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Key Points:
- We find an acceleration of 23% in the annual rate of NE Greenland glacier volume losses since LIA
- We map the reduction in glacier extent of 1,570 ± 314 km^2 since LIA
- Approximately 7% of mass loss from Greenland mountain glaciers and ice caps has come from NE Greenland

Supporting Information:
- Supporting Information S1
- Data Set S1
- Data Set S2

Correspondence to:
J. L. Carrivick,
j.l.carrivick@leeds.ac.uk

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Author Contributions:
Conceptualization: Jonathan L. Carrivick, Clare M. Boston, Duncan J. Quincey, Mark W. Smith, Michael Grimes
Data curation: Jonathan L. Carrivick
Formal analysis: Jonathan L. Carrivick, Clare M. Boston
Funding acquisition: Jonathan L. Carrivick, Jeff Evans
Investigation: Jonathan L. Carrivick, Clare M. Boston
Methodology: Jonathan L. Carrivick, Clare M. Boston, Owen King, William H. M. James
Project administration: Jonathan L. Carrivick, Mark W. Smith, Jeff Evans
Supervision: Jonathan L. Carrivick
Writing - original draft: Jonathan L. Carrivick, Clare M. Boston, Owen King, William H. M. James, Duncan J. Quincey, Mark W. Smith, Michael Grimes, Jeff Evans
(continued)

Accelerated Volume Loss in Glacier Ablation Zones of NE Greenland, Little Ice Age to Present

Jonathan L. Carrivick[1], **Clare M. Boston**[2], **Owen King**[3], **William H. M. James**[1], **Duncan J. Quincey**[1], **Mark W. Smith**[1], **Michael Grimes**[1], **and Jeff Evans**[4]

[1]School of Geography, University of Leeds, Leeds, UK, [2]Department of Geography, University of Portsmouth, Portsmouth, UK, [3]Department of Geography, University of Zurich, Zurich, Switzerland, [4]Department of Geography, University of Loughborough, Loughborough, UK

Abstract Mountain glaciers at the periphery of the Greenland ice sheet are a crucial freshwater and sediment source to the North Atlantic and strongly impact Arctic terrestrial, fjord, and coastal biogeochemical cycles. In this study we mapped the extent of 1,848 mountain glaciers in NE Greenland at the Little Ice Age. We determined area and volume changes for the time periods Little Ice Age to 1980s and 1980s to 2014 and equilibrium line altitudes. There was at least 172.76 ± 34.55-km^3 volume lost between 1910 and 1980s, that is, a rate of 2.61 ± 0.52 km^3/year. Between 1980s and 2014 the volume lost was 90.55 ± 18.11 km^3, that is, a rate of 3.22 ± 0.64 km^3/year, implying an increase of ~23% in the rate of ice volume loss. Overall, at least ~7% of mass loss from Greenland mountain glaciers and ice caps has come from the NE sector.

Plain Language Summary Mountain glaciers are especially important sources of freshwater and sediment to the oceans. They are known to be diminishing globally, but there is a lack of information on how present rates of ice mass loss compare to those in the past. In this study we have for the first time mapped the extent of mountain glaciers in NE Greenland at the Little Ice Age, which was approximately year 1910, and we have determined the glacier area and volume changes from then to the present day. Overall, we find an acceleration in the rate of ice volume loss toward the present day of ~23% but we note considerable differences in that rate between individual glaciers. We suggest that the NE Greenland mountain glaciers contribute ~7% of the entire mass loss from Greenland as a whole. These findings are important because the resultant meltwater and sediment efflux affects North Atlantic and Arctic Ocean circulation and the associated conveyance of mineral, nutrient, and carbon also strongly impacts terrestrial, fjord, and coastal flora and fauna.

1. Introduction

Arctic and subarctic glaciers presently have a total coverage of >410,000 km^2 and account for ~60% of all mountain glaciers and ice caps (GICs) globally (Randolph Glacier Inventory, RGI, v5). Most (~88%) of these GICs each have a surface area <5 km^2 (Pfeffer et al., 2014) and as a function of this small size have faster response times than ice sheets and so are important indicators of climate change over decadal time scales (Dyurgerov, 2003; Dyurgerov & Meier, 2000; Haeberli et al., 2007; Raper & Braithwaite, 2006).

Globally, GIC contributions to sea level rise over the last decades have been more significant than contributions from the major ice sheets (Bamber et al., 2018; Raper & Braithwaite, 2006) and have accelerated recently (Chen et al., 2013), especially in the Arctic (Bamber et al., 2018). This disproportionately large contribution of GICs to global sea level rise is expected to continue for many decades (Huss & Hock, 2015). It is therefore crucially important to (i) not rely solely on glacier area statistics as relied on by inventories such as the Randolph Glacier Inventory (RGI) within GLIMS https://www.glims.org/ but also to incorporate glacier volume changes and (ii) place measurements of recent (satellite era) GIC changes into a longer time scale perspective by reconstructing glacier geometry during the Little Ice Age (LIA; cf. Carrivick et al., 2012; Glasser et al., 2011).

2. Study Area and Previous Research

Ice mass loss across Greenland has not been spatiotemporally uniform (e.g., Sasgen et al., 2012). While the North East (NE) Greenland region (Figure 1) does not contribute a major portion of the total mass loss from

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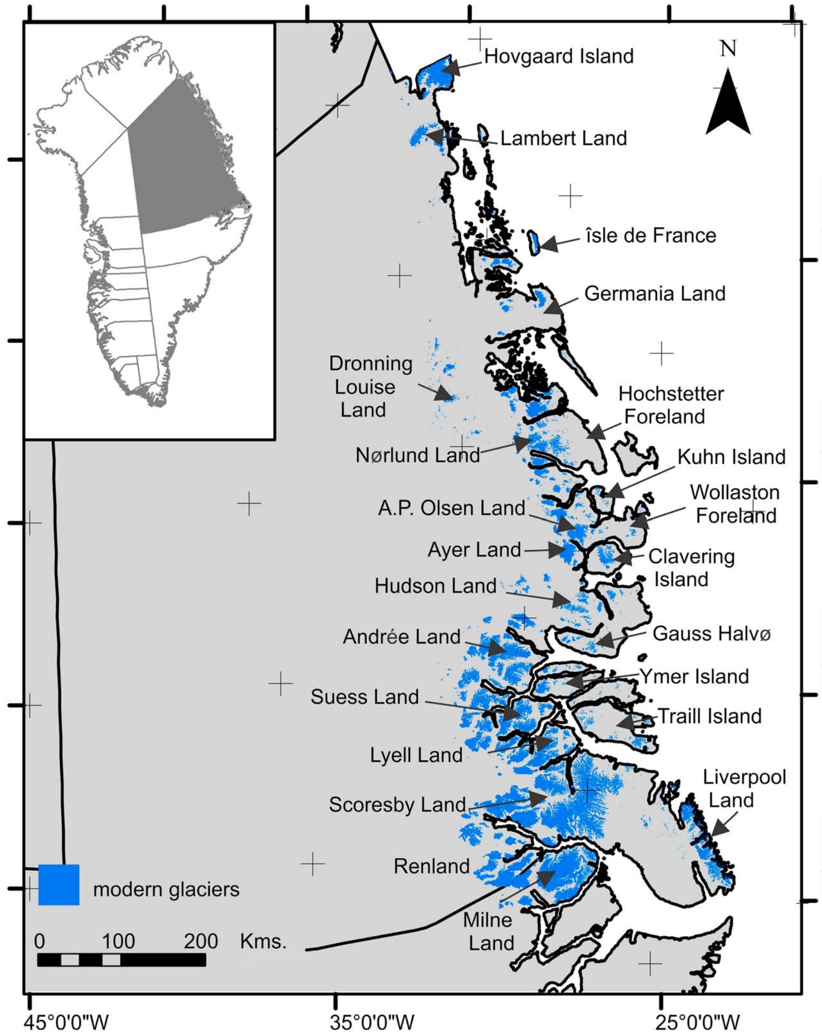

Figure 1. Study area with modern glaciers mapped and major glaciated regions named.

Greenland (Sasgen et al., 2012), it is a crucial freshwater source (Bamber et al., 2012) and a substantial sediment source (Gordeev, 2006; Overeem et al., 2017) to the North Atlantic and Arctic Oceans. This freshwater affects marine water temperature, salinity, and hence regional ocean circulation patterns (e.g., Gordeev, 2006). The runoff of freshwater and sediment also provides nutrients and minerals to fjord and coastal waters, impacting aquatic productivity and ecosystems (Anderson et al., 2017; Sejr et al., 2017). It is therefore perhaps surprising that the NE Greenland region (Figure 1) is underrepresented in the glaciological literature (Kelly & Lowell, 2009). The NE Greenland region is interesting glaciologically because it encompasses both a large sector of the Greenland Ice Sheet (GrIS), >5,000 GICs and an extensive recently deglaciated proglacial zone. The GICs span a local latitudinal extent from 70° 30′N to 80° 30′N and range in size from local ice caps and >50-km^2 valley glaciers to smaller valley glaciers and cirque glaciers.

Longer-term spatiotemporal patterns of the GrIS have been evaluated since the last interglacial 130,000 years ago by Vasskog et al. (2015) and since 1900 by Kjeldsen et al. (2015), respectively. However, studies on Late Pleistocene and Holocene fluctuations of Greenland's GICs have been spatially isolated (e.g., Kelly et al., 2008; Larsen et al., 2017; Möller et al., 2010), often focusing on large marine-terminating or tidewater margins. Consequently, research on mass changes in Greenland GICs (e.g., Bjørk et al., 2012; Larsen et al., 2017; Marcer et al., 2017; Rinne et al., 2011; von Albedyll et al., 2018; Weidick, 1968; Yde et al., 2014; Yde & Knudsen, 2007) has been spatially disparate and temporally fragmented. The most spatially extensive work is by Bjørk et al. (2018) who provided a regional comparison of 334 GIC length changes in east and west Greenland and who showed pervasive glacier length reductions.

During the Last Glacial Maximum glaciers extended offshore from NE Greenland through present-day fjord mouths (Kelly & Lowell, 2009). While the Last Glacial Maximum ice coverage on (interfjord) plateau lands is less well understood, major outlet glaciers are thought to have retreated onto land relatively quickly and much of the present landscape became ice free around 11,000 BP (Hall et al., 2008) to 8000 BP (Bennike & Björck, 2002; Christiansen & Humlum, 1993).

The LIA ice advance in NE Greenland is marked by well-preserved moraine ridges that are typically within 1 to 2 km of modern ice margins. These prominent moraines are associated with erosional and depositional trimlines that often appear "fresh" due to an obvious vegetation contrast (Funder, 1990; Hall et al., 2008). These moraines have been generally summarized to represent an ice advance of the mid-1800s and thus to the LIA (e.g., Ahlmann, 1941; Weidick, 1963, 1968), although these estimates are subject to high levels of uncertainty associated with geochronological analyses. More recently and contrastingly, Kjeldsen et al. (2015) and Bjørk et al. (2018) describe the same regionally widespread geomorphological evidence and assign a date of 1910 to the LIA maximum in east Greenland.

The aim of this study is therefore to present a quantitative spatiotemporal assessment of glacier volume changes across the entire NE Greenland region. Specifically, we will compare recent (decadal) rates of glacier changes with longer (centennial) rates of change by reconstructing the 3-D geometry of glaciers during the LIA.

3. Data Sets and Methods

Modern glacier outlines for NE Greenland were derived from GLIMS. We checked these glacier outlines with reference to Planet (2017) (mostly PlanetScope 3-m resolution from 2016 onward) imagery https://www.planet.com/explorer/. Orthorectified panchromatic aerial photographs and a 25-m resolution digital elevation model (DEM) that was derived from those photographs for the years 1978 and 1987 were obtained for the northern and southern parts of our study area, respectively, from Korsgaard et al. (2016).

Identification of moraines attributed to the LIA was primarily facilitated by interpretation of the 5-m resolution mosaic ArcticDEM, which was constructed from WorldView 1.5-m resolution satellite images (Noh & Howat, 2015). The 2-m ArcticDEM strip files, 3-m Planet imagery, published mapping (Funder, 1990; Hall et al., 2008; Kelly et al., 2008), and observations made as part of our own field work were all used to mitigate ambiguous evidence or obscured/missing parts of the ArcticDEM. Specifically, we edited the GLIMS outlines to a new data set that defined the outermost prominent frontal and lateral moraine crests; that is, what we interpret to be the maximum LIA glacier in each case. Lateral moraine limits that had insufficient topographic expression to be detected on the hillshaded DEM (Figure 2a) were often discernible on Planet imagery by a pronounced contrast in vegetation and weathering (Figure 2b). Using this approach, we were able to map the 2-D LIA glacier extent of 1848 (representing 32% of the total) glaciers in NE Greenland. Surge-type glaciers were identified (cf. Evans & Rea, 1999, 2003; Lovell & Boston, 2017) and included in our analysis in order to assess the full glacial response to climate change since the LIA, but we also report our results without these eight glaciers included for clarity and so as to indicate the impact of calculating volumetric changes in areas with surging glaciers. LIA glacier 3-D surfaces were produced by interpolation between points created from the vertices of the 2-D outlines, whereby these points had ArcticDEM values extracted/attributed to them. Full details of our data sources and methods are given in the supporting information (SI).

Spatially distributed surface lowering was calculated for two time periods: one centennial time period of the LIA to 1980s, for which we used the specific years 1910 to 1978/1987, and one decadal time period of 1980s (specifically years 1978 and 1987) to 2014. The 1978 and 1987 years are defined for the northern and southern parts of our study area, respectively, and are determined by the Korsgaard et al. (2016) data coverage. The LIA in east Greenland is assumed herein as 1910 following the same decision by Bjørk et al. (2018) and noting that Khan et al. (2014) realized that the LIA in SW Greenland was before 1930 and that a Greenland-wide average LIA was put forward by as 1900 by Kjeldsen et al. (2015). The year 2014 is ascribed by the timing of images making up the ArcticDEM mosaic (SI).

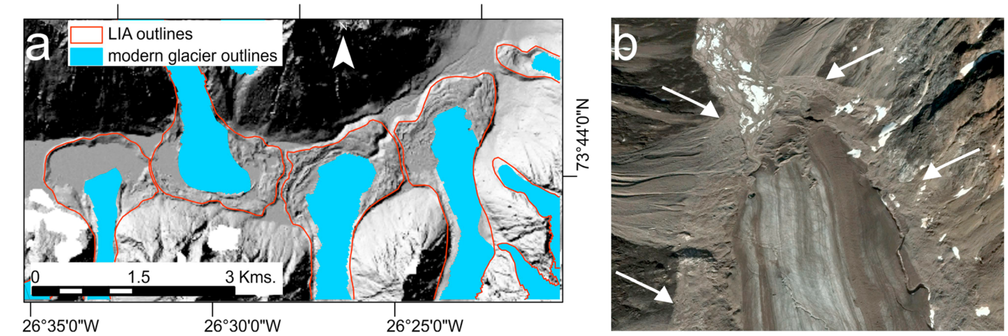

Figure 2. Examples of Little Ice Age (LIA) outlines mapped onto crest of outermost prominent moraine ridges on hill-shaded digital elevation model (a) and of depositional and erosional trimlines at Skillegletscher, Clavering Island, here in perspective view of Planet image (b).

For all spatially distributed surface lowering calculations, we first automatically estimated glacier-specific equilibrium line altitudes (ELA) using the tool developed by Pellitero et al. (2015). Specifically, we used the area altitude balance ratio method with a balance ratio of 2.24, as representative of high-latitude glaciers (Pellitero et al., 2015; Rea, 2009). The ablation area for each individual glacier was subsequently delineated in an automated fashion using the outlines and the ELA. To check the sense of our computed ELAs, we quantitatively compared the resultant glacier-specific ELAs to the maximum elevation of lateral moraines (Figure S5a). For ablation areas only, we differenced both the modern-day ice surface and the 1980s ice surface from the LIA ice surface. Surface lowering for both time periods was converted to a volume change estimate by summing the grid cell elevation changes for each glacier zone and multiplying by cell size. Rates of change were determined per glacier to account for the differing geographical distribution of the 1978 and 1987 DEMs.

Our volume change estimates can only be considered as mass balance estimates if it is assumed that glacier surfaces above the ELA are somewhat protected from warming air temperatures (but not to changes in precipitation). Our volume change estimates should be considered a minimum because (i) they depend on the preservation and identification of geomorphological evidence of an LIA advance, (ii) they pertain only to glaciers where GLIMS outlines exist and some empty cirques in NE Greenland may have held glaciers at the LIA (Figure 5d), (iii) our elevation change calculations only relate to glacier ablation areas, and (iv) a few (<1%) glacier ablation areas have gained mass since the LIA due to surging (see Figure S4).

Errors in area and volume change estimates will result from DEM resolution, LIA identification and digitizing, 3-D surface reconstruction, and surface differencing, as described in detail in the SI. Our area change estimates are subject to uncertainty depending on the DEM (5 m) and optical image (1.5 m) resolution used for digitizing and researcher choice of the most prominent outer moraine and of trimlines. In the vast majority of cases the geomorphological evidence is distinct, while digitizing errors at smaller glaciers will have the largest relative effect in area measurement accuracy. At a typical mountain glacier in NE Greenland of 2-km^2 digitizing errors of one pixel would typically produce an area of ~±0.7% (depending on glacier shape). Critically, the computed rates of volume loss are most subject to error in the choice of a single date to represent the timing of the LIA maximum in NE Greenland. If glacier advance had occurred earlier, for example, at 1850 (as opposed to 1910), then our rates of change between the LIA and 1980s would be lower by ~50% (due to twice the length of time period). Therefore, our computed acceleration in rates of volume loss during this period are also minimum estimates.

For the purposes of evaluating the relative importance of the NE Greenland GICs we converted our volume changes into mass changes. For this calculation we used a density of ice of 900 kg/m^3 (cf. Huss, 2013). The mass of ice was converted to a sea level equivalent using an ocean area of 3.62×10^8 km^2 (cf. Hock et al., 2009).

4. Results

The total glacier area lost between the LIA and the present day was at least 1,570 ± 314 km^2 from ~23,000 ± 4,600 km^2 at the LIA. The maximum area loss of any glacier was 30.1 ± 1.5 km^2, and overall, the mean area change for the 1,848 glaciers was 0.83 ± 0.05 km^2. Normalizing by area, the mean area change was 79.3%, that is, a mean area loss of 21.7%, and the interquartile range of 27.17% was defined by Q1 = 67.85% and Q3 = 95.02%.

There was at least 172.76 ± 34.55-km^3 volume lost between 1910 and 1980s, that is, a rate of 2.61 ± 0.52 km^3/year. Between 1980s and 2014 the volume loss was at least 90.55 ± 18.11 km^3, that is, a rate of 3.22 ± 0.64 km^3/year. Therefore, in recent decades there has been a marked increase of ~23% in the rate of ice volume lost when compared to the rate of change from the LIA to the 1980s. If the eight surge-type glaciers are excluded from analysis, then the volume lost between 1980s and 2014 reduces by 7.41 ± 1.48 km^3, that is, by 8.1% and the volume lost between 1910 and the 1980s reduces by 16.96 ± 3.39 km^3, that is, by 9.8%.

From the LIA to the 1980s we estimate 155.5 ± 31.1-Gt mass loss from NE Greenland GICs, that is, 2.0 ± 0.4 Gt/year. For the 1980s to 2014 we estimate 81.5 ± 16.3-Gt mass loss, that is, 2.5 ± 0.5 Gt/year. We estimate 0.43 ± 0.086-mm total contribution to sea level rise from NE Greenland GICs between the LIA and the 1980s and 0.23 ± 0.046-mm contribution between the 1980s and 2014.

During the LIA to 1980s, 2.5% of the glaciers apparently had no change in volume and this figure increased to 4% during the period 1980s to 2014. Approximately 34% of glaciers experienced a decrease in the rate of volume loss between the 1980s and 2014 compared to their rate between the LIA and the 1980s. One glacier had no change in rate, and 66% of glaciers apparently increased in their rate of volume loss. The maximum change in the rate of volume loss for an individual glacier was at least +0.034 ± 0.0068 km^3/year, and the greatest reduction in the rate of volume loss was at least −0.022 ± 0.0044 km^3/year. There was a positive correlation ($r^2 = 0.22$ for all glaciers and $r^2 = 0.63$ for the largest 50 glaciers) of the change in rate of volume loss with initial (LIA) glacier area.

Figure 3c hints that larger glaciers had higher rates of volume loss, but this figure more obviously illustrates that there was no spatial pattern to the changes in rates of volume loss between the two time periods. We extracted centroid locations for each glacier and statistically evaluated that there was no east-west trend and no north-south trend. We found no association between rate of volume loss and glacier elevation, which is contrary to the findings of Larsen et al. (2017). At the LIA 77 glaciers (4.5%) were terminating into a fjord, whereas with the modern (GLIMS) outlines only 58 (3%) glaciers are tidewater terminating. There was no statistical difference in the rates of volume change of land-terminating and tidewater-terminating glaciers.

5. Discussion

Our novel data on glacier 3-D geometry during the LIA, analyzed and combined with published estimates of glacier changes across Greenland, permit us to make the first assessments of the importance of the NE Greenland region in its contribution to total Greenland ice mass loss on both centennial and decadal time scales. Our most significant finding is that on a centennial-scale NE Greenland GICs contributed an amount equivalent to ~3.3% of total GrIS loss since the LIA to the 1980s, which Kjeldsen et al. (2015) estimated was 75.1 ± 29.4 Gt/year.

Recent (decadal-scale) changes to the GrIS and to the Greenland GICs have received rather more attention, and thus, we can make more comparisons of our findings with other published estimates. Thomas et al. (2006) estimated that total GrIS loss had more than doubled from 4 to 50 Gt/year between 1993/1994 and 1998/1999 to 57 to 105 Gt/year between 1998/1999 and 2004. Bolch et al. (2013) reported that Greenland GICs contributed ~20% of the total ice mass lost from Greenland between 2003 and 2008. Kjeldsen et al. (2015) estimated that total GrIS loss for 1983 to 2003 was 73.8 ± 40.5 Gt/year, and for 2003 to 2010 was 186.4 ± 18.9 Gt/year. Most recently, and considering a longer total time period and several discrete sub–time periods, Bamber et al. (2018) have evidenced an acceleration in the rate of mass loss from the GrIS from the late 1990s to >300 Gt/year post 2008 (450 Gt in 2012).

With these GrIS estimates in mind, our calculations of the NE Greenland glacier changes indicate that they could have been contributing mass loss equivalent to ~1/25th of that of the GrIS in the 1990s. However, into the 2000s that relative importance probably diminished to <1/1000th. For the NE Greenland region only, and for the GrIS and GICs combined, Sasgen et al. (2012) reported 7- to 16-Gt/year loss for 2003 to 2009.

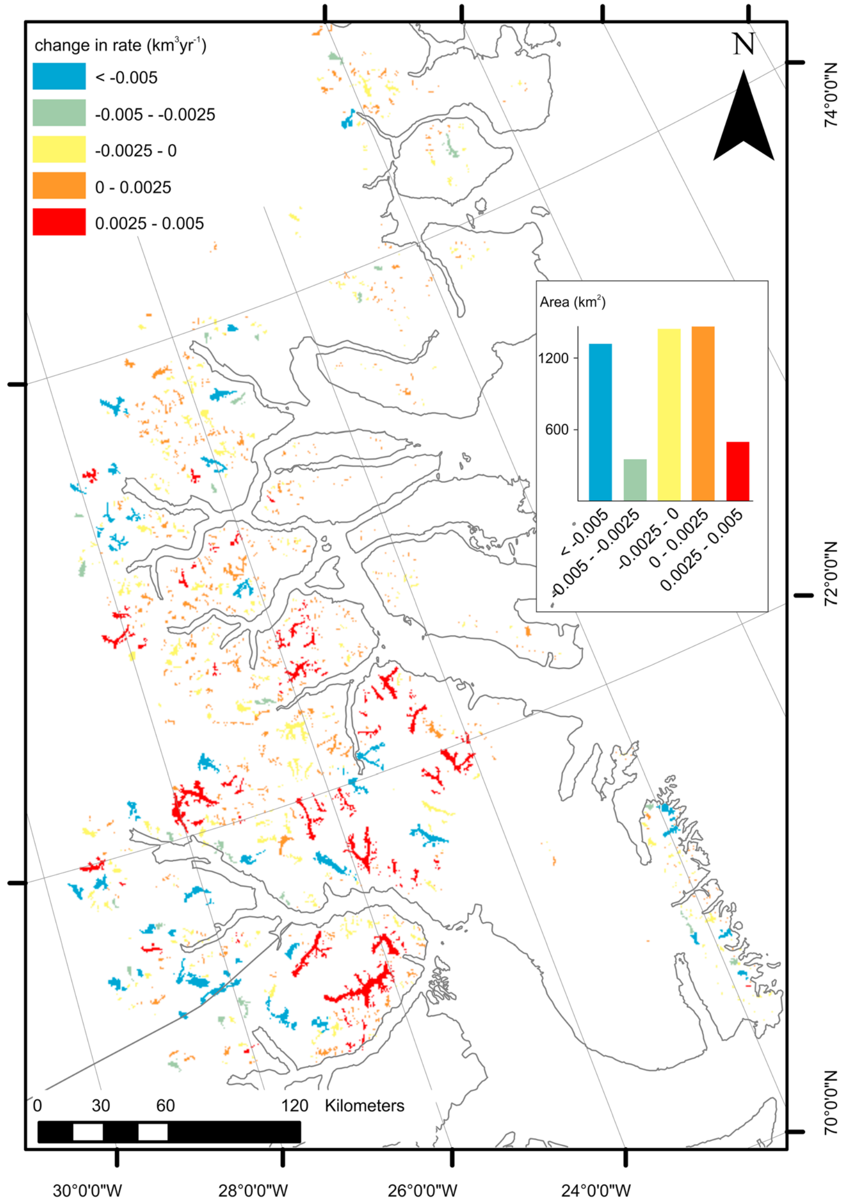

Figure 3. Rate of change between the two time periods Little Ice Age to 1987 and 1987 to 2014. Inset shows total area of all glaciers within each category of change in rate.

Our (decadal mean) value of 2.5 Gt/year would suggest that GICs could account for ~15% to 35% of this regional total. Bamber et al. (2018, their Table 1) report Greenland GICs to have lost mass at ~35 Gt/year between 2003 and 2014 so our estimates suggest that a minimum of ~7% of that was from NE Greenland. Unfortunately, our results are virtually impossible to compare to those of Bjorck et al. (2018) because they only sampled 195 and 139 glaciers in east and west Greenland, respectively, and only considered changes in glacier length over different time periods to our study.

The lack of a spatial pattern that we evidence in individual glacier changes (Figure 3c) is surprising. We had expected the spatial pattern of rates of volume change to reflect any climatic gradients across the NE. We therefore computed glacier-specific ELAs, and these are >2,000 m in the west and <500 m in the east (Figure S5c). This spatial pattern is indicative of a pronounced air temperature and precipitation gradient in NE Greenland between the GrIS margin to the west and the Atlantic Ocean to the east. Our glacier-specific volume changes have no west-east pattern nor a north-south pattern as might be expected due to any latitudinal air temperature gradient. Overall, our observed changes in ice volume loss do not correspond to the spatial variations in ELA and thus do not correspond to a regional climatic control.

It is therefore apparent that local controls are of paramount importance in relation to glacier behavior and evolution in NE Greenland. Furthermore, we note from a detailed study of the DEMs and satellite images that the vast majority of glaciers in NE Greenland do not exhibit many surface crevasses, foliation lines, or other structural features. They support few supraglacial channels and exist in an environment with positive degree days persisting for <90 days per year (Mernild et al., 2007). We therefore suggest that most present-day NE Greenland GICs are likely to be polythermal and perhaps some entirely cold based, although their thermal regime is likely to evolve as thinning progresses and reduces ice overburden pressure and hence basal shear stress (Rippin et al., 2011). Indeed, the distal parts of these glaciers moraines (at least in Skilledal, Clavering Island) contain subrounded and striated boulders (Figure S6), suggesting that subglacial sediment transport was pervasive, and hence, temperate glacier bed conditions were widespread at the LIA. Thus, it is suggested that GICs in NE Greenland have generally cooled (in thermal regime) as they have thinned and slowed and as climate has warmed since the LIA to the present day. The same glacier evolution was found on James Ross Island, Antarctica, by Carrivick et al. (2012).

Studies on Greenland GICs have realized this importance of local controls and specifically of topography (Larsen et al., 2017) on glacier morphology and behavior, but it has never been suggested on a regional scale. This spatiotemporal variability has implications for models seeking to understand past, present, and future glacier geometry changes and dynamics because individual glaciers or a small sample of glaciers are not likely to be representative of the region. These transitions in glacier behavior have big implications not only for glacier evolution but also for valley, fjord, coastal, and marine systems (e.g., Sejr et al., 2017). Therefore, it is important that efforts to understand these transitions are made and to that end our area and volume change data should be useful for a statistical approach to calibrate glacier mass balance models that are driven by surface air temperature data (Marzeion et al., 2015) and reanalysis products (Radić et al., 2014). Unfortunately, there is a dearth of decadal-scale climate data available for NE Greenland (see citations in Orsi et al., 2017). The single exception is the climate data from Zackenberg station (situated at 74° 28′N, 20° 34′W), which experiences a semiarid continental climate.

6. Conclusions

This study is the first to inventory recent decadal glacier changes across NE Greenland into a longer (centennial) time scale context. We quantify that the rate of GIC volume loss from the LIA to the present day has accelerated >124%. For the first time we have also been able to suggest that GICs in NE Greenland account for >5% and more likely ~25% of the (NE Greenland) regional total mass loss. Furthermore, we suggest that a minimum of ~7% of the entire mass loss from Greenland was from the GICs in the NE Greenland region.

Recognition of an acceleration in glacier volume loss is in agreement with the findings of Chen et al. (2013) and Bamber et al. (2018) who have both reported recent (last decade) acceleration in GIC mass loss, especially in the Arctic. Glacier mass loss in NE Greenland is manifest in meltwater and that has great significance for the North Atlantic Ocean and Arctic Ocean circulation as well as profound consequences for fjord and coastal primary production and ecosystems. Glacier mass loss is also manifest in proglacial area expansion, which in this study we show has been by 1,570 ± 314 km^2 since the LIA. These proglacial areas are rapidly adjusting parts of landscapes (Carrivick & Heckmann, 2017), and as such they are hot spots of sediment production and will dominate mineral and nutrient fluxes through fluvial and aquatic domains.

Our results show that it would be impossible to derive a regional trend in glacier change by simply analyzing individual glaciers in this region. Thus, while glacier area changes of >10 km^2 characterize the centennial-scale dynamics of some of the NE Greenland GICs and these provide an important baseline against which modern ice sheet fluctuations may be compared, future work to understand the processes driving those changes needs to link glacier 3-D extent with ice dynamics. To this end glacier dynamics at the LIA might be modeled by reconstructing LIA ice thickness, by taking our reconstructed ice surface, and combining it with contemporary ice thickness (or glacier bed elevation) that could be most simply obtained from a steady state model (e.g., GLABTOP: Linsbauer et al., 2012; VOLTA: James & Carrivick, 2016; Carrivick et al., 2016).

Other future work should seek to construct LIA glacier outline inventory data for the south, west, and north Greenland GICs and also for other Arctic regions.

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