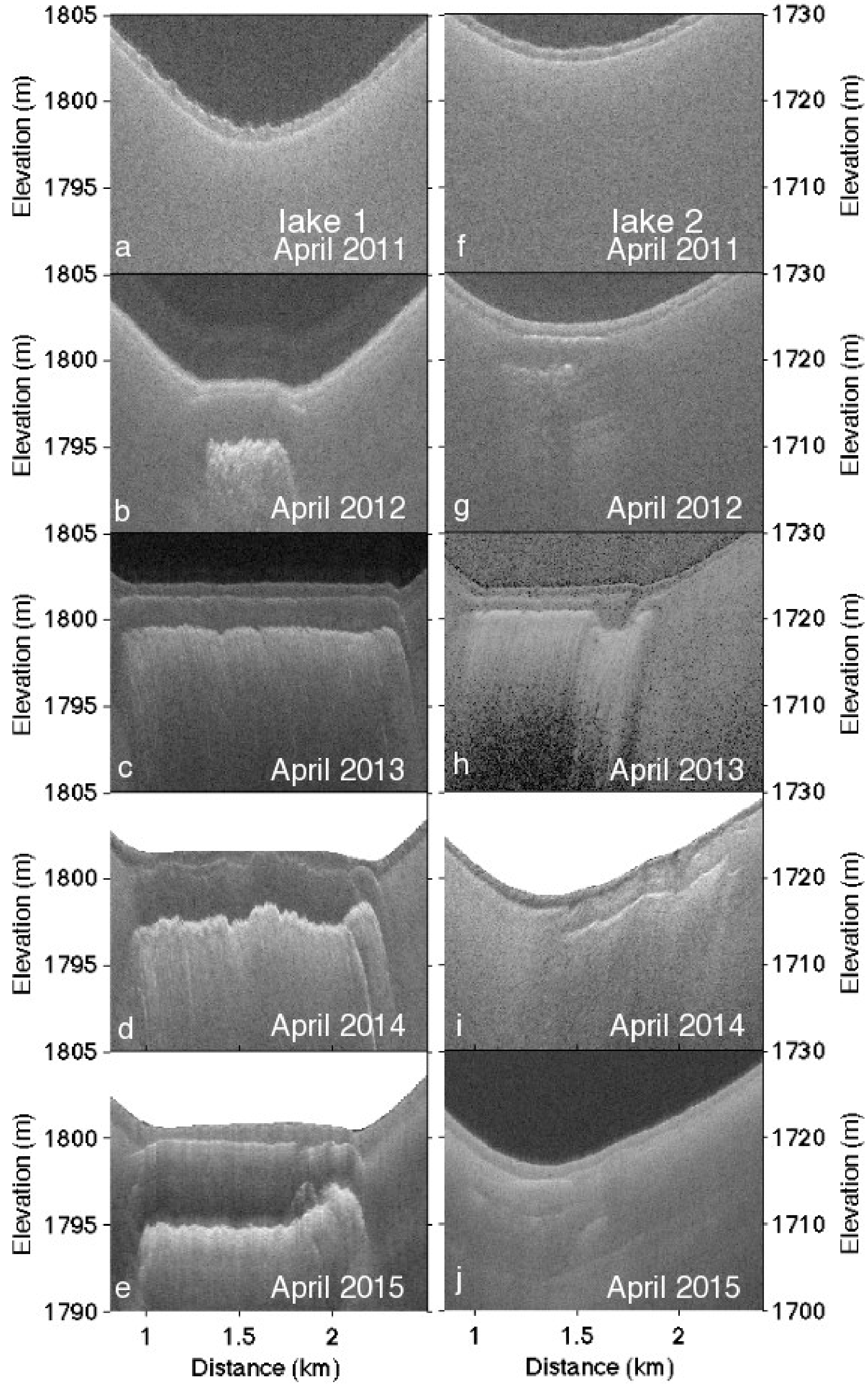

Figure 8. Close ups of snow radar echograms for lakes 1 (a-e) and 2 (f-j).