10Be surface exposure ages on the late-Pleistocene and Holocene history of Linnébreen on Svalbard

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A B S T R A C T
Arctic glaciers were sensitive to past changes in high-latitude winter precipitation and summer temperature. Here we develop a late-Pleistocene to Holocene history for Linnébreen (Linné Glacier) in western Svalbard using 10Be surface exposure ages on isolated erratic and moraine boulders. We show that Linnébreen had separated from the larger ice sheet over Svalbard and was retreating up valley around the start of the Younger Dryas cold period. We attribute this retreat during a cold period on Svalbard to moisture starvation of Linnébreen from advanced sea ice and/or elevated shortwave boreal summer insolation that overwhelmed any reduction in sensible heat. After an ice-free period during the early to middle Holocene, Linnébreen reformed sometime after 4.6 ± 0.2 ka, and was at a position roughly equivalent to its Little Ice Age (LIA) maximum extent before it began to retreat at 1.6 ± 0.2 ka. Comparison with calibrated 14C dates from three other glaciers could suggest that this period of ice retreat at ∼1.6 ka could be regional in extent. Linnébreen occupied the pre-LIA moraine when there was an increased ratio of cold Arctic-sourced relative to warm Atlantic-sourced waters around Svalbard and advanced sea ice. The retreat of Linnébreen at ∼1.6 ka was concurrent with the increased presence of warm Atlantic waters around Svalbard and attendant sea-ice retreat. These coincident changes in ocean temperatures, sea-ice extent, and Linnébreen moraine age could imply a climatic forcing of the pre-LIA advance and retreat of Linnébreen. Summer temperatures, rather than changes in precipitation, would then be dominant in driving ice retreat, although the possibility of stochastic glacier-margin variability cannot be excluded. Our data therefore suggest that Linnébreen may have responded differently to past changes in sea-ice extent that could depend on the background climate state (deglacial climate vs. late-Holocene climate), which highlights the complexity in climatic controls on Arctic glaciers.

1. Introduction

A potential feedback from Arctic warming in response to anthropogenic climate change is an increase in the hydrologic cycle as sea-ice retreats (Rawlins et al., 2010; Ghattak et al., 2012). Increased precipitation could partially offset the effects of the warmer climate on many Arctic glaciers (e.g., Day et al., 2012), reducing the predicted contribution of Arctic glaciers to global sea-level rise (e.g., Radić and Hock, 2011; Marzeion et al., 2012, 2014; Radić et al., 2014). Documenting the response of Arctic glaciers to past changes in Arctic climate and sea ice, during the last deglaciation and the Holocene, is a means for assessing the importance of this potential negative feedback from sea-ice retreat (e.g., Jansen et al., 2007).
The last deglaciation (20–6 ka) was an interval of general warming in response to changes in Earth’s orbit and to rising greenhouse gas concentrations (Shakun and Carlson, 2010; Clark et al., 2012; Shakun et al., 2012). Abrupt cold events punctuated this pattern of general warming, including the Younger Dryas cold period (12.9–11.7 ka), which followed the Bølling-Allerød warm period (14.6–12.9 ka) (Svensson et al., 2008). The Younger Dryas was a return towards glacial conditions over much of Europe and Svalbard, with an advance of sea ice (Denton et al., 2005; Shakun and Carlson, 2010; Carlson, 2013). An ice sheet covered Svalbard at the Last Glacial Maximum and had significantly retreated by the time of the Younger Dryas, leaving many isolated valley glaciers (e.g., Henriksen et al., 2013; Hormes et al., 2013; Landvik et al., 2013). It is unclear if these valley glaciers advanced or retreated in response to Younger Dryas cooling, the resolution of which would help in understanding how sea-ice change impacts Svalbard glaciers (e.g., Mangerud and Landvik, 2007; Henriksen et al., 2013; Hormes et al., 2013).

The latter part of the Holocene (i.e., the last 4 ka) represents another interval of variable Arctic climate. Northern Hemisphere climate generally cooled during the mid-to-late Holocene in response to declining boreal summer insolation (Marcott et al., 2013), but the coldest Arctic conditions occurring during the Little Ice Age (LIA) (Kaufman et al., 2009; Wanner et al., 2011). Northern Hemisphere glaciers and ice caps generally advanced in response to this cooling trend, with the majority of glaciers reaching their maximum extent during the LIA, implying that the most glacial or coldest conditions existed during that period of the Holocene (Jansen et al., 2007; Miller et al., 2010). However, there is increasing evidence for a more complicated Arctic-cryosphere response to late-Holocene climate change (Baranowski and Karlén, 1976; Furrer et al., 1991; Werner, 1993; Humlum et al., 2005; D’Andrea et al., 2012; Müller et al., 2012; Badding et al., 2013; Levy et al., 2013). On Svalbard, lichenometric ages suggested that moraines outward of LIA moraines were late Holocene in age (Werner, 1993). However, the lichen growth curves used were applied beyond their calibration range of ~300 years, with the large uncertainties in this extrapolation precluding confirmation of precisely when such advances occurred (Werner, 1993) and whether they were in response to regional climate change (D’Andrea et al., 2012; Müller et al., 2012) or reflected stochastic glacier variability (e.g., Roe and O’Neil, 2005; Roe, 2011).

Here we use \(^{10}\)Be surface exposure ages on boulders to constrain the late-Pleistocene and late-Holocene history of Linnégren (bre = glacier) in Linnédalen (dal = valley), western Spitsbergen, Svalbard (Fig. 1). With our new \(^{10}\)Be chronology for Linnégren, we investigate the timing and underlying mechanisms that potentially drove past glacier retreat on Svalbard.

2. Setting and methods

Linnédalen is located at the mouth of Isfjorden, on Spitsbergen, Svalbard (Fig. 1). Linnédalen is a tributary valley that opens to the north, with land-terminating Linnégren at its head (Fig. 2). The ice margin is currently retreating within its LIA moraine. Although glaciers on Svalbard can exhibit surge behavior, Linnégren has not shown any evidence of such surge-type behavior (Svenssen and Mangerud, 1997). Down valley of the LIA moraine is an outwash plain hosting Linnéelva (elva = river), which flows into the glacially fed Linnévatnet (vatnet = lake) (Fig. 2). A series of beach terraces separate the lake from Isfjorden (Svenssen and Mangerud, 1997).

The bedrock in Linnédalen is mainly Carboniferous silica-cemented meta-sandstone.

Svalbard has an Arctic continental climate. The Longyearbyen meteorological station (Fig. 1, point 8) shows average western Svalbard summer temperatures of +4 to +6 °C, winter temperatures of −16 to −11 °C, and mean-annual temperatures of −4 to −8 °C over the last century (Førland and Hanssen-Bauer, 2003; Humlum et al., 2003). Annual precipitation is 125–225 mm yr\(^{-1}\) near Longyearbyen, but is likely higher in Linnévatnet on the western Svalbard coast (Førland and Hanssen-Bauer, 2003).

Ice completely covered Linnédalen and surrounding peaks throughout the Last Glacial Maximum (Hormes et al., 2013; Landvik et al., 2013). During the last deglaciation as ice became confined to Linnédalen (e.g., Landvik et al., 2013), local sea level reached the marine limit of 64 m above modern sea level at ~12.8 ka (Landvik et al., 1987), flooding the floor of the valley until isostatic uplift isolated the valley from the ocean by ~10.9 ka (Mangerud and Svenssen, 1990). Large deglacial boulders are present in Linnédalen above the 64 m marine limit and the modern day outwash plain of Linnégren (Figs. 3a and b). All boulders examined in the forefield of Linnégren are of the local meta-sandstone lithology.

The LIA moraine is still ice-cored and Linnégren began retreat from this moraine after 1936 based on air photo observations (Fig. 2) (Svenssen and Mangerud, 1997). Outboard of the right
lateral LIA moraine of Linnébreen is an older moraine thought to be late Holocene in age (Fig. 2), based on its location and lichenometric data (Werner, 1993). The top of the moraine has two low-relief ridges (<1 m) (Fig. 3c). Werner (1993) considered the moraine to be deposited in a single advance rather than multiple advances because there was no discernable difference in crest age or evidence of crosscutting relationships. Most of the rocks in the LIA and pre-LIA moraines are the local meta-sandstone lithology.

We collected surface samples for cosmogenic nuclide measurements from 17 large boulders from the crest of the pre-LIA moraine outboard of the LIA moraine of Linnébreen (Figs. 2, 3c and d; Table 1). Another five samples were collected from individual boulders ~0.5 km down valley of the LIA moraine (Figs. 2, 3a and b; Table 1). These five samples were >64 m above modern sea level, the height of the marine limit, and thus date last deglacial ice retreat in the valley (Landvik et al., 1987). All sampled boulders were >0.75 m in height and had >25% lichen cover (genus Rhizocarpon) to exclude boulders experiencing recent exhumation or excessive snow cover (Gosse and Phillips, 2001). Topographic shielding, thickness, and GPS coordinates were recorded for each sample (Table 1).

Samples were prepared at the University of Wisconsin—Madison (n = 11 late Holocene; n = 5 late Pleistocene) and Oregon State University (n = 6 late Holocene). All samples were crushed and separated into sand size, with magnetic grains then removed. Following etching in acid, quartz purity was checked by ICP-OES. After addition of a 9Be carrier (1 ml of ~240 9Be μg mL⁻¹ carrier at UW—Madison, 0.25 ml of ~1000 9Be μg mL⁻¹ carrier at Oregon State), each sample was dissolved in hydrofluoric acid, with BeO isolated through column chemistry and precipitation techniques. The samples processed at UW—Madison used the OSU-Blue carrier, which has a 10Be/9Be ratio of ~4e⁻¹⁶ (Murray et al., 2012). UW—Madison samples were measured by accelerator mass spectrometry (AMS) at the Scottish Universities Environmental Research Centre.
northeast North American 10Be production rate (Balco et al., 2008) to calculate the ages of our samples (Table 2) with the data).

(Licciardi, 2000; Rinterknecht, 2003) (see Table S1 for full 10Be results in our conclusions. For all 10Be ages, we do not correct for snow cover removal due to their exposure to winds (e.g., Jessen et al., 2010; Hornes et al., 2013). Because the remaining three 10Be boulder ages are not from a discrete landform, they are averaged together. Rather, the three 10Be ages are interpreted as documenting Linnébreen retreat up valley between 13.6 ± 0.5 ka and 12.3 ± 0.5 ka (Fig. 5e).

Our late-Holocene 10Be results are shown in Fig. 4b. Chauvenet’s criterion identifies one statistical outlier in 10Be boulder ages on the pre-LIA moraine crest (NG3, 3.6 ± 0.3 ka), which likely is affected by 10Be inheritance (Fig. 4b). The remaining 16 boulder ages from the pre-LIA moraine date ice retreat from the moraine at 1.6 ± 0.2 ka (Fig. 5e).

4. Late-Pleistocene and early Holocene Linnébreen retreat

The three 10Be ages outboard of the pre-LIA and LIA moraines indicate that Linnébreen had separated from the ice sheet over the west coast of Svalbard by 13.6 ± 0.5 ka to 12.3 ± 0.5 ka (blue diamonds in Fig. 5e), transitioning into a local valley glacier system (e.g., Hornes et al., 2013; Landvik et al., 2013). Because these samples were collected above the marine limit, they record the final deglacial retreat of Linnébreen, not the emergence of the valley from the ocean due to isostatic rebound (Landvik et al., 1987). Our timing of Linnébreen isolation and retreat agrees with overall Svalbard deglaciation and the timing of the regional marine limit.

At the Last Glacial Maximum, the ice sheet extended onto the western continental shelf of Svalbard, and ice-sheet retreat was well underway by 15–14 ka (Mangerud and Svendsen, 1990; Lønne et al., 1997; Henriksen et al., 2013; Hormes et al., 2013). Because these samples were collected above the marine limit, they record the final deglacial retreat of Linnébreen, not the emergence of the valley from the ocean due to isostatic rebound (Landvik et al., 1987). Our timing of Linnébreen isolation and retreat agrees with overall Svalbard deglaciation and the timing of the regional marine limit.

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3. Results

Our deglacial 10Be results are shown in Fig. 4a. Two of the five boulder ages ~0.5 km down valley of Linnébreen are significantly older than the other three (Figs. 2 and 4a) (LW15, 23.3 ± 0.6 ka; LW17, 16.2 ± 0.5 ka) and thus likely contain inherited 10Be (e.g., Chauvenet, 1991; Stone et al., 2000; Balco et al., 2008, 2009): use of a different scaling scheme results in ~6% age difference (Table 2), and therefore does not affect our conclusions. For all 10Be ages, we do not correct for snow cover and assume that our boulders would readily experience snow removal due to their exposure to winds (<5% effect on age; Gose and Phillips, 2001; Day et al., 2012). Additionally, there is no observable trend in boulder height versus age, suggesting that snow cover effect is minimal. We also do not correct for erosion, given the young age of our samples (i.e., late-glacial and late-Holocene age). We correct for the isostatic uplift that late-Pleistocene age boulders have undergone since deglaciation by calculating the integrated average elevation of each sample from regional relative sea-level curves (Landvik et al., 1987), which reduces boulder elevations by ~20 m when calculating their production rate. We excluded outliers using Chauvenet’s criterion (Balco, 2011). Because the scatter in our ages is described by the analytical uncertainty of the dates and because the ages are normally distributed based on Shapiro–Wilks’ normality tests, we use an arithmetic mean age with the standard error of the mean to define the timing of moraine abandonment. Alternatively, using an error-weighted mean does not affect our results or our conclusions (i.e., means are ~0.1 ka different from each other).

<table>
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<th>Sample</th>
<th>Latitude (DD)</th>
<th>Longitude (DD)</th>
<th>Elevation (m asl)</th>
<th>Thickness (cm)</th>
<th>Shielding Correction</th>
<th>10Be Atoms g⁻¹</th>
<th>1σ Atoms g⁻¹</th>
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aasl = above sea level.
bSample has undergone isostatic uplift; elevations should be reduced 20 m for exposure age calculation.
isolated valley glacier in Linnédalen by 13.6 ± 0.5 ka to 12.3 ± 0.5 ka.

The final deglacial retreat of Linnébreen coincides with the transition from the Allerød warm period to the beginning of Younger Dryas cold period (Svensson et al., 2008) (Fig. 5b and e). Because our deglacial samples are from isolated 10Be boulders and no moraines exist between the boulders and Linnébreen’s late-Holocene moraines, we infer that Linnébreen continued retreat after ~12.3 ka to within its late-Holocene extent (Fig. 2). Retreat of Linnébreen during the Younger Dryas cold period is consistent with other glacial records on Svalbard. Similar to Linnébreen, tidewater glaciers were more advanced than present in Svalbard fjords during the Younger Dryas (Figs. 1 and 5d) (Hald et al., 2004; Forwick and Vorren, 2009; Jessen et al., 2010; Hormes et al., 2013). 14C dates from terraces and sediment overrun by valley glaciers during the LIA show that these glaciers were already gone or retreating during the Younger Dryas: 13.2 ± 0.1 ka for Scottbreen (Mangerud and Landvik, 2007), 11.7 ± 0.3 ka for Smutsbreen (Werner, 1993), and 13.6 ± 0.1 ka for glaciers in Liefdefjorden (Furrer et al., 1991) (Fig. 1; red bars in Fig. 5e). The retreat of Linnébreen and possibly other Svalbard glaciers during the Younger Dryas, a presumably cold period on Svalbard, could reflect a reduction in glacier accumulation possibly associated with the growth of sea ice (Mangerud and Landvik, 2007). Elevated summer shortwave radiative forcing (Fig. 5a) may also have overwhelmed a reduction in sensible heat during the Younger Dryas. In contrast to these records of glacier retreat or retraction, Henriksen et al. (2013) suggested that a different local valley glacier, Olssønbreen, may have deposited a moraine during the Younger Dryas (Fig. 1, point 3). This suggestion is, however, based on two 10Be ages from the moraine of 9.2 ± 1.1 ka and 12.1 ± 0.9 ka (blue triangles in Fig. 5e), raising a question as to the precise age of the moraine, particularly because the older age is from a small cobble rather than a boulder. It is also still uncertain how the larger ice caps that persisted on Svalbard during the Holocene is, however, based on two 10Be ages from the moraine of 9.2 ± 1.1 ka and 12.1 ± 0.9 ka (blue triangles in Fig. 5e), raising a question as to the precise age of the moraine, particularly because the older age is from a small cobble rather than a boulder. It is also still uncertain how the larger ice caps that persisted on Svalbard during the Holocene is, however, needed to further test this hypothesis.
the island. Linnébreen is constrained by $^{10}$Be ages (diamonds are deglacial and circle is by Svendsen and Mangerud (1997) were likely less extensive than which suggests that the earlier possible glacier advances inferred from the Linnévatnet sedimentary record at $\sim 1.6$ ka and therefore likely reflects increased ablation of and runoff from Linnébreen, while the decrease after $\sim 0.7$ ka likely records reduced Linnébreen ablation as the ice margin advanced to its LIA maximum that it occupied up to 1930 C.E. (Svendsen and Mangerud, 1997).

Although limited, several records from other glaciers on Svalbard suggest that the retreat of Linnébreen at $\sim 1.6$ ka could have been more than just a local phenomenon. $^{14}$C dates from in situ mosses beneath Longyearbreen (Fig. 1) indicate an interval of retracted ice from $1.8 \pm 0.1$ ka to $1.2 \pm 0.1$ ka (Humlum et al., 2005) (Fig. 6c). Similarly, three $^{14}$C dates from moss between a pre-LIA till and a LIA till at Werenskioldbreen (Fig. 1) show ice had retreated between $1.5 \pm 0.3$ ka and $0.7 \pm 0.2$ ka (Fig. 6c) (Baranowski and Karlén, 1976). Ten $^{14}$C dates on organic materials that were subsequently overrun by glaciers advancing during the LIA record smaller-than-LIA ice in Liefdefjorden between $1.4 \pm 0.1$ ka and $0.4 \pm 0.1$ ka (Fig. 6c) (Peren et al., 1991). Together these dates indicate that at least two glaciers (Linnébreen and Werenskioldbreen) were retreating on Svalbard around $\sim 1.6$ ka, while Longyearbreen and glaciers in Liefdefjorden were also smaller than their LIA extents before $1.8$ and $1.4$ ka, respectively (Fig. 6c). Because these glacier records are from northern, central, and southern parts of Svalbard (Fig. 1), we suggest that this glacier retreat, or interval of retracted glaciers, could be climatically driven rather than reflect local stochastic glacier variability (Roe and O’Neal, 2005; Roe, 2011).

Foraminifera records indicate that the waters west of Svalbard were sourced from the warm Atlantic during the early to middle Holocene, with the sea-ice edge likely located north of the island (Sarnthein et al., 2003; Funder et al., 2011; Müller et al., 2012; Rasmussen et al., 2012, 2013; Werner et al., 2013). The waters west of Svalbard switched to a colder Arctic source $\sim 4$ ka (Fig. 6a) as sea-ice advanced (Sarnthein et al., 2003; Funder et al., 2011; Müller et al., 2012; Rasmussen et al., 2012, 2013; Werner et al., 2013). However, the water source (Arctic vs. Atlantic) also became volatile in the late Holocene, with centennial scale switches in water source (Fig. 6a) (Sarnthein et al., 2003; Spielhagen et al., 2011; Müller et al., 2012; Rasmussen et al., 2012, 2013; Werner et al., 2013). Following an interval of predominately Arctic waters west of Svalbard with advanced sea ice 2.8–1.8 ka, Atlantic waters penetrated northward 1.8–0.6 ka (Fig. 6a) (Sarnthein et al., 2003; Spielhagen et al., 2011; Werner et al., 2013), concurrent with sea-ice retreat (Funder et al., 2011; Müller et al., 2012). An alkenone summer air-temperature record from Kongressvatnet (lake Kong-B) in Linnédalen (Fig. 2) documents warm summer air temperatures concurrent with Atlantic water presence west of Svalbard (Fig. 6b) (D’Andrea et al., 2012). Unfortunately, ice cores on Svalbard only extend back to $1.2$ ka (Iaksson et al., 2005; Divine et al., 2011) so we cannot determine if the warm waters west of Svalbard 1.8–0.6 ka caused warmer winters on the archipelago.

This period of warmer Svalbard climate 1.8–0.6 ka is concurrent, within dating uncertainties, with the retreat of Linnébreen and Werenskioldbreen, as well as the interval of retreated ice for Longyearbreen and glaciers in Liefdefjorden (Fig. 6). We therefore suggest that the pre-LIA advance and retreat of at least Linnébreen and Werenskioldbreen were driven by oceanographic changes west of Svalbard: colder waters with advanced sea ice caused glacier advance while warmer waters with retracted sea ice drove glacier retreat. Such a connection implies that these glaciers were

5. Late-Holocene Linnébreen variability

Svendsen and Mangerud (1997) concluded that the onset of regularly laminated sediment in the Linnévatnet record suggests Linnébreen reoccupied its cirque after $4.6 \pm 0.2$ ka (youngest red bar in Fig. 5e) and before $2.8 \pm 0.1$ ka (oldest blue bar in Fig. 5e), likely in response to regional climate cooling as boreal summer insolation declined (Fig. 5a–b; Sarnthein et al., 2003; Hald et al., 2004; Marcott et al., 2013; Werner et al., 2013). Our $^{10}$Be ages from the moraine just outboard of the LIA moraine show that Linnébreen achieved an extent roughly comparable to its LIA extent $\sim 1.6$ ka and therefore likely retracted back $\sim 1.6$ ka before readvancing to its LIA position (Svendsen and Mangerud, 1997).

Based on peaks in glacier-sourced sediments, four late-Holocene advances of Linnébreen were inferred from the Linnévatnet sedimentary record at $\sim 2.8$ ka, $\sim 2.4$ ka, $\sim 1.5$ ka, and during the LIA (Svendsen and Mangerud, 1997). However, only two late-Holocene Linnébreen moraines are preserved in Linnédalen (Fig. 2). We now precisely date ice retreat from the outer moraine at $1.6 \pm 0.2$ ka, which suggests that the earlier possible glacier advances inferred by Svendsen and Mangerud (1997) were likely less extensive than the $1.6 \pm 0.2$ ka and LIA advances. Our $^{10}$Be ages also help resolve the interpretation of the Linnévatnet sedimentation record with respect to ice-margin position. The sedimentation rate in Linnévatnet began to increase before $\sim 1.4$ ka, reached a maximum at $\sim 0.7$ ka, and then decreased toward present (Fig. 6d). This increase in sedimentation rate is concurrent with our dated moraine abandonment at $\sim 1.6$ ka and therefore likely reflects increased ablation of and runoff from Linnébreen, while the decrease after $\sim 0.7$ ka likely records reduced Linnébreen ablation as the ice margin advanced to its LIA maximum that it occupied up to 1930 C.E. (Svendsen and Mangerud, 1997).

Fig. 5. Late-Pleistocene to Holocene climate and Svalbard-glacier records. (a) Boreal summer insolation at 78°N (Laskar et al., 2004), (b) NGRIP $^{18}$O (Svensson et al., 2008), (c) Two proxy-based temperature reconstructions for 30–90°N (purple; Marcott et al., 2013) and the high Arctic (blue; Kaufman et al., 2009), (d) Fjord ice-rafted debris records from Van Mijefjorden (green; Hald et al., 2004) and Isfjorden (black; Forwick and Vorren, 2009) (see Fig. 1). (e) Svalbard glacier chronology with respect to latitude on the island. Linnébreen is constrained by $^{10}$Be ages (diamonds are deglacial and circle is late-Holocene average; this study). $^{14}$C dates from Linnévatnet non-glacial sediment showing ice absence (red bars), glacial sediment showing ice presence (blue bars), and direct LIA moraine observations (blue square) (Svendsen and Mangerud, 1997). Scottbreen, Smutsbreen and Liefdefjorden glacier chronologies are from overridden $^{14}$C dated material (red bars) and observed LIA position (blue squares) (Furher et al., 1991; Werner, 1993; Mangerud and Landvik, 2007). Olsensbreen is dated by $^{10}$Be dates (blue triangles) (Henriksen et al., 2013). The horizontal yellow bars indicate intervals where these glaciers were smaller than their LIA extent and potentially deglaciated. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
responding to summer temperature changes rather than changes in accumulation. Previous studies of late-Holocene Svalbard glacier–climate relationships have come to a different conclusion. Both Müller et al. (2012) and D’Andrea et al. (2012) suggested that sea-ice advance would starve Svalbard glaciers for moisture and drive glacier retreat, whereas sea-ice retreat would increase precipitation from sea-ice retreat. This conclusion is based on the interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

6. Conclusions

We have investigated the retreat of Linnébreen on Svalbard during the last deglaciation and the Holocene using new \(^{10}\)Be surface exposure ages. We find that Linnébreen had already separated into an isolated valley glacier and was retreating around the start of the Younger Dryas cold period. We suggest that Linnébreen retreat during a presumably cold period on Svalbard is the result of moisture starvation from sea-ice advance and/or that peak boreal summer insolation overwhelmed the effect of Younger Dryas cooling. After an ice-free period during the early and middle Holocene, Linnébreen advanced to an extent roughly comparable to its LIA extent and subsequently began to retreat at \(\sim \)1.6 ka. This advance and retreat may be regional in extent, but additional \(^{10}\)Be ages are needed on Svalbard’s many late-Holocene, pre-LIA moraines (Werner, 1993) to confirm if this truly was a regional glacier fluctuation. We propose that this pre-LIA fluctuation of Linnébreen was climatically driven, because the retreat of Linnébreen was concurrent with the northward penetration of warm Atlantic waters west of Svalbard and attendant sea-ice retreat. We therefore conclude that Linnébreen may have had different responses to past changes in climate and sea ice, with a deglaciation potential driven by moisture starvation and a late-Holocene retreat driven by warmer temperatures. Further research is consequently needed on the timing and causes of glacier variability on Svalbard to understand their responses to a changing climate.

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Appendix A. Supplementary data

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References
