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A millennial perspective on Arctic warming from ^{14}C in quartz and plants emerging from beneath ice caps

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[1] Observational records show that the area of ice caps on northern Baffin Island, Arctic Canada has diminished by more than 50% since 1958. Fifty ^{14}C dates on dead vegetation emerging beneath receding ice margins document the persistence of some of these ice caps since at least 350 AD. In situ cosmogenic ^{14}C in rock surfaces, and ^{14}C in plant macrofossils from lake-sediment cores demonstrate that the plateau remained ice-free through the middle Holocene, but has supported ice caps for more than 2000 of the past 2800 years. The rapid disappearance of these ice caps over the past century, despite decreasing summer insolation, further demonstrates the unusual character of 20th Century warmth. Widespread ice-cap expansion ~1280 AD early in the Little Ice Age, and intensified expansion ~1450 AD, coincide with peak stratospheric volcanic aerosol loading and reduced solar luminosity, suggesting that these mechanisms may have initiated ice-cap growth, subsequently maintained by strong positive feedbacks. **Citation:** Anderson, R. K., G. H. Miller, J. P. Briner, N. A. Lifton, and S. B. DeVogel (2008), A millennial perspective on Arctic warming from ^{14}C in quartz and plants emerging from beneath ice caps, *Geophys. Res. Lett.*, *35*, L01502, doi:10.1029/2007GL032057.

1. Introduction

[2] The Earth has been warming for over a century, with warming over the past 50 years now firmly attributed to anthropogenic greenhouse gases [*Intergovernmental Panel on Climate Change*, 2007]. Warming is greatest in the Arctic with potential global impacts [*Serreze et al.*, 2007]. Of particular importance are improved constraints on whether the magnitude of current warming is within the range of natural variability, or whether it is unprecedented in recent Earth history. A goal of paleoclimate research is to capitalize on archives that provide quantitative metrics that address this question.

[3] The plateau ice caps across the interior of Baffin Island, Arctic Canada (Figure 1) are simple, yet sensitive integrators of climate. Because the ice caps are thin (<100 m thick) and cold (ca. −14°C), they are not only frozen to their beds, but have little internal deformation. Consequently, they preserve intact the landscape on which they grew. Once in equilibrium with climate, the margins of the ice caps define the equilibrium line altitude (ELA), the altitude where summer melt balances winter snowfall. Throughout the Holocene, the ELA was largely controlled by summer temperature; changes in snowfall had a significantly smaller effect [*Paterson*, 1969]. Since 1960, plateau ice caps averaged 0.5 ± 0.2 m water equivalent loss annually [*Braun et al.*, 2004], amounting to a surface lowering of 3 to 8 m/decade. The ice caps overlie an extensive gently undulating plateau where 70% of the topography is between 500 and 800 m asl. Due to the large area of low relief close to the regional snowline altitude, small changes in the ELA correspond to large changes in the area covered by permanent snow and ice. This results in large changes in ice cover following sustained modest changes in summer temperature.

[4] Observational records of the ice caps exist as aerial photographs and satellite imagery beginning in 1949–1958. Total ice cover on the plateau (Figure 1a) in 1958 was ~150 km^2. In 2005, this area had been reduced to 67 km^2, representing a loss of over 80 km^2, more than half the total area ice covered in 1958, in less than 50 years. Projecting the average melt rates linearly and assuming no additional warming suggests disappearance of most ice on the plateau before 2035 AD and all ice by 2070 AD (Figure 1b).

[5] Here we apply multiple dating techniques to the exceptionally well-preserved terrain emerging beneath the receding ice caps to demonstrate that the current warming exceeds any sustained warm episode in at least the past 1600 years in this region of the Arctic; this warming counters the trend toward increased glacierization beginning at least 3 ka ago, as summer insolation decreased across the Arctic.

2. Methods

[6] In situ cosmogenic radionuclide inventories in rock surfaces provide an integrated record of periods of ice-cover and exposure at a specific site since the end of the last ice age. We utilize in situ cosmogenic ^{14}C (in situ ^{14}C) due to its short half-life. In situ ^{14}C production is reduced by 85% under 6 m of ice and is completely attenuated under $\geq$35 m of ice [*Miller et al.*, 2006]. Any ^{14}C that had accumulated in rocks prior to the last glaciation would have decayed below our background after 25 ka beneath the Laurentide Ice Sheet. Consequently, no rocks in our study area had detectable levels of in situ ^{14}C upon regional deglaciation.

[7] In situ ^{14}C was extracted from quartz by first reducing a bulk rock or quartz sample to clean quartz (Colorado University Cosmogenic Isotope Laboratory, available at http://instaar.colorado.edu/cosmolab/, 2006). Carbon was extracted from the quartz at the University of Arizona by

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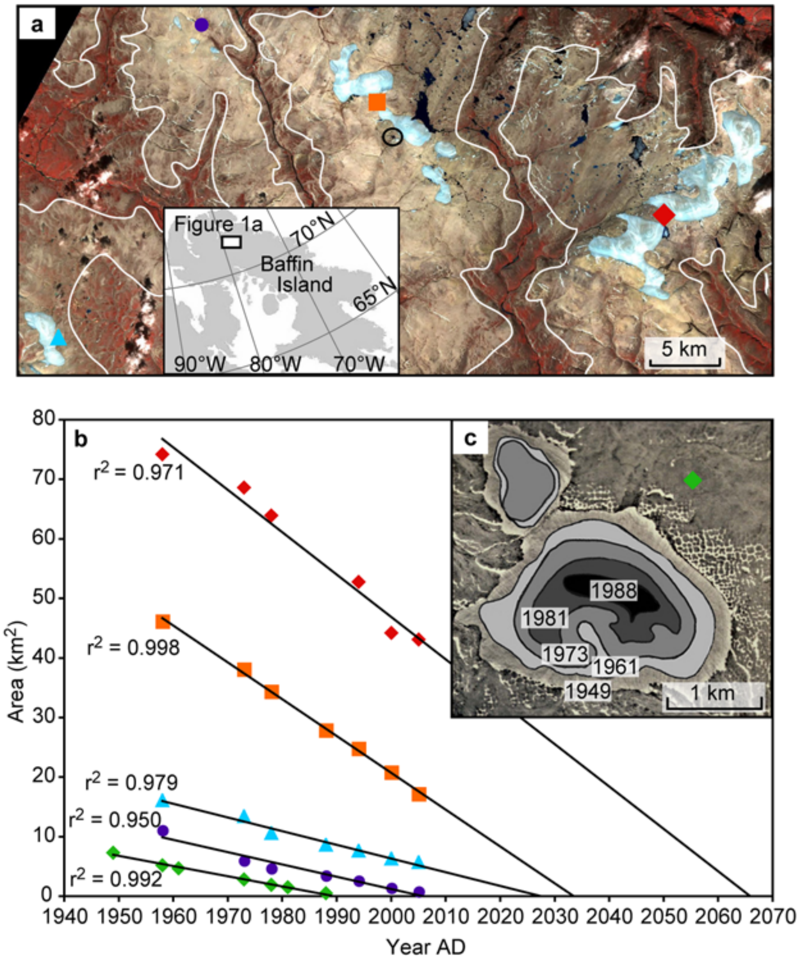

Figure 1. Location map and ice cap retreat. (a) Landsat ETM+ satellite image, 10 August 2000, showing present-day ice caps. White line delineates approximate extent of vegetation-kill zone, corresponding to maximum ice-cap cover during the Little Ice Age [*Locke and Locke*, 1977]. Black circle identifies location of ^{14}C dates of 5.6 ka on aquatic moss in the basal sediment of a lake. (b) Ice cap areas between 1949–2005. Corresponding ice caps are marked by symbols in Figure 1a. Linear regressions project approximate disappearance of ice caps. (c) Areal decrease of the Tiger Ice Cap, 1949–1988, projected to have disappeared in summer 1992.

combustion in ultra-high-purity (UHP) O_2 at 500°C to remove atmospheric/organic contaminants, followed by dissolution of the quartz in a $LiBO_2$ flux at 1100°C, again in a UHP O_2 atmosphere [*Lifton et al.*, 2001; *Pigati*, 2004]. All evolved carbon species were converted to CO_2, then purified and graphitized, and measured at the University of Arizona Mass Spectrometry Facility AMS laboratory [*Lifton et al.*, 2001; *Pigati*, 2004]. Exposure histories were calculated for each measured ^{14}C concentration using a sea level high-latitude (SLHL) production rate of 15.5 ± 0.2 atoms g^{-1} yr^{-1} [*Lifton et al.*, 2001]. This production rate was then scaled with Stone (2000) to a site-specific production rate, using a spatially variable atmosphere to account for variations in sea level pressure, temperature and atmospheric lapse rates [*Miller et al.*, 2006].

[8] AMS ^{14}C dates on vegetation were calibrated using the INTCAL04 data set [*Reimer et al.*, 2004]. The cumulative probability distribution function (Figure 2) was generated from individual Gaussian distributions for the discreet 1 standard deviation (σ) calibrated age ranges for each of the 50 ^{14}C dates. Single samples dated multiple times were given the weight of one date. If two or more 1σ age ranges exist for a single date, a Gaussian distribution was generated for each and weighted according to its probability [*Stuiver and Reimer*, 1989]. All data in Figure 2 are listed in Table S1 in the auxiliary material.[1]

[9] Lake sediments were recovered from the lake ice platform using a simple hammer-driven sediment-coring device equipped with a 63 mm diameter clear plastic barrel.

3. Results

[10] The Laurentide Ice Sheet deglaciated the interior of northern Baffin Island between 7 and 5 ka [*Dyke et al.*, 2003]. We further constrain the timing of deglaciation and ice-cover history using ^{14}C-dated lacustrine sediment cores and in situ ^{14}C inventories in quartz from rock surfaces.

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2007GL032057.

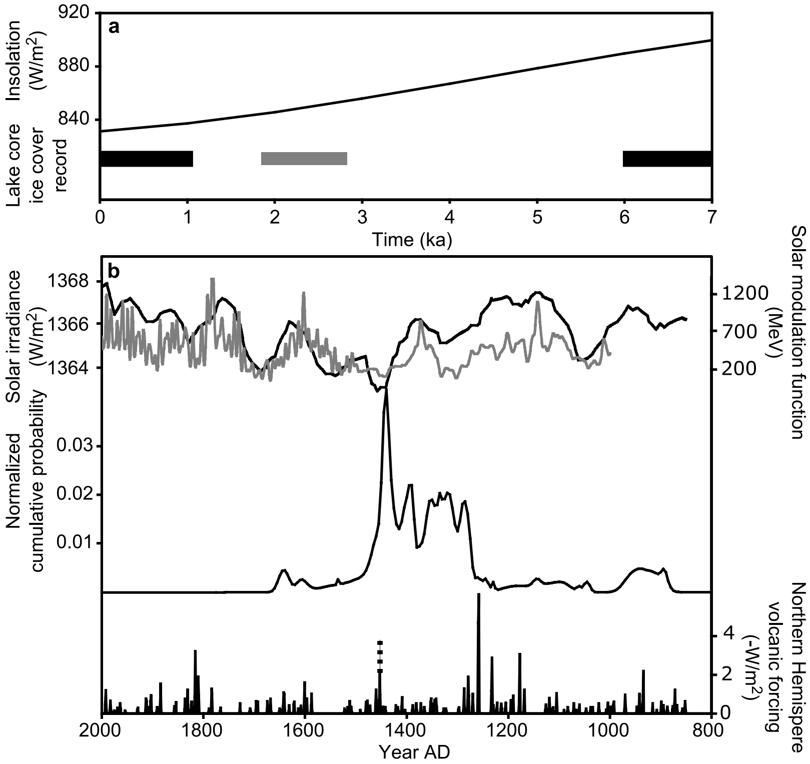

Figure 2. Ice cover history, ^{14}C vegetation dates, and possible forcing mechanisms. (a) Solar insolation 7–0 ka [*Berger and Loutre*, 1991] and generalized reconstruction of ice cover history. Summer insolation over the plateau has decreased 3.5% since 2.8 ka and 7% since 6 ka, corresponding to increasing ice-cap cover, in contrast to the decrease in ice-cap area over the 20th century. Gray bar indicates 900-year period of late Holocene ice-cap cover required by in situ ^{14}C that may have occurred at any time between 2.8–1.1 ka. (b) Solar irradiance [*Bard et al.*, 2000], normalized cumulative probability distribution function of 50 ^{14}C dates, and Northern Hemisphere volcanic forcing record [*Ammann et al.*, 2007].

[11] Two ^{14}C dates on aquatic moss in the basal sediment of a lake that appeared from beneath a receding plateau ice cap within the past 50 years (Figure 1a) are 5.6 ka (Figure S1 and Table S2 in auxiliary material). The basal sediment is overlain by a continuous sequence of mossy lake mud; ^{14}C dates from the uppermost layers are 2.8 ka, suggesting an ice-free plateau between 5.6 and 2.8 ka. In situ ^{14}C inventories in quartz from two rock surfaces within the vegetation-kill area but distant from remnant ice caps yield dates of initial exposure of 5.8 ± 0.4 ka and 6.3 ± 0.7 ka (Figure S1 and Table S3). Based on all of these data we conclude that the age of deglaciation across our study area was ca. 6 ka.

3.1. Emerging Vegetation Dated With ^{14}C

[12] As the modern ice caps melt, they reveal dead vegetation that was buried by snow during ice-cap inception and has been continuously preserved beneath a protective ice cover since that time. The vegetation dates the last time the site was ice-free, but possible earlier periods of ice cover cannot be discerned from such records. Dead vegetation that had only appeared from beneath the melting ice margins within the prior year was collected during July–August 2005. Collection was limited to the modern ice-cap margin because new growth was observed to occur on previously dead and buried vegetation only meters beyond the ice margin. A plot of the normalized cumulative probability of the calibrated ^{14}C dates for 50 of these collections (Figure 2) reveals a non-random distribution of ages, with a concentration of ages at 930, between 1280–1400, and at 1450 AD. Each peak represents a time of ice-cap expansion and the maintenance of permanent ice over that site continuously until 2005 AD. However, earlier ice-cap growth events represented by only a few dates may not necessarily have been of lesser magnitude, but may instead be limited by one or more subsequent warm intervals that melted most ice caps.

[13] Two sites preserve vegetation continuously covered by ice since 300 ± 45 AD and 370 ± 25 AD, indicating that 2005 was the first time these locations had been ice-free in more than 1600 years. Four ^{14}C dates from two ice caps at ~930 AD record the expansion of permanent ice across these sites and its continuous presence since that time. The lack of dated vegetation between ~1000 and 1250 AD coupled with numerous sites at ~1280 AD suggests widespread melting during a period broadly coincident with the Medieval Warm Period (MWP) [*Bradley et al.*, 2003]. The six dated sites that remained ice-covered throughout the MWP demonstrate that warmth over this 250-year interval was insufficient to completely melt all plateau ice caps, implying that 20th Century summer warmth exceeds anything that occurred during the last 1600 years, including during the MWP.

[14] Seven dates from two ice caps clustering at ~1280 AD mark the sudden onset of renewed colder summers and the early inception of the Little Ice Age [*Grove*, 1988] across NE Baffin Island. Sufficient ice grew at all seven sites at

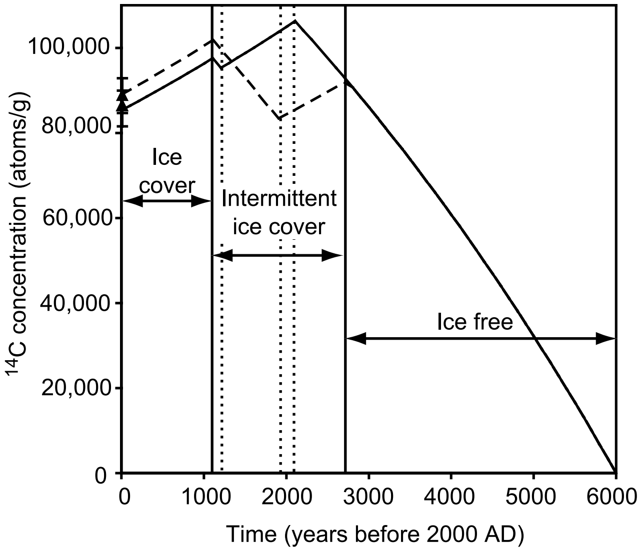

Figure 3. Cosmogenic exposure histories of in situ ^{14}C samples. We model in situ ^{14}C accumulation in recently exposed quartz at two nearby sites as beginning at deglaciation, ~6 ka, and continuing uninterrupted until 2.8 ka (Figure 2). Adjacent dead moss requires continuous ice cover since 1.1 ka. The in situ ^{14}C concentration in quartz requires an additional 900 years of complete attenuation of ^{14}C production between 2.8 and 1.1 ka, but does not uniquely constrain the timing of exposure and ice cover during this time; two possible ice-cover scenarios are shown.

that time to persist through all subsequent warm periods until the present. The interval between 1280 and 1450 AD incorporates 39 of the 50 ^{14}C dates, suggesting an oscillating climate characterized by both ice-cap growth and decay, although the first-order trend must have been toward increasingly colder summers. This interval of variable but cooling climate terminated with a period of widespread ice-cap growth at 1450 AD defined by dates from 12 sites around 3 ice caps. No samples have ages younger than 1650 AD, indicating that extensive ice covered much of the plateau until the onset of current warming. The absence of vegetation over ~50% (~1450 km^2) of the plateau at present defines the extent of permanent snow and/or ice cover at the peak of the Little Ice Age [*Andrews et al.*, 1976; *Ives*, 1962; *Locke and Locke*, 1977; *Williams*, 1978; *Wolken*, 2006]. Presently, ice caps cover only <5% of the vegetation-kill area.

3.2. Emergent Rock Surfaces Dated With ^{14}C in Quartz

[15] We also measured in situ ^{14}C inventories in quartz from two rock surfaces exposed in 2005 by a receding ice-cap margin. Their exposure history began at deglaciation (6 ka), and continued uninterrupted until 2.8 ka (Figure 3). (See Figure S2 in auxiliary material for the effect of deglaciation at 6.5 and 5.5 ka on the duration of exposure.) Radiocarbon dates on two collections of emergent dead vegetation adjacent to the rock surfaces indicate that ice had covered these sites since 920 AD, implying no radionuclide production for the past 1100 years. The ^{14}C inventories in both quartz samples require ice cover over the sites for an additional 900 yr between 1.1 and 2.8 ka (Figure 3). Because some in situ ^{14}C production occurs in surface rocks whenever the covering ice is less than 35 m thick [*Miller et al.*, 2006], our reconstructed ice-cover history between 1.1 and 2.8 ka is a minimum. An additional few hundred years of ice cover would be consistent with measured ^{14}C concentrations if ice-cap growth and decay occurred slowly.

4. Climate Forcing of Ice-Cap Inception

[16] Ice-cap growth at 1280 and 1450 AD coincides with two of the most extreme stratospheric volcanic aerosol loadings of the past millennium and reduced solar irradiance (Figure 2) [*Bard et al.*, 2000; *Gao et al.*, 2006; *Zielinski*, 1995]. The coincidence of ice-cap inception with intervals of volcanic aerosol loading and solar irradiance minima suggests that consequent summer cooling may have triggered rapid, widespread ice-cap growth. Volcanic aerosols have only a few years' residence time in the stratosphere. Consequently, strong positive feedbacks are required to maintain the ice caps. Some of the feedbacks would have been derived from the expanded snow and ice cover over large areas of the Canadian uplands, but we speculate that substantial expansion of Arctic Ocean sea ice would be required to maintain the ice caps through the subsequent centuries. This conjecture is supported by historical records that document the initial occurrence of sea ice around Iceland late in the 13th Century, following minimal sea ice in preceding centuries [*Ogilvie*, 1991].

5. Conclusions

[17] Fifty-year plateau-ice-margin retreat rates on northern Baffin Island show that the rapidly approaching ice-free state of the plateau will occur near the middle of the current century even without additional warming. Radiocarbon-dates on vegetation appearing beneath retreating ice caps indicate that some plateau ice caps have existed continuously since ~350 AD, demonstrating that the current warming is unique in at least the past 1600 years. Lake cores and in situ ^{14}C inventories in quartz document a trend toward more frequent ice cover in recent millennia, coincident with reduced summer insolation (Figure 2a), making the current ice-cap retreat even more unusual. Collectively, these data extend the timeframe in which 20th century warming is unprecedented in this part of the Arctic well beyond the past 400 years established by *Overpeck et al.* [1997].

[18] Our chronologies also offer the first quantitative estimate for the onset of Neoglaciation in the eastern Canadian Arctic, suggesting an early onset consistent with sea-ice expansion documented in historical records from Iceland. Times of widespread ice-cap expansion coincide with the two most severe episodes of volcanic aerosol loading of the past millennium, offering tantalizing evidence for a volcanic trigger to Little Ice Age cooling coupled with strong positive feedbacks that reinforced the volcanic climate perturbation.

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