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Glacier change from the Little Ice Age to present in the Torngat Mountains, northern Labrador, Canada

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Abstract

The glaciers of the Torngat Mountains of northern Labrador are the southernmost of the Canadian Arctic and the easternmost of continental North America. Currently, over 100 small mountain glaciers cover an area in excess of ~21 km^2 confined mostly to small cirques and upland depressions. This study reconstructs and dates the areal extent of Torngat glaciers during the Little Ice Age (LIA); enabling the first assessment of regional glacier changes over the past several centuries. 165 mapped LIA glacier paleomargins are compared to current (2005) glaciers and ice masses showing a 52.5% reduction in glacier area from the LIA to 2005 with 12 formerly active glaciers having since disappeared.

Glacier change is spatially synchronous and independent of topographic factors; however both altitude and glacier size mitigate glacier change. Previously established lichen growth stations were re-visited, and growth rates recalculated based on ~30-year-long records; enabling the construction of low altitude and high altitude lichen growth curves for the area. By comparing *in situ* lichen measurements on LIA moraines to local growth rates we estimate that regional LIA

advance was most likely between ~1491 and ~1664 AD. These results suggest that the magnitude and timing of LIA glacier advance in the Torngats is significantly different from other glaciers in the eastern Canadian Arctic and North Atlantic basin.

Introduction

Small mountain glaciers are valuable indicators of climate change; reacting quickly to changes in both regional and local climatic conditions (Meier, 1984). Changes in glacier surface area and volume, and phases of advance and retreat are strongly indicative of response to both internal glacier dynamics and changes in climatic conditions (Benn and Evans, 2010). Glacier mass balance relies on the magnitude of winter precipitation (snowfall) for ice accumulation and summer temperature for ice ablation (melting).

In both the Northern and Southern hemispheres there have been widespread observations of mountain glacier and ice cap retreat, though regional variations are commonplace (IPCC, 2007). This near global ice reduction is likely a response to recent atmospheric warming attributed to anthropogenic global warming (Santer et al, 2011) and has resulted in large contributions to sea-level rise (Meier et al, 2007, Church and White, 2011). The recent (2003-2010) contribution of glaciers and ice caps to sea-level rise was 0.41 ± 0.08 mm year-1 (Jacob et al, 2012); however, projections suggest that glacier wastage alone will contribute 0.12 ± 0.04 m to global sea-level rise by 2100 (Radic and Hock, 2011).

Excluding the Antarctic and Greenland Ice Sheets, glaciers and ice caps in the Arctic cover the largest area (402,000 km^2) of any region and contain the equivalent of 0.41 m of sea-level rise

(Sharp et al, 2011). Glaciers in the Canadian Arctic represent the majority of Arctic glaciers and have contributed nearly one-third of the sea-level rise from glaciers and ice caps over the past five years (Gardner et al, 2011). In the eastern Canadian Arctic, studies have documented glacial retreat during the past century for Northern and Southern Baffin Island (Paul and Kääb, 2005, Paul and Svoboda, 2009, Svoboda and Paul, 2009), Bylot Island (Dowdeswell et al, 2007), Devon Ice Cap (Burgess and Sharp, 2004) and on Ellesmere Island (Mair et al, 2009). The only glacier range in the Canadian Arctic still without change assessment holds the glaciers of the Torngat Mountains of northern Labrador, the southernmost glaciers in the eastern Canadian Arctic.

Aside from a small mass balance monitoring program from 1981-1984, little to no baseline information is available on the present or prior state of Torngat Mountain Glaciers, hereafter Torngat glaciers (Rogerson, 1986, Rogerson et al, 1986). Launched in 2007, the Torngat Mountain Glacier Project aims to collect baseline information on all Torngat glaciers for an overall assessment of the current, former and future states of these ice masses. This project follows three approaches: topo-climatic analysis of glacier setting; melt-modeling of selected glaciers; and short- (historical photographs) and long-term (recent geological) analysis of past glacier activity. This paper contributes to an assessment of historical glacier activity in the region, focusing on the period from the Little Ice Age (LIA) to present (2005).

In the northern hemisphere, the LIA began with climatic deterioration in the late 13th century (Anderson et al, 2008, Miller et al, 2012) and ended with climatic amelioration at the beginning of the 20th century (Moberg et al, 2005, D'Arrigo et al, 2006, Ljungqvist, 2010). This pronounced cold period is likely caused by a mixture of enhanced volcanism, low solar activity and weakened thermohaline circulation (Mann et al, 2009). The LIA was the coolest period in the Arctic since the Holocene Thermal Maximum ~10,000 to 6000 BP, though the magnitude and timing of the LIA varied regionally (Koerner and Fisher, 1990, Vinther et al, 2009).

During the LIA, there was widespread, though geographically asynchronous, glacier advances through most of the Northern Hemisphere (Davis et al, 2009). In the North Atlantic sector, the period of greatest LIA glacier advance occurred between ~1880 and ~1920 AD (Dowdeswell et al, 2007, Paul and Kääb, 2005, Paul and Svoboda, 2009, Citterio et al, 2009). This study reconstructs former LIA glacier maxima for the Torngat glaciers and provides proxy dates for maximum advance using lichenometric data; the first comprehensive calculation of glacier change for Torngat glaciers.

Study Area

The Torngat Mountains National Park (established 2005) and comprises an area of over 9700 km^2 extending from 58.5°N to 60.4°N (Figure 1). The Torngat Mountains are the highest peaks on the Canadian mainland east of the Rocky Mountains and support the southernmost Arctic Cordilleran landscape in the world (Clark, 1991, Lands Directorate, 1986). They rise from sea level to 1652 m above sea level (asl) in the Selamiut Range just south of Nachvak Fiord. Located above the Arctic treeline the Torngat Mountains support both continuous and discontinuous permafrost (Hachem et al, 2009), as well as glaciers and small plateau ice masses.

The regional geology includes the Churchill and Nain structural provinces of the Canadian Shield with bedrock, for the most part, being granite, gneiss, quartz, marble or anorthosite (Clark, 1991). The interior of the Torngats contains extensive plateau landscape with high overall altitudes but significantly less prominence than the fjords of the coastal Torngats. Coastal regions show a much larger fraction of cirque landscapes contrary to the interior where there are relatively few pronounced cirques due to differences in geology (less erosive rock) (Wardle et al, 1997).

The Wisconsin glacial phase, as well as predated phases, extensively shaped the geomorphology of the region, creating rugged coastlines dotted with fiords and U-shaped valleys (Evans and Rogerson, 1986). The glacial geomorphology of the region suggests the landscape was once heavily glaciated with numerous arêtes, cirques, erratics, eskers, horns, moraines and outwash plains. Many valleys contain moraine sequences leading from empty or currently occupied cirques, signifying a history of glacial recession in the region. The Torngats thus include four physiographic regions: mountain summits and plateaus, extensive low mountain shoulders, upland cirques and outlet valleys, and lowermost valleys (Evans and Rogerson, 1986).

Climate

We estimate temperature and precipitation in the Torngats from ERA-Interim (Dee et al, 2011) due to the lack of credible weather stations in the region. We use temperature estimates at both the 2m (surface) and 850 millibar heights to approximate conditions for both low and high-altitude glaciers. Mean annual air temperature (1979-2009) in the region ranged from -6.2°C (2m) to -8.5°C (850 Mb), with summer temperatures (JJA) between 2.7°C and 4.9°C. The nearby

Labrador Current carries cold polar water southwards along the Labrador coastline causing unusually frigid temperatures for its latitude (Banfield and Jacobs, 1998). The large temperature range (~ 24°C) suggests significant seasonal variation similar to the conditions observed in western Svalbard and the Russian Arctic Islands (Sharp et al, 2011).

Total precipitation in the region averaged 0.73 m per year (1979-2009) with most precipitation occurring in the fall (~230 mm) and summer (~208 mm). The Canadian Polar trough is the main control on precipitation in the region and defines the distribution of winter snowfall by positioning the high-latitude storm track across northeastern Canada. Within the Torngats there appear to be strong precipitation and temperature gradients caused by local meteorological conditions; for example, fog is prevalent in the coastal mountains throughout much of the summer, frequently occurring close to ice masses. Labrador-wide warming of 1.73 ± 0.53°C/century suggests regional warming is ongoing (Way and Viau,In Prep).

Torngat Mountain Glaciers

In total, there are 103 actively flowing Torngat glaciers and 191 ice masses in the region (Way et al, submitted). These glaciers cover an area of ~22 km^2 (2005) with individual glaciers almost all smaller than 1 km^2 (Way et al, submitted). The current median glacier elevation in the Torngats (~776 m above sea level, asl) is lower than in Arctic glaciers on Baffin Island much further north (Paul and Kääb, 2005, Paul and Svoboda, 2009). Torngat glaciers face all aspects but are primarily North to Northeast-east facing, the preferred orientation of Northern Hemisphere glaciers under the control of insolation (Clark, 1991). Most Torngat ice masses have moraine sequences in their foregrounds showing that local glaciers once advanced downvalley as much as

5 km from their current positions (Evans and Rogerson, 1986).

The vast majority are cirque glaciers, which occupy deep basins characterized by high backwalls and local topographic shadowing; however, small plateau ice masses and traditional alpine glaciers exist in some locations (Figure 3a, b, c). Most Torngat glaciers are debris covered, a factor previously observed to reduce surface melting for several glaciers south of Nachvak Fiord (Rogerson et al, 1986). Torngat glaciers mostly occur in small groups directly on, or proximal to the fretted landscape of the coastal mountains. Glaciers further from the coast form only where topography allows, but also as plateau ice caps where altitude is sufficient to sustain their survival (Way et al, Submitted). Previous work on a small number (n=4) of glaciers below Cirque Mountain identified winter precipitation as the controlling climatic variable in mass balance rather than temperature (Rogerson, 1986).

Previous investigations of ice advance in the Torngats by McCoy (1983) and Rogerson et al (1986) occurred south of Nachvak Fiord in glacier foregrounds of the McCornick River Valley. McCoy (1983) conducted lichenometric surveys on moraines in the vicinity of several small cirque glaciers on the northwest face of Cirque Mountain. To estimate the age of former glacier advances, McCoy (1983) used Rhizocarpon Geographicum lichens measured on moraine surfaces and combined them with growth rates recorded on the Cumberland Peninsula of Baffin Island (Miller, 1973). In 1983, Rogerson et al (1986) visited 4 lichen growth stations in the McCornick River Valley which were previously set up by McCoy (1983) in 1978. From these data, Rogerson et al (1986) calculated dates of previous glacier advances for 3 glaciers in the

Selamiut range. These dates were not in agreement with those provided by McCoy (1983), particularly in the glacier foregrounds below Cirque Mountain.

Methods

In this study, we map the extent of Torngat glaciers at the LIA using remotely sensed data from 2005 aerial surveys of the region. Former ice margins dating uses lichenometry with Rhizocarpon Geographicum lichens as the target sub-species. Based on observed moraine characteristics and lichen sizes, we correlate lichens measurements on moraines in glacier foregrounds (Cirque Mountain) to former LIA ice advance. Comparison between lichen sizes on LIA moraines to a new, locally established lichen growth curve allows for dating of LIA moraines.

Little Ice Age Glacier Change

Mapping LIA Ice Margins

Former LIA glacier area mapping uses 1:40,000 color digital aerial photography (0.7 m resolution) provided by Parks Canada. Acquisition followed repeat aerial surveys of the Torngat Mountain National Park in August/September of 2005. Aerial photographs were orthorectified in PCI Geomatica (v10.3) using exterior orientation information provided by the surveyor (X, Y, Z, Omega, Phi, Kappa). This study uses a digital elevation model (DEM) (18 m resolution) provided by Parks Canada to correct for topographic distortions due to alpine relief (Kääb, 2005). Supplemental to the orthophotos, we use pan-sharpened (5 m) SPOT-5 imagery acquired during the summer of 2008 (July 16 to August 11) where orthophotos were difficult to interpret (excessive snow conditions, minimal contrast).

Following mapping and classification of 191 current ice masses observed in the Torngats (Way et al, submitted), moraines and ice-cored debris fields observed immediately downvalley were recorded and mapped. These features were subsequently assessed based on physical characteristics of LIA moraines observed in situ during previous field seasons; this information then informs air photo interpretation of these features. Torngat LIA moraines are large with steep distal slopes and gentle proximal slopes; (Figure 4a) they are often un-differentiable from debris fields in glacier foregrounds.

The most prominent LIA moraines are ice-cored making them prone to instability because of melting interior ice (Figure 4b). These features have remarkably little vegetation growth aside from colonization by Rhizocarpon Geographicum lichens with little to no small shrubbery. In some cases, distinct LIA moraines are not recognizable, but elevated ice-cored debris fields make it possible to identify former ice margins (Figure 4c). For glaciers terminating in lakes without downvalley paleo-margins, we use 1950s ice margins (Barrand et al, in Prep).

Glacier polygons, from both 1950s and 2005 aerial photographs, were manually extended at the glacier snout to encompass hypothesized LIA areas. Given the greater uncertainty in estimating former ice coverage in accumulation zones, we make minimal changes to current glacier margins in these areas. As a result, total area changes are a minimum estimate given the possibility of undetected ice losses at glacier heads.

Factors Influencing Change

We collect potential factors influencing glacier change, and assess relationships visually and using linear regression. Factors chosen for the analysis followed the methodological approaches similar to those used in Debeer and Sharp (2009) and by Paul and Kääb (2005). The parameters calculated for each ice mass, and a brief methodology is listed below in table 1.

Table 1: Topographic variables collected in this study to evaluate geographic, topographic and meteorologic influences on ice masses in the Torngats. Table contains method of collection and reference for method.

Topographic/Geographic Parameter	Method of Collection	Reference
Aspect	Dominant direction (N, NE, NW, S, SE, SW, W, E) of ice mass basins. Measured parallel to glacier flow.	This Study
Length	Length (km) measured along the glacier centerline following flow direction	Paul et al (2004)
Distance to Coast	Distance to Labrador Sea coastline (km) measured from glacier centroid to nearest coastline using euclidean distance algorithm in ArcGIS 10	This Study
Altitude	Area-weighted minimum, maximum and mean elevation (m asl) calculated from DEM	Paul et al (2004)
Backwall Elevation	Mean height difference between ridgeline above glacier and upper ice margin parallel to ridgeline.	Modified from Debeer and Sharp (2009)
Upslope Area	Total area (km^2) between ridgeline above glacier and the upper ice margin	DeBeer and Sharp (2009)
Relative Upslope Area	Ratio between the total Upslope Area and total glacier area	DeBeer and Sharp (2009)
Upslope Area Slope	Upslope Area Slope measured using area-weighted slope (°) of the total Upslope Area	DeBeer and Sharp (2009)
Compactness	Ratio between glacier area and perimeter using the formula: $(4\pi\text{Area})/(\text{Perimeter}^2)$	DeBeer and Sharp (2009)
Solar Radiation	Mean clear-sky incoming (direct + diffuse) solar radiation (WH/m^2) calculated for melt season midpoint (August 1^{st}) in ArcGIS 10 (Fu and Rich, 2002).	This Study

Dating LIA Ice Margins

Local Lichen Measurements

Field work was conducted in the McCornick River Valley (Abraham and Hidden glaciers) and on Mount Caubvick (Minaret glacier) during August of 2007 and 2011 (Figure 5). We measure lichen thalli (body) on boulders occupying moraine surfaces immediately downvalley of nearby glaciers (Rogerson et al, 1986). Operators use a modified tape measure (± 1 mm accuracy) to measure the long-axis diameter of circular, non-coalescing Rhizocarpon Geographicum lichens to the nearest millimetre (mm). Lichen searches used all sides of moraines where surfaces were definitively of glacial origin, avoiding active slopes and glacial-fluvial activity to avoid sample contamination (McCarroll, 1994).

Variable lichen search areas depended on a series of factors, including moraine preservation, accessibility, size and the presence of discernible lichen growth. Search areas ranged from 110 m2 to 1100 m2 with a mean search area of 508 m2 (SD - 305 m2). By recording the 50 largest lichens in each area, we enabled comparison with previous lichenometric dating done in the region (McCoy, 1983, Rogerson et al, 1986, Bradwell, 2007) while providing sufficient measurements for outlier detection. In this study, we use both the largest lichen (LL, Evans et al, 1999) and the 10 largest lichens (10LL, discussed in Bradwell, 2009) approaches to give an age range for maximum advance of glaciers. Using both approaches reduces the impact of erroneously large lichens, a phenomenon that may be due to preferable local conditions rather than lichen age. Recent criticism (Bradwell, 2009) of more complicated statistical methodologies (Jomelli et al, 2007) precludes the usefulness of these methods in this study.

Lichen Growth Data

During the summers of 2007 and 2011, we visited and photographed (with scales) 7 of the 8 lichen growth stations (Figure 6, Lichen photos three panels) that McCoy (1983) and Rogerson et al (1986) established in 1978 and 1983 respectively at low (McCornick River Valley, 460 m asl) and high-altitude sites (Mount Caubvick, 854 m asl). Processing of photographs from the three intervals (1978, 1983, 2007/2011) for all available stations used the photo-editing software GIMP (v2.6). For each photograph without visible distortion, we fit the scales to a grid to calculate the number of pixels occupied by the 1 cm2 and 4 cm2 pieces in the photo frames.

We measured non-coalescing lichens across their long axis diameter in pixels and subsequently converted into millimeters. Calculation of diameter growth rate (DGR) between sequential photographs was possible for 17 lichens resulting in 24 unique DGRs – two DGRs for nine lichens (1978 to 1983, 1983 to 2007) and one DGR for eight lichens (1983 to 2007/2011). Lichen sizes ranged from 1.2 mm to 67 mm with a mean lichen diameter of 26 mm and a median lichen diameter of 21 mm.

To approximate lichen growth at various sizes, we fit 2nd order polynomials to both the high-altitude DGRs (Mount Caubvick, 854 m, R2 = 0.93) and the low-altitude DGRs (McCornick, 460 m, R2 = 0.51). Because the majority of LIA moraine search areas were between 650 and 750 m, we use the mean of the two growth rates (~657 m) as the best estimate for lichen growth rates on these moraines. The low-altitude curve is an upper constraint for the maximum lichen growth while the high-altitude curve is a lower constraint for minimum lichen growth. From these data, we produce age estimates and upper and lower constraints for lichens sized 0 to 70 mm.

Results

LIA Glacier Mapping and Area Change

In total, we find 165 Torngats glaciers at the LIA covering an area of 46.7 km^2 with a mean glacier size of 0.28 km^2 and a median glacier size of 0.20 km^2. The majority of these glaciers (132) were smaller than 0.4 km^2 with 13 being greater than 0.8 km^2 and only 6 being larger than 1.0 km^2. Recorded glacier lengths ranged from 0.15 km to 2.1 km (median, 0.56 km). 29 glaciers were longer than 1 km with one glacier being longer than 2 kms. Mapped glaciers were on average 18.3 km from the coastline; however, the median distance to the coast (13.9 km) is less skewed by outliers making it a better approximation. The mean and median latitude of glaciers were ~59.2° N with the majority of glaciers between 58.9 and 59.5°N. The most southern LIA glacier (58.6°N) is ~140 kms further south than the northernmost glacier (59.8°N) in the Torngats.

Mountain groups near Nachvak Fiord (59.0°N) and Ryan's Bay (59.4°N) hold over 70% of LIA glaciers. In these specific mountain environments, LIA glaciers were observable in all aspects unlike many other portions of the Torngats where the dominant aspect is north to northeast. The orientation of most Torngat glaciers (67%) is northwards with 51 glaciers facing the northeast, 37 facing north and 23 facing northwest. In total, 27 glaciers faced east with just 10 facing west. Southerly oriented LIA glaciers were about 10% of the inventory with only four glaciers facing south while six faced southeast and seven facing southwest.

Area Change

The total area of Torngat glaciers during the LIA was 46.7 km^2 and in 2005 was 22.2 km^2. This represents a cumulative reduction in glacier area of 24.5 km^2 or 52.5%. The mean and median changes in glacier area were 56.8% and 55.4%, respectively, with a standard deviation of 21.7% (1σ). The magnitude of change ranged from 15.7 to 100%, and the 25th and 75th percentiles were 37.9% and 71.2%. We summarize change results in Table 2.

Table 2: Characteristics of Torngat glacier change from the LIA to 2005. Table includes total count (Count), cumulative area (∑Area, km^2), median area (Q2Area, km^2), minimum area (MinArea, km^2), maximum area (MaxArea, km^2), median length (Q2Length, km), mean minimum elevation (µMinElev, m asl), and mean compactness (µCompact**,** undefined**).**

Dataset	**Count**	**∑Area**	**Q2Area**	**MinArea**	**MaxArea**	**Q2Length**	**µMinElev**	**µCompact**
2005	154	22.25	0.08	0.00	1.26	0.34	687.00	0.41
LIA	165	46.65	0.20	0.03	1.70	0.57	637.00	0.50
|Change|	11	24.40	0.12	0.03	0.44	0.23	50.00	0.11

In this analysis, we also find that 11 former glaciers altogether disappeared in the Torngats. Median glacier length decreased by 0.23 km or 41%. A noticeable decrease in the compactness of glaciers (0.11) implies a change in glacier morphometry from more to less regular shape and demonstrates that glaciers have become further confined to areas receive mass input from nearby slopes (Debeer and Sharp, 2009). Mean minimum glacier altitude also changed significantly with an increase in glacier elevation from 637 m asl at the LIA to 687 m asl in 2005 (+ 50 m). Consistent with these calculations, we find that the minimum altitude of the lowest glacier in the Torngats has increased by 90 m from ~147 m asl (LIA) to ~ 237 m asl (2005).

Factors influencing Change

We show results of the regression analysis comparing LIA glacier change and factors influencing glacier change in table 3. No single factor explains more than 15% of the variance in glacier change. However, we find statistically significant relationships (95%) that explain more than 5% of the variance between glacier change and upslope area slope, glacier elevation (max, mean, min) and glacier area. Results show that mean upslope area slope is the variable that explains the most variance (15%) in glacier change with larger slopes being positively correlated with larger ice changes. Maximum glacier elevation is the 2nd most important variable (10% of total variance) where higher altitude glaciers have correspondingly lower glacier changes.

Table 3: Pearson Correlation Matrix cross-comparison of glacier change and geographic, topographic and meteorologic variables for Torngat LIA glaciers. Table includes individual ice mass area, incoming solar radiation, ice mass latitude, mean/max/min elevation, distance to coastline, upslope area slope, ice mass length, mean backwall height, relative upslope area, and compactness. Table summarizes the correlation (R), the coefficient of determination and the number of degrees of freedom (DF) between variables and glacier change. Only statistically significant (95% confidence level (CL)), correlations are bolded and italicized in the table.

Variable	**R**	**R^2**	**DF**
Upslope Area Slope	***0.38***	***0.15***	153
Maximum Elevation	***-0.32***	***0.10***	164
Mean Elevation	***-0.29***	***0.09***	164
Minimum Elevation	***-0.22***	***0.05***	164
Area	***-0.22***	***0.05***	164
Backwall Height	***0.20***	***0.04***	153
Length	***-0.20***	***0.04***	164
Relative Upslope Area	***-0.20***	***0.04***	153
Latitude	0.14	0.02	164

Incoming Solar Radiation	-0.11	0.01	164
Distance to Coast	-0.08	0.01	164
Compactness	-0.02	0.00	164

In table 4, we show highly similar change rates across the 8 main aspects. Observations show marginally greater change rates for glaciers flowing to the southeast and east, though this result is tentative given the lower sample size relative to other directions.

Table 4: Summary of mean (µChange (%)) and median LIA glacier change (Q2Change (%)) relative to the 8 dominant aspects.

Aspect	**µChange (%)**	**Q2Change (%)**	**Count**
North	56.8	55.3	37
Northeast	58.8	61.9	51
Northwest	49.7	40.7	23
East	60.1	59.8	27
West	49.8	46.8	10
South	48.2	48	4
Southeast	77.4	77.2	6
Southwest	49.9	44.8	7

LIA Dating

Local Lichen Measurements

Field work conducted in the McCornick River Valley and at the base of Minaret Glacier (Mt. Caubvick) during August of 2011 resulted in 23 sampling transects on selected moraine segments across the region. Largest lichens recorded on individual transects encompass a range of 3 to 290 mm in diameter with no lichens found between 62 and 110 mm in size. In total, we interpret 10 sampling transects covering six unique glacier positions as being of LIA origin with these surfaces being altitudinal located between 657 and 955 m. The largest lichens recorded on

LIA surfaces ranged in diameter from 31 to 62 mm, the smallest on the highest LIA moraine and the largest on the lowest moraine.

Lichen Growth Rates

Regional lichen growth rates calculated for both the McCornick River and Mount Caubvick stations are presented in Figure 7, also shown is the mean of the two growth rates which estimates the growth rate for 657 m asl. The approximate shapes of regional growth curves show three phases of lichen growth, including: (1) Slow lichen growth at small lichen sizes gradually accelerating; (2) period of "great growth" with faster lichen growth accelerating until it plateaus at mid-sized lichens (~40-50 mm) and; (3) slow deceleration of lichen growth at larger lichen sizes after the period of "great growth" concludes (Bradwell and Armstrong, 2007).
The potential for additional phases of lichen growth exists for larger lichens (> 70 mm), but the lack of DGR data at these sizes cannot confirm or reject this notion. We show growth rate statistics comparing this study and previous studies in Table 5.

Table 5: Diameter growth rates measured on lichens in this study at the McCornick and Minaret growth stations compared to DGRs observed by Rogerson et al, 1986. Comparisons using the same range of lichen sizes are provided. All measurements are in mm/year.

Investigator	**Count**	**Range**	**SD**	**Min**	**Mean**	**Max**
This Study(McCornick)	18	1.2 - 67	0.08	0.09	0.17	0.34
This Study (McC 17-52 mm)	8	17 - 43	0.09	0.13	0.21	0.34
This Study (Minaret)	8	1.7 - 63	0.04	0.001	0.07	0.11
This Study (Minaret 17-52 mm)	4	32 - 52	0.02	0.07	0.09	0.11
Rogerson et al, 1986	7	17 - 52	0.19	0.1	0.34	0.58

Figure 8 shows estimated lichen age-size relationship with upper and lower constraints used for the analysis. As Bradwell and Armstrong (2007) showed in Iceland, the relationship between lichen size and surface age is considerably un-linear. The resultant age-size relationship (Figure 8) shows age increasing sharply for smaller lichens (<15 mm), as well as marginally for larger (>60 mm) lichens indicative of slower growth at both sizes ranges. Lichens of medium size (15-60 mm) have an age-size relationship which is mostly linear where age of lichens increases at a constant rate with increases in size.

Lichenometric LIA dates

Using the *in situ* lichen measurements taken on LIA moraines in combination with the regional lichen growth curve gives a mean LIA advance date between 1556 and 1595 depending on the method used. The earliest LIA advance (all techniques) occurs in 1491 AD with the youngest advance being in 1664 AD. Age constraints on the LIA using the lowermost and uppermost growth rates show that the maximum LIA advance of any glacier was unlikely to occur prior to 818 AD or after 1787 AD. We show mean LIA dates for individual sampling transects in Figure 9 with the upper and lower constraints on regional lichen growth. We find significant overlap for all moraine segments between the LL and 10LL approaches used to summarize the lichen data – this demonstrates the agreement between the different methodologies.

Discussion

Area Change Results

Quantified changes from the LIA to present (2005) for Torngat Mountain glaciers indicate an overall ice loss of ~52.5%. Compared to changes observed elsewhere in the Northern Hemisphere (Figure 10) these rates are dissimilar from most glaciers in the North Atlantic sector, but are similar in magnitude to those observed in the Austrian, Italian and Swiss Alps (Baumann et al, 2009, Knoll et al, 2009, Paul et al, 2004).

Glaciers in the eastern Canadian Arctic and the North Atlantic sector are the closest analogues to Torngat glaciers both geographically and climatically. However, we find glacier changes in the Torngats vastly exceed those observed on the Queen Elizabeth Islands (LIA to 1960) (Wolken, 2006, Wolken et al, 2008), in Norway (Baumann et al, 2009), on the Cumberland Peninsula of Baffin Island (Paul and Kääb, 2005), in Southern Baffin Island (Paul and Svoboda, 2009), in West Greenland (Citterio et al, 2009) and on Bylot Island (Dowdeswell et al, 2007).

These results suggest that glacier activity in the Torngats does not reflect widespread North Atlantic glacier patterns in magnitude. Ice losses in the Torngat Mountains are more so correlated with changes observed in mid-latitude alpine regions such as the European Alps and Southern Norway. Future projection of glacier changes in the region must be de-coupled from those of other Arctic Canadian glaciers and be considered separately.

Factors influencing change

(a) Spatial

We summarize the spatial distribution of changes observed in the Torngat glaciers   in figure 11. Change rates exhibit spatial homogeneity across all significant glacier bearing regions and show noteworthy variance within regions. Glaciers with both small (15-25%) and great ice loss (75-

100%) exist all across the entire range with non-statistically significant predominance of greater losses in the North. Climatic warming would suggest a northern migration of the glacier viability zone; however, these results show no relationship between glacier latitude and change (Table 3). Many southerly glaciers, in fact, show remarkably small overall change suggesting relative stability or the importance of non-climatic factors in the region (Way et al, submitted).

Previous work identified distance to coastline (Way et al, submitted) as a significant controlling mechanism on mean glacier altitude; however, we find no relationship between distance to coast and change (Table 3). These data allude to synchronous factors impacting both inland and coastal glaciers equally as we find no appreciable differences in change rates between inland plateau glaciers and coastal fretted mountain glaciers.

(b) Topographic

We examined several topographic factors, which may affect Torngat glacier change; however, only upslope area slope explains more than 5% of the variance in the dataset (15%). This dynamic contrasts the results of previous studies by Hoffman et al (2007), Debeer and Sharp (2009), Li et al (2011) and Basagic and Fountain (2011) who all note significant topographic influences on glacier change. In particular, several of these authors note the importance of backwall height in regulating glacier changes because of the topographic shadowing provided by the large backwalls. However, we do not note any strong correlations with backwall height (Table 3). The importance of upslope area slope on glacier changes reflected in the results is intriguing because this variable is a proxy for avalanching and funneling of snowfall onto glacier surfaces. This relationship with change (though weakly correlated) indicates that glaciers with greater upslope slopes and dependency on avalanching experienced larger changes since the LIA. An interpretation of this relation is that these glaciers are more dependent on mass inputs; thereby, a reduction in precipitation (snowfall) would experience these glaciers more proportionally.

(c) Altitude, Size and Length

We find that mean maximum glacier altitude has a weak (R^2 = 0.10) but statistically significant influence on glacier change (Table 3). This implies that glaciers with lower accumulation areas tend to incur greater ice losses relative to higher glaciers. This dynamic is interpreted as being indicative of upwards migration in the regional glaciation level. This finding is supported by observations that glaciers above 1000 m (n=20) experienced 19% less change on average (52%) compared to glaciers below 500 m asl (n=21, 71%). Additionally, we find no glacier above 780 m asl fully downwasted and that the mean elevation for glaciers that have melted away was 534 m asl, much lower than the mean glacier altitude (729 m asl) at the LIA. To support this observation, we also find a significant (~90 m) upwards migration of glacier viability (minimum altitude) in the Torngats (see results).

Previous works (Paul et al, 2004, Paul and Kääb, 2005) have observed areal extent changes greater amongst glaciers smaller than 5 km^2 in both the Canadian Arctic and the Swiss Alps. All glaciers in the Torngats are considerably smaller than the < 5 km^2 size threshold used in other studies; however, we observe larger change and greater variability in change among smaller glaciers in the study area consistent with results observed elsewhere (Table 3) (Paul et al, 2004, Paul and Kääb, 2005). A natural break in the data exists whereby glaciers larger than 0.8 km^2

(n=13) show significantly less change (40 %) than those smaller than 0.8 km^2 (n= 152) (58 %). Similarly, we find that for glaciers longer than 1 km (n=29) there is considerably less ice loss (11% less) than shorter glaciers (<0.5 km, n=72).

LIA timing in the Torngats

The estimated timing of the LIA throughout the northern hemisphere is extremely variable but corresponds to the period from ~1400 to ~1900 AD (Moberg et al, 2005). In the Torngats, we dated the maximum LIA glacier advance to be between ~1491 and 1664 AD; however, we find the mean period of maximum LIA advance to be between 1556 and 1595 AD. Including the uncertainties in the regional growth rate, we constrain the period of largest LIA advance to be between 818 and 1787 AD with the most likely outcome between closer to the latest date rather than the earliest. By comparison, Rogerson et al (1986) dated the same moraines as used in this study and received LIA dates between ~1857 and ~1904 by linearly extrapolating mean lichen growth rates from seven growth stations.

Using maximum lichen growth rates from their stations, they find LIA dates between ~1907 and 1935 AD while use of their minimum lichen growth rates gives LIA ages between ~1568 and ~1728 AD. The LIA dates presented in this study supercedes those of Rogerson et al (1986) because of a significantly larger database of DGRs and a more accurately modeled lichen growth relationship.

Comparison with Northern Hemisphere LIA advance timings

Dates provided from this study for the LIA in the Torngats (~1491 to ~1664 AD) are significantly earlier from LIA dates across the remainder of the northern hemisphere (Figure 10). The timing of the maximum LIA advance in the Torngats is unique relative to other alpine glaciers, but is, in particular, much earlier compared to its most geographically and climatically similar neighbours in the North Atlantic and the Arctic which reached their LIA maximums between ~1870 and ~1920 AD – far later than in the Torngats.

Although authors find younger LIA dates compared to the North Atlantic sector throughout the Alps, eastern Russia (~1700 to ~1880, Solomina, 2000, Solomina et al, 2004) and Western Europe, neither is comparable to those of the Torngats (Figure 10). These comparisons suggest that the magnitude of LIA advance in northern Labrador was a unique event specific to this region and that this event occurred independent of advances elsewhere in the North Atlantic. Supporting the LIA dates provided in this study is a 400 year tree-ring chronology which shows reduced tree-ring growth at the treeline in northern Labrador over the same period as we propose for maximum ice advance (Figure 13, D'Arrigo et al, 2003, Kinnard et al, 2011). Viau and Gajewski (2009) find similar using the North American Pollen Database and the modern analog technique for the Labrador region.

In both reconstructions, there is a pronounced late 19th century cooling, which coincides with glacier advances in the North Atlantic, however, reconstructed precipitation anomalies for Labrador (Viau and Gawjeski, 2009) suggest significantly lower precipitation than preceding centuries. This may provide some insight as to the nature of the de-coupling between Torngat glacier advance and those in the remainder of the North Atlantic. An additional consideration is that peak glacier advance in the Torngats coincides with a period of pronounced cooling in the

Northern Hemisphere associated with decreased solar activity known as the Maunder Minimum from ~1645 to ~1715 AD (Eddy, 1976, Shindell et al, 2001). Solar radiation as a control on former ice advance in the Torngats is a plausible scenario; particularly given that Torngat glaciers are preferentially situated in areas with reduced incoming solar radiation (Way et al, Submitted).

Local Lichen Growth Rates

Previous work in the region by McCoy (1983) and Rogerson et al (1986) tentatively dated moraine sequences in the region using lichenometry with both coming to decidedly different conclusions about the local glacial history. McCoy (1983) applied growth rates established on the Cumberland Peninsula of Baffin Island of 0.03 mm/year (Miller, 1973) to collected lichen sizes on moraines and debris fields. McCoy (1983) rationalized this method assuming climatological and geographical similarities between northern Labrador and the Cumberland Peninsula. In the time since that study, Rogerson et al (1986b) contested the application of the growth rate from Baffin Island to Labrador and Bradwell and Armstrong (2007) challenged the use of a single linear growth rate across all sizes in lichenometry.

A later study, Rogerson et al (1986), incorporates locally measured lichen growth rates measured from growth stations between 1978 and 1983 using the photogrammetric method (Locke et al, 1978). Rogerson et al (1986) estimates moraine ages linearly providing a range of ages from the minimum, maximum and mean growth rates from measured lichens. The rates recorded by Rogerson et al (1986) are much higher than those recorded in this study (Table 5). Rogerson et al (1986) provide no growth rates for lichens smaller than 18 mm in size and include only one growth rate for lichens above 36 mm in size. In addition, careful examination of outlines of lichen growth across their seven lichens reveal that half of their measured lichens do not meet the suitable criteria for DGR estimation owing to their irregular shape and/or coalesced nature (Bradwell, 2009). The points mentioned above cast doubt on moraine dating in Nachvak Fiord by Rogerson et al (1986) and reflect on advances in lichenometry since that time (Table 5).

In this study, we provide both low altitude and high-altitude lichenometric curves and use the mean growth rate between the two as a reasonable estimate for lichen growth at LIA moraines. These curves rely on more DGR measurements than previous work in the region (n=24 versus n=7) and encompass a greater range in lichen sizes. Using this growth curve on lichen data from Rogerson et al (1986) reveals LIA dates between ~1645 and ~1747 AD, very similar to this study's proposed LIA advance dates. Further discrepancies between these studies could reflect differences lichenometric field techniques where McCoy (1983) and Rogerson et al (1986) measured and recorded only the largest lichens found during 20-minute searches of moraine debris. In this study, we recorded a much larger sample (>15) of largest lichens within greater search areas and just on individual moraine surfaces rather than debris fields. Longer search periods (~3 hours per moraine vs ~20 minutes per moraine) in this study revealed large lichens on moraine surfaces that missed during previous surveys by other authors.

Universal Lichen Growth Rates

In total, 12 studies have reported growth data on Rhizocarpon subgenus lichens; however, only two studies (Armstrong, 1983, Bradwell and Armstrong, 2007) have produced comprehensive growth curves considering growth as a function of diameter. We present the first such curve for the eastern Canadian Arctic, and the first set of curves produced within close proximity (<20 km) at different altitudes. From these data, we conclude that lichen growth rates observed in the Torngats are for the most part significantly smaller than those observed elsewhere in glacial environments except for and Antarctic Peninsula (Bradwell and Armstrong, 2007). The Torngat growth data compares favorably in both shape and absolute growth rate to a hypothesized growth curve for West Greenland at 68°N (Bradwell and Armstrong, 2007). This is not surprising as the local climate conditions in West Greenland are similar to those in the Torngats.

Bradwell and Armstrong (2007) hypothesize, using their data from both north Wales and southern Iceland that lichens show three distinct phases of lichen growth. We find strong evidence of these hypothesized phases at the moderate-climate lichen growth station (McCornick) and a significantly attenuated version at the harsh-climate lichen growth station (Minaret) – a result hypothesized by Bradwell and Armstrong (2007). This work provides direct evidence that rates, shapes, and phases of lichen growth curves hypothesized by Bradwell, and Armstrong (2007) are accurate and reproducible.

Conclusions

Using a combination of remote sensing, in situ field data and lichenometry, this study reconstructs former Little Ice Age glacier advances in the Torngats, quantifies change from the LIA to present (2005), explores factors influencing these changes and provides a range of dates for the LIA in the Torngats.

In summary:

[1] We reconstruct the glacier paleomargins at the LIA for 165 Torngat glaciers covering an area of 46.7 km^2;

[2] observations show an overall decrease in glacier area of ~52.5% from the LIA to 2005 including the loss of at least 12 glaciers;

[3] findings show statistically significant relationships between glacier change, and upslope area slope interpreted as a reflection of glaciers being impacted by less snowfall; additionally results imply that higher, larger Torngat glaciers are less susceptible to change;

[4] ten lichen measurement transects of 6 LIA paleomargins reveal that glaciers advanced synchronously at their LIA maximum;

[5] we create both low altitude and high altitude lichen growth curves in neighbouring valleys each showing significant differences in shape and absolute growth rate;

[6] using a combination of these growth curves reveals LIA moraine abandonment ages between ~1491 and ~1664 AD and;

[7] results suggest that Torngat glaciers are all retreating/shrinking making their future survivability in a warming climate yet unknown.

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Figure Captions

Figure 1: Geographic location of the study area: (left) Torngat Mountain glacier range in relation to the eastern Canada (right) Torngat Mountain glacier range with regions of interest illustrated in white. A and B show the locations of lichenometry field work during August of 2011, locations are shown in depth in Figure 5, panels A and B.

Figure 2: (Histogram) Average monthly precipitation (mm) for the Torngat Mountains region derived from ERA-Interim reanalysis for the period 1980-2011 (Dee et al, 2011). (Lines) Average monthly temperature (°C) for the Torngat Mountains derived from ERA-Interim reanalysis for the period 1979-2009 at 2 m asl and ~1500 m asl (850 millibars) (Dee et al, 2011). Dotted black line depicts 0°C.

Figure 3: Examples of some current ice masses in the Torngats Mountain glacier range: (a) Cirque Glaciers (b) Simple Basin Glaciers (c) Summit Ice Mass. Panels A & C are photograph while panel B shows digital air photos draped over an 18 m resolution DEM.

Figure 4: Photographs of little ice age glacier margins used for mapping past glacier margins: (a) steep sided ice-cored terminal moraine (b) elevated ice-cored debris field.

Figure 5: Location of lichen sampling transects (red) and lichen growth stations (green dots) visited during the field season of 2011: (A) McCornick River Valley (B) Mount Caubvick. Transects, stations and ice masses are plotted on digital air photos.

Figure 6: Photographed chronology of a *Rhizocarpon Geographicum* lichen growing at a lichen growth station covering the following time intervals: (a) 1978 (b) 1983 (c) 2007. 1 cm^2 scale piece is also located in photo frame.

Figure 7: Lichen growth curves derived from 2^{nd} order polynomial fits of diameter growth rate data for the McCornick River Station (460 m asl) (red) and Minaret (Mount Caubvick) Station (854 m asl) (green). The mean of the two rates (black) is used as an approximation of lichen growth at 657 m asl.

Figure 8: Estimated lichen ages (year AD) for lichen sizes 0 to 70 mm for the McCornick River Station (red), Minaret (Mount Caubvick) Station (green) and for the mean growth rate of both stations (black).

Figure 9: Estimated dates for maximum little ice age glacier advances in the Torngats for 10 moraine segments sampled in August of 2011. Moraines are dated using the Largest lichen (red dots) and 10 Largest lichens (black squares) approaches. Estimates use the mean growth rate of the McCornick and Minaret stations, while the upper and lower constraints are from the two respective stations (red and black lines).

Figure 10: Geographic distribution of little ice age glacier change and little ice age maximum advance timing across the North Atlantic. All sources are detailed in the text of the discussion.

Figure 11: Spatial distribution of glacier changes in the Torngats from the little ice age to 2005,

the magnitude of change is depicted by graduated points and a graduated colour scheme.

Figure 12: Tree ring width anomalies from northern Labrador RCS tree ring chronology constructed by D'Arrigo et al (2006) and made available by Kinnard et al (2011). Anomalies are with respect to the 1570-1995 average, cold deviations from the mean are shown in blue and warm deviations from the mean are shown in red.

FIGURES

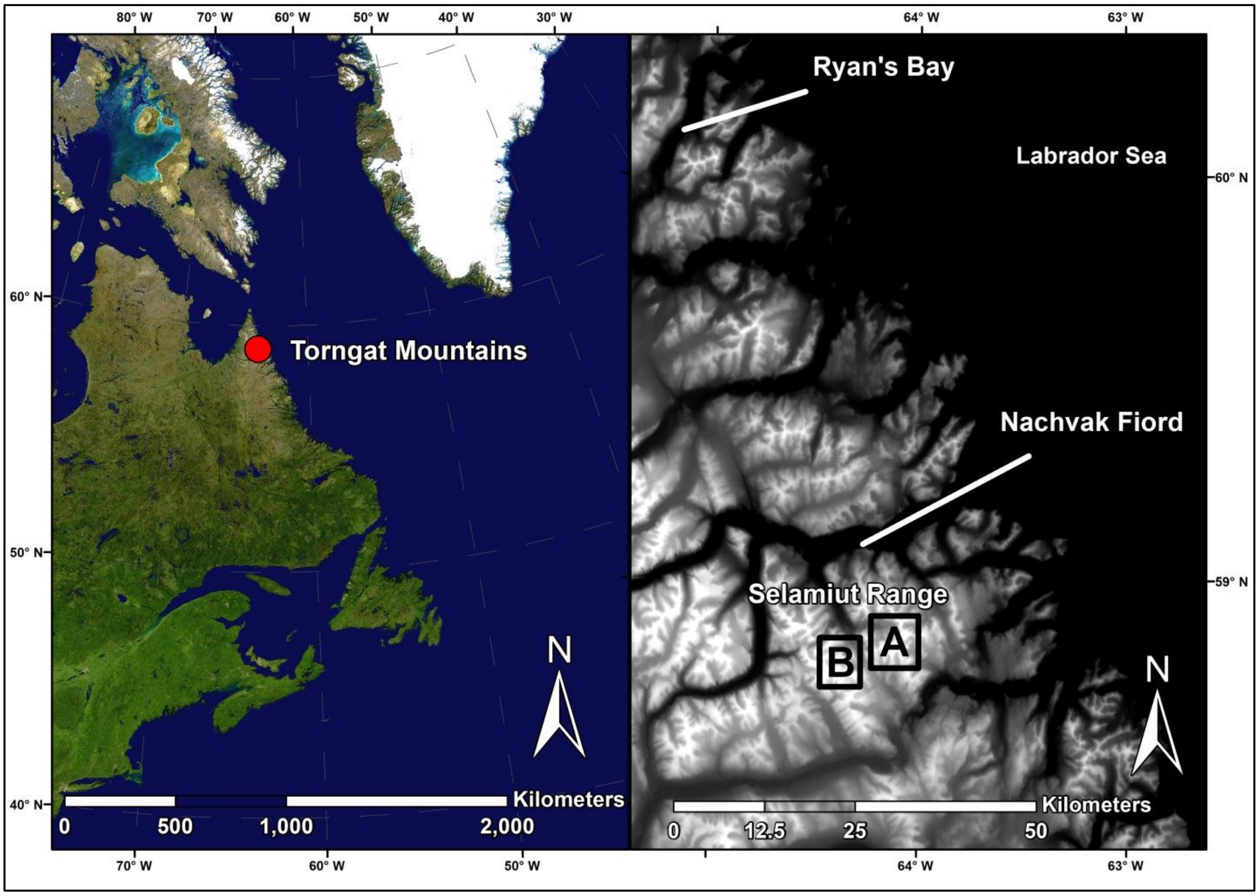

Figure 1

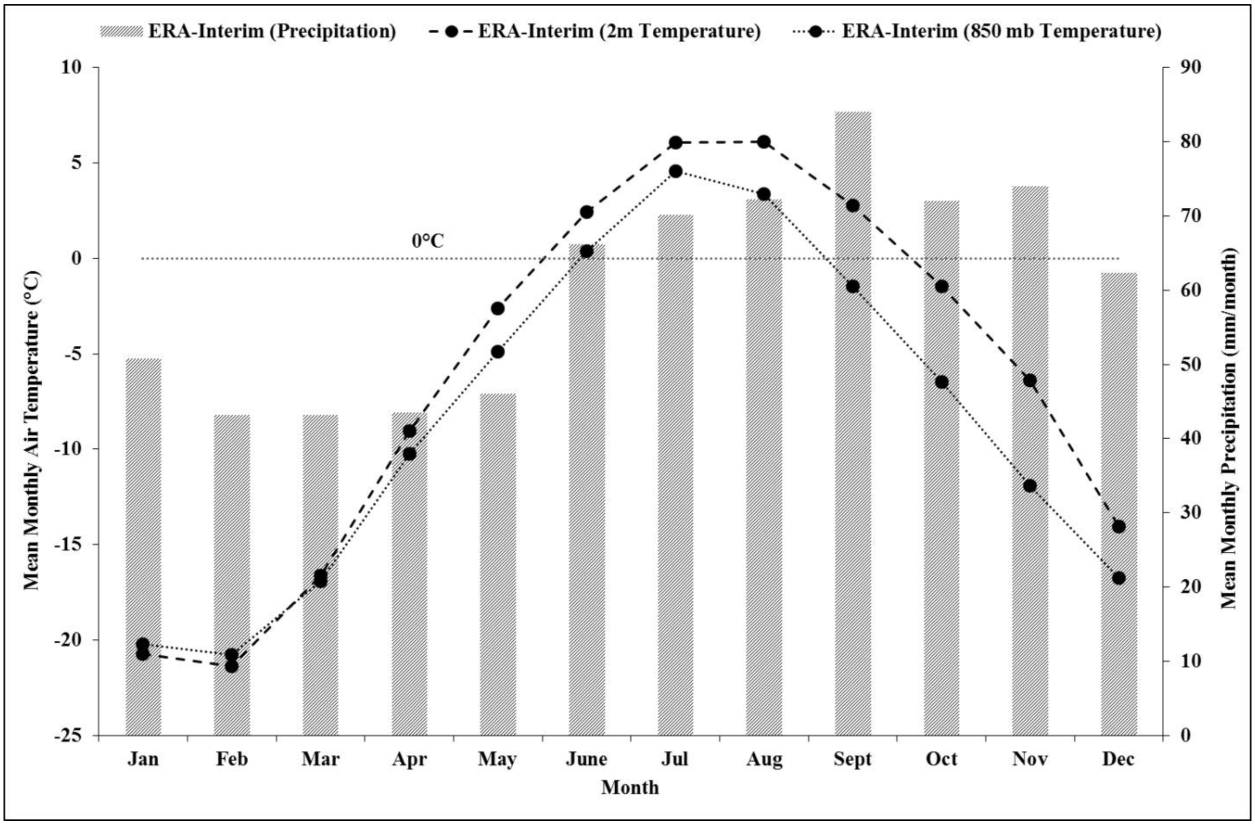
ERA-Interim (Precipitation)
ERA-Interim (2m Temperature)
ERA-Interim (850 mb Temperature)
Mean Monthly Air Temperature (°C)
Mean Monthly Precipitation (mm/month)
0°C
10
5
0
-5
-10
-15
-20
-25
90
80
70
60
50
40
30
20
10
0
Jan
Feb
Mar
Apr
May
June
Jul
Aug
Sept
Oct
Nov
Dec
Month

Figure 2

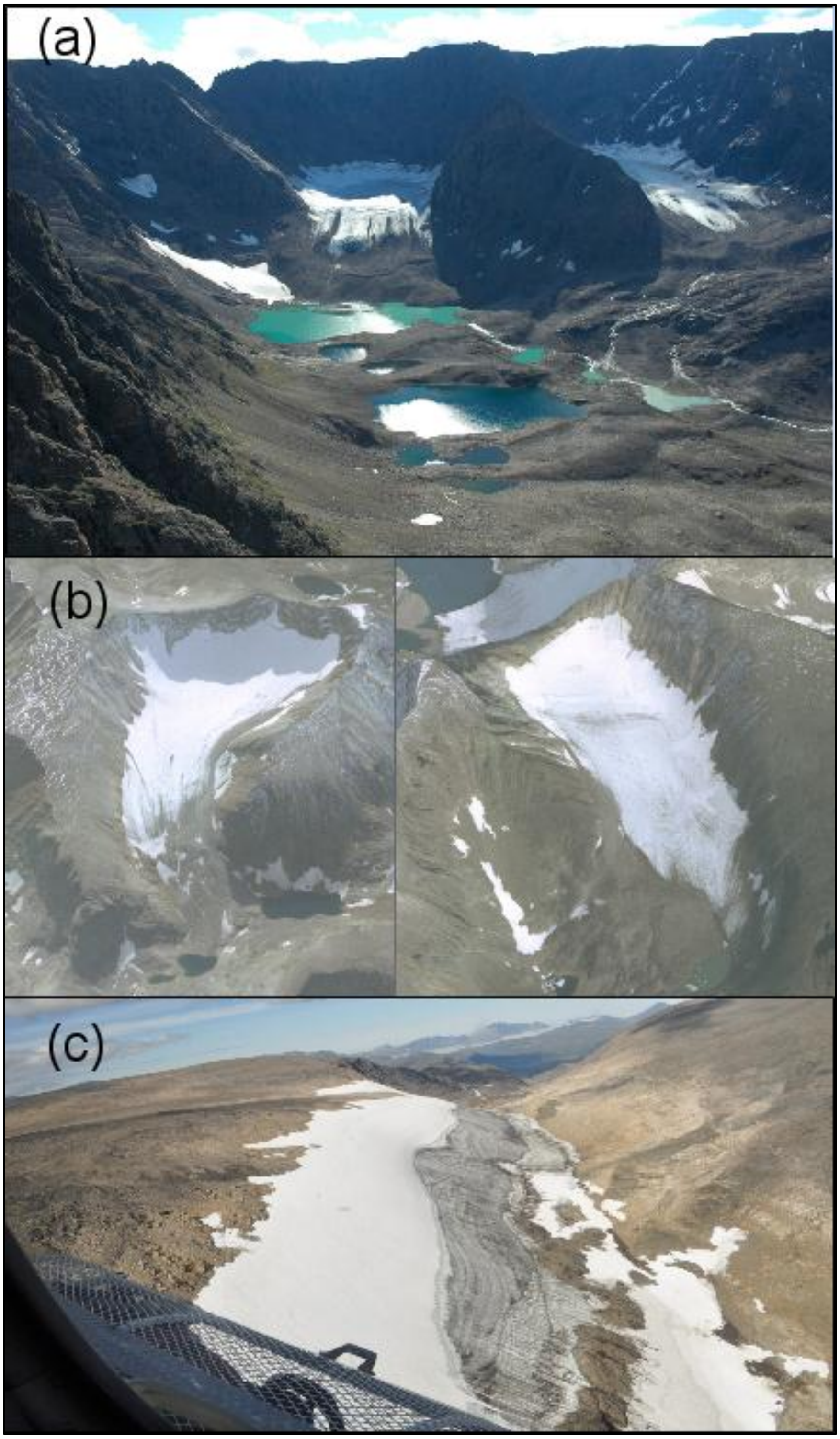

Figure 3

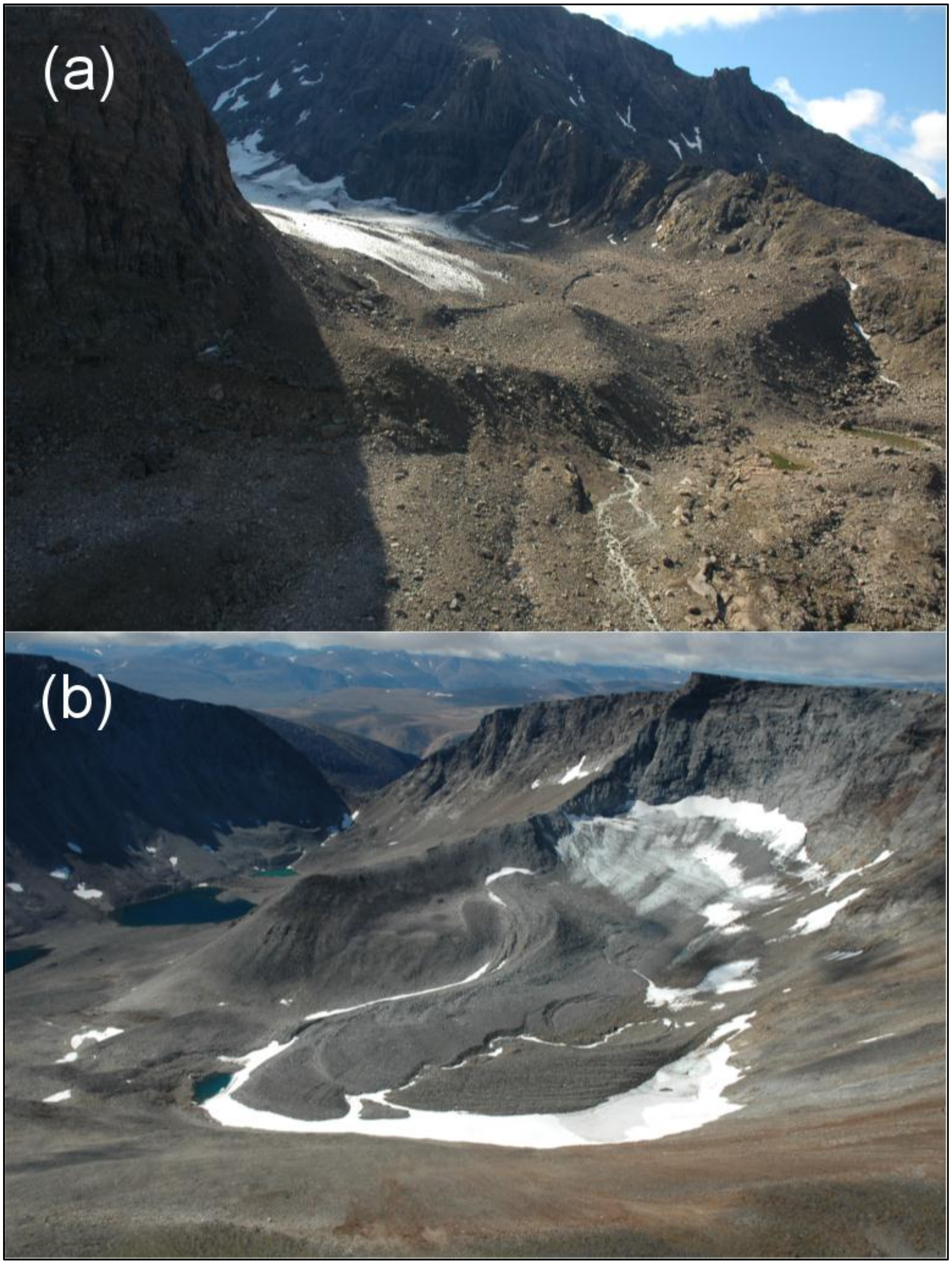

Figure 4

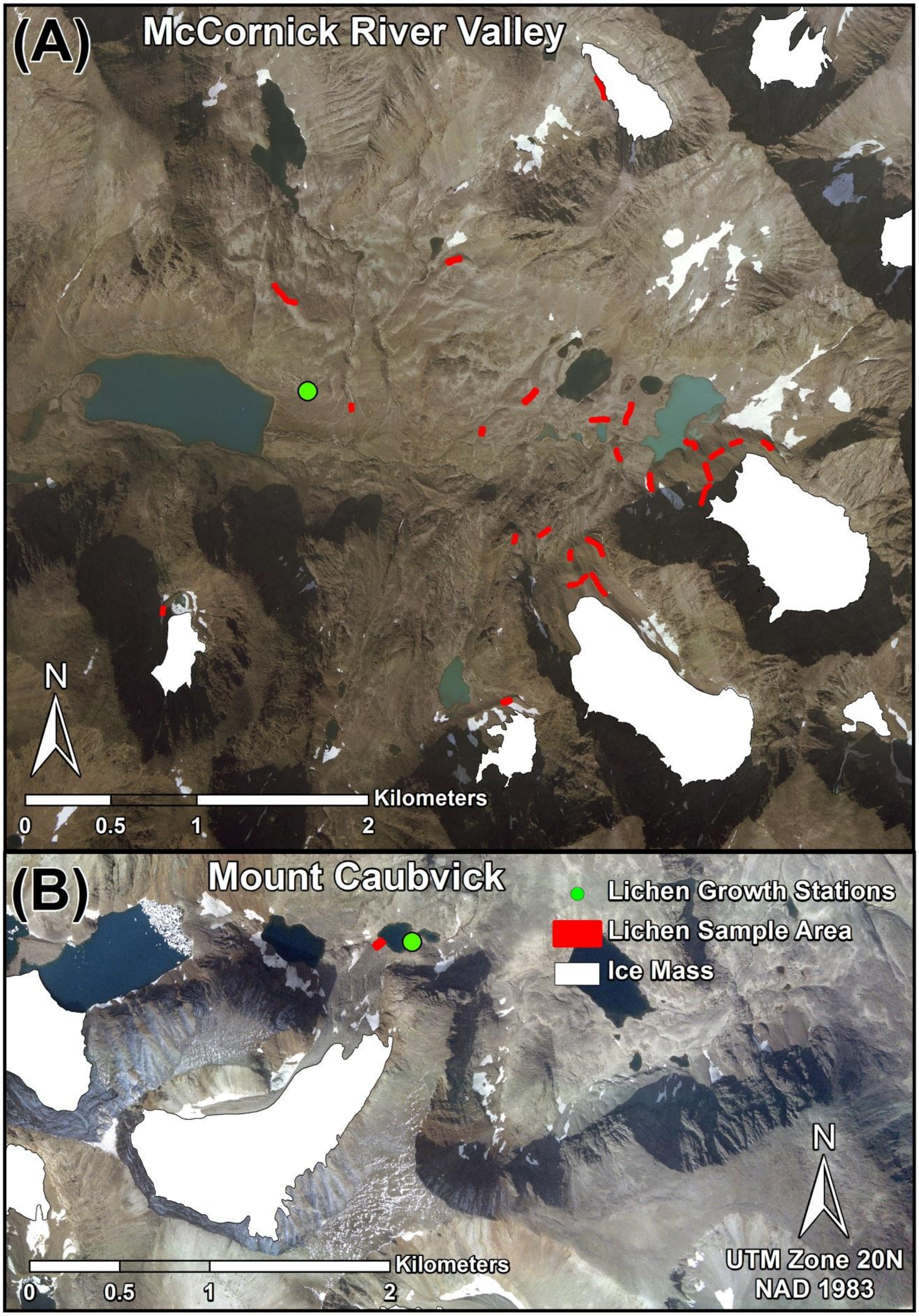
(A)
McCornick River Valley
N
Kilometers
0
0.5
1
2
(B)
Mount Caubvick
Lichen Growth Stations
Lichen Sample Area
Ice Mass
N
Kilometers
0
0.5
1
2
UTM Zone 20N
NAD 1983

Figure 5

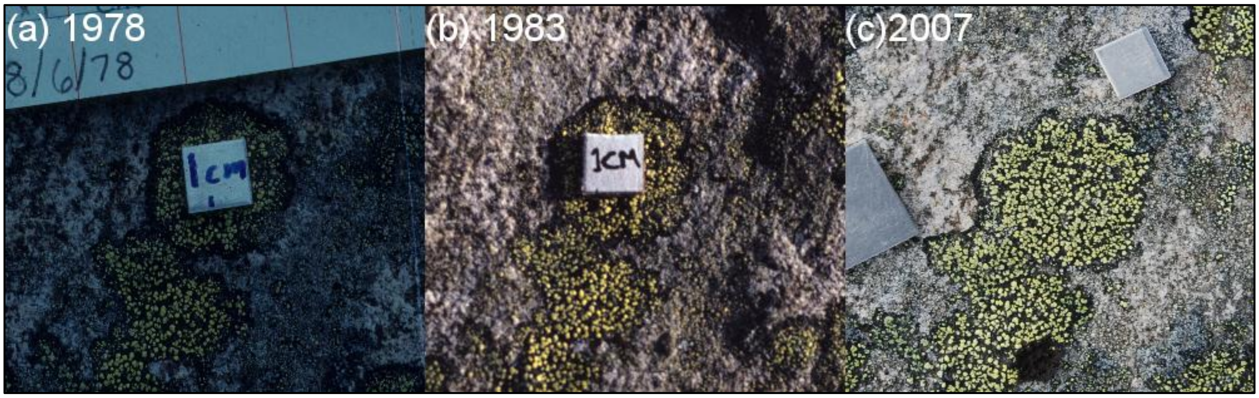

Figure 6

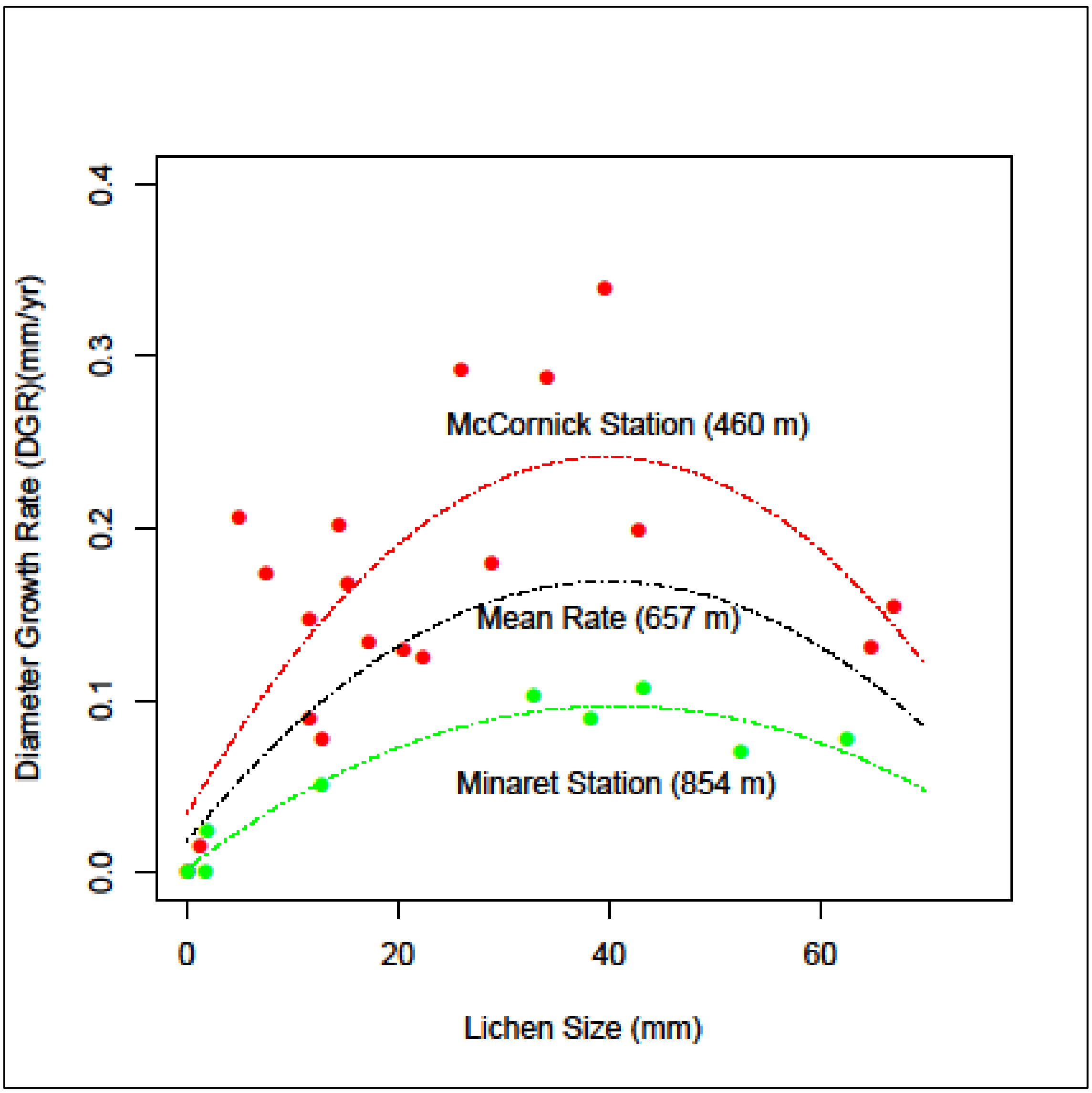

Figure 7

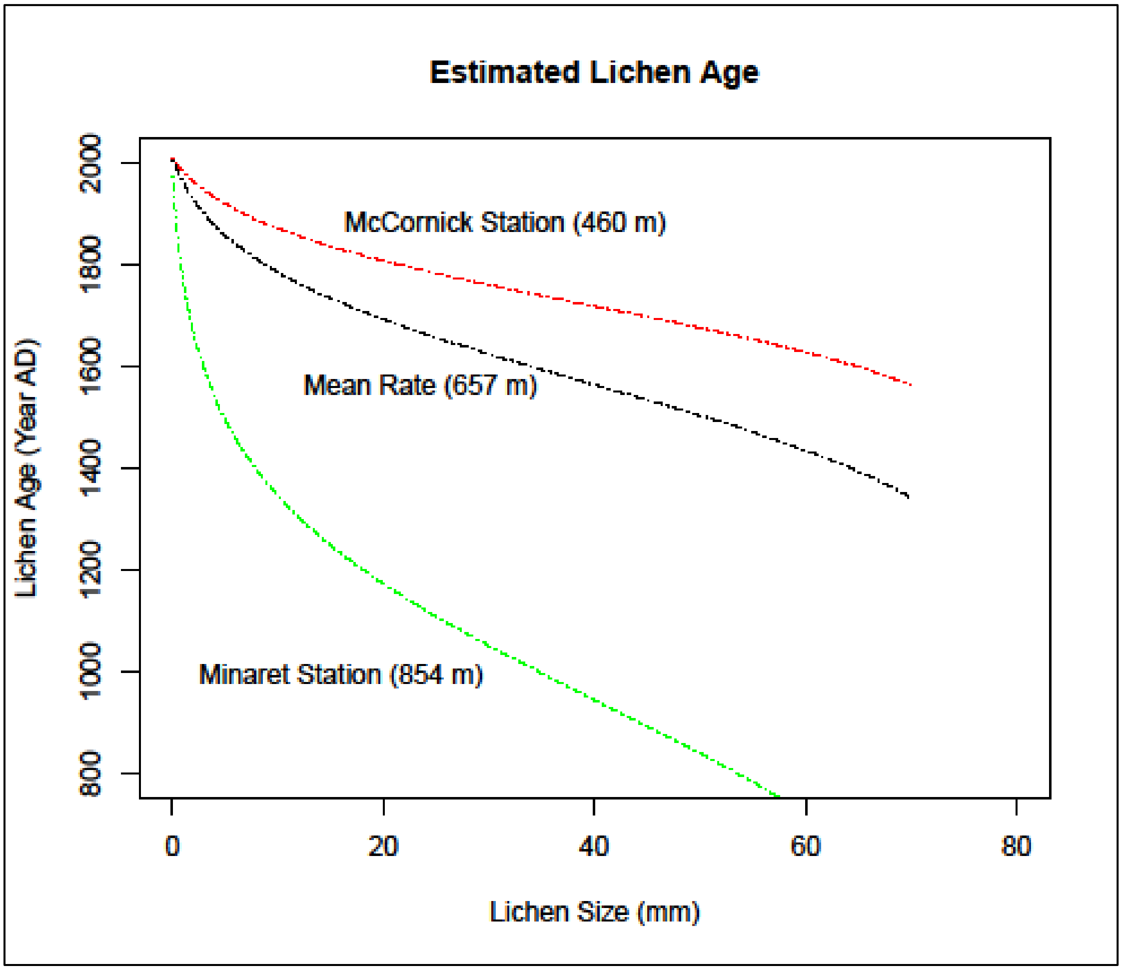

Figure 8

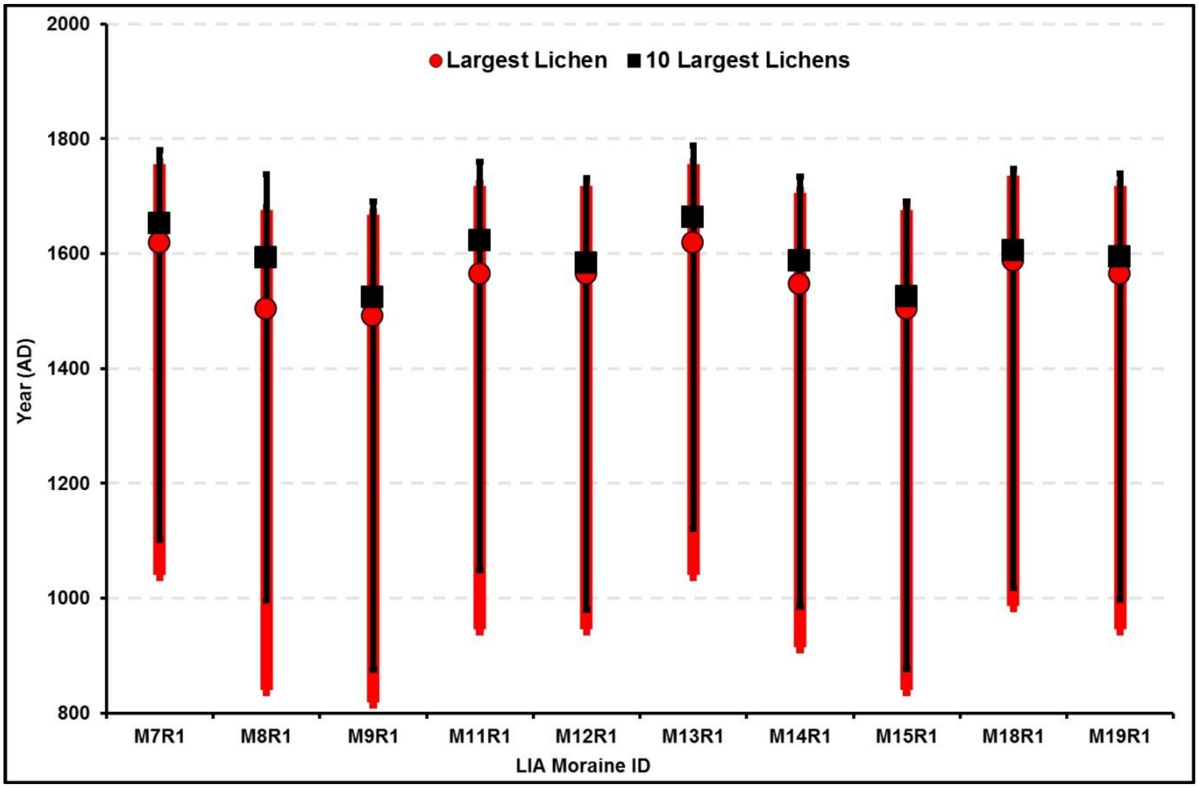

Figure 9

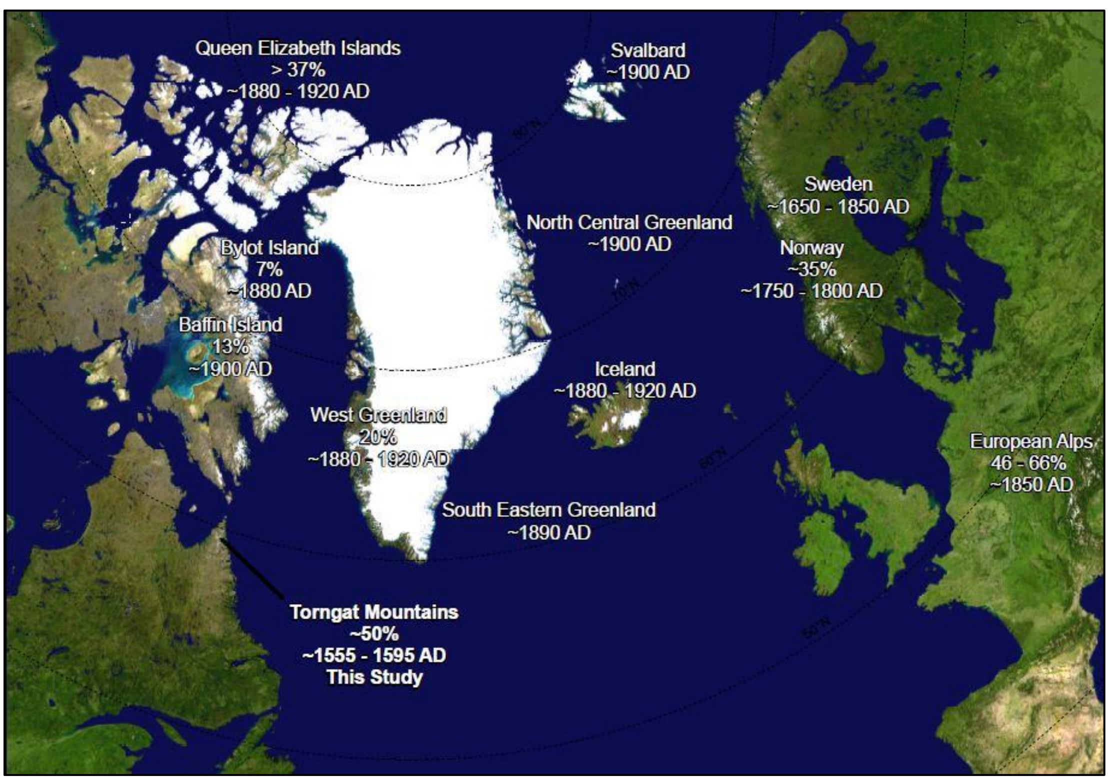

Figure 10

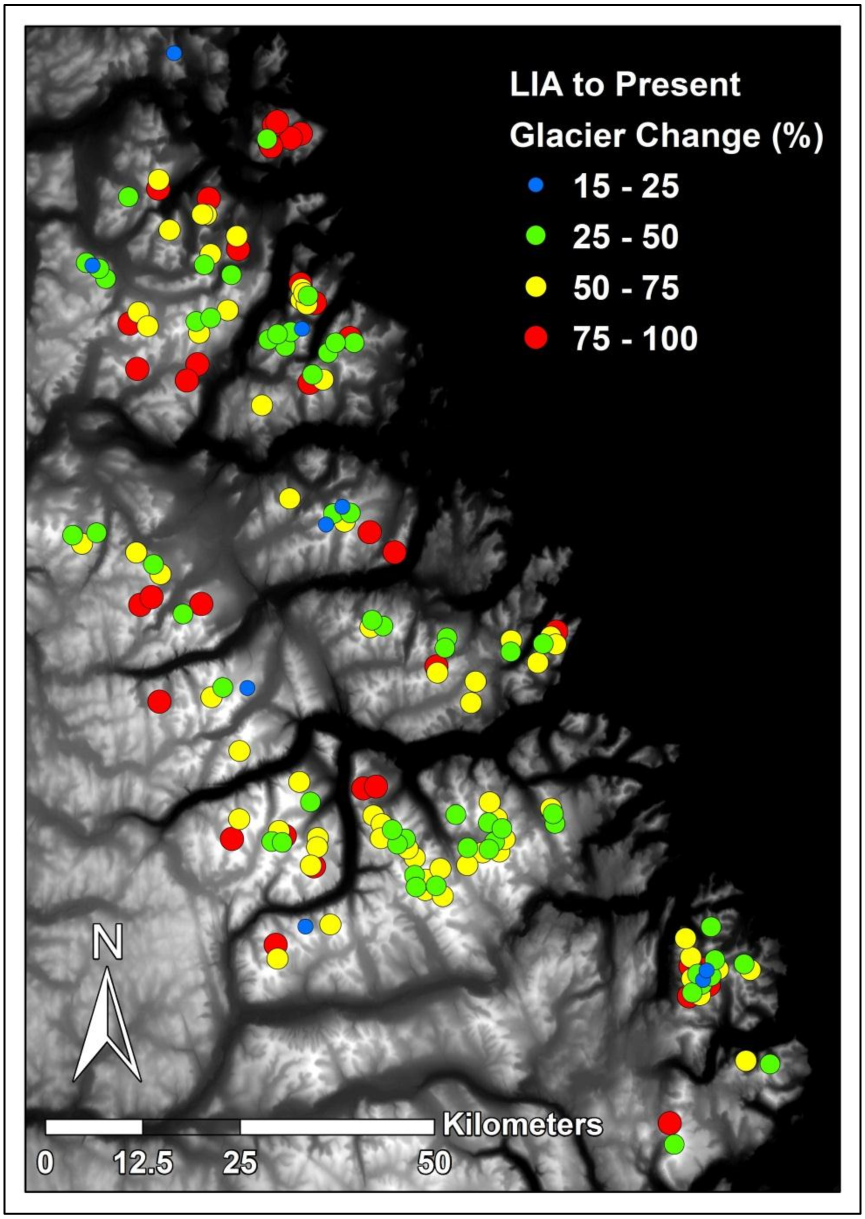
LIA to Present
Glacier Change (%)
15 - 25
25 - 50
50 - 75
75 - 100
N
Kilometers
0
12.5
25
50

Figure 11

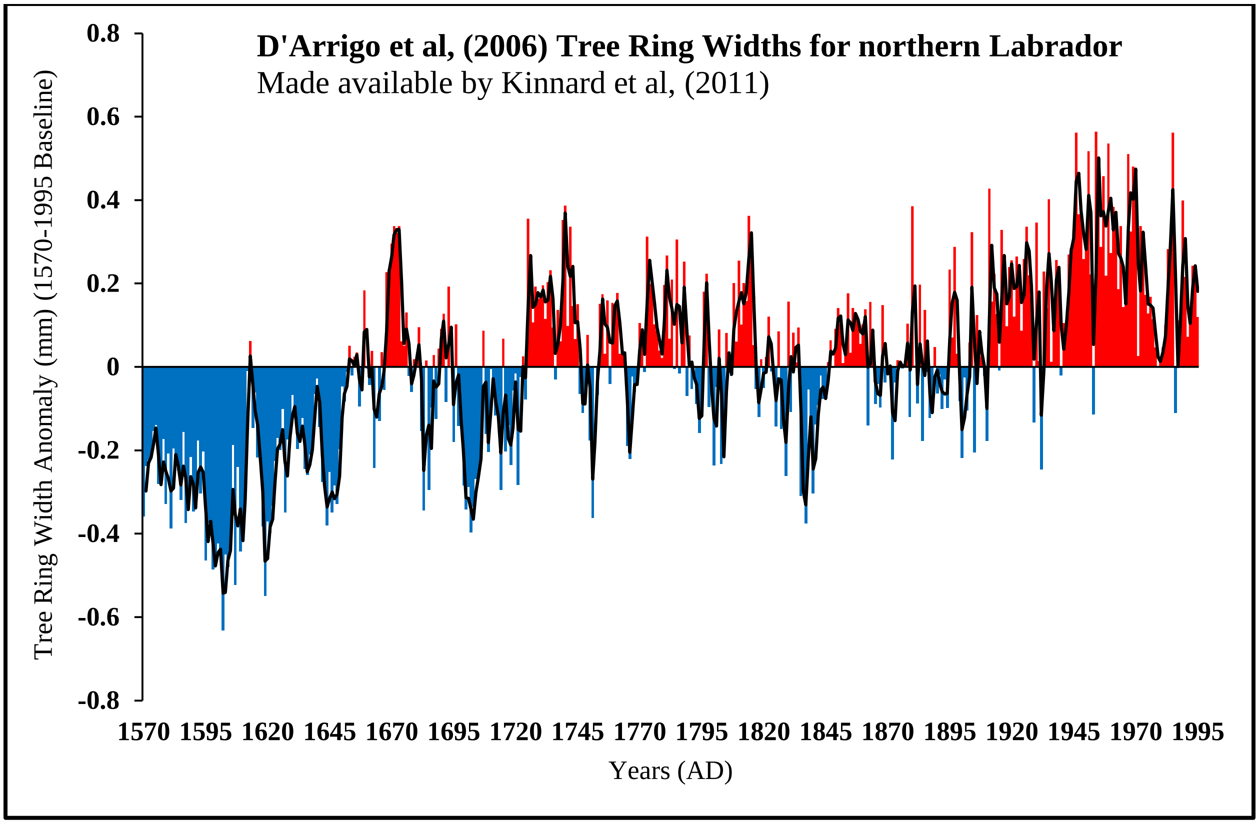
D'Arrigo et al, (2006) Tree Ring Widths for northern Labrador
Made available by Kinnard et al, (2011)
Tree Ring Width Anomaly (mm) (1570-1995 Baseline)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
1570 1595 1620 1645 1670 1695 1720 1745 1770 1795 1820 1845 1870 1895 1920 1945 1970 1995
Years (AD)

Figure 12