Quaternary Science Reviews 197 (2018) 142–161

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Holocene mountain glacier history in the Sukkertoppen Iskappe area, southwest Greenland

Avriel D. Schweinsberg [a, *], Jason P. Briner [a], Gifford H. Miller [b], Nathaniel A. Lifton [c, d], Ole Bennike [e], Brandon L. Graham [a]

[a] Department of Geology, University at Buffalo, Buffalo, NY, 14260, USA
[b] Department of Geological Sciences, University of Colorado, Boulder, CO, 80309, USA
[c] Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN, 47906, USA
[d] Department of Physics and Astronomy, Purdue University, West Lafayette, IN, 47906, USA
[e] Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350, Copenhagen k, Denmark

A R T I C L E I N F O

Article history:
Received 21 March 2018
Received in revised form
11 June 2018
Accepted 12 June 2018

Keywords:
Greenland
Holocene
Glacier fluctuations
Lake sediment
Cosmogenic *in situ* ^{14}C
Neoglaciation

A B S T R A C T

Mountain glaciers and ice caps (GIC) independent of the Greenland Ice Sheet respond rapidly to climate variations and records of their past extent provide information on the natural envelope of climate variability. Here, we use a multi-proxy approach that combines proglacial lake sediment analysis, cosmogenic nuclide surface-exposure dating (*in situ* ^{10}Be and ^{14}C), and radiocarbon dating of recently ice-entombed moss to generate a centennial-scale record of Holocene GIC fluctuations in southwestern Greenland. Following local deglaciation ~10-9 ka, sediments from proglacial Crash Lake record a glacier advance at ~9 ka that is indistinguishable from nearby ice sheet moraines, implying a synchronous response of GIC and the Greenland Ice Sheet to a centennial-scale climate event. Following this local glacier advance, GIC experienced net recession until ~4.6 ka. Radiocarbon ages of *in situ* moss ($n = 29$) and Crash Lake sediments reveal intervals of glacier expansion at ~1.8, 1.2 and 0.7 ka that are superimposed on an overall trend of net glacier expansion throughout the late Holocene. *In situ* ^{14}C concentrations from bedrock adjacent to radiocarbon-dated moss samples further constrain the duration of ice cover through the Holocene in this region. We find that our glacier-size proxy records during the past ~4 ka are broadly consistent with relatively lower temperatures recorded in GISP2 and occur during, or following, intervals of volcanic perturbations. Thus, we speculate that volcanic activity, although less frequent and intense than in the early Holocene and during the Little Ice Age, may have led to centennial-scale variability imprinted on net glacier expansion due to decreasing summer insolation through the late Holocene.

1. Introduction

Progressive cooling throughout the Holocene in the Northern Hemisphere, primarily driven by a gradual reduction in summer insolation, has been punctuated by multi-decadal to millennial-scale climate variability (e.g., Mayewski et al., 2004; Wanner et al., 2008, 2011; Marcott et al., 2013; Solomina et al., 2015; Kobashi et al., 2017). Numerous studies document short-lived Holocene climate perturbations in terrestrial and marine archives in the Arctic and North Atlantic regions (e.g., Kobashi et al., 2011; Larsen et al., 2012; Miller et al., 2013a; b; Geirsdóttir et al., 2013; Axford et al., 2009; Balascio et al., 2015; Schweinsberg et al., 2017), yet the spatio-temporal patterns of these climate changes and the forcing mechanisms that drive this variability remain under debate. Recent summaries (Wanner et al., 2008, 2011) suggest that a complex interaction of factors likely influenced Holocene climate, including Atlantic Meridional Overturning Circulation (AMOC) variability (McManus et al., 2004), meltwater forcing (Clark et al., 2001), solar irradiance (Bond et al., 2001; Wiles et al., 2004), explosive volcanism (Miller et al., 2012; Geirsdóttir et al., 2013; Kobashi et al., 2017), and internal unforced dynamics (Trouet et al., 2009), with increasing evidence for abrupt (Mayewski et al., 2004) and periodic (Denton and Karlén, 1973; Bond et al., 2001) climate changes. Additional high-resolution archives of climate fluctuations

* Corresponding author.
E-mail address: avrielsc@buffalo.edu (A.D. Schweinsberg).

https://doi.org/10.1016/j.quascirev.2018.06.014
0277-3791/

with vast spatial coverage are necessary to discern the leading mechanisms driving sub-millennial Holocene climate variability (Mayewski et al., 2004).

Although contemporary observations are critical for understanding the current mechanisms driving glacier behavior, geological reconstructions of mountain glacier and ice cap (GIC) fluctuations that extend beyond the instrumental period place constraints on the magnitudes of glacier responses to climate forcings, and illustrate the spatio-temporal variability of past climate. GIC are ideal for paleoclimatic reconstructions because they respond rapidly to small changes in glacier mass balance, and their records often preserve small-scale climatic signals, which are useful indicators of regional and global climatic changes (Oerlemans, 2005; Bakke et al., 2005). GIC reconstructions from the North Atlantic region demonstrate that GIC record centennial-scale climate variability superimposed on the millennial-scale insolation-driven cooling trend (Larsen et al., 2012; Geirsdóttir et al., 2013; Balascio et al., 2015). The non-linear nature of these sub-millennial-scale changes reflects both complex interactions in response to declining insolation, and the presence of additional climate drivers or strong local to regional feedbacks operating on varying timescales (Larsen et al., 2012; Geirsdóttir et al., 2013). Past centennial-scale variations in GIC extent have been linked to changes in ocean circulation in West and East Greenland (Balascio et al., 2015; Levy et al., 2014; Schweinsberg et al., 2017) and Iceland (Larsen et al., 2012). However, changes in ocean circulation have been attributed to solar forcing (Bond et al., 2001; Moffa-Sanchez et al., 2014; Jiang et al., 2015) and some modeling studies have confirmed that AMOC can switch between distinct modes in response to a small external forcing, such as solar variability (Jongma et al., 2007). Alternatively, late Holocene GIC fluctuations in Iceland (Larsen et al., 2011; Geirsdóttir et al., 2013), Baffin Island (Anderson et al., 2008; Miller et al., 2012), and on Disko island, West Greenland (Jomelli et al., 2016), suggest that periods of cooler temperatures (and glacial advances) are influenced by explosive volcanism and associated sea-ice/ocean feedbacks. Recently, volcanic forcing has been postulated as a driver of Holocene temperature fluctuations reconstructed from Greenland ice cores (Kobashi et al., 2017). In general, many studies postulate that sub-millennial scale Holocene climate variability was likely driven by a combination of mechanisms, yet regional discrepancies illustrate the ongoing need for additional continuous sub-millennial scale glacier and paleoclimate archives.

Few Holocene glacier records with centennial-scale resolution exist because in locations such as Greenland, extensive glacier advances during the last few hundred years commonly destroyed the geomorphic evidence of former glacier activity earlier in the Holocene (Gibbons et al., 1984; Kelly and Lowell, 2009). The majority of information on past local glacier activity in Greenland is fragmentary and primarily concerned with the timing of maximum extent and rates of twentieth century retreat (e.g., Citterio et al., 2010; Bjørk et al., 2012; Rastner et al., 2012; Bolch et al., 2013). Thus, little is known about local glacier evolution throughout the Holocene (Kelly and Lowell, 2009). Only a few studies have provided continuous records of Holocene mountain glacier fluctuations in East Greenland (Lowell et al., 2013; Levy et al., 2014; Balascio et al., 2015) and West Greenland (Fig. 1; Larsen et al., 2017; Schweinsberg et al., 2017).

In this study, we reconstruct Holocene GIC fluctuations at the centennial-scale in southwestern Greenland to 1) investigate the synchrony of GIC response to Holocene climate variability, and 2) explore climate forcing mechanisms that may have driven local glacier change during the Holocene. To achieve these objectives, we reconstruct GIC change in the Sukkertoppen region of southwest Greenland using proglacial lake sediment analysis, radiocarbon dating of formerly ice-entombed *in situ* moss, and cosmogenic nuclide exposure dating of erratics (*in situ* ^{10}Be) and bedrock (*in situ* ^{14}C). We compare our glacier reconstructions with previously published local glacier records in the North Atlantic region and nearby Greenland Ice Sheet (GrIS) margin chronologies. Combined, the reconstructions reported here provide a comprehensive view of GIC change throughout the Holocene in the Sukkertoppen region of southwest Greenland, and complement the instrumental records by providing a longer temporal context within which to interpret the magnitude and rate of recent GIC changes (Marcott et al., 2013).

2. Study area

Local glaciers in the study region include the Sukkertoppen Iskappe (~2000 km^2, average thickness of ~300 m) and associated valley glacier outlets, a second large ice cap, Qaarajuttoq (~2000 km^2), and the nearby ice caps and mountain glaciers on uplands from Søndre Isortoq to Søndre Strømfjord (Figs. 1 and 2; Weidick et al., 1992; Kelly and Lowell, 2009). The region is located between the coastline of Davis Strait and the western GrIS margin located ~200 km to the east. Sukkertoppen Iskappe and Qaarajuttoq, as well as the other nearby GIC, rest atop large, relatively flat plateaus that are dissected by Søndre Strømfjord, Evighedsfjord, and Søndre Isortoq, resulting in mountainous alpine topography that rises to more than 1700 m asl. These areas of high terrain support weathered bedrock tors and blockfields (felsenmeer) above presently glaciated terrain (Kelly, 1985), which have been utilized to decipher the long-term glacial history of the area (Beel et al., 2016; Strunk et al., 2017). The research area is underlain by Precambrian gneisses and granitic rocks with numerous intrusions of basaltic and diabasic dikes (Loewe et al., 1962; Henriksen, 2008). Many glaciers flow into the large glacial troughs that dissect the region, which routed inland ice streams to the coast and onto the continental shelf during previous expansions of the GrIS (Roberts et al., 2009, 2010).

3. Previous work in the Sukkertoppen region

Previous work in the Sukkertoppen region has primarily focused on reconstructing fluctuations of the GrIS margin from the Last Glacial Maximum (LGM; 26-19 ka; Clark et al., 2009) to present (Funder et al., 2011) with few studies on local glacier change. In our field area, the LGM ice margin likely extended to the continental shelf edge ~100 km offshore from the present coastline (Funder et al., 2011; Vasskog et al., 2015; Winsor et al., 2015b), and GIC across the Sukkertoppen area coalesced with the GrIS (Weidick, 1968).

Chronological data suggest that the GrIS margin reached the present day outer coastline between ~15 and 10 ka in areas to the north and south of the study region (Bennike and Björck, 2002; Larsen et al., 2014; Kelley et al., 2015; Winsor et al., 2015a; b). Several discontinuous moraine systems are preserved between the coast and the present-day margin of the GrIS indicating that retreat of the western GrIS margin during the Holocene was punctuated by stillstands or readvances (Weidick, 1968; Ten Brink, 1975; Kelly, 1985; Lesnek and Briner, 2018). Recently, the ages of two GrIS moraine belts preserved in the Sukkertoppen area were identified using ^{10}Be-dating; the western and eastern moraines belts are dated to ~9.8 ± 0.7 ka and 9.0 ± 0.3 ka, respectively (Lesnek and Briner, 2018). These results suggest that many of the southern and eastern outlets of Sukkertoppen Iskappe and Qaarajuttoq may have been confluent with the GrIS during the early Holocene (Weidick, 1968; Lesnek and Briner, 2018). As a result, differentiating the deposits associated with local glaciation prior to this time is complex in the study region (Weidick, 1968).