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LITTLE ICE AGE GLACIER EXTENSION AND RETREAT IN SPITSBERGEN ISLAND (HIGH ARCTIC, SVALBARD ARCHIPELAGO)

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ABSTRACT. *The influence of the Little Ice Age on the glaciers of Spitsbergen has been well documented by many investigations since long time. This paper studies, measures and presents new data on the Little Ice Age maximum glacier extension and retreat by aerial photo interpretation and Geographic Information Systems (GIS) tools use. It also elaborates cartography where all the results are expressed in greater detail. During the Little Ice Age maximum the glaciers covered 23,034 km² of the Island. After the Little Ice Age, the total ice area loss was 12.83%, which means a total of 2957.3 Km² over the 20,076.7 Km² of the total glaciated in the current context. The analysis of the maximum Little Ice Age glacier extension in the major drainage basins brings important differences among them; hardly 100 years ago some basin drainage increased the glacier area more than 19% (in the western and central region of Spitsbergen), while others less than 5% (in the northeast region of the Island). The greatest retreats are found in the tidewater glaciers that extend into the sea, which we explain due to different factors: their glacier front beds are found below the sea level, the intense ablation of the calving process, the fact that their tidewater fronts are thin and temperate (which make them more dynamic and very sensitive to climate fluctuations), and that the advances of these glaciers may correspond with surges, which means that the rapid retreats are motivated by the post-surging phases as well. The conclusions of the present research point out a very important ice loss in the whole Island since the Little Ice Age, and the high vulnerability of this Arctic Archipelago to global warming.*

Extensión y retroceso glaciar durante la Pequeña Edad del Hielo en Spitsbergen (Alto Ártico, archipiélago de Svalbard)

RESUMEN. *El alcance de la Pequeña Edad del Hielo (PEH) en los glaciares de Spitsbergen ha sido bien documentada desde antiguo por numerosas investigaciones. El presente artículo estudia, cuantifica, y presenta nuevos datos sobre la extensión máxima y retroceso glaciar desde la Pequeña Edad del Hielo a partir del uso de fotointerpretación y herramientas de Sistemas de Información*

Geográfica (SIG). También elabora cartografía donde se reflejan los resultados obtenidos. Durante la Pequeña Edad del Hielo los glaciares cubrían 23.034 km² de la isla. Tras la Pequeña Edad del Hielo, la pérdida glaciar total fue de un 12,83%, lo que significan 2957,3 Km² sobre los 20.076,7 Km² totales que perduran en la actualidad. Se ha analizado el máximo de la Pequeña Edad del Hielo en las mayores cuencas de drenaje, lo que ha arrojado importantes diferencias entre ellas: desde hace poco más de 100 años algunas cuencas han perdido un 19% (como la localizada en la región central y oeste de Spitsbergen), mientras que otras solo han retrocedido un 5% (en las regiones noreste de la isla). Los mayores retrocesos del hielo se dan en los glaciares de marea que terminan en el mar, lo que se explica por diferentes motivos: los lechos subglaciares de los frentes se encuentran bajo el nivel del mar, la intensa ablación de los procesos de calving o producción de icebergs, el hecho que los frentes de este tipo de glaciares son poco potentes y templados (lo que les hace más dinámicos, pero más vulnerables ante los cambios climáticos), y que los mayores avances glaciares corresponderían con surges u oleadas glaciares. Los resultados de la investigación señalan la importante pérdida de hielo en la totalidad de la isla de Spitsbergen desde el máximo de la Pequeña Edad del Hielo, y prueban la elevada vulnerabilidad de este archipiélago ártico ante el calentamiento global.

Key words: glacier retreat, aerial photo interpretation, GIS, Little Ice Age, Spitsbergen.

Palabras clave: retroceso glaciar, fotointerpretación, SIG, Pequeña Edad del Hielo, Spitsbergen.

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1. Introduction

The glaciers of Svalbard and Spitsbergen have been intensely studied since long time. Many of these researches have been focused on the geomorphology and the deglaciation after the Little Ice Age (LIA) (e.g. Ziaja, 1994; Lønne and Lyså, 2005; Lukas *et al*., 2005; Rasmussen, 2006; Rachelewicz *et al*., 2007; Bate, 2008); or on the glacier retreat during the last decades (e.g. Ziaja, 2001, 2005; Palli *et al*., 2003; Bartkowiak *et al*., 2004; Zagórski and Bartoszweski, 2004; Navarro *et al*., 2005; Ziaja and Pipala, 2007; Sobota and Lankauf, 2010; Ai *et al*., 2013; Lapazaran *et al*., 2013).

All investigations show the importance of this short cooling period in Svalbard. However, the total increase of the glacial area during the LIA for the whole Archipelago (or the main islands), remained still unknown. This paper attempts to present new quantitative data on the extension of the Spitsbergen Island glaciers during the LIA by using aerial photo interpretation, GIS tools and cartography, proposing a total percentage of ice area loss since then. Knowledge of these values may help to understand the reach and effects of the global warming on the Svalbard Archipelago.

2. Study area. Geographic and climatic setting

Svalbard is a Norwegian high arctic archipelago in the Arctic Ocean, at the same latitude as the northernmost parts of Greenland. The main islands -Spitsbergen, Nordaustlandet, Barentsøya, Edgeøya, Prins Karls Forland, Kong Karls Land, and Bjørnøya-, are found between 74ºN and 81ºN latitude (just 1000 Km away from the Geographic North Pole), and 10ºE and 35ºE longitude (Fig. 1). The total area is 62,000 Km^2, while the biggest island, Spitsbergen, is 37,705 Km^2. Mountains and glaciers of different sizes -and only some lowlands in the western coast- characterize the geography of the Island. The highest altitude is Newtontoppen with 1717 m. a.s.l. Svalbard has been described as a ”geologist paradise” due to the complete geologic sequence from the Precambriam until the Quaternary (Hisdal, 1985). The pattern of faults and fractures is aligned NNW-SSE, and explain the distribution of the macroforms as fjords, valleys, cirques, and coasts.

The climate of Spitsbergen is the result of its high latitude and the strong influence of the warm West Spitsbergen Current (a branch of the North Atlantic Current), which make the climatic conditions much milder than expected. The temperature varies significantly within the Archipelago, but on average the temperatures in the coldest month (February) are found between -13ºC and -20ºC, and 3ºC and 7ºC in July (Førland *et al.,* 1997); the northern parts of the island is about 5ºC colder in winter than the south, and only 3ºC in summer. Currently, the mean annual air temperature (MAAT) is about -5°C close to sea level in central Spitsbergen (Humlum *et al.,* 2003). Precipitation also changes greatly on the island; at the sea level might be so low as 190 mm yr^{-1}, while in the eastern and southeastern Spitsbergen can reach 1000 mm yr^{-1} (Torkildsen *et al.,* 1984; Hisdal, 1985). The snow cover lasts from the beginning of October until June (Eckerstorfer *et al.,* 2008; Martín and Serrano, 2013). Permafrost is continuous, with maximum thickness up to 450 m. (Liestøl, 1980; Humlum *et al.,* 2003; Humlum 2005).

Global warming is amplified in the Arctic region (Pithan and Mauritsen, 2014), much more pronounced than in mid latitudes (ACIA 2005, IPCC 2007). Svalbard displays also this unique climatic high sensitivity (Lamb, 1977; Houghton *et al.,* 2001; Humlum *et al*., 2003). For instance, since the 1920s the mean annual air temperature (MAAT) at sea level changed from -9ºC to -4ºC, which possibly was “the most pronounced increase in surface air temperature documented anywhere on the planet during the observational period”, decreasing 5ºC from 1957 to 1968 (Humlum *et al.,* 2003), and increasing gradually in the end of the 20th century and beginning of 21th. Experiencing the greatest temperature increase in Europe during the latest three decades (Isaken *et al.,* 2007).

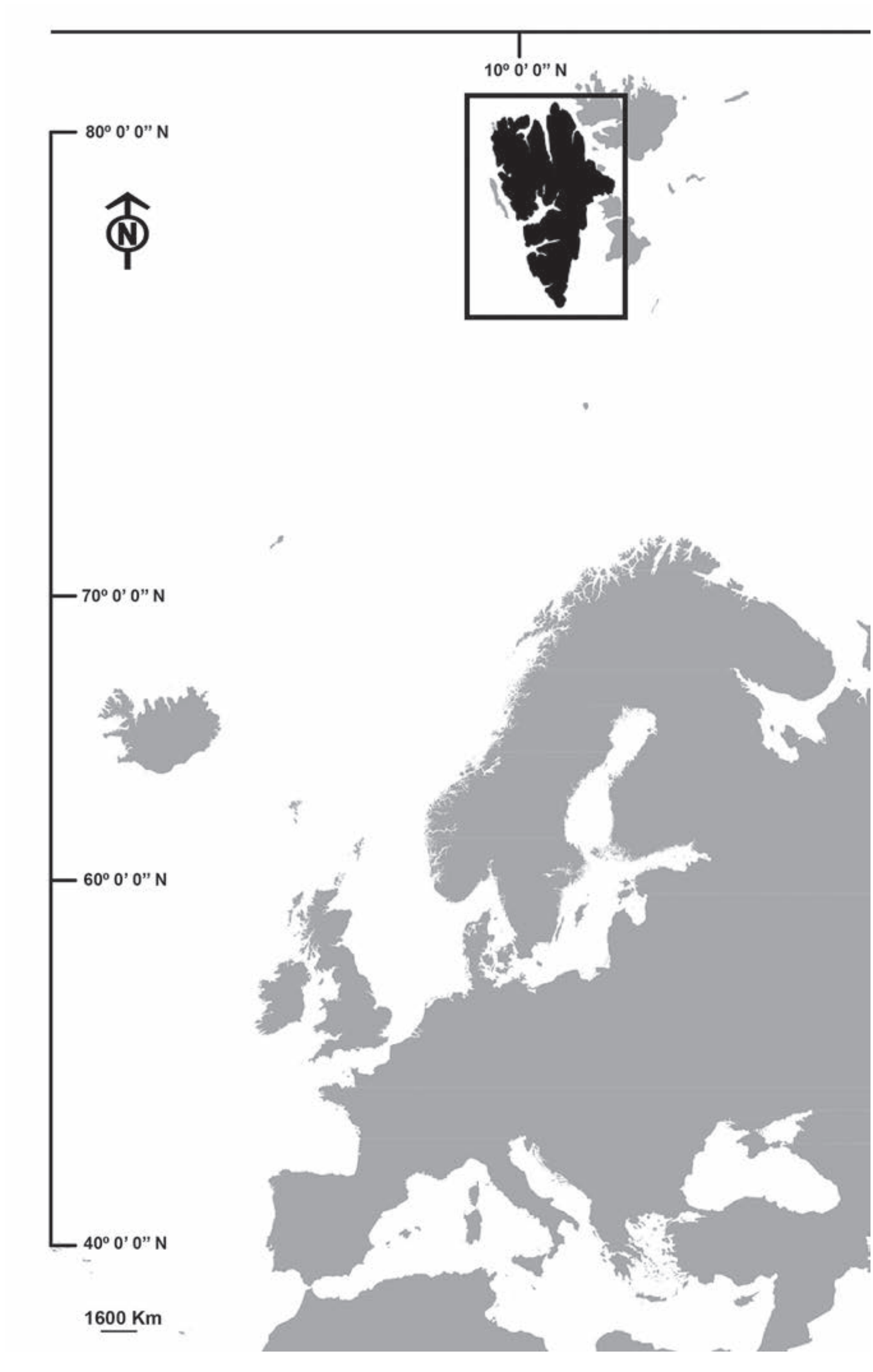


Figure 1. The Svalbard Archipelago and Spitsbergen Island within the Atlantic and European context.

2.1. Glaciers of Spitsbergen

In Svalbard there are more than 2100 glaciers (Liestøl, 1993), covering about 36,000 Km^2, which represents 60% of the archipelago (Hagen *et al.* 1993). The complexity of the glaciated areas is so high than the ice masses of Svalbard have been described as “transection glaciers” (Ahlmam, 1948). In Spitsbergen the total glaciated area is 28,008 Km^2, which represents 53.1% (according to König *et al*., 2014; 57.5% according to Hagen *et al*., 1993). Several types of glaciers are found; many of them are small cirque glaciers in the mountains of the western part of Spitsbergen, glaciers individualized by ice streams, mountain ridges and nunataks, but also large ice caps –mostly located in the eastern part of Spitsbergen–, with maximum thickness of 600 m, that flow and calve in the ocean (Blaszczyk *et al*., 2009). The Equilibrium Line Altitude (ELA) varies greatly upon the location in within the island; while in the inner parts of Spitsbergen is more than 800 m above the sea level, in the east side is just at 200 m a.s.l. (Liestøl, 1993). Surge glaciers are very common in Svalbard and Spitsbergen (Liestøl 1969; Lefauconnier and Hagen, 1991; Hagen *et al.* 1993; Dowdeswell *et al*., 1991; Jiskoot *et al*., 2000). A surge is a sudden discharge of ice from the upper to the lower areas, which increases the velocity of the ice. In Svalbard, it has been registered velocities up to 100 m per day (Liestøl, 1969). Surges might hinder highly the front position glaciers and deglaciation studies, as we will discuss later.

Much of the small and mid glaciers of Spitsbergen are subpolar or polythermal, where the ablation area is below 0ºC and partly frozen to the ground, while the accumulation zone is at the melting point due to the thermal isolation of the snow. However, some of the smaller glaciers are fully polar as well, where their whole ice mass is below the freezing point (Liestøl, 1993). Only the subpolar glaciers develop icings in their fronts produced by the winter subglacial water (Liestøl, 1993; Martin Moreno and Serrano, 2015). Both types of glaciers are characterized by very low velocities (Hagen *et al*., 2003).

Tidewaters glaciers are present in about 20% of the Svalbard archipelago coastline (Dowdeswell and Forsberg, 1992), which means that more than 60% of all glaciers terminate in the sea at calving ice-cliffs (Blaszczyk *et al*., 2009). Tidewaters glaciers end in marine deep waters or in relatively shallow fjord waters. There are 163 glaciers in Svalbard having contact with the ocean (Blaszczyk *et al*., 2009). According to the same source, 14 glaciers retreated from the sea during the last 30-40 years, while 11 advanced from the land into the water. 43% of Svalbard tidewater glaciers are classified as surge type (Blaszczyk *et al*., 2009).

The glacier net mass balance has been mostly negative during the last 30 years of observations (Hagen *et al.* 2003). Many ice masses had presumably “stable negative mass balance since about 1920” (Lefauconnier and Hagen, 1990). According to some observations of front positions (Blaszczyk *et al*., 2009), there is a general retreat in Svalbard since the last 80 years. Later investigations show significant thinning at most of the smaller glacier fronts (Nutch *et al*., 2010). Considering the glaciated area, Svalbard glaciers mass balance is the most negative of the Arctic (Nutch *et al*., 2010).

2.2. The Little Ice Age (LIA) in Svalbard-Spitsbergen

The LIA was a cooling period during the 14th-19th centuries, when the temperature dropped between 0.6ºC and 2.0ºC and the glaciers advanced, affecting mostly –but not only– the North Atlantic region (Mann, 2002; Grove, 2004). It has been estimated that in Svalbard the temperature rose by almost 5ºC since the end of the LIA. It has been widely researched or mentioned in the study area (e.g. Dahl and Nesje, l994; Svenden and Mangerud, 1997; Lankauf, 1999; Lyså and Lønne, 2001; Szczucinski *et al*., 2009; Martín-Moreno and Serrano, 2011). In Svalbard, the LIA corresponds essentially with the maximum glacier extension of the Holocene (Snyder *et al*., 2000; Humlum *et al*., 2005; Blaszczyk *et al*., 2009; Cwiakala *et al*., 2015). In some areas of Spitsbergen, glaciers were reduced or even not present during the Holocene before the LIA (Snyder *et al.,* 2000).

The glacier major advances have been dated in 1890-1900 (Mangerud and Svendsen, 1990; Glasser and Hambrey, 2006), 1900 (Snyder *et al.,* 2000)*,* 1910 (Humlum *et al*., 2005) and even 1920 (Svendson and Mangerud, 1997), considerably later that much of the mountain glaciers of the world. This could be explained due to the delayed climatic sensitivity of many of the glaciers of Spitsbergen and their slow ice flow velocities (Humlum *et al*., 2003). The fresh sedimentary landforms and the low rates of erosion facilitate the glacial position reconstruction.

3. Methodology

We have employed aerial photo interpretation and Geographic Information Systems (GIS) tools. The GIS software tools used are *ArcGis v.10.2* and *Norwegian Polar Topographic Map* series (NPTS) in GIS format with a basemap reference (basisdata_NP_Basiskart_Svalbard_WMTS_ 25833.lyr, NPT, 2014b), and satellite images, ortophotos and terrestrial photographs. We have utilized information GIS-compatible from a variety of sources:

- Shapefiles of glacier area in 1936, 1938, 1960, 1966, 1969–1971, 1990 and 2001–2010 (GLIMS archives at the *National Snow Center and Ice Data Center* are available through the *CryoClim* data portal, http://www.cryoclim.net).
- Shapefile of island boundary (S100 Kartdata, Norwegian Polar Institute, 2014a).
- Shapefile of moraines (Norwegian Polar Institute, 2014b).
- Different sources via web map server (WMS): satellite images and ortophotos (Norwegian Polar Institute, 2014b).
- Additional geolocation information provided by terrestrial photographs (*NPI, TopoSvalbard,* 2015).
- Digital Elevation Model (GRID) of Spitsbergen (Norwegian Polar Institute, 2014b) with 20x20 m cell size resolution.

Information available via WMS and shape files were used at time and these have provided photo interpretation and digitalizing tasks with direct linkage into a GIS interface (*ArcGis 10.2)*. LIA was estimated with a detailed analysis of imagery and past and present position of glacier fronts and moraines. Shapes, when was relevant, were edited and redefined by photo-interpretation. We have followed the recommended accuracy by Norwegian Polar Institute (up of a scale 1:10,000). However the photo-interpretation was tested with a detailed analysis of terrestrial photographs (online map of Svalbard, Norwegian Polar Institute, 2014b).

As a reference for calculation glacier area during the LIA we have used basin numeric references of Hagen *et al*. in *Glacier Atlas of Svalbard and Jan Mayen* (1993). Hydrological analyses of *ArcGis v. 10.2* provided a tool for calculate basin areas only for Spitsbergen land surface (islands were excluded). We have generated automatic basin areas from *Data Digital Terrain Model* (Norwegian Polar Institute, 2014b) with GIS algorithms. The obtained boundaries were edited and topological validated and coded with numeric references to Hagen *et al*. (1993). The database was designed with two information fields in numeric format: major drainage basin (e.g. 11) and secondary drainage basin (e.g. 111). LIA shapes and glacier surface from 2000-2010 (König *et al*., 2014) were intersected to obtain a single database. From these data we have considered the ice surface (km^2), which have allowed us to calculate the percentage of the area that has changed since the LIA.

Complementary to the desktop work, we have carried out some fieldworks in Spitsbergen (Nordeskiöld area) during July 2002, March and April 2004, and June 2010.

3.1. Methodological difficulties

We have faced several methodological difficulties conducting the present research, which are described below:

3.1.1. The interpretation of the so-called “ice-cored moraines” of the small polythermal and cold glaciers (“Longyearbreen-type”): It has been an intense debate if here there is dead-ice isolated from the glacier, or if the glacier is just debris-covered (Lønne and Lyså, 2005; Lukas *et al*., 2005; Lukas *et al*., 2007; Lønne, 2007). The implications of this issue for the glacier reconstruction are very relevant, whether the glacier advance beneath the debris, the real front will still be at the maximum LIA position. This means that some glaciers in Spitsbergen did not retreat after the LIA, but rather thinning and losing volume (Lukas *et al*., 2007), up to 30 m less in thickness (Humlum *et al*., 2005).

By aerial photography interpretation, we have tried to differentiate between that moraines consequence of the differential ablation at the ice-debris interface (Lukas *et al*., 2005), from those that show constructional and retreat features as push and thrust ridges, small recessional moraines, flutes, hummocky moraines, symmetric concave forms, trim lines, proglacial lakes, etc., in order to reconstruct the LIA glacier maximum positions. The topographic map series of Svalbard from 1936 were also used to distinguish between the glaciers that retreated from those that stayed.

3.1.2. Surging glaciers: surges are very common in Svalbard; where up to 90% of the glaciers are or have been affected sometime by surges (Lefauconnier and Hagen, 1991). Some authors (Jiskoot *et al*., 1998) described many surges as maximum glacier extension during the LIA. As previously seen, a surge is sudden increase in the glacier motion of 100-200 times more than normal velocity (Sund *et al*., 2014). In its abrupt downward movement, the ice dismantles the erosional and sedimentary landforms suitable for use in glacial reconstruction. However, it seems that in Spitsbergen none glaciers have advanced during the surge stage over the LIA maximum position. Just few glaciers had the same maximum extension during the surge than during the LIA maximum (Lefauconnier and Hagen, 1991). That means that none contemporary surges could be confused with the maximum LIA advances.

3.1.3. Tidewaters glaciers: the reconstruction of the some LIA ice fronts that end in open waters (mostly found in the NE of Spitsbergen) seemed difficult due to the absence of subaerial sediments and deposits (in some other cases, we have used small morainic island such as Kvalrossøya, from the Negribreen, or bathymetric maps). Due to the influence of the water temperatures at the front, Svalbard calving glaciers have mostly temperate tidewaters tongues (Hagen *et al*., 2003); radio echo measurements, ice surface profiles and shore-coast bathymetry demonstrate that these glaciers are grounded not having floating termini (Dowdeswell *et al*. 1984; Hagen and Saetrang 1991; Jania *et al*., 1996; Hagen *et al.,* 2003). In Spitsbergen, as in the rest of the Archipelago, none of the tidewater glaciers form floating ice shelves like those found in Antarctica (Kohler, 2009), which means that during the LIA many of the tidewaters glaciers had kind of similar positions due to the impossibility of advance far over the open waters. The descriptions from the old sailors and whalers suggest this fact (Liestøl 1993). However, the tidewater glaciers found in sheltered bays and shallow fjords waters had a different behavior due to the protection from the sea dynamics, and mostly the not-too deep sills creating semi-enclosed basins (Elverhøi *et al*., 1980; referenced in Dowdeswell, 1989). We have identified clear moraines in most of the fjords that facilitate the reconstruction and show the very important retreat of these types of glaciers.

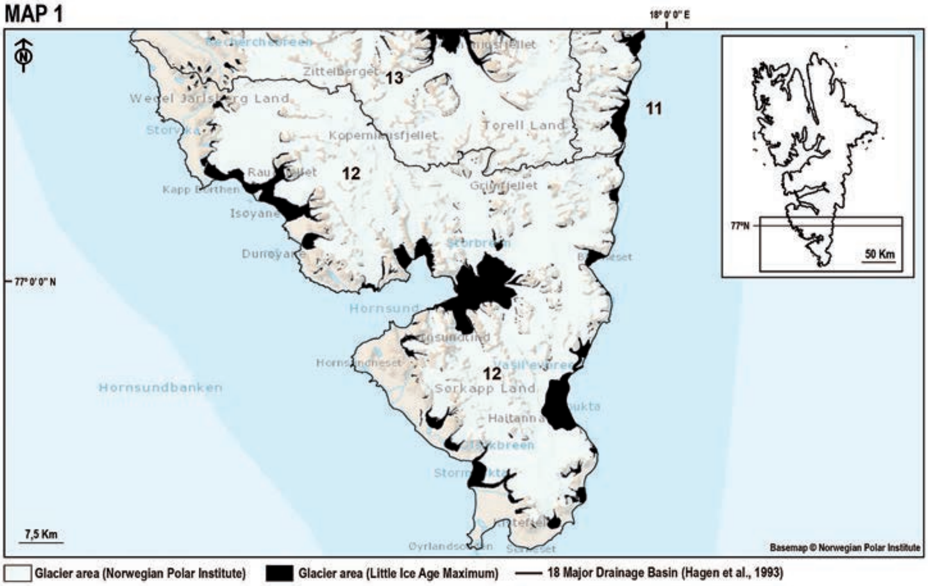
4. Maximum Little Ice Glacier extension and glacier retreat in the major drainage basins of Spitsbergen

During the LIA maximum the glaciers covered 23,034 km^2 of the island. After the Little Ice Age, the total ice area loss was 12.83%, which means a total of 2957.3 km^2 over the 20,076.7 km^2 of the total glaciated in the current context.

The maximum LIA glacier extension in each of the major drainage basins (proposed by Hagen *et al*., 2003) brings important differences among them; 100 years ago some basin drainage increased the glacier area more than 19% (basin no. 14), while others less than 5% (basin number 17). We describe below the results obtained in each major drainage basins:

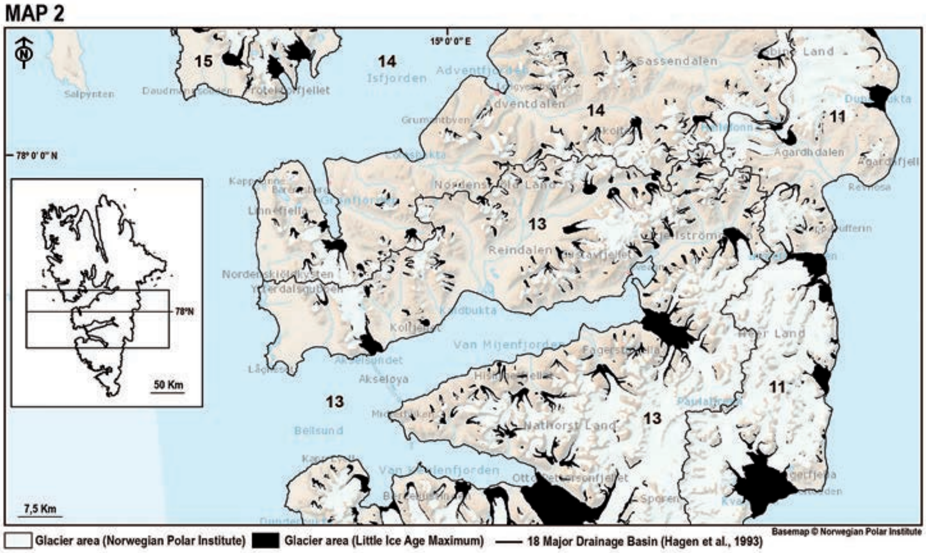
- The drainage basin 11 is located in the east region of the Island, comprising the Sabine and Heer Land. During the maximum LIA the glaciers covered 3681.9 km^2. Today, it has a glaciated area of 3095.3 km^2, which means an ice retreat of 15.93%. In this basin there are some tidewater glaciers, which mean one of the largest ice loss in the whole Island: Negribreen and Strongbreen, both with calve front recession of more than 12 km. Other tidewater fronts that also retreated are Sonklabreen –6 km–, Ulvebreen –>4 km– or Nordsysselbreen –4.5 km– (Map 1, Map 2, Map 3).
- The drainage basin 12 is located in the southernmost region of the Island. It includes Sørkapp Land, and partly Wedel and Torell Land. 100 years ago, the glaciers covered 2271.4 km^2 of the basin. The glacier retreat since the maximum LIA is 16.56%, placing the current ice area in 1895.086 km^2. There are several tidewater glaciers in this basin with very important front recessions such as Hambergbreen (with almost 3 km of retreat), Vestre and Austre Torellbreen (>3 km), Vasilevbreen (7 km), and the dramatic case of Hornbreen, where we have observed 13 km of front retreat (Map 1).
- The drainage basin 13 includes Nathorst Land and part of Wedel, Heer and Nodenskiöld Land. The glaciers reached in the LIA 2769.4 km^2, and lost 16.9% of ice since then. Currently they occupy 2301.3 km^2. Again, the most important ice losses are found in tidewater glaciers, such as Nathorstbreen (whose front retreated more than 16 km), Paulabreen (9 km), Fridjovbreen (which retreated more than 4 km). Inland, there are some valley glaciers that present important retreats compared to their size, like Slakbreen, Kokbreen and Marthabreen, with retreats of 2.5, 2.3, and 1.8 km respectively (Map 1, Map 2).

MAP 1



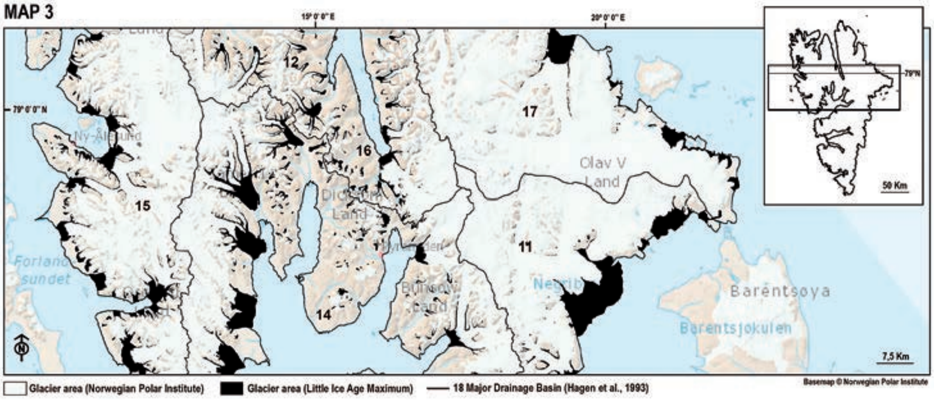
Map 1. Maximum glacier extension during the LIA in the major drainage basins 11, 12, 13.

MAP 2



Map 2. Maximum glacier extension during the LIA in the major drainage basins 11, 13, 14, 15.

MAP 3

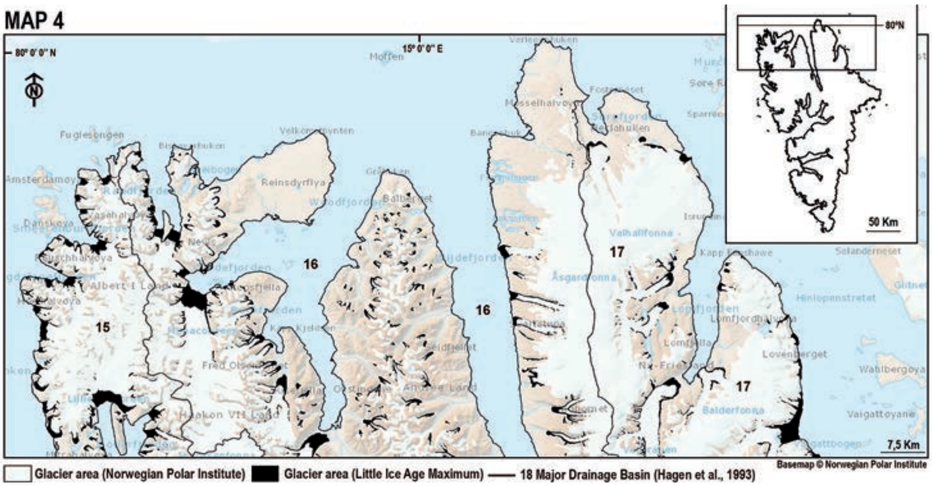


Map 3. Maximum glacier extension during the LIA in the major drainage basins 11, 14, 15, 16, 17.

- The drainage basin 14 is located in the central region of Spitsbergen. It extends over the north of Nodenskiöld Land, and Bünsow, Dickson, James I and Oscar II Land. During the maximum LIA the glaciers covered 2862.9 km^2. Today, it has a glaciated area of 2301.8 km^2, i.e. an ice retreat of 19.59%, making it the basin with the largest glacier loss. Most of it is due to the tidewater glaciers found in the east coasts of James I and Oscar Land, such as Sefströmbreem (which lost more than 11 km from its front), Borebreen (10 km), Wahlenbergbreen (more than 7 km), Sambreen (almost 7 km), and Nansenbreen (about 4 km). In James I Land, we have found one of the large outlet glacier that ends on land

(Holmströmbreen, Morabreen, Orsabreen), which recessed more than 8 km, leaving behind a proglacial lake. In the north of Nordeskiöld Land, the ice loss is not so significant, which is obviously explained due to smallest glaciated area compared to the other regions of Spitsbergen, and the fact that small glaciers, "Longyearbreen type", do show barely some changes since the LIA or do represent negligible percentages within the overall area of the Island (Map 2, Map 3).

- The drainage basin 15 is located in the northwest region of the Island. It includes Albert I Land, and partially Haakon VII and Oscar Land. A century ago, the glaciers covered 3692 km^2 of the basin. The glacier retreat since the maximum LIA is 12.02%, placing the current ice area in 3180.2 km^2. All the tidewater fronts present clear evidences of glacier recession, such Lilliehööbreen, which has lost 3.5 km (Map 2, Map 3, Map 4).
- The drainage basin 16 is located in the north of the Island, comprising the Andrée Land and partly Haakon Land and Ny-Friesland. During the maximum LIA the glaciers extended over 3184.7 km^2. Today, it has a glaciated area of 2875.9 km^2, which means an ice retreat of 9.69%. Most of the glacier loss is found in the east coast, with tidewater fronts as Monacobreen, which has recessed up to 5 km (Map 3, Map 4).
- The drainage basin 17 is located in the northeast parts of Olav V Land and Ny-Friesland. It is the basin of Spitsbergen with the largest ice area and the one which shows the smallest retreat: 4571.8 km^2 of glacier extension during the LIA, 4.65% of ice loss since then, and a glaciated area of 4359.1 km^2 at the present time. Ny-Friesland is a striking case, as with the exception of few glaciers that reach the sea in the Western coast (Nordbreen, Midtbreen and Stubendorffbreen, included in the basin 16), in the ice caps that partly covered the peninsula (Åsgardfonna and Valhallafonna) the recession is minimal or absent. This could be explained due to the cold-based glaciers and the slow response to the climatic fluctuations, as well as the



Map 4. Maximum glacier extension during the LIA in the major drainage basins 15, 16, 17.

fact that the glaciers that end on land, over continuous permafrost and with cold-based fronts, might remain steady or move slowly since the LIA (Map 3, Map 4).

As seen above, the greatest retreats are found in the glaciers that extend into the sea. We explain this due to several factors:

- Their glacier font beds are found below the sea level.
- The intense ablation of the calving process; some of these tidewater glaciers, such as the Negribreen, still produces some tabular icebergs of around 100 m. (Hagen *et al.*, 1993).
- The fact that their tidewater fronts are thin and temperate, which make them more dynamic and very sensitive to climate fluctuations.
- The advances of these glaciers during the LIA correspond with surges (Lefauconnier and Hagen, 1991), which means that the rapid retreats are motivated by the post-surging phases as well.

5. Conclusions

This paper has attempted to measure and quantify the glacier maximum extension during the LIA in the whole Island of Spitsbergen, and present the results in cartography. It has been shown that the glacier retreat after the LIA is the predominant trend in Spitsbergen. The total glaciated area loss since the LIA maximum is larger that we expected: 12.83%, which means a change in Spitsbergen from 23,034 km^2 of ice surface, to 20,076.7 km^2 of the total actual glaciated area. This means a great glacier retreat for a short period of slightly 100 years.

All the major drainage basins of Spitsbergen have shown glacier retreat. A detailed study of each of them has exhibited that the tidewater glaciers found in fjords and along the coast are responsible of the largest ice loss due to their temperate fronts, the calving processes, and that in some cases the greater advances corresponded with surges during the LIA. The large outlet glaciers that ends on land also present important ice recessions, but not comparable with the tidewater ones. Many inland valley glaciers show significant retreats relatively to their size, but represent negligible percentages within the total area of the Island. Finally, some cold-based fronts from small glaciers remain steady or move slowly since the LIA.

The study of the glacier LIA extension and retreat since then has proved the great vulnerability of Spitsbergen to global warming, and the need to continue working on further regional works on Svalbard, which measure the total glacier retreat and ice loss for the whole Archipelago, to confirm the profound change that this arctic region is going through.

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