Glacier response to North Atlantic climate variability during the Holocene

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ABSTRACT

Small glaciers and ice caps respond rapidly to climate variations and records of their past extent provide information on the natural envelope of past climate variability. Millennial-scale trends in Holocene glacier size are well documented and correspond with changes in northern hemisphere summer insolation. However, there is only sparse and fragmentary evidence for higher frequency and continuous variations in glacier size because in many northern hemisphere regions glacier advances of the past few hundred years were the most extensive and destroyed the geomorphic evidence of ice growth and retreat during the past several thousand years. Thus, most glacier records have been of limited use for investigating centennial-scale climate forcing and feedback mechanisms. Here we report a continuous record of glacier activity for the last 9.5 ka from southeast Greenland, derived from high-resolution measurements on a proglacial lake sediment sequence. Physical and geochemical parameters show that the glaciers responded to previously documented northern hemisphere climatic excursions, including the '8.2 ka' cooling event, the Holocene Thermal Maximum, Neoglacial cooling, and 20th Century warming. In addition, the sediments indicate centennial-scale oscillations in glacier size during the late Holocene. Beginning at 4.1 ka, a series of abrupt glacier advances occurred, each lasting ~100 years and followed by a period of retreat, that were superimposed on a gradual trend toward larger glacier size. Thus, while declining summer insolation caused long-term cooling and glacier expansions during the late Holocene, climate system dynamics resulted in repeated episodes of glacier expansion and retreat on multi-decadal to centennial timescales. These episodes coincided with ice rafting events in the North Atlantic Ocean and periods of regional ice cap expansion, which confirms their regional significance and indicates that considerable glacier activity on these timescales is a normal feature of the cryosphere. The data provide a longer-term perspective on the rate of 20th century glacier retreat and indicate that recent anthropogenic-driven warming has already impacted the regional cryosphere in a manner outside the natural range of Holocene variability.

1 Introduction

Glaciers and ice caps represent a small but important portion of the cryosphere (~785,000 km^2; Dyurgerov and Meier, 2005). Their mass wasting during the 20-21st century is responsible for 60% of the sea-level rise unattributable to ocean warming (Meier, 2007) and they continue to retreat at an exceptional rate (Zemp et al., 2012). Moreover, because small glaciers and ice caps respond rapidly to climate changes and there is a strong relationship between glacier mass balance and summer temperature (Oerlemans, 2005), past glacier extent can inform us about past climate variability.

Holocene glacier activity in the Arctic is reasonably well documented at millennial timescales (Miller et al., 2010). Northern hemisphere glaciers receded in the early Holocene and were smaller than present during the mid-Holocene. Centennial-scale variations, however, are not well constrained because there are few high-resolution and continuous records, and because in many regions the most extensive glacier advances since the early Holocene took place within the past few hundred years, destroying geomorphic evidence of intervening glacier positions. This is generally the case in Greenland, where historical (AD 1200-1940) advances of local glaciers were generally the most extensive since at least the early Holocene (Kelly and Lowell, 2009).

Evidence from the Greenland Ice Sheet (Kobashi et al, 2011), marine sediments (Bond et al., 1997, Thornalley et al., 2009, Moffa-Sánchez et al., 2014; Jiang et al., 2015), and terrestrial archives (D'Andrea et al., 2011; Larsen et al., 2012; Olsen et al., 2012) indicate that abrupt changes in atmospheric circulation and ocean dynamics, including abrupt cooling events, have punctuated the Holocene. These episodes have alternately been attributed to solar variability, freshwater forcing, volcanic activity, and/or changes in Atlantic Meridional Overturning Circulation (Wanner et al., 2011). How sensitive were glaciers to these abrupt episodes, and did glaciers throughout the North Atlantic respond uniformly? During the period from AD 1250-1900, often referred to as the "Little Ice Age," well-resolved records from the North Atlantic region suggest coherence in ice cap activity that was potentially driven by volcanic activity coupled with sea-ice/ocean feedbacks (Miller et al., 2012). However, prior to the last 1,000 years there are sparse data for use in investigating the synchrony of glacier response to climate variability in the North Atlantic region.

Lakes that receive meltwater from temperate glaciers can be used to develop continuous records of glacier activity. Bedrock erosion at the base of glaciers provides sediment supply for meltwater transport to proglacial lakes. In catchments where other sources of sediment are limited, such as from mass wasting, paraglacial effects or the release of stored sediment, there is a strong relationship between sediment properties and glacier size (Nesje et al., 2000; Dahl et al., 2003; Jansson et al., 2005), which also follows from the assumption that large glaciers produce more minerogenic material and meltwater than small glaciers. Measurements of physical and geochemical properties of proglacial lake sediments can therefore be used to reconstruct records of past glacier size. Here we report a continuous 9.5 ka record of glacier activity on Kulusuk Island, southeast Greenland developed using sediment cores recovered from Kulusuk Lake (65.56°N, 37.11°W; 202 m) (Fig. 1). We characterize changes in sedimentation using measurements of physical sediment properties, including: bulk density, organic matter content, magnetic susceptibility, and accumulation rates. We also measured the relative elemental compositions of the sediment using scanning X-ray fluorescence (XRF) to characterize minerogenic changes at higher resolution and with greater sensitivity. These data provide detailed information on sedimentation in Kulusuk Lake related to glacier input.

2 Study site

Kulusuk Lake (0.8 km^2, 69 m maximum depth) is located below a cirque with two small glaciers and is within a low arctic maritime region (MAT -1°C, MAP 900 mm). Characteristic erosional features indicate that local glaciers have temperate thermal structures (Humlum and Christiansen, 2008). Distinct moraines defined by sharp crests are located in front of both glaciers and the recently glaciated area accounts for ~50% of the catchment, which is composed of Archaen gneisses (Bridgwater, 1976) (Fig. 1). Kulusuk Lake is ideally situated to capture and preserve a clear sedimentary record of glacier activity because: (i) it only receives runoff from a very small catchment (catchment:lake area ratio of ~2:1), minimizing the potential for long-term storage of sediments prior to deposition and limiting sediment input from non-glacial processes, (ii) the proximity of the glaciers to the lake results in minimal sediment transport distance, and (iii) the small size of the glaciers makes them sensitive to minor climate variations (Fig. 1). Therefore, bedrock erosion by the glaciers provides the primary source of minerogenic sediment to the lake and changes in glacier size should clearly be reflected in sediment properties.

3 Methods

3.1 Sediment core collection and analysis

Sediment cores were recovered from Kulusuk Lake in April 2010 when the lake was ice covered. Bathymetric measurements were made manually through holes drilled in the ice and sediment cores were collected using Uwitec gravity and percussion coring devices from the deepest location, which has a water depth of 69 m. A composite 3.5-m record was compiled by matching the physical stratigraphy and scanning XRF profiles from a 26 cm gravity core (Kul-10D-B) and multiple overlapping percussion cores (Kul-10G-A1, -B1, -A2).

The magnetic susceptibility of the cores was measured every 0.5 cm using a Bartington MS2E sensor. The organic-matter content of the cores was measured by loss-on-ignition (LOI) on contiguous 1-cm^3 samples taken at 1 cm intervals. Organic-matter content was calculated as the difference between the weight of dried 1-cm^3 samples and their weight after heating for 4 hours at 550°C (Dean, 1974). Bulk density measurements (g/cm^3) and the calculated sedimentation rates (cm/year) were used to determine mass accumulation rates (MAR; g/cm^2/year). Grain size measurements were made at 10 cm increments. Samples were pretreated with a 30% hydrogen peroxide solution to digest organic material and analyzed using a Beckman Coulter LS200 particle-size analyzer.

3.2 Chronology

An age-depth model was established based on ^{210}Pb analysis of the upper sediments and AMS radiocarbon dates on macrofossils. The ^{210}Pb activity of samples taken every 1-cm from the upper 10 cm of the record was measured by Flett Research Ltd. (Winnipeg, Canada) and ages were modeled from these data using a constant rate of supply model. AMS radiocarbon measurements were made on plant/wood fragments and *Daphnia* ephippia that were wet sieved from core samples. All radiocarbon ages were calibrated to calendar years using CALIB v. 6.0 (Stuiver and Reimer, 1993) with the IntCal09 calibration dataset (Reimer et al., 2009). Ages are presented in calendar years prior to AD 1950 (BP) unless otherwise indicated.

3.3 Scanning X-ray fluorescence

To characterize minerogenic changes at higher resolution and with greater sensitivity, an Itrax™ XRF core scanner was used to produce profiles of relative elemental compositions (Croudace et al., 2006). The Itrax™ continuously scans the surface of sediment cores at sub-mm resolution with a micro X-ray beam (20mm x 100 μm) and the relative concentrations of a range of elements are determined based the detection of dispersive energy spectra. Dispersive energy spectra are acquired across each measured interval and peak area integrals are calculated for each element. Peak area integrals are related to elemental concentrations within the sediment, but can also be influenced by characteristics of the sedimentary matrix and therefore only indicate relative changes in elemental composition (Croudace et al., 2006; Rothwell et al., 2006). Our analysis focused on the elements: K, Ca, Ti, Mn, Fe, Zn, Rb, Sr, which have detection limits that range from 150 ppm to 5 ppm (Croudace et al., 2006). All of the cores were scanned at 200-μm intervals with an exposure time of 10 s, voltage of 30 kV, and current of 55 nA.

4 Results

4.1 Sediment stratigraphy and chronology

The 3.5-m composite sediment record from Kulusuk Lake contains distinct lithologic changes, defined by visual stratigraphy, magnetic susceptibility, organic matter content, and elemental data acquired by scanning XRF. The record can be divided into four lithologic units (Fig. 2). Unit I, 3.0-3.5 m, is a gravelly sand. Unit II, from 3.0-1.8 m, is a massive gray clayey silt. There is an abrupt transition to Unit III, a brown, organic-rich sediment that extends from 1.8-1.2 m. Unit IV, 1.2-0 m, is a laminated sequence with frequent sandy layers. Laminations consist of fining-upward sequences and impart strong variability in all datasets.

Chronologic data show that there are significant changes in sedimentation rate that correspond to lithostratigraphic units (Fig. 2). An age-depth model was generated assuming that changes in sedimentation rate occurred at the boundaries of these units. In Unit IV, a third-order polynomial was applied to the radiocarbon ages, the core top date that represents when the cores were collected in AD 2010 (-60 cal yr BP), and the date of the base of the 210Pb profile at 10 cm (111 cal yr BP) (Table 1). This relationship was extrapolated to the base of Unit IV. Linear interpolation between the remaining radiocarbon ages was used to generate the age-depth relationship for Units III and II. There is no chronologic control below 215 cm so we did not interpret sedimentation prior to 9.5 cal ka BP.

Magnetic susceptibility, organic matter, and mass accumulation rate (MAR) profiles further define these lithologic changes with higher magnetic susceptibility values across intervals with coarser sediment and with lower organic content (Fig. 3). Moderate organic matter, 5%, and magnetic susceptibility, ~400 SI 10^{-5}, values characterize the interval from 2.5-1.8 m. From 1.8-1.6 m, magnetic susceptibility values decrease to zero and organic matter values increase to 19% (with the exception of two brief intervals of decreased values at 176 and 171 cm) and remain elevated to 1.4 m. From 1.4-1.2 m, organic content declines and magnetic susceptibility values increase and then display more minor fluctuations across the upper 1.2 m. These intervals are clearly defined by MARs, which incorporate sediment density measurements that range from ~0.8-1.8 g/cm^3, but are primarily controlled by the large sedimentation rate changes (Fig. 2).

4.2 Scanning XRF data analysis

Elemental scans acquired by scanning XRF show a similar response to magnetic susceptibility with higher values across coarser, clastic intervals. However, the XRF data have a greater sensitivity to minerogenic changes and were measured at higher resolution (0.2 mm) (Fig. 3). We focused our analysis on the elements: K, Ca, Ti, Mn, Fe, Zn, Rb, and Sr, which are common in siliciclastic sediments. Changes in the concentrations of these elements reflect changes in the contribution of minerogenic material eroded from catchment bedrock and delivered to the lake. Statistical analysis of the scanning XRF data indicate that all of the elements are highly correlated and that there is a strong primary trend in the data. Correlation coefficients show the strong significant relationships among the majority of the elements (Table 2). Rather than relying on a single element (e.g., Ti), we used principal component analysis (PCA) to define the leading mode of variability (PC1) among the elemental data. PCA allows for a multidimensional examination of the dataset in order to identify the primary signal(s). PCA results indicate that there is one strong primary trend in the elemental data with the first eigenvector (PC1) accounting for 76% of the total variance. The factor loadings reveal the high correlations between individual element profiles and PC1 (Table 2). The trends in PC1 are similar to those in the lower resolution magnetic susceptibility and organic matter content records, justifying use of PC1 data to infer past minerogenic changes (Fig. 3). The choice to use PC1 rather than a single representative element (e.g. Ti) to represent changes in sedimentary minerogenic content has no impact on any of our conclusions.

5 Discussion

5.1 Sedimentation in proglacial lakes

Sedimentation in proglacial lakes can be the result of a complex set of physical processes associated with the erosion, storage, and transport of sediment within glacial and proglacial systems (Dahl et al., 2003; Jansson et al., 2005). It is important to consider these complicating factors when selecting sites for glacier reconstructions and when interpreting sedimentary records. Glaciers fundamentally impact the amount and character of minerogenic sediment in proglacial lakes. Glacier size, erosive ability, and meltwater production directly influence the amount of minerogenic sediment delivered to a proglacial lake. However, sedimentation processes in a proglacial lake can also be impacted by mass wasting processes in paraglacial environments (particularly in landscapes with steep unstable slopes), and by the delayed release of sediment stored along the transport pathway between the glacier and the lake (for example, sediment stored in extensive meltwater stream channels). Relative to minerogenic material, organic sedimentation is typically a minor component in proglacial lakes and is related to the input of organic matter from autochthonous and allochthonous primary productivity, and the preservation therof. In proglacial environments in the Arctic, low temperatures restrict vegetation and soil cover, and minerogenic sediment input to lakes from glacial meltwater results in turbidity that impedes autochthonous productivity.

Techniques for analyzing sediment from proglacial lakes therefore focus on investigating changes in the character of minerogenic sediment. The minerogenic content of lake sediments, used as a proxy for glacier size, is commonly evaluated by measuring the magnetic susceptibility and organic matter content of the sediments. The abundance of the major elements from bedrock material (measured by XRF) similarly serve as a proxy for the relative contribution of minerogenic material, versus organic matter, to the lake. Magnetic susceptibility reflects the amount of magnetic minerals eroded and input to a lake, the abundance of major elements from bedrock (measured by XRF) also reflects the relative contribution of minerogenic material input to the lake, and organic matter content is a function of dilution by minerogenic input, changes in primary productivity, and preservation.

At Kulusuk Lake, processes that can complicate the mechanistic link between minerogenic input and glacier size are fundamentally limited. Input of sediment from non-glacial processes is restricted due to the small catchment and small catchment to lake-area ratio (~2:1), and the proximity of the glaciers to the lake. These factors also limit the potential for sediment storage between the glaciers and the lake. Furthermore, the landscape surrounding the lake is composed of shallow, low-elevation slopes that minimize the likelihood of mass wasting events. Therefore, at Kulusuk Lake, it is reasonable to interpret changes in minerogenic content as a function of glacier size.

Variations in magnetic susceptibility, organic matter content, and scanning XRF data (PC1) represent changes in the relative amount and grain size of minerogenic sediment delivered to Kulusuk over the last 9.5 ka (Fig. 3). Magnetic susceptibility and PC1 are directly related to, and organic content is inversely proportional to, minerogenic content. The highest magnetic susceptibility and PC1 values correspond to intervals with coarser grain size. We therefore interpret the sedimentological system in Kulusuk Lake as follows: During periods of increased glacier size, more coarse minerogenic sediment was eroded from the bedrock and delivered to the lake by meltwater; during periods of smaller glacier size, less minerogenic sediment was deposited and a greater relative proportion of organic matter content accumulated.

5.2 Holocene glacier fluctuations in southeast Greenland

Dramatic changes in minerogenic input to Kulusuk Lake over the last 9.5 ka reveal that the size of the Kulusuk glaciers has varied significantly throughout the Holocene (Fig. 3). Beginning c. 8.7 ka, increasing organic matter content and decreasing minerogenic content, inferred from magnetic susceptibility and XRF data, indicates significant retreat of the Kulusuk glaciers, corresponding closely in time with the deglaciation of a nearby inland catchment c. 8.4 ka

(Balascio et al., 2013), following deglaciation of local coastal areas c. 11.1-9.5 ka (Long et al., 2008; Roberts et al., 2008). A brief interval of increased minerogenic input shows that this early Holocene retreat was interrupted by an episode of advance at 8.5 ka, coeval with reductions in sea surface temperatures and bottom water circulation in the subpolar North Atlantic, as seen in high-resolution marine records (Ellison et al., 2006; Kissel et al., 2013). Another abrupt episode of minerogenic input c. 8.2 ka signifies another glacier advance. This advance occurred contemporaneously with the largest abrupt Holocene climate cooling event inferred from Greenland ice core records (Thomas et al., 2007), which is also marked by the advance of Jakobshavn Isbræ, an outlet glacier of the Greenland Ice Sheet in western Greenland (Young et al., 2011, 2013). The temporal resolution and age control of this section of our record cannot provide new constraints on the exact timing of these events, however it clearly demonstrates the sensitivity of the Kulusuk glaciers to rapid, regional climate events.

Between 7.8-4.1 ka, the Kulusuk glaciers were at their minimum Holocene extent, inferred from low minerogenic content, low MAR, and high organic matter content in the lake sediments (Fig. 3). We interpret this as an interval with little to no glacier ice in the catchment, primarily based the XRF and magnetic susceptibility data, which are lowest and show reduced variability at this time, relative to the last 4.1 ka. This interval is also marked by extremely high organic matter content that is greater than 12% (with a maximum of 19%), suggesting that this period was accompanied by an increase in primary productivity due to a lack of input of glacial flour. If the catchment was completely deglaciated, this indicates that the regional equilibrium-line altitude would have been greater than ~676 m, which is the elevation of the mountain peak above the lake. Magnetic susceptibility remains close to zero throughout the mid-Holocene section of the core and appears insensitive to the minor minerogenic changes inferred from the XRF data, which could be attributed to paraglacial processes or seasonal runoff contributing very minors amounts of clastic sediment. There are two excursions in the PC1 record during this interval (c. 7.2 and 6.2 ka), which we interpret as sediment influxes from paraglacial activity rather than as glacier advances because they are short-lived and do not match the amplitude of variation observed elsewhere. Thus, this record provides well-dated constraints on the Holocene

Thermal Maximum (HTM) in this area, which refine previous estimates extrapolated for this region (Kaufman et al., 2004) and is similar to the interval when the Greenland Ice Sheet margin was behind its present limit, broadly constrained to c. 7-4 ka (Larsen et al., 2015).

At 4.1 ka, a sharp increase in XRF- and MS-inferred minerogenic content and decrease in organic matter content, indicate the glaciers once again grew large enough to contribute minerogenic material to the lake. The regrowth of the Kulusuk glaciers represents the lowering of the regional snowline, and the precise timing could be considered unique to this catchment. However, the timing is contemporaneous with hydrologic changes at nearby Flower Valley Lake, likely related to an increase in the duration of lake ice cover (Balascio et al., 2013). We propose that this represents significant cooling and the onset of the regional Neoglacial period. The oscillatory and stepwise increase in minerogenic input (decrease in organic matter content) after 4.1 ka suggests that rather than advancing steadily toward their historical extent, the Kulusuk glaciers episodically advanced and retreated at centennial timescales until c. 1.3 ka. After advancing at c. 1.3 ka, they stabilized after 0.7 ka until their rapid 20th century retreat (Fig. 3). Importantly, the major sedimentological transitions in the record are all located near radiocarbon dates, thereby maximizing the certainty of their timing and the calculations of sediment accumulation rates. The timing of glacier size variations between radiocarbon-dated intervals since 4.1 ka are interpolated, and we estimate the accuracy to be better than ±100 years, the average 2-σ uncertainty of the ages.

5.3 Evidence for synchronous regional glacier response during the late Holocene

The Kulusuk glacier reconstruction documents centennial scale episodes of glacier advance during the Neoglacial (4.1 to 1.3 ka) coeval with other records of glacier growth in the North Atlantic region. After 4.1 ka, six major advances of the Kulusuk glaciers occurred (4.1, 3.9, 3.2, 2.8, 2.1, and 1.3 ka) and each successive advance resulted in greater glacier extent (Fig. 4). The progressive increase in glacier size is consistent with declining NH summer insolation, which is likely the mechanism driving millennial-scale changes in glacier size. However, each episode of glacier advance was followed by a period of retreat (or at least stabilization), possibly suggesting that the glaciers repeatedly grew out of equilibrium with external insolation forcing and then retreated back toward an equilibrium state showing centennial-scale variability likely driven by internal climate dynamics. The episodic advances of the Kulusuk glaciers during the past 4.1 ka are similar in timing to the cooling episodes in the North Atlantic Ocean inferred from ice-rafted hematite-stained grains identified in marine sediment cores (Bond et al., 1997, 2001) (Fig. 4). Cooling events at these times have also been documented on the East Greenland and Icelandic Shelves and attributed to increased strength of the East Greenland Current (Giraudeau et al., 2000; Jennings et al., 2002; Ran et al., 2008). Moreover, the Langjökull ice cap in Iceland advanced along with the Kulusuk glaciers and the North Atlantic IRD events (Larsen et al., 2012) (Fig. 4), and advances of the Bregne ice cap in east Greenland at c. 2.6 and 1.9 ka (Levy et al., 2014), within chronological uncertainty of the Kulusuk glacier advances c. 2.8 ka and 2.1 ka, have also been documented. We propose that continuous records of glacier activity around the North Atlantic during the Neoglacial are beginning to show evidence that suggests synchronous glacier response to abrupt episodes of climate change.

During the late Holocene, it is also worth noting that Winsor et al. (2014) found evidence for an advance of an outlet glacier of the Greenland Ice Sheet in southern Greenland ending at c. 1.5 ka, the timing of which is supported by minimum-limiting radiocarbon ages from the same region dating to c. 1.2 ka (Bennike and Sparrenbom (2007). We acknowledge that this is the only location on the ice sheet margin where such a late Holocene advance has been documented, but nonetheless it highlights that changes in the ice margin position are continuing to be constrained more accurately.

The amplitude of variability in the proxy measurements during the past 1.3 ka are lower than earlier in the Holocene, due to the greater size and stability of the Kulusuk glaciers, however, it is worthwhile to examine the changes in the sediment properties during this time where advances are interpreted as sustained above average PC1 values. The very high sediment accumulation rates during this interval (0.8 mm/yr), allow sub-annual XRF measurements and, if interpreted in the same manner as periods with smaller glacier size, can afford a detailed examination of changes in glacier size using the XRF PC1 data (Fig. 5). The overall trend reveals a small and very gradual glacier expansion after 0.7 ka followed by 20th century retreat, which resembles the overall trend in Arctic temperatures over the last 2 ka (Kaufman et al., 2009).

Multi-decadal variations in inferred glacier size during the past 1.3 ka also appear to be synchronous with those of other glaciers in the region after c. AD 1250 (Fig. 5). Kulusuk glaciers increased in size c. AD 1250-1300 and again AD 1450, similar to when ice caps on Baffin Island (Miller et al., 2012) and Iceland (Larsen et al., 2011) were expanding (Fig. 4). After AD 1450 Kulusuk glaciers continued to expand, as did Langjökull on Iceland, while evidence from the Baffin ice caps indicates continuous ice cover (Miller et al., 2012).

Both Kulusuk and Langjökull glaciers appear to have advanced in at least two phases, at c. AD 1450-1630 and c. AD 1700-1930. Magnetic susceptibility trends, linked to glacier size changes, from another high-resolution proglacial lake record on Baffin Island (Big Round Lake) reveal two similar distinct glacier advances at these times (Fig. 5) as well as an earlier advance c. AD 1250-1300, which is also observed in the Kulusuk record (Thomas et al., 2010). Varve thickness data from Big Round Lake resemble trends in magnetic susceptibility at times, however varve thickness is positively correlated with summer temperatures (Thomas and Briner, 2009). This discrepancy can possibly be attributed to how the two proxies track different sedimentary processes . Regardless, these records seem to be consistent with data from around Greenland that indicate the most extensive glacier advances since the early Holocene occurred between AD 1250-1900, and provide evidence for regionally coherent cooling phases during the Little Ice Age (Grove, 2001). We note that this timing contrasts with evidence from east Greenland that suggests the Istorvet Ice Cap advanced approximately 100 years earlier (c. AD 1150; Lowell et al., 2013), unless the data are reinterpreted as suggested by Miller et al. (2013).

Therefore, there seems to have been regional coherence in glacier activity not only during the past 1.3 ka, as previously suggested (Miller et al., 2012), but also during the past 4.1 ka, and glacier growth in response episodic climate change has been a common feature of glaciers in the North Atlantic region throughout, at least, the last 4.1 ka.

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Cold events are an important feature of centennial-scale climate of the Holocene (Wanner et al., 2011). Cooling events in the North Atlantic region are possibly associated with changes in Atlantic Meridional Overturning Circulation (AMOC) (Denton and Broecker, 2008). IRD data suggest that periodic circulation changes of the North Atlantic Ocean resulted in an advection of cold, fresh surface water south and east during ice-rafting events throughout the Holocene (Bond et al., 1997). Ocean circulation changes associated with IRD events and sea-surface temperatures have been attributed to solar forcing (Bond et al., 2001; Moffa-Sánchez et al., 2014; Jiang et al., 2015) and some modeling studies have confirmed that AMOC can switch between distinct modes in response to a small external forcing, such as solar variability (Jongma et al., 2007). However, modeling results are inconsistent and it is also possible that cooling events might have simply resulted from internal ocean dynamics (Schulz and Paul, 2002). Regardless of the mechanism, our results demonstrate that glaciers responded quite actively to natural climate variations of the Holocene.

5.4 Rates of glacier change during the Holocene

This well-dated, high-resolution record of changes in the size of the Kulusuk glaciers also allows comparison among the rates of past glacier size variations. We present relative rates of change inferred from the first derivative of the XRF PC1 data in 105-year binned averages, an interval chosen using the interval with the lowest resolution (Fig. 6). We acknowledge the caveat that they are based on the assumption that the relationship between minerogenic input and glacier size has remained constant. The analysis indicates that the rate of 20th century retreat of the Kulusuk glaciers was greater than during any other century of the past 1.3 ka, including during the Medieval Climate Anomaly. Furthermore, the 20th century retreat rate was two to three times the rate of any other period of retreat during the past 4.1 ka, and almost twice as rapid as the early Holocene retreat that marked the transition into the regional HTM (Fig. 6). This comparison helps to place the rate of 20th century glacier loss in the context of natural episodes of past glacier activity.

6 CONCLUSIONS

The Kulusuk Lake sediment record was used to generate a high-resolution record of changes in the size of the Kulusuk glaciers over the last 9.5 ka. Characteristics of the lake and catchment limit the potential for sedimentation from non-glacial processes making it ideally situated to clearly capture changes related to glacier activity. The record shows that the glaciers were sensitive to a number of previously documented regional climate fluctuations and extends our understanding of Holocene climate dynamics in this sector of the Arctic. In particular, the record clearly constrains the Holocene Thermal Maximum at this site to between 7.8 and 4.1 ka, when the glaciers likely completed melted away. The regrowth of the Kulusuk glaciers at 4.1 ka corresponds with regional hydrologic changes and reflects the onset of the Neoglacial Period. The last 4.1 ka is marked by a series of abrupt glacier advances as the size of the Kulusuk glaciers increased. These episodes of glacier growth seem to correspond with ice rafting events in the North Atlantic Ocean, as well as regional ice cap expansion, and demonstrate that glaciers in this sector of the Arctic were likely very active during the late Holocene in response to abrupt cooling events that punctuated millennial-scale insolation-driven cooling. The reconstruction of Kulusuk glacier activity provides a new and refined perspective on late Holocene cold events, which are important features of centennial-scale climate variability.

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Table 1. Geochronologic data for the Kulusuk Lake record.

Composite Depth (cm)	Description	Laboratory ID[a]	^{14}C Age (yr BP)	Calibrated Age Range (1 σ)	(2 σ)	Median Age (cal yr BP)
0	Core Top	--	--	--	--	-60
1	^{210}Pb	--	--	--	--	-53
2	^{210}Pb	--	--	--	--	-46
3	^{210}Pb	--	--	--	--	-36
4	^{210}Pb	--	--	--	--	-25
5	^{210}Pb	--	--	--	--	-7
6	^{210}Pb	--	--	--	--	24
7	^{210}Pb	--	--	--	--	44
8	^{210}Pb	--	--	--	--	57
9	^{210}Pb	--	--	--	--	83
10	^{210}Pb	--	--	--	--	111
34	Daphnia ephippia	OS-96479	335 ± 40	316-459	306-486	393
59.5	Plant/wood	UCI-89386	940 ± 20	798-914	795-919	852
95	Daphnia ephippia	OS-96454	1290 ± 25	1183-1276	1178-1283	1237
132	Plant/wood	UCI-87240	3410 ± 60	3574-3814	3484-3832	3664
138.5	Plant/wood	UCI-87241	3820 ± 60	4095-4378	4008-4415	4224
170.5	Daphnia ephippia	OS-96461	7620 ± 50	8377-8452	8359-8539	8418
214.5	Daphnia ephippia	OS-96746	8510 ± 130	9312-9659	9135-9887	9501

[a] *UCI* - University of California Irvine Keck-CCAMS Facility; *OS* - National Ocean Sciences AMS Facility

Table 2. XRF PC1 factor loadings and correlation matrix for scanning XRF elemental data.

	PC1 Loadings	K	Ca	Ti	Mn	Fe	Zn	Rb	Sr
K	0.950	1							
Ca	0.868	0.891	1						
Ti	0.969	0.938	0.797	1					
Mn	0.815	0.672	0.594	0.783	1				
Fe	0.945	0.876	0.748	0.946	0.814	1			
Zn	0.861	0.759	0.609	0.842	0.727	0.836	1		
Rb	0.831	0.743	0.601	0.791	0.637	0.790	0.727	1	
Sr	0.686	0.689	0.803	0.583	0.412	0.488	0.436	0.455	1

Figure Captions

Figure. 1 Location and catchment setting of Kulusuk Lake. The white dashed line marks the watershed boundary and the red dashed line defines the crest of moraines in front of both glaciers mapped in the field. Cores were collected in the deepest basin (red circle). (Image: Google, NASA).

Figure. 2. Magnetic susceptibility profile, percent sand, and mass accumulation rate (MAR) shown next to the age-depth model for the composite Kulusuk Lake record. The four lithostratigraphic units and the corresponding sedimentation rates are shown. A dash line marks the period below the last radiocarbon age (9.5 cal ka BP) where rates of sedimentation are extrapolated.

Figure. 3 Kulusuk Lake record. (Top) First principal component of the scanning XRF data (PC1). (Middle) Magnetic susceptibility presented on a log scale. A dotted line defines the interval from 165-140 cm where some zero values were measured. (Bottom) Organic-matter content. Black bars indicate the location and age of chronologic control points (Table 1). The yellow shaded region on the PC1 plot shows where we have interpreted little to no glacier ice in the catchment during the Holocene Thermal Maximum (HTM). Blue shading defines the Neoglacial period when ice was reformed during the late Holocene (4.1 ka–present).

Figure. 4 Regional response of glaciers to Holocene climate changes. (A) Kulusuk glaciers interpreted from PC1 data with July insolation anomalies at 65°N (Berger and Loutre, 1991). (B) Hematite-stained grains (HSG) identified in core MC52-VM29-191 interpreted to indicate ice-rafting events (Bond et al., 1997). (C) Ratio of total organic carbon to total nitrogen (C/N) and (D) changes in sedimentation rate from Hvítárvatn, interpreted to reflect changes in the size of the Langjökull ice cap, Iceland and catchment instability in response to climate cooling (Larsen et al., 2012). Yellow shading marks the timing of the Holocene Thermal Maximum (HTM), as interpreted at Kulusuk, and the dashed line on the PC1 plot shows where we have interpreted the absence of ice from the catchment during the HTM. Blue bars highlight intervals of glacier advance and increased ice rafting that define Neoglacial cooling events comparable among the records.

Figure. 5 Change in the size of the Kulusuk glaciers since AD 700 compared with other high resolution glacier and ice caps records from the region. (A.) The Kulusuk PC1 record. Black horizontal line shows average value over this period. (B.) Big Round Lake, Baffin Island, varve thickness and magnetic susceptibility (Thomas and Briner, 2009; Thomas et al., 2010). (C.) Baffin Island ice cap activity reconstructed using vegetation kill dates with text showing original interpretations (Miller et al., 2012). (D.) Langjökull ice cap, Iceland based on varve thickness from Lake Hvítárvatn

(Larsen et al., 2011). Blue shading marks periods of increased glacier size (sustained above average PC1 values).

Figure. 6 Relative rates of change in the size of the Kulusuk glaciers interpreted from scanning XRF PC1 data. Red bars show 105-year intervals when the average rate was positive indicating glacier retreat, and blue bars show intervals when the average rate was negative indicating glacier advance. Values not calculated during the mid-Holocene when we interpret glaciers to be absent.

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5	^{210}Pb	--	--	--	--	-7
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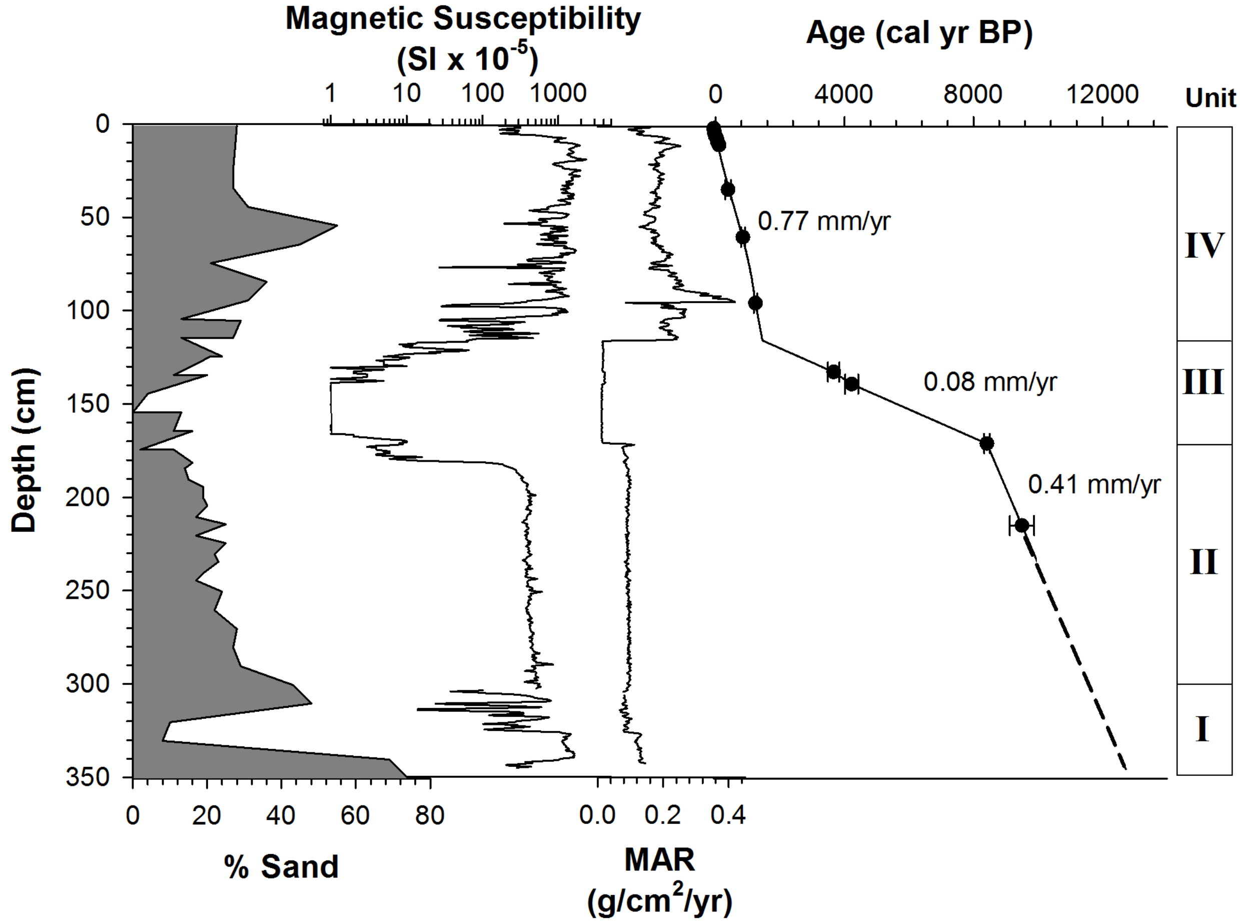
Rb	0.831	0.743	0.601	0.791	0.637	0.790	0.727	1	
Sr	0.686	0.689	0.803	0.583	0.412	0.488	0.436	0.455	1


Kulusuk
Lake
0.5 km
N

Figure 2



Magnetic Susceptibility (SI x 10^-5)
1 10 100 1000
Age (cal yr BP)
0 4000 8000 12000
Unit
Depth (cm)
0 50 100 150 200 250 300 350
0.77 mm/yr
0.08 mm/yr
0.41 mm/yr
IV
III
II
I
0 20 40 60 80
% Sand
0.0 0.2 0.4
MAR (g/cm2/yr)

Figure 3

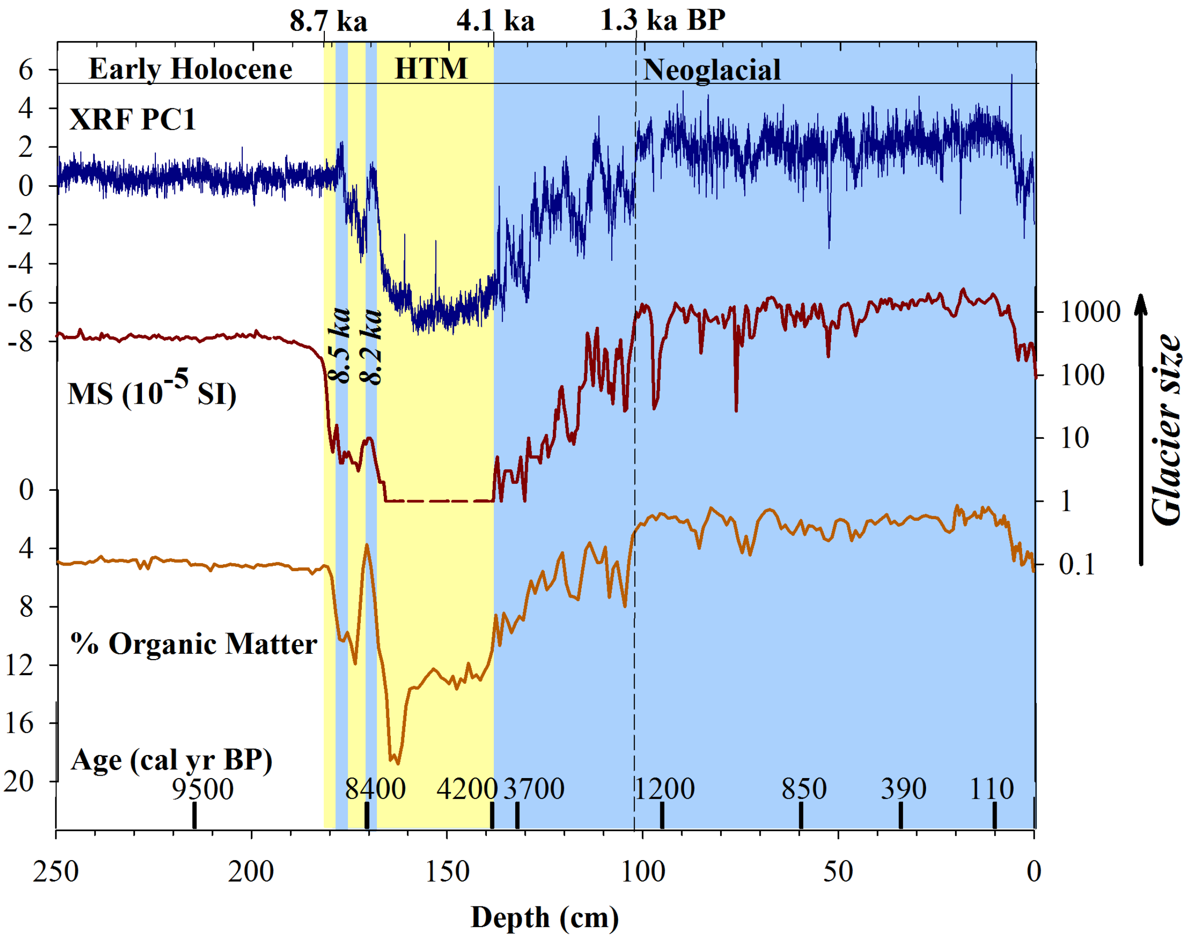

8.7 ka
4.1 ka
1.3 ka BP
Early Holocene
HTM
Neoglacial
XRF PC1
MS (10-5 SI)
8.5 ka
8.2 ka
% Organic Matter
Age (cal yr BP)
9500
8400
4200
3700
1200
850
390
110
Glacier size
Depth (cm)
6
4
2
0
-2
-4
-6
-8
0
4
8
12
16
20
1000
100
10
1
0.1
250
200
150
100
50
0

Figure 4

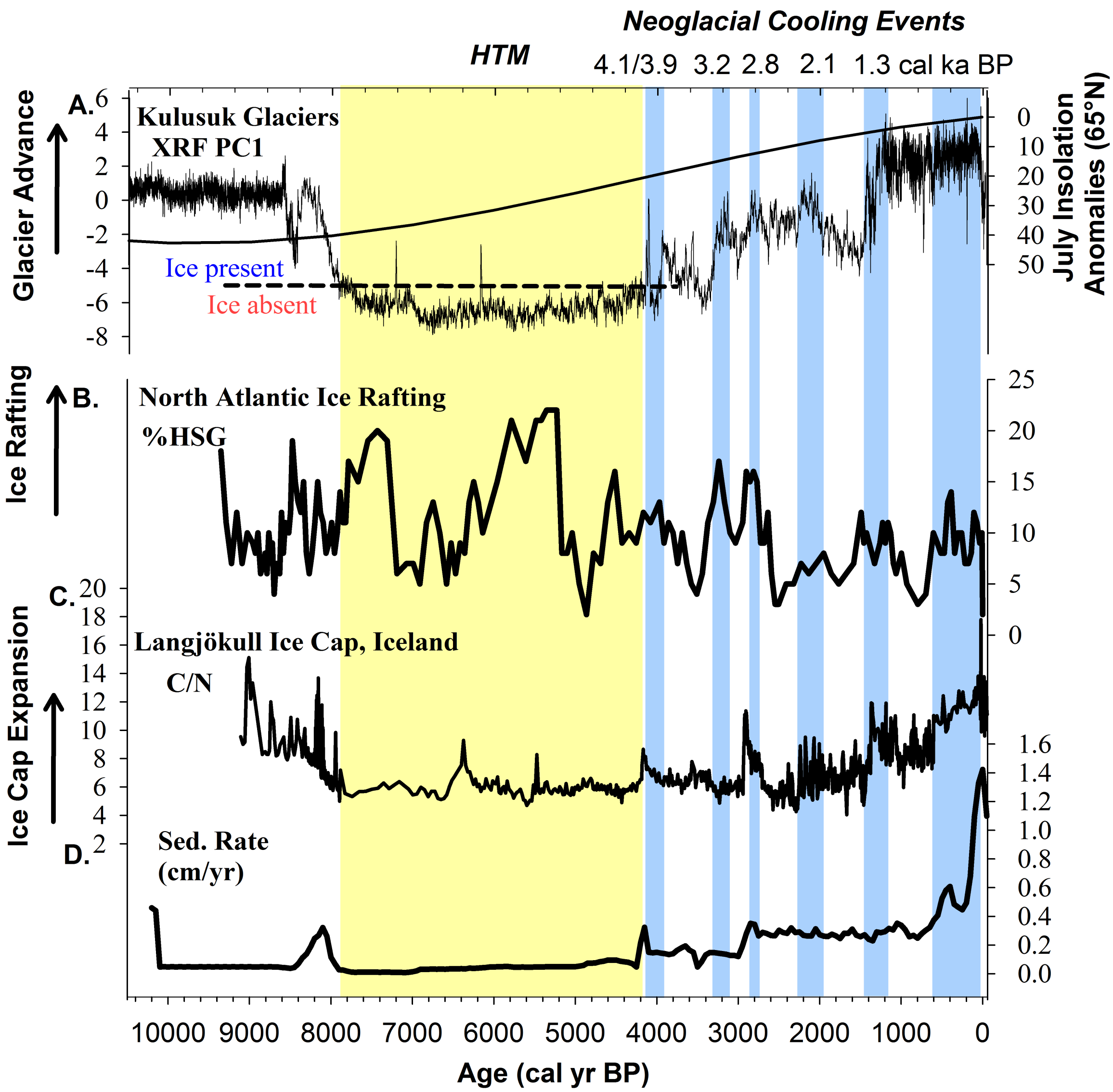

Neoglacial Cooling Events
HTM
4.1/3.9 3.2 2.8 2.1 1.3 cal ka BP
A.
Kulusuk Glaciers
XRF PC1
Glacier Advance
Ice present
Ice absent
July Insolation Anomalies (65°N)
B.
North Atlantic Ice Rafting
%HSG
Ice Rafting
C.
Langjökull Ice Cap, Iceland
C/N
Ice Cap Expansion
D.
Sed. Rate
(cm/yr)
Age (cal yr BP)

Figure 5

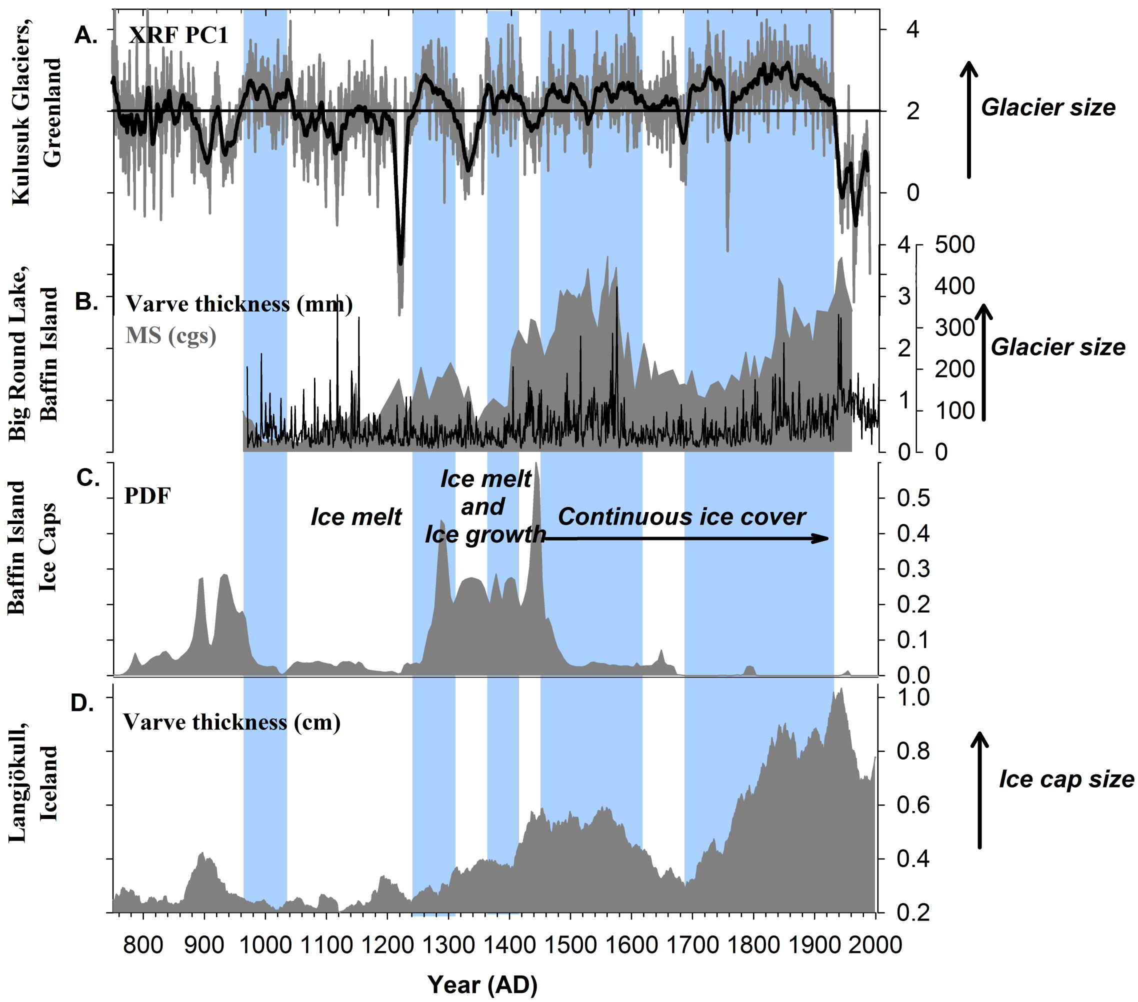
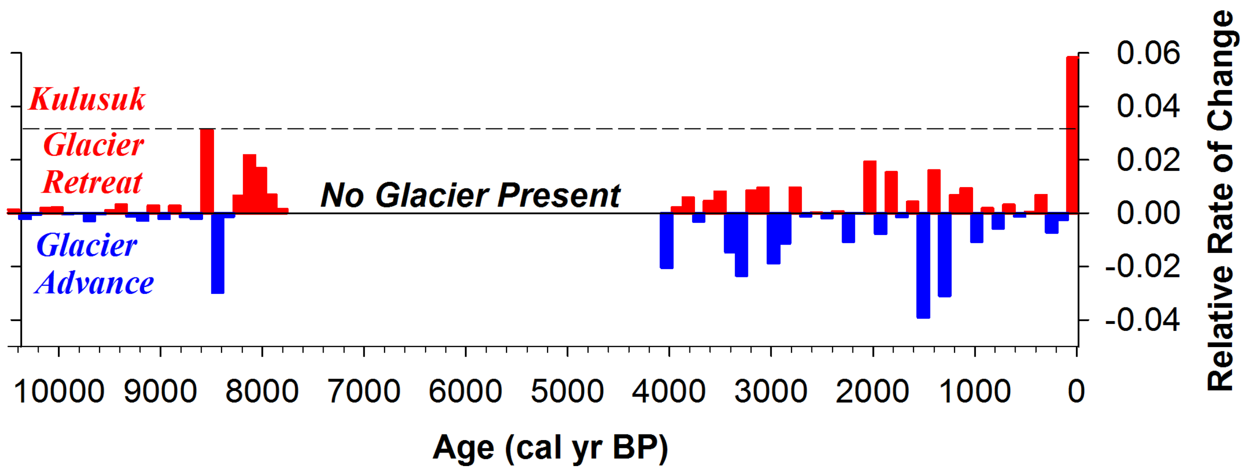

Kulusuk Glaciers, Greenland
A.
XRF PC1
Glacier size
Big Round Lake, Baffin Island
B.
Varve thickness (mm)
MS (cgs)
Glacier size
Baffin Island Ice Caps
C.
PDF
Ice melt
Ice melt and Ice growth
Continuous ice cover
Langjökull, Iceland
D.
Varve thickness (cm)
Ice cap size
800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000
Year (AD)

Figure 6



Kulusuk
Glacier
Retreat
Glacier
Advance
No Glacier Present
0.06
0.04
0.02
0.00
-0.02
-0.04
Relative Rate of Change
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Age (cal yr BP)

We appreciate the constructive comments by Anders Carlson and three anonymous referees. We have provided detailed responses to each of their comments and explain how we have modified the manuscript.

Response to Anonymous Referee #1

General Comments

I have two main substantive general comments and a few others:

1. My first main comment relates to the author's explanation of the basis for their interpretation of the XRF PC1 record. While the low-resolution (millennial) record presented in the paper is based on multiple proxies (visual stratigraphy, magnetic susceptibility, per- cent organic matter, and scanning X-ray fluorescence [XRF PC1]), the high-resolution record, which is the central focus of the paper, is based almost exclusively on the XRF PC1 record. While the other methods are well established, and their relationship to up- valley glaciation also fairly well established (%OM reflecting dilution of autochthonous and allocthonous biological productivity by glacigenic clastic-sediment input; MS re- flecting the ratio of non-weathered [glacially eroded] vs. weathered [eroded by other watershed processes] materials), the X-ray fluorescence (XRF PC1) is newer and its interpretation probably needs a fuller justification than is given in the paper. In section 4.2 the paper states that the elements analyzed by XRF "K, Ca, Ti, Mn, Fe, Zn, Rb, Sr . . . are common in silicate sediments" and that "Changes in concentration of these elements reflect changes in the contribution of minerogenc material eroded from catch- ment bedrock and delivered to the lake." What is "going up", when these elements "go down"? Organic matter? Some other type of minerogenic material that is not a product of glacial erosion? That the overall pattern of the XRF PC1 record is very similar to the patterns of MS and %OM is clear. Since the latter have been shown to be related to (driven by?) glaciation in the catchment, the authors make a plausible assumption that XRF PC1 is also driven by glaciation. Plausible . . . but I would like to see the reason- ing more fully explained – especially since record of centennial-scale glacier variation proposed in the paper is based almost exclusively on the XRF PC1 record.

-The reviewer makes a reasonable point. We overlooked explaining this because it seems quite obvious, but in fact, a line of explanation might be warranted due to the fact that XRF data are "new on the scene." The explanation for the response in sedimentary elemental composition to changes in glacier size is quite simply that the major elements we have listed and included in the PC1 are components of the bedrock. Indeed, the increase in the elemental abundances during times of larger glacier size is because there is a greater proportion of minerogenic input relative to organic input to the lake at these times. Conversely, when the glaciers are smaller the relative contribution of minerogenic (eroded bedrock) material to the lake decreases relative to organic matter. This happens due to smaller glacier size yielding less minerogenic material and also because warm intervals that result in glacier recession also result in an increase in primary productivity in the lake, and therefore increases organic matter input to the sediments. We have added the explanation of this interpretation to section 5.1, second paragraph.

2. My second main comment (which is discussed in more detail in my comment below on page 2020 – lines 3 & 4) concerns what can really be inferred from existing geochronology about synchrony/asynchrony. This is perhaps a question of predilection. I don't doubt that most of the glacial chronology developed from Kulusuk core could be synchronous with the other records cited. If one is inclined to believe that things should be synchronous, this might be interpreted as sufficient evidence to say things are synchronous. If, on the other had, one begins either without that predilection, or with a feeling that synchrony is the exception rather than the rule, I am not sure how compelling some aspects of the correlation argument would be. Why, for example, should a reader accept a suggestion that centennial-scale advances in one area dated at 2.8 ka and 2.1 ka in one area are really synchronous with those in another area dated at 2.6 and 1.9 ka, simply because they overlap "within chronological uncertainty"? All that really indicates is that it is possible that they are synchronous, not that they actually are. I am not arguing that the authors should abandon their model of synchrony, but perhaps that they should phrase it a little more carefully to suggest that the new data are permissive/suggestive of synchrony.

-We have modified the language in several places, as described in the Detailed Comments below, and also on Lines 310, 332-333, 343-344, 364-365, and 388-391 to state that the evidence we have compiled 'suggests' or 'appears to show synchrony' rather than definitively shows regional synchrony in glacier behavior.

I would feel a bit more confident in interpreting the short duration variability of the Kulusuk core as a clear indication of tributary glacier activity (rather than some sort of non-climatic event) if there were multiple cores from the lake in which the events appeared. This is particularly true of short-lived XRF PC1 that don't show up in other, lower-resolution, proxies as long as the controls on XRF PC1 aren't completely clear.

-We are comfortable with our interpretation concerning the controls on XRF-PC1 and the individual elemental abundances derived from XRF. We have also explained our interpretation of these records in the text.

Figures 2 and 3 might be combined, as there is some redundancy and a reader is left jumping back and forth from one to the other while reading the paper. If the authors do leave them as two separate figures, they might consider rearranging the axes on one or the other so they would be easier for a reader to relate one to the other.

I think the authors should introduce their approach to interpretation of the core earlier in the paper – as is, it is left to two sections on 2016 lines 20-27 and 2017 lines 14-18. I would move some of this to page 11 – at least by referring to how previous studies have interpreted specific aspects of core sedimentology as indicators of upvalley glacial activity.

-We now provide more information on our approach, including the techniques that we use to interpret minerogenic input in the last paragraph of Section 1.

Detailed Comments (note: the page numbers referred to here are off by one)

Page 2009 – line 10 – Shouldn't centennial-scale be hyphenated?
-Modified as suggested.

Page 2011 – lines 10-12 – Yes, but probably worth mentioning paraglacial effects, etc. Glaciers may not produce the highest sediment yield when they are at their max- imum extents, but rather highest sedimentation rates are commonly associated with rapid recession. Timescale is critical here. At centennial or shorter timescales, such paraglacial effects may be significant and might be expected to differ glacier-to-glacier.
-Potential influence of paraglacial effects added to this sentence.

Page 2014 – lines 11 – data show (not shows)
-Modified as suggested.

Page 2014 – line 25 – 2.5-1.8 m is not really the base of the record. The actual base (3.5 – 3.0 – shown in figure 2) shows strong variability.
-Text clarified.

Page 2015 – line 4 – MAR is shown in figure 2, not figure 3.
-Figure number changed.

Page 2015 – lines 10-12 – This is not a very clear explanation of origin of variations in the elements – when they are in low concentrations, what is replacing them, and what does that indicate about glaciation?
-We would like to leave the discussion of how we interpret minerogenic changes in the Discussion section. In the following paragraph, we do discuss in detail what drives variations in minerogenic input related to glacier activity. We have also added text to section 5.1 (2nd paragraph) to explicitly state the reasoning as to why elemental abundances reflect minerogenic input and thereby glacier size.

Page 2016 – lines 20-26 – should this explanation be placed somewhere earlier in the paper? As is, a reader not versed in these techniques would have little idea why you are measuring these characteristics and what they can tell you.
-Text has been added to the Introduction to state this information earlier in the manuscript:
"We characterize changes in sedimentation using measurements of physical sediment properties, including: bulk density, organic matter content, magnetic susceptibility, and accumulation rates. We also measured the relative elemental compositions of the sediment using scanning X-ray fluorescence (XRF) to characterize minerogenic changes at higher resolution and with greater sensitivity. These data provide detailed information on sedimentation in Kulusuk Lake related to glacier input."

Page 2017 – line 6 – Mass-wasting events are not always so easily identifiable in glacial lake sediment as this section suggests.
-Text was removed that suggested mass wasting events could be easily identified, however their presence in our record is unlikely because of the catchment characteristics, as stated in this section.

Page 2018 – line 3 – As I interpret figure 3 and the calibrated radiocarbon age, the "8.2 ka" advance was well underway by 8539-8359 BP. Is that consistent with other records of the timing of this advance. More generally – how close in time do your centennial and sub-centennial events need to be for you to consider them synchronous?

-In the previous sentence, we do acknowledge the earlier advance and provide references to other sites in the region that document cooling c. 8.5 ka prior to the 8.2 ka event. We also state clearly that the age control in this section of our record is not sufficient to exactly constrain the timing of these events, but our age model indicates they are similar in timing at centennial scale.

Page 2018 – line 11-13 – How much ELA rise would be necessary to deglaciate the drainage entirely?

-If the catchment was completely deglaciated, our data indicate that the regional equilibrium-line altitude would have been greater than ~676 m, which is the elevation of the mountain peaks above the lake. We added this information to the second paragraph of Section 5.2.

Page 2018 – line 19 – Are these two peaks based on a single measurement each? If so, how much confidence do you have that they are real?

-There are at least two data points supporting each of the peaks and therefore we do not want to discount their potential for being 'real' indicators of changes in sediment characteristics, even though they are indeed very minor sedimentary changes.

Page 2019 – line 7 – In figure 3 (or figure 5) the evidence for any sort of trend (slow or fast) after 1.3 ka is not at all clear.

-There is evidence in that data that after 0.7 ka (AD 1250) there is a very gradual increase in XRF PC1 and MS data. This is visible in Figure 3 and highlighted in Figure 5 where values are consistently above (albeit only slightly above) the average over the last 1.3 ka. We did however clarify the text where the reviewer suggested to specify that the slight increasing trend we are referring to is after 0.7 ka.

Page 2019 – line 12 – Well, since the error is the pooled sum of errors from each age and from the interpolation, I think it would be greater than this. Whatever the error on each individual age is, the error on interpolated ages would be the square root of the sum of the squares of the errors on each age and the square of the error on the interpolation. I'm not sure what that would be, but it would be greater than the 2-σ uncertainty on each age.

-We have applied a conservative estimate of uncertainty (2-σ) to the chronology. Without generating a large set of simulations for the chronology that could yield an estimate of additional uncertainty downcore, we have no way of estimating the uncertainty of error on any interpolated depth. We argue that applying the uncertainty of the radiocarbon dates obtained at intervals is appropriately (and sufficiently) cautious; it is very unlikely that the statistical exercise called for by the reviewer would change the broad picture that we observe, linking glacier changes across the region.

Page 2020 – lines 3-4 – OK, here is the crux of one of my concerns. Yes, you might be able to argue that within error 2.6 and 1.9 ka advances of the Bregne Ice Cap are synchronous with the 2.8 and 2.1 ka advances at Kulusuk Lake. (Although, if I accept your argument on the previous page – 2019 – line 12 – that the interpolated ages are accurate to better than 100 years [2σ] you probably could not make this argument on a statistically valid basis). However – really all you would be saying is that it is statistically possible that they were synchronous. It is also statistically possible that they are asynchronous. Given the mean spacing of 500 years between dated Kulusuk advances in the 4.3 – 1.9 ka interval and you willingness to accept a 200 year apparent age difference and still correlate events ("within chronological uncertainty"), it will be fairly difficult to find any dates of advances within that interval that could not be correlated within uncertainty – even if none of them were in fact synchronous.
My concern here is that while the records you cite, and with their uncertainties, allow the possibility of correlation, I am uncomfortable saying that they prove the correla- tion. If you are inclined to believe that such events are in fact correlated, you can find in these data evidence to support that belief. On the other hand, I do not think that the chronologies are really well enough constrained that they preclude the possibility that for whatever reason (regional differences in climate forcing, differences in sys- tem response times, paraglacial sedimentation effects) that the events recorded are in fact out of sync by a century or more – a significant interval when one is considering centennial-scale climate.

-We stand by this observation and we are comfortable offering it as a discussion point in this manuscript. We cannot "close the case" on this and say with 100% certainty that all centennial-scale changes in glaciers around the North Atlantic have been synchronous, and we have not done this. However, we are comfortable proposing that there is evidence for synchronicity and that the Kulusuk record adds to this evidence.

Page 2020 – line 15 – I don't really see evidence for this "slow and very gradual expan- sion after 1.3 ka". Perhaps from 1.3 to about 0.75 ka, but there really does not seem to be any trend after about 0.75 ka. If anything, there might have been an overall step change at about 0.75 ka.

-We have added text to clarify here (as we did earlier in the manuscript, above) that there is evidence after 0.7 ka indicated by a gradual increase in XRF PC1 and MS data. This is visible in Figure 3 and highlighted in Figure 5 where values are consistently greater than the average over the last 1.3 ka.

Page 2020 – line 21 – "Precisely"? Looking in detail at figure 5 – your blue lines ("periods of increased glacier size" – at Kulusuk? or generalized for all areas?) seem to bracket periods of highest glacigenic sedimentation (highest XRF PC1) at Kulusuk, but commonly seem to end just as glacigenic sedimentation rates are increasing at Big Round Lake on Baffin and especially at Langjökull in Iceland. Perhaps we are looking at a paraglacial effect in the latter two areas and not at Kulusuk – but in any case, the records do not seem "precisely" the same.
-Text was modified to indicate the timing is "similar"

Page 2020 – line 22 – I think you mean figure 5 here for Baffin Island at least.
-Text modified as suggested

Page 2020 – line 22 – What evidence for post-1450 expansion?
-We do have language in the figure caption indicating that we are interpreting periods of advance as, "sustained above average PC1 values." We have also added a similar statement at the beginning of Section 5.3 so this is clearer (lines 357-358)

Figure 1 – Moraines seem to extend beyond the red line on the northern glacier.
-These lines define the primary ridge crests mapped in the field. Text was added to the caption to clarify.

Figure 3 – I don't see the dashed line on the PC1 plot.
-Text was removed.

<u>Response to Anonymous Referee #2</u>

My only suggestion here would be to throw in a sentence or two in the final conclusions section that again highlights the unique lake setting and why the authors were able to generate such a clean glacier signal from proglacial sediments. I think it is that important.

-A sentence was added to the conclusions highlighting the geomorphic setting, as suggested.

Comparison to Greenland Ice Sheet fluctuations: The authors have noticeably stayed away from comparing their record of cirque glacier fluctuations to recorded fluctuations of the Greenland Ice Sheet margin. I'm guessing that the authors wanted to compare "apples to apples" and just stick to other cirque/mountain glacier records. Rather, you can back out a climate record from cirque glacier fluctuations, but not really from ice sheet fluctuations. I think that approach is fine, but a brief paragraph that makes a few links to the GIS would make this paper stronger and likely garner more citations, while at the same time it would remain clear that this paper's focus is on climate records that can be deduced from cirque glaciers. It looks like Carlson eludes to this very same point with his posted comment on the interactive discussion page that accompanies this manuscript. Again, a paragraph making the link between key advances seen in the Kulusuk record and key advances of the GIS margin would make for an important paragraph. Luckily for the authors, but unfortunately for the scientific community, the list is going to be short as the detailed Kulusuk record spans an interval where detailed GIS margin records are lacking. The authors could mention the ~1.5 ka advance seen in both the Kulusuk and GIS records that Carlson suggests, and also mention the clear 8.2 ka advance seen at in the Kulusuk record and the glacier margin record at Jakobshavn Isbræ. For the 1.5 ka advance from the southern GIS per Carlson's suggestion, I would add the caveat that this is the only place along the GIS margin where this advance is seen, and unlike the 8.2 ka event for example, there is not a clear and well-established cooling event at 1.5 ka that can easily explain the synchronous advance of both types of ice margins. The 1.5 ka advance could indeed have been driven by cooling, but it could just as easily been driven by ice dynamical processes and the timing is just pure coincidence. Again, I would add this record to the text, but just include the aforementioned caveat. For the 8.2 ka records, the authors could even mention that the coeval response of the small and responsive Kulusuk glacier and Jakobshavn Isbræ speaks to the sensitivity of GIS outlet glaciers. Rather, here is direct evidence that at least a portion of the GIS is able to respond just as quickly to a climate perturbation as a small 'responsive' cirque glacier. This would be an interesting and important point because the authors use the small and responsive cirque glacier argument as part of their initial motivation for this study. The appropriate references for the 1.5 ka advance of the GIS are Bennike and Sparrenbom, 2007; The Holocene, v 17 and Winsor et al., 2014, QSR, v. 98. For the 8.2 ka event related GIS papers, the authors could consult Young et al., 2011, Geophysical Research Letters, v. 38 and Young et al., 2013, QSR v. 60.

-For the reasons that the reviewer states, we had avoided comparisons to fluctuations of the ice sheet margin, but we have now included some references to provide readers with information about the Greenland ice sheet margin during the Holocene. We added a sentence stating that that [at least] one area of the Greenland ice margin did respond to the 8.2 ka event (Young et al., 2011, 2013) (lines 279-281) and a paragraph discussing the late Holocene advance of the southeast sector of the ice sheet based on Winsor et al. (2014) and Bennike and Sparrenbom, 2007) (lines 346-352).

Comparison to other regional records of glacier variability over the last ~1200 years: The authors try to make the case that the Kulusuk record is coeval with the Baffin Island record of ice cap expansion. The authors state "Kulusuk glaciers increased in size ca. AD 1250–1300 and again ca. AD 1350 and AD 1450, precisely when ice caps on Baffin Island (Miller et al., 2012) and Iceland were expanding." I agree that there is synchronous ice-cap expansion at ~ AD 1250-1300. This is the first sharp peak in the Baffin Island probability plot and also coincident with a period of extreme volcanism (cited cooling mechanism in Miller et al., 2012). However, I think the authors here are misinterpreting the Baffin probability plot a bit, maybe in a bit of an effort to argue for more synchroneity that there actually is. Mainly, a period of synchronous glacier expansion at ~1350 AD is a bit of a stretch. I see this pulse in the Kulusuk record, but this coincides with a period of ice growth and melt in the Baffin probability plot, not just ice expansion. Rather, the entire Baffin probability hump is not one large period of ice-cap expansion, nor can you pick out pulses of ice-cap expansion beyond the 1275 and 1450 AD peaks; those are the only clear pulses of ice-cap expansion (both peaks linked to volcanism). To make a claim about synchronous glacier growth at 1350 AD is not supported. Moreover, the overall comparison between the Kulusuk record and the Baffin Island record is a bit tenuous because while I agree there are similarities between the two beginning ~1275 AD, this relationship breaks down back in time. In fact, the Baffin Island record depicts ice cap expansion between ~AD 875- 975 whereas the Kulusuk record depicts the exact opposite – a significant period of glacier recession at the exact same time. I think at best the authors can claim there appears to be a synchronous advance at ~1250-1300 AD, and that glaciers remain extended after AD 1450, which is also seen in the Iceland and Baffin lake records. I would modify this text accordingly and make note that prior to ~AD 1275 there does not appear to be much similarity. This does not include the mention of glacier expansion coincident with Bond events seen in the Kulusuk and Iceland lake records, this is all fine and good.

-We agree with the reviewer and have modified the language in this section (Lines 365-367). We back off the strength of our language and use of the word, "precisely" to describe the similarities among records. We now state that the advances of the Kulusuk glaciers and ice caps on Baffin Island and Iceland are 'similar' after AD 1250 and correlate during the intervals AD 1250-1300 and AD 1450.

Minor comments:
Page 2011, line 15: maybe add "geomorphic" before "evidence"
-Change made as suggested.

Page 2020, line 21: "possibly" instead of "possible"
-Change made as suggested.

Page 2021, line 13: "Likely" seems a bit strong here. This paper presents a valid hypothesis, but "likely" makes it sounds as if this hypothesis is set in stone.
-Change made as suggested using 'possibly' instead of 'likely'

Figure 3 caption: Does there need to be letters in the figure that correspond to the a,b.c in the caption? Also, I see no dashed line on the PC1 plot. I see the dashed line down in Figure 4, but not Figure 3.
-Figure captions updated

Response to Anonymous Referee #3

Holocene Thermal Maximum:
p. 2019, lines 22-24: this study ". . .refines previous estimates for [the HTM] onset and termination", but does not clarify in what way these estimates are refined. Does the 7.8 to 4.1 ka HTM in Kulusuk align with estimates of HTM, as described in Kaufman et al. (2004)?

-The Kaufman et al. (2004) estimates are based on extrapolated estimates from sites around this region and roughly place the HTM in the early-to-mid Holocene (roughly 9-4 ka). Text has been added to the sentence to clearly state this, Lines 301-303.

It would be informative to address whether the Kulusuk data align with the body of work examining North Atlantic glacier and Greenland Ice Sheet response to early Holocene warmth (e.g., Briner et al., 2014; Funder et al., 2011; Larsen et al., 2015; Lecavalier et al., 2014; Solomina et al., 2015; Tarasov, 2003).

-We agree that some mention of Greenland Ice Sheet margin reconstructions are necessary, as also suggested by Reviewer #2. However, we do not agree that all of the references listed by Reviewer #3 are comparable. We have primarily focused on comparisons to high-resolution and continuous records. Moreover, we want to compare our site to small glaciers and ice caps that likely respond rapidly to climate changes, whereas the response of the Greenland Ice Sheet is more complicated due to large-scale ice dynamical processes and many of the studies cited only broadly define trends in the extent of the ice sheet. We have added references to Young et al. (2011, 2013), Winsor et al. (2014), Bennike and Sparrenbom (2007), and Larsen et al. (2014), which now provide readers with some context to the response of the ice sheet during the period we examine of the Kulusuk record.

There is some signal and variation in the XRF PC1 data from 7.8 to 4.1 ka, so there must be some source of allochthonous minerogenic material, even though the glaciers were small or absent. What is the source of this material? Could the source be per- mafrost and periglacial processes? Or snowmelt and rainwater runoff? Or something else?

-This minor signal in the XRF data likely indicates some input from runoff or paraglacial processes. We added text to state what the processes that could be responsible for any minerogenic input during this interval.

Interpreting centennial-scale variability after 1.3 ka:

Because small-scale variability exists in the XRF PC1 from 7.8 to 4.1 ka, when the authors assume that the Kulusuk glaciers were small or nonexistent, it is unclear to me how the small-scale PC1 variability after 1.3 ka, which is of a similar magnitude to the PC1 variability from 7.8 to 4.1 ka, can be interpreted to represent changes in glacier size. Could this variability be related to other sources of allochthonous minerogenic material?

-We agree that the centennial-scale trends after 1.3 ka are minor, but it is not appropriate to directly compare it to the interval from 7.8-4.1 ka. The mid-Holocene interval is marked by the extremely low and sustained magnetic susceptibility values, high organic matter content, and low sedimentation rate. After 1.3 ka, MS values are very high, the sediment is laminated, with strong variability in the XRF data and the sedimentation rates are higher. Therefore the processes driving minerorgenic input are quite different.

Synchrony of glacier & climate response:

I agree with Reviewer 1 about interpreting synchrony. It could be helpful to use prob- abilistic methods (an example is Anchukaitis and Tierney (2012)) to determine the likelihood of synchrony between the different glacier and climate records.

-A statistical analysis similar to the one suggested by the reviewer is beyond the scope of this paper. It would require significant additional effort to assemble chronological data from sites that we have not worked on. We encourage the reviewer to carry out such a regional analysis, to assess whether the conclusions that we have drawn stand up to further scrutiny.

Minor comments:

p. 2010, lines 6-9: Perhaps "continuous records of variations in glacier size" is more appropriate than "higher frequency variations in glacier size": sites in the Arctic that do have early Holocene moraines (e.g., Alaska) don't necessarily have centennial resolu- tion.

-Text modified as suggested.

Geochronological data:

How do the authors deal with terrestrial vs. aquatic 14C ages? There is often a reser- voir effect in arctic terrestrial 14C ages, due to storage in permafrost.

-We have dated macrofossils from terrestrial and aquatic sources and there doesn't appear to be a reservoir effect in this system, which would likely show-up as large age offsets between samples that we do not observe.

Some geochron. information that is important to provide for recalculation if necessary in the future: Raw 210Pb activity data used to model the age of surface sediments. Fraction Modern for 14C measurements

p. 2020 line 19-p. 2021, line 7: It seems to me as if there are two separate mechanisms being called upon here as the main driver of glacier change: insolation and North Atlantic cooling. Right now the following two statements seem rather disparate:
p. 2020 line 20-23: "each episode of glacier advance was followed by a period of retreat. . .possible suggesting that the glaciers repeatedly grew out of equilibrium with external insolation forcing and then retreated back toward an equilibrium state"
p. 2021 line 5-7 (following discussion of synchronous ice rafting/cooling events in the North Atlantic and ice cap advances in Iceland and Greenland) "continuous records of glacier activity. . .reveal synchronous glacier response to abrupt episodes of climate change".
These two statements are not necessarily independent from each other, but it would be helpful to clarify which mechanism is most likely causing the observed changes. Or are both mechanisms at play? This would be good to clarify.

-Text was added to the first paragraph of Section 5.3 (lines 321-326) to more clearly explain that: On millennial time-scales the glaciers are responding to insolation changes. So the gradual decline in northern hemisphere summer insolation is driving the progressive growth of glaciers from the mid- to late Holocene. Superimposed on that long-term trend is centennial-scale variability likely driven by dynamics internal to the climate system.

Fig. 1: Would it be possible to add bathymetry of Kulusuk Lake? This would help clarify if there are bathymetric highs related to glacier deposition (e.g. moraines) that may have been deposited during the period studied and therefore influence the "glacial" signal in the lake sediments.

-Unfortunately, detailed bathymetric data is not available that would resolve the features the reviewer is interested in.

Fig. 2. What does percent sand indicate? Could it be a signal of IRD? Why is Holocene maximum percent sand not at maximum glacial extent inferred from other proxies (ap-prox. 10 cm)?

-The grain size measurements were made at much lower resolution (every 10 cm) so can't be compared directly to the other proxies. We use it to show how overall the amount of coarse sediment changes across each interval.

Fig. 3: Add a, b, c labels and dashed line on PC1 indicating absence of ice.

-Labels added and the reference to the dashed line was removed.

Fig. 4: What data are yellow and blue shading based on? The Kulusuk record, or previous publications?

-More detail was added to the figure caption to explain that the yellow shading is based on Kulusuk data, and the blue bars indicated cooling events that are comparable among the records.

Figs. 4 and 5: Why use different data in Fig. 4 and 5 to represent Langjökull? Do the C/N and sedimentation rate data in Fig. 4 reveal the same patterns as varve thickness in Fig. 5?

-C/N and sedimentation rate do generally resemble trends in varve thickness over this time interval. We choose to present the data this way because the varve data is the highest resolution proxy at that site and we are comparing high resolution data over the last 1200 years.

It would be informative to show the full Holocene magnetic susceptibility record from Big Round Lake. The timing of minimum Holocene glacier extent from the Big Round Lake record is different than at Langjökull and Kulusuk glaciers, but that is interest- ing information, which perhaps tells us something about regional climate and glacier variability.

-We don't agree that the full comparison would be worth adding to the manuscript.

It seems important to mention the different glacier-lake systems shown in Figs. 4 and 5. The transport path between Kulusuk glaciers and Kulusuk Lake and Langjökull and Hvítárvatn is much shorter than the transport path between the glacier and Big Round Lake, so there could be more sediment storage and other related processes influencing the Big Round Lake record. For example, MS seems to reflect thickness of sand layers deposited in late summer, so higher MS at 1250-1300 AD is perhaps not solely due to glacier activity. Big Round Lake varve thickness was originally interpreted to represent temperature, the opposite interpretation is used here. It seems important to at least mention the differences between these sites, and to mention the difference in interpretation from the original publication.

-We agree that we didn't provide enough context when including the Big Round record and its interpretation. We have now added a more detailed explanation (Lines 372-). On longer timescales, the magnetic susceptibility data from Big Round have been interpreted as indicating glacier size changes (Thomas et al., 2010) and it is worth showing that there are interesting similarities in trends among the records we present in Figure 5. We also include the varve thickness data because at times it also resembles MS, although not at all intervals, even though there is a significant correlation between varve thickness and summer temperature that cannot be ignored (Thomas and Briner, 2009). We suggest that both interpretations can still be valid and that the discrepancy in the proxies could be related to the timescales on which they affect sedimentation and/or the geomorphic characteristics of the proglacial system, which as the Reviewer points out, is different than Kulusuk and Langjökull.

Response to A. Carlson

Dear Balascio et al., I am intrigued by your study and would like to point you to another record of late Holocene glacier change (and summary of southern Greenland records) that was presented in Winsor et al. (2014, QSR). This study found a glacier advance in southern Greenland ending at ~1.6 ka, similar in timing to your advance documented in Kulusuk.

-We appreciate the comment and reference to a related study from the Greenland Ice Sheet margin. As mentioned above in responses to suggestions by Reviewer #2 and #3, we were originally avoiding comparisons to the ice sheet margin because of the potential differences in response time and influence of large-scale ice dynamical processes that might complicate movement of the ice sheet margin. However, it does seem appropriate to reference ice sheet margin advances to provide a more complete context for our study. In reference to your specific comment, we have added a citation to this paper and a paragraph discussing the late Holocene advance of the southeast sector of the ice sheet (Section 5.3, 2nd paragraph).