Earliest Holocene south Greenland ice sheet retreat within its late Holocene extent

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Key Points:

- South Greenland ice retreated within its near-present margins 11.1-10.6 ka
- South Greenland ice receded inboard of modern extent 3-4 ka earlier than west
- Current south Greenland summer climate may be similar to that of the early Holocene

Supporting Information:

- Readme
- Figure S1
- Figure S2
- Table S1
- Table S2
- Text S1

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Earliest Holocene south Greenland ice sheet retreat within its late Holocene extent

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Abstract Early Holocene summer warmth drove dramatic Greenland ice sheet (GIS) retreat. Subsequent insolation-driven cooling caused GIS margin readvance to late Holocene maxima, from which ice margins are now retreating. We use ^{10}Be surface exposure ages from four locations between 69.4°N and 61.2°N to date when in the early Holocene south to west GIS margins retreated to within these late Holocene maximum extents. We find that this occurred at 11.1 ± 0.2 ka to 10.6 ± 0.5 ka in south Greenland, significantly earlier than previous estimates, and 6.8 ± 0.1 ka to 7.9 ± 0.1 ka in southwest to west Greenland, consistent with existing ^{10}Be ages. At least in south Greenland, these ^{10}Be ages likely provide a minimum constraint for when on a multicentury timescale summer temperatures after the last deglaciation warmed above late Holocene temperatures in the early Holocene. Current south Greenland ice margin retreat suggests that south Greenland may have now warmed to or above earliest Holocene summer temperatures.

1. Introduction

The most recent Northern Hemisphere millennia-long warm climate interval occurred during the early Holocene. Elevated boreal summer insolation relative to present and attendant summer warming [*Kaufman et al.*, 2004; *Marcott et al.*, 2013] caused a negative Greenland ice sheet (GIS) mass balance, which drove the GIS to a smaller than present extent [*Kelly*, 1980; *Bennike and Björck*, 2002; *Tarasov and Peltier*, 2002; *Simpson et al.*, 2009; *Funder et al.*, 2011]. Boreal summers subsequently warmed into the Holocene thermal maximum (HTM), which varied in timing across the Northern Hemisphere [e.g., *Kaufman et al.*, 2004; *Carlson et al.*, 2008]. The decline in boreal summer insolation through the Holocene led to eventual summer cooling and advances of GIS margins, with the coldest summer temperatures and maximum ice extent occurring in the late Holocene. Over the last century, south and west Greenland summers have warmed ~1°C [*Hanna et al.*, 2009] and GIS margins are retreating back from their late Holocene maximum extents [*van den Broeke et al.*, 2009; *Kelley et al.*, 2012].

Observations and modeling suggest that marine-terminating GIS margins can respond to climate change within decades [*Andresen et al.*, 2012; *Kelley et al.*, 2012; *Nick et al.*, 2013], while land-terminating margins can respond within a century to centuries [*Tarasov and Peltier*, 2002; *Simpson et al.*, 2009; *Kelley et al.*, 2012]. As there are no notable major changes in Greenland ice accumulation over the Holocene [*Cuffey and Clow*, 1997] and assuming ice margin position tracked regional summer temperatures on a centuries to longer timescale, dating when GIS margins retreated within their late Holocene limits in the early Holocene could place a minimum constraint on when after the last deglaciation summer temperatures rose consistently above the eventual late Holocene temperature minimum on a multicentennial to millennial timescale [*Kelly*, 1980; *Funder et al.*, 2011; *Young et al.*, 2011; *Kelley et al.*, 2012; *Miller et al.*, 2013].

Outside of the well-studied Disko Bugt region in west Greenland (~70°N) [*Briner et al.*, 2010, 2014; *Corbett et al.*, 2011; *Young et al.*, 2011, 2013a; *Kelley et al.*, 2012], data directly constraining Holocene south to west GIS margin history are limited [e.g., *Levy et al.*, 2012; *Larsen et al.*, 2014]. Consequently, much of the GIS Holocene history is based on inferences from minimum- and maximum-limiting ^{14}C dates that do not necessarily closely constrain when ice margins retreated to a smaller than late Holocene extent [*Kelly*, 1980;

Weidick et al., 1990, 2004; *van Tatenhove et al.*, 1996; *Kaplan et al.*, 2002; *Larsen et al.*, 2011]. Because of these loose ^{14}C-based constraints, it is still unclear if Greenland ice retreated to a smaller than late Holocene extent during the HTM and peak warmth or prior to the HTM. Here we directly date with ^{10}Be surface exposure ages the last time that south GIS margins retreated past their maximum late Holocene extents (Figure 1). We also present new ^{10}Be data from southwest and west Greenland, complimenting existing ^{10}Be ages from these regions.

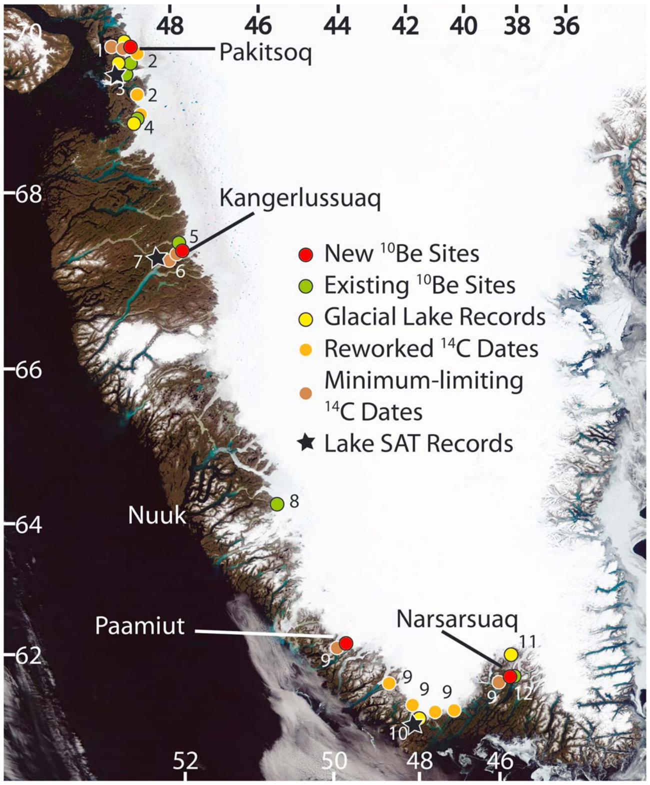

Figure 1. Greenland sample locations indicated by red symbols (see Figures 2 and S1). Locations of other south to west GIS margin constraints and temperature records indicated. 1 = *Long et al.* [2006], *Håkansson et al.* [2014]; 2 = *Weidick et al.* [1990], *Briner et al.* [2010, 2014]; 3 = *Corbett et al.* [2011], *Young et al.* [2011, 2013a], *Axford et al.* [2013]; 4 = *Weidick et al.* [1990], *Kelley et al.* [2012]; 5 = *Levy et al.* [2012]; 6 = *van Tatenhove et al.* [1996], *Willemse and Törnqvist* [1999]; 7 = *D'Andrea et al.* [2011]; 8 = *Larsen et al.* [2014]; 9 = *Weidick et al.* [2004]; 10 = *Kaplan et al.* [2002], *Wooller et al.* [2004], *Fréchette and de Vernal* [2009]; 11 = *Larsen et al.* [2011]; 12 = *Nelson et al.* [2014].

2. Methods

We collected ^{10}Be samples from boulders and bedrock near Pakitsoq in west Greenland, Kangerlussuaq in southwest Greenland, and near Paamiut and Narsarsuaq in south Greenland (Figures 1 and 2, and Figure S1 and Table S1 in the supporting information). We chose these regions because they span ~9° of latitude and thus climate settings from relatively warm and wet south Greenland to cooler and drier southwest and west Greenland [*Hanna et al.*, 2009]. We also selected each region because it has at least one Holocene lake summer temperature record to compare the ^{10}Be chronologies against.

We made a specific point of sampling multiple boulders and bedrock from a small region (indicated in Figure 2 as a point, see Figure S1 for detailed locations) that has a simple geological interpretation, minimizing postdepositional geomorphic effects on the samples. In all study areas, ^{10}Be samples are from near the late Holocene limit and therefore constrain when after the last glacial period the ice margin had retreated as far inland as its eventual late Holocene maximum extent. Near Pakitsoq, Kangerlussuaq, and Paamiut, the late Holocene limit dates to the historical period and is within 0.1–0.5 km of the currently retreating ice margin (Figure 2d) [*Kelly*, 1980; *Kelley et al.*, 2012]. Near Narsarsuaq, a late Holocene advance of the outlet glacier Kiagtût sermiat ended ~1.5 ka, which deposited the Narsarsuaq moraine 1.5–5.5 km in front of the historical limit (Figure 2d) [*Kelly*, 1980; *Winsor et al.*, 2014]. We sampled boulders just outside of the Narsarsuaq moraine. Where possible, we sampled from both terrestrial- and marine-terminating ice margins to assess any effect of dynamic discharge on the early Holocene retreat of marine ice margins via iceberg calving to the ocean and additional ocean temperature effects on ice margin ablation [e.g., *van den Broeke et al.*, 2009; *Andresen et al.*, 2012; *Nick et al.*, 2013].

Twenty-seven erratic-boulder and two bedrock samples were collected and analyzed for ^{10}Be surface exposure dating. All samples were from above the marine limit and thus date ice margin retreat. With the exception of five boulder samples from a small Ørkendalen moraine just outside of the Russell glacier historical moraine (Figure 2b) [*van Tatenhove et al.*, 1996], all sampled erratic boulders were resting directly on bedrock (Table S1). Ages were determined using the northeast North American ^{10}Be production rate [*Balco et al.*, 2009] that is applicable to Greenland [*Young et al.*, 2013b] and the Lal/Stone time-varying

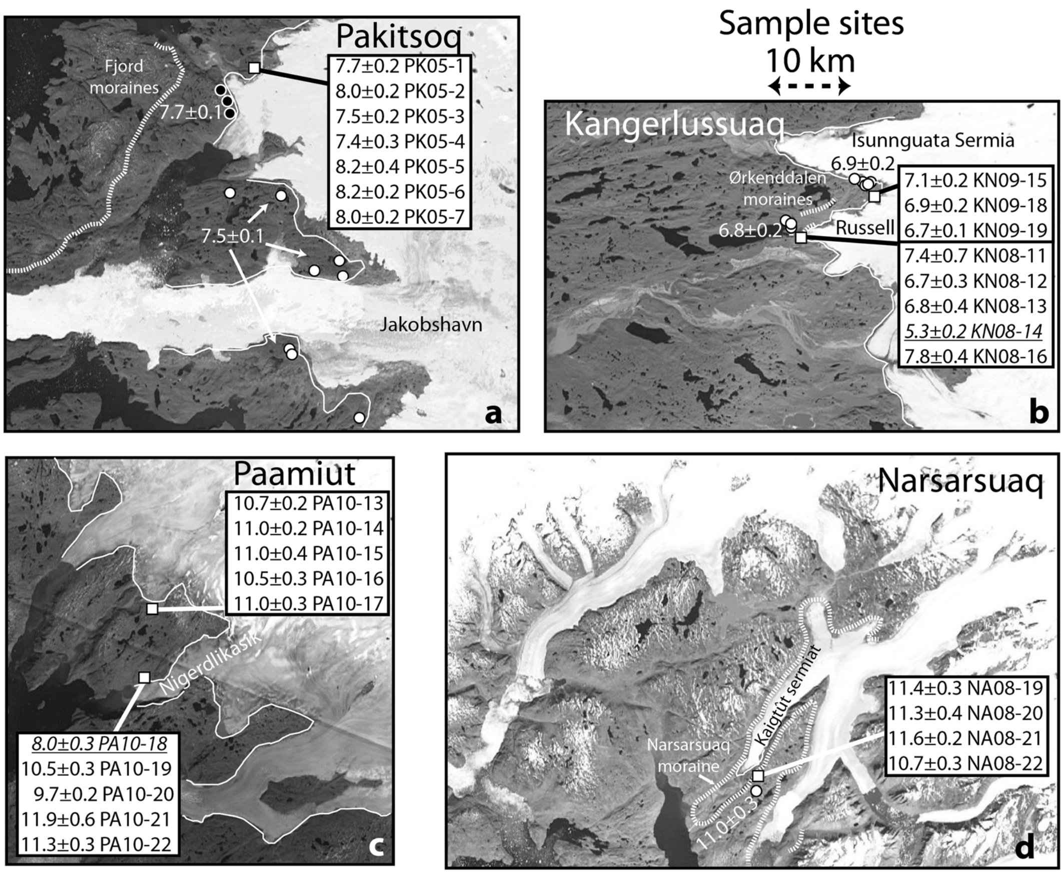

Figure 2. Ice margin ^{10}Be sampling locations (white squares) with sample age and 1σ analytical uncertainty; italic-underlined indicates an outlier. (a) Pakitsoq: dashed line is the inner Fjord moraine, white circles are ^{10}Be samples of *Young et al.* [2011, 2013a], and black circles are the ^{10}Be samples of *Corbett et al.* [2011] (additional *Kelley et al.* [2012] samples are further south, off the figure). (b) Kangerlussuaq: dashed lines are the Ørkendalen moraines, white circles are the ^{10}Be samples of *Levy et al.* [2012]. (c) Paamiut. (d) Narsarsuaq: thin dashed line is the Narsarsuaq moraine; white circle is the average ^{10}Be ages of *Nelson et al.* [2014]. The thin white lines denote the historical ice margin extent.

production scaling (Figure S2 and Table S2) [*Lal*, 1991; *Stone*, 2000]. Because the analytical uncertainty of each age varies between samples and this range in analytical precision should be accounted for when estimating the mean age of the sample population, we calculate the error-weighted mean age for samples collected from the same geological setting and report this with the standard error of the mean as the best estimate of when ice retreated from that location. We recalculated existing ^{10}Be ages using this same approach, production rate, and scaling to directly compare ages. Recalculated ^{10}Be ages are not significantly different from published ^{10}Be ages. We also recalibrated all discussed ^{14}C dates (Calib7.0) [*Stuiver et al.*, 2014]. When comparing ^{10}Be ages to calendar ages, there is an additional uncertainty in the ^{10}Be production rate of ~2% [*Young et al.*, 2013b], which is minor relative to the uncertainty of the mean age; we do not propagate this uncertainty into the standard error of the mean.

3. ^{10}Be Results

The four boulders from just outside the Narsarsuaq moraine have an error-weighted mean age of 11.3 ± 0.2 ka, dating the last time Kiagtût sermiat was near its late Holocene maximum extent (Figure 2d). Near Paamiut (Figure 2c), five boulder samples adjacent to the historical inland ice margin have an error-weighted mean age of 10.8 ± 0.1 ka. For the other five boulder samples from the outlet glacier Nigerdlikasik Bræ, we identify one young outlying ^{10}Be age (PA10-18, 8.0 ± 0.5 ka) (Figure 2c). Removing this outlier results in an error-weighted mean age for the remaining four samples of 10.6 ± 0.5 ka. Inland from Kangerlussuaq, we

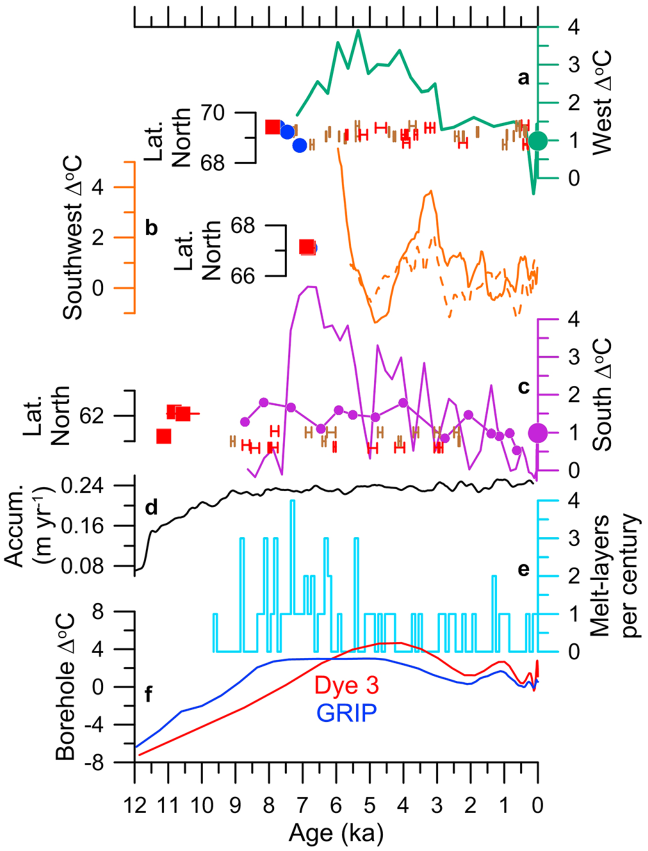

Figure 3. Holocene Greenland records. Isolated symbols show GIS margin constraints: red squares are our mean ^{10}Be ages, blue circles are existing mean ^{10}Be ages (note 1 sigma uncertainty bars are smaller than the symbol), red bars are ^{14}C dates on terrestrial and marine (in this case reservoir corrected) materials reworked into historical moraines, and brown bars are ^{14}C dates from organic intervals in ice-marginal lakes that received glacial sediment during the early and late Holocene. (a) West Greenland Δ temperature record (green) [*Axford et al.*, 2013] with large green circle showing 1990–2000 Common Era (C.E.) average Δ temperature from Illulisat in Disko Bugt relative to 1880–1890 C.E. [*Hanna et al.*, 2009]. ^{10}Be ages (our study; *Corbett et al.* [2011]; *Young et al.* [2011, 2013a]; *Kelley et al.* [2012]) and ^{14}C dates [*Kelly*, 1980; *Weidick et al.*, 1990; *Briner et al.*, 2010, 2014; *Kelley et al.*, 2012; *Håkansson et al.*, 2014]. (b) Southwest Greenland Δ temperature records (orange solid Braya Sø, dashed Lake E; smoothed to century timescale due to higher sample resolution than other records) [*D'Andrea et al.*, 2011] and ^{10}Be ages (our study; *Levy et al.* [2012]). (c) South Greenland Δ temperature records from pollen (purple line) [*Fréchette and de Vernal*, 2009] and chironomids (purple line with symbols) [*Wooller et al.*, 2004] with large purple circle showing 1990–2000 C.E. average Δ temperature from Narsarsuaq relative to 1880–1890 C.E. [*Hanna et al.*, 2009]. ^{10}Be ages (our study; *Nelson et al.* [2014]) and ^{14}C dates [*Kelly*, 1980; *Kaplan et al.*, 2002; *Weidick et al.*, 2004; *Larsen et al.*, 2011]. (d) GISP2 accumulation rate (black) [*Cuffey and Clow*, 1997]. (e) GISP2 melt layers (light blue) [*Alley and Anandakrishnan*, 1995]. (f) GRIP (blue) and Dye 3 (red) borehole Δ temperature [*Dahl-Jensen et al.*, 1998].

exclude one young outlier (K08-14, 5.3 ± 0.3 ka) from the five samples from the Ørkendalen moraine next to Russell glacier (Figure 2b). The remaining four boulder samples have an error-weighted mean age of 7.0 ± 0.3 ka. Another three boulder samples from just outside of the late Holocene inland margin have an error-weighted mean age of 6.8 ± 0.1 ka (Figure 2b). Near Pakitsoq in west Greenland (Figure 1), five boulder samples and two bedrock samples from just outside of the GIS late Holocene margin have an error-weighted mean age of 7.9 ± 0.1 ka (Figure 2a).

4. Early Holocene Ice Margin Retreat Pattern

Our ^{10}Be ages from just outside of the Narsarsuaq moraine of 11.3 ± 0.2 ka agree with two adjacent ^{10}Be ages from a new boulder (11.5 ± 0.3 ka)-bedrock (10.8 ± 0.2 ka) pair measured to test for nuclide inheritance (Figure 2d) [*Nelson et al.*, 2014]. Including these two ages, we calculate an error-weighted mean and standard error of 11.1 ± 0.2 ka ($n = 6$) (Figure 3c), which agrees with minimum-limiting ^{14}C dates from >15 km outside of the Narsarsuaq moraine that show ice retreat before 9.8 ± 0.3 ka (shell sample) [*Weidick et al.*, 2004] and 10.8 ± 0.2 ka (bulk organic sample) [*Larsen et al.*, 2011]. Reworked organic material in historical moraines and intervals of organic sediment deposition in ice-marginal lakes suggest that ice had retreated within its historical extent in south Greenland before ~9.1 ka (Figure 3c) [*Kelly*, 1980; *Kaplan et al.*, 2002; *Weidick et al.*, 2004; *Larsen et al.*, 2011]. Because Kiagtût sermiat is a land-terminating outlet glacier, climate effects on surface mass balance rather than dynamic discharge should control this early Holocene retreat.

Near Paamiut, our inland ice mean ^{10}Be age of 10.8 ± 0.1 ka and outlet glacier mean ^{10}Be age of 10.6 ± 0.5 ka are consistent with a minimum-limiting ^{14}C date of 8.7 ± 0.1 ka from ~3 km down fjord of the ^{10}Be ages [*Weidick et al.*, 2004]. The similar timing of retreat between the outlet glacier and the inland ice margin suggests that climate rather than dynamic discharge was responsible for driving early Holocene ice retreat on at least a century timescale. Our Paamiut ^{10}Be ages are also consistent with the *Larsen et al.* [2014] ^{10}Be ages of 10.3 ± 0.2 ka ($n = 3$) from near ice margins inland of Nuuk (Figure 1).

Our ^{10}Be ages from near Kangerlussuaq agree with the ^{10}Be ages of *Levy et al.* [2012]. The 7.0 ± 0.3 ka ^{10}Be age for the Ørkendalen moraine next to Russell glacier are similar to the Ørkendalen moraine age of 6.8 ± 0.2 ka ($n = 4$) of *Levy et al.* [2012] (Figure 2b). The *Levy et al.* [2012] ^{10}Be ages of 6.9 ± 0.2 ka ($n = 5$) next to the outlet glacier Isunnguata Sermia are consistent with our ^{10}Be ages of 6.8 ± 0.1 ka from where Russell glacier and Isunnguata Sermia meet at the inland ice (Figure 2b). All of these ^{10}Be ages are consistent with the minimum-limiting ^{14}C date of 4.6 ± 0.1 ka from next to the modern Russell glacier moraine [*van Tatenhove et al.*, 1996] and of 7.3 ± 0.1 ka from a lake ~2 km down valley of Russell glacier [*Willemse and Törnqvist*, 1999]. Because these are land-terminating ice margins, climate change was likely the driving force behind ice retreat.

Near Pakitsoq in west Greenland, our mean ^{10}Be age of 7.9 ± 0.1 ka is consistent with a minimum-limiting ^{14}C date of 7.6 ± 0.1 ka from ~20 km west of the historical ice margin [*Long et al.*, 2006] and 6.6 ± 0.1 ka from ~3 km west of the historical ice margin [*Håkansson et al.*, 2014]. Our ^{10}Be ages are older than, but still consistent with, the timing of organic deposition in a Pakitsoq ice-marginal lake beginning before 5.4 ± 0.1 ka (Figure 3a) [*Håkansson et al.*, 2014]. These ^{10}Be ages agree with error-weighted mean ^{10}Be bedrock boulder ages in similar glacial-geologic settings of 7.7 ± 0.2 ka ($n = 6$), 7.5 ± 0.1 ka ($n = 8$), and 7.1 ± 0.1 ka ($n = 2$) from ~10, 25, and 80 km south of Pakitsoq, respectively (Figures 1, 2a, and 3a) [*Corbett et al.*, 2011; *Young et al.*, 2013a]. The ^{10}Be ages also concur with ^{14}C dates on organic material reworked into historical moraines and periods of organic deposition in ice-marginal lakes that record smaller than late Holocene ice south of Pakitsoq before ~5.7 ka and ~7.2 ka, respectively (Figure 3a) [*Weidick et al.*, 1990; *Briner et al.*, 2010, 2014; *Kelley et al.*, 2012]. The general agreement between terrestrial and marine ice margins suggests that climate drove early Holocene ice margin retreat on a multicentennial timescale, with local topography and ice margin setting (terrestrial or marine) potentially explaining variability between sites [*Corbett et al.*, 2011; *Young et al.*, 2013a].

In summary, our ^{10}Be ages on the timing of early Holocene ice retreat are supported by previous evidence (^{14}C ages and in some cases ^{10}Be ages). At sites in the south, our new ^{10}Be ages significantly refine understanding of the ice margin history, providing direct dates on ice retreat previously constrained only by minimum-limiting ^{14}C ages. We find that ice margins retreated to within their late Holocene maximum extents at 11.1 ± 0.2 ka to 10.6 ± 0.5 ka in south Greenland, significantly earlier than previous estimates from the south and contrasting with 6.8 ± 0.1 ka to 7.9 ± 0.1 ka in southwest to west Greenland. This difference in retreat timing is similar on a century timescale for both terrestrial and marine ice margins and is consequently not likely due to local ice margin setting.

Dates on ice-margin retreat will reflect a complex interplay between factors affecting the timing and degree of early Holocene inland ice retreat and the magnitude of late Holocene ice advance. *Briner et al.* [2013] hypothesized that difference in timing of GIS margin retreat to a smaller than late Holocene extent reflected greater inland margin retreat from the coast in west Greenland and/or more extensive late Holocene ice advance in south Greenland. The greater amount of ice-free land in southwest and west Greenland relative to south Greenland (Figure 1) would support this hypothesis [*Briner et al.*, 2013], if Holocene climate change were uniform across south to west Greenland. Relative sea level records provide an additional constraint and suggest a longer period of inland ice retreat in west Greenland during the middle Holocene and an earlier onset of late Holocene ice readvance in south Greenland [*Long et al.*, 2011; *Sparrenbom et al.*, 2013; *Woodroffe et al.*, 2014]. Ultimately, these ice-margin changes are driven by climate change and the earlier deglacial ages in south Greenland could be due to greater warming in the earliest Holocene in south Greenland relative to southwest and west Greenland. Indeed, peak Holocene warmth may have been over 1 ka earlier in south Greenland [*Andresen et al.*, 2004; *Wooller et al.*, 2004; *Fréchette and de Vernal*, 2009; *Massa et al.*, 2012] relative to southwest and west Greenland [*D'Andrea et al.*, 2011; *Axford et al.*, 2013], which would be consistent with earlier warming in the south driving south Greenland ice within its late Holocene limit before southwest and west Greenland ice.

5. Ice Margin Response to Early Holocene Warmth

What constraints can be placed upon the temperatures that drove these ice margins to retreat to within their eventual late Holocene limits? Because GIS accumulation did not significantly change during the Holocene relative to earlier deglacial changes (Figure 3d) [*Cuffey and Clow*, 1997], Holocene GIS margin retreat and advance were likely driven mainly by summer temperature. This assumption neglects the direct effect on surface melt of increased shortwave radiation in the early Holocene relative to the late Holocene. However, shortwave radiation is thought to play a smaller role in driving glacial retreat than summer temperature [*Kaufman et al*., 2004; *Carlson et al*., 2008; *Miller et al*., 2013] and is likely within the uncertainty of the temperature estimates [*Wooller et al*., 2004; *Fréchette and de Vernal*, 2009; *D'Andrea et al*., 2011; *Axford et al*., 2013].

We compare the timing of ice retreat at our study sites to the earliest available summer temperature estimates from nearby lake sediment records to assess how warm temperatures might have been when ice retreat occurred. These temperature reconstructions do not extend back to when ice retreated past its late Holocene extent, but several complementary lines of evidence suggest that these records provide maximum estimates of temperatures during early Holocene GIS retreat. Overall, data sets from the larger region that extend back into the earliest Holocene suggest cooler temperatures in the region in the earliest Holocene, followed by warming into the HTM, albeit with significant spatiotemporal variability [*Kaufman et al*., 2004; *Marcott et al*., 2013]. In central Greenland, melt layers (summer temperature proxy) were essentially absent from the Greenland Ice Sheet Project 2 (GISP2) ice core (72.6°N) before ~10 ka, increasing to a maximum at ~7 ka (Figure 3e) [*Alley and Anandakrishnan*, 1995]. The Dye 3 (65.2°N) and Greenland Ice Core Project (GRIP) (72.6°N) borehole records from Greenland show annual mean warming across the early Holocene to a HTM after ~8 ka (Figure 3f) [*Dahl-Jensen et al*., 1998]. West, southwest, and southeast Greenland marine records document surface ocean warming across the early Holocene to a HTM in the middle Holocene [*Ren et al*., 2009; *Jennings et al*., 2011, 2014].

In west Greenland at North Lake, the earliest reconstructed summer temperature is ~1.5°C warmer than the preindustrial period at ~7.1 ka (from chironomid assemblages), followed by warming into a HTM by ~6 ka (Figures 1 and 3a) [*Axford et al*., 2013] (all temperature anomalies are referenced to the late 1800 C.E. average temperature). Amino acid ratios of marine bivalves in west Greenland also imply the onset of the HTM at ~6 ka [*Briner et al*., 2014]. In southwest Greenland near Kangerlussuaq, the earliest summer lake water temperatures reconstructed at Braya Sø (from alkenones) ~6.1 ka were ~5°C warmer than those during the preindustrial period [*D'Andrea et al*., 2011] (Figures 1 and 3b), during a time when paleolimnological evidence suggests aridity in the same region [*Perren et al*., 2012; *Anderson and Leng*, 2004] and when North Lake was also registering relatively warm temperatures. In south Greenland, quantitative reconstructions from Qipisarqo Lake extend to 8.6–8.7 ka and indicate that summer temperatures at that time were ~0.5°C (pollen assemblages) to ~1.5°C (chironomid assemblages) warmer than preindustrial temperatures (Figures 1 and 3c) [*Wooller et al*., 2004; *Fréchette and de Vernal*, 2009]. Beyond quantitative temperature inferences, complementary paleoenvironmental inferences from lakes in south and southeast Greenland suggest general warming in the first millennia of the Holocene and a HTM in the early Holocene [*Kaplan et al*., 2002; *Andresen et al*., 2004; *Massa et al*., 2012; *Balascio et al*., 2013].

At all our study sites, GIS margins had retreated within their late Holocene maximum extents prior to the earliest nearby quantitative summer temperature estimates (Figures 3a–3c). In south and west Greenland, it nonetheless appears that the earliest summer temperature estimates from lakes provide maximum constraints on the summer warmth that drove ice margin retreat, because peak HTM temperatures in south and west Greenland seem to have occurred after local GIS margins were already within their late Holocene limits. In contrast, ^{10}Be ages from the southwest near Kangerlussuaq show ice retreating to a smaller than late Holocene extent during or after peak HTM temperatures.

Instrumental records from Narsarsuaq in south Greenland document ~1°C of summer warming over the last century [*Hanna et al*., 2009]. South Greenland temperatures of the past decade are now likely comparable to or slightly warmer than the summer temperatures that probably drove early Holocene ice retreat within its late Holocene maximum in south Greenland (Figure 3c). Accordingly, south Greenland ice margins are presently retreating back from their late Holocene extents [*van den Broeke et al*., 2009; *Kelley et al*., 2012].

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