Mountain glacier fluctuations during the Lateglacial and Holocene on Clavering Island (northeastern Greenland) from ^{10}Be moraine dating

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Despite an increasing interest in Greenlandic mountain glaciers over the last decades, their evolution during the Lateglacial and Holocene still needs to be better constrained. Here we present 25 ^{10}Be cosmic-ray exposure (CRE) ages of boulders collected on moraines from three glaciers located on Clavering Island (northeastern Greenland). CRE ages span 16.29±0.79 ka to 0.37±0.05 ka and reveal three periods of moraine formation during the Lateglacial, the early and the late Holocene. Data show a multimodal distribution of the ages during the Lateglacial with exposure ages spanning from 16.29±0.79 ka to 12.31±1.3 ka. At least two glaciers experienced a greater expansion at the beginning of the Holocene than at the end of the Holocene, dated to 11.3±0.3 ka and 10.8±0.6 ka, respectively. At the end of the Holocene, glacial advances occurred during the Dark Ages Cold Period and the during the Little Ice Age (LIA), synchronous with glacial advances documented in nearby lake sediments. This new CRE chronology highlights that the LIA extent is not the largest glacier advance in the Late Holocene in Clavering Island. This broadly corresponds with other mountain glaciers of western and northern Greenland, and does not appear to reflect northern high latitude summer insolation that would suggest progressive temperature decrease, but instead mimics recent regional continental temperature reconstructions that show a long term warming driven by different forcing.

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From the Lateglacial to the end of the Holocene, Greenlandic ice core records (e.g. GRIP, NGRIP and GISP2 projects) reveal a period of fluctuating climate with strong centennial-scale variability in the order of 1-2 °C throughout the Holocene (Vinther *et al.* 2006, 2009; Kobashi *et al.* 2017). Due to their sensitivity to summer temperature and their short response time, the numerous mountain glaciers (or local glaciers as described by Kelly & Lowell (2009)) at the periphery of the Greenland Ice Sheet (GrIS) offer a unique opportunity to analyze glacier response to these periods of fluctuating palaeo-climate conditions (Masson-Delmotte *et al.* 2012). The application of the cosmic ray exposure (CRE) dating to moraine boulders is a pertinent method for obtaining direct evidence of the glacier history (Gosse & Klein 2015). However, despite some studies that focused on local glacier fluctuations over the last decades (Kelly & Lowell 2009; O'Hara *et al.* 2017; Schweinsberg *et al.* 2019), robust moraine chronologies based on CRE dating remain limited in Greenland. As a result, it is difficult to determine the chronology of the Holocene maximum extent, the possible regional asynchronies of this maximum extent in Greenland and the external/internal climate forcing responsible for this change of behavior.

At present, the most reliable CRE dating reconstructions of mountain glacier fluctuations since the Lateglacial Maximum (LGM) are in northwest and northeast Greenland. At Jensen Land, north Greenland, ^{10}Be CRE dating evidences a Younger Dryas (YD) glacier advance (and subsequent retreat) of three glaciers. The Sifs valley moraine, the Henson Bugt moraine, and the Moore glacier moraine are dated at 12.1±06, 12.8±0.8 and 12.8±0.7 ka, respectively (Möller *et al.* 2010; Larsen *et al.* 2016; O'Hara *et al.* 2017). This is one of the only Greenlandic mountain glacier locations where a YD readvance has been documented. However, the Holocene trend of these glaciers behaviour remains unknown. Further south, on Disko Island, west Greenland, Jomelli *et al.* (2016) provided ^{36}Cl CRE ages for four moraines from Lyngmarksbræen glacier dated to the Lateglacial/Holocene transition (11.9±1.7 ka), and during the last millennium (0.82±0.13, 0.57±0.09, and 0.3±0.06 ka), with the largest glacier extent prior the Little Ice Age (LIA ~ AD 1450 to AD 1850). Close to Disko Island, a local glacier from Nakàgajoq advanced at 10.4±0.2 ka (O'Hara *et al.* 2017), and at Uigordleq Lake Young *et al.* (2015) provided evidence of a glacial advance during the period of the Medieval Climate Anomaly (MCA ~ AD 950 to AD 1250) from a moraine dated to 0.8±0.04 ka. Finally, two glacial advances were dated from a local glacier on the Nuussuaq Peninsula, with the largest advance occurring at 1.5 – 0.7 ka, and a second less extensive advance occurring during the LIA (Schweinsberg *et al.* 2019).

In Scoresby Sund (northeast Greenland), ^{10}Be CRE ages of bedrock and boulders down valley from moraines indicate that Bregne ice cap was within 250 m of its present-day limit by at least 10.7 ka (Kelly *et al.* 2008; Levy *et al.* 2014). A second Late Holocene or LIA unweathered and unvegetated moraine was identified, but uncertainties associated with the ^{10}Be CRE ages prevented precise dating. Nevertheless this glacier advance during Historical time was the most extensive since the Early Holocene. Results from Milne Land, Scoresby Sund, reveal that a local glacier retreated during the YD and deposited the inner Milne Stade moraines at ~11.4 ± 0.6 ka, in phase with fluctuations of the GrIS Fonfjord marine outlet glacier (Levy *et al.* 2016).

Overall, our understanding of local mountain glacier fluctuations since the Lateglacial based on CRE ages remains elusive, due to: (i) the limited number of mountain glaciers studied, (ii) the uncertainties concerning the age of moraine deposition, and (iii) the difficulty of developing a continuous Lateglacial to Late Holocene glacial chronology at the same site, either because of field constraints or CRE dating uncertainties. To improve knowledge of glacier behaviour through the Lateglacial and Holocene, we present a new ^{10}Be CRE dating based on moraine chronology from three mountain glaciers on Clavering Island, northeast Greenland. We then compare our local glacier chronology to independent lake sediment records close to our study area and with previously CRE dated local glacier advances in other parts of Greenland.

Regional setting

Clavering Island is located in High Arctic northeast Greenland (74°N) in Gael Hamkes Bugt (Fig.1A). The island has a surface area of ~1500 km² and is located ~8 km south of the Zackenberg Research station. The basement rocks are primarily granite and gneiss combined with some mica-schist and basalt (Koch & Haller 1971). The island hosts two main ice caps; the Skillgletcher ice cap on northern Clavering Island is ~250 km², with a highest point at 1619 m a.s.l. and a depth < 200 m and Taggletscher, a smaller ice cap (~16 km²) on the southern part of the island. Smaller valley glaciers are also present, mostly in the Northern part of the island. The region has a typical High Arctic climate (Kottek *et al.* 2006), with mean annual air temperature of -9 °C (annual range: ~ -24.5 to 6.6 °C) based on 1996–2015 values measured at the Zackenberg Research station (Hobbie *et al.* 2017). Summer air temperature averages 4.5 °C (Hobbie *et al.* 2017) and average precipitation is 200 mm a^{-1} (Hansen *et al.* 2008).

This study focuses on the Theodolit plateau (Fig.1B) and, more specifically, on three glaciers flowing to the northwest on the west side of the Skillgletcher ice cap, informally named TheoA, TheoB, and TheoC. TheoA glacier is the smallest glacier with a catchment area of ~3.5 km² and with an elevation range between 1466 and 660 m a.s.l. TheoB glacier is the largest glacier with a catchment area of ~7 km² and an elevation range of 1547 to 620 m a.s.l. A proglacial lake (~0.3 km^2) has formed in front of TheoB, close to its current ice margin, present since at least 1980. TheoC glacier has a catchment area similar to TheoB (~6.5 km²) and its elevation ranges from 1436 to 760 m a.s.l.

In front of all three glaciers are successions of well-preserved, unvegetated or partly vegetated moraines (Fig. 2). In front of TheoA are three moraines, located 250 m, 630 m, and 1000 m from the current ice front, at elevations ranging from 650 to 520 m a.s.l. Four moraines were identified in front of TheoB, very close to each other, 1420 - 1220 m from the current ice margin. An additional moraine remnant was identified 2120 m from the current ice margin. Moraines and remnants have elevations ranging from ~ 620 to ~ 530 m a.s.l. Finally, two moraines were identified in front of TheoC 100 m and 250 m from the current ice front, with elevations from 760 to 720 m a.s.l., respectively. Downstream, two moraines remnants located at 860 m and 2000 m from the present ice margin have elevations ranging from ~ 690 to ~ 600 m a.s.l.

Material and methods

Field sampling

Large (>2 m high and >20 m long), accessible and easily identified moraines or moraine remnants without evidence of disturbance (river, possible rock fall) were sampled and mapped in the field with a Garmin GPS survey. These moraines were named from the furthest from the glacier front (M1) to the closest (Mx) (Fig. 2; Table 1). All moraines and moraine remnants identified in the forefield of the TheoB glacier were sampled. The moraines located proximal (<10 m) to the current front position of TheoA and TheoC glaciers were not sampled. 30 granitic boulders (>60 cm in height) were sampled from the crests of the selected moraines on broadly horizontal or sub-horizontal surfaces using a hammer and a chisel. Only sampled boulders with minimal signs of erosion were sampled. Topographic shielding was estimated in the field using a compass clinometer of the sample positions. Sample elevations were extracted from a handheld Garmin GPS (vertical uncertainty of 10 m). All boulders were photographed and their height from ground-to-sample measured.

Analytical procedure

The chemical procedure was conducted at CALM lab (Cosmonucléides Au Laboratoire de Meudon - France). Samples were crushed and sieved to retain 1 mm-710 µm fractions then sieved again to retain the 250-500 µm fractions. The 250-500 µm grain size fractions were leached in a dilute HF/HNO_3 acid mixture to remove atmospheric ^{10}Be. Pure quartz was spiked with 500 µL of a commercial standard solution from the Scharlau Company (1000 mg L^{-1} of ^{9}Be) and then digested in 48% hydrofluoric acid. Beryllium was extracted using anion and cation exchange columns and alkaline precipitation. The obtained beryllium hydroxides were dried, and finally oxidized for one hour at 900 °C. The final BeO oxides were combined with Nb powder for AMS measurements at the French 5 MV AMS national facility ASTER (Aix-en-Provence) (Klein *et al.* 2008; Arnold *et al.* 2010). Measurements were calibrated against in-house standard STD-11 with an assigned $^{10}Be/^{9}Be$ ratio of $1.191\pm0.013 \times 10^{-11}$

(Braucher *et al.* 2015) using a ^{10}Be half-life of 1.387±0.0012 x 10^6 years (Chmeleff *et al.* 2010; Korschinek *et al.* 2010).

Age calculation

Surface cosmic ray exposure ages were calculated with the CREP online calculator (Martin *et al.* 2017; https://crep.otelo.univ-lorraine.fr/#/) applying the Lal-Stone time corrected scaling scheme (Lal 1991; Stone 2000), the ERA 40 atmosphere model and the atmospheric ^{10}Be based VDM for geomagnetic data base. Given the location of the study, the "Arctic" ^{10}Be production rate of 3.93±0.15 atoms g^{-1} a^{-1} established by Young *et al.* (2013) was applied here. ^{10}Be CRE ages are reported with 1σ "external" uncertainties, which include measurement, production rate and scaling uncertainties (e.g. Balco *et al.* 2008). For a given moraine, its age corresponds to the arithmetic mean of the sample ages from that moraine, which has successfully passed a Chi² test (Ward & Wilson 1978) used to identify outliers. We also considered the stratigraphic relationships to identify outliers.

Results

Glacial chronology in each valley

We first analyze the three glaciers separately and focus on the ^{10}Be CRE ages of the samples collected on the observed moraines (Table 1, Figs. 3-5). Fig. 6 reports ages with their associated internal uncertainties. Otherwise, in the main text and the other figures, we report individual ages with their associated external uncertainty and in Table 1 ages with both their associated internal and external uncertainties (including analytical and production rate uncertainties).

TheoA glacier. - Two moraines (M1 and M2) were dated from TheoA (Table 1, Fig. 3, 6A), in the northeast of Theodolit Plateau. A fresh moraine located few meters downslope of a small lake 50 m from the glacier front position was not sampled due to suspected instability. Two boulders were dated from lateral moraine on the left of the glacier (M1, ~1000 m from the glacier front) to 11.07±0.82 ka (Cla 48) and 10.6±0.74 ka (Cla 47), resulting in a mean age of 10.8 ± 0.6 ka. Further upstream, two boulders were sampled from the moraine next closest to the glacier front (M2) yielding ages of 1.23±0.1 ka (Zack 40) and 1.41±0.28 ka (Cla 54b), yielding a mean age of 1.2±0.09 ka.

TheoB glacier. - Five moraines and moraine remnants were identified and sampled in front of the TheoB glacier, downslope from the ice-contact proglacial lake (near the front position of the glacier) (Fig. 4). About 2 km from the glacier front, two moraine terminal remnants (M1 and M2a) on the left side of the main river, ~20 m above the river, were selected for sampling. Close to the front a large rampart ~60 m high is distinguishable, dissected by two rivers draining the lake. The largest river erodes the front of this rampart and flows northerly across the Theodolit plateau (Figs 1, 2, 4). Three distinct, sequential moraine segments that compose this rampart were sampled (M3, M4, M5) (Fig. 4). A single sample located on an external moraine remnant named here M1 (Zack 30) provided a ^{10}Be CRE age of 14.79±1.9 ka (n = 1). Five boulders partly covered by lichens on the external side of the rampart at both sides of the glacier are from lateral remnants M2b; Cla 01, 02, 05 on the right side of the glacier and Cla 38, Cla 39b on the left side of the glacier. Cla 02 (0.68±0.08 ka) was considered as an outlier based on the Chi² test and not further considered for analyses (Fig. 6A). The other samples yielded a mean ^{10}Be CRE age of 11.3±0.4 ka (n = 4). The arcuate remain on the other side of the main river in front of the rampart. The location of this moraine segment makes it difficult to determine if this landform was formed by separate ice advance or if it corresponds to the front position of the lateral moraine M2b. We thus consider these two hypotheses separately. Assuming this segment corresponds to a different glacier advance (named M2a here), this remnant would yield a mean CRE age of 11.4±0.4 ka based on three boulders Cla 24, Zack 31 and Zack 32. However, hypothesizing that this arcuate remnant corresponds to the frontal location of the lateral moraines M2b (thereby amalgamating ages from M2a and M2b), it yields a mean ^{10}Be CRE age of 11.3±0.3 ka (M2a + M2b: n = 7). Three other boulders (Cla 03, 08 and Zack 35) were sampled on M3, the largest moraine. The ^{10}Be CRE ages of these three boulders range from 3.5±0.29 to 2.46±0.2 ka. Based on the Chi² test, Cla 03 (2.46±0.2 ka) was considered as an outlier likely due to post-depositional modification and rejected from the mean calculation. Following this, M3 yielded a mean ^{10}Be CRE age of 3.3±0.2 ka (n = 2). Four boulders collected on moraine M4 (Cla 10, 14, 15 and Zack 34) yielded a mean ^{10}Be CRE age of 1.2±0.1 ka (n = 4). Upstream of M4, two samples were taken from M5, ~10 m above the current lake level (Cla 11, 13). Cla 13 (3.49±0.27 ka) was considered as an outlier (possibly due to inheritance) and rejected from the analysis. The remaining sample (Cla 11), and therefore the age ascribed to M5, returned an age of 0.37±0.05 ka.

TheoC glacier. - On TheoC, three moraines were selected for dating (Figs 5, 6A, Table 1). The moraine closest to the current front position of the glacier was not sampled due to suspected instability. Three boulders (Cla 26: 16.21±1.2 ka, Cla 29: 19.56±1.08 ka and Cla 31: 16.29±0.79 ka) were sampled on a large and high moraine surface covered by few large boulders, interpreted as a medial moraine remnant (M1), possibly formed by the coalescence of west and southwest Skill glaciers. Cla 29 was considered as an outlier by the Chi² test and rejected from the mean calculation. The other samples yielded a mean ^{10}Be CRE age of 16.2±0.6 (n = 2). About 1 km upstream of M1, two partly lichen- and moss-covered boulders were sampled from a lateral moraine (M2). These two boulders (Cla 36 and Cla 37) yielded a CRE age of 14.53±0.73 and 10.5±1.12 ka, respectively. These boulders may have been deposited during the Lateglacial/Early Holocene transition. However, because their ages are significantly different, it is not possible to provide an age for the moraine M2. On M3, three lichen-free boulders were sampled. Cla 32 yielded a ^{10}Be CRE age of 0.48±0.07 ka, Cla 33 of 0.5±0.07 ka, and Cla 34 of 0.21±0.03 ka. According to their Chi² test, Cla 34 was considered as an outlier and not included in age calculation. Therefore, Cla 32 and 33 yielded a mean ^{10}Be CRE age of 0.49±0.05 ka for M3.

Glacier pattern at Theodolit plateau

To provide an overview of the three glacier fluctuations and develop a regional chronology, we combined ^{10}Be ages from all three glaciers, except previously rejected samples (Fig. 6B). This allowed our dataset to be divided into three periods: the Lateglacial, the early and the Late Holocene. A probability density function of the ages reveals a mutltimodal distribution of the ages during the Lateglacial, with exposure ages spanning from 16.29±0.79 to 12.31±1.3 ka. During the Early Holocene the distribution is modal, with a mean age of 11.11±0.82 ka (n = 9). The Late Holocene samples span from 3.5±0.29 to 0.37±0.05 ka (n = 11). Two major modes then appear: one centered on the DACP with a mean CRE age of 1.25±0.18 ka (n = 6) and the other one during the LIA with a mean age of 0.45±0.07 ka (n = 3). This dataset reveals two important points about the investigated glaciers: (i) these glaciers were larger during the Early Holocene than the Late Holocene and (ii) larger during the Late Holocene than during the LIA.

Discussion

The ^{10}Be CRE ages of boulders collected on moraines and remains of three mountain glaciers located on Clavering Island made it possible to interpret the timing of deglaciation during the Lateglacial and Holocene near Zackenberg. The TheoB site displays the highest number of moraines preserved in the field. Based on the competing hypotheses of M2 (see above), we favor the association of M2a and M2b as a single moraine for preserving a high number of samples to date this landform. Furthermore M2a and M2b are both within their uncertainties and completely overlapping. We thus assumed that the moraine remnant M2a is geomorphologically linked to the lateral moraines of M2. These ^{10}Be ages indicate that the glacier recorded at least one advance during the Early Holocene. The M1 moraine remnant reveals that the glacier reached an extensive position at the end of Lateglacial period close to the maximum extent reached by the glacier during the Early Holocene. Following this Early Holocene maximum position, the glacier retreated, before re-advancing at least three times during the Late Holocene at ~3 ka, 1 ka and the LIA. This long-term Holocene pattern of change is broadly consistent with the glacier advances of TheoA, which shows at least one moraine formed during the Early Holocene and one moraine formed during the last millennium. In front of TheoC glacier, we identified moraines formation during the Lateglacial (M1) and during the LIA (M3). However, regarding M2, the scattering of the ages of the samples prevents any conclusion about the moraine's age, which may have been formed during the Lateglacial or the Early Holocene. Because we did not document moraine formation during the Middle Holocene, we suspect that these glaciers were smaller during this time than in the Late Holocene.

Lake sediment records close to the glaciers investigated in this paper provide independent indirect high-resolution evidence of glacier advances and retreats. At Zackenberg, northeast Greenland, lake sediment record from Madsen Lake suggests that three glacier advances occurred over the last 2000 years (Adamson *et al.* 2018). The first two advances (1.3 – 0.8 ka) occurred prior to the LIA, corresponding to the Dark Ages Cold Period (DACP ~1.75 – 1.25 ka) and the MCA respectively. Our moraine record suggests that the advance during the DACP was larger than the advance during the LIA at least for two glaciers, consistent with Madsen Lake record. In Kulusuk, ~1000 km south of Zackenberg, sediment core analyses document glacier advances since 9.5 ka (Balascio *et al.* 2015). Interestingly, DACP and LIA glacier advances were also identified from Kulusuk lake sediment record. However, the reconstruction of Kulusuk glacier activity from XRF PC1 data over the last 9.5 ka indicated that the most extensive glacier advances occurred at the end of the LIA (Fig.7D) and not during the DACP (Balascio *et al.* 2015).

Despite the development of this new glacial chronology in Clavering Island, the limited number of absolute ^{10}Be moraine chronologies of local mountain glaciers across Greenland makes our knowledge of their overall trends during the Holocene still incomplete. In particular, the understanding of the chronology of the maximum Holocene extent remains unclear, potentially occurring during the Early Holocene or the last millennium. At Clavering Island, two of the three investigated glaciers recorded their maximum during the Early Holocene. These data can be correlated with other moraine records in West Greenland where mountain glaciers displayed their maximum Holocene advance in the Early Holocene (Larsen *et al.* 2016; O'Hara *et al.* 2017). At Scoresby Sund, ~400 km south of Zackenberg, Kelly *et al.* (2008) and Levy *et al.* (2016) dated the inner Milne Land Stage moraines to the Early Holocene, broadly synchronous with our Clavering glacier advances. However, at Istorvet ice cap near Scoresby Sund, the glacier reached its maximum Holocene extent by ~0.87 ka and retreated from this limit ever since (Lowell *et al.* 2013). Similarly, mountain glaciers in the Stauning Alper appear to have reached their maximum Holocene extents during the Late Holocene (Hall *et al.* 2008; Kelly *et al.* 2008). Moreover, as mentioned above, at Kulusuk, glaciers reached their largest extent in the past 9.5 ka during the LIA. Consequently, these studies suggest possible regional differences in the chronology of the Holocene maximum glacier extent in Greenland.

The contrast and variability in glacier behaviour across Greenland throughout the Holocene suggests complex interactions between glacier and regional climate conditions constrained by various forcings. During the Holocene, two contrasting trends in temperature change may be considered. Declining summer insolation through the Holocene (Solomina *et al.* 2015) leads to the warmest temperature occurring in the Early Holocene (Buizert *et al.* 2018; Lesnek *et al.* 2020), followed by long-term cooling (Fig.7A). This cooling trend would suggest a progressive increase of mountain glacier size during the Holocene with the maximum Holocene extent during the LIA (Pendleton *et al.* 2019). Mountain glaciers at Clavering do not reflect this overall pattern. In contrast, recent summer temperature reconstructions from pollen records suggest cooler temperature in the Early Holocene than in the Late Holocene (Fig. 7B), consistent with ice core records (Marsicek *et al.* 2018). The combination of large ice cover and meltwater forcing (McKay *et al.* 2018) could have favored cooler temperatures during the Early Holocene than during the Late Holocene. This Holocene temperature evolution is consistent with our moraine record at Clavering and some other glacier chronologies documented in other regions of Greenland.

Superimposed on long-term temperature changes are episodes of glacier expansion and retreat on multi-decadal to centennial timescales. These are likely to be caused by forcings that include sea ice change variation (Fig.7E) (Bond *et al.* 1997), volcanic eruption, short-term solar variability or internal climate variability (e.g. Kelly & Lowell 2009; Levy *et al.* 2014; Jomelli *et al.* 2016; van der Bilt *et al.* 2019). Ice rafting events in the North Atlantic were invoked by Balascio *et al.* (2015) to explain these ice advance periods during the Late Holocene documented from Kulusuk lake sediment record. In addition, Moffa-Sanchez & Hall (2017) revealed three periods of enhanced cold and fresh polar waters from the east Greenland current around 3 ka, 1 ka and the LIA, which would explain the synchronicity of glacier advances at Clavering and Kulusuk. However, further data are needed from both moraine dating and lake sediment records before a robust understanding of the impacts of such forcing on glacier changes can be established, especially because of the specific character of moraine records (Gibbon *et al.* 1984). The respective influence of the geomorphic context (for instance slope, size of the catchment) (Chenet *et al.* 2010; Brun *et al.* 2019) and the local-regional climatic conditions responsible for variation in glacier behaviour could then be established. Interestingly, we showed that during the Late Holocene some episodes of glacier changes were synchronous from 74°N to 65°N on the eastern side of Greenland suggesting a regional climate change rather than a local glacier pattern driven by specific geomorphological conditions or ice dynamic. However, causes of these glacier advances are also still unclear. Gathering additional data from cosmic ray exposure dating on moraine will help our understanding of mountain glacier volume loss that has increased over the last centuries in NE Greenland (Carrivick *et al.* 2019).

Conclusions

Cosmic ray exposure dating of moraines from three adjacent mountain glaciers on western Clavering Island provide a new chronology of the glacial history in northeast Greenland from the Lateglacial to present. Only one glacier with a moraine dated at 16.2±0.6 ka allows identifying the extent of glaciers during the Lateglacial. During the Holocene, several glacial advances are well constrained. TheoA and TheoB glaciers exhibit a maximum Holocene glacial extent during the Early Holocene at 10.8±0.6 and 11.3±0.3 ka, respectively. This maximum Holocene extent on Clavering Island is broadly synchronous with some glacier advances recorded across Greenland. We suggest that this larger Early Holocene glacier expansion may have been caused by cooler temperature during the Early Holocene in the

Arctic compared to the Late Holocene. The absence of Middle-Holocene moraines in the study area suggests that these glaciers were smaller during this period than during their Late Holocene extension that occurred at ~3 ka. Advances at ~3 ka, during DACP and the LIA are synchronous with glacial advances documented from lake sediments in the northeast Greenland.

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Table caption:

Table 1. Detailed cosmogenic nuclide sample concentrations and calculated exposure durations from the three glaciers in the Clavering Island. Measurements were calibrated against in-house standard STD-11 with an assigned ^{10}Be/^{9}Be ratio of 1.191±0.013 x 10^{-11} (Braucher *et al.* 2015) using a ^{10}Be half-life of 1.387±0.0012 x 10^{6} years (Chmeleff *et al.* 2010; Korschinek *et al.* 2010). In samples Cla 02, 29, 32, 33, 34, 38, 47, 48, 54b, ^{10}Be/^{9}Be ratios were corrected for a process blank value of (5.31±0.50) x 10^{-15}. In samples Cla 05, 13, 14, 15, 36, Zack 35, 40, ^{10}Be/^{9}Be ratios were corrected for a process blank value of (2.5±0.42) x 10^{-15}. In samples Cla 03, 08, 11, Zack 32, ^{10}Be/^{9}Be ratios were corrected for a process blank value of (4.26±0.46) x 10^{-15}. In samples Cla 01, 31, 37, Zack 34, ^{10}Be/^{9}Be ratios were corrected for a process blank value of (4.59±0.48) x 10^{-15}. In samples Cla 10, 24, Zack 30, 31, ^{10}Be/^{9}Be ratios were corrected for a process blank value of (5.49±0.46) x 10^{-15}. In samples Cla 26, 39b, ^{10}Be/^{9}Be ratios were corrected for a process blank value of (9.11±0.82) x 10^{-15}. Samples rejected by the Chi^{2} test or for stratigraphic reasons are highlighted in italics. See text for more explanation.

Figures caption:

Fig. 1. A. Map of Clavering Island region in northeast Greenland with the location of the study area (red box). B. Location of the three investigated glaciers and moraines (yellow lines) on Theodolit plateau. Sampling areas on studied moraines in this paper are indicated with white circles. Source photography: Earthstar Geographics.

Fig. 2. View of TheoB glacier from the Theodolit plateau with the two rivers cutting the rampart composed of several moraines in July 2017. A lake not visible on this picture is located behind the frontal moraine M5.

Fig. 3. Chronology of glacial advances dated from two moraines of TheoA glacier on Clavering Island. Source imagery: KMS.

Fig. 4. Chronology of glacial advances dated from five moraines of TheoB glacier on Clavering Island. Source imagery: KMS.

Fig. 5. Chronology of glacial advances dated from three moraines of TheoC glacier on Clavering Island. Source imagery: KMS.

Fig. 6. A. Camel plot of the individual (thin lines) and summed (thick lines) ^{10}Be CRE ages (with their internal uncertainties) collected on the investigated glaciers on the Clavering Island. Distributions were calculated with free-MATLAB code from Greg Balco at the University at Washington Cosmogenic Isotope Lab available from
http://depts.washington.edu/cosmolab/pubs/gb_pubs/camelplot.m.
B. Combination of the all individual ^{10}Be CRE ages (with their internal uncertainties) from the three glaciers on Clavering Island. Specific climatic periods/events: YD = Younger Dryas; DACP = Dark Age Cold Period; LIA = Little Ice Age (after Kolling *et al.* 2017). Realized with the KDX application (Spencer *et al.* 2017).

Fig. 7. Clavering moraine record compared with forcing. A. GRIP temperature, CO_2 from Shakun *et al.* (2012) and summer insolation in the Northern Hemisphere. B. Temperature reconstruction of Northern marine margins, North America and Europe from Marsicek *et al.* (2018). C. Moraine record from TheoB glacier. TheoB chronology is the most complete in this study (dashed line = hypothetic glacier evolution). D. XRF PC1 Kulusuk proglacial lake representing glacier size from changes in the relative amount and grain size of minerogenic sediment (Balascio *et al.* 2015). E. Hematite-stained grains (HSG) identified in core MC52-VM29-191 interpreted to indicate ice-rafting events (Bond *et al.* 1997).

References

Adamson, K., Lane, T., Carney, M., Bishop, T. & Delaney, C. 2018: High-resolution proglacial lake records of pre-Little Ice Age glacier advance, Northeast Greenland. *Boreas 48*, 535‑ 550.

Arnold, M., Merchel, S., Bourlès, D.L., Braucher, R., Benedetti, L., Finkel, R.C., Aumaître, G., Gottdang, A. & Klein, M. 2010: The French accelerator mass spectrometry facility ASTER: Improved performance and developments. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 268*, 1954–1959.

Balascio, N. L., Andrea, W. J. & Bradley, R. S. 2015: Glacier response to North Atlantic climate variability during the Holocene. *Climate of the Past 11*, 1587–1598. https://doi.org/10.5194/cp-11-1587-2015

Balco, G., Stone, J. O., Lifton, N. A. & Dunai, T. J. 2008: A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. *Quaternary Geochronology 3*, 174–195.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I. & Bonani G. 1997: A Pervasive Millennial-Scale Cycle in North Atlantic Holocene and Glacial Climates. *Science 278*, 1257–1266. https://doi.org/10.1126/science.278.5341.1257

Braucher, R., Guillou, V., Bourlès, D. L., Arnold, M., Aumaître, G., Keddadouche, K. & Nottoli, E., 2015: Preparation of ASTER in-house ^{10}Be/9Be standard solutions. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 361*, 335–340.

Brun, F., Wagnon, P., Berthier, E., Jomelli, V., Maharjan, S. B., Shrestha, F. & Kraaijenbrink, P. D. A. 2019: Heterogeneous influence of glacier morphology on the mass balance variability in high mountain Asia. *Journal of Geophysical Research: Earth Surface 124*, 1331‑ 1345.

Buizert, C., Keisling, B. A., Box, J. E., He, F., Carlson, A. E., Sinclair, G. & DeConto, R. M. 2018: Greenland-wide seasonal temperatures during the last deglaciation. *Geophysical Research Letters*, 45, 4, 1905-1914.

Carrivick, J. L., Boston, C. M., King, O., James, W. H. M., Quincey, D. J., Smith, M. W., Grimes, M. & Evans, J. 2019: Accelerated volume loss in glacier ablation zones of NE Greenland, Little Ice Age to present. *Geophysical Research Letters 46*, 1476‐ 1484.

Chenet, M., Roussel, E., Jomelli, V., Grancher, D., 2010: Asynchronous Little Ice Age glacial maximum extent in southeast Iceland. *Geomorphology 114*, 253–260. https://doi.org/10.1016/j.geomorph.2009.07.012

Chmeleff, J., von Blanckenburg, F., Kossert, K. & Jakob, D. 2010: Determination of the ^{10}Be half-life by multicollector ICP-MS and liquid scintillation counting. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 268*, 192–199.

Gibbons, A. B., Megeath, J. D. & Pierce, K. L. 1984: Probability of moraine survival in a succession of glacial advances. *Geology 12*, 327–330.

Gosse J. & Klein J. 2015: Terrestrial cosmogenic dating. In Rink, W., Thompson, J. & Jeroen W. (eds.): *Encyclopedia of Scientific Dating Methods*, 799–812, Springer, Dordrecht.

Hall, D. K., Williams, R. S., Luthcke, S. B. & Digirolamo, N. E. 2008: Greenland ice sheet surface temperature, melt and mass loss: 2000–06. *Journal of Glaciology 54*, 81‐ 93.

Hansen, B. U., Sigsgaard, C., Rasmussen, L., Cappelen, J., Hinkler, J., Mernild, S. H., Petersen, D., Tamstorf, M. P., Rasch, M. & Hasholt, B. 2008: Present-day climate at Zackenberg. Advances in *Ecological Research 40*, 111–149.

Hobbie, J. E., Shaver, G. R., Rastetter, E. B., Cherry, J. E., Goetz, S. J., Guay, K. C., Gould, W. A. & Kling, G. W. 2017: Ecosystem responses to climate change at a Low Arctic and a High Arctic long-term research site. *Ambio 46*, 160–173.

Jomelli, V., Lane, T., Favier, V., Masson-Delmotte, V., Swingedouw, D., Rinterknecht, V., Schimmelpfennig, I., Brunstein, D., Verfaillie, D., Adamson, K., Leanni, L., Mokadem, F., Aumaître, G., Bourlès, D.L., Keddadouche, K. & ASTER Team. 2016: Paradoxical cold conditions during the medieval climate anomaly in the Western Arctic. *Scientific Reports 6*, 32984. DOI: 10.1038/srep32984

Kelly, M. A. & Lowell, T. V. 2009: Fluctuations of local glaciers in Greenland during latest Pleistocene and Holocene time. *Quaternary Science Reviews 28*, 2088–2106.

Kelly, M. A., Lowell, T. V., Hall, B. L., Schaefer, J. M., Finkel, R. C., Goehring, B. M., Alley, R. B. & Denton, G. H. 2008: A ^{10}Be chronology of lateglacial and Holocene mountain glaciation in the Scoresby Sund region, east Greenland: implications for seasonality during Lateglacial time. *Quaternary Science Reviews 27*, 2273–2282.

Klein, M. G., Gottdang, A., Mous, D. J. W., Bourlès, D. L., Arnold, M., Hamelin, B., Aumaître, G., Braucher, R., Merchel, S. & Chauvet, F. 2008: Performance of the HVE 5MV AMS system at CEREGE using an absorber foil for isobar suppression. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 266*, 1828–1832.

Kobashi, T., Menviel, L., Jeltsch-Thömmes, A., Vinther, B. M., Box, J. E., Muscheler, R., Nakaegawa, T., Pfister, P. L., Döring, M., Leuenberger, M., Wanner, H. & Ohmura, A. 2017: Volcanic influence on centennial to millennial Holocene Greenland temperature change. *Scientific Reports*, 8, 1, 4292.

Kolling, H. M., Stein, R., Fahl, K., Perner, K., & Moros, M. 2017: Short-term variability in Late Holocene sea ice cover on the East Greenland Shelf and its driving mechanisms. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 485, 336‐350.

Kottek M., Grieser J., Beck C., Rudolf B. & Rubel F. 2006: World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift 15*, 259–263.

Koch, L. & Haller, J. 1971: Geological map of East Greenland 72°-76°N. *Meddelelser om Grønland 183*, 1-26.

Korschinek, G., Bergmaier, A., Faestermann, T., Gerstmann, U.C., Knie, K., Rugel, G., Wallner, A., Dillmann, I., Dollinger, G., von Gostomski, Ch. L., Kossert, K., Maiti, M., Poutivtsev, M. & Remmert, A. 2010: A new value for the half-life of ^{10}Be by Heavy-Ion Elastic Recoil Detection and liquid scintillation counting. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 268*, 187–191.

Lal, D. 1991: Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models. *Earth and Planetary Science Letters 104*, 424–439.

Larsen, N. K., Funder, S., Linge, H., Möller, P., Schomacker, A., Fabel, D., Xu, S. & Kjær, K.H. 2016: A Younger Dryas re-advance of local glaciers in north Greenland. *Quaternary Science Reviews 147*, 47–58.

Lesnek, A .J., Briner, J. P., Young, N. E., & Cuzzone, J. K. 2020: Maximum southwest Greenland Ice Sheet recession in the Early Holocene. *Geophysical Research Letters*, 47,1. DOI:10.1029/2019gl083164

Levy, L. B., Kelly, M. A., Lowell, T. V., Hall, B. L., Hempel, L. A., Honsaker, W. M., Lusas, A. R., Howley, J. A. & Axford, Y. L. 2014: Holocene fluctuations of Bregne ice cap, Scoresby Sund, east Greenland: a proxy for climate along the Greenland Ice Sheet margin. *Quaternary Science Reviews 92*, 357–368.

Levy, L. B., Kelly, M. A., Lowell, T. V., Hall, B. L., Howley, J. A. & Smith, C. A. 2016: Coeval fluctuations of the Greenland ice sheet and a local glacier, central East Greenland, during late glacial and Early Holocene time: Beryllium-10 ages of Late Glacial moraines. *Geophysical Research Letters 43*, 1623–1631.

Lowell, T. V., Hall, B. L., Kelly, M. A., Bennike, O., Lusas, A. R., Honsaker, W., Smith, C. A., Levy, L. B., Travis, S. & Denton, G. H. 2013: Late Holocene expansion of Istorvet ice cap, Liverpool Land, east Greenland. *Quaternary Science Reviews*, 63, 128‐140.

Marsicek, J., Shuman, B. N., Bartlein, P. J., Shafer, S. L. & Brewer, S. 2018: Reconciling divergent trends and millennial variations in Holocene temperatures. *Nature 554*, 92–96.

Martin, L. C. P., Blard, P.-H., Balco, G., Lavé, J., Delunel, R., Lifton, N. & Laurent, V. 2017: The CREp program and the ICE-D production rate calibration database: A fully parameterizable and updated online tool to compute cosmic-ray exposure ages. *Quaternary Geochronology 38*, 25–49.

Masson-Delmotte, V., Swingedouw, D., Landais, A., Seidenkrantz, M.-S., Gauthier, E., Bichet, V., Massa, C., Perren, B., Jomelli, V., Adalgeirsdottir, G., Hesselbjerg Christensen, J., Arneborg, J., Bhatt, U., Walker, D. A., Elberling, B., Gillet-Chaulet, F., Ritz, C., Gallée, H., van den Broeke, M., Fettweis, X., de Vernal, A. & Vinther, B. 2012: Greenland climate change: from the past to the future: Greenland climate change. *WIREs Climate Change 3*, 427–449.

McKay, N. P., Kaufman, D. S., Routson, C. C., Erb, M. P. & Zander, P. D. 2018: The onset and rate of Holocene Neoglacial cooling in the Arctic. *Geophysical Research Letters*., 45, 22, 12,487-12,496.

Moffa-Sánchez, P. & Hall, I. R. 2017: North Atlantic variability and its links to European climate over the last 3000 years. *Nature Communications 8*, 1726. DOI: 10.1038/s41467-017-01884-8

Möller, P., Larsen, N. K., Kjær, K. H., Funder, S., Schomacker, A., Linge, H. & Fabel, D. 2010: Early to Middle Holocene valley glaciations on northernmost Greenland. *Quaternary Science Reviews 29*, 3379–3398.

O'Hara, S. L., Briner, J. P. & Kelley, S. E. 2017: A ^{10}Be chronology of Early Holocene local glacier moraines in central West Greenland. *Boreas 46*, 655–666.

Pendleton, S., Miller, G., Lifton, N. & Young, N. 2019: Cryosphere response resolves conflicting evidence for the timing of peak Holocene warmth on Baffin Island, Arctic Canada. *Quaternary Science Reviews*, 216, 107-115.

Schweinsberg, A. D., Briner, J. P., Licciardi, J. M., Bennike, O., Lifton, N. A., Graham, B. L., Young, N. E., Schaefer, J. M. & Zimmerman, S. H. 2019: Multiple independent records of local glacier variability on Nuussuaq, West Greenland, during the Holocene. *Quaternary Science Reviews 215*, 253–271.

Shakun, J. D., Clark, P.U., He, F., Marcott, S.A., Mix, A.C., Liu, Z., Otto-Bliesner, B., Schmittner, A., Bard, E., 2012: Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation. *Nature 484*, 49–54. https://doi.org/10.1038/nature10915

Solomina, O. N., Bradley, R. S., Hodgson, D. A., Ivy-Ochs, S., Jomelli, V., Mackintosh, A. N., Nesje, A., Owen, L. A., Wanner, H., Wiles, G. C. & Young, N. E. 2015 Holocene glacier fluctuations. *Quaternary Science Reviews*, 111, 9‐34.

Spencer, C. J., Yakymchuk, C. & Ghaznavi, M. 2017: Visualising data distributions with kernel density estimation and reduced chi-squared statistic. *Geoscience Frontiers 8*, 1247–1252.

Stone, J. O. 2000: Air pressure and cosmogenic isotope production. *Journal of Geophysical Research: Solid Earth 105*, 23753–23759.

Van der Bilt, W. G. M., Born, A. & Haaga, K. A. 2019: Was Common Era glacier expansion in the Arctic Atlantic region triggered by unforced atmospheric cooling? *Quaternary Science Reviews 222*, 105860.

Vinther, B. M., Buchardt, S. L., Clausen, H. B., Dahl-Jensen, D., Johnsen, S. J., Fisher, D.A., Koerner, R. M., Raynaud, D., Lipenkov, V., Andersen, K. K., Blunier, T., Rasmussen, S. O., Steffensen, J. P. & Svensson, A. M. 2009: Holocene thinning of the Greenland ice sheet. *Nature 461*, 385–388.

Vinther, B. M., Clausen, H. B., Johnsen, S. J., Rasmussen, S. O., Andersen, K. K., Buchardt, S. L., Dahl-Jensen, D., Seierstad, I. K., Siggaard-Andersen, M. -L., Steffensen, J. P., Svensson, A., Olsen, J. & Heinemeier, J. 2006: A synchronized dating of three Greenland ice cores throughout the Holocene. *Journal of Geophysical Research: Atmospheres* 111, D13102. DOI: 10.1029/2005JD006921

Ward, G. K. & Wilson, S. R. 1978: Procedures for comparing and combining radiocarbon age determinations: A critique. *Archaeometry 20*, 19–31.

Young, N. E., Schweinsberg, A. D., Briner, J. P. & Schaefer, J. M. 2015: Glacier maxima in Baffin Bay during the Medieval Warm Period coeval with Norse settlement. *Science Advances* 1, e1500806. DOI: 10.1126/sciadv.1500806

Young, N. E., Schaefer, J. M., Briner, J. P. & Goehring, B. M. 2013: A ^{10}Be production-rate calibration for the Arctic. *Journal of Quaternary Science 28*, 515–526.