Volume changes in the glaciers and ice caps of west Greenland since the Little Ice Age (1890 – 2014)

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"Submitted in accordance with the requirements for the degree of Masters by Research"

The University of Leeds School of Geography

October 2021

The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

Acknowledgements:

I would like to thank both of my supervisors, Dr Jonathan Carrivick and Dr Duncan Quincey, whose help and guidance has been invaluable during this project especially in the challenging conditions that COVID-19 has presented. I would also like to thank my friends and family, who have been sources of sanity and calmness throughout.

Abstract

Local glaciers and ice caps in Greenland are important contributors to global sea level rise yet are relatively understudied. This study has mapped the extent of 2907 glaciers and ice caps in west Greenland and calculated glacier-specific equilibrium line altitudes during the Little Ice Age (LIA). Surface lowering and volume loss between the LIA, which is taken as 1890, and 2014 reveals that there has been at least 184 ± 29 km^3 of volume loss from west Greenland glaciers and ice caps at a rate of 1.5 ± 0.2 km^3/year, since the LIA. The contribution to sea level rise from these glaciers has been 0.47 ± 0.07 mm since the LIA. The volume loss observed was lower than expected, when compared to NE Greenland for example, and the average rate of loss for the period was only equivalent to 5% of the rate of loss for all glaciers and ice caps in Greenland not connected to the main ice sheet.

Statistically significant relationships with volume loss were found for both latitude and coastal proximity across glaciers and ice caps in west Greenland, between the LIA and 2014. Both of the observed relationships produced weak negative correlations; as the distance from the coast increased, volume loss decreased ($r = -0.041$), as latitude increased, volume loss decreased ($r = -0.071$). The volume loss seen from west Greenland glaciers on a centennial scale has a sea level rise contribution comparable to the three largest outlet glaciers of the Greenland Ice Sheet. This indicates that glaciers and ice caps in west Greenland are significant in terms of the total sea level rise contribution from Greenland land-ice, in line with trends predicting that local glaciers and ice caps will become a major control on sea level rise over the 21st Century.

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Abbreviations

GIC – Glaciers and ice caps

GrIS – Greenland Ice Sheet

RGI – Ranolph Glacier Inventory

LIA – Little Ice Age

ELA – Equilibrium line altitude

GRACE – Gravity Recovery and Climate Experiment

IPCC – Intergovernmental Panel on Climate Change

GLIMS – Global Land Ice Measurements from Space

MAAT – Mean annual air temperature

NAO – North Atlantic oscillation

DEM – Digital elevation model

AABR – Altitude area balance ratio

1.0 Introduction

The global mean sea level rose by approximately 17 centimetres over the 20th century, mainly due to land based ice loss and thermal expansion of the oceans (Gregory et al., 2013; Bamber et al., 2019; Khan et al., 2020). The contribution of glaciers and ice caps (GIC) to global sea level rise is agreed to be increasing (Gardner et al., 2013; Zemp et al., 2019), with increased summer temperatures thought to be driving changes in mass balance throughout the Holocene (Machguth et al., 2013; Larsen et al., 2017).

Contemporary estimates for global GIC contributions to sea level rise suggest that those contributions are of a comparable magnitude to Greenland Ice Sheet (GrIS) contributions (Khan et al., 2013; Zemp et al., 2019) and are significantly greater than the contribution of the Antarctic Ice Sheets (IMBIE, 2018). As a result of the disproportionate contribution of local glacier volume loss to sea level rise, it is especially important to study volume changes and not rely solely on area statistics such as constrained within the Randolph Glacier Inventory (RGI) (Carrivick et al., 2019). The trends in sea level rise contribution over recent decades show the need to place recent measurements of volume loss in a longer timeframe in order to see if recent fluxes are anomalous, when compared to previous periods of deglaciation (Glasser et al., 2011).

Greenland hosts a multitude of GICs around the periphery of the GrIS that are disconnected from the main ice sheet, and these make up an important part of the regional cryosphere. Glaciers in Greenland that are weakly, or not connected to, the main ice sheet have a cumulative area of 89,721 km^2, accounting for 19,323 glaciers (Pfeffer et al., 2014).

In every region included in the RGI, mean glacier area was significantly lower than the median (Pfeffer et al., 2014), indicating that smaller glaciers are very important in the distribution of area. The relatively small GICs in Greenland represent a powerful tool in the context of climate change because it is widely accepted that glaciers with lower area and mass have a faster response time to short term changes in climate (Haeberli et al., 2007; Raper and Braithwaite, 2009), meaning they can give insights to change on both centennial and decadal timescales. This is especially important as centennial scale changes can be used to improve climate modelling (Khan et al., 2020). As the climate continues to warm it is more important than ever to frame volume loss from GICs in a centennial timeframe, to aid modelling estimates for sea level rise over the 21st century and beyond. As a result of their heightened sensitivity to short-term climatic factors, reconstructions of GICs close to the margin of the GrIS may also be useful as proxies for historical climate changes at the edge of the ice sheet, and possibly to understand the controls behind historical mass balance changes of the GrIS (Levy et al., 2014; Schweinsberg et al., 2019). Centennial scale volume changes seen of GICs in Greenland that are distant from the coast, and therefore in closer proximity to the ice sheet margin, could be a crucial tool in improving the currently poor understanding of the long-term response of the GrIS to past climate change (Rignot et al., 2011; Levy et al., 2014).

Advancements in technology in recent years mean that glacier volume changes can now be measured in the short-term using equipment such as the Gravity Recovery and Climate Experiment (GRACE), but it is important to extend volume loss measurements beyond the last few decades into a centennial time scale in order to better understand the cryosphere’s response to climate change.

Most local glaciers in west Greenland are thought to have reached their Holocene maximum extents during the Little Ice Age (LIA) (Sugden, 1972; Kelly and Lowell, 2009) but there is a lack of consensus in the literature regarding the onset of LIA deglaciation in west Greenland, and several dates are proposed: 1850 (Weidick, 1968; Beschel and Weidick, 1973), 1890 (Weidick, 1968; Bjørk et al., 2018), 1900 (Csatho et al., 2008), and 1920 (Weidick, 1968; Dowdeswell, 1995). In west Greenland, the most prominent geomorphological evidence for GIC activity is related to the LIA, the well preserved moraines provide the opportunity to investigate volume losses on a centennial scale. This is crucial for understanding regional contributions to sea level rise and will provide future modelling with more data, allowing a higher level of accuracy.

1.1 Aims and Objectives

This research aims to use a desk-based GIS approach to present the first quantitative estimate of volume loss from local glaciers and ice caps in west Greenland since the Little Ice Age.

1.1.2 Objectives

- Investigate and define the maximum Little Ice Age extents of local glaciers and ice caps in west Greenland.
- Calculate glacier surface lowering statistics from their maximum Little Ice Age extents to 2014 for glaciers and ice caps in west Greenland, in order to define volume loss.
- Calculate the average rates of volume and mass loss in west Greenland glaciers and ice caps from their maximum Little Ice Age extents.
- Calculate the sea level rise contribution of local glaciers and ice caps in west Greenland from their maximum Little Ice Age extents.

2.0 Literature Review

When reviewing the methodology behind estimates for sea level rise contributions, Chen et al. (2013) used data from the GRACE to conclude that a significant proportion of ocean mass change is driven by the melting of mountain glaciers and ice caps. The results showed that GIC ice loss had a larger contribution to sea level rise than previously thought (Solomon et al., 2007; Chen et al., 2013), and more recent findings are concurrent with the widely held view that rates of change for GIC volume loss are increasing. (Rignot et al., 2011; Sasgen et al., 2012; Bamber et al., 2018).

Models produced for the Inter-Governmental Panel on Climate Change (IPCC) projected sea level rise to 2100 for different climate change scenarios; in the high emission simulation, the most significant uncertainty was the contribution of land ice (IPCC 2013; Bamber et al., 2018b). Current estimates for sea level rise from GICs in Greenland is approximately 0.08mm/year (Bolch et al., 2013). It is crucial to understand the processes of ice melt because a future sea level rise of 1m has the potential to displace approximately 187 million people (Nicholls et al., 2011). However, this figure assumes the relatively unlikely scenario of over 4°C of global warming by 2100.

Rates of GIC volume loss are increasing in other areas of Greenland, it has been found that GICs in the north-east contribute approximately 7% to overall Greenland GIC mass loss, with rates of volume loss increasing by 23% in the last 40 years (Carrivick et al., 2019). There has been little research into the sea level rise contribution of GICs in west Greenland, and in this region most research has focused on the contributions of marine terminating outlet glaciers of the GrIS. Patterns in the sea level rise contribution from west Greenland GICs need to be investigated and quantified on a centennial scale, to see if the trends follow the global pattern of increasing GIC contribution to sea level rise and to help model future trends as temperatures continue to increase. As well as this, understanding patterns of loss relative to other areas of Greenland will build a more detailed account of how GICs retreated from their Holocene maximum extents across the country.

2.1 Glaciation in west Greenland

Across the whole of Greenland, GICs smaller than 0.5 Km^2 account for more than 50% of the total number but only 1.5% of total area whereas the 25 largest GICs represent 28% of total area (Rastner et al., 2012). This disparity is reflected in the literature and many studies choose to focus only on the largest glaciers, often outlet glaciers for the ice sheet (e.g. Khan et al., 2020), this leaves GICs in Greenland relatively understudied, especially in the west. Currently there are very few studies that investigate volume changes since the LIA in Greenland, and none that cover west Greenland as a whole on a centennial scale.

The most comprehensive summary of the literature regarding west Greenland GICs is provided by Kelly and Lowell (2009); research regarding the fluctuations of GICs throughout the late Pleistocene and Holocene is compiled to give a broad account of past GIC extents and their changes. The changes in glacier extents throughout the Holocene have been seen to be somewhat uniform across the country and likely mirror variations in summer temperatures (Kelly and Lowell, 2009 and references therein).

2.2 Study area

There are over 5000 GICs in west Greenland from Kap Farvel at the southern tip to Thule Air Base in the north (Weidick et al., 1992), the study area for this project is from the Sukkertoppen area (66° N) in the south-west to the area around Thule Air Base (76° N). The latitudinal range covers approximately 2000 Km with a total glaciated area of 17,926 Km^2 (GLIMS, 2014). The GICs included in this study have been displayed in figure 1, the central-west region has been highlighted as this is includes Disko Island; the largest island in Greenland at 8575 Km^2 (Humlum, 1987), and is the area covered with the most depth in the literature. There is a scarcity of climate data available for west Greenland especially when compared to the other regions of the country, but in the central-west region the mean annual air temperature (MAAT) is -4.3°C (Yde and Knudsen, 2007).

Glaciers and ice caps in the west vary greatly both in size and the style of glaciation; there are valley, alpine and cirque types alongside ice caps both with and without outlet glaciers (Citterio et al., 2009). For example the Sukkertoppen ice cap in the south of the study area has a thickness of up to 300m and an area of 2000 Km^2 (Schweinsberg et al., 2018), this is a stark contrast to the Nuussuaq peninsula where almost all activity is by valley and cirque glaciers and the glaciated area is only 1271 Km^2. It is important to focus on west Greenland when looking at volume loss because of the range of sizes and characteristics seen in GICs, a study that encompasses the majority of GICs in the west can be used as a powerful dataset when analysing long-term volume loss across Greenland. As well as this, it is important to understand large GICs such as Sukkertoppen and their fluctuations in the context of anthropogenic climate change, because it is likely that they will make larger contributions to sea level rise than the smaller glaciers.

There were 29 surge-type glaciers within the study area, these were identified using a shapefile (H Lovell, J Yde, J Carrivick and O King, pers. comm); they were constrained to Svartenhuk, Nuussuaq and Disko Island as part of the known Disko-Nuussuaq Surge cluster (Yde and Knudsen, 2007). In some cases they were easily identifiable as surge-type glaciers by the presence of hummocky and thrust moraines (Evans and Rea, 1999; Yde and Knudsen, 2007). Shown in figure 2 is a surge-type glacier on a northern peninsula of Disko Island, it has decreased in length by 2.1 Km since its maximum position during the LIA and displays hummocky moraine behind the terminal ridge. Some surge-type glaciers in the Disko-Nuussuaq surge cluster travelled at rates of up to 50 m/day during the 1990's (Gilbert et al., 2002; Yde and Knudsen, 2005).

This study area provides an exciting opportunity to investigate the impact of coastal proximity on centennial scale volume and mass change, GICs in west Greenland range from 1.99 Km to 152.9 Km away from the coastline on a west to east transect. The large range in coastal proximity may reveal interesting patterns in GIC volume loss as the local climate becomes less maritime and more continental; GIC behaviour has been seen to mirror changes in continentality (Holmlund and Schneider, 1997), with glaciers in maritime climates experiencing accelerated mass balance turnover when compared to GICs in continental climates (Grinsted, 2013). As well as this, it is possible that volume loss from GICs may be impacted by the colder and drier climate at the GrIS margin.

Glaciers in west Greenland extend across a vast latitudinal range, from 77 degrees in the north to 61 degrees in the south, representing a latitudinal transect of almost 2000 Km. As a result of the significant latitudinal range among the glaciers sampled, it would not be unreasonable to predict that this variable could have an effect on rates of volume loss across west Greenland. As latitude increases the average summer air temperature is likely to fall, and it has been observed that historical volume and length fluctuations in Greenland GICs are correlated with changes in summer air temperature (Weidick, 1968; Leclercq et al., 2012; Larsen et al., 2017).

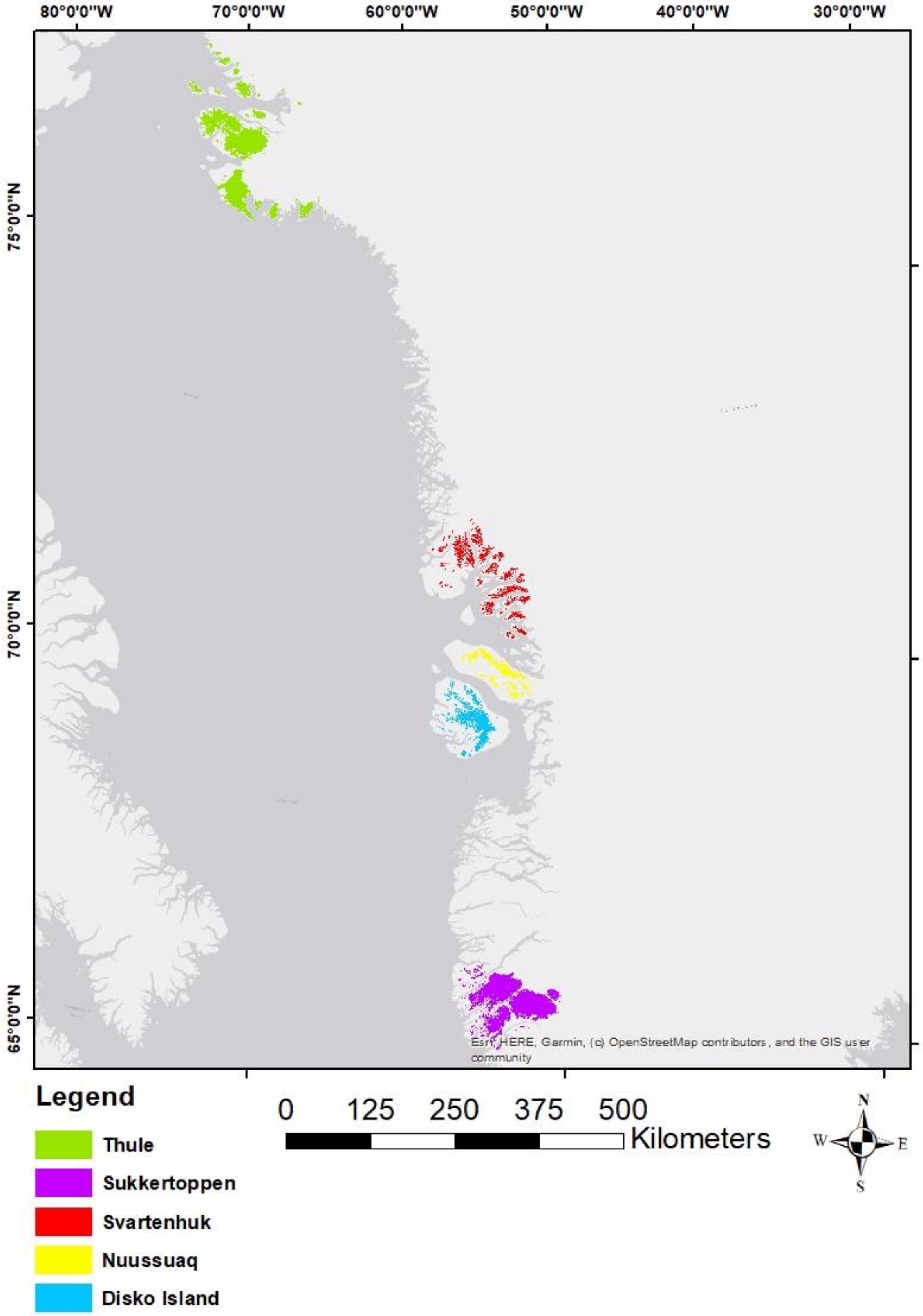

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Figure 1: GICs sampled in this study colour coded to their relevant sub-region. Inset: central-west regions, the locations of most previous GIC study in west Greenland.

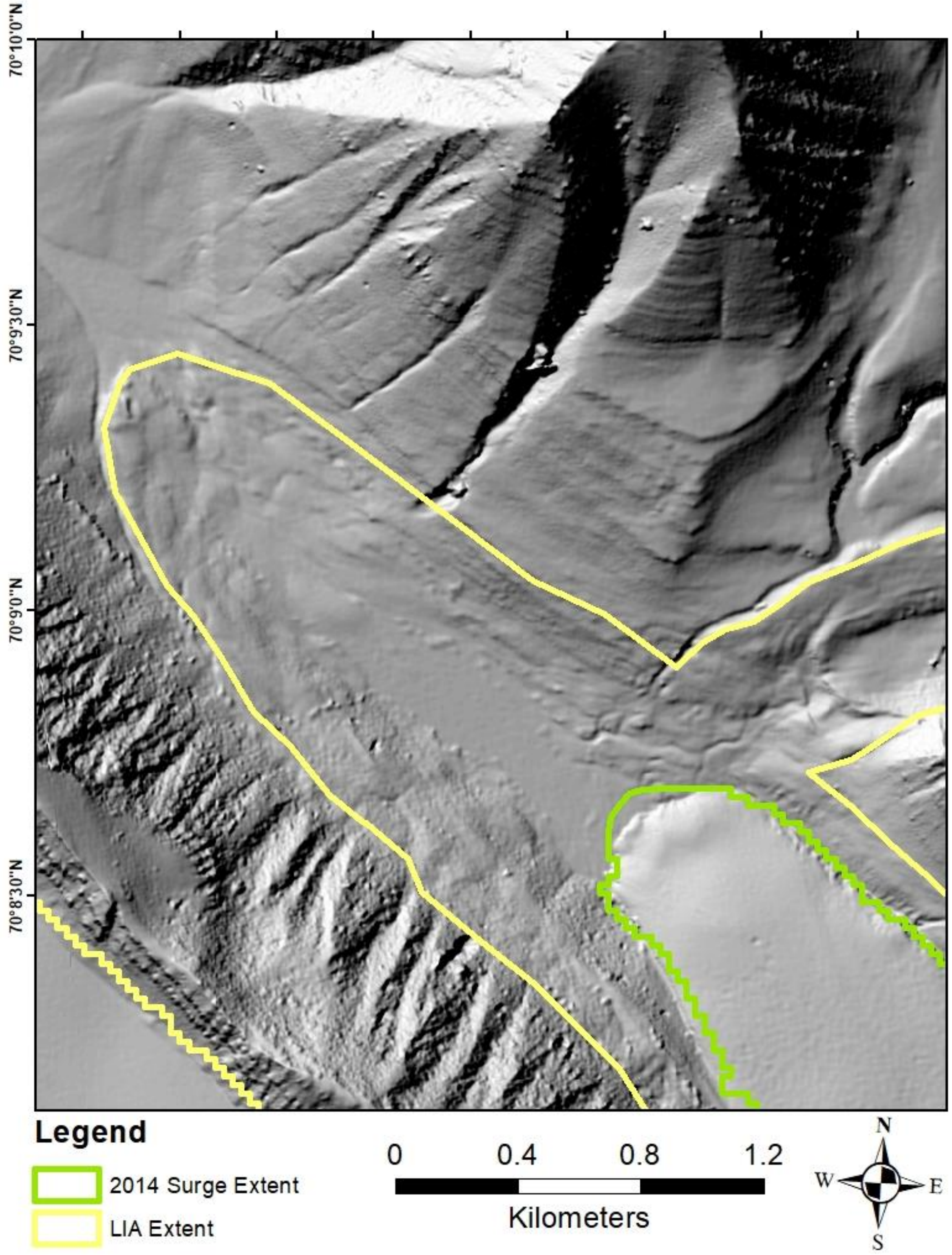

Figure 2: A surge glacier in northern Disko Island, most surge-type glaciers are in the Disko Island or Nuussuaq regions

2.3 Dates for the Little Ice Age in west Greenland

Holocene records for GIC fluctuations are sparse across Greenland and especially so in the west (Kelly and Lowell, 2009; Schweinsberg et al., 2019), this a contrast to other northern regions such as Alaska, Canada and Scandinavia where late Holocene GIC changes are well recorded and dated (Briner et al., 2016). There has been some recent work to date GIC fluctuations in west Greenland during the Holocene but studies are spatially limited, locations of studies dating LIA glacier changes are shown in figure 3. Research has been carried out in; the Sukkertoppen area (Sugden, 1972; Schweinsberg et al., 2018); the Nuussuaq Peninsula (Young et al., 2015; Schweinsberg et al., 2017); Disko Island (Donner, 1978; Ingólfsson et al., 1990; Jomelli et al., 2016), the Ameralik area (Larsen et al., 2017), and further south (Larocca et al., 2020). ^{14}C and ^{10}Be dating has been carried out in some of these studies, dates found for glacial activity during the LIA are outlined in tables 1 and 2 for ^{14}C and ^{10}Be dates respectively.

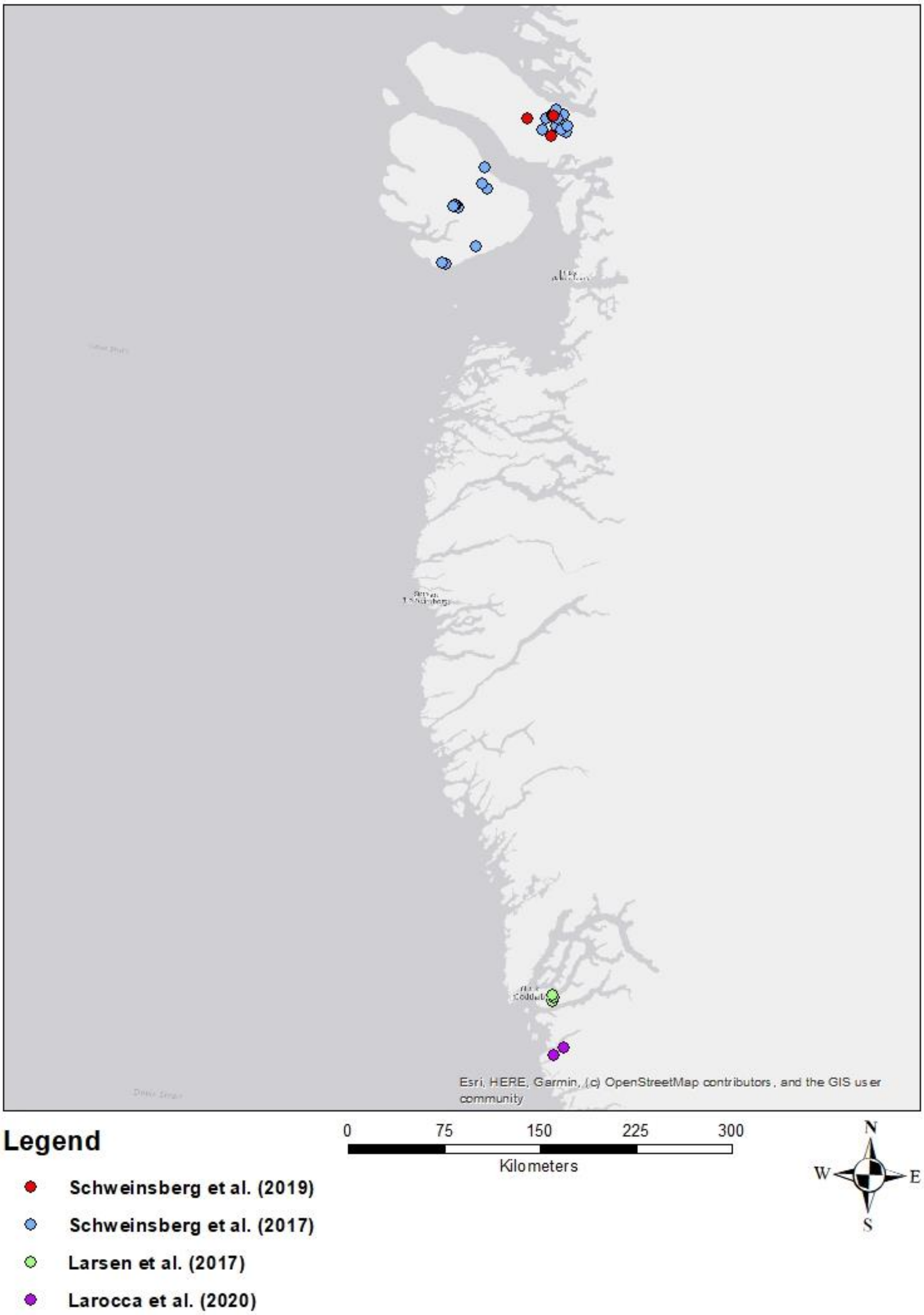

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Figure 3: Locations of previous dating studies in west Greenland, these studies used Carbon and Beryllium dating and are outlined in tables 1 and 2 respectively

Study	**Location**	**Co-ordinates**	**Age (^{14}C yr BP)**	**Cal yr BP**	**Material**
Goldthwait, 1961	Near Nunatarssuaq, NW coast		<200	200	Plants
Larocca et al., 2020	Buskefjord region	N 63.8032 W 51.19869	335 ± 20	390 ± 75	Lake sediment
Schweinsberg et al., 2019	Nuussuaq	N 70.33596 W 51.44075	555 ± 40	580	Aquatic macrofossils
Larsen et al., 2017	Badesø Lake	N 64.13 W51.36	340 ± 28	315 to 483	Terrestrial Macrofossil
Schweinsberg et al. 2017	Disko Island	N 69.67835 W 53.38693	130 ± 45	140 ± 130	Polytrichastrum alpinum
	Disko Island	N 69.67398 W 53.39941	245 ± 20	230 ± 70	Polytrichum piliferum
	Disko Island	N 69.67398 W 53.39943	235 ± 25	230 ± 70	Salix arctica
	Disko Island	N 69.67413 W 53.40079	340 ± 25	420 ± 80	Pohlia cruda
	Nuussuaq	N 70.21835 W 51.06252	260 ± 20	300 ± 10	Polytrichum hyperboreum
	Nuussuaq	N 70.21599 W 51.05363	310 ± 25	370 ± 60	Racomitrium canexcens
	Nuussuaq	N 70.34024 W 51.25237	400 ± 20	490 ± 20	Racomitrium lanuginosum

Table 1: 14C dates of glacial advances coinciding with the LIA in west Greenland

Study	**Location**	**Co-ordinates**	**Age (10Be yr BP)**	**Material**
Schweinsberg et al., 2019	Nuussuaq moraine 1	N 70.315 W 52.015	260 ± 20	Moraine
	Nuussuaq moraine 1	N 70.315 W 52.015	280 ± 30	Moraine
	Nuussuaq moraine 1	N 70.315 W 52.015	250 ± 20	Moraine
	Nuussuaq moraine 2	N 70.315 W 52.014	320 ± 20	Moraine
	Nuussuaq moraine 2	N 70.315 W 52.014	540 ± 40	Moraine
	Nuussuaq moraine 2	N 70.315 W 52.014	500 ± 20	Moraine

Table 2: 10Be dates of glacial advances in west Greenland during the LIA

Although there are few pieces of research that provide absolute dates for LIA glacial re-advance, the literature agrees that there was a significant period of renewed glaciation that coincided with the LIA. Deglaciation after the LIA was attributed to 1890 by Bjørk et al. (2018) for west Greenland, historical photographs and travel diaries were used to determine the onset of deglaciation rather than ^{14}C or ^{10}Be dating but the resulting date is similar to that suggested by pollen cores on Disko Island (Schweinsberg et al., 2017). The most spatially comprehensive study to cover west Greenland is Bjørk et al. (2018), who presented and compared the length changes of 334 GICs across east and west Greenland since the LIA. It was found that retreat has been less severe in the east than the west, possibly attributable to changing precipitation associated with a positive phase of the North Atlantic Oscillation (NAO) (Bjørk et al., 2018).

Tables 1 and 2 demonstrate that the dates associated with glacial re-advance during the LIA vary widely across west Greenland, dates for the maximum extent of LIA glaciation are thought to vary even within local areas. For example; Lichenometric dating data show that outlet glaciers in the east of the Sukkertoppen ice-cap reached their maximum extents between 1850 and 1890 but outlet glaciers on the west of the ice cap possibly reached their maximum extent during the 1700s (Beschel, 1960; Beschel and Weidick, 1973; Kelly and Lowell, 2009). The stark difference seen at Sukkertoppen may show that local variables such as terrain and aspect may be more important controls of re-advance during the LIA than previously thought.

2.4 Little Ice Age moraines

After a renewed period of glaciation during the LIA, GICs in Greenland receded leaving an extensive proglacial environment characterised by well-preserved moraines (Grove, 1988; Kelly and Lowell, 2009); in west Greenland, these moraines are well defined and generally within 3 km of contemporary ice limits. Moraines for GICs in western Greenland have been attributed to the LIA because of their prominent appearance, the sharp ridgelines can be seen clearly on a hillshaded DEM (figure 5). It was suggested by Sugden (1972) that the sharp moraine ridges associated with the LIA in west Greenland represent the greatest extent of GICs in the Holocene because of their contrast with surrounding vegetation (figure 4) (Schweinberg et al., 2018). But subsequent studies have found pre-LIA moraines on Disko Island (Ingólfsson et al., 1990; Jomelli et al., 2016) and on the Nuussuaq Peninsula (Young et al., 2015; O'Hara et al., 2017). Moraines attributed to the LIA may represent the maximum Holocene extent in some areas but not others; possibly providing rationale for the theory that local factors may have dictated the style and extent of glaciation during the LIA.

There are surge-type glaciers in some areas of west Greenland, mostly confined to the Disko Island and Nuussuaq regions as part of the Disko-Nuussuaq surge cluster (Yde and Knudsen, 2005; Rastner et al., 2012). It is important to note that surge glaciers may have anomalous moraines leading to an inaccurate representation of glacier characteristics during the LIA. Surge glaciers should be included in analysis to give a holistic view of GIC response to climate change, but it is also useful to remove surge-type glaciers from overall volume loss figures to assess their importance within the total volume loss of a region.

Having evaluated the available and relevant literature, there is a knowledge gap regarding volume loss from GICs in west Greenland since the LIA. There is also poor understanding of the controls that govern GIC volume loss in response to climatic factors in west Greenland, and the relationships of latitude and coastal proximity with volume loss may provide crucial insights into future GIC change in the region. Quantifying volume loss in west Greenland GICs since their maximum Holocene extents will provide a centennial scale reconstruction of their response to climate change, and their contribution to sea level rise over the 20th century, aiding efforts to model the response of local glaciers and ice caps to future climate change.

2.5 Hypotheses

1. There will be a statistically significant relationship between latitude and glacier volume loss in west Greenland. As latitude increases, lower summer air temperatures are likely to cause GIC volume loss to be lower (Weidick, 1968; Leclercq et al., 2012; Larsen et al., 2017).
2. There will be a statistically significant relationship between coastal proximity and glacier volume loss in west Greenland. As coastal proximity decreases, the impact of a maritime climate will be less, and rates of volume loss are likely to be lower (Holmlund and Schneider, 1997; Grinsted, 2013).

3.0 Datasets and Methodology

Contemporary extents for present-day glaciers in the west of Greenland were acquired from GLIMS (Raup et al., 2007) for 2014; this was the most recent year that data was fully available. There were several outlines for glaciers in 2018 but only for some glaciers in some areas, so they were discounted from analysis for consistency. A flowchart describing the methodology, from obtaining data to producing volume loss statistics, has been created (figure 9) and is aimed at undergraduate students who may follow these methods.

GICs in west Greenland vary greatly in size, for this study glaciers under 1 Km^2 were not mapped. This threshold size was selected partly for the efficiency of covering the large study area but also to remove the confounding impact of seasonal snow (Rastner et al., 2012). This can lead to inaccurate area data and the effect is more pronounced in smaller GICs. The total glacier area sampled in this project was 17,211 Km^2 and the total glaciated area as downloaded from GLIMS is 17,926 Km^2, in other words a coverage of 96%. A small amount of glaciers exist around Melville Bugt close to Upernivik, these were not sampled because they have a high proximity to the GrIS and have a higher level of connectivity to the ice sheet than glaciers in the other areas (Rastner et al., 2012).

3.1 Identification and interpretation of moraines

In order to identify 2-D palaeo-glacier extents a landform approach was used, ice-marginal features were identified using mosaicked ArcticDEM tiles at a 2m resolution. These DEMs (Polar Geospatial Center, 2018) were created from stereoscopic imagery of the Arctic from the WorldView series of satellites and processed by Noh and Howart (2015) to create DEM tiles. In conjunction with the ArcticDEM, satellite imagery was used to improve accuracy when mapping LIA extents, the Arctic Imagery Terracolor basemap from ESRI was used at a 15m resolution in ArcMap v. 10.6.2 (ESRI, 2020) (figure 4). Landforms used to interpret LIA maximum extents included: terminal and lateral moraines, drift limits, trimlines, and proglacial fans. Most focus was placed on the accurate identification and interpretation of terminal and lateral moraines because they are generally the most reliable indicators of lateral extent (Pearce et al., 2017). In west Greenland these moraines are typically well developed and easily identified on both satellite imagery and the hillshaded 2m ArcticDEM (figures 4 and 5).

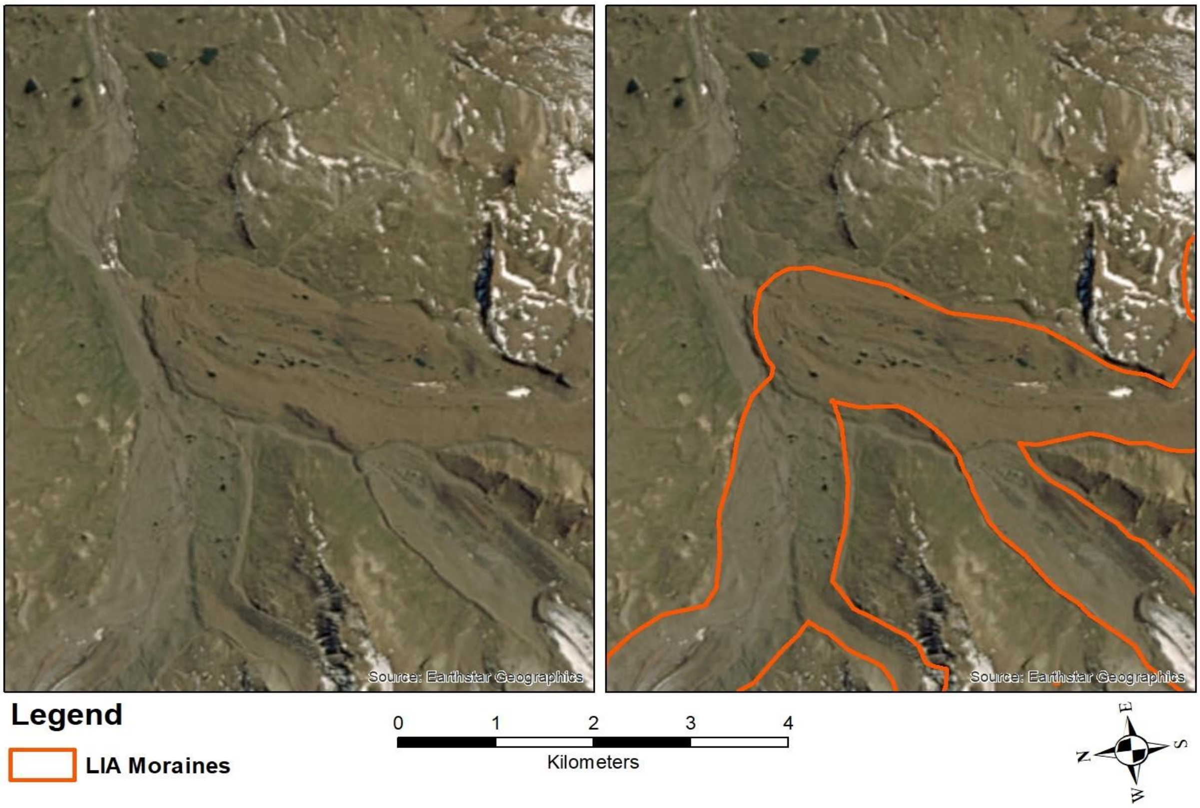


Figure 4: The 15m Terracolour Arctic Imagery base map used in ArcMap 10.6.2 to aid identification of landforms showing a confluence of 2 LIA moraines in the Svartenhuk region. Moraine ridges are clearly identifiable as sharp ridges and a change in vegetation.

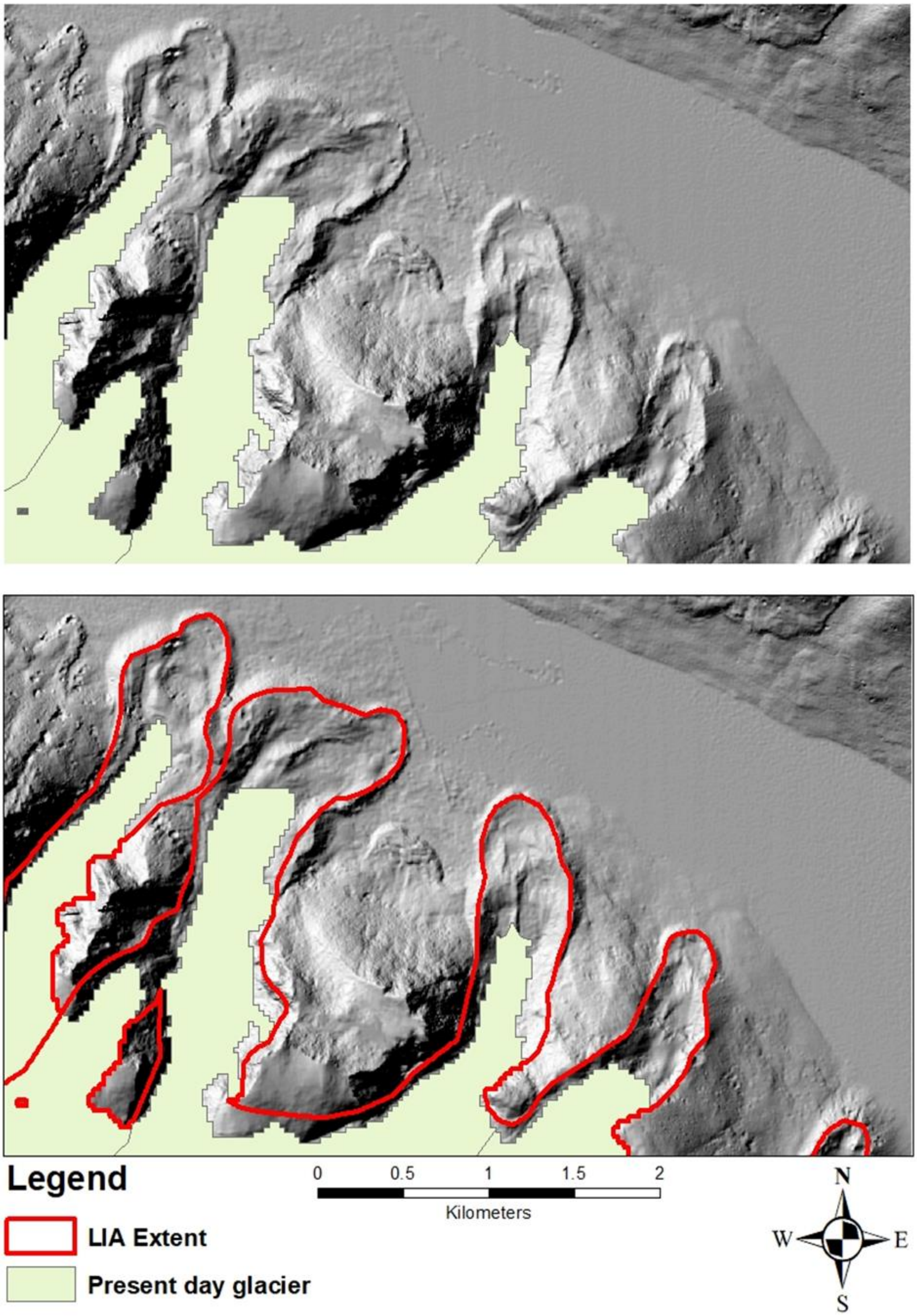


Figure 5: Interpretation of LIA moraines in Nuussuaq. LIA moraine ridges often have sharp crests and are easily identifiable using a hillshaded DEM

Although the satellite imagery is clear enough to identify large features, the 15m resolution limited its usability on a smaller scale for example; when interpreting the confluence of two glaciers from LIA moraines it was much less effective than the hillshaded 2m ArcticDEM imagery (figure 6).

To map the LIA extents of GICs the GLIMS shapefile was duplicated, after filtering out glaciers less than 1 Km^2 in area and outlines from 2018. The duplicate shapefile was extended to the interpreted LIA ice margin using the 'reshape feature' tool in ArcMap, in most cases this was the outermost and most prominent moraine ridges of the terminal and lateral moraines (figure 5). Where there is clear evidence that GICs were connected during the LIA but had since retreated into separate valleys, their respective polygons were merged at the confluence of the moraine ridges. In cases where landform evidence was not clearly identifiable on the hillshaded ArcticDEM, the 15m resolution Arctic Imagery base map was used to locate the LIA ice margin. Prominent moraine ridges can be identified in satellite imagery as there is often a stark change in vegetation or ground cover at the LIA margin, this was easily identifiable using the Arctic Imagery base map (figure 4). The joint use of DEMs and satellite imagery is common in palaeo glacier reconstructions, similar methods have been utilised in Greenland; by Carrivick et al. (2019) in the north-east and Citterio et al. (2009) in central-west areas.

The highly detailed 2m ArcticDEM has allowed the identification and analysis of 2907 glaciers, and their retreat since the LIA. The 2m resolution makes identification of landforms simple but in some areas there are large holes in the DEM as shown in figure 7, these holes sometimes cut through moraines leaving them unable to be identified from the hillshaded layer. Huber et al. (2020) commented on the poor quality of DEMs currently available for many areas around Greenland and suggested that areas with no data could be caused by radar penetration. There were some areas with large holes in the DEM and the 15m Arctic Imagery base map was not of a high enough resolution to be able to interpret the landform evidence. Sukkertoppen was the region with the most holes in the DEM (e.g. figure 7), and in some cases landform evidence could not be identified on the 15m Arctic Imagery base map meaning 39 glaciers could not be analysed, although this only represents 4.9 % of the number of GICs sampled in Sukkertoppen.

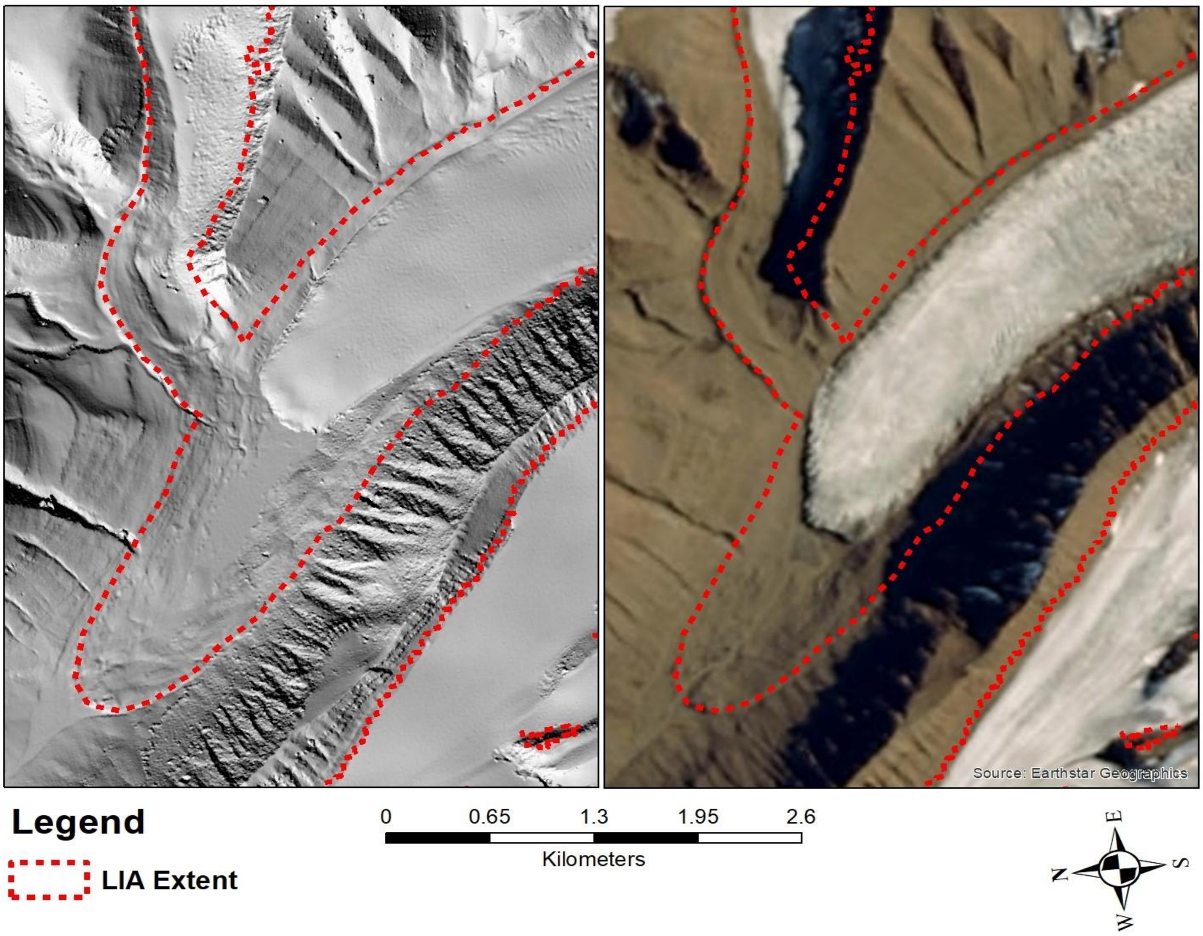


Figure 6: The confluence of 2 valley glaciers on the Nuussuaq peninsula, on the hillshaded image (left) the landform evidence is much clearer than on the 15m Terracolour Arctic Imagery base map (right).

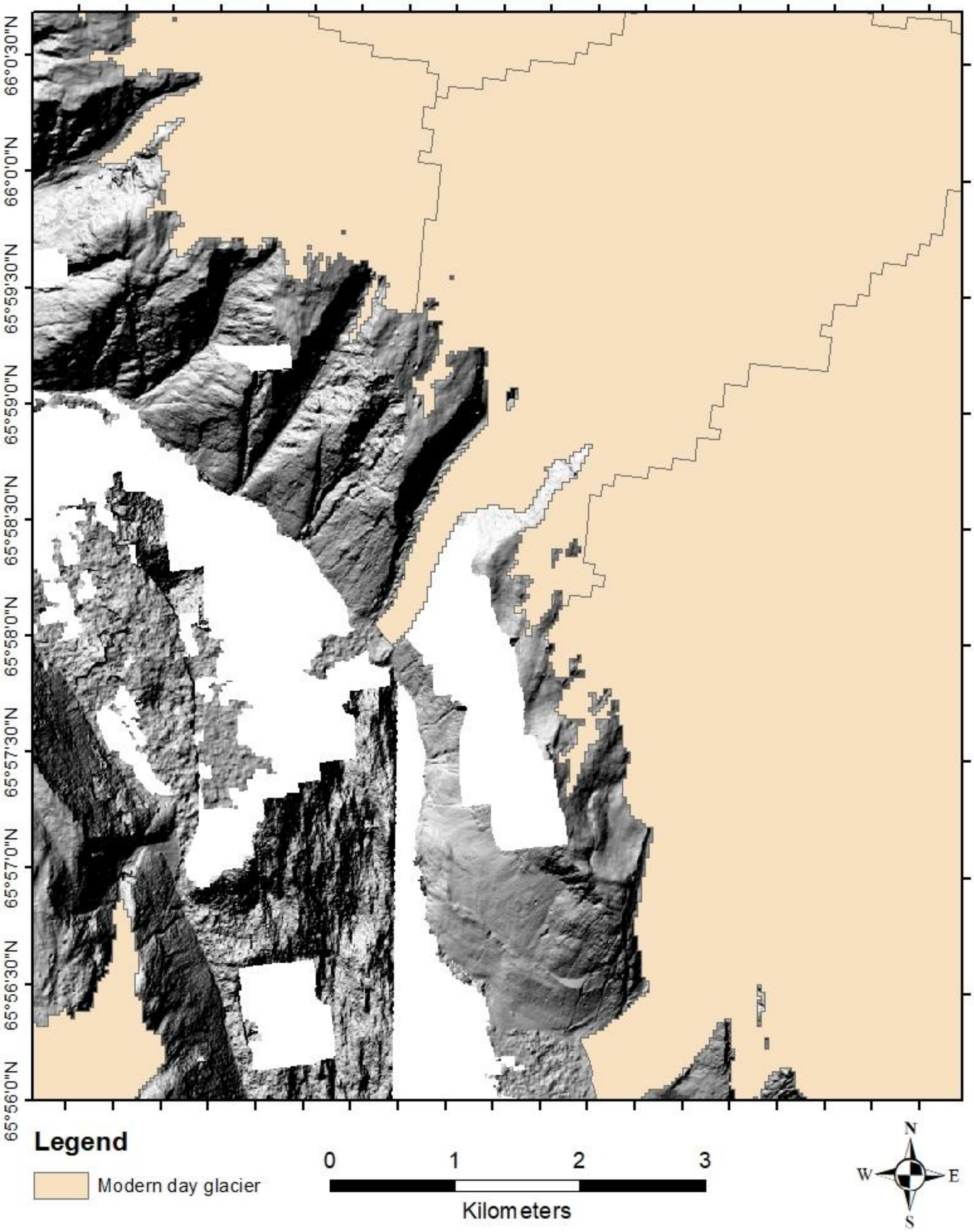


Figure 7: An area of the Sukkertoppen region that could not be sampled due to large and frequent holes in the DEM.

In the areas where holes were so large that no interpretation was possible, ground observations would have allowed moraines to be sampled, although this methodology would be entirely impractical over such a large study area. In the future, advancements in remote sensing will produce higher quality DEMs so problems such as holes in the DEM will have less of a confounding impact.

3.2 Surface differencing

After moraines had been digitised to show the LIA extents, the LIA equilibrium line altitudes (ELA) and subsequently the LIA ablation areas were found for each LIA glacier. This is because deposition occurs below the ELA whilst erosion and entrainment occur in the accumulation area (Cogley et al., 2010), the processes of volume loss from GICs since the LIA will have been limited to the ablation zone. Firstly, LIA ELAs were calculated automatically for each LIA glacier, this was done using an ArcGIS toolbox created by Pellitero et al. (2015). The toolbox uses the Area Altitude Balance Ratio (AABR) method, this is a widely used method and is reliable because it accounts for glacier hypsometry as well as altitudinal change in mass balance (Benn and Lehmkuhl, 2000; Osmaston, 2005; Pearce et al., 2017); the method is best suited for clean, snow-fed glaciers that receive little input from avalanches (Pellitero et al., 2015). GICs in west Greenland are well suited to using the AABR method, which needs a pre-determined balance ratio as part of the equation. Rea (2009) created a dataset of balance ratios appropriate for glaciers across the globe, this study used a balance ratio of 2.24 which is representative of high latitude mountain glaciers (Rea, 2009; Pellitero et al., 2015).

After glacier specific ELAs had been calculated, ablation areas could be delineated for each glacier. This process involved a toolbox developed by Carrivick et al. (2019) based on the toolbox used for ELA calculation, the polygon for the LIA outline is intercepted at the ELA which creates the ablation area, reconstructed ablation areas on Disko Island can be seen in figure 8.

To reconstruct the LIA glacier surface within the ablation zones the ‘densify’ tool was used to add more vertices to the ablation area polygons and smooth edges, then each vertex was converted to a point in a new shapefile. The ‘add values to points’ tool was used to assign elevation values to each vertex point, the 2m ArcticDEM was resampled to 20 m in order to reduce the workload of interpolation. A 3-D LIA glacier surface was created by interpolating between these points using natural neighbour analysis; Carrivick et al. (2019) found that kringing analysis produced similar results but was much more time consuming and required more computing power. The ArcticDEM was subtracted from the LIA surface using the raster calculator tool to give a new raster layer of surface lowering. The ‘zonal statistics as table’ tool was used to extract these surface lowering values for glacier specific ablation areas, and these values were exported to Microsoft Excel in order to calculate volume and mass changes.

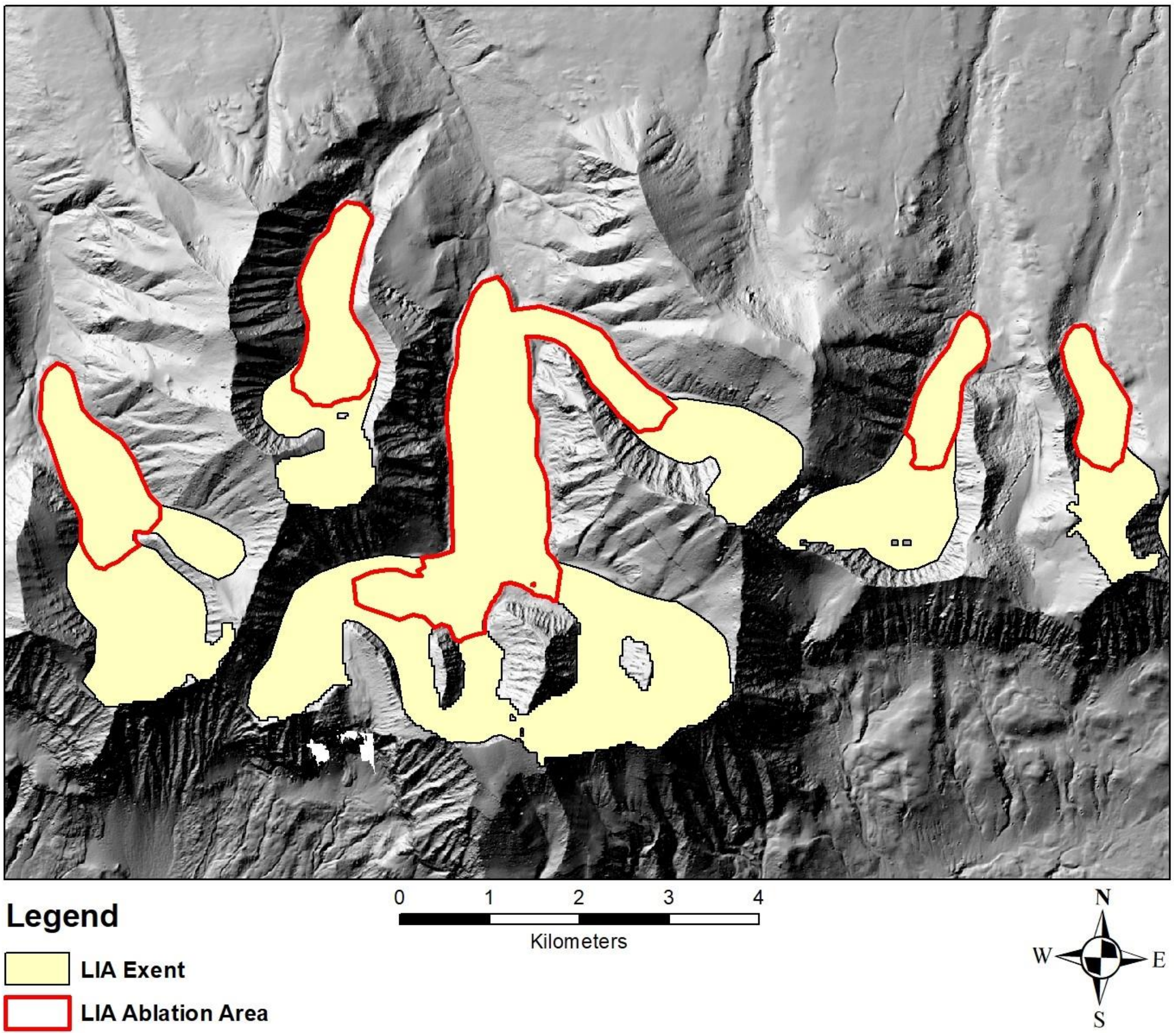


Figure 8: Results of the ablation area tool, the portion of the glacier below the ELA is identified as the zone of volume loss.

3.3 Volume loss, mass loss and sea level contribution.

In order to derive volume and mass loss figures, cell size has to be accounted for; because the ArcticDEM was resampled to 20m x 20m, the surface lowering values were multiplied by 400 to show volume loss in m^3. This was converted to mass loss by multiplying by 0.917, an ice density of 917 kg/m^3 can be used in higher latitudes with low surface air temperatures (Cogley et al., 2010); this is an appropriate value for west Greenland because of the low MAAT and latitudes up to 76°. Values were also converted to average annual loss figures since the LIA by dividing by 124, the years between 1890 and 2014.

It was important to calculate the contribution of local glaciers in west Greenland to global sea level rise, it has been recognised that GICs have had a larger role in sea level rise relative to area than the main ice sheets in recent decades (Gardner et al., 2013; Zemp et al., 2019). Mass loss was converted into gigatonnes and multiplied by the volume of water required to increase sea levels by 1mm, an ocean area of 3.62 x 10^8 km^2 was used for the calculation (Hock et al., 2009).

3.4 Rates of change

After calculating estimates for volume and mass loss, it was possible to determine a long-term rate of change for the volume and mass losses seen in west Greenland GICs from the end of the LIA to 2014. A long-term rate of change value can be used to compare centennial scale volume loss to the rates of loss seen in contemporary studies (e.g. Bolch et al., 2013), providing insights into the changing state of Greenland's GICs and their accelerating volume loss. Studies similar to this such as Carrivick et al. (2019) have calculated rates of volume loss on decadal timescales as well as centennial; but the lack of previous studies and dated evidence, such as photographs, available for west Greenland means showing decadal rates of volume loss are outside the scope of this project.

The year 1890 is chosen as the onset of LIA deglaciation in west Greenland based on findings by Bjørk et al. (2018), historical aerial photography and travel diaries were used to infer the onset of retreat. Although the methodology used by Bjørk et al. (2018) does not include radiocarbon dating, the resulting date of 1890 is concurrent with C^{14} dating on Disko Island (Schweinsberg et al., 2017) (Table 1). As a result of 1890 being chosen as the date of the onset of LIA deglaciation, rates of volume and mass change were calculated over a period of 124 years; because contemporary GIC outlines are constrained to 2014 by GLIMS.

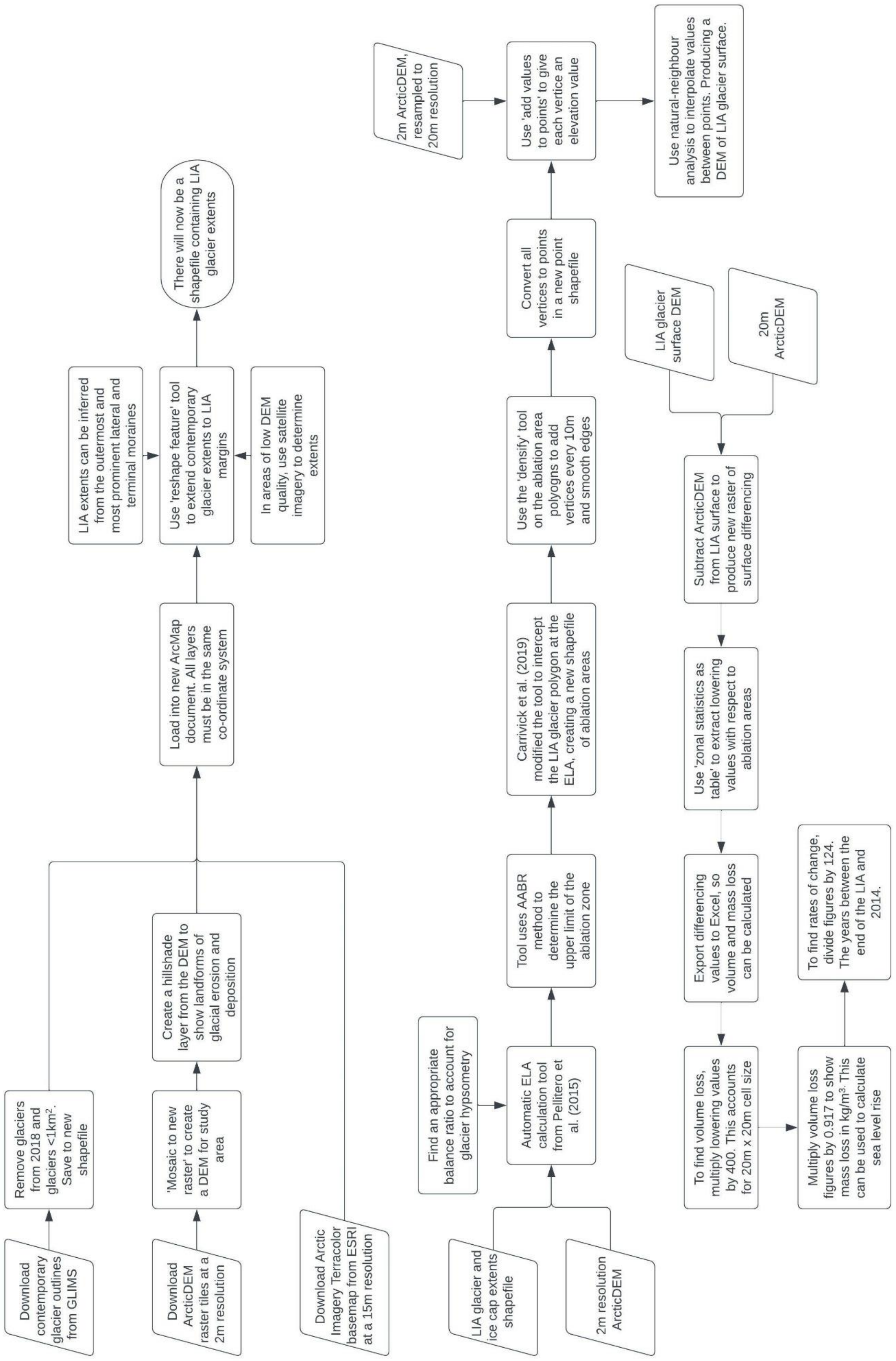


Figure 9: A flowchart designed so that an undergraduate with some ArcGIS knowledge would be able to replicate this study and produce similar results.

3.5 Latitude and coastal proximity

The two hypotheses of this project stated that volume loss would have a statistically significant relationship with both latitude and distance from the coast. To facilitate this analysis, a point shapefile was derived from the LIA ablation areas, placing a point in the centre of each polygon. A column was added to the attribute table of the point shapefile and latitude was calculated for each glacier. To find the distance from the coast, a shapefile for the entire Greenland coast (Hijmans, 2015) was used to create a simplified coastline covering the study area. The 'Near' tool was used to assign each point a value, dependant on the distance from the coast polyline in metres. The attribute table of the point shapefile was joined to the zonal statistics table of surface differencing, using each glacier's ID number as the common element.

To investigate the relationship of GIC volume loss since the LIA with latitude and coastal proximity, regression models were used (95% confidence). This revealed whether the relationship was statistically significant, and illustrated how well both variables explained the variation seen in volume change using the R^2 value.

3.6 Limitations and uncertainty analysis

Uncertainty analysis was carried out in order to determine the margin of error resulting from the digitisation of moraines. Glaciers in the Disko Island region were re-digitised to their interpreted LIA extents, with no data available from the first time the region was analysed and with the same GIS methods. Disko Island was chosen as the region most appropriate for uncertainty analysis because it is where the ArcticDEM has the highest quality and least amount of holes. This means that the impacts of low quality areas of the DEM are minimised, reducing the effects of confounding variables so the uncertainty analysis can be applied to the rest of the study area. Once the moraines had been re-digitised, the same methodology for calculating surface differencing and volume loss was followed so the two sets of results could be compared and an uncertainty level determined. The volume loss of the re-digitised Disko Island GICs was 4.6 Km^3 lower than the initial figure, meaning that the volume loss results of this study likely have an uncertainty range of approximately 15%.

A crucial area of uncertainty regards the rate of volume loss seen in GICs since the LIA. There is a lack of consensus in the literature concerning the onset of deglaciation from the LIA in west Greenland, the most recent date given is 1890 by Bjørk et al. (2018) who reviewed past dating studies, aerial photographs and travel journals. 1890 is chosen as the onset of LIA deglaciation in this study because of the robust methodology used by Bjørk et al. (2018), as well as the concurrence with C^{14} dates such as Schweinsberg et al. (2017) (Table 1). But there are other estimated dates for the end of LIA in west Greenland in the Literature; other dates proposed are 1850 (Weidick, 1968; Beschel and Weidick, 1973), 1900 (Csatho et al., 2008) and 1920 (Weidick, 1968; Dowdeswell, 1995). There is uncertainty in the dates of deglaciation with a magnitude of up to 40 years, depending on the date chosen, the rate of volume loss changes drastically as shown in table 3. It is important to mention the uncertainty in the rate of volume loss because it is a crucial statistic when comparing volume loss between different areas of Greenland, as well as helping to depict long-term patterns of volume loss.

Onset of LIA deglaciation	Difference from 1890 (years)	Difference in volume loss (%)
1850	40	-32.3
1900	10	+8
1920	30	+24.2

Table 3: Dates presented in the literature for the onset of LIA deglaciation. Column 3 shows the change in rate of annual volume loss compared to 1890.

This study estimates the volume loss of west Greenland GICs since the end of the LIA, but the results presented should be considered as a minimum estimate. A reason for this is that the dataset of 2014 glacier outlines from GLIMS sometimes did not show a glacier in a valley or cirque where there is clear landform evidence of glaciation (figure 10). The likely reason for this is that a glacier in that valley or cirque has disappeared completely since the LIA, but this cannot be said with complete confidence so volume loss was not calculated in valleys with no GLIMS outline. Another possible reason for valleys appearing empty is that a rock glacier exists but was not identifiable from remote sensing. Rock glaciers are fairly common in central-west areas of Greenland (Humlum, 1988; Citterio et al., 2009); on Disko Island, there are approximately 20 rock glaciers per 100 Km^2 (Humlum, 1988). Rock glaciers can be challenging to identify (Citterio et al., 2009) and may not have been included in the GLIMS database, resulting in their volume loss between the LIA and 2014 not being calculated.

Surge-type glaciers present a unique issue because their retreat is de-coupled from climatic factors (Evans and Rea, 1999), this could lead to anomalous moraines. A surging glacier may have reached its Holocene limit after the end of the LIA, so interpretation from the outermost and most prominent moraine ridge could lead to inaccurate volume loss statistics. The best way to remove this as an issue would be to date the moraine ridges of surge-type glaciers, but this would be impractical given the study area. Results are presented with the inclusion of surge-type glaciers in order to give a realistic view of volume loss since the LIA, but results are also shown without surge-type glaciers in order to explore the role of these glaciers within overall volume loss.

Tidewater glaciers exist in west Greenland and were included in this study, several GICs terminate in the ocean, most examples are found in Thule but a small amount of GICs terminate in fjords in every region. Tidewater glaciers present an area of potential uncertainty because in many cases their LIA terminal moraines cannot be seen on the hillshaded DEM or satellite imagery, as contemporary sea levels have risen above LIA moraine ridges. In circumstances where LIA terminal moraines were not visible, lateral moraines were subjected to increased focus. The terminal extent was inferred from the point at which lateral moraines disappeared under the surface of the fjord. The volume loss of tidewater glaciers in west Greenland between the LIA and 2014 should be considered a minimum estimate.

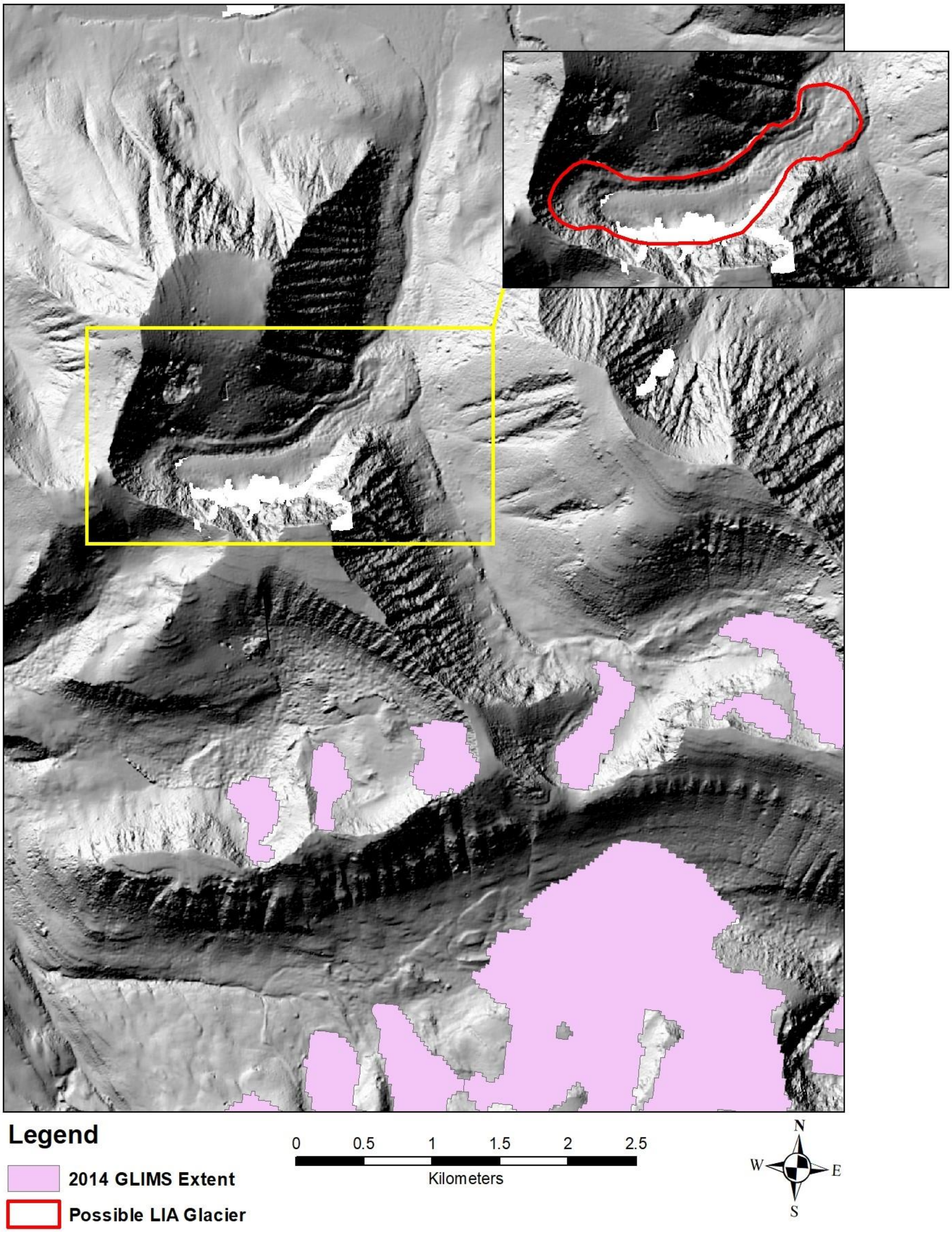


Figure 10: A valley on Disko Island with clear glacial landform evidence but no GLIMS outline, holes in the DEM are also visible. This valley was not sampled.

4.0 Results

The total area lost from local glaciers and ice caps in west Greenland between 1890 and 2014 is calculated to be at least 2002 ± 300 Km^2, this represents a 12% loss from an initial LIA area of 17,211 km^2. The loss of GIC area between the end of the LIA and 2014 is visible in figure 11, which displays GIC extents in the central-west area of Greenland.

The volume loss between the end of the LIA and 2014 has been calculated to at least 184 ± 27 Km^3. If the 29 surge-type glaciers are excluded from the total figures, volume loss falls to 163 ± 24 Km^3, this is a change of approximately 20.59 Km^3 or 11%. The mass lost from west Greenland GICs between 1890 and 2014 was found to be at least 169 ± 25 Gt. This has been calculated as a 0.47 ± 0.07 mm global sea level rise contribution.

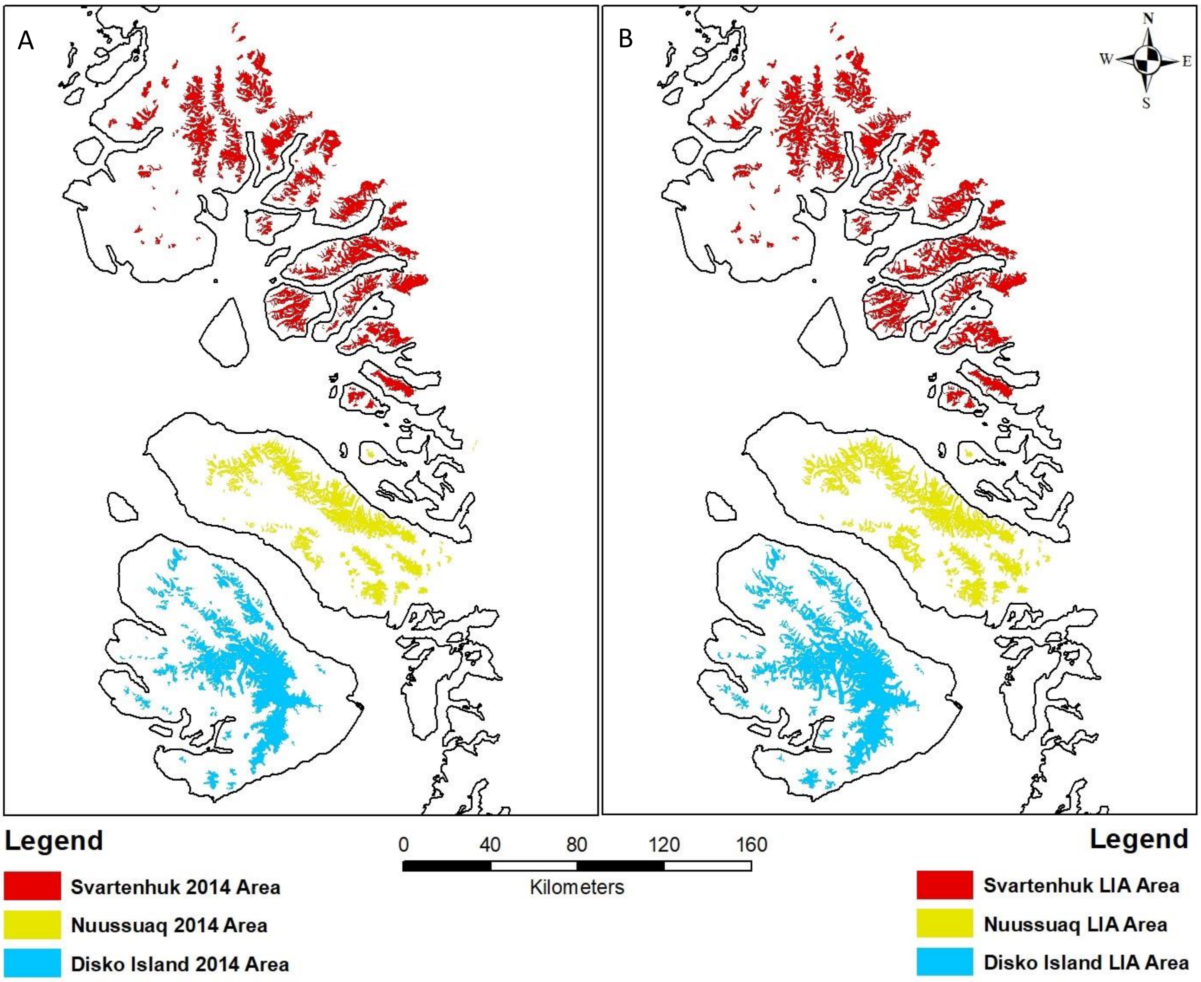


Figure 11: (A) The modern-day (2014) extents of GICs in central-west Greenland. (B) The LIA extents of GICs in central-west Greenland, reconstructed from interpretation of LIA moraine ridges.

4.1 Rates of change

The average annual rate of volume loss from GICs in west Greenland from 1890 to 2014 is at least 1.5 ± 0.2 Km^3 per year, this equates to an average rate of mass loss of 1.4 ± 0.2 Gt per year. The average annual contribution to sea level rise of west Greenland GICs from the end of the LIA to 2014 is 0.004 mm per year. Different dates for the onset of LIA deglaciation in west Greenland are suggested in the literature, if these are taken into account, the rate of change seen in GICs varies. Table 4 presents the difference in resultant long-term rates of change if other dates from the literature are used to constrain the end of the LIA.

Onset of LIA deglaciation	Rate of volume change (Km^3/year)	Rate of mass change (Gt/year)	Sea level rise contribution (mm/year)	Difference in rate of change (%)
1850	1.1	1.0	0.003	-32.5
1900	1.6	1.5	0.004	+8
1920	1.9	1.8	0.005	+24.2

Table 4: A comparison between the rates of volume change, mass change and annual sea level rise contribution when alternative dates proposed by the literature for the onset of LIA deglaciation are used.

4.2 Spatial patterns of volume loss

Every GIC in west Greenland sampled in this study has lost volume since the end of the LIA in 1890, although the magnitude of this decay has not been uniform across west Greenland. The volume loss of some regions is far greater than that of others, the distribution of volume loss across different regions of west Greenland is presented in table 5 and in figures 12 to 16. Thule and Sukkertoppen have by far the largest contributions to total west Greenland GIC volume loss since the end of the LIA, while GICs on the Nuussuaq Peninsula account for the least volume loss (table 5). The regions responsible for the largest proportion of volume loss also had the largest initial glaciated area at the end of the LIA; in order to identify the relative volume loss of each region, the volume loss of each region has been presented as a function of initial LIA glacier area in table 5.

Region	Volume Loss (Km^3)	LIA GIC Area (Km^2)	Relative Volume Loss (Km^3/Km^2)
Sukkertoppen	50	6100	0.008
Disko Island	29	2100	0.013
Nuussuaq	16	1470	0.011
Svartenhuk	30	2897	0.010
Thule	58	6645	0.009

Table 5: Volume loss of different regions of west Greenland presented as a function of initial LIA GIC area.

Within each of the 5 regions sampled, there are no identifiable spatial patterns of volume loss on a north to south transect (figures 12 to 16). There is a clear trend in volume loss from west to east in Sukkertoppen, the glaciers with the highest volume loss figures are located in the east of the region furthest from the coast (figure 12). There is also somewhat of a west to east pattern in the volume loss of GICs on the Nuussuaq Peninsula (figure 14), glaciers in the west have higher volume loss, but it is not as clear as the trend in Sukkertoppen.

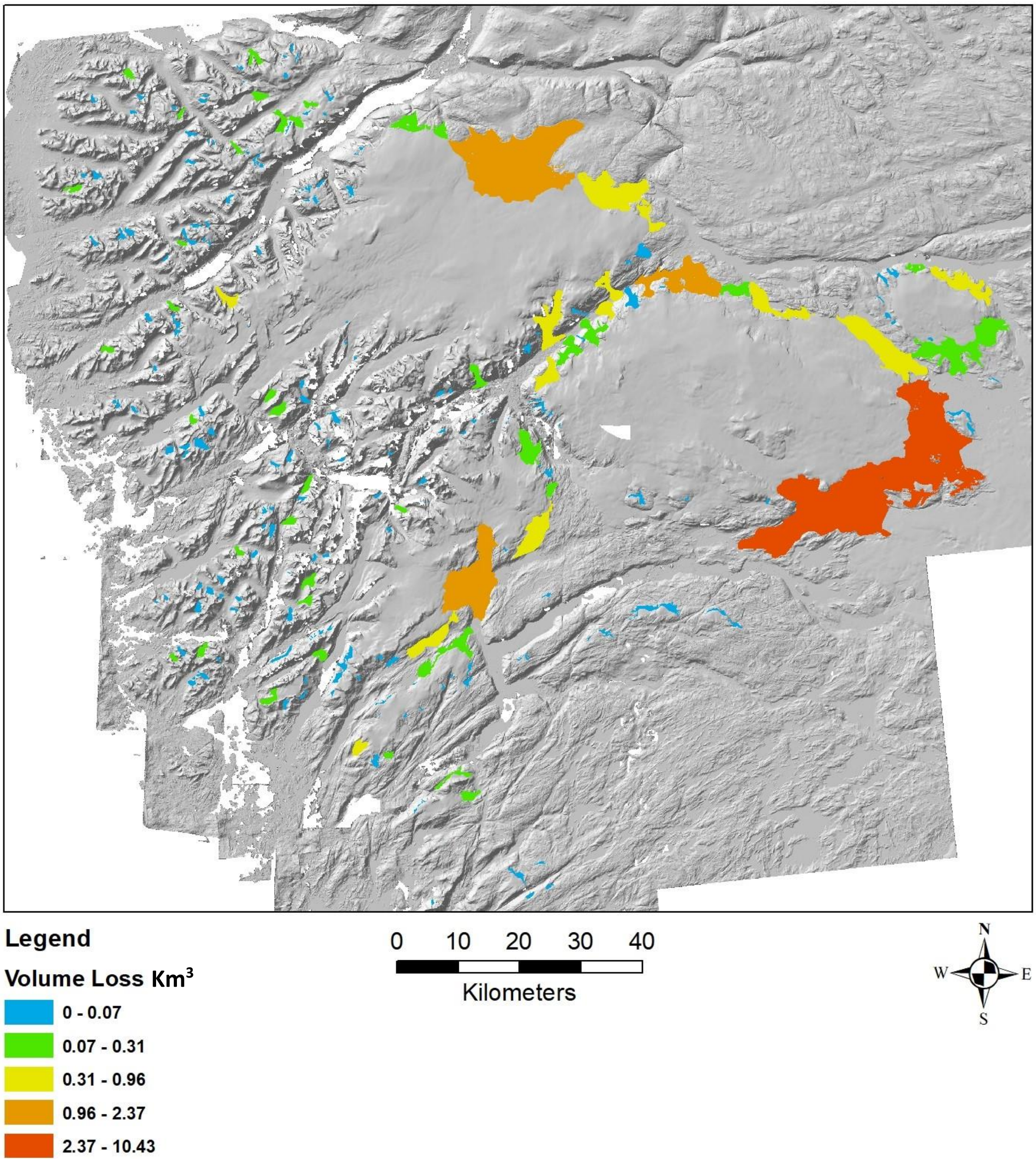


Figure 12: The spatial distribution of GIC volume loss in Sukkertoppen since the end of the LIA (1890)

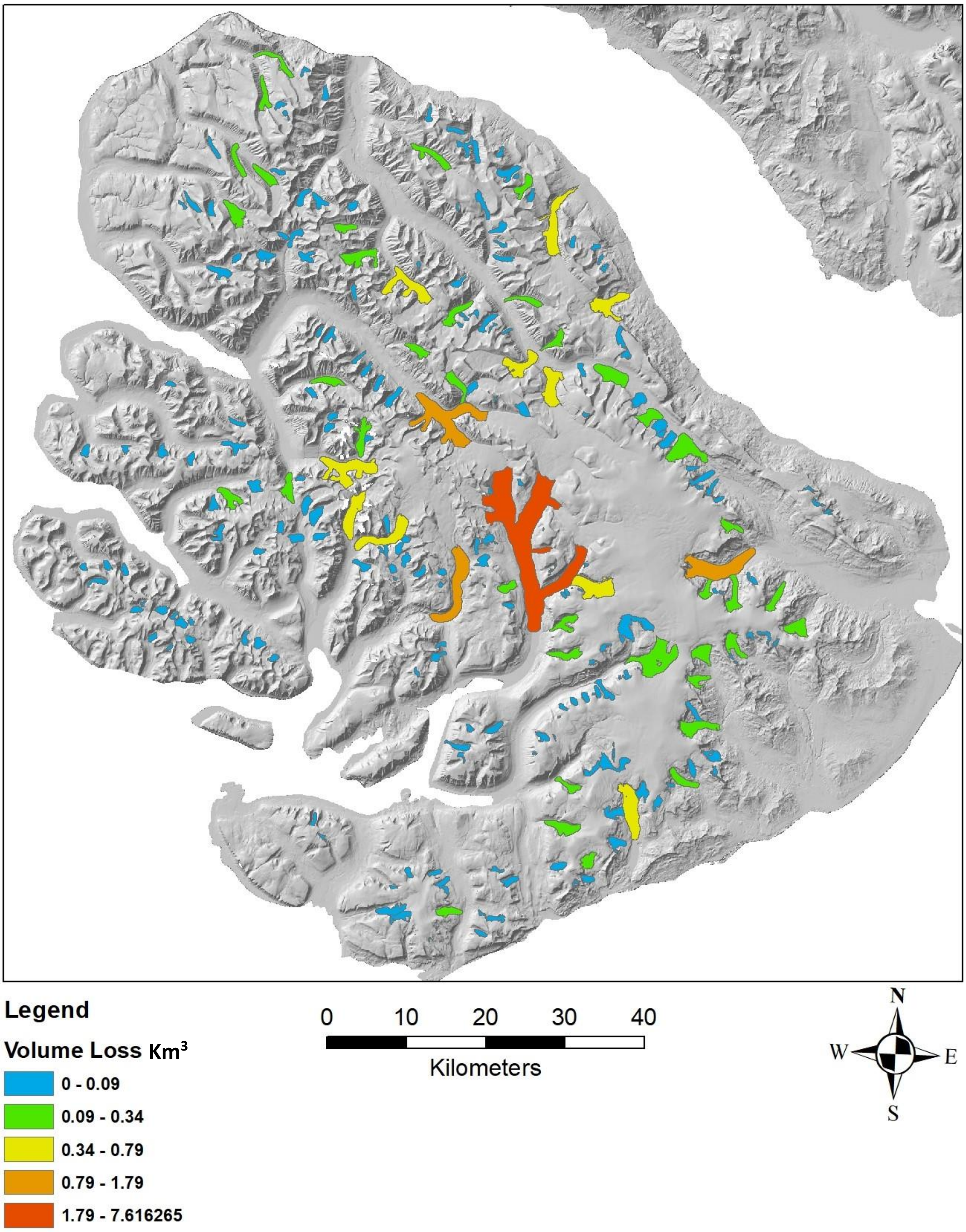


Figure 13: The spatial distribution of GIC volume loss since the end of the LIA (1890) on Disko Island.

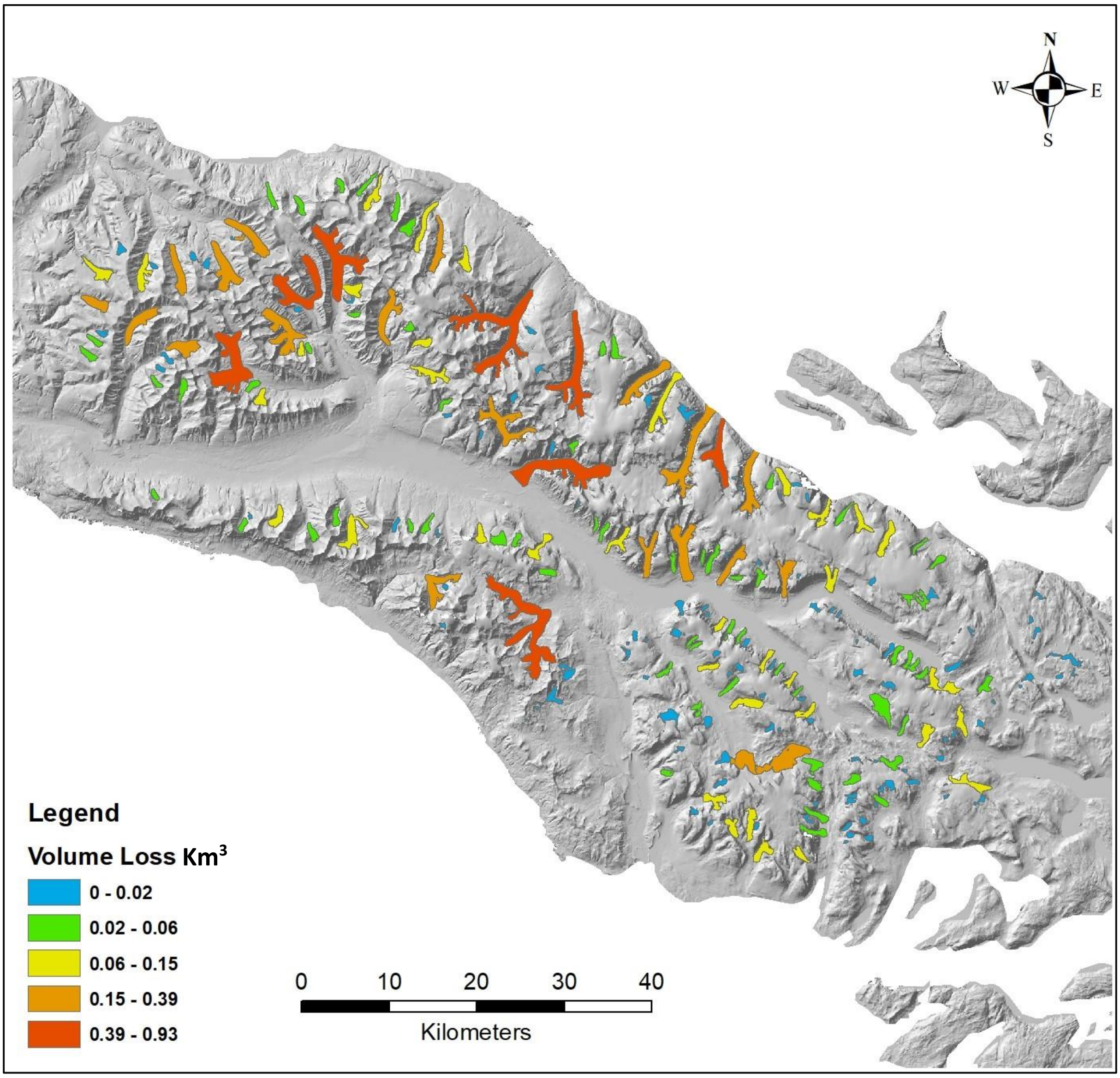


Figure 14: The spatial distribution of GIC volume loss since the end of the LIA (1890) on the Nuussuaq peninsula

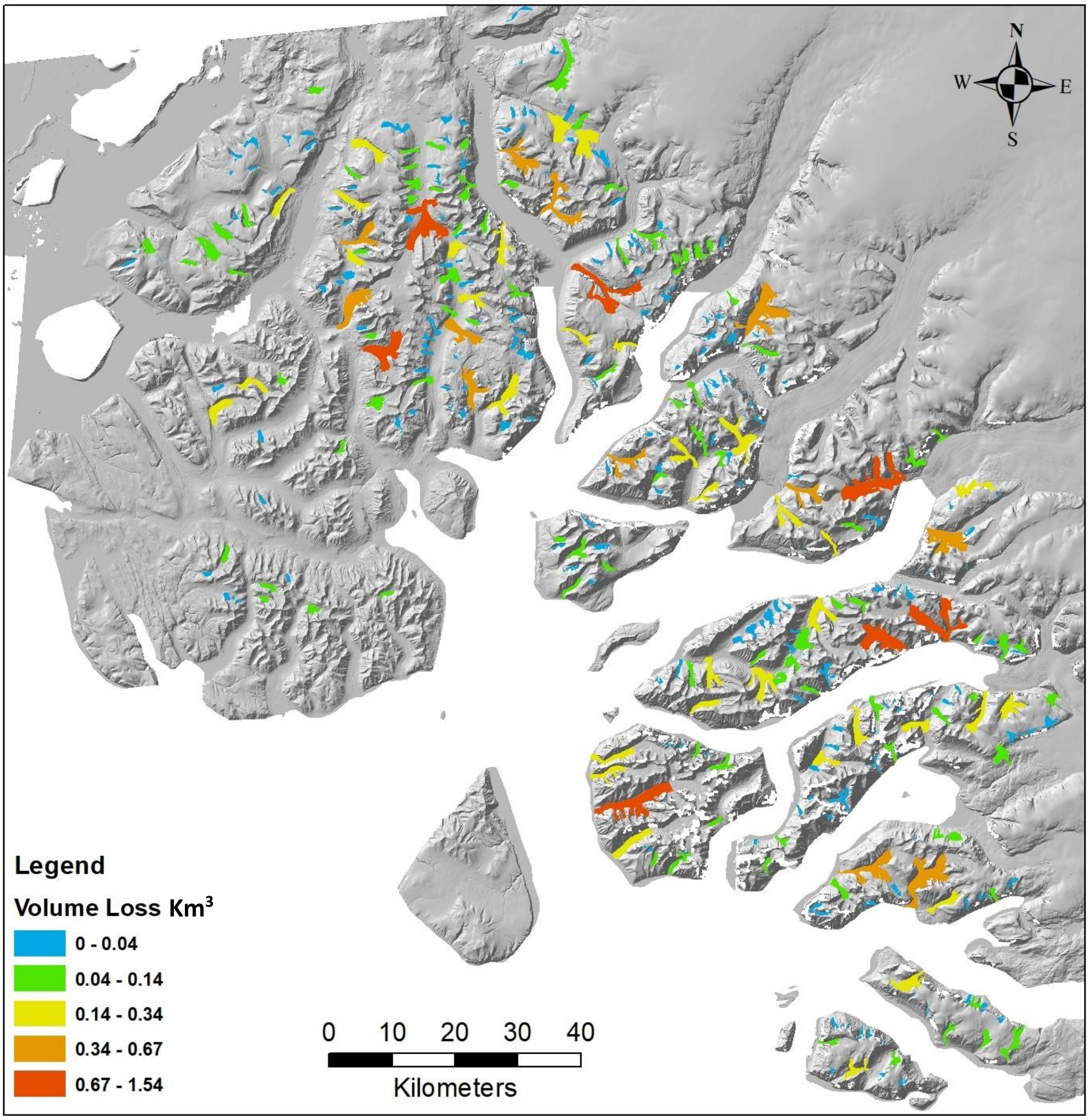


Figure 15: The spatial distribution of GIC volume loss since the end of the LIA (1890) in Svartenhuk.

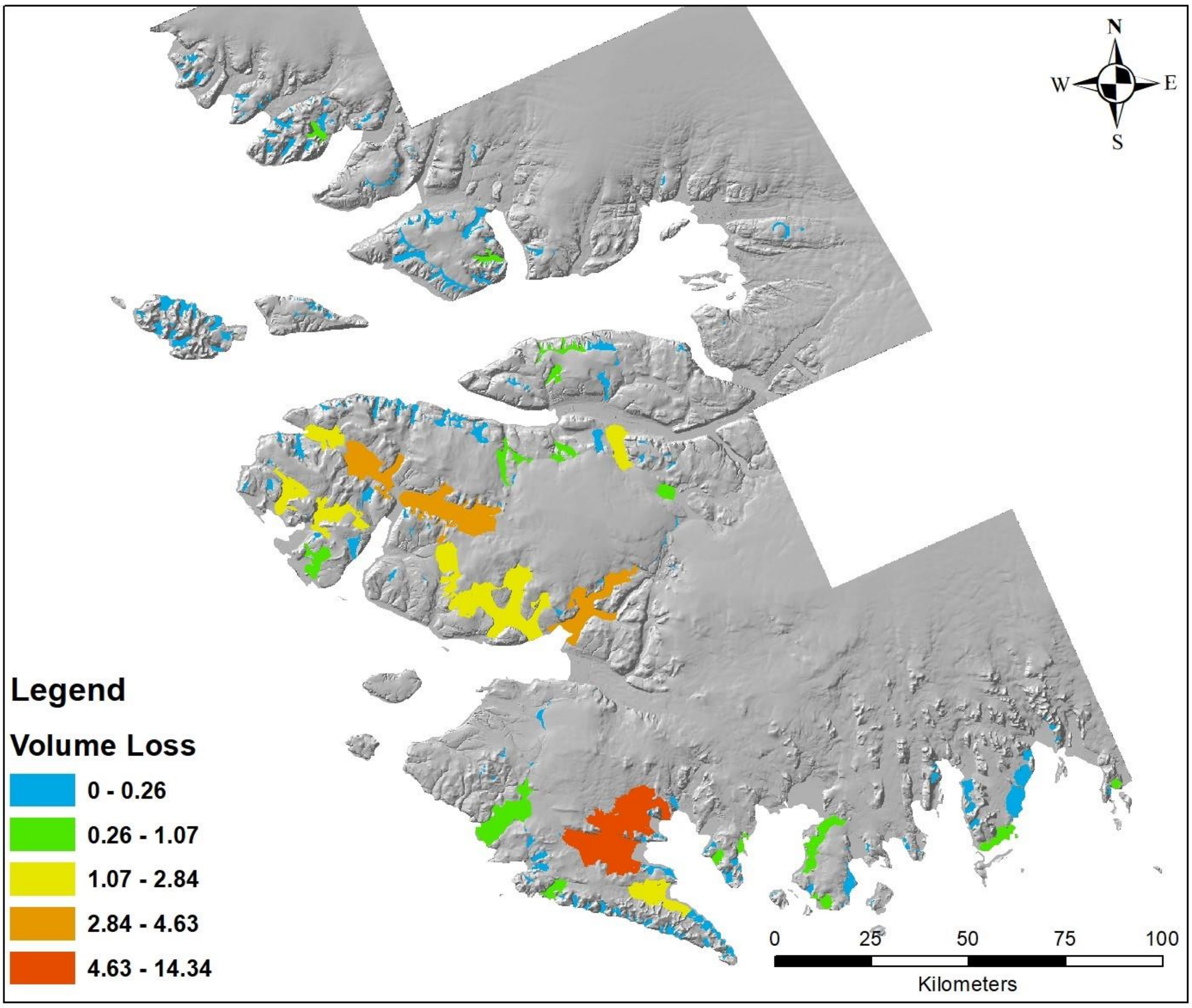


Figure 16: The spatial distribution of GIC volume loss since the end of the LIA (1890) in Thule.

In the Disko Island region, the majority of volume loss is focused in the central region (figure 13). This is a result of a large surge-type glacier losing at least 7 Km^3 of volume since the LIA, approximately 24% of the total volume loss for the whole of Disko Island. The surface differencing data in the ablation area of this glacier is displayed in figure 17, there is an area of significant surface lowering in the lower end of the ablation area with up to 410 m of loss. There are also some areas of the glacier that have experienced positive surface elevation gain, but not to the same magnitude; the maximum gain seen in the ablation zone is only 43 m.

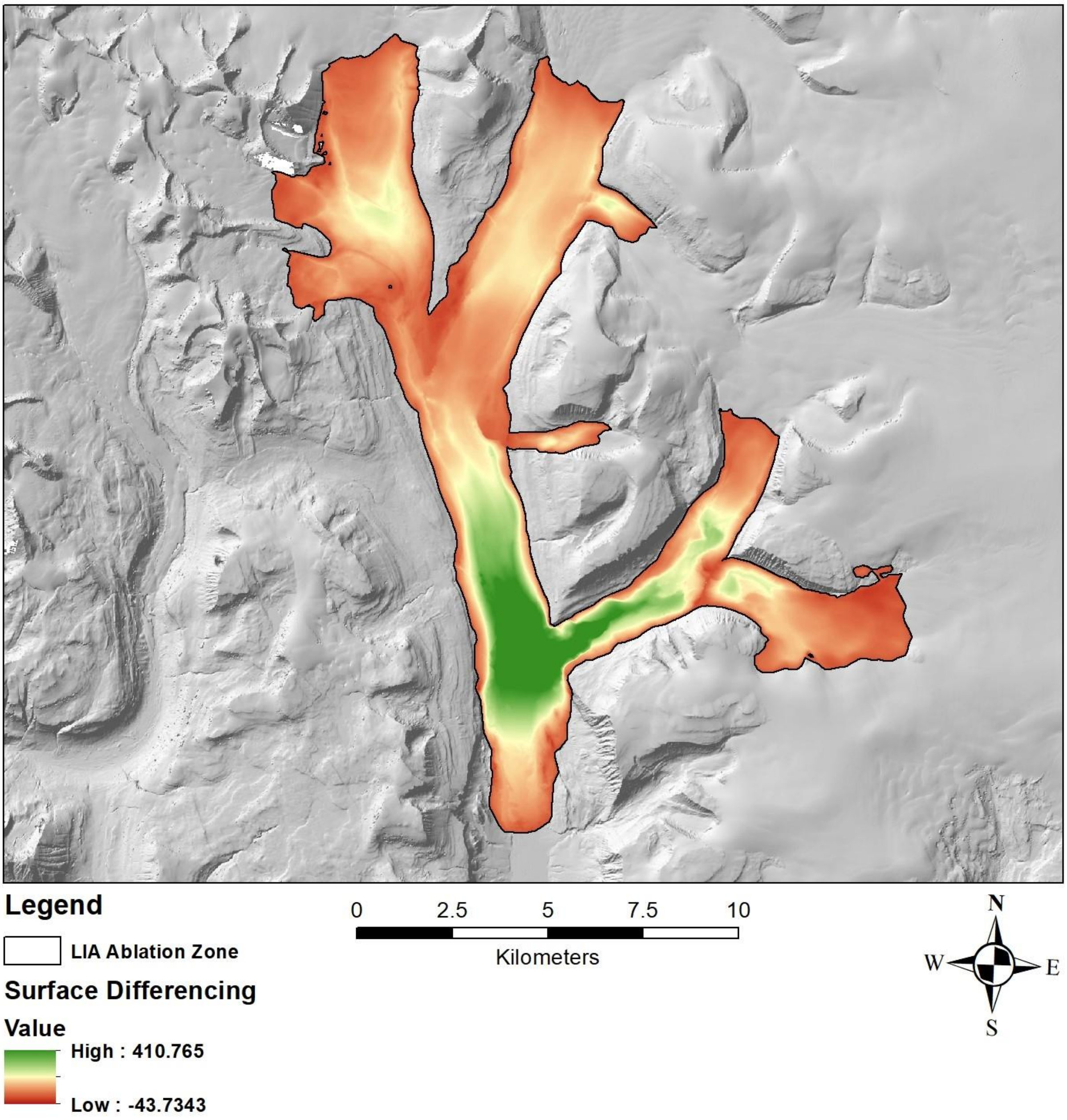


Figure 17: Surface differencing data since the end of the LIA for the ablation area of a surge-type glacier on Disko Island responsible for a large proportion of total volume loss in the area.

4.3 Latitude

In order to test the relationship between volume loss and latitude, a regression model was created (95% confidence). A significant relationship was identified (P = 0.002) with a weak negative correlation (r = -0.071); indicating that as latitude increases, the volume loss seen in west Greenland GICs decreases. This relationship is presented in figure 18, the different latitudes split GICs into 3 main groups, although a relationship between latitude and volume loss is not immediately obvious from figure 18. The calculated relative volume loss data is concurrent with the statistical relationship, with the exception of Sukkertoppen, the relative volume loss of each area decreases with increased latitude (figure 19).

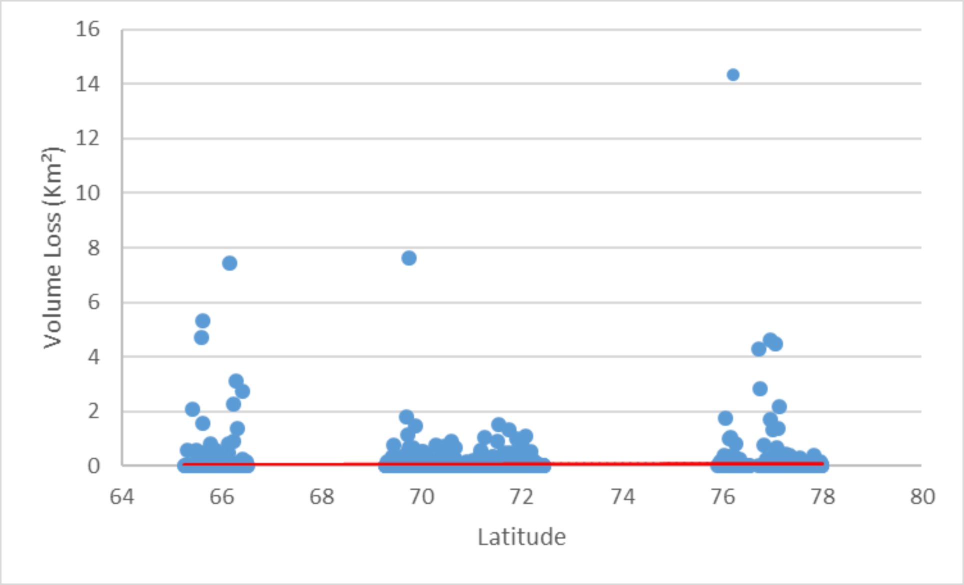


Figure 18: Plot of the relationship between latitude and volume loss for local glaciers and ice caps in west Greenland since the LIA.

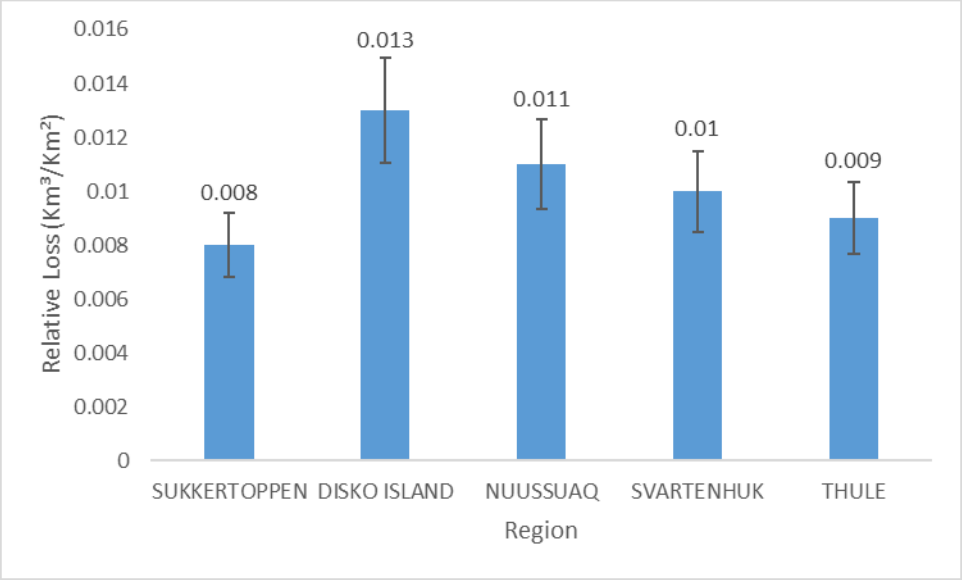


Figure 19: The relative mean volume loss for each region of west Greenland. Mean volume loss is presented as a function of initial LIA area.

4.4 Coastal proximity

The relationship between volume loss and coastal proximity was also tested by creating a regression model (95% confidence). A significant relationship was identified (P = 0.016), similarly to the relationship between latitude and volume loss, a weak negative correlation was identified (r = -0.041) indicating that as you move further away from the coastline volume loss decreases.

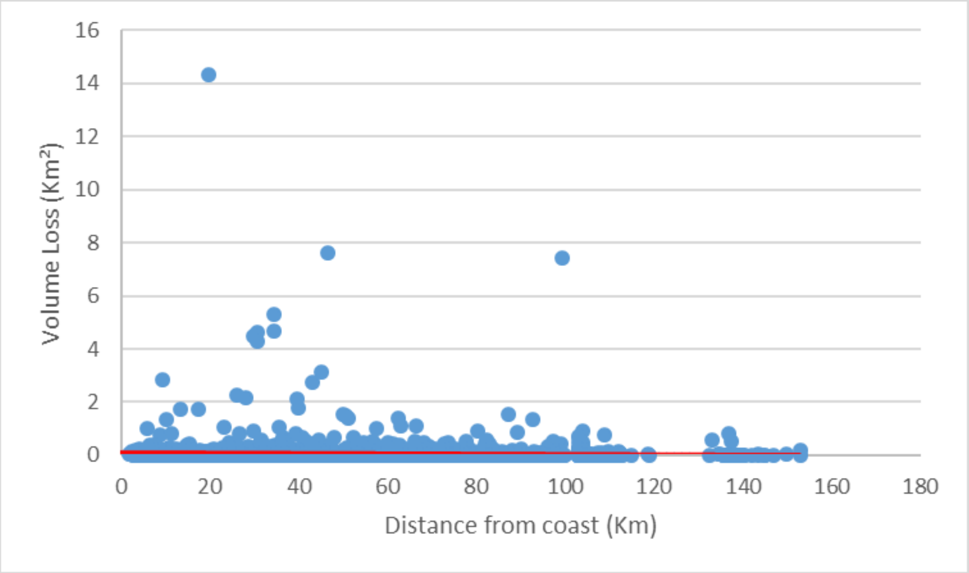


Figure 21: Plot of the relationship between coastal proximity and the volume loss seen in west Greenland GICs since the LIA.

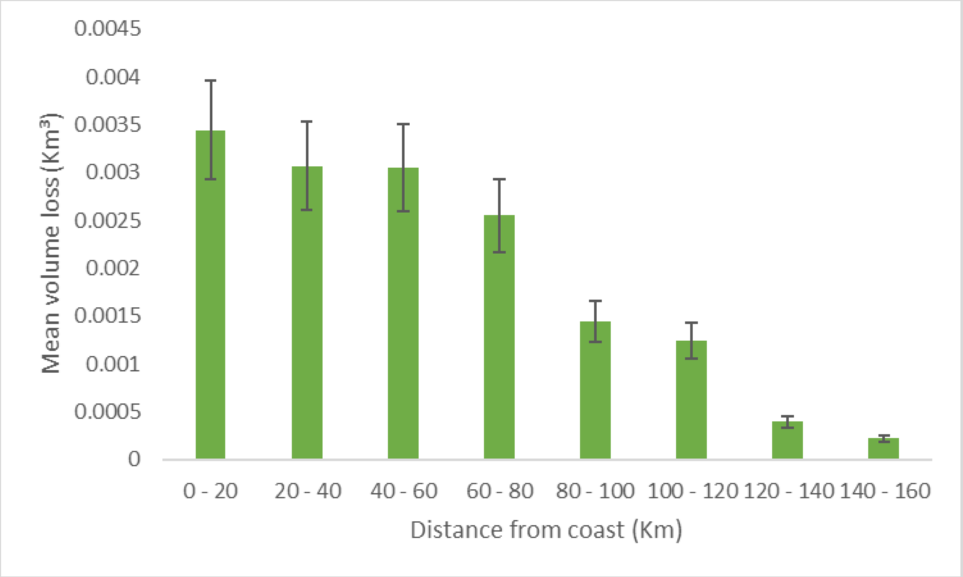
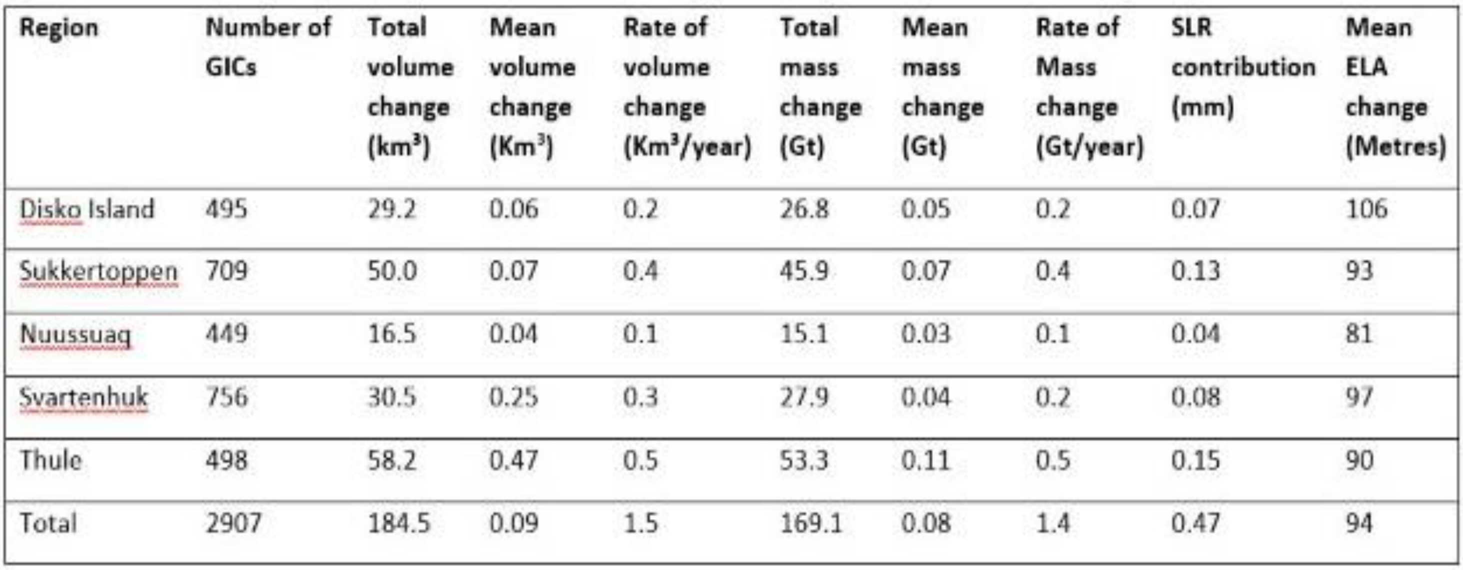


Figure 20: The mean volume loss of GICs in west Greenland, split into 20km bands with decreasing proximity to the coast.

This relationship is shown in figure 20, there is a slight visible trend to lower volume loss further from the coast, but it is not completely clear. Glacier centre points were split into 8 bands of 20 Km, based on their distance from the coast. The mean GIC volume loss from the LIA to 2014 was calculated for each coastal proximity band, the mean volume losses are compared between bands in figure 21. The negative relationship between volume loss and distance from the coast is clearly visible in figure 21, with an overall gradual decline in mean volume loss and a sharp decrease after a distance of 80 Km from the coast is reached.



Region	Number of GICs	Total volume change (km^3)	Mean volume change (Km^3)	Rate of volume change (Km^3/year)	Total mass change (Gt)	Mean mass change (Gt)	Rate of Mass change (Gt/year)	SLR contribution (mm)	Mean ELA change (Metres)
Disko Island	495	29.2	0.06	0.2	26.8	0.05	0.2	0.07	106
Sukkertoppen	709	50.0	0.07	0.4	45.9	0.07	0.4	0.13	93
Nuussuaq	449	16.5	0.04	0.1	15.1	0.03	0.1	0.04	81
Svartenhuk	756	30.5	0.25	0.3	27.9	0.04	0.2	0.08	97
Thule	498	58.2	0.47	0.5	53.3	0.11	0.5	0.15	90
Total	2907	184.5	0.09	1.5	169.1	0.08	1.4	0.47	94

Table 6: A summary of descriptive statisticss regarding GIC volume loss, sea level rise contribution and ELA change in west Greenland between 1890 and 2014.

5.0 Discussion

The results presented in this study provide a comprehensive analysis of GIC change in west Greenland since the LIA (table 6). Total volume loss of 184 ± 29 Km^3 seen in west Greenland GICs studied was lower than initially expected. Carrivick et al. (2019) used similar datasets and methodology to review volume loss in NE Greenland GIC ablation zones since the LIA, showing a loss of 172 ± 34 Km^3 between 1910 and the 1980s and 90 ± 18 Km^3 between the 1980s and 2014. Considering that this project analysed more glaciers at a lower latitude than Carrivick et al. (2019), the data were surprising. Importantly, it has previously been observed that rates of retreat are asynchronous between east and west Greenland, with sensitivity to changes in the NAO a possible cause (Bjørk et al. 2018). There are likely many reasons for this discrepancy, the differences seen may point towards factors such as the local ocean currents and sensitivity to changes in precipitation being more impactful than previously thought.

5.1 West Greenland volume loss compared to total Greenland volume loss

The rate of mass loss from GICs in this study has been calculated to 1.4 ± 0.2 Gt/year from 1890 to 2014, these figures are corroborated by Bolch et al. (2013) who found a rate of 1.4 ± 0.5 Gt/year for GICs in the western area between the years 2003 and 2008. Although this project is set in a centennial timeframe rather than decadal, it is still useful to refer to Bolch et al. (2013) as they provide an excellent account of GIC change all over Greenland between 2003 and 2008.

Bolch et al. (2013) estimated that Greenland's GICs were losing mass at a rate of 27.9 ± 10.7 Gt/year between 2003 and 2008, the results of this study suggest that the GICs in west Greenland have been losing mass equivalent to 4.9% of this rate between the LIA and 2014. This implies that west Greenland has a relatively insignificant contribution to total rates of GIC mass loss across the country. The GICs in west Greenland cover 17,925 Km^2 constituting 20% of total Greenland GIC area, found to be 89,720 Km^2 by Rastner et al. (2012). The GICs investigated here contribute significantly to total area but not to the total rate of mass loss, suggesting that local factors are highly influential in GIC mass changes across different areas of Greenland. An asymmetry in GIC sensitivity to precipitation has been observed between east and west Greenland, GICs in the east may be four times more sensitive to changes in precipitation than those in the west (Bjørk et al., 2018). A difference in sensitivity to climatic factors between different areas of Greenland may help to explain why the volume loss results in west Greenland were lower than expected, but more studies into mass balance sensitivity are needed in other areas of the country to confirm this.

GICs in west Greenland should be analysed with respect to other local glaciers in the country, but also with respect to the GrIS, because it has been recognised that GIC contributions to sea level rise are comparable with those of the Greenland and Antarctic ice sheets (Gardner et al., 2013). Kjeldsen et al. (2015) evaluate mass loss since 1900 to 2010 as well as dividing data into three sub-periods, so the average rate of mass loss from west Greenland GICs since the LIA can be compared with both centennial and decadal rates of mass loss from the whole of Greenland. GICs in west Greenland lost 1.4 ± 0.2 Gt/year of ice between 1890 and 2014, equivalent to 1.8% of the yearly loss from the GrIS from 1910 to 1983, calculated to be 75.1 ± 29.4 Gt/year by Kjelsden et al. (2015). This proportion increases to 1.9% between 1983 and 2003, then decreases sharply to 0.7% between 2003 and 2010. It was to be expected that this study's mean mass loss rate would be the smallest compared to the GrIS between 2003 and 2010 because there has been a well evidenced increase in the rate of mass loss from the GrIS from the late 1990's (Bolch et al., 2013; Kjeldsen et al., 2015; Carrivick et al., 2019), rising to 450 Gt/year in 2012 (Bamber et al., 2018). This acceleration has been shown to be significant in the west and northwest regions where ice discharge and runoff have been exceeding the inter-annual variability of precipitation from 2002 to 2011 causing mass loss to accelerate by 26 ± 7 Gt/year (Sasgen et al., 2012). In the future, comparisons between the volume loss of GICs and the GrIS may become more important because the contribution of GICs to sea level rise is rapidly increasing relative to that of ice sheets (Gardner et al., 2013; Zemp et al., 2019).

The sea level rise contribution of west Greenland GICs from 1890 to 2014 was calculated to be 0.47 ± 0.007 mm, equal to a contribution of 0.004 mm per year. This is equivalent to 5% of the sea level rise contribution of the three largest GrIS outlet glaciers from 1880 to 2012 (Khan et al., 2020). This is a significant comparison considering that west Greenland GICs had a rate of mass loss equivalent to only 1.8% of the GrIS (Kjeldsen et al., 2015) over a similar time scale. This is in line with current theories stating increased variability in summer temperatures are causing GICs to have an increasing contribution to global sea level rise when compared to the Greenland and Antarctic ice sheets (Gardner et al., 2013; Zemp et al., 2019). In the future, this contribution is likely to increase further; because changes in albedo and surface air temperatures disproportionately affect smaller ice masses (Machguth et al., 2013). This highlights the importance of further centennial scale investigations into mass loss from GICs, which will improve long-term models of the cryosphere's response to climate change.

5.2 Hypothesis 1: Latitude

It is challenging to determine the real impact of latitude on GIC volume loss since the LIA in west Greenland because of the scarcity of long-term climate records in the region. Without accurate estimates of surface air temperature constrained on a centennial scale, it cannot be concluded that GIC volume loss since the LIA was less severe at higher latitudes as a result of lower summer air temperatures; thought to be the main control on GIC volume change throughout the Holocene (Machguth et al., 2013; Larsen et al., 2017).

A statistically significant relationship with a negative correlation ($r = -0.071$) was found between latitude and volume change, but the relative volume loss seen in Sukkertoppen was the lowest of any region (figure 19), despite being the furthest south of the regions sampled. The regression model also suggested that latitude poorly explained the variance in volume change ($R^2 = 0.6$), which suggests that latitude has not been the only control on GIC volume loss in west Greenland since the end of the LIA.

A reason for the model's poor explanation of variation in volume loss may be that GICs are affected differently by changes in climate as latitude changes; Masson-Delmotte et al. (2015) found evidence that the Atlantic ridge and the main landmass of Greenland appeared to block weather regimes in north-west Greenland. This may lead to decreased sensitivity to climatic factors in Thule, the region with the highest latitude in the study area, but this region presented the highest volume loss (table 6). However, when volume loss is divided by initial LIA area; GICs in Thule are shown to have a much lower relative volume loss than all other regions except Sukkertoppen, illustrated in figure 19. With the exception of the Sukkertoppen region, the relative loss figures show a trend of decreasing as latitude increases (figure 19) which supports the relationship between latitude and volume loss. This trend may indicate that as you move further towards the north-west, GICs are less sensitive to changing weather patterns; as described by Masson-Delmotte et al. (2015). If it is the case that the north-west is shielded from weather regimes, the negative correlation seen in the relationship between latitude and volume loss could be a result of changing firn compaction rates for different regions. It was observed that there was higher compaction in wetter climates with lower compaction in drier areas, which can have an effect of up to 15% on total mass loss (Bolch et al., 2013). If differing levels of firn densification are observed across west Greenland, it may help to explain the relationship seen between GIC volume loss and latitude in west Greenland between 1890 and 2014.

The low relative volume loss shown in the Sukkertoppen region is interesting because it is the region at the lowest latitude, so would be expected to have the largest losses as a function of initial area according to the relationship described by regression analysis. There may be a system similar to that observed in the north-east where weather regimes are blocked by topography, but there is no evidence for this in the literature.

Low relative losses seen in Sukkertoppen may be the result of a style of glaciation unique from other regions in west Greenland. Glaciation is focused on the two ice caps (Qarajugtoq and Sukkertoppen) that rest on high plateaus with outlet glaciers flowing into fjords (Sugden, 1972; Kelly and Lowell, 2009). The unique style can be seen in figure 12, the largest ablation zones drain the ice caps and have experienced the greatest levels of volume loss since the end of the LIA. The surrounding valley glaciers and cirques also tend to have high elevations (Schweinsberg et al., 2018) because the area is more mountainous than the other regions; it may be the case that local factors such as mountainous topography and a plateau style of glaciation reduce the sensitivity of GICs in Sukkertoppen to changes in climate. Additional long-term climate reconstruction studies in the literature would mean that historical volume loss in Sukkertoppen could be compared to the climate record, and the sensitivity of GICs in this region to climate change may be inferred.

5.3 Hypothesis 2: Coastal Proximity

Regression analysis of volume loss seen in GICs in west Greenland revealed that there was a statistically significant relationship seen between the distance from the coast and volume change between the end of the LIA and 2014. Similarly to the relationship between volume loss and latitude, there was a weak negative correlation seen in the relationship between proximity to the coast and GIC volume loss since the LIA ($r = -0.041$).

However figure 12 illustrates that in Sukkertoppen, volume loss rises with increased distance from the coast, defying the relationship described by the regression model. Regression analysis was carried out in Sukkertoppen to test this relationship and it was found that there is no significant relationship between volume loss and coastal proximity ($P = 0.568$). The apparent trend of volume loss increasing further inland in Sukkertoppen is most likely a result of the largest ablation zones being located the furthest inland. The outlet glaciers that drain the Qarajugtoq and Sukkertoppen ice caps naturally have the largest area (figure 12) and have experienced the most volume loss since the LIA, creating a perceived relationship of coastal proximity and volume loss, but there are few of these outlet glaciers compared to the many valley glaciers in the region so the relationship was not significant.

The mean volume loss continually decreases as you move away from the coastline in bands of 20 Km as shown in figure 21. Although the change in mean volume loss is a continuously downwards trend as coastal proximity decreases, it is not linear, there is a sharp decrease after you move past 80 Km inland. This suggests a threshold distance where the influence of the maritime climate is less impactful on GIC volume change. This supports the widely recognised theory that as you move to a more continental climate, glacier mass balance becomes more stable and mass loss is generally lower (Holmlund and Schneider, 1997; Grinsted, 2013).

The significant relationship between coastal proximity and volume loss appears to be a novel finding in west Greenland, such a relationship has not been found in other areas of Greenland since the LIA. Carrivick et al. (2019) noted that there was no significant east to west gradient in volume loss seen in GICs in north-east Greenland, suggesting that coastal proximity does not have a significant control over rates of GIC volume loss in that area. It is not possible to conclude that coastal proximity only has an impact on rates of GIC volume loss in west Greenland, because there have been so few centennial scale studies of volume loss over large areas of Greenland's GICs.

A potential explanation for the relationship seen between GIC volume loss and coastal proximity may include an interaction with the margin of the GrIS and volume loss in GICs located further inland. As you move eastwards away from the coast in west Greenland you naturally become closer to the GrIS margin, where GICs have a higher level of connectivity and the effects of the ice sheet on climate regimes are more pronounced (Rastner et al., 2012). A specific association between the proximity of a GIC to the GrIS margin and its volume loss has not been identified in west Greenland and very few studies have investigated any such relationship. Studies in Greenland where the volume loss of GICs and the GrIS have been studied in the same area are very rare, and there are very few places where this is possible (Larsen et al., 2021). However, it has been seen that local glaciers are similarly sensitive to climate forcing when in close proximity GrIS outlet glaciers in north-west Greenland (Søndergaard et al., 2019). This may indicate that if a GIC is located closer to the GrIS margin it may become more hydrologically connected to the ice sheet, and sensitivity to climatic factors may change.

It is highly likely that in the future, the relationship seen between GIC volume loss and distance from the ocean will change. On a centennial scale, there are differences between temperature trends for Greenland and the rest of the world, current warming is happening faster in Greenland than the global average (Chylek and Lesins, 2006). As well as this, changes in ocean temperature had a significant impact on the rate of retreat seen in tidewater terminating outlet glaciers of the GrIS in north-west Greenland; (Wood et al., 2018) so the negative relationship between coastal proximity and GIC volume loss may become more stronger. GICs in west Greenland in more maritime climates could begin to accelerate their volume loss when compared to GICs in a continental climate. Among the regions sampled GICs, those in Svartenhuk are in closest proximity to the coast as they are located on coastal peninsulas and Upernivik Island (figure 15). If ocean warming trends continue as described by Chylek and Lesins (2006) it is likely that the relatively small valley glaciers close to the coast, such as those in Svartenhuk, will be the first to disappear in west Greenland. Larsen et al. (2017) concluded that the smallest GICs in the Kobbefjord region of south-west Greenland will lose all of their mass in the next 70 to 90 years. But as a result of the centennial scale of this study, and scarcity of climate data for the region, it is not possible to predict when the first GICs will disappear from west Greenland.

The changing relationship between coastal proximity and GIC volume loss will inevitably cause changes in the relative contribution to sea level change. GIC contribution is expected to rise over the 21st century (Machguth et al., 2013), and in west Greenland Thule and Sukkertoppen are the regions with the highest contributions to sea level rise (table 6). But if maritime glaciers begin to lose volume at a faster rate as predicted by Larsen et al. (2017); GICs in Svartenhuk, Nuussuaq and Disko Island may have the largest sea level rise contributions in the near future.

5.4 Surge-type glaciers

It is important to recognise the role of surge-type glaciers during analysis as they often do not follow typical patterns of change, their instability comes from within the glacial system as opposed to external climate forcing (Evans and Rea, 1999). Volume change since the LIA in west Greenland GICs was smaller by 11% when surge glaciers were removed from analysis, which is broadly similar to the findings of Carrivick et al. (2019); showing surge-type glaciers in the north-east of Greenland accounting for between 8.1% and 9.8% of mass loss since the LIA. However, this study encountered 29 surge glaciers whereas Carrivick et al. (2019) only found 8; this may suggest that surge-type glaciers have a lower impact on total volume loss than in other areas of Greenland.

A surge-type glacier had the most significant contribution of any GIC on Disko Island to total volume loss for that region (figure 13); and there were areas of surface elevation gain for this GIC since the LIA (figure 17), indicating a likely surge (Carrivick et al., 2019) at some point between 1890 and 2014. Yde and Knudsen (2007) concluded that there may be many more surge-type glaciers in Greenland than previously thought; if this is the case then past accounts of GIC volume loss may become less useful as a tool in climate reconstructions because of the decoupled nature of the relationship between climate change and surge-type glaciers (Evans and Rea, 1999).

5.5 Future research

The rate of volume change is an area where future studies may wish to focus as it is the metric most prone to error, the timing for the LIA maximum given by Bjørk et al. (2018) is not universally accepted. Some research suggests that the LIA maximum was 1850 (Weidick, 1968; Beschel and Weidick, 1973), 1900 (Csatho et al., 2008) or even as late as 1920 (Dowdeswell, 1995), a difference of up to 40 years. If an LIA maximum extent of 1920 is used, mass loss would be 1.8 Gt/year, this is more akin to faster rates seen in other areas of Greenland (e.g. Carrivick et al., 2019). These uncertainties may bring into question the relative contribution of GICs in the west to total rates of mass loss. It is important that future research into the glacial history of west Greenland establishes a certain date for the onset of LIA deglaciation, to remove the largest portion of uncertainty when calculating rates of GIC volume loss on a centennial scale.

Subsequent research investigating GICs in Greenland may wish to study volume loss trends and their association with variations in the NAO. When analysing the changing lengths of GICs since the LIA; Bjørk et al. (2018) found that the accumulation rates of glaciers in the west of Greenland were statistically less sensitive than those in the east to changes in precipitation associated with changes in the NAO cycle. In a negative NAO phase, accumulation may be 25% lower than usual in the south-east especially but the accumulation anomaly was seen to be under 5% for areas in the west and closer to 0% for central-west areas (Bjørk et al., 2018) such as Disko Island and Nuussuaq. These findings could mean that west Greenland GICs have an inherent resilience to some climatic forcing; which is corroborated by results presented in this study depicting a low contribution to total GIC rate of annual mass loss, despite the western regions having one of the largest glaciated areas (Rastner et al., 2012).

The literature suggests that for large periods of the 21st century the NAO will move into a positive phase (Mosely-Thompson et al., 2005; Gillet and Fyfe, 2013; Bjørk et al., 2018), which is predicted to bring a negative accumulation anomaly to Greenland's western regions with particular focus on central-west areas (Bjørk et al., 2018). If the polarity of the NAO inverts, observed accumulation anomalies between the east and west may develop a significant asymmetry, variations in total mass loss contributions will likely be seen when viewed on a centennial scale. It is important to investigate and understand relative mass loss changes on a centennial scale to improve climate models, especially as the relative contribution of GICs to sea level rise is rising (Zemp et al., 2019). Implications of a changing NAO should be accounted for in future research to allow for an accurate depiction of future GIC change; especially as anomalous precipitation becomes an increasing issue, demonstrated by a rainfall event at the summit of the GrIS during an intense warm period in 2021, the first time since records began in 1950 (NSIDC, 2021).

Another area where studies may wish to focus in the future is the thermal regimes of GICs. As a result of using the high resolution 2m ArcticDEM; it can be noted that the great majority of glaciers surveyed did not present many crevasses or other structural features, as seen from the hillshaded DEM and satellite imagery. There were some glaciers with existing but poorly developed fluvial networks mainly confined to small supraglacial and englacial routes, this can be characteristic of glaciers with a polythermal regime (Hambrey and Glasser, 2012). Using evidence from the ArcticDEM and satellite imagery, it is possible to suggest that many of the GICs in west Greenland have a polythermal regime and some small GICs may even be entirely cold-based. In the future, it may be possible that air temperatures rise to a point where the smallest glaciers become warm based and rapidly accelerate their volume losses. However, because there is almost no data regarding positive degree days or the characteristics of entrained sediment for GICs in west Greenland, this is purely speculation and much more research is required to determine the thermal regimes of these GICs and how they might change in the future.

This project shows that there are significant relationships seen between GIC volume loss since the LIA and both latitude and distance from the coast. On a smaller scale, local controls such as topography and glaciation style have been crucial in determining the behaviour of GICs in some areas such as Sukkertoppen and Thule. The reliance on local factors will likely increase as the climate changes more rapidly in northern latitudes; topographical controls on volume loss, as seen in the north-west, will become of paramount importance as they can render a region more or less sensitive to climatic forcing. The NAO will have a large influence on the climate of Greenland during the 21st century, and I agree with the conclusions of Bjørk et al. (2018) that GIC sensitivity to changes in the NAO should be considered in future studies investigating rates of glacier ice loss. The evidence that local factors are important controls on GIC behaviour suggests that in the future, multi-variate statistics should be used to explore these relationships further. Although not within the scope of this study, investigations into the contributions of factors such as aspect, slope, altitudinal range, and topographic shading on GIC volume loss may reveal important new patterns of volume loss in west Greenland GICs. As well as this further research that includes multi-variate analysis may reveal interactions between different controls, this will build a deeper knowledge of volume loss from local glaciers and ice caps in Greenland. Understanding controls on volume loss at a local scale will allow more detailed modelling of the Cryosphere's reaction to climate change and produce more detailed estimates of global sea level rise.

6.0 Conclusions

This study provides a comprehensive analysis of the volume loss seen from glaciers and ice caps in west Greenland since the LIA. GICs in west Greenland have lost significant volume up to 2014 but the scale of the losses seen were lower than in areas of Greenland sampled in other studies over the same time period. West Greenland GICs do not constitute a significant portion of total land ice volume loss in Greenland but are very important contributors to sea level rise, supporting the theory that volume loss from GICs is fast becoming a major contribution to global sea level rise.

6.1 Hypothesis 1

A statistically significant relationship was seen between latitude and volume loss in west Greenland, so hypothesis 1 can be accepted. As latitude increases, GIC volume loss since the LIA decreases with a weak correlation (r = -0.071). It may be the case that GICs in the north-west of the country have experienced a shielding effect from the Greenland landmass, rendering them less sensitive to climatic changes in comparison to GICs further south. Analysis of the relationship between latitude and volume loss has revealed that local controls such as topography and glaciation style have a significant effect on GIC volume loss, especially in the Sukkertoppen region.

6.2 Hypothesis 2:

A statistically significant relationship between coastal proximity and volume loss has been observed in west Greenland GICs between the LIA and 2014, so hypothesis 2 can be accepted. Similarly to the relationship of latitude and volume loss, a weak negative correlation was observed (r = -0.041), showing that GIC volume losses since the end of the LIA decrease as you move further away from the coast. The influence of maritime climate becomes less impactful as you move further inland, and mean volume loss decreased sharply after reaching 80 Km distance from the coast. It is possible that GICs located further inland have lost less volume since the LIA because of their increased proximity to the GrIS margin; the cooler and drier climate of the ice sheet margin may be reflected in the relatively more stable mass balance of inland GICs, when compared to GICs more influenced by the maritime climate.

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