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Key Points:

- Both Early Holocene and Little Ice Age moraines are present in northwest Greenland
- Humboldt Glacier moraines were deposited during a period of ice margin stability along western Greenland around 8.3 ka
- The western GIS margin was sensitive to subcentennial-scale atmospheric temperature fluctuations during the early Holocene

Supporting Information:

- Supporting Information S1
- Table S1
- Table S2
- Table S3

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Early to Late Holocene Surface Exposure Ages From Two Marine-Terminating Outlet Glaciers in Northwest Greenland

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Abstract Terrestrial chronologies from southern Greenland provide a detailed deglacial history of the Greenland Ice Sheet (GIS). The northern GIS margin history, however, is less established. Here we present surface exposure ages from moraines associated with two large outlet glaciers, Petermann and Humboldt, in the northwestern sector of the GIS. These moraine chronologies indicate a Little Ice Age advance of the ice sheet margin before ~0.3 ka and a possible equivalent advance of similar magnitude prior to ~2.8 ka. An early Holocene moraine at Humboldt Glacier was abandoned by 8.3 ± 1.7 ka and is contemporaneous with other moraines deposited along the entire western GIS margin. This widespread ice margin stability between ~9 and 8 ka indicates that while this margin was influenced by warming atmospheric temperatures during the early Holocene, the warming was likely overprinted with the effect of the abrupt climate cooling at 9.3 and 8.2 ka.

Plain Language Summary The global climate is warming, and the Greenland Ice Sheet is responding. A more complete understanding of this process is needed to better predict its future response to climate change. We determine how the ice sheet changed following the last ice age in northwest Greenland. The northwest sector of the ice sheet retreated to the coast by ~10,000 years ago during a period of warming atmospheric temperatures. About 8,300 years ago the ice stopped retreating despite relatively high atmospheric temperatures. A similar standstill occurred in areas along western Greenland between ~9,000 and 8,000 years ago. This suggests that despite the long-term warming, well-known abrupt cooling events that occurred in the region at this time influenced the ice sheet margin and temporarily stopped the long-term pattern of ice retreat. The ice sheet retreated after 8,300 years ago and then advanced during the latest cold period, the Little Ice Age (1350–1850 CE), in a fashion similar to elsewhere in Greenland. Our study finds that the Greenland Ice Sheet margins are sensitive to both long-term (>1,000 years) and short-term (<100 years) atmospheric temperature changes. This sensitivity of the ice margin has important implications when assessing ongoing and future ice loss today.

1. Introduction

Depending on future emission scenarios, melting of the Greenland Ice Sheet (GIS) will contribute 5–20 cm to eustatic sea level by 2100 CE (Church et al., 2013; Stocker et al., 2013). These latest projections include some of the potential dynamic response of the ice sheet, aspects of which still carry a large uncertainty (Nick et al., 2013). Documenting the response of the GIS to past climatic shifts is one way to improve the accuracy of predicted changes. A myriad of paleoclimate and geologic data exist to aid this endeavor (Funder et al., 2011; Kelly & Lowell, 2009; Sinclair et al., 2016; Sundqvist et al., 2014); the large variation in these data sets from region to region indicates that further investigation into the past fluctuations of the GIS in data-sparse areas is needed.

Variation in ice extent is archived as moraines formed by the ice sheet during stabilization and by erratic boulders deposited across the landscape after ice melt. Moraine abandonment reflects glacial retreat, which in turn implies a change in climate. The subtler chronologic and spatial disparity of moraines across the different sectors of the ice sheet is overprinted on this multimillennial record (Briner et al., 2016). These

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Figure 1. (a) Inset map of Greenland with locations of ocean (red circles) and ice (blue circles) cores used in Figure 3. The black rectangle denotes study area. (b) Map of study area with locations of previous work discussed in the text. The purple circles are ³⁶Cl exposure ages (Zreda et al., 1999); the red circle is core HLY03-05GC (Jennings et al., 2011); the black circles are oldest ¹⁴C ages (Bennike, 2002); the blue circle is location of Agassiz Ice Core (Lecavalier et al., 2017); the green circle is location of Secret Lake record (Lasher et al., 2017). The yellow circles are moraine locations from this study (base imagery courtesy of Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community).

discordant depositional histories suggest that the variable climate and oceanic conditions along the ice sheet may play a large role in determining the timing of ice advance and retreat (Funder et al., 2011; Sinclair et al., 2016).

Here we present a ¹⁰Be surface exposure chronology from 33 boulders from the crests of ice-proximal lateral moraines at Petermann and Humboldt glaciers in northwestern Greenland to determine the sensitivity of these glaciers to the millennial-scale climate dynamics during the early to late Holocene (Figure 1). Both glaciers are marine-terminating; due to this oceanic influence they are sensitive to local variations in ocean temperature and sea level as well as surface air temperature changes and can be prone to dynamic and rapid ice loss (Marcott et al., 2011; Nick et al., 2012; Rignot et al., 2010; Scambos et al., 2004). Petermann Glacier alone drains ~6% of the GIS today (Bamber et al., 2013; Rignot & Kanagaratnam, 2006), and as such it

represents a relatively large drainage area of the GIS. This northwestern sector of the ice sheet is therefore vital for modeling the deglaciation patterns of the larger GIS over the past ~20 ka as well as into the future. Our work addresses the lack of chronologic constraint in this sector of the ice sheet (Sinclair et al., 2016) and builds on limited, previous work on the coast of Washington Land (Figure 1), the Canadian coast of Ellesmere Island, and a single ocean core from Nares Strait (Bennike, 2002; Bennike & Björck, 2002; Blake, 1992; England, 1999; Jennings et al., 2011; Kelly & Bennike, 1992; Zreda et al., 1999).

2. Geographic Setting and Methods

Washington Land is the ice-free area bracketed by Petermann Glacier to the north and Humboldt Glacier to the south (Figure 1b). The local geology consists of flat-lying Paleozoic carbonate platform and reef deposits that are dissected into isolated plateaus reaching to ~1,000 m in elevation (Bennike, 2002). At the LGM the whole of Washington Land is thought to have been covered by the GIS, based on the presence of glacial erratics (Bennike, 2002). The ubiquitous carbonate bedrock accounts for ~80% of the erratics on the landscape. The remaining erratics are carbonate-cemented, arenitic sandstone and a variety of intrusive igneous and metamorphic rocks. These rock types do not outcrop outside of the ice sheet margin within the study area and thus have been transported from the interior by the ice sheet.

We collected samples from 33 boulders for surface exposure dating with ¹⁰Be from four lateral moraines: two along the right and left margins of Petermann Glacier and two right-lateral moraines along Humboldt Glacier. Our goal was to reconstruct the most recent glacial history of these two largest outlet glaciers of the northwestern sector of the GIS. We targeted boulders situated on moraine crests to decrease the likelihood of postdepositional movement. All sampled boulders were above the marine limit as defined by dated shells in raised marine deposits (~65 m; Bennike, 2002). Samples were processed at University of Wisconsin-Madison following procedures for ¹⁰Be extraction (Licciardi, 2000; Reusche, 2017). Ages were calculated with the CRONUS-Earth online calculator version 3 (Balco et al., 2008) using the regional Arctic, Baffin Bay production rate (Young, Schaefer, et al., 2013) and the nuclide- and time-dependent scaling scheme of Lifton et al. (2014) (Tables S1-S3). The ages are reported as years exposed prior to sampling (Balco et al., 2008). No correction was made for postglacial isostatic rebound. The median elevation of the relative sea level curve for southern Washington Land (Lecavalier et al., 2014) yields an uplift correction that would result in a 0-5% increase for the boulder ages in this study; thus, we do not report uplift-corrected ages here. No corrections were made for snow cover given the dry conditions and modern average annual snowfall ~10-20 cm (Bennike, 2002; Ohmura et al., 1999). Based on the relatively fresh appearance of moraines sampled, their proximity to the modern ice margin, and our targeting of boulders with striations, no spallation, and smooth surfaces, we do not apply an erosion correction. We report the error-weighted mean age of each moraine boulder group to account for the variation in analytical uncertainty of the data set (Table S1). The uncertainty of this mean is presented as the standard deviation of the boulder population unless otherwise noted. We interpret the mean of the moraine ages as marking the timing of moraine abandonment following a period of advance or stabilization of the GIS.

3. Exposure Age Results

The left-lateral moraine of Petermann Glacier yields surface exposure ages ranging from 9.4 \pm 0.8 ka to 0.1 \pm 0.05 ka with an error-weighted mean age of 0.3 \pm 0.2 ka (n = 5) after identifying two sample outliers using Chauvenet's criterion and rejecting them from the calculation (Table S1 and Figure 2a). The samples of the right-lateral moraine of Petermann Glacier have a bimodal distribution with mean ages of 2.8 \pm 0.3 ka (n = 3) and 0.3 \pm 0.02 ka (n = 3) for the two distributions (Figure 2b). The ice-proximal moraine of Humboldt Glacier yields an age range of 9.4 \pm 0.8 to 0.1 \pm 0.05 ka with two samples identified as statistical outliers (Table S1) and an error-weighted mean age of 0.3 \pm 0.1 ka (n = 12; Figure 2c). The samples from the ice-distal right-lateral moraine of Humboldt Glacier have an error-weighted mean exposure age and standard deviation of 8.3 \pm 1.7 ka (n = 6; Figure 2c). The boulder ages of this moraine are slightly bimodal with two boulders likely affected by prior exposure. However, none of these ages were identified as statistical outliers using Chauvenet's criteria and all boulder ages were included in the calculated moraine age and uncertainty.



Figure 2. ¹⁰Be sampling locations (yellow dots) with sample age and 1 σ uncertainty. (a) Left-lateral moraine at Petermann Glacier. (b) Right-lateral moraine at Petermann Glacier. (c) Northern margin of Humboldt Glacier; ice-proximal moraine on the left, ice-distal on the right. The asterisks denote outliers and separate boxes with bold text contain the reported error-weighted mean and standard deviation of each moraine. The yellow lines outline moraine crests. (imagery (a) and (b) courtesy of Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community; imagery (c) imagery copyright (DigitalGlobe, Inc. imagery).

4. Early to Late Holocene GIS Moraines

4.1. Neoglaciation of Northwestern to Southern Greenland

Following the Holocene Thermal Maximum (HTM; ~9–5 ka with significant variation across the Arctic; Kaufman et al., 2004), a period of atmospheric cooling and renewed glaciation (Neoglacial) ensued and ended following the Little Ice Age (LIA) between 1350 and 1850 CE (Kaufman et al., 2009; Marcott et al., 2013). The lateral moraines along Petermann and Humboldt Glaciers represent moraine abandonment at ~0.3 ka and coincide with the culmination of Neoglacial cooling during the LIA (Figure 3). The right-lateral moraine of Petermann Glacier records a complex, bimodal sample distribution likely representing both a post-LIA abandonment at 0.3 ± 0.02 ka and a Neoglacial moraine-building phase prior to 2.8 ± 0.3 ka; we interpret the latter as an earlier moraine-building event of equal extent to the subsequent LIA advance. The near-ice moraine of Humboldt indicates the ice margin also reached its maximum late Holocene extent during the LIA. Previous work along the northern margin of Humboldt Glacier obtained seven radiocarbon ages from clam shell fragments (n = 4) and terrestrial mammal bones (n = 3) ranging in age from 37,000 to 330 ± 50 ¹⁴C year before present (BP) (300–500 cal. year BP, from *Rangifer tarandus*) and have been interpreted to indicate that Humboldt Glacier was within its present margin from ~4.0 to 0.40 ka after



Figure 3. Late Pleistocene and Holocene climate records and the moraine chronology from this study. (a) Boreal June insolation at 60°N (red; Berger and Loutre, 1991). (b) Three proxy records for temperature. Mean temperature anomaly at 30°–90°N (purple) with 1 σ uncertainty band (light purple) from Marcott et al. (2013), temperature anomaly (green) at Secret Lake, N. Greenland (Lasher et al., 2017), and high Arctic mean temperature anomaly (black; Kaufman et al., 2009). (c) NGRIP δ^{18} O (orange; Rasmussen et al., 2006) and Agassiz temperature (gray; Lecavalier et al., 2017). (d) ARC3 sea ice proxy IP₂₅ flux (pink; Vare et al., 2009) and planktic foraminifera per gram of sample from Hall Basin (purple; Jennings et al., 2011). (e) ³⁶Cl surface exposure ages (mean and 1 σ uncertainty) from Hans and Pim islands (light blue squares; Zreda et al., 1999). (f) ¹⁰Be surface exposure ages separated by location (black open circles). Error-weighted means and propagated uncertainty (yellow squares; this study).

excluding the oldest age. Of these, three clam shell fragments and one bone fragment (*Rangifer tarandus*) were sampled from within the same fresh, ice-cored moraine as the near-ice feature sampled as part of this study (Bennike, 2002; Figure 1). The radiocarbon ages of these samples range from 670 to 570 cal. yr BP (using reservoir age of 550 years) to 300–500 cal. yr BP (from *Rangifer tarandus*; Bennike, 2002). Our ¹⁰Be ages are consistent with this interpretation. Together, these data suggest an advance and onset of moraine development at this ice margin between ~700 and 400 years ago constrained by the radiocarbon ages (Bennike, 2002) before moraine abandonment following the end of the LIA at ~0.3 ka based on the ¹⁰Be based surface exposure ages (Figure 2).

Across Greenland, LIA-equivalent deposits of fresh, ice-cored moraines have been mapped as the late Holocene maximum extent in most areas (Kelly & Lowell, 2009; Weidick, 1968). These ubiquitous features have been constrained using several relative and geochronological techniques (e.g., Briner et al., 2010, 2011; Geirsdóttir et al., 2000; Hjort, 1997; Kelly et al., 2008; Kelly & Lowell, 2009; Young, Briner, Stewart, et al., 2011). In northern Greenland, several studies have mapped LIA moraines along local glaciers and ice caps based on their fresh appearance and proximity to the ice margin (Davies & Krinsley, 1962; Kelly & Lowell, 2009; Weidick, 2001). The few pre-LIA, late Holocene moraines that have been mapped are in western and southeastern Greenland and are associated with local glaciers and ice caps (Kelly, 1980; Kelly & Lowell, 2009; Weidick, 1968), yet few have numerical age constraints. At Jacobsen fjord in southeastern Greenland, lichenometry measurements constrain a moraine to 1.5–1.0 ka (Geirsdóttir et al., 2000). In southern Greenland, the Narsarsuaq moraines of Kiagtût Sermiat were first dated to >1.2 ka using radiocarbon dating (Bennike & Sparrenbom, 2007) and then further constrained with ¹⁰Be exposure dating to ~1.6 ka (Winsor et al., 2014). Radiocarbon ages from overrun, in situ mosses record Neoglaciation beginning at ~5 ka at Qangattaq ice cap just north of Disko Bugt; this site then records glacial advance at ~3.7 ka (Schweinsberg

et al., 2017). In northern Greenland, organic material within till deposits was dated using radiocarbon measurements to between 5.5 and 5.0 ka, suggesting an ice advance during this interval (Möller et al., 2010). The minimal LIA deposits in this area suggest that any earlier Neoglacial advances were generally less extensive than the LIA advance and subsequently overridden during the LIA cold phase that culminated ~200– 300 years BP (Kaufman et al., 2009; Marcott et al., 2013). The main exceptions are the ~5 ka advance along the northernmost GIS (Möller et al., 2010) as well as the Narsarsuaq moraine set in southern Greenland, at which the pre-LIA advance was ~5 km outboard of the LIA advance (Winsor et al., 2014).

Our work in northwest Greenland is congruent with observations across the subcontinent: prevalent LIA moraines and a potential preservation bias against pre-LIA advances. At Humboldt Glacier, the abandonment age of the LIA moraine agrees with that of Jakobshavn Isbrae (Young, Briner, Stewart, et al., 2011). Jakobshavn is the only other marine-terminating outlet glacier of a comparable size to Petermann with well-constrained ages of LIA moraines from western Greenland marking an advance between 1500 CE-1640 CE and retreat by 1850 CE (Young, Briner, Stewart, et al., 2011). The ages of the youngest lateral moraines of Petermann Glacier $(0.3 \pm 0.2 \text{ ka})$ are also synchronous with those of Humboldt Glacier $(0.3 \pm 0.1 \text{ ka})$. The set of older ages on the right-lateral moraine suggest a pre-LIA advance of a similar extent to the LIA; however, given the limited number of pre-LIA moraines it is difficult to point to an extensive spatial pattern. In Johannes V. Jensen Land, which faces the Arctic Ocean in farthest north Greenland, radiocarbon ages from within moraine and adjacent sediments suggest an ice advance ~5 ka (Möller et al., 2010). At Petermann Glacier, the older exposure ages at the right-lateral moraine may indicate a similar pre-LIA advance with final abandonment dating to ~2.8 ka ± 0.3 ka (Figure S1). The age disparity between our moraine age at Petermann Glacier and the ~1.6 ka moraine age at Narsarsuaq (Winsor et al., 2014) could be an ice dynamical effect at the two sites causing variations in timing of advance and retreat: the marine terminus at Petermann may have been more sensitive to ocean temperature changes prior to the LIA than Kiagtût Sermiat, which was potentially inland at this time (Winsor et al., 2014).

4.2. Early Holocene Glaciation of Northwestern to Southern Greenland

The age of the distal lateral moraine of Humboldt Glacier demarcates an early Holocene abandonment at 8.3 \pm 1.7 ka. The timing of this deposition is generally consistent with previous interpretations of minimum-limiting, radiocarbon-based chronologies from the area surrounding Nares Strait (Figure 1), which suggest that the GIS completely inundated Washington Land and coalesced with the Innuitian Ice Sheet along the coast of Ellesmere Island until the strait opened at ~8 ka (Bennike, 2002; Bennike & Björck, 2002; Blake, 1992; England, 1999; Kelly & Bennike, 1992; Zreda et al., 1999). The distribution of radiocarbon ages surrounding the strait illuminates the deglacial pattern: the oldest ages are in the north and south (~11–10 ka) and the youngest in Kane Basin, along the northern edge of Humboldt Glacier (~7.6 ka; Bennike, 2002; Figures 1 and S1). Kane Basin is inferred to be the ice divide for the Nares Strait ice stream at the LGM (England, 1999; Jennings et al., 2011), with the Humboldt region feeding the ice to the North and South (Bennike, 2002; England, 1999).

Previously reported ³⁶Cl surface exposure ages on glacial erratics and scoured bedrock from two islands in Nares Strait (Zreda et al., 1999) constrain when ice abandoned the center of the strait to between 10.4 \pm 1.5 and 9.6 \pm 2.1 ka. These ages are consistent with a study of marine sediment core HLY03-05GC from Hall Basin in northern Nares Strait (Jennings et al., 2011), which indicates that the entirety of Hall Basin was ice-free by 10.3 ka, with Petermann Glacier grounded on a shallow sill within the mouth of Petermann Fjord by 9.7 ka (Figures 1 and 3). This is supported in part by new bathymetric mapping of Petermann Fjord indicating that the glacier stabilized at the fjord mouth building a large grounding-zone wedge between 9.3 and 8.7 ka (Jakobsson et al., 2018). Our exposure ages at Humboldt Glacier postdate the initial opening of Nares Strait based on the ocean sediment cores and existing surface exposure ages but suggest that following the opening of Nares Strait Humboldt Glacier stabilized at ~8 ka. This general pattern of ice retreat out of Nares Strait at approximately 10.5 ka followed by ice advance and moraine construction at around 8 ka is consistent with a similar pattern of the marine-terminating glacier Harald Moltke Bræ near Thule, Greenland, approximately 300 km to the south of our field site (Corbett et al., 2015). At that site, exposure ages indicate that the initial retreat of the GIS occurred at 10.8 \pm 0.6 ka; surficial mapping and maximum-limiting radiocarbon ages from shells within moraine sediments indicate that Harald Moltke Bræ advanced after 10.2-9.8 ka. This is further supported by a lacustrine paleotemperature record of chironomid assemblages near Thule that indicates onset of rapid deglaciation of the local GIS margin at \sim 10 ka (McFarlin et al., 2018).

In southwestern Greenland, ¹⁰Be exposure ages, radiocarbon dates, and deposits dated using optically stimulated luminescence for the Godthåbsfjord system and the Buksefjord-Sermilik region indicate rapid retreat during the early Holocene to the inner fjord by 11.4-10.4 ka (Larsen et al., 2014). Farther north at Disko Bugt, ice retreated from the continental shelf at ~13.8 ka based on radiocarbon-dated clam shells in a marine sediment core from a trough just outboard of Disko Bugt (Cofaigh et al., 2013). Following the initial retreat in this area, an increase in ice rafted debris at ~12.0 ka is interpreted as an ice readvance followed by an abrupt retreat, which is hypothesized to reflect surge behavior, rather than a climatically-driven advance (Cofaigh et al., 2013; Jennings et al., 2014). Exposure ages generally agree with these results and suggest that the GIS retreated from the bay between 12.2 and 11.6 ka with final deglaciation from the outer bay at ~10.8 ka (Kelley et al., 2013; Rinterknecht et al., 2014; Young, Schaefer, et al., 2013). At northernmost Baffin Bay, radiocarbon ages from a marine sediment core in the Uummannag Trough suggest that deglaciation had begun by ~14.8 ka, and a recent ¹⁰Be exposure age chronology indicates that ice had collapsed from the continental shelf and into the Uummannaq fjords by ~11 ka (Cofaigh et al., 2013; Philipps et al., 2017; Roberts et al., 2013). ¹⁰Be exposure ages from the Upernavik fjord system to the north indicate rapid retreat at ~11.3 ka. Farther north an ocean sediment core marks deglaciation from northern Baffin Bay at ~12.5 ka (Knudsen et al., 2008). Peary Land marks the only true readvance of three local glaciers during the Younger Dryas cooling event (12.9–11.7 ka; Rasmussen et al., 2006), at ~13.0–11.8 ka with bracketed minimum-limiting ¹⁰Be exposure ages and maximum limiting optically stimulated luminescence dates on three terminal moraines (Larsen et al., 2016). At the Northeast Greenland Ice Stream, ¹⁰Be and ¹⁴C chronologies record a retreat between 11.7 \pm 0.6 ka and 9.3 \pm 0.4 ka also associated with increased atmospheric and ocean temperatures at the end of the YD (Larsen et al., 2018).

It is probable that the moraine age of Humboldt Glacier records a period of renewed stability or readvance at or before ~8 ka, after the glacier had retreated within its fjord. Similar moraines demarcating readvance or a stable ice margin during the early Holocene are observed along the western coast of Greenland. Just north of Kangerlussuag at Sisimut the Keglen moraine appears to have been abandoned at 8.0 ± 0.2 ka (Winsor et al., 2015). A series of studies surrounding Disko Bugt also use ¹⁰Be surface exposure dating of moraine boulders to find that the Fjord Stade moraines and several other inset moraines date to around ~9-8 ka (Corbett et al., 2011; Lesnek & Briner, 2018; Weidick, 1968; Weidick & Bennike, 2007; Young, Briner, et al., 2013; Young, Briner, Stewart, et al., 2011). The Fjord Stade moraines are interpreted to be advances, possibly in response to the 8.2 and 9.3 abrupt cooling events (Alley et al., 1997; Rasmussen et al., 2008; Thomas et al., 2007). These advances are regarded as a regional phenomenon, as similar-aged moraines are found at southeastern Disko Bugt (Young, Briner, et al., 2013) as well as at a Jacobshavn tributary (Skuijuitfoq Fjord) to the north (Corbett et al., 2011). At the latter location, boulders immediately inboard of the Fjord Stade moraine yielded an average exposure age of 8.0 ± 0.7 ka (Corbett et al., 2011). Farther north, the Uummannag ice stream also experienced rapid retreat and was within its current margin by 8.7 ka following a period of stabilization (Roberts et al., 2013). At Peary Land on the Arctic coast of Greenland, radiocarbon dating of organic material within moraine and onlapping sediments places the moraine formation to between ~9.6 and 6.3 ka (Möller et al., 2010).

5. Climate Forcing of Early to Late Holocene Glaciation

5.1. Surface Air Temperature During the Late Holocene

After ~5 ka, widespread evidence of cooling across Greenland is observed in surface air temperature proxies from ice cores and lake records (Briner et al., 2016; Kindler et al., 2013; Sundqvist et al., 2014; Vinther et al., 2006, 2009). This cooling trend is in agreement with other climate reconstructions from the Northern Hemisphere (Kaufman et al., 2009; Mann et al., 2009) and is attributed to the decrease in Northern Hemisphere summer insolation across the Holocene epoch (Wanner et al., 2011). The cooling is expressed Arctic-wide with ice margin advances recorded as moraines, and increased sea ice coverage reconstructed from driftwood counts (Briner et al., 2016; Funder et al., 2011; Oerlemans, 2005; Sundqvist et al., 2014).

In the region adjacent to Washington Land, several paleoclimate records mark cooling beginning ~6–5 ka (England et al., 2008; Funder et al., 2009; Jennings et al., 2011; Lasher et al., 2017; Möller et al., 2010; Polyak et al., 2010; Vare et al., 2009; Figure 3). Just south of our study area at Secret Lake, a lacustrine δ^{18} O record

derived from chironomid and aquatic moss samples indicates cooler summer temperatures of 1.5–3 °C below present beginning at 4 ka and culminating during the LIA (Lasher et al., 2017). Surface air temperatures modeled from sedimentation in the Lower Murray Lake on Ellesmere Island indicate local surface air temperatures at ~5 ka that were 3.5 °C cooler than present (Cook et al., 2009) followed by warmer conditions similar to present temperatures between 4 and 1 ka and a cooling trend of 2 °C beginning at 1 ka and culminating by 0.2 ka. This reconstruction is consistent with several records from central Greenland ice cores including oxygen isotope and temperature reconstructions from NGRIP, a gas isotope surface snow temperature reconstruction from GISP, and a borehole temperature inversion record from GRIP in the northcentral part of Greenland as well as the more local Agassiz Ice Cap on Ellesmere Island (Dahl-Jensen et al., 1998; Kobashi et al., 2011; Lecavalier et al., 2017; Rasmussen et al., 2008; Vinther et al., 2006). Several local sites around Nares Strait document increasing sea ice cover at this time (Antoniades et al., 2008). We interpret our moraine chronology as an advance of the northwestern GIS margin in response to this widespread Neoglacial surface air cooling, which corresponds with similar features observed in other parts of the Arctic (Briner et al., 2016; Funder et al., 2011; Sundqvist et al., 2014).

5.2. Surface Air and Ocean Temperatures During the Early Holocene

Following the end of the Younger Dryas at ~11.7 ka, glaciers across western Greenland retreated from their ocean-terminating positions likely in response to a combination of rapid and sustained warming in surface air temperatures (Lecavalier et al., 2017; Rasmussen et al., 2008; Rinterknecht et al., 2014) and an intrusion of warm subsurface ocean water along the western Greenland margin (Jennings et al., 2006; Larsen et al., 2014; Rinterknecht et al., 2014). Superimposed on this large-scale retreat beginning at ~11.7 ka, glaciers across the western GIS margin advanced and stabilized to construct moraines just distal to the modern GIS margin including Humboldt Glacier (Carlson et al., 2014; Corbett et al., 2011, 2015; Lesnek & Briner, 2018; Levy et al., 2012; Möller et al., 2010; Roberts et al., 2013; Winsor et al., 2015; Young, Briner, et al., 2013). Other glacial advances along the northwestern GIS margin also occurred over this same time interval (Corbett et al., 2015; Lesnek & Briner, 2018; Young, Briner, Axford, et al., 2011, and others) and have been attributed to the rapid cooling events at 9.3 and 8.2 ka (Alley et al., 1997; Rasmussen et al., 2008), which are thought to be caused by large outbursts of freshwater from North America into the North Atlantic Ocean (Barber et al., 1999; Carlson & Clark, 2012; Clark et al., 2001; Dubé-Loubert et al., 2018). At sites near Kangerlussuag in west-central Greenland, the regional signal is much the same indicating overall retreat following the Younger Dryas with a period of ice margin stabilization by ~8-7 ka (Carlson et al., 2014; Levy et al., 2012; Winsor et al., 2015), again potentially related to the 8.2 ka event.

The short-term cooling associated with the 9.3 and 8.2 ka events is also invoked farther south in the Disko Bugt region to explain the formation of the older Fjord Stade moraines and an adjacent moraine (Corbett et al., 2011; Young, Briner, et al., 2013). While these specific events coincide with the Fjord Stade moraines, an inboard moraine was dated to ~8.0 \pm 0.7 ka using ¹⁰Be and a further inboard moraine was dated to ~7.6 \pm 0.4 ka. This suggests that the Disko Bugt area may also record the 8.2 ka cooling event, and there appear to be other instances of ice margin stabilization throughout the early Holocene warm interval ranging from ~9.3 to 7.6 ka (e.g., Corbett et al., 2011; Lesnek & Briner, 2018; Young, Briner, Axford, et al., 2011). In Baffin Bay paleotemperature data from several lakes indicate a sharp cooling of 4–5 °C relative to present day at 8.2 ka, possibly associated with not only the abrupt cooling event, but also the opening of Nares Strait (Axford et al., 2009). This is further supported by nearby ¹⁰Be and ¹⁴C chronologies that record a synchronous advance of the Laurentide Ice Sheet and regional mountain glaciers ~8.3–8.0 ka associated with the 8.2 cooling event (Young et al., 2012).

At Humboldt Glacier, the earliest portion of the HTM, as recorded in the Agassiz Ice Cap from 11 to 9 ka (Lecavalier et al., 2017), likely forced the glacier to within its modern position until a period of ice advance and stabilization around 8 ka. As noted in other studies, this moraine construction may be associated with cooler surface air temperatures during the 8.2 ka event (Alley et al., 1997) and suggests that the western GIS margin is likely influenced by centennial-scale changes in atmospheric temperature even during relatively warm periods, such as the early Holocene.

Our new data set provides evidence that the evolution of the northwestern sector of the GIS has likely been predominantly controlled by atmospheric temperature fluctuations following the Younger Dryas. The abrupt

cooling events at 9.3 and 8.2 ka (Alley et al., 1997; Rasmussen et al., 2008) punctuate the early Holocene and are recorded along the entirety of the western GIS margin. The possibility of a pre-LIA, Neoglacial advance at Petermann Glacier similarly supports that short-lived temperature changes have a significant impact on the GIS margin history and highlights the sensitive nature of the GIS to atmospheric forcings. Our data along with other studies suggests that the entirety of the western GIS margin is capable of rapid responses in accordance with centennial atmospheric temperature fluctuations and is sensitive to both changes in surface air temperature coolings and warmings.

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