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Proglacial icings as indicators of glacier thermal regime: ice thickness changes and icing occurrence in Svalbard

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Abstract

Proglacial icings (also known as naled or aufeis) are frequently observed in the forefields of polar glaciers. Their formation has been ascribed to the refreezing of upwelling groundwater that has originated from subglacial melt, and thus the presence of icings has been used as evidence of polythermal glacier regime. We provide an updated analysis of icing occurrence in Svalbard and test the utility of icings as an indicator of thermal regime by comparing icing presence with: (1) mean glacier thickness, as a proxy for present thermal regime; and (2) evidence of past surge activity, which is an indicator of past thermal regime. A total of 279 icings were identified from *TopoSvalbard* imagery covering the period 2008-2012, of which 143 corresponded to icings identified by Bukowska-Jania and Szafraniec (2005) from aerial photographs from 1990. Only 46% of icings observed in 2008-2012 were found to occur at glaciers with thicknesses consistent with a polythermal regime, meaning a large proportion were associated with glaciers predicted to be of a cold or transitional thermal regime. As a result, icing presence alone may be an unsuitable indicator of glacier regime. We further found that, of the 279 glaciers with icings, 63% of cold-based glaciers and 64% of transitional glaciers were associated with evidence of surge activity. We therefore suggest

that proglacial icing formation in Svalbard may reflect historical (rather than present) thermal regime, and that icings possibly originate from groundwater effusion from subglacial taliks that persist for decades following glacier thinning and associated regime change.

Keywords: Icing, aufeis, naled, glacier thermal regime, proglacial, Svalbard.

1. Introduction

Icings are sheet-like accretions of stratified subsurface water-origin ice, also known as naled or aufeis, which occur in High Arctic regions (e.g. Carey, 1973; Hodgkins et al., 2004; Yoshikawa et al., 2007; Morse and Wolfe, 2015; Sobota, 2016). Proglacial icings (Fig. 1a) are common in the forefields of High Arctic glaciers, forming in the winter months as a result of subaerial refreezing of upwelling subpermafrost and subglacial waters (Wadham et al., 2000). The spatial distribution of icings in Svalbard has only been previously mapped by Bukowska-Jania and Szafraniec (2005) (henceforth BJS (2005)) using 1990 aerial imagery. Rapid rates of glacier retreat and thinning driven by recent accelerated warming in the region (Malecki, 2016), and associated changes in glacier-permafrost systems, suggests that the distribution of proglacial icings may have changed significantly since 1990.

Icings have been frequently used as indicators of glaciers with a polythermal regime (e.g. Paterson et al., 1994; Björnsson et al., 1996; Hagen et al., 2003; Rachlewicz et al., 2007; Sobota, 2016) due to the assumed need for winter meltwater discharge for icing formation. However, multiple observations of proglacial icings in the forefields of cold-based glaciers have been recorded (e.g. Hodgkins et al., 2004; Baelum and Benn, 2011; Sapper et al., 2018), contradicting the traditional interpretation of icing formation processes. Icings show a tendency to form in the same locations, but do not form each year, and show great variation in both the areal size of individual icings, as well as the spatial distribution of icings in a region (Morse and Wolfe, 2015).

Icing formation and preservation is controlled by a number of factors, including: air temperature (Morse and Wolfe, 2017); ground temperature (Wainstein et al., 2010); precipitation type and volume, which is particularly important during the formative winter months (Nowak and Hodson, 2013); groundwater recharge regimes (Haldorsen et al., 2010); rate of subsurface water discharge (Gokhman, 1987); and glacier forefield morphology (Bukowska-Jania and Szafraniec, 2005). Many of these factors affect winter groundwater flow processes and the ground thermal regime, which are the key controls on proglacial icing formation and preservation. However, flow pathways between glacial, proglacial and permafrost systems are poorly understood (Wainstein et al., 2008). Groundwater effusion from subglacial taliks formed before the end of the Little Ice Age (LIA) maximum has the potential to explain the presence of icings at currently cold-based glaciers (e.g. Hodgkins, 1997), if they have undergone a transition in thermal regime since the LIA maximum (Liestøl, 1977; Åkerman, 1987). However, there remains limited field investigation of the origins of water sources, including those leading to icing formation, at cold-based glaciers (Sapper et al., 2018).

The aim of this study is to use high-resolution imagery available from *TopoSvalbard* (Norwegian Polar Institute, 2018a) for the years 2008 to 2012 to update previous work on the locations of icings in Svalbard glacier forefields produced by BJS (2005) using 1990 aerial imagery. The hypothesis that icings are indicators diagnostic of glacier thermal regime is then evaluated, using glacier thickness as a proxy for present glacier thermal regime, and evidence for, or direct observation of, palaeo-surge activity (e.g. Farnsworth et al., 2016) as an indicator of the past glacier thermal regime.

2. Study Area

Svalbard (Fig. 1b) is an archipelago located in the Arctic Circle, covering latitudes from 74° N to 80° N, and situated at the northern limit of the North Atlantic Current. The latter causes uncharacteristically warmer and wetter weather than would be expected elsewhere at such high latitudes (Nuth et al., 2010). Glaciers in Svalbard are therefore characterised by a variety of thermal regimes (Blatter and Hutter, 1991), ranging from entirely cold-based to predominantly warm-based with lenses of cold ice. The recorded ~4°C of warming that has been experienced in Svalbard since the LIA maximum (Etzelmüller et al., 2011), has led glaciers in Svalbard to undergo substantial retreat and thinning (Pälli et al., 2003). This has resulted in the transition of many glaciers from polythermal to colder thermal regimes since the LIA maximum, leaving many in disequilibrium with contemporary climates (Irvine-Fynn et al., 2011).

Crevasse squeeze ridges (CSRs, also known as crevasse-fill ridges) have been used by Farnsworth et al. (2016) to identify previously undocumented surge-type glaciers because they are associated exclusively with warm-based glacier surging (Rea and Evans, 2011). CSRs are more widespread and less circumstantial evidence of surging than other surge-related geomorphological features, such as trimlines, and in Svalbard provide reliably recent evidence of surging because they are observed in forefields revealed by retreat from the glaciers' LIA maximum extent (Farnsworth et al., 2016). Whilst active glacier retreat would likely destroy CSRs, downwasting during the quiescent phase of the surge cycle is likely to preserve CSRs (Evans and Rea, 1999), though absence of CSRs is not necessarily indicative of absence of surging or presence of active retreat (Ingólfsson et al., 2016).

3. Methods

3.1 Mapping of icings

Icings were identified from ~ 0.5 m resolution *TopoSvalbard* imagery (e.g. Fig. 2), provided by the Norwegian Polar Institute (NPI, 2018a), with all imagery used dating from between 2008 and 2012. Imagery was captured during the late ablation season, from July to August, each year. Consequently, the images provide a minimum estimate of the extent and number of icings. A small number of icings that exhibit high annual variability may have been missed due to absence in the particular year that the imagery was collected.

Proglacial icings were identified using a set of criteria that distinguish them from other patches of snow and ice, ordered here by decreasing importance:

1) Located in the forefield of a glacier, or directly adjacent to an ice margin.
2) Comparatively cleaner ice than the glacier terminus, due to lower debris coverage/content (Gokhman, 1987)
3) Located within a topographic basin, such as behind moraines deposited at the LIA maximum. (Extra-marginal icings may extend beyond terminal moraines).
4) Meltwater stream flowing from or over the icing (Gokhman, 1987).
5) Icing domes, blisters or collapsed domes (slush pools) visible (Åkerman, 1980).

As the morphology and surface characteristics of icings in Svalbard are highly variable (Bukowska-Jania and Szafraniec, 2005), icing presence was considered positive if the first and at least two of the final four criteria were met.

3.2 Present glacier regime

Average glacier thickness was used as a proxy for glacier thermal regime because there is currently no definitive dataset covering the regime of all Svalbard glaciers. Ground penetrating radar (GPR) is currently the most reliable direct method to interpret thermal regime, but to date only a handful of Svalbard glaciers have been surveyed using this technique (e.g. Murray et al., 1997; Baelum and Benn, 2011; Martin-Español et al., 2013).

Thickness is a critical control on thermal regime (Irvine-Fynn et al., 2011) as it affects the relative depth of penetration of the winter cold-wave into the glacier body and the pressure melting point of ice at the bed (Cuffey and Paterson, 2010). For High Arctic glaciers, a threshold ice thickness above which at least some warm-based ice can persist year-round has been identified between 80 and 100 m (Hagen et al., 1993; Murray et al., 2000).

Average glacier thickness was estimated using the empirical glacier area-depth relation established for Svalbard by Hagen et al. (1993):

$$D = 33 \times \ln A + 25 \quad (1)$$

where D is mean glacier depth and A is the ice covered area. The latter was gained from the *Svalbardkartet*, also provided by the Norwegian Polar Institute (NPI, 2018b), using glacier area outline data obtained from the same imagery available on *TopoSvalbard* from the 2008-2012 period. All data can be found in the supplementary file provided. Glaciers 80 m thick or less were classified as cold-based, and those thicker than 100 m classified as polythermal. Glaciers with thicknesses between these values were classified as ‘transitional’ because, for these glaciers, thickness alone is unlikely to be a reliable indicator of regime. These classifications of thermal regime are likely to be an oversimplification of the true, complex thermal structure of each glacier.

3.3 Past thermal regime

Historically warm-based glaciers were identified using the dataset of Farnsworth et al. (2016), which documents glaciers that have either been directly observed to have surged or have been inferred to have surged from the presence of crevasse squeeze ridges (CSRs) in their forefields. Comparison of surge evidence with present thermal regime, estimated using average glacier thickness (as described above), was then used to classify the past glacier thermal regime at the LIA maximum (Fig. 3). As discussed above, not all warm-based glaciers surge, and surging does not always produce CSRs (Farnsworth et al., 2016), meaning this dataset may underrepresent the true number of glaciers with historically warm-based conditions. The implications of this caveat are discussed below.

4. Results

4.1 Number and distribution of icings

From the period 2008-2012, 279 icings were identified in the forefields of approximately 30% of Svalbard glaciers. Icings were found across all six regions of Svalbard (Fig. 4): 106 in NW Spitsbergen; 45 in NE Spitsbergen; 52 in Central Spitsbergen; 43 in S Spitsbergen; 28 across the islands of Barentsøya and Edgeøya; and 5 in Nordaustlandet. Thus, icings were not distributed uniformly, and in both this study and BJS (2005), were most common in western Svalbard (Fig. 4), with NW Spitsbergen having 38% of the total, and Nordaustlandet (where many glaciers are in contact with the ocean) having just 2% . Of the 279 icings, only 143 were in locations identified in 1990 aerial imagery by BJS (2005) (Fig. 4). This leaves 74 of the 217 icings from the 1990 study as absent from the *TopoSvalbard* (NPI, 2018a) imagery, suggesting that the total number of icings could be greater than 279, if accounting for inter-annual variation. The distribution of icings between regions is similar for both studies, with the greatest difference between the studies found in Central Spitsbergen, which has an approximately 6% greater share of the total number of icings in 2008-2012 than in 1990.

4.2 Present glacier thermal regime

Of the 279 glaciers with icings identified in 2008-2012 imagery, 128 were classified as having a polythermal regime, 44 as transitional, and 107 as cold-based (Fig. 5). This equates to only 46% of glaciers with icings being polythermal, with 16% being transitional and 38% cold-based (Table 1). Icings were not therefore found exclusively in the forefields of polythermal glaciers, with 56% of icings being found in transitional or cold-based glacier forefields. Fig. 5 shows a large amount of regional variation in the proportions of glaciers with icings that are of a specific thermal regime. Polythermal glacier regime varied from 40% of glaciers with icings in NW Spitsbergen to 87% in NE Spitsbergen. Generally, there was a longitudinal trend in the glaciers' thermal regimes, with glaciers becoming thicker and trending towards a more polythermal regime further east. This is in agreement with Nuth et al. (2007), who found a strong regional trend in the geodetic mass balance of Svalbard glaciers related to the precipitation gradient. Independent sample t-test results showed that glaciers with icings for all thermal regimes were significantly thicker than glaciers without icings by ~ 10.7 m ± 3.6m (Fig. 6), at a 99.7% confidence interval.

Fig. 6 shows that the distribution of thickness values for glaciers without icings was leptokurtic and positively skewed around thinner glaciers, with the modal thickness value occurring well below the threshold thickness value and being more typical of Svalbard glaciers generally. Polythermal glaciers accounted for 46% of the total glaciers with icings, compared to only 34% of those without (Table 1).

4.3 Past thermal regime

The forefields of 187 glaciers with icings (67%) (Fig. 7) had past warm-based conditions, according to evidence of past surge activity. Of these 187, 92 were glaciers that are presently estimated to be polythermal, 28 are presently transitional, and 67 are presently cold-based (Table 2). Across all three categories of present thermal regime, more than half of glaciers with icings had a surge history. This number comprised 72% of polythermal glaciers, 64% of transitional type glaciers, and 63% of presently cold-based glaciers.

5. Discussion

5.1 Number and distribution of icings

There is a clear difference in the occurrence of icings in Svalbard between 1990 and the 2008-2012 period, with a far greater number of proglacial icings recorded in 2008-2012. The differences can be explained by a number of factors which can be attributed to the variability of conditions affecting the formation and preservation of icings. As imagery in both studies was obtained at similar times seasonally (towards the end of the glacier ablation period), proglacial icing occurrence will be at a minimum, exaggerating any existing inter-annual variability (Bukowska-Jania and Szafraniec, 2005). Though using imagery from late in the melt season helped to minimise the possibility of misidentifying ice patches as icings, it is appreciated that some annually recurring proglacial icings will not have been identified in this study due to factors affecting their preservation and thus seasonal longevity. We note, however, that any bias due to this factor would lead to an underestimate of the number of glaciers with icings, at a time when glacier thinning should be causing thermal regime transition from warm-based or polythermal to more cold-based regimes.

Previous studies of polar regions have found high rates of interannual variability of icing formation. For example, Morse and Wolfe (2015), found that approximately 93% of icings in the Great Slave Plain, Canada, occurred for only a quarter of the observation period. However, studies in Svalbard have recorded much lower rates of variation, with icings often recorded annually in the same forefields (e.g. Baelum and Benn, 2011; Sobota, 2016). We therefore believe that interannual variation alone is unable to completely explain the unaccounted for 74 icings and the additional 136 newly mapped icings in this study. Smaller icing volume, and subsequent earlier melt-out during the ablation season may also have altered the distribution of icings (Pavelsky and Zarnetske, 2017), as well as more intense melting due to increased summer temperatures and rainfall volumes. Svalbard mean annual temperatures have warmed by approximately 1-2°C over the past couple of decades, with much of this focussed in the winter months, which have warmed by 2-3°C over this period (Førland et al., 2011), increasing winter rainfall volumes. Nowak and Hodson (2013) suggest that these changes favour more frequent icing formation. Thus, in light of the numbers of icings identified by BJS (2005) and in our study, we speculate that it is likely that more than 300 glaciers still have proglacial icings across Svalbard.

Glacier retreat is also a potential source of observed changes in icing numbers, with retreat causing an increase in the size of glacier forefields that are favourable for icing growth (Bukowska-Jania and Szafraniec, 2005). Observations from Bamber et al. (2005) between 1996 and 2002 indicate that rates of glacier termini retreat (and thus foreland growth) should be greatest at lower latitudes. However, we observed no clear latitudinal trend in the number of icings to reflect this, suggesting that change in forefield size was not an important factor in this case. Nonetheless, we appreciate that any latitudinal trend may be difficult to observe, given the complexity of factors involved in icing formation and preservation.

Though variation in the spatial distribution of icings can be attributed to a range of factors affecting the formation and preservation of icings, the resolution of imagery used by Bukowska-Jania and Szafraniec (2005) must also be considered a possible limitation in terms of the identification of temporal trends. Notably, the 1990 aerial photographs have a much lower resolution of 20 ± 3m (Nuth et al., 2007) than used in this study, which may have limited the identification of smaller icings or those adjacent to snow patches.

5.2 Present glacier thermal regime

Despite the observed preference for their occurrence in the forefields of thicker glaciers, icings were not found to be exclusively present at polythermal glaciers, with 151 non-polythermal glaciers identified as having proglacial icings in the 2008-2012 period. Consequently, the use of icings as an indicator of present polythermal glacier regimes is not supported by our study. This strengthens the argument that cold-based glacier dynamics have been oversimplified (Waller, 2001; Lorrain and Fitzsimons, 2011). Notably, icings at Scott Turnerbreen (Hodgkins et al., 2004), Tellbreen (Baelum and Benn, 2011) and Rieperbreen (Sapper et al., 2018) all occur at host glaciers that have been recognised as cold-based. The implications of this are significant. For instance, Sobota (2016) used icings to identify all Kaffiøyra region glaciers as polythermal. Glacier thickness data from this study suggests that only one of these (Elisebreen) can be confidently identified as polythermal. As the majority of glaciers with icings in Svalbard are likely to be non-polythermal, present glacier thermal regime only exerts a weak influence on the presence of icings, with other factors having a larger impact on processes of icing formation and preservation.

5.3 Past glacier thermal regime

The presence of surging evidence at 187 glaciers with icings, including over half of all cold regime glaciers with icings, suggests that the past glacier thermal regime does have some influence on the presence of icings. Thermal regime transition since the LIA maximum has been widespread in Svalbard (Lønne and Lyså, 2005). Larger, warm-based glaciers at the LIA maximum are thought to have caused permafrost thaw and subglacial talik formation (Etzelmüller and Hagen, 2005; Haldorsen et al., 2010). It is possible that many of these subglacial taliks may have persisted at glaciers which have subsequently transitioned to a cooler thermal regime during post-LIA maximum retreat. This relies upon sufficiently pressurised water flow to maintain the talik in the face of increased post-LIA maximum permafrost aggradation in glacier forefields (Murray et al., 2000). Despite the reduced groundwater recharge regimes often associated with the transition to more cold-based thermal regimes, Haldorsen et al. (2010) argue that groundwater flow in permafrost regions of

Svalbard may be sufficiently robust to maintain an adequate level of winter flow for icing formation. Åkerman (1982) identifies that these processes enable talik water effusion for icing formation. Proglacial taliks are thought to be the source of water for icing formation at the polythermal Fountain Glacier, Bylot Island, Canada (Moorman, 2003; Waintstein et al., 2008). We propose that similar taliks may be the source of water effusion for icing formation at glaciers which demonstrate evidence of a past polythermal regime in Svalbard. This may be the case at the 95 transitional and cold-based glaciers with icings that have evidence of a surge-type history, and thus evidence of a past polythermal regime.

The presence of icings in the forefields of 95 non-polythermal glaciers with surging evidence supports the observation of BJS (2005) – that icings are often located in the forefields of glaciers with a surge-type history. It is possible that it is surge-type glacier activity in particular that has been responsible for icing presence at these glaciers. Notably, surging is associated with initial thickening and rapid sliding that increases the area of the bed that is warm-based and enhances rates of basal melt (Murray et al., 2003). Over-extension of the glacier at the end of the active surge phase causes the glacier to become thin and vulnerable to cold-wave penetration (Lovell et al., 2015), resulting in a gradual shift to a cold-based thermal regime.

However, 40 glaciers with icings lacked any evidence of having a polythermal regime either presently or at the LIA maximum. Though these glaciers may not have a history of surging or a polythermal regime, there are a variety of reasons to explain why surge evidence may not be present, Reasons for a lack of CSRs according to Farnsworth et al. (2016) include: (1) CSRs, like many proglacial depositional features, have a low preservation potential; (2) A lack of exposure of CSRs, for instance if proglacial water bodies were obscuring the glacier forefield; (3) Smaller glaciers are associated with slower rates of retreat and foreland exposure, also reducing the extent of CSR exposure such as in Central Spitsbergen, and; (4)

Not all surge-type glaciers produce CSRs, with Farnsworth et al. (2016) finding that around a third of the previously documented surge-type glaciers lacked CSRs.

Although CSRs are widely accepted as characteristic of surging, with genetic evidence of formation during surging (Lovell and Boston, 2017), Evans et al. (2012) have proposed an alternative, yet somewhat related, formation hypothesis for the CSRs found at Hørbyebreen, based on *jökulhlaups* at non-surging glaciers. Though the formation processes of CSRs are poorly constrained (Ingólfsson et al., 2016), suggested formation hypotheses have links to polythermality. It was considered that the low likelihood of CSRs being found in the forefields of non-surge type glaciers justified the use of the Farnsworth et al. (2016) data as a proxy for past thermal regime. This was for two reasons: (1) due to unfavourable preservation conditions at actively retreating non-surge type glaciers (Evans and Rea, 1999); and (2) CSRs were often found in networks by Farnsworth et al. (2016), allowing for a confident interpretation that they are associated with surge-type glaciers rather than non-surge type (cf. Evans et al.,2016). This resource greatly extends the documented number of surge-type glaciers in Svalbard, though it does require verification.

5.4 Alternative explanations and outlook

Observations of icings at cold-based glaciers have been more numerous in recent years (Hodgkins et al., 2004; Baelum and Benn, 2011; Sapper et al., 2018). Alternative explanations for sources of water for icing formation at these glaciers include supraglacially fed englacial channels (Naegeli et al. 2014), also termed cut and closure conduits (Gulley et al., 2009a). Outflow from such channels at cold-based Tellbreen has been observed to persist through winter (Naegeli et al., 2014), and may be a viable source of water for icing formation at this location (Baelum and Benn, 2011). Similar channel systems have been observed at up to 14 glaciers in Svalbard (Gulley et al., 2009b), including Rieperbreen and Scott

Turnerbreen, which are likely cold-based and have proglacial icings. Water-filled englacial structures inherited from a previously polythermal state have also been proposed as a mechanism of icing formation at cold-based glaciers by Hodgkins (1997), which enable drainage in a similar way to cut and closure conduits. Further, relict drainage structures are likely to persist in cold ice that is slowly deforming.

Nonetheless, flow paths between glacial, proglacial and permafrost systems are still poorly understood (Wainstein et al., 2008), and the volumes and locations of subglacial and groundwater stores remain poorly constrained (Hagen et al., 1993; Baelum and Benn, 2011). Before any mechanism can be considered the main cause of proglacial icing formation at cold-based glaciers, detailed field investigation of winter hydrological sources, stores and pathways is required. Based on our finding of proglacial icings at a large proportion of formerly polythermal glaciers that are now cold-based or transitional in thermal regime, we further advocate that studies employ other indicators of thermal regime, including past thermal regime, to validate the glacier thermal regime results from this study.

It remains uncertain whether differences in the number of proglacial icings between 1990 and 2008-2012 was largely due to interannual variability of icing formation and preservation, or other factors such as short and long term changes to climatic forcing. To better determine the controls on the presence of icings, conducting a further study of a different period is recommended. The results of which could be compared to those from this study and BJS (2005).

6. Conclusion

This study has taken the first steps towards updating the temporal record of the location of icings in Svalbard, following the work of Bukowska-Jania and Szafraniec (2005). Our updated analysis of the occurrence and distribution of proglacial icings in Svalbard found

279 icings, 143 of which were also present in 1990. This difference may be due to inter-annual variability of icing formation, which is likely to be exaggerated by the use of summer imagery for icing identification. If this is the case, more than 300 glaciers across Svalbard may have proglacial icings. Glacier thickness data indicated that 54% of glaciers with proglacial icings were of transitional or cold-based thermal regimes presently. These results, albeit obtained using glacier thickness as a proxy for thermal regime, supports previous indications from Hodgkins et al. (2004) and Baelum and Benn (2011) that icings are not exclusively found in the forefields of polythermal glaciers in Svalbard. As a result, we strongly recommend that studies do not solely rely upon the use of icings as an indicator of a polythermal glacier regime, as it relies upon out-dated knowledge and assumptions of the structure and dynamics of cold-based glaciers.

A large proportion (63%) of glaciers identified as transitional and cold-based by this study also had a history of surging, which indicates a past polythermal regime, and therefore had likely transitioned in terms of thermal regime since the LIA maximum. Icings at these glaciers may reflect the continued presence of subglacial taliks formed under thicker and warmer ice prior to recent glacier retreat and thermal regime change. These taliks may provide a source of winter groundwater effusion for icing formation, as previously suggested by Åkerman (1982). However, there is a need for further detailed studies of hydrological sources, stores and pathways in relation to proglacial groundwater systems in Svalbard, particularly of glaciers with a polythermal history, to test the viability of the idea of the groundwater effusion from subglacial taliks at cold-based glaciers.

Finally, the implications of our finding that proglacial icings are not exclusively present at glaciers identified as polythermal suggests a need to revise our understanding of the potential sensitivity of glacier and glacier-permafrost systems to changes in short and long-term climatic forcing, in the context of glacier thinning, retreat and thermal regime change, Notably, hydrological structures within such systems may adjust more slowly than previously anticipated to climate changes, and this is worthy of future investigation.

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Supplementary information

Data used in this paper is provided as an Excel spreadsheet and GIS shapefiles and can be found via the journal webpage for this article.

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Figures and captions

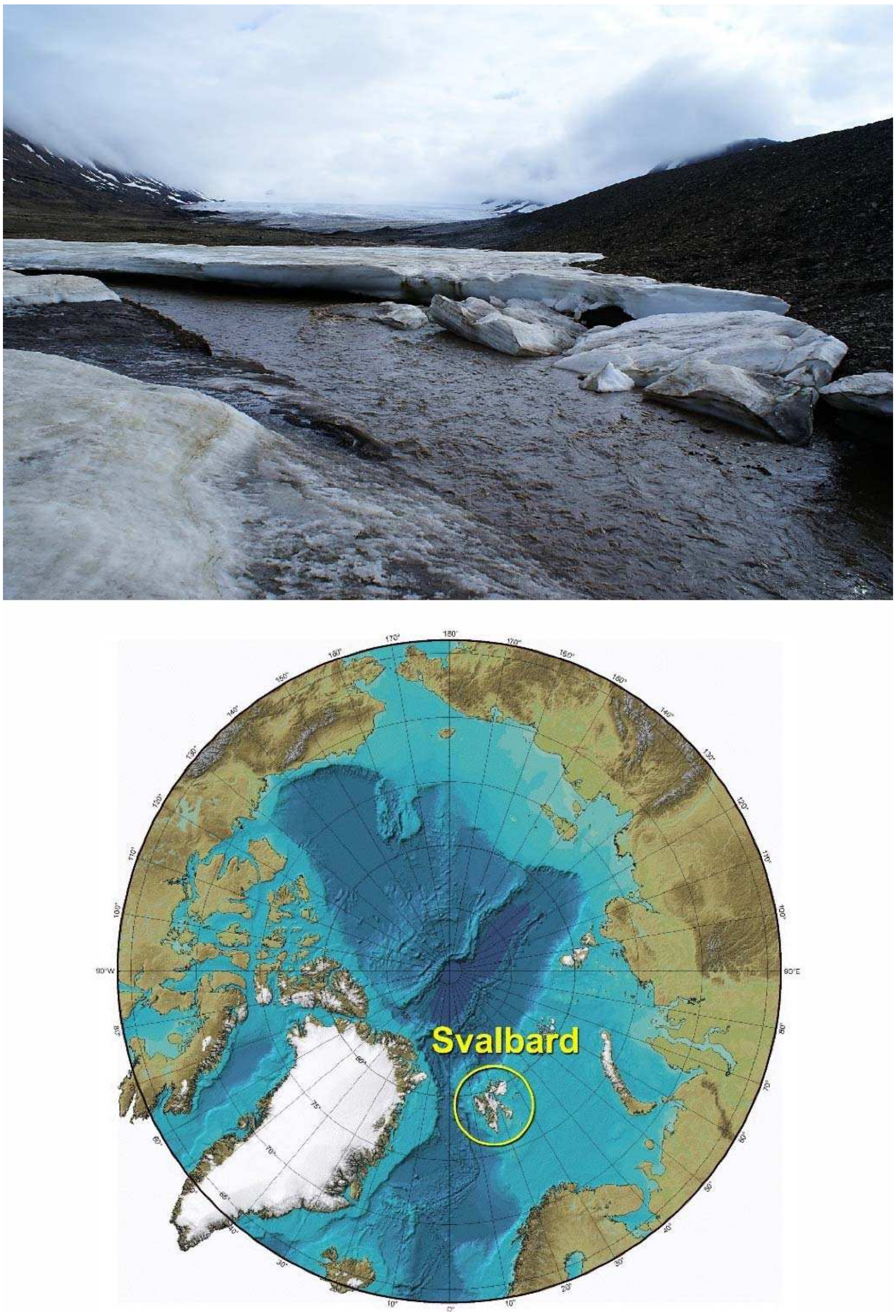

Figure 1. Above: A proglacial icing in the forefield of the Svalbard glacier Austre Gronfjordbreen (Photo: D. A. Swift). Below: Location of the Svalbard archipelago in the Arctic (map courtesy of www.ngdc.noaa.gov).

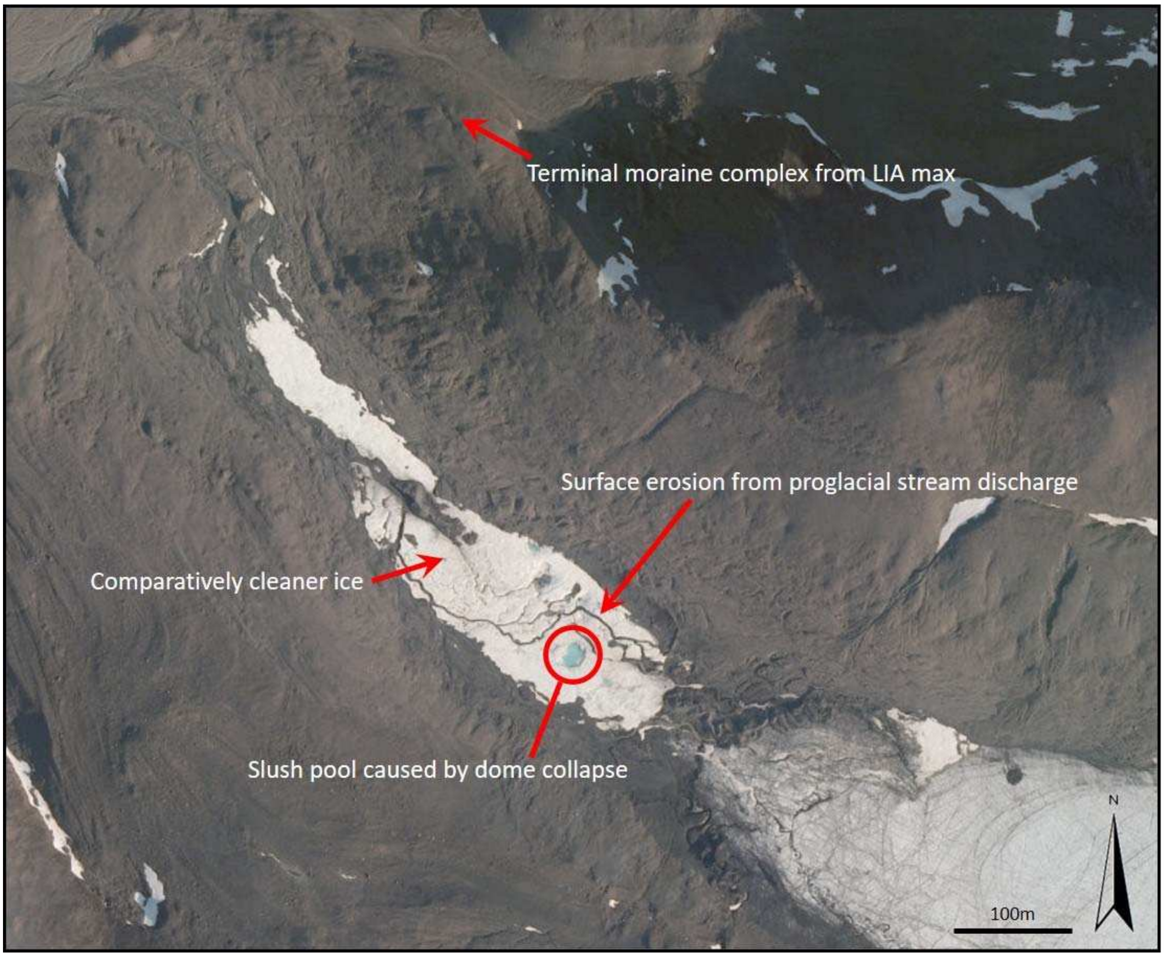

Figure 2. Screenshot from TopoSvalbard (NPI, 2018) of Arthurbreen proglacial zone and its proglacial icing. Visible features used as identifying criteria for proglacial icings are labelled.

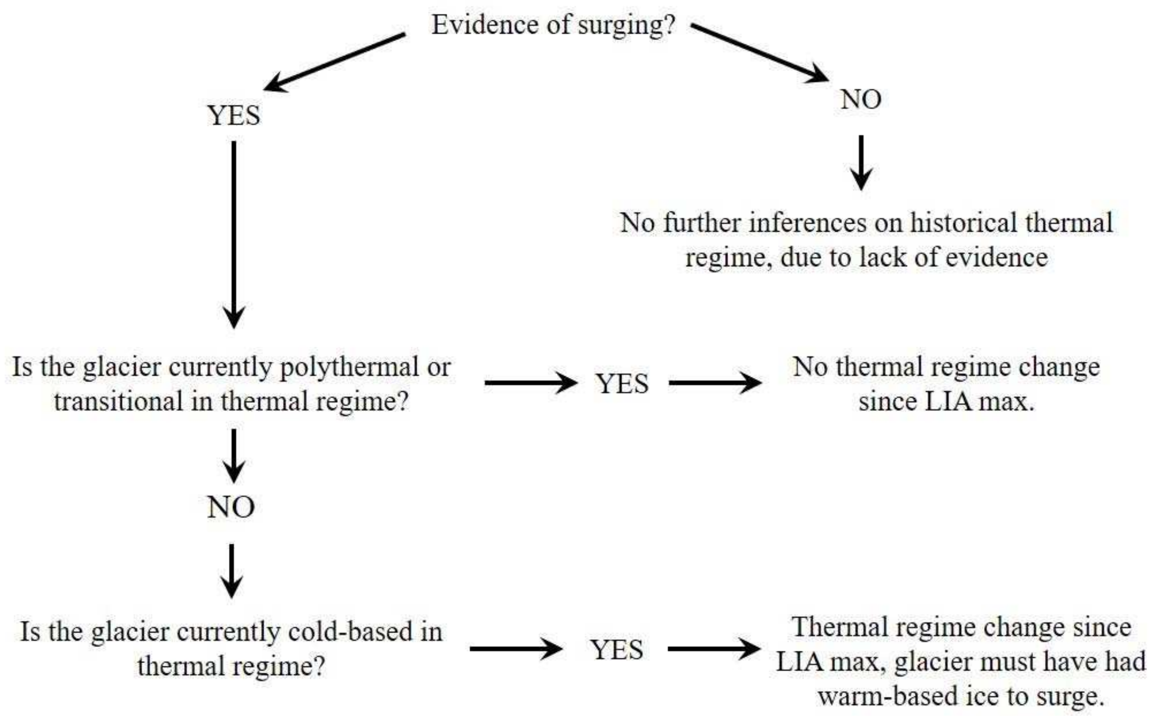

Figure 3. Flowchart of the decision-making process used to determine whether glaciers have a history of surging, and from this, whether they may have been warm-based around the LIA maximum.

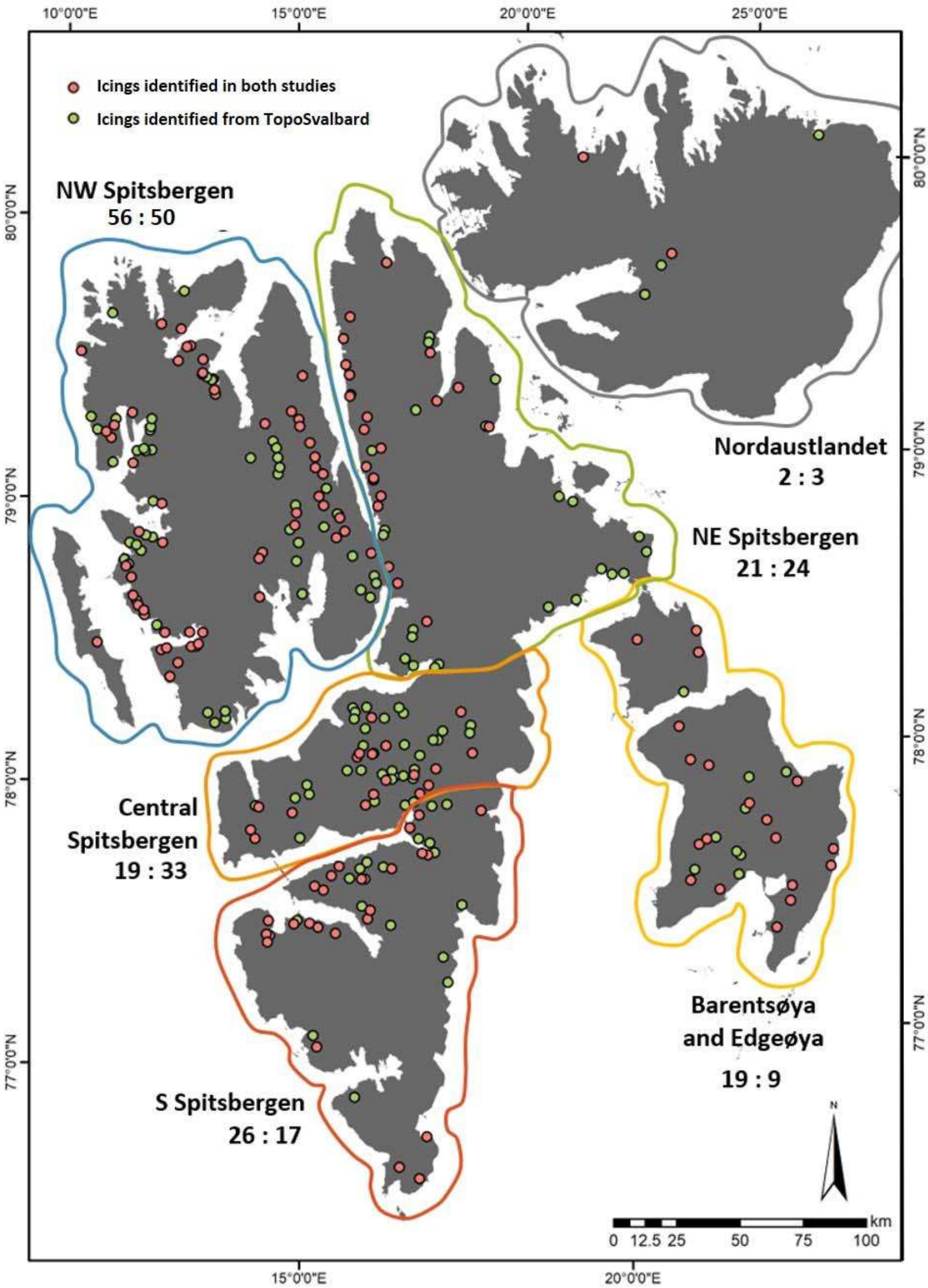

Figure 4. Locations of glaciers with icings identified in this study are presented in green. Any glaciers with icings that were also identified by Bukowska-Jania and Szafraniec (2005) are shown in pink. Left number denotes number of glaciers with icings identified in both studies, right number denotes those identified in this study only.

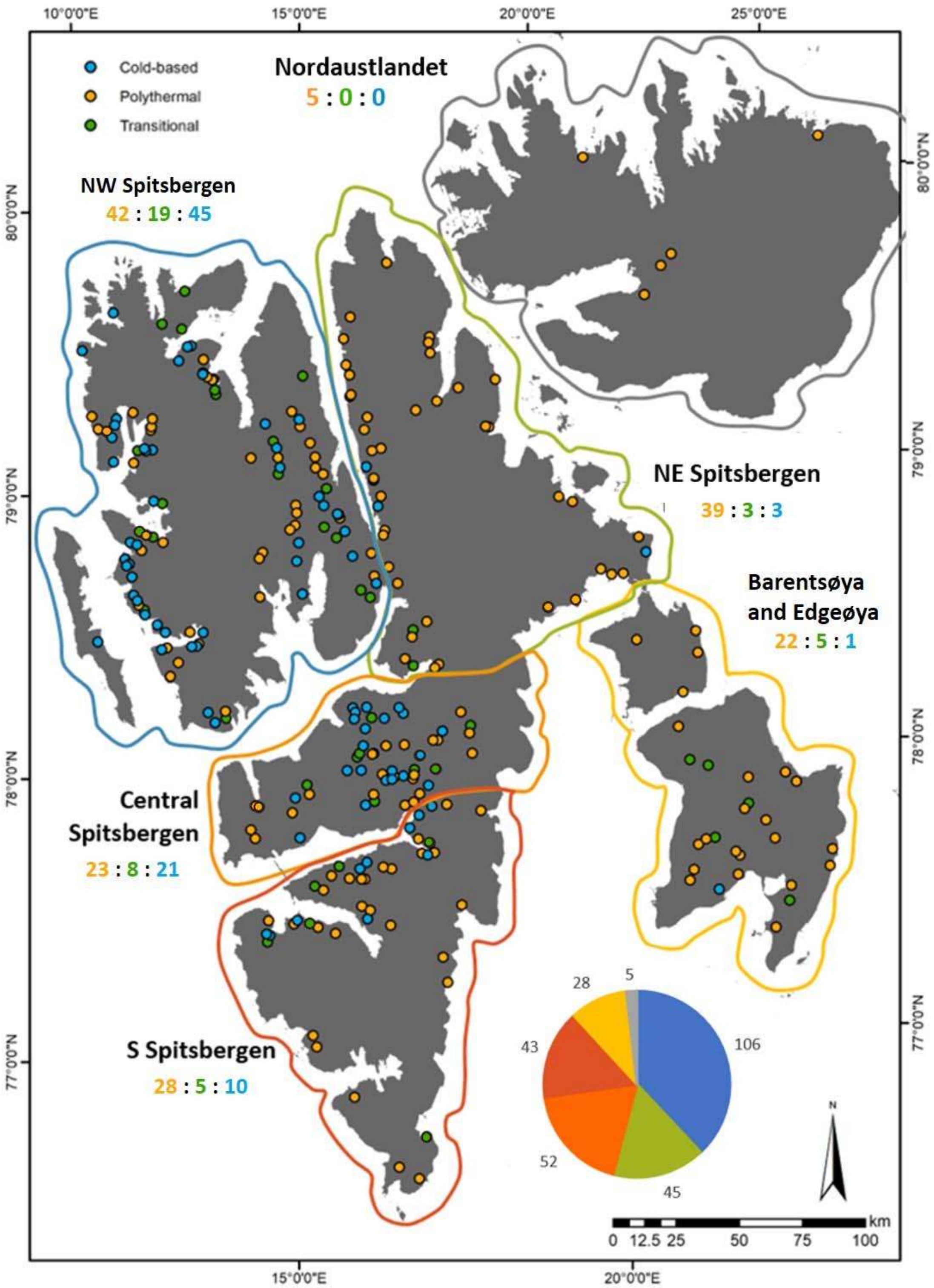

Figure 5. Locations of glaciers with icings identified in this study, colour-coded by inferred thermal regime, with regional numbers of present glacier thermal regime associated with icings. Inset pie chart shows the numbers of glaciers with icings in each region.

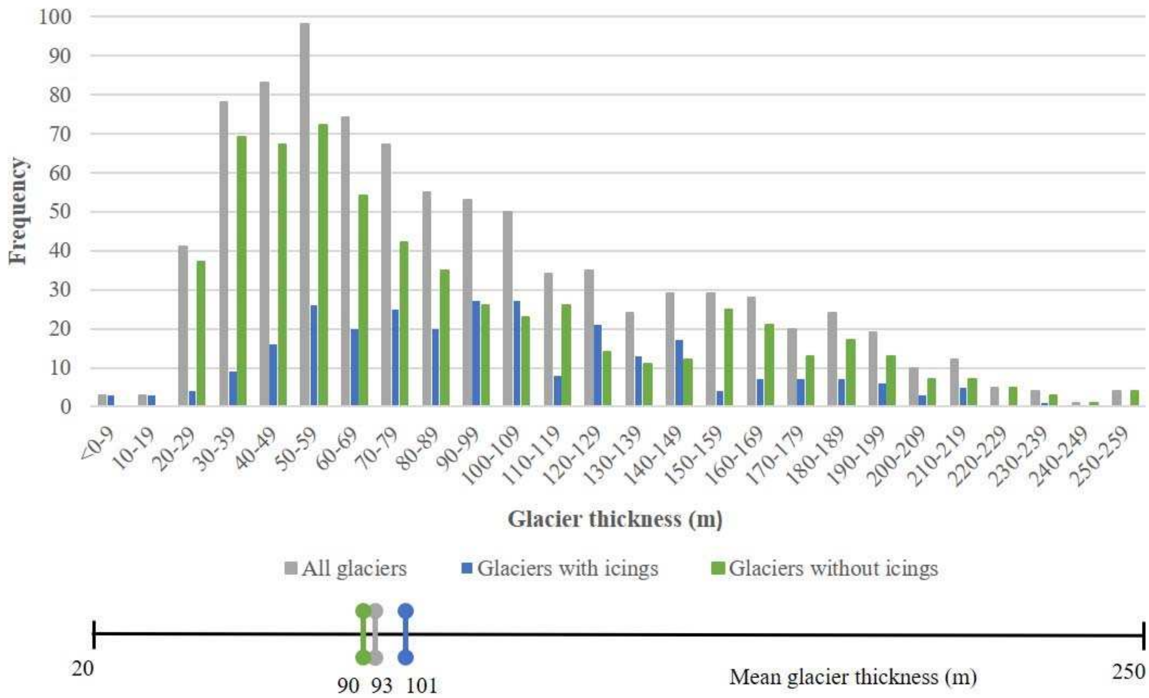

Figure 6. Bar graph showing the frequency distribution of glacier thicknesses, grouped by the presence of icings, including the total frequency distribution of all land terminating glaciers. Glacier thickness data was derived from the empirical area-depth relation established for Svalbard glaciers by Hagen et al. (1993), using glacier area outline data from *Svalbardkartet* (NPI, 2018b). T-test statistic = -2.978. This test showed that glaciers with icings had a mean thickness difference of 10.7 ± 3.6 m compared to glaciers without icings, shown by the lower diagram.

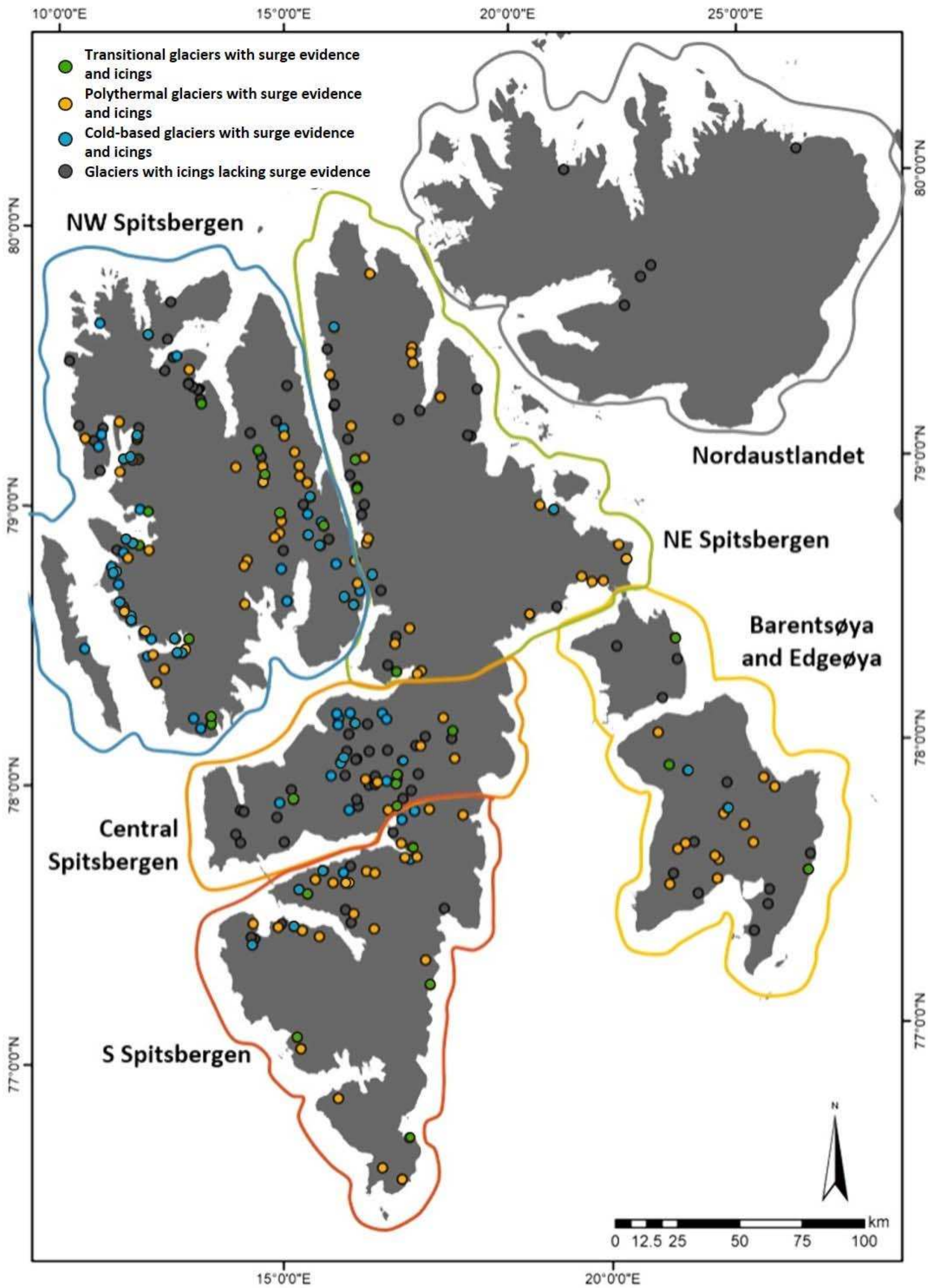

Figure 7. Locations of glaciers with icing fields and CSRs are shown in colour, according to the present glacier thermal regime. Glaciers with icings but lacking CSRs in their forefields are shaded grey.

Tables

Table 1. Number and proportion of glaciers with and without icings, categorised by present (inferred) glacier thermal regime.

Thermal regime	Number with icings	Percentage with icings	Number without icings	Percentage without icings
Polythermal	128	45.9	205	33.9
Transitional	44	15.8	56	9.3
Cold-based	107	38.3	343	56.8
TOTAL	279	-	604	-

Table 2. Numbers of glaciers with icings categorised by presence of forefield CSRs.

Thermal regime	Number with CSR	Number without CSR
Polythermal	92	36
Transitional	28	16
Cold-based	67	40
TOTAL	187	92