Quaternary Science Reviews 199 (2018) 18–29

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Glaciers on Svalbard survived the Holocene thermal optimum

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ARTICLE INFO

Article history:
Received 7 June 2018
Received in revised form
27 August 2018
Accepted 2 September 2018

Keywords:
Holocene
Svalbard
Glaciation
Sea level changes
Glacial isostasy

ABSTRACT

About 60% of Svalbard is covered by glaciers today, but many of these glaciers were much reduced in size or gone in the Early Holocene. High resolution modeling of the glacial isostatic rebound reveals that the largest glaciers in Nordaustlandet and eastern Spitsbergen survived the Early Holocene warming, while the smaller, more peripheral glaciers, especially in the northwest, started to form about 5,500 years ago, and reached 3/4 of their current size about 600 years ago. Relative sea level has been rising during the last few millennia in the north and western parts of Spitsbergen, while land still emerges in the remaining part of Svalbard. Here we show that this sea level rise in the northwest is caused by the regrowth of glaciers in the Mid- to Late Holocene that slowed down, and even reversed, the post-glacial isostatic uplift and caused the crust to subside over large areas of Spitsbergen.

1. Introduction

Today there are more than 2000 glaciers on Svalbard (Liestøl, 1993), but during the exceptional warm climatic optimum in the Early Holocene on Svalbard (Mangerud and Svendsen, 2018), it has been assumed that many of these glaciers were completely deglaciated or much reduced in size (e.g. Hughes et al., 2016). However, it is not known to what extent the glaciers on Svalbard were absent or smaller than today in the Early- and Mid-Holocene. In this paper, we try to find that answer by modeling the isostatic response due to the decay and regrowth of the Holocene glaciers on Svalbard. We compare the output of the modeling to the observed sea level curves, and test different scenarios for the Holocene ice growth against these observations. By this approach, we are able to show that the largest glaciers must have survived the climatic optimum and that the regrowth of glaciers reversed the isostatic uplift and caused the crust to subside over a large part of Spitsbergen (Fig. 1).

A clear sign of this subsidence is the recent rise in relative sea level in the northwestern corner of Spitsbergen (Fig. 1). Here, cultural remains are found closer to sea than when they were built. Coastal erosion of cultural remains from the 17th century has been reported from Amsterdamøya (Vogt, 1932), Ebeltofthamna in western Spitsbergen (Forman et al., 1987) and at Kapp Wijk in Isfjorden (Feyling-Hanssen, 1955); cf. Fig. 1 for locations. Also in Nordaustlandet, at the island Nordre Russøya in Murchinsonfjorden (Fig. 1), the location of a Russian hunting station built in the late 1700, was levelled at only 0.8 m above the highest tide in 1958, and suggests a sea level rise since the settlement was built (Blake, 1961). Stratigraphic evidence for this transgression includes thousand-year-old driftwood anchored in sediments about 1 m below mean tide level at the head of Bockfjorden (Salvigsen and Høgvard, 2005), and present-day beach gravel found on top of 2000-yr-old peat (Fig. 1) (Forman, 1990). The observations of the transgression in northwestern Spitsbergen were published many years ago, and were explained by Vogt (1927, 1932) as a result of isostatic subsidence due to the Late Holocene growth of the glaciers.

Farther east and south on Svalbard the situation is the opposite; the sea level curves show emergence over the last 2000 yr. Sea level curves from both Hopen and Kongsøya in eastern Svalbard (Fig. 1) show a recent relative uplift of 3 and 4.5 mm/yr, respectively (cf. Table 2). Hoppe et al. (1969) observed that in a zone between 2.5 and 4.4 m above the local driftwood limit on Hopen the stranded driftwood had saw-cut logs obviously made by humans. In this zone they also identified logs belonging to wooden Russian ships ("Lodjas" type) probably used for hunting on Svalbard some 300–500 years ago. This change in behavior from east to west

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https://doi.org/10.1016/j.quascirev.2018.09.003
0277-3791/

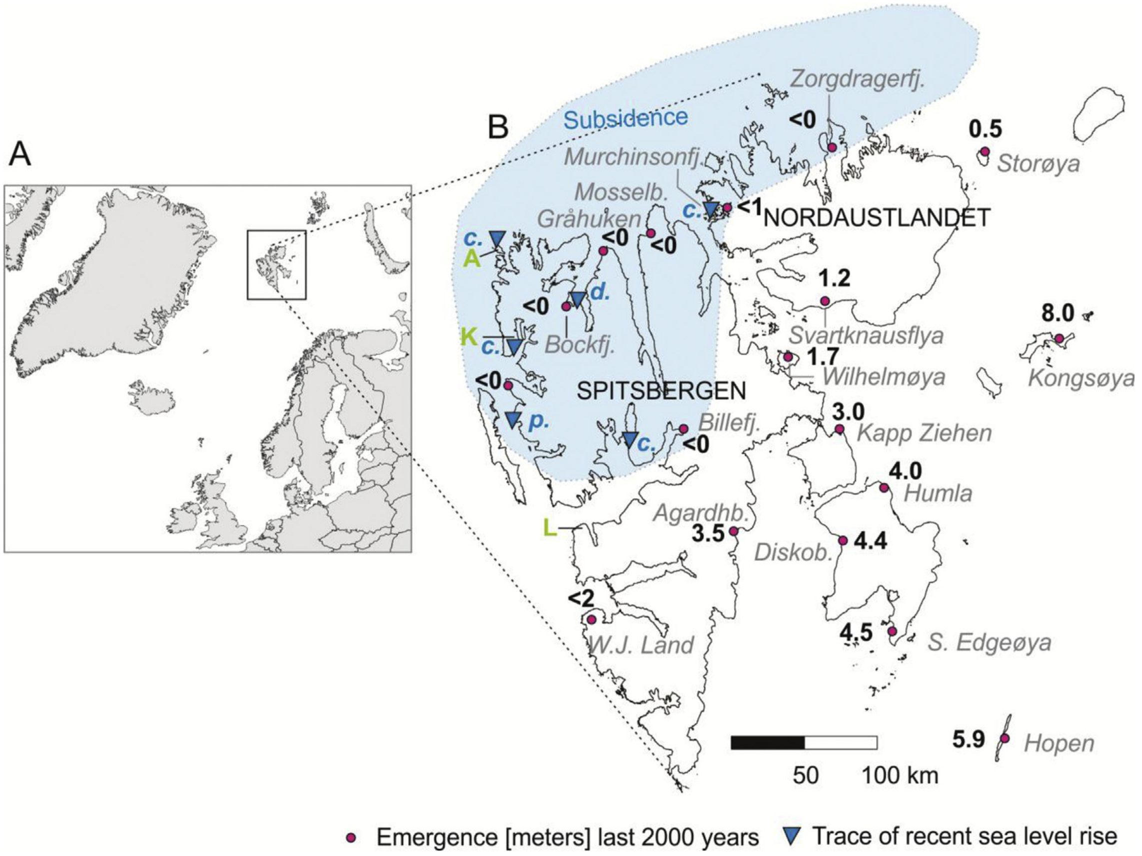

Fig. 1. Observed emergence and submergence (black numbers in meters) of Svalbard (location in A) over the last 2,000 years relative to modern sea level deduced from sea level curves (B). In the northwest (blue shaded) the emergence is negative (submergence) with evidence of a recent transgression: p. = peat below shore gravel, c. = coastal erosion of cultural remains and d. = driftwood stuck in sediments below mean tide level. A = Annabreen glacier (absent 8,400-1,000 cal yr BP), K = Karlbreen glacier (absent 9,200-3,500 cal yr BP) and Linnébreen glacier (absent 9,300-3,000 cal yr BP). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

excludes eustasy as the driving mechanism, and is evidently caused by movements of the solid earth.

Evidence of decreased or absent glaciers comes from two sources: sediments in lakes downslope of present-day glaciers, and beaches and other sediments containing marine shells or vegetation that were overrun by advancing glaciers in the Late Holocene. At the coast of western Spitsbergen the sediments in proglacial lakes revealed the total disappearance of glaciers in their catchments between ca. 9,000-3,000 cal yr BP. See Fig. 1 for locations (Linnébreen; Svendsen and Mangerud, 1997; Karlbreen; Røthe et al., 2015; Annabreen; de Wet et al., 2017). Glacially overridden vegetation and beaches are known from both Spitsbergen (*e.g.* Humlum et al., 2005; Salvigsen and Høgvard, 2005) and eastern Svalbard (*e.g.* Jonsson, 1983; Ronnert and Landvik, 1993; Blake, 1989). Most glaciers on Svalbard reached their maximum Holocene extent by the termination of the Little Ice Age in the beginning of the 1920s (Hagen et al., 2003). Today the largest glaciers can in places exceed a thickness of 500 m (Dowdeswell et al., 1986).

The modeling takes into account the entire glaciation history, from the Last Glacial Maximum (LGM, 20,000 cal yrs BP) of the Svalbard-Barents Sea and Scandinavian ice sheets (the Eurasian ice sheet) until today. We compare the output of the glacial isostatic modeling to the observed sea level at 2,000 yr and 6,000 cal yr BP, and test different scenarios for ice growth in the Holocene against these observations. We have used an Earth model with a low viscosity asthenosphere and a weak elastic lithosphere, but other Earth models are also tested and compared to the sea level observations.

2. Methods

2.1. Late- and post-glacial ice sheet model

Our deglaciation model of the Eurasian ice sheet follows the spatial reconstructions of Hughes et al. (2016) from 20,000 to 12,000 cal yr BP. This was not subject to any change in this study. Ice thicknesses were calculated independently from the glacial isostatic modeling, and based on the Glen-Nye flow law and a long term balance ratio between ablation and accumulation gradients (for more details about the model cf. Appendix). Fig. A1 shows the extent and thickness of the modeled Eurasian ice sheets through the deglaciation, from 20,000 to 12,000 BP. This ice sheet configuration is called the AA2 model. Hughes et al. (2016) present maximum and minimum scenarios for 10,000 cal yr BP. The minimum scenario is that Svalbard was completely deglaciated 10,000 years ago; their maximum scenario is equal to present Svalbard glaciers.

2.2. Earth model

The Earth's isostatic response to the load of the changing sea level and glaciers is here modeled by using a high resolution flat Earth model with three layers (Table 1). The top layer is the elastic lithosphere, which overlies the viscous asthenosphere. The lowest layer is the uniform mantle with a viscosity of 10^{21} Pa s. The spatial resolution in the model is 10 km; this high resolution, compared to a global model, is a requirement in order to do the detailed modeling of the isostatic response to the changes of the Holocene