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Local glaciation in West Greenland linked to North Atlantic Ocean circulation during the Holocene

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ABSTRACT

Recent observations indicate that ice-ocean interaction drives much of the recent increase in mass loss from the Greenland Ice Sheet; however, the role of ocean forcing in driving past glacier change is poorly understood. To extend the observational record and our understanding of the ocean-cryosphere link, we used a multi-proxy approach that combines new data from proglacial lake sediments, ^{14}C-dated *in situ* moss that recently emerged from beneath cold-based ice caps, and ^{10}Be ages to reconstruct centennial-scale records of mountain glacier activity for the past ~10 k.y. in West Greenland. Proglacial lake sediment records and ^{14}C dating of moss indicate the onset of Neoglaciation in West Greenland at ca. 5 ka with substantial snowline lowering and glacier expansion at ca. 3.7 ka followed by additional ice expansion phases at ca. 2.9, ca. 1.7, and ca. 1.4 ka and during the Little Ice Age. We find that widespread glacier growth at ca. 3.7 ka in West Greenland coincides with marked cooling and reduced strength of the West Greenland Current in Disko Bugt. The transition to cooler ocean conditions at ca. 3.7 ka identified in Disko Bugt is registered by marine proxy data farther afield in East Greenland and on the northwestern Icelandic shelf, implying large-scale paleoceanographic changes across the North Atlantic during this interval. The similarity between glacier change on West Greenland and multiple marine and terrestrial records across the North Atlantic suggests that glaciers are strongly influenced by changes in ocean circulation and consequently implies that the ocean-cryosphere teleconnection is a persistent feature of the Arctic system.

INTRODUCTION

The behavior of the Greenland Ice Sheet is of critical interest due to its predicted impact on future global sea-level changes and ocean circulation (e.g., Joughin et al., 2012). Whereas the observational record has focused almost exclusively on ice-sheet outlet glaciers, land-terminating glaciers and ice caps in Greenland are highly sensitive to changes in temperature and are rapidly losing mass today (Bolch et al., 2013). Although contemporary observations are critical for understanding the mechanisms driving glacier change, geological reconstructions of former glacier change provide additional data on glacier behavior over longer time scales and during periods that were warmer than present. Glacier reconstructions coupled with paleoceanographic records can provide insight on the influence of the ocean on nearby terrestrial climate, especially through the influence of sea-surface conditions on air temperature (Thomas et al., 2016). Identifying linkages between past glacier change and forcing mechanisms, such as changes in ocean circulation, can help to predict changes in glacier and ice-sheet behavior.

In the North Atlantic region, continuous records of glacier change have been inferred from lake sediments and used to assess the response of the cryosphere to climate change (e.g., Larsen et al., 2013; Balascio et al., 2015). On Greenland, however, the majority of glacier records are discontinuous and temporally restricted, owing in part to the obliterative nature of glacier expansion during the past few millennia, and in particular, extensive ice advances during the Little Ice Age (LIA; ca. A.D. 1250–1900). In contrast to extensive research on Greenland Ice Sheet margin changes during the Holocene (e.g., Briner et al., 2016), the timing and magnitude of mountain glaciation is relatively unknown (Kelly and Lowell, 2009). Only three studies of ice caps in East Greenland provide continuous records of local glacier change during the Holocene (Lowell et al., 2013; Levy et al., 2014; Balascio et al., 2015).

West Greenland is ideally suited to examine the influence of ocean forcing on past glacier change due to its large number of local glaciers and numerous regional paleoceanographic reconstructions in the adjacent Disko Bugt and Baffin Bay (e.g., Moros et al., 2016). A number of these paleoceanographic studies resolve ocean circulation through the Holocene on decadal to multi-centennial time scales (e.g., Moros et al., 2016). Ocean circulation changes in this region are largely modulated by the strength of the western branch of Atlantic Meridional Overturning Circulation (AMOC), which links the West Greenland Current (WGC) to the North Atlantic climate system (Lloyd et al., 2007). Here, we reconstruct local glacier variability in West Greenland through the Holocene and investigate whether past oceanic variability and glacier change are synchronous at the centennial scale.

APPROACH AND METHODS

We used a multi-proxy approach to generate a detailed record of glacier change throughout the Holocene in West Greenland by combining (1) proglacial lake sediment analysis, (2) ^{14}C dating of formerly ice-entombed *in situ* moss, and (3) ^{10}Be dating of erratics and late Holocene moraines. We targeted small glaciers and ice caps independent of the Greenland Ice Sheet because they respond rapidly to changes in mass balance (Oerlemans, 2005) and can therefore be used for high-resolution paleoclimate reconstructions.

We cored Sikuiui Lake on the Nuussuaq peninsula to capture a clear sedimentary record of glacier activity, because the close proximity of the Qangattaq ice cap to the lake results in minimal sediment transport distance, and the small size of the ice cap makes this site particularly sensitive to minor climate variations (Fig. 1A; see the GSA Data Repository[1] for detailed methods, and Fig. DR1). The age-depth model for Sikuiui Lake was developed using 12 ^{14}C-dated macrofossils. We used principal component analysis (PCA) to identify the leading modes of variability among the physical parameters (magnetic susceptibility [MS], density, organic matter content) and elemental data from Sikuiui Lake sediments. PCA results indicate that there is one strong primary trend in the lake sediment data (PC1) accounting for 56% of the total variance.

[1]GSA Data Repository item 2017051, materials and methods, Figures DR1–DR7, and Tables DR1–DR5, is available online at www.geosociety.org/datarepository/2017 or on request from editing@geosociety.org.

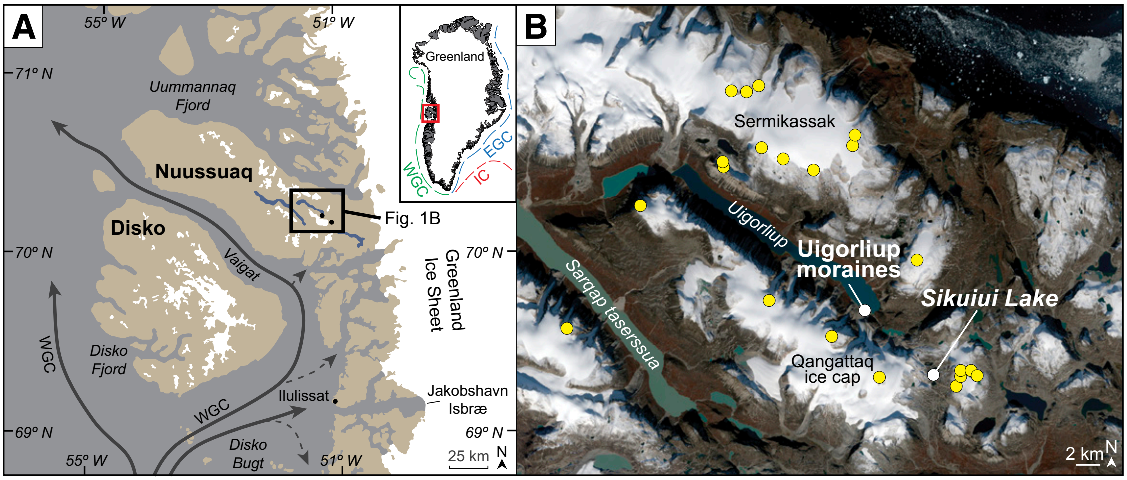

Figure 1. A: Central West Greenland; West Greenland Current (WGC) is depicted after Perner et al. (2013). Inset map shows Greenland and relative locations of WGC, East Greenland Current (EGC), and Irminger Current (IC). B: Eastern Nuussuaq showing tundra moss sample sites (yellow dots; see Data Repository [see footnote 1] for map of all sites), Sikuiui Lake, and Uigorliup moraines.

Trends in PC1 are similar to those in MS and density, parameters typically used to reconstruct glacier extent (e.g., Bakke et al., 2005; Røthe et al., 2015), and support the use of PC1 to represent changes in the lake record.

We obtained 54 ^{14}C ages of *in situ* moss from 22 different ice caps across an elevation range of 760–1500 m above sea level (asl) to examine the timing of Holocene ice expansion in West Greenland (Fig. DR7 and Table DR5 in the Data Repository). We sampled recently exposed moss along cold-based sectors of polythermal ice caps following Miller et al. (2013). We interpret changes in glacier snowline elevation as a proxy for summer temperature change. Furthermore, we interpret clusters of moss ages to represent periods of persistent snowline lowering (Miller et al., 2013; Margreth et al., 2014). Gaps in the moss chronology are interpreted to represent lack of ice growth, which could reflect retracted ice due to regional warming, a stagnant ice margin under stable climate conditions, or local phenomena related to glacier dynamics (Margreth et al., 2014). Following these interpretations, we expect PC1 scores from Sikuiui Lake, which track fluctuations in glacier erosion and dimension, to peak decades to centuries after age clusters in the moss data set, which date the onset of summer cooling.

Samples were collected for ^{10}Be dating from large, stable erratics perched on bedrock to determine the timing of regional deglaciation (n = 5; Fig. DR1; Table DR3). Nine recently published ^{10}Be ages from a late Holocene moraine sequence in a nearby valley (Fig. 1; Table DR3; Young et al., 2015) are compared to the lake-sediment and moss records. All ^{10}Be ages are calculated using the locally calibrated Baffin Bay production rate (Young et al., 2013b; see the Data Repository).

FLUCTUATIONS OF LOCAL GLACIERS IN WEST GREENLAND

The average ^{10}Be age of five erratics indicates that deglaciation of inner Nuussuaq occurred at ca. 10.5 ± 0.3 ka (Table DR3). The transition from basal mineral-rich sediments to gyttja at ca. 9.4 ka in Sikuiui Lake places a minimum constraint on the timing of local ice-cap disappearance or significant reduction in size (see the Data Repository). An interval of increased mineral-rich input punctuates the organic-rich sediments in the Sikuiui Lake record between ca. 8.8 and 8.0 ka (Fig. 2A) and may reflect a brief interval of early Holocene cooling and glacier readvance correlative with the deposition of nearby ice-sheet moraines (Cronauer et al., 2016). This glacier readvance may also relate to the 8.2 ka event (e.g., Alley et al., 1997), as has been suggested for fluctuations of Jakobshavn Isbræ (Young et al., 2013a) and local glaciers in southeast Greenland (Balascio et al., 2015).

Between ca. 7.5 and 5 ka, during the regional Holocene Thermal Maximum (Briner et al., 2016), glaciers on Nuussuaq were at a reduced extent as inferred from relatively low PC1 scores in the Sikuiui Lake record, with the possible exception of a thin mineral-rich unit that may represent a brief glacier advance at ca. 5.7 ka (Fig. 2A). ^{14}C ages of *in situ* mosses reveal that net snowline lowering and summer cooling began at ca. 5 ka (Fig. 2B). Widespread ice expansion at ca. 3.7 ka is inferred from the large number of ^{14}C ages (n = 17) in the moss data set (Fig. 2B). These samples were collected across 15 different ice caps at elevations from 800 to 1420 m asl, suggesting that the snowline lowered significantly across central West Greenland during this interval. This mode of persistent summer cooling at ca. 3.7 ka in the moss chronology occurs just prior to the highest PC1 scores in the Sikuiui Lake record, which we interpret to represent a glacier advance in response to snowline lowering (Fig. 2). Similarly, Sikuiui Lake PC1 scores reflect a glacier advance following snowline lowering at ca. 1.4 ka (Fig. 2A). These cooling episodes are recorded by two independent glacier-size proxies and strengthen our interpretation of significant summer cooling at ca. 3.7 ka and ca. 1.4 ka in central West Greenland. Other intervals of snowline lowering and ice expansion across the study region occurred at ca. 2.9 ka, ca. 1.7 ka, and during the LIA, evidenced by modes of ^{14}C ages in the moss chronology and increased mineral-rich sediment flux to Sikuiui Lake (Figs. 2A and 2B).

The mean ^{10}Be ages of nested moraines in the Uigorliup Lake valley date to 1.1 ± 0.2 ka (n = 3), 1.2 ± 0.3 ka (n = 3), and 0.9 ± 0.03 ka (n = 3) for the distal, intermediate, and proximal positions, respectively (Young et al., 2015). The moraines record extensive ice, but minor net retreat, during the Medieval Warm Period (MWP) and date between ^{14}C age clusters of *in situ* moss at ca. 1.4 cal. (calendar) yr B.P. and the LIA, and synchronously with elevated PC1 scores in Sikuiui Lake (Figs. 2A–2C). Radiocarbon dating of *in situ* moss from Baffin Island also reveal a hiatus during the deposition of the Uigorliup moraines, which was interpreted as evidence of oscillating or retreating ice corresponding to the MWP (Miller et al., 2012). The relationship between ^{10}Be ages and the ^{14}C moss chronology developed here illustrates that gaps in the moss chronology may reflect minor ice-margin recession during the MWP following an earlier ice advance (prior to ca. 1.2 ka).

DISCUSSION

Local glacier reconstructions from West Greenland record centennial-scale episodes of summer cooling and glacier advance coeval with changes in regional ocean circulation during the past ~6 k.y. (Fig. 2). During the mid-to late Holocene transition, the WGC weakened and cooled (e.g., Moros et al., 2016). This is reflected by an increased abundance of sea ice–associated diatoms at ca. 4.1–3.8 ka (Moros et al., 2006), a sharp decrease in Atlantic water (warm) indicator species at ca. 4.0–3.0 ka (Perner et al., 2013), and a marked decrease in WGC strength, and therefore northward advection of ocean heat content, at ca. 4.0 ka (Fig. 2H; Perner et al., 2013). The cooling of the WGC likely resulted from a weaker Irminger Current (IC)

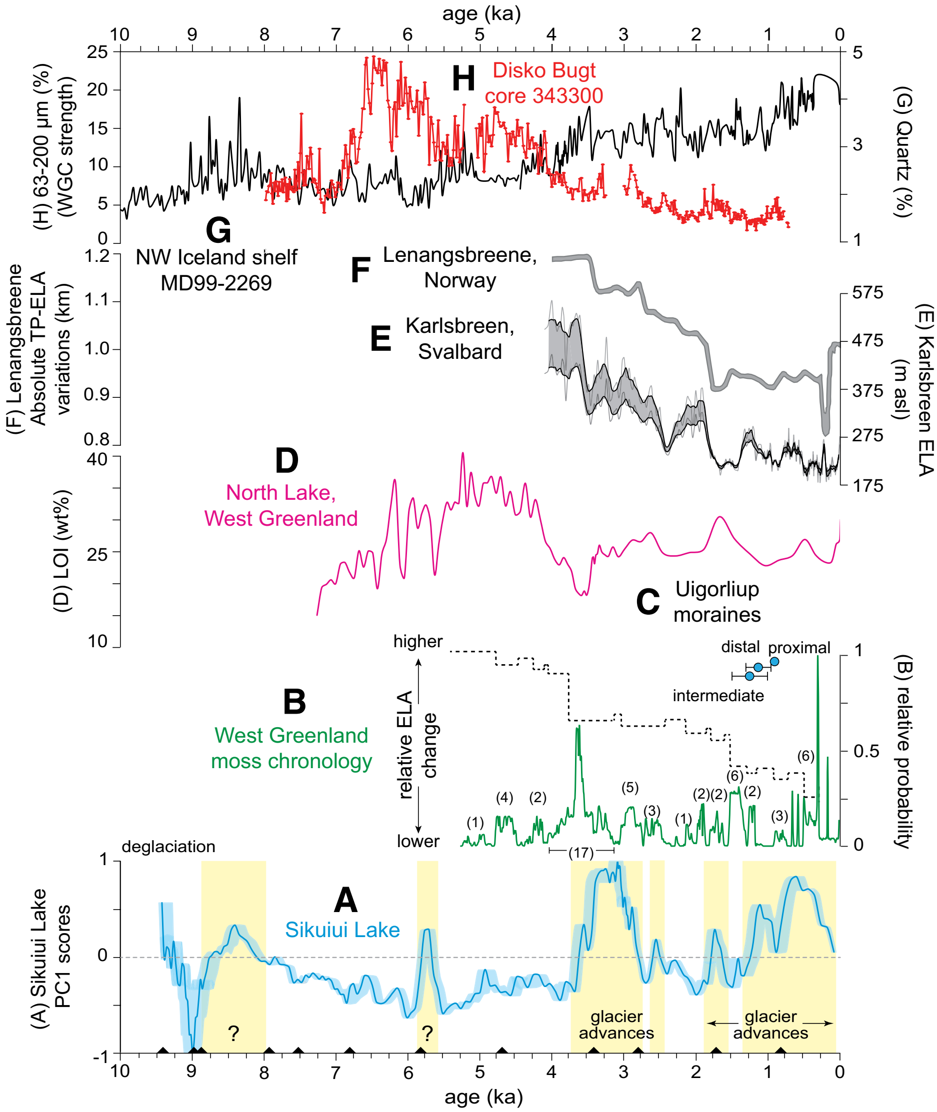

Figure 2. West Greenland glacier records compared with other regional data sets. Yellow panels indicate West Greenland glacier advances; our interpretations are less certain before ca. 5 ka when moss record begins. A: Principal component analysis PC1 scores from Sikuiui Lake (blue; shading = 95% age uncertainty; triangles show locations of ^{14}C ages). B: Aggregated probability density function for 54 ^{14}C ages of mosses from study area; number of dated samples in each cluster shown in parentheses. Dashed line represents relative equilibrium-line altitude (ELA) change (see Data Repository [see footnote 1]). C: Mean ages (blue circles) and 1σ uncertainty of Uigorliup moraines (Young et al., 2015). D: Loss-on-ignition (LOI) record from North Lake, West Greenland (Axford et al., 2013). E: ELA variations from Karlsbreen, Svalbard (asl—above sea level) (Røthe et al., 2015). F: Absolute TP-ELA variations from Lenangsbreene, Norway (Bakke et al., 2005). G: Drift ice proxy data (% quartz) from core MD99–2269 (IMAGES V cruise, Leg 3, to the Nordic Seas), northwest Iceland (Moros et al., 2006). H: West Greenland Current (WGC) strength proxy from core 343300 (cruise MSM05/03 of the R/V *Maria S. Merian*), Disko Bugt, West Greenland (sand content [% fraction 63–200 µm); Perner et al., 2013).

and/or stronger East Greenland Current (EGC) and coincides with increased deposition of ice-rafted debris off southeast Greenland (e.g., Jennings et al., 2011). Snowline lowering and ice expansion at ca. 3.7 ka is nearly identical in timing with the transition to colder conditions recorded in Disko Bugt. Colder and drier conditions during this interval are also documented by terrestrial records in West Greenland, including relatively low lake levels in the Kangerlussuaq area (south of the study area) (Aebly and Fritz, 2009) and decreased organic matter values from ca. 4.3 to 3.2 ka from maritime lakes adjacent to Disko Bugt (Fig. 2D; Axford et al., 2013). A Holocene hydrogen isotope record from a maritime lake adjacent to Disko Bugt suggests cooler conditions and decreased winter snowfall during this period, likely caused by increased sea-ice cover and cooler regional surface ocean temperatures (Thomas et al., 2016).

Ocean conditions reconstructed from Disko Bugt sediments after ca. 3.0 ka are variable. However, dinocyst assemblage data indicate cool ocean conditions at ca. 1.7–1.5 ka that are contemporaneous with the timing of glacier expansion in our dataset (Perner et al., 2013; Ouellet-Bernier et al., 2014). Indistinguishable ^{10}Be ages between late Holocene moraines on Baffin Island and the Uigorliup moraines suggests a synchronous culmination of glacier advances in response to a common regional climate forcing over Baffin Bay (Young et al., 2015).

Geological records across the North Atlantic region reveal ice expansion episodes synchronous with glacier advance at ca. 3.7 ka in West Greenland, supporting a broader connection between North Atlantic Ocean circulation and the adjacent cryosphere. Sea-surface cooling associated with increased sea-ice extent and a stronger EGC is documented on the East Greenland shelf at ca. 3.8 ka (Jennings et al., 2002) and on the northwest Icelandic shelf at ca. 4.5–3.5 ka (Fig. 2G; Moros et al., 2006). Equilibrium-line altitude reconstructions of glaciers from Norway and Svalbard record cooling between 4.0 and 3.5 ka (Figs. 2E and 2F; Bakke et al., 2005; Røthe et al., 2015). Glacier expansion at ca. 3.7 ka and ca. 1.4 ka in West Greenland is synchronous with ice-cap advances in Svalbard, where *in situ* mosses have been dated to between ca. 4.0 and 3.4 ka and between ca. 1.7 and 1.0 ka (Miller et al., 2017), which occurs only a few centuries after the flux of warm Atlantic water reached minimum levels for the entire Holocene (Ślubowska-Woldengen et al., 2007). In addition, late Holocene glacier expansion documented in West Greenland is similar in timing to ice advances on Baffin Island at ca. 1.5 ka (Thomas et al., 2010; Miller et al., 2013; Margreth et al., 2014), in Iceland at ca. 2.9 and ca. 1.4 ka (e.g., Larsen et al., 2013), and at ca. 2.8 ka and ca. 1.3 ka in southeast Greenland (Balascio et al., 2015).

Our glacier reconstruction from West Greenland, combined with existing terrestrial and marine records from around the North Atlantic, pinpoint a strong connection between glacier change and variations in ocean circulation during the Holocene. However, to fully implicate a North Atlantic circulation influence on glaciation, one would need to examine detailed glaciation histories throughout the Northern Hemisphere, particularly in regions far removed from the influence of AMOC. At present, this objective is complicated by a lack of continuous centennial-scale glacier records.

CONCLUSIONS

This multi-proxy glacier reconstruction approach yields the first continuous centennial-scale record of Holocene local glacier change in West Greenland and provides details not achievable with a single proxy. Our data reveal net glacier growth beginning at ca. 5 ka in West Greenland and subsequent glacier expansion episodes at ca. 3.7, 2.9, 1.7, and 1.4 ka and during the LIA. A major episode of glacier expansion at ca. 3.7 ka coincides with the transition to colder ocean conditions in the Disko Bugt and other North Atlantic marine records, suggesting that ocean circulation variability is strongly connected to glacier change in West Greenland. The late Holocene synchronicity of centennial-scale mountain glacier change throughout the North Atlantic region suggests a response to a common forcing mechanism, and paleoceanographic reconstructions demonstrate that fluctuations in ocean circulation may have played an important role.

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