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Substantial agreement on the timing and magnitude of Late Holocene ice cap expansion between East Greenland and the Eastern Canadian Arctic: a commentary on Lowell et al., 2013

1. Summary

Lowell et al. (2013) present a large series of radiocarbon dates on tundra plants preserved beneath ice caps and cosmogenic nuclide exposure ages on moraine boulders and bedrock that document changes in the dimensions of Istorvet, an independent coastal ice cap on East Greenland. They argue that their reconstruction of Istorvet advances during the Late Holocene is inconsistent with the reconstructions of Miller et al. (2012) for Arctic Canada. Here we show that a careful interpretation of their data reveals a remarkable similarity with the compilation of radiocarbon dates on rooted tundra plants long-entombed beneath over 50 different ice masses in a 1000 km transect along Baffin Island, Arctic Canada and with the high-resolution record from an Icelandic ice cap (Miller et al., 2012). Collectively, these results suggest synchronous responses of ice masses across the northwestern sector of the North Atlantic Arctic during recent millennia. We also emphasize that the interpretation of radiocarbon ages of rooted plants exposed by receding ice depends to a large extent on the collection protocols employed. The sampling protocols outlined below maximize the value of these key new datasets to provide unambiguous constraints on past climates and changes in glacier dimensions. Examples of settings that meet these criteria are shown in Figs. 1 and 2.

- Collect only demonstrably *in situ* plants (rooted and in growth position) that are at the surface revealed by recent recession of cold-based non-erosive ice caps
- Collect within 1 m of the current ice margin to ensure the plants were exposed during the year of collection and so avoid altered ^{14}C activity by regrowth.
- Collect plants that have brief life cycles. Our preferred plant types are mosses (we target species of the common *Polytrichum* moss genus, but other moss taxa should be fine). Avoid lichens and woody plants that have long life cycles.
- Avoid animal remains; animals can die on the ice and later be let down during an ice-melt phase; hence, they frequently lack a firm stratigraphic context.
- Make at least two collections, tens to hundreds of meters apart; ice-cap complexes may warrant many collection sites as different portions may have different climate thresholds
- Collect from as many different ice bodies as possible
- Collect across as wide an elevation range as possible

The goal of this comment is twofold: (1) to clarify sampling protocols that yield securely interpretable vegetation-kill-dates tied to ice-cap expansion and summertime cooling, and (2) to point out the substantial agreement in timing and magnitude of ice caps in east Greenland presented by Lowell et al. (2013) with those on Baffin Island and Iceland presented by Miller et al. (2012).

2. The record of entombed plants from Baffin Island, Arctic Canada

Although glaciers are widely recognized as highly efficient erosive agents, cold, relatively thin ice bodies on low-relief topography may act instead as exceptional preservation agents, preserving intact the landscape that existed when snowline dropped below a given site, for as long as the site remained beneath a perennial snow or ice cover. This was first recognized in the field by Falconer (1966) who realized that mature patterned ground apparent on aerial photographs appearing beneath the receding "Tiger Ice Cap", a small ice cap on the central plateau of Baffin Island, Arctic Canada, must indicate landscape preservation instead of erosion. When Falconer visited the site he discovered rooted tundra plants coming out from beneath the receding ice margin. His collection of rooted *Polytrichum* moss yielded a radiocarbon age of 330 ± 75 BP, which he interpreted to indicate that the Tiger Ice Cap expanded across an unglaciated plateau during the Little Ice Age (LIA) and did not melt from his collection site until the year of his sampling (Falconer, 1966). Miller visited the Tiger Ice Cap in 1981 AD, found Falconer's ice-marginal cairn, noted 60 m of recession in the intervening 18 years, and collected another sample of rooted *Polytrichum* moss from beneath the thin ice margin. This sample yielded a more precise radiocarbon age (450 ± 25 BP), which when calibrated gave an age of 1445 ± 30 AD, defining a time when substantial portions of the central plateau were ice-free. The sample also dates when snowline dropped below the site, entombing the moss beneath the Tiger Ice Cap until 1981 AD.

With rapid ice retreat apparent across Baffin Island in the past decade, we initiated a field campaign in 2005 AD to capitalize on the anticipated wide distribution of this unambiguous climate proxy, sampling over as great an elevation range as possible. Data from that campaign led to the conclusions articulated in Anderson et al. (2008) and Miller et al. (2012), the latter based on ^{14}C ages from 94 rooted plants collected at the ice margin (within 3 m for samples collected in 2005, and within 1 m for subsequent collections). The timing of the onsets of persistent cold summers derived from the vegetation-kill-dates are supported by the changing dimensions of Langjokull, second largest of Iceland's ice caps. The key conclusions are:

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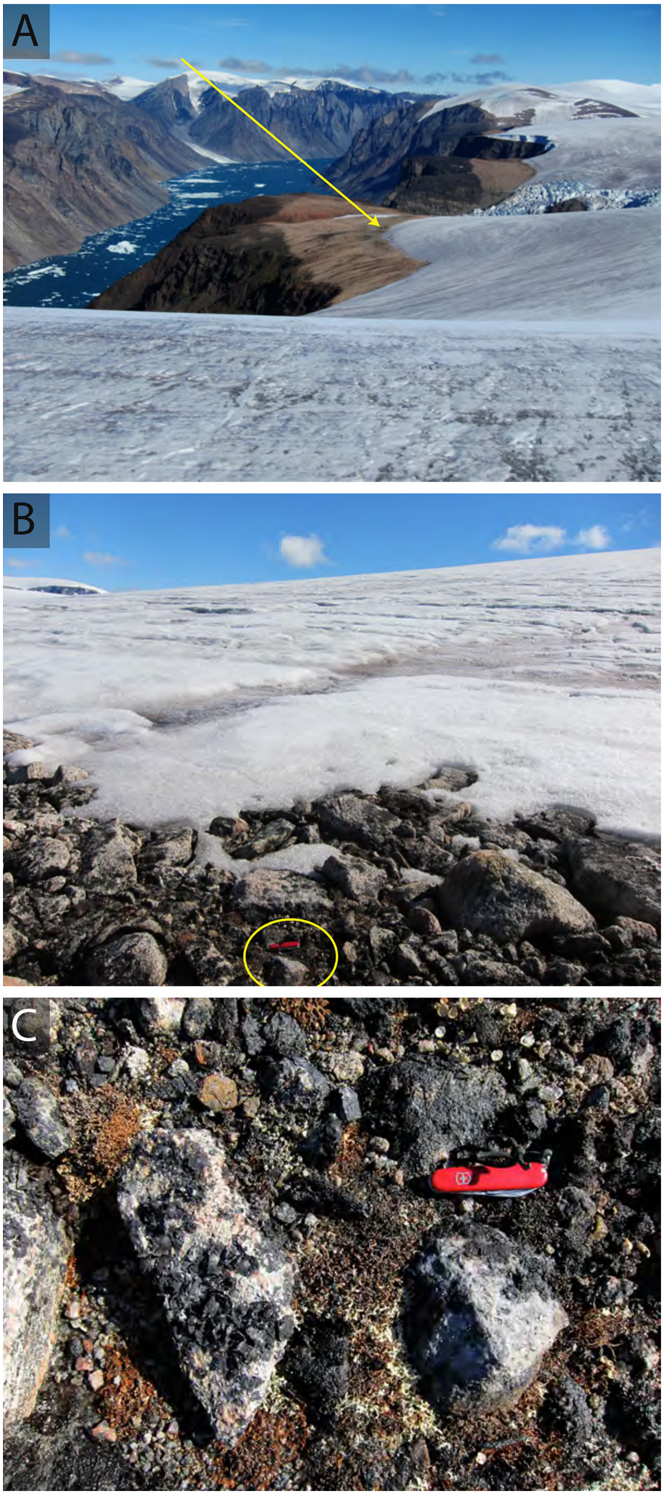

Fig. 1. Although large Baffin Island ice cap complexes may be drained by fast flowing erosive outlet glaciers, flat interfluves frequently are occupied by cold, non-erosive ice. A) Distant image of collection site M10-B236v (arrow). The spectral contrast between the area within the LIA boundary (plant free) and the well-vegetated landscape distal to the former ice margin illustrates the brief preservation of dead plants once they are exposed by ice recession. B) M10-B236v collection site 0.5 m from the melting ice margin (note circled red pocketknife and triangular rock that are visible in Fig. 2C). C) Undisturbed ancient vegetated surface exposed for less than three weeks by recent ice recession. *Polytrichum* moss from this site has a radiocarbon age of 1235 ± 20 BP (M10-B236v, UCIAMS-84676, 67.39745°; −64.51963°, 1202 m asl). Most of the dead plants in C) will be removed by subaerial erosive processes within a few years, as is apparent in panel A). Photos by G. H. Miller, 27 July 2010. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

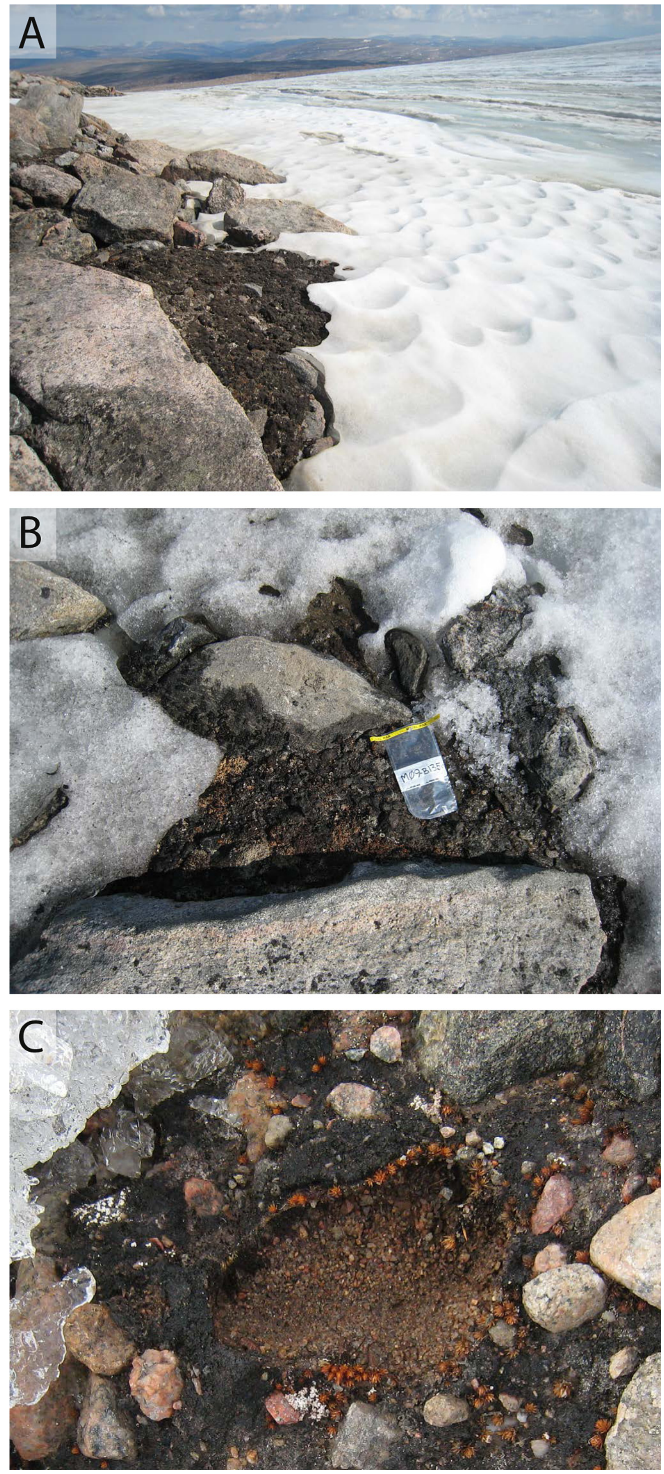

Fig. 2. Examples of *in situ* tundra plants within 1 m of a receding ice margin that meet our collection criteria. A) Tundra plants colonizing Pleistocene till, ice edge of Tortuga Ice Complex. B) *Polytrichum* moss (M09-B135v) from this site at the ice margin (1073 m asl), has an age of 1140 ± 15 BP (CURL-11070, 71.2297°; −74.0696°). C) *Polytrichum* moss at the ice margin of Tortuga Ice Complex (912 m asl) revealed by removing a till boulder. A single strand has an age of 1125 ± 15 BP (CURL-11433, 71.0632°; −74.7095°). Photos by G.H. Miller, July, 2009.

1) 24 sites that became ice covered between 800 and 950 AD did not melt out during Medieval times, remaining continuously ice covered until the most recent decade.
2) No significant ice-cap inception occurred during Medieval times (950–1250 AD)
3) At least 13 sites that became ice covered between 1275 and 1300 AD did not subsequently melt
4) Irregular cooling continued between 1300 and 1425 AD
5) At least 13 additional sites became ice-covered between 1430 and 1455 AD, after which all of our sites remained continuously ice covered until the most recent decade.

3. Sub-fossil plants overridden by ice on East Greenland

Lowell et al. (2013) present 50 radiocarbon dates on subfossil plants revealed by recession of Istorvet. They interpret the range of subfossil plant ages at each site to represent an interval of time when the site was ice free and Istorvet was as small or smaller than its present dimensions (Lowell et al., 2013 p. 134). This is not unreasonable. However, Lowell et al. (2013) employed a different strategy in their sampling of dead plants than that outlined above, which led them to incorrectly conclude that the history of local ice cap expansion in East Greenland differed significantly from the Arctic Canada reconstructions of Miller et al. (2012). Lowell et al. (2013) frequently sampled some distance from the ice margin, and in some cases below till, and thus were not able to sample only those plants emerging at the surface during the year of their collection.

A key locality is their West Margin site (450–520 m asl), where they found extensive plant remains buried beneath a thin till, with some plants contorted or broken, presumably by overriding ice (Lowell et al., 2013 p. 134). They report calibrated ages of 8 plants collected in close proximity to each other that range in age from 790 ± 105 to 1005 ± 20 AD. However, the 3 youngest dates are tightly grouped (965 ± 35 AD), and we assert that this is likely to be a close maximum age for the advance of Istorvet across that site. Lowell et al. (2013, p. 137) argue that the termination of plant growth at the West Margin (8 dates) and Middle Nunatak (4 dates) sites occurred ~1025 AD. This is an unusual way of interpreting calibrated ages; none of the 12 ages reported from these sites has a calibrated age range that includes an age as young as 1025 AD.

Our contention that the West Margin ages suggest that ice advanced across that site shortly after 965 ± 35 AD is supported by the youngest ages on dead plants from two of their three nunataks. The three youngest dates from Middle Nunatak (~615 m asl) overlap statistically, averaging 960 ± 30 AD. The youngest of nine ages from the High Nunatak (~725 m asl) is 890 ± 85 AD, although 3 other dates statistically overlap that date, and collectively average (825 ± 55 AD). Additional support comes from the North Margin site (680 m asl), where the youngest of four dated samples has an age of 795 ± 90 AD. The two ages from the Highest Nunatak (380 ± 50 and 600 ± 50 AD) are older but too few to conclude anything other than that the site was ice free at these times.

Taking the geologically secure interpretation that the youngest date(s) at each site provides the closest maximum age for when ice covered these sites then leads to the logical conclusion that the youngest plant kill dates are consistent with a lowering of snowline that buried the High Nunatak and North Margin sites beneath a persistent snow/ice cover between 800 and 900 AD and allowed Istorvet to expand over the lower Middle Nunatak and West Margin sites between 900 and 1000 AD. Two ages on aquatic moss from the threshold Bone Lake are statistically identical at 1125 ± 80 AD, from which it can be inferred that it took Istorvet about a 150 years (range: 60–280 years) to advance the 140 m from the West Margin site to the Bone Lake threshold, a rate of advance of ~1 m a^{-1} (range 0.5–2 m a^{-1}). This is similar to the rate at which ice advanced after crossing the Bone Lake threshold (1125 ± 80 AD) until it reached the fresh drift limit (1660 ± 20 AD [Lowell et al., 2013 Table 3 and p. 135]), a distance of 365 m in ~500 years (~1 m a^{-1}). This assumes, of course, that the ^{10}Be age on the moraine correctly dates when the ice reached its maximum, but no other ages are available, hence an advance rate of 1 m a^{-1} on average is not unreasonable.

Lowell et al. (2013) also report 23 dates on presumably rooted plants from three sites at similar elevations along North Istorvet, which may have responded differently to the same climate forcings than did South Istorvet (Lowell et al., 2013, Fig. 2). Unfortunately, most of the dates from North Istorvet fall in the time window where their calibrated ages range over several centuries. Although Lowell et al. (2013) do not draw any firm conclusions from these dates, we argue that two important points are apparent in the North Istorvet dataset. Firstly, three of four samples from the Northwest Margin site (unexpectedly, only two ages are shown in their Fig. 4, whereas four are listed in their Table 1) have small uncertainties when calibrated, ranging from 1406 to 1452 AD (average 1430 ± 15 AD). The other date from this site, on moss, is much younger (potentially as young as 1952 AD) and likely represents regrowth/recolonization after deglaciation. We interpret the ages from the Northwest Margin site to indicate that snowline dropped below the site 1430 ± 15 AD, and that the site remained continuously ice covered through the LIA. The other 19 ages are all younger than 1445 AD, with the old end of the probability distributions of their calibrated ages clustering at 1447 AD ($n = 2$), 1510 ± 20 AD ($n = 5$), 1643 ± 3 AD ($n = 5$) and 1670 ± 10 AD ($n = 7$). From these ages we conclude that North Istorvet must have experienced both advance and recession after 1450 AD, but that the final and most extensive advance began no earlier than 1670 AD, contrary to the conclusion by Lowell et al. (2013, p. 135) that Istorvet receded from its drift limit ~1660 AD (1600 AD, when the ^{10}Be age is correctly converted to calendrical years, see below).

We find that the date of Istorvet's withdrawal from its LIA drift limit is not well constrained. Lowell et al. (2013) report two ^{10}Be dates on moraine boulders at the maximum drift limit with ages of 7200 ± 140 BP and 350 ± 20 BP. Because one boulder clearly has inherited ^{10}Be, the other boulder may also have some inheritance, and without replication of the younger date, there is no secure age for when the ice cap reached its maximum dimensions of the LIA. The younger of the two ^{10}Be ages is used in the text to indicate when Istorvet receded from its drift limit, with the age expressed in calendar years as ~1660 AD (Lowell et al., 2013, p. 135). However, because the age is given by them as "350 ± 20 cal yr BP" (Lowell et al., 2013, Fig. 3 caption), and BP by convention is taken as 1950 AD, then the calibrated age is actually 1600 ± 20 AD.

Given the uncertainties outlined above, we suggest that the timing of South Istorvet's maximum extent is best expressed as "no older than 1600 AD", and that ice likely remained at or near the drift limit until the mid 19th Century, consistent with many other local ice masses around Greenland (Kelly and Lowell, 2009), and suggesting that the advance of Istorvet from the West Margin site to the drift limit was well below 1 m a^{-1}, on average.

What can be reasonably derived from the observations and ages presented by Lowell et al. (2013) using standard geological principles? We have shown that the ages are most consistent with:

1) A warm interval with snowline above the highest sites for several centuries prior to 800 AD
2) A lowering of snowline sometime between 800 and 900 AD led to persistent snow or ice cover for two high-elevation South Istorvet sites by 900 AD

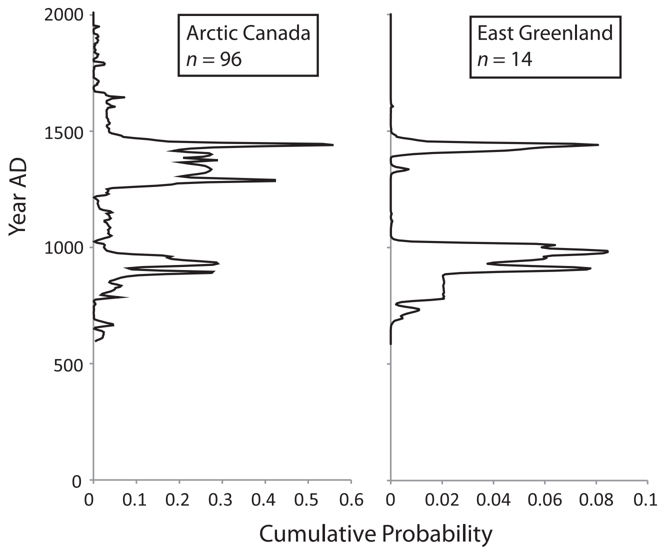

Fig. 3. Cumulative probability density functions (pdf) of the calibrated ages for sites younger than 600 AD from Baffin Island (Miller et al., 2012) and the youngest age(s) from each of the collection sites at South Istorvet except the Highest Nunatak site. We define the youngest age(s) for the Istorvet sites as all samples with calibrated age ranges that lie within one standard deviation of the youngest sample's age range. From South Istorvet this consists of the three youngest ages from the West Margin, the three youngest from the Middle Nunatak, the four youngest from the High Nunatak, and the youngest from the North Margin, whereas, from North Istorvet we used the three concordant ages from the Northwest Margin site. All ^{14}C dates in Miller et al. (2012) were calibrated using OxCal v4.1 using IntCal09 (Bronk Ramsey, 2009), whereas the Istorvet ages in Fig. 3 were calibrated using OxCal v4.2 using IntCal09 (Bronk Ramsey, 2009). The individual pdfs in 5-year bins were summed to provide the cumulative pdfs for each region.

3) South Istorvet subsequently expanded over the Middle Nunatak and West Margin sites by 950 AD (or 1000 AD at the latest)
4) South Istorvet continued to advance, crossing the Bone Lake catchment threshold 1125 ± 80 AD (possibly as early as 1045 AD)
5) South Istorvet's margin remained beyond the Bone Lake threshold throughout the LIA, but is receding rapidly at present
6) North Istorvet may have also advanced between 800 and 1100 AD, but if it did, Medieval warmth led to sufficient ice recession that the LIA advance obliterated any evidence of an earlier expansion.
7) During the LIA North Istorvet advanced across a landscape that was vegetated long after the recorded South Istorvet advance. North Istorvet's earliest recorded LIA advance occurred 1430 ± 15 AD, but there were apparently numerous fluctuations of the ice margin subsequently, with the maximum LIA advance occurring after 1670 AD.

4. Similar ice-cap histories for Baffin Island and East Greenland

The record of Istorvet growth and decay defined by the data presented in Lowell et al. (2013) is nearly identical to that derived from a much larger dataset (~50 ice caps; 96 ages younger than 600 AD[1]) reported by Miller et al. (2012), who show that snowline lowering between 800 and 950 AD led to permanent snow and ice entombing plants at 24 sites that remained ice-covered through Medieval times, and only melted back behind those sites in the past decade, virtually identical to the behavior of South Istorvet. There were no episodes of persistent snowline depression during Medieval times, but two pulses of snowline lowering occurred subsequently, initially between 1275 and 1300 AD, with the most extreme snowline lowering occurring between 1435 and 1455 AD, and maximum LIA ice cover reached in the late 1800s AD (Andrews et al., 1976). The coincidence of widespread snowline depression on Baffin Island (1445 ± 10 AD) with the kill date for three plants at the Northwest Margin site (1430 ± 15 AD) suggests that ice caps in both regions were responding to the same climate forcing. It is reasonable to assume that South Istorvet also advanced after 1430 AD, but there is no archive yet found that can test that

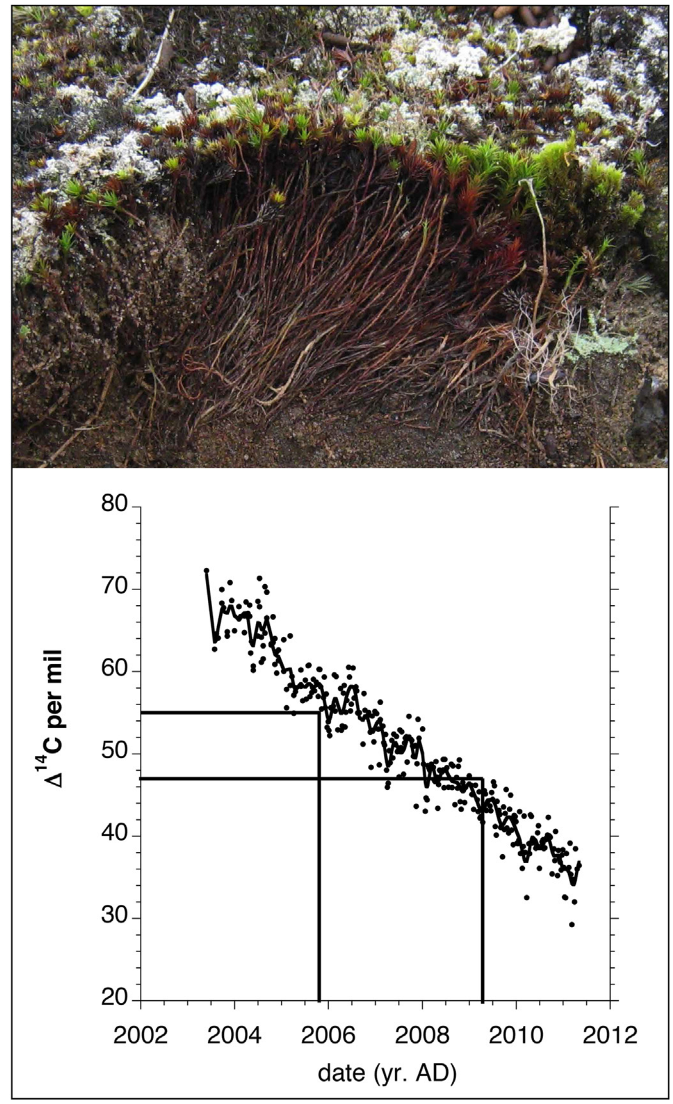

Fig. 4. The ^{14}C activity of a single strand of the living clump of *Polytrichum* moss shown in the photo collected from central Baffin Island in summer 2009 AD (M09-B213V) was 51 ± 4‰ (±2σ, CURL-11658). Comparison to direct measurements of $\Delta^{14}C$ in CO_2 from the relatively well-mixed free troposphere over North America (Niwot Ridge, Colorado at 3523 m asl) indicate that the sample was well equilibrated with the contemporary atmosphere and that the bulk of the sample carbon was assimilated within a few years of collection. Sustained atmospheric $\Delta^{14}C$ gradients from mid- to high-latitudes of the Northern Hemisphere of a few ‰ may lead to a bias in the projected age solution of about −1 year (i.e., moving the gradient-corrected solution to the right). Atmospheric results are from Lehman et al. (in press).

[1] Miller et al. (2012) used 94 dated samples, all with ages younger than 800 AD; here we include two additional samples with calibrated ages between 600 and 800 AD, to provide a better overlap with the data of Lowell et al. (2013).

Table 1
Replicate ^{14}C dates on individual strands of *Polytrichum* moss from a single clump at the ice margin, and between different clumps of *Polytrichum* moss collected at similar elevations at the ice margin, but separated by tens to hundreds of meters. The replication supports our assertion that our collection protocols produce ages with little variance.

Field ID	Lab ID	Proximity	^{14}C date ± 1σ (years BP)	Lat.	Long.	Elev. (m asl)
05ORN-03A	CURL-8202	Same clump	1150 ± 15	71.5906	−78.2032	803
05ORN-03B	CURL-8891	Same clump	1140 ± 15	71.5906	−78.2032	803
05ORN-03C	CURL-8892	Same clump	1135 ± 15	71.5906	−78.2032	803
M09-B133v	CURL-11069	40 m	1140 ± 15	71.2300	−74.0703	1070
M09-B135v	CURL-11070	40 m	1135 ± 15	71.2297	−74.0696	1069
M09-B089v	CURL-11418	200 m	450 ± 20	71.0173	−74.8122	727
M09-B090v	CURL-11431	200 m	460 ± 15	71.0185	−74.8172	727
05SRP-09	CURL-8888	195 m	1685 ± 15	71.4698	−77.5697	824
05SRP-08	CURL-9001	195 m	1625 ± 15	71.4705	−77.5748	826

assumption. The cumulative probability density plots limited to the youngest dates at each site from East Greenland but incorporating all of the Baffin Island dates (Fig. 3) illustrate their exceptionally close correspondence.

The similar reconstruction of ice-cap growth derived from radiocarbon dates on *in situ* vegetation from Istorvet and that derived from the same type of data from Baffin Island raises the question why Lowell et al. (2013, pp. 134–137) argue so strongly that the two records disagree. Disagreement centers on how the ages of *in situ* dead plants are interpreted. Lowell et al. (2013, p. 134) argue "plant ages represent times when Istorvet ice cap was as small as or probably smaller than it is today". This is consistent with how both Anderson et al. (2008) and Miller et al. (2012) interpret their ages, which they argue define the last time summers were warm enough for plants to grow at each site (until the most recent decade). Lowell et al. (2013, p. 134) state that Miller et al. (2012) argue that "rather than indicating warmth, peaks in the age distribution of subfossil plants are thought to represent times of widespread plant kill and burial by ice and snow". This is also essentially correct. Due to our strict sampling protocols, our samples accurately date the end of the warm time and the onset of persistent cold summers at each site, because this is when the plants were killed by snow/ice cover that never melted again until the year of collection. These are mutually compatible interpretations: the dates given in Miller et al. (2012) define the transition from warm summers and protracted ice retreat, to colder summers and entombment of the plants beneath ice/snow at each site. All of our plant collections are at the surface (Fig. 2) where spring runoff and snow driven by winter winds efficiently remove dead moss within a few years of their exposure. That dead plants are rapidly eroded is supported by the ~12,000 km^2 of vegetation-free landscape apparent in mid 20th Century aerial photography of the Baffin Island central plateau. The plant-free zone has been interpreted to indicate LIA perennial snow or cold-based ice persisted long enough to kill all of the vegetation, and that the dead plants were removed by subaerial processes as warmer summers led to ice recession over the past century (Ives, 1962; Andrews et al., 1976; Locke and Locke, 1977).

Why then is there an apparent contradiction in interpretation of dated subfossil plants associated with ice retreat? The answer is in the difference in our collection strategies. And the differences are substantial.

1) The only plant type we collect for dating is moss, usually *Polytrichum* species. The reason for this is that most moss filaments die each year, so that the radiocarbon age is as close as possible to the year that the site became entombed in snow/ice. To test this assertion, we dated live *Polytrichum* moss we collected in 2009 AD outside the LIA limits on central Baffin Island. We compared the ^{14}C activity of the moss with the ^{14}C activity of the contemporary atmosphere, which is changing very rapidly now as fossil fuel CO_2 dilutes the atmospheric burden of $^{14}CO_2$. Fig. 4 shows that the ^{14}C activity of the moss is equilibrated with that of the atmosphere with an uncertainty of no more than 5 years, confirming our assertion.
2) Lowell et al. (2013) state that their preferred plant-type for dating is willow (*Salix*), a slow-growing woody plant, because they were confident it had not been transported (Lowell et al., 2013 p. 133), suggesting that other plants may not have been securely *in situ*. However, willows have life spans of decades to centuries (Savile, 1979). Consequently, the ^{14}C activity of dead willows may not coincide with their kill date. Furthermore, woody plants have a much greater survival potential than do moss, so they may remain on the landscape long after an interval of ice recession and be re-covered by a younger advance. They still date a warm time, but may not date the onset of persistent cold, as mosses do. Hence, we avoid all woody plants for dating. We have also dated a variety of lichens from the same sites where we have moss ages, and find lichens, which also are slow growing, invariably have older ages than contemporaneous moss.
3) We only collect demonstrably *in situ* (rooted) moss exposed at the surface within 1 m of the ice margin (Fig. 2). Such samples have only been exposed during the year of collection, usually only for the few weeks before we collect. We tested this assertion by measuring horizontal and vertical ice recession rates between 2006 and 2009 AD using ablation stakes and laser surveying (>1 m vertical lowering per year and typically ~10 m of horizontal recession per year). These rates are consistent with NASA Icebridge repeat lidar altimetry on both the Barnes and Penny ice caps (Baffin Island) that show 2.0 to 0.5 m a^{-1} ice-cap lowering at the elevations we collect from (700–1400 m asl) between 2000 and 2005 AD (Webb et al., 2009). On the relatively flat terrain we target for collections, 0.5 m of vertical ice lowering in summer results in several meters of horizontal ice retreat, ensuring that plants within 1 m of the ice margin appeared during the year of collection.

In contrast, many collections made by Lowell et al. (2013) are not at the actual ice margin, and in several cases are beneath till. This complicates the interpretation of their ages.

4) Lowell et al. (2013, p. 134) "had concerns about the rapid recolonization of some relict moss patches by modern growth". Mosses regenerate sexually from spores and vegetatively by sprouting from specialized gametophyte tissues and from stem fragments and rhizoids (Hobbs et al., 1984). Desiccated moss stems, similar to moss melting out from beneath ice caps, may regenerate from dormant stem buds (Yashina et al., 2012). Our observations are that within 2–3 years after re-exposure, moss clumps that have avoided erosion exhibit noticeable new

growth, compromising their ^{14}C inventories that would otherwise reflect their date-of-burial beneath expanding ice caps, but also ensuring that the moss radiocarbon clock is rapidly reset during deglacial intervals. Hence, our restrictive criterion that we only date moss that was exposure in the year of its collection.

5) We only collect from non-erosive portions of ice caps, which contain no debris and leave no drift (Figs. 1 and 2). Cold ice in such settings does no work on the landscape. Thus, there is no possibility of transported plants. Istorvet is polythermal, with some erosion occurring, as confirmed by the glacial rock flour found in the Bone Lake cores. Transportation of plants is possible in such a regime.
6) The collection strategy of Lowell et al. (2013) results in a range of radiocarbon ages for samples collected in close proximity. In contrast, our collection strategy produces almost no variance in the sample ages at any one site, hence our confidence that kill dates represent the termination of the warm times that allowed plants to live at that site. Plant death is due to a snowline lowering that covered the site with persistent snow and or ice. Death by inclement climate is highly unlikely, as tundra plants are well adapted to weather extremes, and had they died from extreme weather, without a protective ice cover they would have been removed efficiently from the landscape by the processes outlined previously.
7) We have tested both intra-sample and inter-sample replication on collections made under our rigorous collection protocols. Three different strands of a single clump of *Polytrichum* moss exposed the year of its collection returned ^{14}C ages within analytical uncertainty (Table 1). Three sites where we dated moss clumps within 200 m of each other and at similar elevations along the same ice-cap margin also are well replicated (Table 1). However, not all sites around a single ice cap are likely to be the same age because ice-cap growth and retreat is often highly asymmetric, allowing some margins to persist far longer than others during intervening warm times, as well illustrated by the differing histories of North and South Istorvet.

5. Concluding remarks

Based on the differences in sampling protocols outlined above, we challenge the logic of comparing the kill dates of Miller et al. (2012), which accurately define the onset of persistent snowline lowering, with the groups of Istorvet ages that can only be interpreted securely as dating past warm times (Fig. 7 of Lowell et al., 2013). This is a classic example of "comparing apples and oranges". The two datasets at face value are not expected to directly align. However, the youngest dates at each site reported by Lowell et al. (2013) should closely date when each site became ice covered, and that subset is indeed coincident with peaks in the Miller et al. (2012) reconstruction (Fig. 3).

We also need to correct the assertion of Lowell et al. (2013, p. 138) that Miller et al. (2012) postulate that single volcanic eruptions at ~1275 AD and 1452 AD were responsible for persistent snowline depression in subsequent decades to centuries. As articulated in that paper and in more detail in Zhong et al. (2010, also referenced by Lowell et al., 2013), we explicitly point out that decadally paced repeated eruptions (as occurred in the late 13th and middle 15th Centuries) can lead to greater ocean surface water cooling than can result from even very large single eruptions (see also Schneider et al., 2009), and that an expanded state of Arctic Ocean sea ice requires multiple eruptions over several decades to become self-sustaining, potentially explaining the persistence of cold summers long after volcanic aerosols are removed from the atmosphere.

Although Lowell et al. (2013) emphasize the differences between their Istorvet record and the more comprehensive survey of Miller et al. (2012), we find that a careful interpretation of their datasets demonstrates remarkably close agreement with the Arctic Canada record. Both datasets document snowline depression leading to ice cap expansion between 800 and 900 AD, with some, but not all ice caps remaining expanded through Medieval times, and a final LIA snowline depression dated in both regions between 1415 and 1455 AD, with maximum LIA ice cap dimensions attained after ~1670 AD. When combined with recent high-resolution glacial reconstructions over the past 1.5 ka from Iceland (Larsen et al., 2011) and Arctic Canada (Miller et al., 2012) the Istorvet data provide strong support for coherent glacier responses to regional climate forcing over the past two millennia across the northwest sector of the North Atlantic Arctic, from Iceland, across Greenland, to the Eastern Canadian Arctic.

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