Climate of the Past Resubmission
Manuscript Track Changes and Reviewer Responses
Monday, July 24, 2017

To the Editor and to Whom is may concern:

My coauthors and I are please to resubmit our manuscript "Episodic Neoglacial expansion and rapid 20th Century retreat of a small ice cap on Baffin Island, Arctic Canada and modeled temperature change" along with responses to reviewer and editor comments.

Attached below is the revised manuscript with track changes showing the major changes from initial submission. Following that is a detailed list of the Reviewer comments and associated responses.

Per Editor and Reviewer suggestions, the supplemental sections regarding the glacier model have been moved into the main manuscript. Most of it was moved into the methods section, and the remainder (including model calibration and full simulations) were moved to the results section. All of the other comments from the reviewers and editor are addressed in the section of comments and responses following the manuscript.

We look forward to your comments and decision,

Sincerely,

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Episodic Neoglacial expansion and rapid 20th Century retreat of a small ice cap on Baffin Island, Arctic Canada and modeled temperature change

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Abstract. Records of Neoglacial glacier activity in the Arctic constructed from moraines are often incomplete due to a preservation bias toward the most extensive advance, often the Little Ice Age. Recent warming in the Arctic has caused extensive retreat of glaciers over the past several decades, exposing preserved landscapes complete with *in situ* tundra plants previously entombed by ice. The radiocarbon ages of these plants define the timing of snowline depression and glacier advance across the site, in response to local summer cooling. Erosion rapidly removes most dead plants that have been recently exposed by ice retreat, but where erosive processes are unusually weak, dead plants may remain preserved on the landscape for decades. In such settings, a transect of plant radiocarbon ages can be used to construct a near-continuous chronology of past ice margin advance. Here we present radiocarbon dates from the first such transect on Baffin Island, which directly dates the advance of a small ice cap over the past two millennia. The nature of ice expansion between 20 BCE and ~1000 CE is still uncertain, but episodic advances at ~1000, ~1200, and ~1500 CE led to the maximum Neoglacial dimensions ~1900 CE. We employ a two-dimensional numerical glacier model calibrated using the plant radiocarbon ages ice margin chronology to assess the sensitivity of the ice cap to temperature change. Model experiments show that at least ~0.44°C of cooling over the past 2 ka is required for the ice cap to reach its 1900 CE margin, and that the period from ~1000 to 1900 CE must have been at least 0.25°C cooler than the previous millennium; results that agree with regional temperature reconstructions and climate model simulations. However, significant warming since 1900 CE is required to explain retreat to its present position, and, at the same rate of warming, the ice cap will disappear before 2100 CE.

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1. Introduction

Although summer insolation in the Northern Hemisphere has declined steadily through the Holocene, favoring cryosphere expansion, glaciers worldwide are currently losing mass (Stocker et al., 2013). Globally, summer temperatures have been increasing over the last 60 years, a trend that is more pronounced at high latitudes due to strong positive feedbacks (Serreze and Barry, 2011). Since summer temperatures are the dominant control on glacier mass balance in the Canadian Arctic (Koerner, 2005), the reversal of late Holocene cooling (Kaufman et al., 2009) has caused recent retreat of ice caps and glaciers in the region. This continued shrinkage of the cryosphere reinforces the need for records of past glacier and climate change to provide context for contemporary warming.

Patterns of Neoglacial advance and retreat in the Arctic remain poorly constrained (Solomina et al., 2015, and references therein), largely because the most recent advance, during the Little Ice Age (LIA; 1250-1850 CE) was, for most of the Arctic, also the most extensive and therefore obliterated most evidence of previous advances. Lake sediment records provide continuous records of climate, but typically require glacial activity to be inferred indirectly. 'Threshold' lakes record a glacier entering and exiting a well-defined catchment, but provide the timing of a glacier margin at a single point (Briner et al., 2010). Lichenometric surface exposure dating, often used on glacial landforms, provides relative age information, but conversion to absolute exposure age has large uncertainties (e.g., Osborn et al., 2015; Rosenwinkel et al., 2015). Furthermore, even though significant advances have been made improving analytical measurements for cosmogenic radionuclide (CRN) exposure ages of moraine boulders, the technique can be compromised by issues of nuclide inheritance and post-depositional moraine destabilization (Crump et al., *in press*; Pendleton et al., 2016). Consequently, moraines can be difficult to date precisely, and moraine records by nature are discontinuous.

Recent ice-margin retreat of cold-based ice caps on Baffin Island is exposing preserved landscapes. The radiocarbon ages of *in situ* plants on these preserved lands record the time when snowline lowering and/or ice advance covered the site, killing and entombing the plants beneath the glacier. Commonly, the re-exposure of dead plants leaves them highly susceptible to erosion, most often by meltwater flowing along the margins of cold-based ice, but also by blowing snow in winter. The ephemeral nature of these re-exposed dead plants means that their ages are representative of the most recent snowline advance at that location; multiple exposures and burials are unlikely (Miller et al., 2013).

However, in certain topographic settings, where plant removal by meltwater has been inefficient, dead plants may remain for decades. A transect of dead plant radiocarbon ages perpendicular to a receding ice margin can provide a more reliable and more continuous record of ice advance than is possible from moraine records (Miller et al., 2017). The occurrence of long-preserved ice-killed tundra plants under optimal circumstances hundreds of meters beyond retreating ice margins provides an opportunity to derive near-continuous records of ice-margin advance through the Neoglacial period. Here we present a chronology of ice-margin advance from Divide Ice Cap (informal name), a small mountain ice cap in southeastern Baffin Island, derived from radiocarbon-dated dead plants, and utilize numerical modeling to estimate the changes in summer temperature required to reproduce the observed record of ice margin advance.

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2. Neoglaciation in the Eastern Canadian Arctic

There is substantial evidence of repeated glacier advances on Baffin Island during Neoglaciation (~5 ka through Little Ice Age; Miller et al., 2005) as summer temperatures declined, but absolute chronologies remain sparse and imprecise. Foundational mapping and initial chronologies derived from lichenometry from nested moraines show that some glaciers were approaching their Neoglacial maximum dimensions as early as 3.5 ka (Davis, 1985; Miller, 1973). Radiocarbon ages of tundra plants killed by snowline depression, and only now re-emerging from beneath cold-based ice, show that glaciers began to expand as early as ~5 ka, followed by episodic intensifications culminating in the Little Ice age (Anderson et al., 2008; Miller et al., 2012; 2013; Margreth et al., 2014). Although most studies conclude that glaciers reached their maximum Neoglacial dimensions during the LIA, Young et al. (2015) produced a CRN chronology of nested moraines in northeastern Baffin Island that suggests that Naqsaq glacier advanced to a position similar to that of its LIA extent at ~1050 CE. However, moraine chronologies hinting at the nature of pre-LIA temperature change are sparse, and the chronology from an individual site can be influenced by non-climatic factors; thus, other datasets that provide direct evidence of Neoglacial ice advance are needed.

3. Field Setting: Divide Ice Cap

Divide Ice Cap (DIC) is situated ~60 km southwest of the settlement of Qikitarjuaq on eastern Baffin Island (Fig. 1). The ice cap currently mantles the northern slope of a local summit between ~1550 and 1180 m asl, spilling down into a local saddle, where it separates into two outlet glaciers flowing down either side of the saddle, orthogonal to the main ice cap flow. A vegetation trimline high on the south-facing slope on the opposite side of the saddle defines the maximum LIA limit (Fig. 1). The uniform nature and clarity of this trimline as well as the southerly aspect of the slope all suggest that the trimline is indeed the result of an ice margin and not persistent snow. Aerial imagery from 1960 shows the ice margin ~15 m below this trimline (Fig. 1; National Air Photo Library, 1960).

The 2015 ice margin lies 60 m below the LIA trimline. Our sample transect runs from the modern ice margin upslope toward the LIA trimline and is aligned with the topographic drainage divide where ice growth upslope is driven by internal deformation (Fig. 2). Between the ice margin and the trimline, the land surface is carpeted by till boulders amidst finer-grained morainal debris. The presence of preserved plants still in growth position exposed by the retreating ice margin is evidence for a high degree of subglacial landscape preservation, indicating a cold-based, non-erosive basal regime for the DIC at our transect.

Until now, the majority of studies utilizing dates on previously ice-entombed plants rely on plants collected close to the ice margin at multiple ice caps to build a composite dataset that highlights periods of regional cooling (e.g., Anderson et al., 2008; Miller et al., 2013; Margreth et al., 2014). However, because meltwater erosion at the location of our transect was inefficient, *in situ* dead plants remain preserved from the ice margin to the trimline, although with decreasing abundance at higher elevations as the trimline is approached (Fig. 1). Miller et al. (2017) recently employed a similar method on Svalbard by collecting a transect of six, dead, *in situ* mosses up to 250 m away from the 2013 CE ice margin. The radiocarbon ages of these plants provide evidence of an episodically advancing ice margin over the last ~1200 years.

4. Methods

4.1. Vegetation Collection

In August 2015, when seasonal melt was at its maximum, 11 *in situ* dead mosses were collected along a ~200 m transect between the 2015 CE ice margin (1185 m asl) and the LIA trimline (1238 m asl) (Fig. 1). Within ~5 m of the ice margin, all exposed vegetation was dead. Regrowth and recolonization of plants began ~30 m from the ice margin, with dead plants increasingly rare and living plants increasingly abundant up the transect. A single ice margin plant was also collected on the western margin of the ice cap in August of 2014. During field collection, plants are closely inspected for spontaneous regrowth, which is discernable in the field based on plant color (La Farge et al., 2013). Woody plants were avoided because of their higher survival potential and because their stems have an average radiocarbon age that is older than the actual kill date. In the previous year, we collected *in situ* dead vegetation at the southern margin of the ice cap, closer to the summit (1438 m asl; Fig. 1).

Between 1 and 3 filaments from each sampled plant were washed with deionized water and freeze dried before being graphitized at the Laboratory for AMS Radiocarbon Preparation and Research (NSRL). Graphite targets were measured at the W.M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory at the University of California Irvine. Final radiocarbon dates were calibrated using OxCal 4.2.4 (Bronk-Ramsey, 2009; Reimer et al., 2013) and reported here as the weighted mean, 1σ, and 2σ uncertainties.

4.2. Glacier Model

We employ a two-dimensional finite difference numerical model in conjunction with the *in situ* vegetation to further investigate the evolution of the Divide Ice Cap over the last ~2000 years. The model, modified from Kessler et al. (2006), calculates an ice thickness on a two-dimensional terrain model governed by explicit equations for ice flux and mass balance using shallow-ice physics (e.g., Blatter et al., 2011), an approach similar to (Åkesson et al., 2016).

4.2.1. Terrain Production

Prior to model implementation, a terrain model of the bedrock surface is required. This involves removing (to the best approximation) the modern DIC from an existing digital elevation product. ASTER digital elevation data from 2011 CE was used as a base for the two-dimensional terrain model, resampled to a 60 m pixel size. The ASTER data product was retrieved from the online Data Pool, courtesy of the NASA Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota,

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https://lpdaac.usgs.gov/data access/data pool. The resulting surface was smoothed using a 7x7 mean filter to remove artifacts in the raw data that would lead to instabilities in the model. Modern ice, including Divide Ice Cap and the ice on the surrounding summits, had to be removed to create an ice-free terrain to model upon. Using the best approximation of basal shear stress (τ_b) to be ~100 kPa (Haeberli, 2016), current ice thicknesses (H) were calculated following Cuffey and Paterson (2010):

$$H = \frac{\tau_b}{\rho g \theta}$$

where ρ is the density of ice (917 kg m^{-3}), g is gravitational acceleration (9.81 m s^{-2}) and θ is the surface slope of the modern ice surface. Calculated thicknesses were then subtracted from the modern terrain surface to produce an ice-free surface. Eventual model runs show that calculated and modelled modern ice thickness are the same within 10% of each other.

4.2.2. Mass Balance

Kessler et al. (2006) drove ice formation with a climate dictated by an equilibrium line altitude (ELA), a mass balance gradient with elevation, and a maximum positive balance (maximum accumulation). However, the overall low accumulation rates of our high-latitude site and the variable aspect of the Divide Ice Cap, which increases the influence of solar radiation during the melt season, necessitates a different approach (Benn and Evans, 2010). Ice core records, observational studies in the eastern Canadian Arctic, and previous modeling work suggest a maximum accumulation of 0.3 m water equivalent (m.w.e.) per year throughout the Holocene (Hooke, 1976; Serreze et al., 1995; Anklin et al., 1998; Mair et al., 2005), which, given the limited elevation range of the Divide Ice Cap location, is applied as the annual accumulation across the whole model surface.

Although precipitation records are sparse near the study site, ice core records from the summit of the Greenland Ice Cap show that regionally, precipitation varied by only ~6% over the last 1200 years (Alley, 2004). Given the relatively low accumulation rates, summer temperature is likely the dominant driver of glacier advance and retreat at Divide Ice Cap (Koerner, 2005).

Temperature index melt models generally capture the majority of summer melt due to the strong relationship between air temperature and components of the surface energy balance (Braithwaite and Olesen, 1989; Lang and Braun, 1990), and have been successfully applied on larger scales in the eastern Canadian Arctic (Marshall and Sharp, 2009). However, the relatively low accumulation rates, small elevation range, and variable aspect and slope at Divide Ice Cap along with the asymmetric trimlines surrounding summits (Fig. 4) suggests that the glacier system is sensitive to small temperature changes and that incoming solar radiation is an important factor in the overall glacier mass balance. Additionally, previous studies of the orientation of cirque glaciers on Baffin Island (Williams, 1975) and summertime snow patch distribution in the eastern Canadian arctic (Lauriol et al., 1986) emphasize the role of solar energy in enhancing melt on southerly aspects. Wind redistribution of snow could be another factor in the more positive mass balance of northerly aspect of the Divide Ice Cap. However, available meteorological wind direction data from Clyde River to the north and Iqaluit to the southwest both show the prevailing winds to be north-north westerly (Gearheard et al., 2010; Nawri and Stewart, 2010). While these observations do not rule out the possibility that local winds at Divide Ice Cap differ, and move snow from south-facing to north-facing slopes, they strongly suggest that the dominant wind patterns cannot explain the asymmetric mass balance. In areas of overall low accumulation and relatively low relief where the snowline is only just below mountaintops, solar radiation modulated by slope and aspect can exert a strong control on the annual pattern of accumulation (Benn and Evans, 2010).

Given the above concerns regarding melt driven by temperature and solar radiation, we calculate the summer melt rate (M, mm day^{-1}) using a radiation modified positive degree day melt model for air temperatures (T) above 0°C (Hock, 2005; Jonsell et al., 2012; Kane et al., 1997):

$$M = \begin{Bmatrix} m_T(PDD) + m_R(1-\alpha)R); T > 0°\mathrm{C} \\ 0 \qquad ; T < 0°\mathrm{C} \end{Bmatrix}$$

The melt contribution from air temperature is calculated using the product of a degree-day melt factor (m_T, 6.3 mm day^{-1} °C^{-1}; Braithwaite, 1981) with positive-degree days (PDD) over the terrain surface. Using a prescribed sea-level mean annual temperature (MAT), a MAT at elevation is calculated using a near surface lapse rate of -4.9°C km^{-1} (derived from Candian Arctic glaciers; Gardner et al., 2009). Annual temperature cycles are then calculated at all elevations using an amplitude of 20°C (based upon daily temperature records from Dewar Lakes meteorological data from 1959-2015) around the MAT. Integration of the portion of the curve where T>0°C provides the PDD for each location on the terrain surface.

Calculation of the melt contribution from radiation employs the product of a radiation melt factor (m_R, 0.036 mm day^{-1} (W m^{-2})$^{-1}$; obtained via model calibration, see below section 5.3.1.) with that portion of the incident solar radiation (R; W m^{-2}) that is not reflected from the surface (albedo = a = 0.5 (Benn and Evans, 2010)). Solar radiation (R) for the Divide Ice Cap latitude and elevation is calculated following Kustas et al. (1994 and Kumar et al. (1997). In this case, radiation is also modulated based on slope and aspect (Cuffey and Paterson, 2010; Hock, 2005; Kumar et al., 1997). Melt from solar radiation only takes place when T>0°C, which is calculated from the annual temperature cycle from the PDD component. Net mass balance is then calculated as the winter mass balance (accumulation) minus the summer mass balance (melt).

4.2.3. Modelling Ice Surfaces

Driven by the above mass balance, the model, following Kessler et al. (2006) calculates an ice surface on the supplied 2-D terrain surface using explicit equations for ice flux and mass conservation (equations 1 and 8 respectively in Kessler et al. (2006)). Using a shallow ice approximation and the recommended coefficient for Glen's flow law for polar ice of 3.5x10^{-25} Pa^{-1}s^{-1} (Cuffey and Paterson, 2010), ice discharge is driven by the shear stress associated with ice thickness and surface slope. Field observations of the highly-preserved land surface, including vegetation still in growth position, justify a no-slip basal boundary condition. Sliding was therefore disallowed, and ice moves only by internal deformation.

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5. Results and Interpretation

5.1. Plant Ages

The single *in situ* sample collected on the western margin of DIC produced a calibrated age of 26 +29/-21 CE (Fig. 1, Table 1). Calibrated radiocarbon ages of plant material from the transect become younger away from DIC, ranging from 942 +41/-36 and 1029 +33/-3 CE at the 2015 ice margin to 1780 +111/-165 CE near the trimline. The ages of four samples closest to the 2015 ice margin, although collected up to ~20 m away from the margin, overlap at ±2σ (Table 1). A single plant collected near the LIA trimline returned a post-bomb age; this likely reflects random death of a plant that recolonized after deglaciation (Fig. 1, Table 1).

5.2. Neoglacial Divide Ice Cap Expansion and 20th Century recession

The kill date at the western margin of DIC indicates ice expansion across that location ~2 ka and continuous ice-cover until 2014 CE. The ages near the 2015 CE ice margin (henceforth the 1000 CE margin) define DIC expansion ~1000 CE. Since the ages define the time when ice advanced through that location, the distribution of ages requires that the rate of ice margin expansion increase around ~1000, 1200, and 1500 CE (Fig. 3). These periods of accelerated ice expansion with periods of enhanced regional cooling and ice expansion shown in the compilation of dated ice-entombed mosses from Baffin Island from Miller et al. (2013) and Margreth et al. (2014) (Fig. 3). This correlation between the transect ages and periods of regional expansion shows that DIC responded similarly to regional cooling as the rest of the cryosphere on Baffin Island. Given that each transect plant age represents the time when the ice margin advanced through that position (not necessarily a standstill such as a moraine deposit would represent), the distribution of plant ages, at minimum, requires a change in the rate of ice margin expansion between samples sites (dashed line; Fig. 3). The resolution of our transect does not allow for the definitive detection of any periods of ice margin standstill, but the change in rate of ice margin advance between transect ages indicates that DIC episodically advanced over the past ~1000 years.

Possible explanations for the change in rate of ice margin advance include continued expansion, ice margin stasis, or ice recession. However, the spatial and temporal distribution of the transect data and their correspondence with regional ice-expansion records supports our interpretation that DIC expanded episodically between ~1000 and 1900 CE. The proximity of the highest elevation radiocarbon sample to the trimline suggests that DIC approached its Neoglacial maximum position sometime between ~1600 CE and the end of the 19th century. Aerial photographs from 1960 show that the ice margin had already retreated ~15 m vertically from its maximum extent (trimline), indicating abandonment of its Neoglacial maximum position prior to 1960 (Fig. 1).

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5.3. Ice Cap Modelling

Using the above spatial and temporal constraints on ice margin movement over the last ~2000 years, model simulations can be used to explore the climate sensitivity of the Divide Ice Cap system, and to estimate the temperature changes required to reproduce the observed advance and retreat cycle.

5.3.1. Model Calibration

Prior to running full simulations of the last ~2000 years, the model must be calibrated for an appropriate solar radiation melt factor (m_R). Traditionally this value is calibrated using in situ solar flux and melt rate data. However, since that information is lacking here, a different approach must be taken.

Given the transect chronology observed, the simplest (and most likely) history involves continuous ice advance (though likely at varying rates) from ~26 BCE – 1900 CE followed by modern retreat from ~1900 to present. Given this scenario, the model was calibrated to the observed transect chronology and run to maximum Holocene extent conditions (or at ~1900, culmination of the LIA) using a range of accepted m_R (Jonsell et al., 2012) values. In other words, we iteratively tested m_R values to most closely match the maximum LIA diemsions. With this approach, we find that a m_R value of 0.036 mm day^{-1} (W m^{-2})$^{-1}$ provides the best reproduction of Holocene maximum ice extent (Fig. 4). Values of m_R values above or below 0.036 mm day^{-1} (W m^{-2})$^{-1}$ produced far too much or too little ice, respectively (Supplemental Fig. 1), making this value our closest approximation.

5.3.2. Full Simulation

Using the calibrated model from above, it is possible to reproduce the full history of advance and retreat at Divide Ice Cap over the last ~2000 years. Assuming a stable ice cap with a margin just inside sample 12, the model requires an average minimum summer cooling of 0.19°C persisting for 1000 years to grow ice across the sample 12 location and reach the 1000 CE margin in the allotted ~1000 years. A subsequent additional cooling of ~0.25°C is required for ice to advance across the 1000 CE margin to the LIA trimline by 1900 CE. It is of course likely that some decades were much colder than others; our modeling suggests that a minimum average cumulative summer cooling of ~0.44°C over the ~1900 years is required to advance the observed DIC ice margin through the constraints provided by the kill dates.

Building upon the ice expansion simulations, the model was used to investigate recent warming and ice retreat. DIC likely began receding around ~1900 CE, retreating from its maximum extent to its modern position over the past ~100 years. Under a simple linear warming scenario of 0.028°C yr^{-1}, the modeled DIC retreats from the LIA trimline to its 2015 position in 105 years (Fig. 5). This rate of warming is slightly higher than the 0.014°C yr^{-1} (since 1959 CE) documented from the interior Dewar Lakes weather station ~320 km to the northwest, but significantly lower than the recent warming rate from Qikiqtarjuaq (0.87 °C yr^{-1} 1995-2009 CE). The modeled rate of warming amounts to ~2.7°C of cumulative warming over the last century, which is similar to values recorded elsewhere in the Eastern Canadian Arctic (Bekryaev et al., 2010; Stocker et

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al., 2013). Compared to the simulations of glacier advance up through the LIA, it would appear that the last century of elevated warming has reversed the last ~1000 years of advance from slow cooling. Continuing under the same rate of warming, DIC will disappear by ~2100, and sooner if local warming accelerates.

The temperature changes reported here are minimum values due to assumptions made in the model. The best available data was used for both model initial conditions and mass balance forcings, but limitations in these data introduce uncertainty to the model (see Supplemental Information). However, the general agreement of ice cap simulations to observational data in the region support the first-order model results presented here.

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6. Discussion

6.1. Regional Comparisons

The timing of episodes of ice expansion found here agree well with those found by Miller et al. (2017) at ~1100 and 1500 CE, using a similar transect method in Svalbard. The episodic nature of ice advance in Svalbard and in this study, in the face of steadily decreasing Northern Hemisphere insolation, indicates additional mechanisms and feedbacks are likely significantly influencing local climate. Also, similar to the Svalbard study, we find that DIC reached its maximum Neoglacial extent during the LIA and that warming since the early 1900s has reduced glacier dimensions to a smaller size than any time since 1000 CE. Across the North Atlantic, episodic cryosphere expansion despite steadily declining insolation is no unique. Balascio et al. (2015) found that glaciers in southeast Greenland periodically advanced throughout the late Holocene at similar times as DIC. The authors pointed to large ice rafting events and changes in the Atlantic Meridional Overturning Circulation as the likely driver of regional coolings. Glacier records from the North Atlantic also show episodic advances over the past ~1000 years, suggesting strong climate connections across the region (Solomina et al., 2015). Additionally, the magnitude from the glacier model agrees well with reconstruction of Arctic temperatures over the past 2000 years from Kaufman et al. (2009) (Fig. 6).

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The magnitude of Neoglacial glacier advances and derived climate interpretations presented here differ somewhat from those based on the Naqsaq valley moraine suite farther north on Baffin Island. Based on sets of tightly clustered ^{10}Be ages on moraines boulders in a nested moraine complex, Young et al. (2015) suggests that the Naqsaq glacier reached a position similar to that of its LIA extent at ~1050 CE. This led the authors to suggest that the climate was similar, with little or no additional cooling from ~1050 CE through the LIA. This interpretation differs from both the observed significant expansion of DIC from ~1000 CE to its LIA maximum, and the model simulations requiring that the same time period must have been, on average, ~0.25°C cooler than the preceding millennium.

This discrepancy between the two records may be explained by non-climatic factors affecting the deposition and preservation of moraines. Glaciers with a majority of their area at high elevations relative to the glacier tongue may not respond uniformly to equilibrium line altitude (ELA) fluctuations (e.g., Pedersen and Egholm, 2013). At the site studied by Young et al. (2015), the majority of the glacier area resides on a high plateau, with a narrow outlet glacier occupying a deeply incised valley, terminating in an open, wide valley floor. Although the moraine chronology developed by Young et al. (2015) itself is convincing, it is possible that the terminal position is relatively insensitive to small Late Holocene ELA changes. This is because once the ELA drops below the plateau and is within the narrow outlet glacier, each incremental ELA lowering increases the accumulation area only slightly. In contrast, DIC has a more symmetric hypsometry (i.e., the glacierized area is more evenly distributed over glacier elevation). Consequently, we expect that the correlation between ELA change and glacier dimension response should be more linear than for Naqsaq Glacier. Both the plant radiocarbon dates and glacier model simulations require increased summer cooling between ~1000 CE and the LIA.

6.2. Climate model/glacier model comparisons

A recent climate simulation with an earth system model provides a test of our glacier-model derived estimate of temperature change over the past 2 ka. Here we make use of a new 1-2005 CE simulation with the Community Earth System Model (CESM) (Hurrell et al., 2013), which adopts the same model version of the CESM as used for the CESM – Last Millennium Ensemble (Otto-Bliesner et al., 2016) driven by natural (i.e. orbital parameters, solar irradiance, and volcanic eruptions) and anthropogenic forcings (i.e. greenhouse gases and land-use) compiled by the PMIP4 working group (Jungclaus et al., 2016). The past2k CESM simulation suggests that the period from 0-1000 CE was, on average, ~0.24°C cooler than 1 CE control conditions (Fig. 6), and that the period from 1000-1900 CE was on average ~0.30°C cooler than the preceding millennium, meaning that the period from 1000-1900 CE was, on average, ~0.54°C cooler than 1 CE conditions, and that the second millennium CE temperature decline was dominated by cooling through the LIA (Fig. 6). The period encapsulating the LIA, from 1250-1850 CE, was on average 0.40°C cooler than 1-1000 CE. In general these temperature trends agree well with the glacier model outputs in this study (Table 2).

Both the CESM simulation and Kaufman et al. (2009) Arctic temperature reconstructions show less overall warming following the LIA up to present than the cumulative warming from the glacier model. It is possible that the imposed linear warming in our glacier model does not accurately capture the non-linear warming that is likely taking place in the region, or that the CESM simulation and temperature reconstruction may not capture local factors influencing warming at DIC. However, the overall agreement between the climate and glacier models and the similarity of both to regional temperature reconstructions (Fig. 6, Table 2) supports the contention that the record of DIC expansion derived from the death ages of entombed plants faithfully records the average cooling that occurred in the region over the past 2000 years.

7. Conclusions

We have used radiocarbon-dated *in situ* tundra plants exposed by retreating ice margins to construct a spatially and temporally constrained record of ice cap expansion over the past 2 ka. DIC grew between ~26 BCE and 1000 CE, then advanced episodically at ~1000, 1200, and 1500 CE, reaching its Neoglacial maximum during the LIA. The LIA was terminated by the warming of the 20th century.

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Glacier model simulations show that a minimum average cooling of ~0.44°C is required to match the radiocarbon constrained pattern of ice expansion over the last 2000 years, with the period from 1000 to 1850 CE being on average ~0.25°C colder than the preceding ~1000 years. A climate model simulation for the past 2ka driven by natural and anthropogenic forcings, as well as reconstructed Arctic temperatures show similar summer temperature decreases, reinforcing the glacier modeling conclusions. Both the radiocarbon record and climate model simulations indicate that the coldest interval of the past ~2000 years was during the LIA (1250-1850 CE). Glacier model simulations matching observed ice-cap retreat since 1900 CE suggest that a cumulative warming of 2.7°C over the last ~100 years has reversed ~1000 years of ice cap expansion under only ~0.25°C cooling, suggesting modern warming is unprecedented over the past 2 ka.

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At the present rate of warming, DIC will likely disappear before ~2100. Future collection of *in situ* plants exposed as DIC continues to retreat will both extend the record of ice cap advance and provide more constraints for modeling of ice cap activity and climate perturbations during Neoglaciation.

Code Availability

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The Matlab code for the glacier model utilized here is available at https://github.com/paleo-glacier/DivideGlacier.

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Figure 1

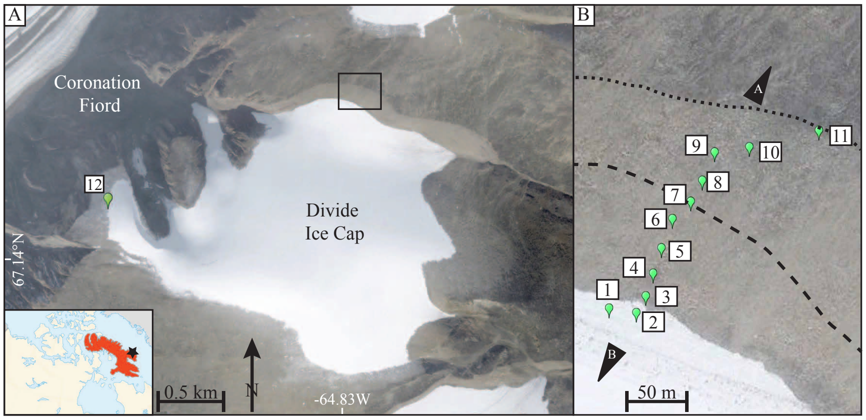

Figure 1: A) A map view of Divide Ice Cap, with location in inset map; note prominent trimlines and location of sample #12. B) Detail of sampling transect along which mosses were collected (sample numbers noted), with trimline (dotted line) and 1960 ice margin (dashed line; based on aerial photographs) shown. Locations of camera angles for Figure 2 are also noted with black triangles with panel letters. Imagery courtesy DigitalGlobe, 2011.

Deleted: C) Example of sampled in situ preserved moss along transect (sample #5).

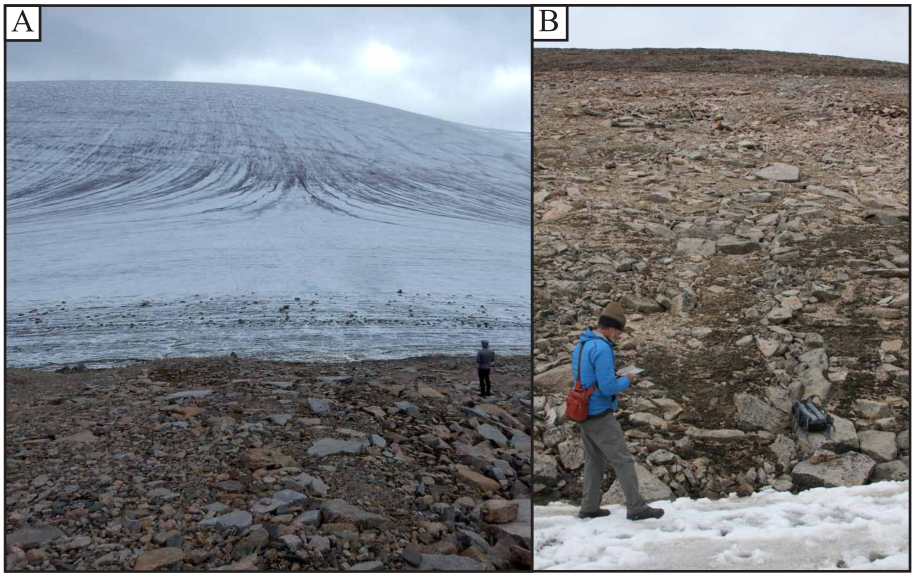

Figure 2: A) View south towards north aspect of DIC, with supraglacial channels demarcating the modern topographic divide. B) View north along transect up towards the maximum Neoglacial DIC extent; note large mats of dead vegetation diminish away from current ice margin.

Figure 3

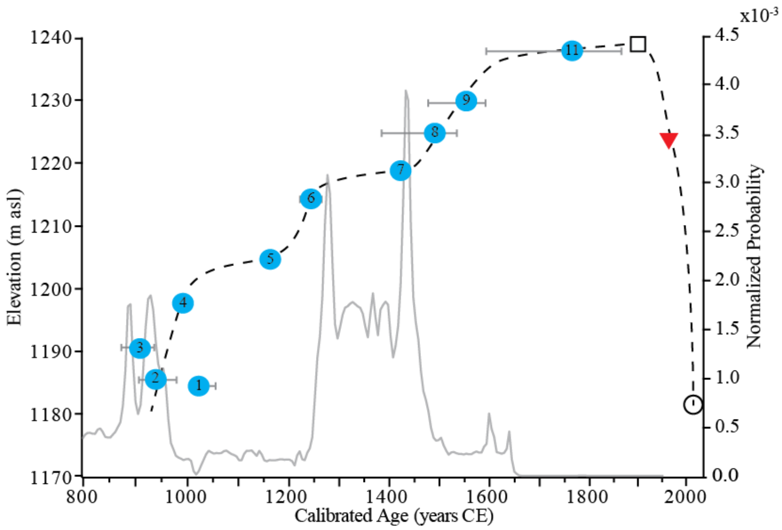

Figure 3: Plot of transect radiocarbon ages with elevation, showing median age (dots with sample numbers) and 1-sigma uncertainty (gray bars). Position of ~1900 CE Neoglacial maximum extent (square) also shown. The position of the DIC margin interpreted from 1960 aerial photography is shown (triangle), as well as its observed 2015 position (circle). The inferred ice margin history (dashed line) plotted through samples ages illustrates the episodic nature of ice margin advance. The episodic nature of DIC expansion agrees well with the normalized probability compilation of recently exposed ice margin *in situ* plant ages from Baffin Island (gray line), which shows periods of regional ice expansion (Margreth et al., 2014; Miller et al., 2013; see supplement for data).

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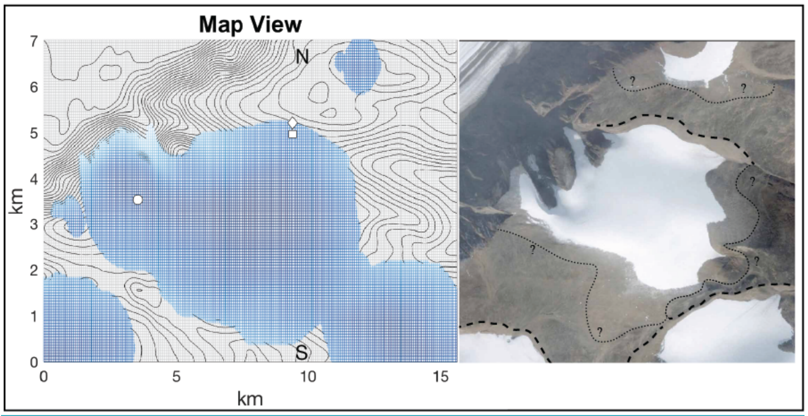

Figure 4: Map view of simulation (left panel) output showing the modeled maximum Neoglacial extent (contour interval is 30 m). Also shown is sample #12 (circle), 1000 CE margin (square), and Neoglacial maximum trimline (diamond). Right panel shows a google earth 2011 image with Neoglacial maximum extent trimlines (dashed lines) and approximate trimlines (dotted lines) shown.

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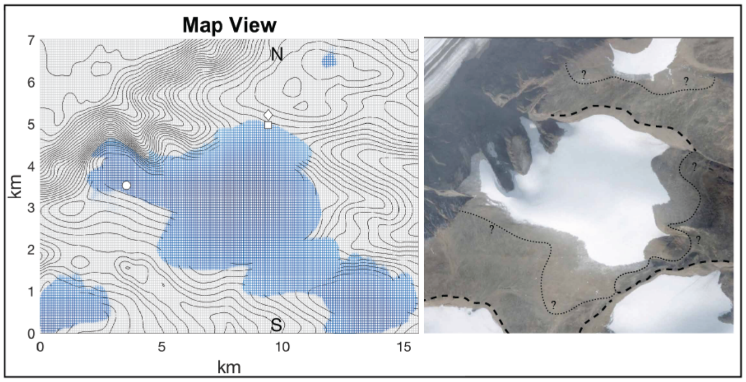

Figure 5: Final output from the full simulation model showing the modelled modern (2015 CE) extent of the ice cap following the advance and retreat scenarios outlined in text.

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Figure 6

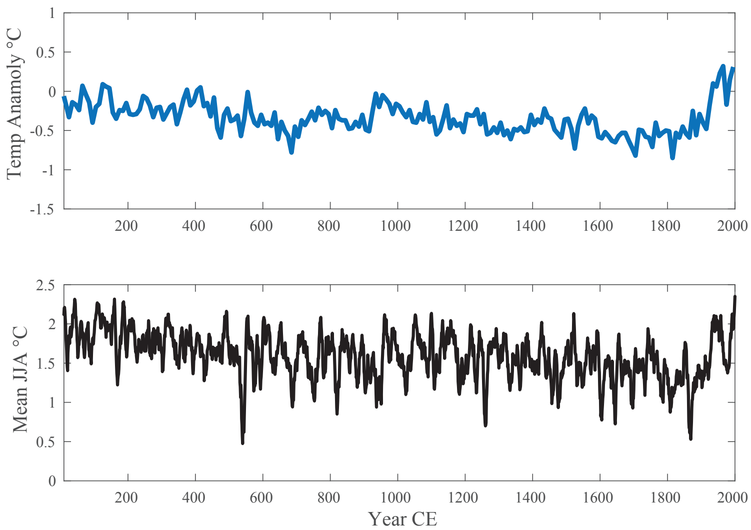

Figure 6: Top Panel: CESM-simulated decadal 2 m air temperature (°C) during JJA spanning the terrestrial region of the Atlantic Arctic (60-90°N, 90°W-60°E). Overall, the CESM modelled temperature shows similar coolings to the glacier model results presented here. Bottom Panel: Reconstructed Arctic-wide late Holocene temperatures (relative to the 1961-1990 instrumental mean; Kaufman et al. (2009)) showing similar structure and magnitude of change to the CESM simulation and our glacier model.

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Table 1: Plant Radiocarbon Ages

Table 1

Sample # (Fig. 1)	Lab ID	Field ID	Latitude	Longitude	Altitude (m asl)	Distance from 2015 ice margin	^{14}C age (yr)	± (yr)	Calibrated Median Age (yr CE)	1σ Uncertainty (-yr)	1σ Uncertainty (+yr)	2σ Uncertainty (-yr)	2σ Uncertainty (+yr)
1	UCIAMS-167159	M15-B072V	67.15198	-64.82164	1185	0	1005	25	1029	3	33	118	43
2	NSRL-28798	M15-B071V	67.15195	-64.82115	1186	0	1100	15	942	36	41	45	47
3	NSRL-28797	M15-B070V	67.15207	-64.82098	1191	16	1145	15	910	39	28	61	132
4	NSRL-28796	M15-B069V	67.15223	-64.82084	1198	34	1055	15	996	16	9	23	23
5	NSRL-28795	M15-B068V	67.15241	-64.82069	1205	53	880	5	1172	11	13	35	16
6	NSRL-28794	M15-B067V	67.15261	-64.82049	1215	79	770	20	1254	20	24	22	30
7	NSRL-28793	M15-B066V	67.15273	-64.82016	1219	95	505	15	1424	6	7	13	13
8	NSRL-28792	M15-B065V	67.15288	-64.81995	1225	114	380	15	1505	104	50	113	56
9	NSRL-28791	M15-B064V	67.15308	-64.81972	1230	143	310	15	1569	72	45	75	53
10	NSRL-28790	M15-B062V	67.15312	-64.81909	1229	157	1.4933*	0.0025*	1971	8	1	N/A	N/A
11	NSRL-28799	M15-B076V	67.15323	-64.81783	1238	202	175	15	1780	165	111	170	113
12	NSRL-26071	M14-B0170	67.14353	-64.87985	1483	NA	1975	20	26	21	29	29	44

*Sample M15-B062V returned a post-bomb ^{14}C measurement; Fraction modern and uncertainty shown here. Age calculated using OxCal v4.2.4 Bronk and Ramsey (2013) with Post-bomb atmospheric NH1 curve (Hua et al., 2013).

Table 2	0-1000 CE (°C)*	1000-1900 CE (°C)*	Total (°C)
Glacier Model	0.19	0.25	0.44
CESM	0.24	0.3	0.54
Kaufman et al. (2009)	0.22	0.22	0.44

*Cooling relative to preceding millennium

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Here we briefly describe the model setup; for a detailed explanation see Supplemental information. The model, modified from Kessler et al. (2006), calculates an ice thickness on a two-dimensional terrain model governed by explicit equations for ice flux and mass balance using shallow-ice physics (Blatter et al., 2011). Modern ice was removed (using an approximation of basal shear stress of ~1 bar) from 2011 ASTER digital elevation data to create the base terrain on which glacier growth was modeled.

Glacier growth on the base terrain was driven using a modified distributed mass-balance approach. Annual accumulation is assumed to be uniform (0.3 m water equivalent) across the ice cap, given the small area and limited elevation range (Fisher et al., 1998; WGMS, 2012). Annual melt is calculated using a positive degree day method (Hock, 2005) with an additional component from incoming solar radiation (Jonsell et al., 2012). We apply a positive degree day melt factor of 6.3 mm day^{-1} °C^{-1} (Braithwaite, 1981). Solar radiation melt factors (mm day^{-1} (W m^{-2})$^{-1}$) are traditionally calibrated using measurements of mass balance (e.g., Jonsell et al., 2012); at this study site we lack such measurements. However, using the temporal and spatial constraints above, including the maximum Neoglacial ice configuration recorded by trimlines, the local solar radiation melt factor can be approximated from the model run that produces the best-fit ice extent to the observed Neoglacial maximum extent.

Reviewer #1

General Comments	Action/Justification
It sounds like you are effectively tuning your model to the transect chronology and (assumed) maximum LIA extent using the solar radiation melt factor, but then you argue that your model to reconstruct patterns of ice expansion - isn't that circular reasoning	In terms of model calibration, knowing that our glacier simulations must fit the transect chronology provided by the plant radiocarbon ages and the LIA maximum extent delimited by prominent trimlines, we select a solar radiation melt factor that best reproduces the ice cap chronology and geometry. The primary purpose of the glacier simulations is not to reconstruct ice margin activity (this is already known from our transect chronology), but rather to use the known chronology within a mass-balance driven (and thus climate driven) glacier model to approximate the necessary temperature changes required to reproduce the observed glacier activity over the past ~2000 years. Yes, the model does reproduce the observed ice margin activity, but the end purpose of the model is to determine the temperature change driving ice advance and retreat over the past ~2000 years. This is clearly laid out in the beginning of section 5.3. However, the text in lines 24-25 in the abstract is ambiguous regarding the end purpose of the modeling experiments. We have reworded text in the abstract to more closely match that in section 5.3.
What about the other factors and parameters of your model that are unknown such as the degree-day factor (is that one for snow or ice or both?) or the lapse rate? Presumably you could combine a variety of factors / values and get similar fits to the observations (SI, Figure 3).	The degree-day factor from Braithwaite (1981) is empirically derived from summer ablation data taken from four glaciers in the Canadian Arctic and is the most appropriate value to use given the location of our Divide Ice Cap (see Cuffey and Paterson, (2010) for a more recent discussion). Empirical nature specified in text (Section 4.2). With regards to lapse rate, Gardner et al. (2009), working on glaciers in the Canadian Arctic, found that the moist-air adiabatic lapse rate can differ significantly from the lapse rate measured near glacier surfaces, hence our use of their slightly lower glacier-surface lapse rate of 4.9°C km^{-1}. This is also now specified in section 5.3.2.
As I understand it, superimposed ice formation is an important factor in the mass and energy balance of these types of ice caps and should be included in the model.	The authors agree that superimposed ice can be an important part of the mass balance an small ice caps such as DIC. However, the effect of refreeze is highly heterogeneous and difficult to incorporate in our model without detailed observational data. lacking this data, and given the goal of the glacier model, we believe attempting to account for refreeze would introduce significant uncertainty to the model. Text pertaining to this subject has been added to the supplemental (section 5).
I'm certainly not an expert in glacier modeling, but it seems to me that this manuscript should be reviewed by such an expert in order to make more confidence in Section 5.3 (see below). Much of the material included in the Supplemental Information should be included in the manuscript itself (e.g. Section 4.2).	The authors originally decided to place a majority of the modeling into the supplemental to maintain a short and concise manuscript, but we agree with the Reviewer that moving some of the modeling material into the manuscript could be useful. The authors defer to the editor's judgement about relocation of supplemental material within the manuscript. In response to recommendations from both reviewers and the editor a majority of the supplemental regarding the numerical simulations has been moved into the main text. Including: creation of the base terrain (5.3.1.), the mass balance approach and model (5.3.2.), modeling of ice surface (5.3.3.), and glacier model calibration (5.3.4.). The Full Simulations section from the supplement was in incorporated into section 5.3.5. Original supplemental figure 3 and 4 were also moved into the main text, (supplemental figures 1 and 2 were deemed unnecessary and were discarded).

A similar argument applies to climate/glacier model comparisons in Section 6.3. The methods underlying this section are presented in the Supplemental Information and include a series of steps and assumptions that are not adequately explained and defended.	Regarding the climate/glacier model comparisons: the submission deadline of Feb 11, 2017 for the special issue prevented us from waiting until the CESM climate model had finished its run, hence the composite with the LME simulations to get the full 2000 year temperature record. The CESM simulation has since reached 2005 CE, allowing us to compare our temperatures derived from our glacier model directly to the CESM run. The supplemental section on compositing the two climate simulations can now be removed entirely.
It seems like sample #12 is critical as it defines the ice expansion ~ 2 ka and continuous ice cover until a few years ago. First I would not call it the southern margin - the sample seems to be from the western edge of a small outlet glacier. Is it also possible that snow and ice persisted in this (maybe topographically-sheltered?) location while the remainder of the ice margin behaved differently?	I agree with the Reviewer than sample twelve is more westerly than southerly, location will be changed in a revised manuscript. Given the low topographic relief around the summit of the ice cap, shielding/shading is negligible, and the ice margin at sample #12 should behave in concert with the rest of the ice cap.
In line 12 you argue that for a specific type of ice advance: a) how does your data show that and b) why is that relevant?	In line 12 we argue for episodic ice margin advance based on the spatial and temporal distribution of plant kill ages. Each plant kill age represents the time when the ice margin advanced through that location; the kill ages don't necessarily represent a standstill like a moraine might (it is possible, and likely, that the ice margin was not continuously advancing, but our kill ages only record times of ice advance). For example, the distribution of samples #1-4 suggest that the ice margin advance rapidly (a few decades) from 1185 to 1198 masl, but then advanced to 1205 masl over a period of ~200 years, which requires, at a minimum, a change in the rate of ice advance (if not a standstill), hence the conclusion that ice margin advance is episodic in nature, with periods of faster and slower ice margin advance. We agree that this is not clearly laid out in the manuscript and text to clarify will be added. This episodic nature is relevant because one could argue that the systematic decrease in Northern Hemisphere insolation during the Holocene should drive continuous cooling and glacier expansion, but here we are seeing gradual ice cap expansion punctuated by episodes of fat ice advance, suggesting that other mechanisms are involved in the late Holocene climate evolution.
Line 20 / Figure 3: Why are you plotting the ages of the dead plants against elevation - isn't more common and appropriate to plot against distance (e.g. distance from 2015 margin)? Some of elevation changes are quite small and well-within typical GPS uncertainties.	We agree that the age/elevation plot in Figure 3 is not as common as age/distance plots. However, given the steep topography of the saddle where the samples were collected, the plant kill ages are tracking the inflation of the ice cap uphill. The authors determined (after much deliberation) that the age/elevation plot was more representative of the ice margin activity in this case. Per the Editors suggestion, an alternative time-distance plot has been added to the supplemental materials.
Figure 3: What is the relevance/meaning of the data shown on the secondary y-axis and how does the data support your analysis? This may be obvious to you, but not necessarily to the reader.	The secondary axis in Figure 3 is a normalized PDF of ice margin plant kill ages from the Cumberland Peninsula region which shows periods of regional ice margin advance. The record is the combined published results of Miller et al. (2013) and Margreth et al. (2014). The agreement between this record and the transect of plant kill ages supports the conclusion that our periods of accelerated ice margin advance are occurring during periods of increased regional ice expansion (and therefore cooling). This is perhaps not well explained in the text (section 5.2) and text has been added to section 5.2 to clarify this comparison. We have removed the unpublished ages in order to simplify things and only utilize the ages reported by Miller et al. (2013) and Margreth et al. (2014) (ages added to supplement, section 2).

I'm confused here. It seems from the text in Section 5.2 that the ice cap in 2014/2015 was more-or-less the same size as it was 2,000 years ago as defined by Sample #12. Figure 3 shows to me that the ice cap margin at 1,000 CE was more-or-less at the same elevation as today at ~1185 m asl. Therefore it is not clear why the 0.19 deg C cooling is needed? Figure 3 shows that the ice cap advanced to its (assumed) LIA maximum (~1240 m asl), so the 0.25 deg C makes more sense. A table summarizing the different temperature changes for the different dates would be helpful.	As of summer 2014 (time of sampling), sample #12 was exposed, and its age suggests it had been ice covered for ~2000 years. As of 2015, the ages of samples #1-4 at the 2015 ice margin suggest they had been ice covered for ~1000 years. It is important to note that ice caps do not advance and retreat symmetrically. The modern ELA is everywhere above the elevation of the ice cap, so rapid retreat is exposing both areas that have been ice covered for ~2000 and ~1000 years simultaneously. A table summarizing the coolings reported in this study, from the CESM model and from Kaufman et al. (2009) has been added (referenced in section 6.2).
Page 6 / Lines 4 to 11: These values (e.g. 0.028 deg C / year) should be derived and explained in the main manuscript, not in the Supplemental Information. There also seems to be a discrepancy in the amount of cooling it took to grow the ice cap from 1,000 CE to its LIA maximum (0.25 deg C) and the warming that caused the ice cap shrink from its LIA maximum to today (2.8 deg C). A summary table as suggested above might clarify the issue.	Page 6/Line 4-11: I agree that some of the supplemental regarding the rates of warming could be moved in to the main text to clarify how warming rates were derived. The reversal from slow cooling during the period ~1000-1900 CE, to rapid warming in recent decades is not a discrepancy, but rather further evidence that modern warming is well outside the norm of at least the last ~2000 years. This is actually an important conclusion of the study (see Conclusions), but is not as clearly laid out in section 5.3. The magnitude of cooling between 1000 CE and its LIA maximum need not be the same as the warming over the last century as DIC is not in equilibrium during theses periods. Text was added to clarify this and a table showing the reported coolings from this study, the CESM simulation and from Kaufman et la., (2009) has been added to section 6.2.
Page 6, Lines 12 to 15: This is a weak paragraph. Why do the model assumptions translate to minimum values for temperature changes? Explain and defend the model limitations and uncertainties. For example - present a series of charts showing the ice margin elevation under changing model assumptions and parameters.	Page 6/Lines 12-15: A clarification here, since the glacier model is forced by stepwise temperature changes, the model reports the average temperature required to advance the ice margin over the required distance in the allotted amount of time. A figure showing the glacier simulation under different parameterizations was added to the supplemental. Additional text was also added to the supplemental regarding glacier model uncertainties.
Section 6.2 This section is confusing - important methodological steps and considerations are only included in the Supplemental Information and should be part of the main manuscript. It seems like much of the issue revolves around splicing a model simulation starting in 850 CE to a model simulation that has currently only reached 1270 CE using a simple offset. I suggest waiting for the model simulation to finish or to cut-out this section.	Per our comment above, the CESM temperature simulation to which our data is compared has now run up to 2005 CE, allowing us to compare to the full run instead of the composite temperature in the current record. This significantly simplifies section 6.2.

Specific Comments	Action/Justification
1. What 'happened' before 20 BCE? Discuss the overall Holocene history of the ice cap as context for the last 2,000 years, perhaps in Section 2.	This manuscript was submitted for consideration into a special PAGES2ka issue regarding the last 2000 years of climate change in the Arctic, hence the authors focus on the late Holocene. Work elsewhere on Baffin suggests glaciers were regrowing as early as 5ka, but our data do not speak to ice activity prior to 2ka. Given the age and position of sample #12, it is likely that the ice cap was behind the sample location but growing in the decades to centuries prior to 20 BCE (before expanding through sample site #12). Section 2 provides general Holocene glacial activity on Baffin. This study is the first to look at the late Holocene activity of this particular ice cap. Section 6.1 Regional Comparisons has been expanded to incorporate the broader history of the cryosphere during the Holocene in the area.

Page 3 / Line 18: That’s the standard assumption - a vegetation trimline defining the maximum LIA ice extent, but is there actually any evidence for it? How do you know that? Could it be, for example, perennial or long-lasting seasonal snow cover, especially in what appears to be a topographic setting conducive to the persistence of snow?	Page 3/Line 18: The uniform nature and clarity of the trimline suggests it is the LIA ice margin. A perennial snowline would not be as uniform in elevation or clarity. The southerly aspect of this slope would also limit snow cover. Finally, the radiocarbon ages approaching the trimline also indicate LIA timing. Text clarifying this has been added to section 3.
See also Page 6 / Line 19 and 20: you have not shown that in the manuscript	We respectfully disagree with the Reviewer here. The presence of a prominent trimline and the suite of transect radiocarbon ages and field observations combined all indicate DIC's maximum Neoglacial extent was reached during LIA times and has since shrunk to a size not seen in ~1000 years.

Technical Corrections	**Action/Justification**
Page 2 / Line 18: Also include an existing reference/citation here in addition to the ‘in-review’ one	Pendleton et al. (2016) also deals with moraine degradation and scatter in CRN ages. Reference added to manuscript.
Page 3 / Line 14: Is that an official name ?	Divide Ice Cap (DIC) is an informal name; noted in text (section 1).
Page 5 / Line 7: a post-bomb age - what does that mean?	A post bomb ^{14}C age is one that dates to post 1950 CE (after nuclear weapons testing loaded the atmosphere with more 14C). See Reimer et al. (2004) for more information.
Page 7 / Line 3: Reword the sentence - the word ‘strong’ seems not appropriate here.	Replaced ‘strong’ with ‘convincing’.
Figure 1: Draw the trimlines into A - they may be obvious and prominent to you, but not necessarily to the reader. The image used seems ‘fuzzy’ - what’s the source of the image (should be included in the caption). Add a scale to 1B and 1C.	Quality of figure checked (fuzziness due to upload issue). All trimlines now shown in figure 4. Scale added to Figure 1B
Figure 2: Can you indicate the approximate photo locations on Figure 1B?	Camera location can be added to figure 1B.
Figure 3: Label the blue circles with the Sample # from Table 1.	Sample #s from Table 1 added to blue circles.
There are many other minor typos and stylistic inconsistencies throughout the manuscript and especially the Supplemental Information.	Manuscript has been thoroughly edited for grammatical and syntax errors during revisions.

Reviewer #2

General Comments	**Action/Justification**
The modelling section needs to be included in the paper itself, not just in the SI. Text can easily be moved from the supplement and into the paper itself.	See response above to reviewer #1

<table>
<tr><td>Assuming, as the authors have done, that annual accumulation is constant (and ignoring wind) is problematic. In rationalizing this choice the authors write in the SI that Although precipitation records are sparse near the study site, ice core records from the ˊ- of the Greenland Ice Cap show that regionally, precipitation varied by only ~6% over the last 1200 years (Alley, 2004)˙. This might be true, but it might also be an underestimation of the precipitation changes at the study site because we do not know how well the two sites correlate. Considering that this can have some bearing on the summer temperature estimate it deserves to be discussed more than it currently is (and also wind, as acknowledge by the authors).</td><td>The Reviewer brings up two important assumptions dealing with wind redistribution of snow and precipitation over the late Holocene, both of with are important for determining the mass balance. Field observations from our sampling campaigns have suggested that wind redistribution may be a factor in glacier mass balance, however, without local, long-term wind records accounting for this is difficult. Additionally, the complexity of accurately modeling wind redistribution is highly localized and beyond the scope of this model. Furthermore, the available records of dominant wind direction cannot explain the N-S asymmetry in the LIA ice cap trimlines, suggesting that another factor (e.g., solar radiation) is the dominant control on glacier shape at this location. As for precipitation, in addition to the data from Greenland, and older study from Devon Ice Cap on Ellesmere Island also suggest that precipitation was steady over at least the past ~1300 ka (Paterson and Waddington, 1984). Without more detailed records of precipitation, I believe that assuming steady precipitation (and thus accumulation) throughout the model run is the most accurate and reasonable approach.</td></tr>
<tr><td rowspan="3">A pan-Arctic perspective would require the authors to dig deeper into the available literature. Citing for instance Jason Briner et al on the use/value of threshold lakes is inappropriate. Look for instance up studies carried out by John A Matthews and Wibjörn Karlén (Geology, 1992) decades ago. Citing papers that are in review (Crump et al) is something I don’t recommend. Referencing Miller et al (2016) for maximum Neoglacial during the LIA is fine, but there are a number of other datasets from Svalbard that both have discovered this earlier and also datasets that contradict this observation (see for instance Reusche et al. 2014).</td><td>In the initial manuscript submission, the authors kept the broader comparisons (section 6.1 Regional Comparison) focused on pertinent ones in the immediate area around the study site, to maintain the focus of the manuscript. We agree with Reviewer #2 here that a more pan-Arctic comparison could provide new information on connections across the Arctic. Several other studies from Baffin and Greenland, including both glacial and lacustrine records (e.g., Briner et al., 2009; Schweinsberg et al., 2017; Thomas et al., 2010) provide different perspectives on Holocene climate and provide interesting comparison. The Reviewer is correct that work on Holocene climate and glacier records has been ongoing for several decades around the North Atlantic (nicely summarized by Solomina et al., 2015). A comparison to broader Holocene glacial trends has been added to section 6.1.</td></tr>
<tr><td>The mention of threshold lakes from Briner et al. (2010) (as well as CRN moraine chronologies) is used to highlight the often-discontinuous nature of glacial records compared to the plant kill age transect method used here. The transect method provides tighter spatial and temporal constraints on the exact position of the ice margin, whereas threshold lakes may have good temporal resolution, but only provide data on when the ice in in the catchment or not (no additional information on glacier dimensions). Conversely, moraine CRN records can provide good constraint on glacier margin dimensions, but many issues plague boulder dating and due to the destructive nature successive glacier advances, the records are often discontinuous. All of these examples set the stage for the transect method used in this study, which provides more continuous records of actual glacier dimensions through time.</td></tr>
<tr><td>It is well known that individual glaciers can deviate significantly from regional climate forcings, due to localized climate effects or individual catchment features, the authors want to take care with respect to this when comparing our study. We believe comparison to broader regional trends may be more useful.</td></tr>
</table>

	The reviewer also recommends comparison to Reusche et al. (2014), a CRN study of a late Holocene moraine on Svalbard where the authors suggest moraine abandonment at ~1.6 ka, in apparent contradiction to our chronology. There are two aspects of this study that raise concern with us. First, the reported age of 1.6±0.2 ka is the mean of 16 individual CRN boulder ages from a single moraine (with multiple crests) that range from 0.5-3.6 ka. It is unclear if the spread in ages is due to continuous occupation of this moraine limit (with pulses of glacial advance), degradation of the moraine over time due to an ice core, or a combination of both. Therefore a simple average of such a spread in ages is an inappropriate representation of the true moraine age. This moraine record is also discontinuous by nature and makes comparison to our more continuous record difficult (in addition to the limited temporal overlap). Secondly, the proximity of Linnébreen to the Arctic ocean might suggest that it's has a strong maritime influence, including fluctuations in sea ice. Our location is also close to the ocean and would be influenced by ocean temperature and sea ice, but likely in different ways at different times. Given the concerning nature of age calculation and local climate effects, we are hesitant to compare these two records explicitly, but agree that broader comparisons to the Northern North Atlantic may be worthwhile.
Figure 1and 2 is of poor quality. I challenge the authors to find a better way to present the sites and the data. A conceptual model might be in place.	As mentioned to Reviewer #1, upload issues created fuzzy images for Figures 1 and 2. High resolution versions have been placed in the revisions. An alternative depiction of the data has been added to the supplement per Reviewer #1 and the Editors suggestion.
As of now the glacier dataset is only presented in Figure 3. Choosing not to compare this new dataset to other records is a bad decision.	Additional text has been added to section 6.1 comparing our record to other Arctic records
Moreover, the data is not discussed with respect to the normalized probability due to radiocarbon dating, which is represented by a grey curve – why?	The Reviewer is directed to the response to Reviewer #1 regarding the comparison to the data from Miller et al. (2013) and Margreth et al. (2014).
I'm not a big fan of the dashed line, which most likely is hand-drawn? For obvious reasons (how do you account for uncertainty when drawing that line?) I suggest that it is removed.	Per Reviewer #2's comment regarding the dashed line in figure 3, we defer to the response given to Reviewer #1. Obviously, the true trajectory of the ice margin is unconstrained between our plant kill ages, but the line represents the best representation of the episodic advances imprinted on overall cooling and ice expansion over the past ~1000 years. We would reiterate that since plant kill ages represent the time when ice likely advanced through that location, the inflections in the dashed line are necessary in order to fit the kill age chronology.
Why not show the ESM output in figure 4 compared to existing paleorecords of actual data? Surely differences between a model and existing datasets are worthwhile discussing considering that the authors end up concluding that a minimum average cooling of ~0.44°C is required to explain the observed variations in horizontal ice cap fluctuations?	High resolution temperature records of the last ~2000 years for this region are difficult to come by, however, we agree that comparison to records from farther afield (i.e. Greenland) or from more regional compilations would improve Figure 4 (now figure 6) greatly. The temperature reconstruction from Kaufman et al., 2009 has been added to Figure 6 and referenced within the text.
The authors state in the SI that at the time of submission, the simulation was still running and had only reached 1270 CE Fair enough, but not a very convincing argument. Should we still trust the data? For what reason? Why not wait until the run was complete?	With regards to the CESM climate simulation, we refer to the response given to Reviewer #1, that our submission deadline of Feb 11 , 2017 was a hard deadline and we were not able to finish the mode run in time. The model has since run up to 2005 CE, enabling us to use the full simulation and remove the text regarding the compositing of multiple records.