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The response of the southern Greenland ice sheet to the Holocene thermal maximum

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ABSTRACT

To determine the long-term sensitivity of the Greenland ice sheet to a warmer climate, we explored how it responded to the Holocene thermal maximum (8–5 cal. kyr B.P.; calibrated to calendar years before present, i.e., A.D. 1950), when lake records show that local atmospheric temperatures in Greenland were 2–4 °C warmer than the present. Records from five new threshold lakes complemented with existing geological data from south of 70°N show that the ice margin was retracted behind its present-day extent in all sectors for a limited period between ca. 7 and 4 cal. kyr B.P. and in most sectors from ca. 1.5 to 1 cal. kyr B.P., in response to higher atmospheric and ocean temperatures. Ice sheet simulations constrained by observations show good correlation with the timing of minimum ice volume indicated by the threshold lake observations; the simulated volume reduction suggests a minimum contribution of 0.16 m sea-level equivalent from the entire Greenland ice sheet, with a centennial ice loss rate of as much as 100 Gt/yr for several millennia during the Holocene thermal maximum. Our results provide an estimate of the long-term rates of volume loss that can be expected in the future as regional air and ocean temperatures approach those reconstructed for the Holocene thermal maximum.

INTRODUCTION

Predictions of future climate suggest that the Arctic region may warm by 2–7 °C by C.E. 2100 (Common Era), accelerating the melting of the Greenland ice sheet (GIS) with a resultant increase of 0.05–0.25 m in mean global sea level (Church et al., 2013). However, estimates of the GIS response to future warming are limited by the short interval for which we have detailed observations of the ice sheet behavior; this is reflected in the wide range of future scenarios (Robinson et al., 2012). Accordingly, it is critical to study former ice marginal and ice volume changes over longer time scales to learn how the ice sheet responded to periods that were warmer than present.

In southern Greenland, the currently ice-free land areas were rapidly deglaciated during the early Holocene, and the ice margin reached a position close to the late Holocene maximum extent ca. 11–7 cal. kyr B.P. (calibrated to calendar years before present, A.D. or C.E. 1950) (Corbett et al., 2011; Hughes et al., 2012; Carlson et al., 2014; Nelson et al., 2014). The retreat of the GIS behind its present extent, in response to Holocene warm events such as the Holocene thermal maximum (HTM) and the Medieval Warm Anomaly, and its return to the Little Ice Age (LIA) maximum extent, are only constrained by few field observations such as threshold lakes and radiocarbon-dated reworked organic material found in Neoglacial moraines (Weidick et al., 2004; Briner et al., 2010; Larsen et al., 2011). However, numerical ice sheet models predict that the GIS reacted most vigorously to the HTM, with ice margins retreating 20–60 km behind their present positions (Lecavalier et al., 2014).

In this study we present five new threshold lake records from southwest and southeast Greenland (Fig. 1), and review a compilation of previously published records constraining the mid-Holocene retreat from southern Greenland at 60–70°N. We compare our results with existing ice sheet models and discuss the plausible climate forcing mechanisms and their implications.

METHODS

We use threshold lake records to investigate when the GIS was significantly retracted behind its present-day ice extent (Briner et al., 2010). The analyzed threshold lakes are all located close to the present ice margin. During periods with ice extents close to the current extent, the lakes received meltwater and gray clayey silt was deposited. As the ice margin retreated behind its present-day position and out of the lake catchment, the clastic-dominated sedimentation was replaced by deposition of brown to dark brown organic-rich gyttja. We used visual inspection in combination with X-ray fluorescence, magnetic susceptibility, and loss on ignition to identify changes from organic to clastic sediment. Samples of terrestrial plant macrofossils and bulk sediment samples were dated and calibrated to calendar years using OxCal 4.2 and IntCal13 (Reimer et al., 2013). A detailed description of the new threshold coring sites, lake records, and

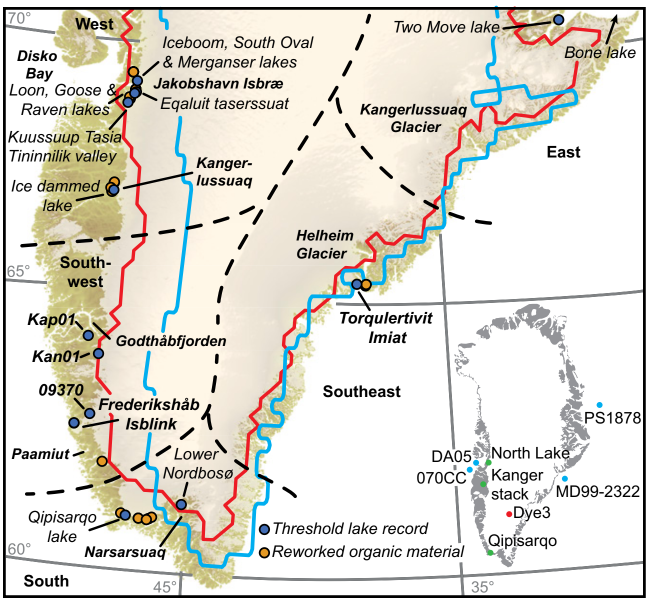

Figure 1. Map of southern Greenland (60–70°N) with locations of threshold lakes and sampled reworked organic material. Inset shows sites mentioned in Figure 3. The solid lines mark the minimum modeled ice marginal extent of the Greenland ice sheet: red line—Huy3 model, 4 cal. kyr B.P. (see text) (Lecavalier et al., 2014); blue line—GrB model, 8 cal. kyr B.P. (Tarasov and Peltier, 2002).

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age models is presented in Figures DR1–DR9 in the GSA Data Repository[1].

RESULTS

New Threshold Lake Records

Four threshold lakes in southwest Greenland were analyzed (Fig. 2). The two records from Godthåbsfjorden, Kap01 and Kan01, show that the ice retreated out of the lake catchments between ca. 8.9 and 8.8 cal. kyr B.P., respectively, and the ice margin only reentered the catchment of Kan01, which is located closest to the present ice margin, ca. 0.4 cal. kyr B.P. Farther south at Frederikshåb Isblink glacier, two records show a complex pattern. In lake 09370, the ice margin retreated out of the lake catchment at ca. 8.2–7.5, 6.5–3.7, and 1.9–0.8 cal. kyr B.P. The other record, from lakes 09354 and 09356, shows a deglacial sequence starting at 11 cal. kyr B.P., after which the ice lobe retreated out of the catchment at ca. 9.7 cal. kyr B.P. Following a long hiatus, most likely caused by a Neoglacial ice advance, the ice lobe was located in the catchment until ca. 1.6 cal. kyr B.P., after which it retracted until ca. 0.55–0.5 cal. kyr B.P. The remaining part of the record is characterized by several fluctuations, suggesting that the ice lobe was close to the threshold of the lake.

In southeast Greenland, at the entrance to Sermilik fjord, which hosts the Helheim Glacier, we have a record from the Torqulertivit Imiat that reveals continued meltwater input to the lake except for a short interval, ca. 7.3–6.3 cal. kyr B.P. However, Torqulertivit Imiat is insensitive to small mass-balance changes, as the small glacier feeding the lake must retreat between 3 and 5 km before it exits the lake catchment.

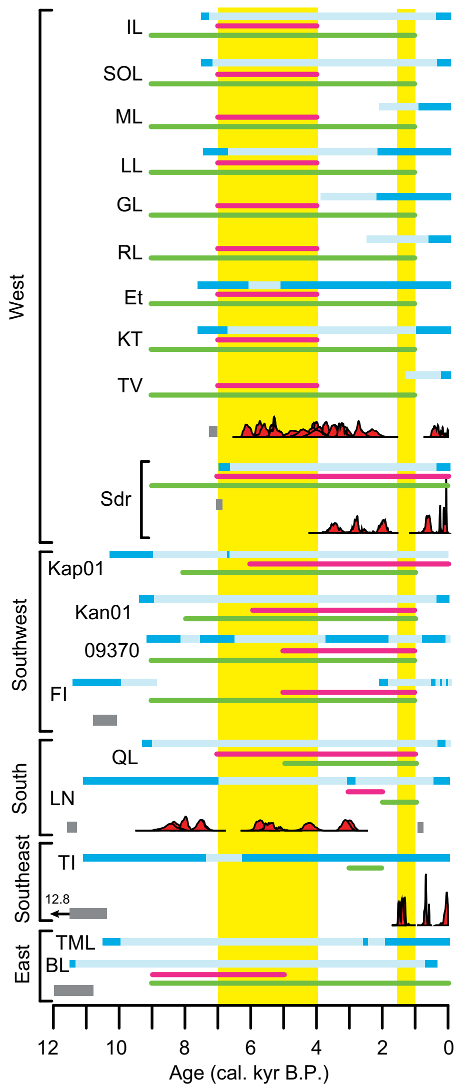

Figure 2. A compilation of threshold lake records, ages of reworked organic material in moraines, and ^{10}Be ages of the deglaciation in southern Greenland (60–70°N). Blue and light blue bars represent periods with glacier margin inside or outside the present lake catchment, respectively. Vertical yellow bars represent periods were the ice margin in all sectors and at most lake sites was retracted behind the present-day extent. Data sources: west Greenland—van Tatenhove et al. (1996), Briner et al. (2010), Corbett et al. (2011), Young et al. (2011), Kelley et al. (2012), Levy et al. (2012), Axford et al. (2013), Carlson et al. (2014), Nelson et al. (2014); southwest Greenland—Larsen et al. (2014); south Greenland—Kaplan et al. (2002), Weidick et al. (2004), Larsen et al. (2011), Carlson et al. (2014), Winsor et al. (2014); southeast Greenland—Roberts et al. (2008); east Greenland—Lowell et al. (2013), Levy et al. (2014). Dark gray bars indicate ^{10}Be deglaciation ages from just outside present-day ice margin (recalculated using the northeast North American ^{10}Be production rate; Young et al., 2013) and red curves are calibrated radiocarbon ages of reworked organic remains in moraines indicating periods with retracted ice margin. The horizontal green (GrB) and red (Huy3) lines represent periods where the models predict ice margin retreat behind the present extent. Abbreviations: IL—Iceboom lake, SOL—South Oval lake, ML—Merganser lake, LL—Loon lake, GL—Goose lake, RL—Raven lake, Et—Eqaluit taserssuat, KT—Kuussuup lake, TV—Tininnilik Valley, Sdr—Søndre Strømfjord (Kangerlussuaq), FI—Frederikshåb Isblink, QL—Qipisarqo lake, LN—Lower Nordbosø, TI—Torqulertivit Imiat, TML—Two Move lake, BL—Bone lake.

Synthesis of Existing Geological Data

In west Greenland, close to Jakobshavn Isbræ, a number of threshold lake records have demonstrated that the ice margin retreated behind the present extent at ca. 7–6.5 cal. kyr B.P., and the ice margin readvanced to the present extent at ca. 2.2, 1–0.8, and 0.2 cal. kyr B.P. (Briner et al., 2010; Young et al., 2011; Kelley et al., 2012). One exception is Eqaluit taserssuat, which was retracted only for a short period from ca. 6 to 5 cal. kyr B.P. (Briner et al., 2010). Reworked organic material from LIA moraines in this area have radiocarbon ages between ca. 6.1 and 0.3 cal. kyr B.P. (Fig. DR9; Table DR2 in the Data Repository). Near Kangerlussuaq (Søndre Strømfjord), the age constraints of the Ørkendal moraine, located a few kilometers in front of the present ice margin, suggest that the ice extent was smaller than that at present from ca. 6.8 to 0.2 cal. kyr B.P. (van Tatenhove et al., 1996; Levy et al., 2012; Carlson et al., 2014). Reworked organic material from LIA moraines near Kangerlussuaq have radiocarbon ages between ca. 3.5 and 0.6 cal. kyr B.P. (Fig. DR9; Table DR2).

In south Greenland, there are two threshold lake records from adjacent to the Qassimiut ice lobe. The Qipisarqo lake record shows that the ice lobe was retracted from ca. 9.1 to 0.4 cal. kyr B.P. (Kaplan et al., 2002), although the age model of the upper part of the core is poorly constrained (Winsor et al., 2014). Reworked organic material from the LIA moraines at the ice lobe reveal radiocarbon ages between ca. 8.5 and 3 cal. kyr B.P. (Fig. DR9; Table DR2). In Lower Nordbosø lake, the ice retreated out of the catchment from ca. 6.9 to 3 cal. kyr B.P. and ca. 2.8 to 0.45 cal. kyr B.P. (Larsen et al., 2011). Cosmogenic exposure ages from Narsarsuaq and Paamiut show a marginally earlier deglaciation than recorded in the threshold lakes (Carlson et al., 2014) and a readvance of a local glacier at ca. 1.51 cal. kyr B.P. (Winsor et al., 2014).

In southeast Greenland, animal and plant remains melted out from beneath the local Mittivakkat glacier, revealing a smaller than present ice extent from ca. 1.6 to 0.4 cal. kyr B.P. (Fig. DR9; Table DR2).

In east Greenland there are no records from the GIS margin, but threshold lake records from the local Istorvet and Bregne ice caps show that the ice margin receded behind its present extent ca. 11.7–0.8 cal. kyr B.P. (Lowell et al., 2013), ca. 10–2.65 cal. kyr B.P., and ca. 2.6–1.9 cal. kyr B.P. (Levy et al., 2014).

DISCUSSION

The threshold lake records from southern Greenland show variability in the ice marginal response to the HTM, but there are some general trends and a regional pattern (Fig. 2). In most sectors, the ice margin began to retreat behind the present ice margin by ca. 10–9 cal. kyr B.P., whereas this stage had not been reached in west Greenland until ca. 7 cal. kyr B.P. (Briner et al., 2010; Corbett et al., 2011; Carlson et al., 2014). The ice margin began to readvance in south-

[1]GSA Data Repository item 2015102, methodology, threshold lake records, and radiocarbon ages of reworked organic material, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

west and south Greenland at ca. 3.8 cal. kyr B.P., and by ca. 2.2 cal. kyr B.P. the ice margin had readvanced to the present extent in all sectors, although some lakes first received glacial meltwater inflow during the LIA ca. 0.4 cal. kyr B.P. (Kaplan et al., 2002; Larsen et al., 2011). Our results show that the ice sheet in southern Greenland was generally smaller and retracted behind the present extent between ca. 7 and 4 cal. kyr B.P. and for most sectors between ca. 1.5 and 1 cal. kyr B.P.

The threshold lake data are compared to two models of the GIS during the last deglaciation; the GrB model (Tarasov and Peltier, 2002) and the Huy3 model (Lecavalier et al., 2014). According to the GrB model, the ice margin in south Greenland retreated behind the present extent from 9 to 1 k.y. ago, except in the southwest and south sector, where it only retreated behind the present ice extent for a short period in the late Holocene (Fig. 2). The misfits between the GrB model and threshold lake observation are significant, particularly in the timing of the initial ice retreat, which according to the model began earlier than recorded in the threshold lakes, and in the lack of model ability to detect the observed Neoglacial ice marginal fluctuations. There is a better agreement between the Huy3 model and threshold lake data in most sectors, in particular concerning the timing of the onset of ice retreat behind the present ice margin, but this model is also unable to detect Neoglacial ice marginal fluctuations. The lack of ability of both models to record ice marginal fluctuations in detail, particularly during the Neoglacial, may reflect that they are largely insensitive to ice marginal changes due to a series of model weaknesses, because both models parameterize poorly constrained forcings to account for the misrepresentation of topographical features and subgrid processes (Lecavalier et al., 2014). Furthermore, model resolution may be too coarse to capture minor ice marginal changes <20 and <25 km, the model grid sizes in the Huy3 and GrB models, respectively. However, as the Huy3 model provides the best fit to the observational data, we use the model output to evaluate the potential response of the GIS. According to the Huy3 model, the ice sheet generally became land based by ca. 10 cal. kyr B.P., after which the GIS reached its minimum extent 4 cal. kyr B.P., when the ice margin had retreated 20–60 km behind its present extent in southwest Greenland, while in other sectors the ice margin remained close to its present extent. This produced a deficit volume of 0.16 m ice-equivalent sea level relative to present for the entire ice sheet at a maximum centennial rate of 103 Gt/yr. This is within the uncertainty of more recent centennial time-scale mass loss rates, inferred from regional climate modeling, of 86 ± 20 Gt/yr during the period C.E. 1865–1990 (Zuo and Oerlemans, 1997), and it is marginally within the uncertainty of observation during the period C.E. 1992–2011 of 142 ± 49 Gt/yr (Shepherd et al., 2012).

We here discuss the observed ice marginal fluctuations in relation to regional centennial- to millennium-scale climate variation in southern Greenland (Fig. 3). The first phase of major ice retreat out of the lake catchments, located several kilometers behind the present-day extent, occurred in all sectors from ca. 7 to 4 cal. kyr B.P.; this coincides with a significant ocean and atmospheric warming. In east and southeast Greenland, two records from the Greenland Sea show that the early Holocene had the highest concentration of planktonic foraminifers indicative of a stronger Atlantic water advection (Telesiński et al., 2013) and the highest and most consistent sea surface temperatures (SSTs) (Jennings et al., 2011). Both records show a decline ca. 5.5–5 cal. kyr B.P. followed by lower SSTs and a significant decrease in the number of planktic foraminifers until the late Holocene. A similar pattern is observed for the middle and late Holocene in the Disko Bay area, west Greenland, where benthic conditions (bottom waters) were relatively warm from ca. 7.0 to 3.7 cal. kyr B.P. (Lloyd et al., 2007; Jennings et al., 2014). Southern Greenland proxy-inferred atmospheric temperatures also peaked between ca. 7 and 4 cal. kyr B.P. at 2–4 °C higher than present, followed by a Neoglacial cooling reaching a minimum during the LIA (Fréchette and de Vernal, 2009; D'Andrea et al., 2011; Axford et al., 2013). The second phase of ice retreat behind the present-day extent in southwest and south Greenland was from ca. 1.5 to 1 cal. kyr B.P., following an early Neoglacial advance, coinciding with a strengthening of Atlantic water advection (Lloyd et al., 2007; Jennings et al., 2011, 2014; Telesiński et al., 2013). It also coincides with a cooling of northwest Europe (i.e., Dark Ages) and might suggest antiphase centennial-scale variability between northwest Europe and southern Greenland, as hypothesized by Winsor et al. (2014).

CONCLUSION

The new threshold lake records presented here, supplemented with the existing geological records, demonstrate that the GIS reached a minimum in south Greenland between ca. 7 and 4 cal. kyr B.P., and for most sectors between ca. 1.5 and 1 cal. kyr B.P. Comparing field data with ice sheet models suggests that ice marginal fluctuations in south Greenland are best resolved by the Huy3 reconstruction (Lecavalier et al., 2014). This agreement supports the conclusion that the GIS had a negative mass balance for several millennia during the HTM and lost ice at centennial rates exceeding 100 Gt/yr. We conclude that this was in response to a combination of atmospheric warming and ocean forcing. However, due to the model resolution,

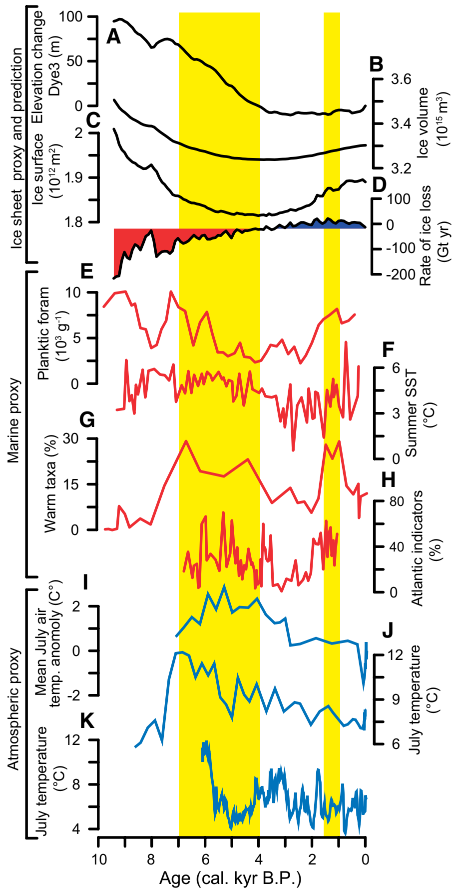

Figure 3. Ice and climate data from southern Greenland (see Fig. 1 for locations). The vertical yellow bars at ca. 7–4 cal. kyr B.P. and ca. 1.5–1 cal. kyr B.P. (see text) represent intervals when the ice margin in all sectors retreated behind the present-day extent. A–D: Predicted ice thinning at Dye3, total ice volume change, total ice surface area, and average centennial predicted rate of mass balance from the optimal Huy3 model (Lecavalier et al., 2014). E–H: Proxy-inferred marine sea-surface temperature (SST) from east and west Greenland. E: Core PS1878 (Telesiński et al., 2013). F: Core MD99–2322 (Jennings et al., 2011). G: Core 070CC (Jennings et al., 2014). H: Core DA05 (Lloyd et al., 2007). I–K: Summer temperature (temp.) reconstruction from local sites close to the present ice margin in south and west Greenland. I: Qipisarqo lake (Fréchette and de Vernal, 2009). J: Kanger stack (D'Andrea et al., 2011). K: North lake (Axford et al., 2013).

which insufficiently resolves fjord complexes and limits ice-ocean interactions, it is possible that the ice sheet is significantly more sensitive to ocean forcings. Considering that model projections suggest that future ocean warming around Greenland may reach almost double the global mean (Yin et al., 2011), and atmospheric temperature will rise by 2–7 °C (Church et al., 2013) by C.E. 2100, the response to the HTM quantified here most likely represents a lower bound on what can be expected in the coming centuries to millennia.

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