Accepted Manuscript

Recent melt rates of Canadian Arctic ice caps are the highest in four millennia

David Fisher, James Zheng, David Burgess, Christian Zdanowicz, Christophe Kinnard, Martin Sharp, Jocelyne Bourgeois

PII: S0921-8181(11)00097-X
DOI: doi: 10.1016/j.gloplacha.2011.06.005
Reference: GLOBAL 1700

To appear in: *Global and Planetary Change*

Received date: 3 January 2011
Revised date: 12 June 2011
Accepted date: 13 June 2011

Recent Melt Rates of Canadian Arctic Ice Caps are the Highest in Four Millennia

David Fisher[1] ,James Zheng[1], David Burgess[1], Christian Zdanowicz[1], Christophe Kinnard[2], Martin Sharp[3], Jocelyne Bourgeois[1]

1 Glaciology Section, Northern Division, Geological Survey of Canada, 601 Booth Street , Ottawa ,Ontario, K1A 0E8.

2. Centro de Estudios Avanzados en Zonas Aridas-CEAZA, Casilla 599-Campus Andres Bello, Colina El Pino s/n La Serena, Chile

3. Earth and Atmospheric Sciences, University of Alberta, Edmonton,Ab, T6G 2E3, Canada

Abstract

There has been a rapid acceleration in ice-cap melt rates over the last few decades across the entire Canadian Arctic. Present melt rates exceed the past rates for many millennia. New shallow cores at old sites bring their melt series up-to-date. The melt-percentage series from the Devon Island and Agassiz (Ellesmere Island) ice caps are well correlated with the Devon net mass balance and show a large increase in melt since the middle 1990s. Arctic ice core melt series (latitude range of 67 to 81 N) show the last quarter century has seen the highest melt in two millennia and The Holocene-long Agassiz melt record shows the last 25 years has the highest melt in 4200 years. The Agassiz melt rates since the middle 1990s resemble those of the early Holocene thermal maximum over 9000 years ago.

Key Words

Ice core, melt layers, Holocene, warming, ice caps

1. Introduction

Ironically, paleo-climate records usually suffer because their recent end points are too far in the past to connect with the contemporary climate change discussion. Since the ice-core melt percent series are simple and have been extensively used in climate reconstructions many of the ice core sites across the Canadian Arctic have recently been re-drilled to overlap the old records some of which ended in the 1960s. With the up-to-date series it is clear the last quarter century's melt rates in the high accumulation zones (~1800 m asl.) of Canada's Arctic ice caps have been the highest in many millennia and since the middle 1990s, the melt percent and net mass balance losses (Devon Ice Cap) have accelerated very sharply.

2. Sites and Methods

For high elevation accumulation regions of Canadian Arctic ice caps (Fig. 1a and Table 1) there is usually some part of the summer when temperatures are high enough to produce surface melt that re-freezes at depths of a few tens of centimeters. Because re-frozen melt has few bubbles compared to ice that forms by compression of un-melted firn, it is easy to recognize (Koerner,1977; Koerner and Fisher, 1990; Fisher et al.,1995). Figure 1b shows recent ice layers from the Agassiz site.

Table 1 Site information

Name	Latitude	Longitude	Elevation	Deep cores years	Hand cored in years	Accumulation rate cm(ice)/a	Refs
Devon72/73	75.47	82.5	1800	1971,72,73	2004,06,10	Recent 25 Long term 24	a,b
Devon99	75.32	81.64	1903	1999	None	16.7	c
Agassiz 1984/87	80.7	73.1	1860	1984,87	2009	1962-09 13.78 pre-1962 10	d,e,f,g
Penny 1995	67.253	65.77	1860	1995	2010	37	h,i
Prince of Wales 2005 (POW)	78.4	80.4	1630	2005	None	30	j

. [a](Koerner, 1977), [b](Paterson et al., 1977), [c](Kinnard et al., 2006) [d](Fisher et al., 1983), [e](Vinther et al., 2008), [f](Vinther et al.,2009), [g](Fisher et al., 1995), [h](Fisher et al., 1998), [i](Goto-Azuma et al., 2002), [j](Kinnard et al., 2008).

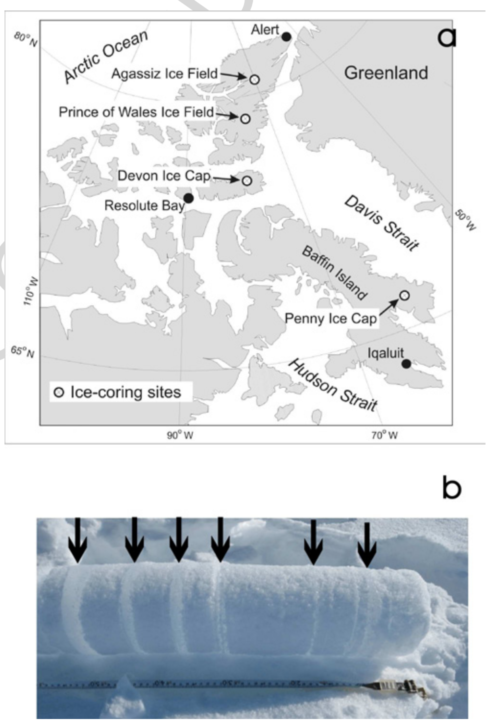

Figure 1: a, Location map for the drill sites in the Canadian Arctic.

b, Arrows show examples of the bubble-free ice layers from the Agassiz site in firn laid down in the recent warm period, post 1993.

Routine quantitative measurements of density and melt features in the ice cores have resulted in many records of melt-feature percentage, (MF). This percentage denoted, MF, pertains to some number, N, of annual increments of total length N λ (where λ is the annual accumulation rate in ice-equivalent/year). The MF for N years is defined:

$$MF = \Sigma[\text{ N years of melt features in ice equivalent}] / (N\lambda) \times 100.$$

Two methods have been used to calculate the MF series. Only bulk-core densities are available for deep cores and most of the new cores, in which case MF is calculated using “Method-1” (Supporting Online Material, SOM). For the Agassiz-2009 extension-core there are densities for the stratigraphic elements at sufficient resolution so “Method-2” can be used, (SOM). For both methods and in all cases there was substantial multi-decadal overlap between the deep and new cores, (see Figure 2). The time scales used for the various ice cores are found in the literature cited in Table 1. The Agassiz record which is the longest and most accurate has been tied into the Greenland chronology (Vinther et al.,2008;2009). Figure 2 shows 5 year MF-averages for all sites. Melting produces statistically very “noisy” series, which must be averaged over several nearby sites or over many years in order to produce reasonably robust series, (see eg. Fisher et al.,1985; Fisher and Koerner,1994).The deep core MF is shown in black and the extension MF in grey. All the deep core stratigraphies were produced by the same experienced observer (R M Koerner) but the extensions were produced by various people in the author list. As described in the SOM, the pure ice layers (MF=100%) are easy to see (and comprise about 70 % of the melt, see Fig. 1b). But when only bulk density is available, accessing the amount and density of partial melt features like “icy firn” is subjective. The MF appropriate to the “icy firn” category was adjusted so the new core overlap averages were close to the old, (SOM). This did not have to be done for the Agassiz extension where sufficient density data was available.

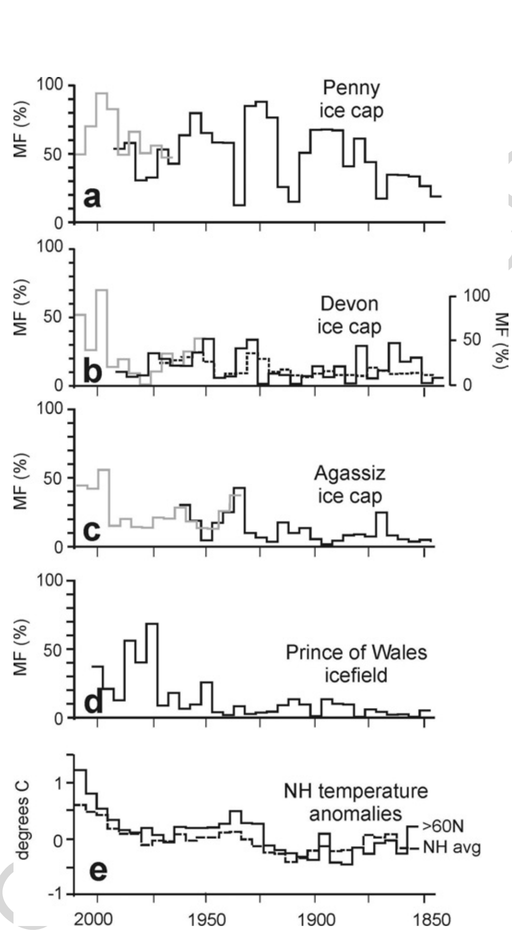

Figure 2 : Recent (5 year average) melt-percentage series from original deep cores (black) and recent hand drilled extension cores in grey . **a,** Penny . **b**, Devon 1972,73 cores (black), 1999 core (dashed and with MF-axis on the right). **c,** Agassiz 1984,87 cores. **d,** Prince of Wales , POW. Note there is no extension core for POW. **e,** Northern Hemisphere JJA temperature anomalies (dashed) and north of 60^{o} N JJA-temperature, (black).

3. Results

3.1 Overlap and the recent records.

The most recent 150 years of melt-percentage are presented in Fig.2. The small temporal offsets seen are due to slightly different averaging intervals for the deep and extension cores. Because the site-average accumulation rate was used in the age-depth model, there is some internal error due to accumulation-rate variance. The age error in these plots is <5%. MF for the Penny ice cap (Fig. 2a) has often been very high since the late 1800s, indicating (Fig. SOM-4) that average temperatures there are relatively high .The Prince of Wales Icefield record from central Ellesmere Island shows an increase in melt starting earlier, in the 1970s. This icefield is influenced climatically by the neighboring North Open Water polynya, such that the MF-temperature relationship there is likely more site-specific than regional (Kinnard et al.,2008).

3.2 The last 2000 years' of Canadian melt records.

All these records are now to be presented in 25 year averages over a much longer interval, where it becomes clear, there is a large increase in melt rates in the late 20th century. The quarter century averaging interval balances the need for lowering noise with that for resolution. Figure 3b-f shows the MF series for 2000 years. Also shown is the Arctic stacked summer-temperature record (Kaufman et al.,2009) (Fig.3a) that uses 23 summer-temperature proxies. None of the MF records were used in this stack, although some stable isotope records from the Table 1 sites were. The Penny MF record (Fig. 3b) is clearly tracking the stack and portrays the recent warming as well as the 2000-year long cooling trend. The Agassiz record (Fig. 3e), shows the extent of the recent melt in the context of 2000 years but lacks the cooling trend. The Agassiz stable isotope record does show (Vinther et al.,2008,2009) the cooling-trend over the last 2000 years, but it was simply too cold to register much melt during this interval (see SOM-2.2). The Devon 1999 site (Fig. 3d) has a temperature intermediate between the Penny and Agassiz sites and its MF-record shows some of the cooling trend as well as the recent warming. The records from Devon 72,73 and POW (Figs 3c and 3f) also demonstrate the recent maximum, although they are both limited to the last 8 centuries.

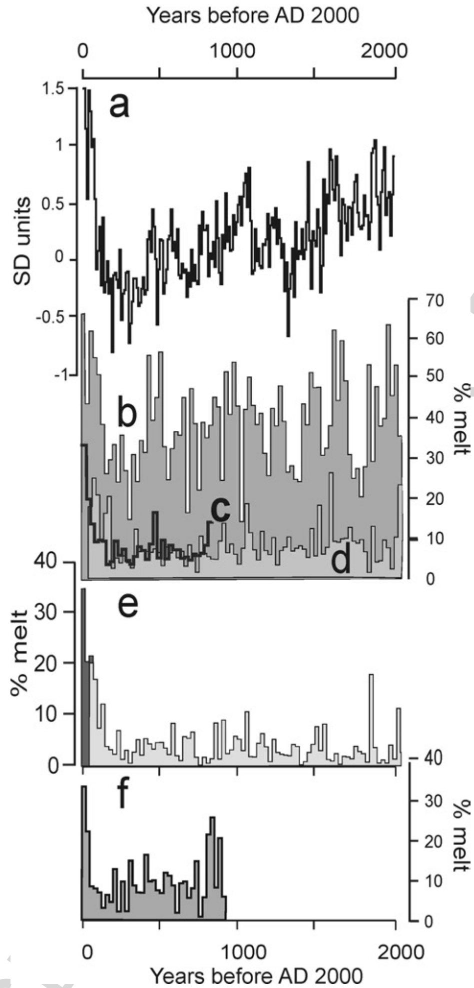

Figure 3 : The last 2000 years. **a,** A stack of 23 polar proxy-summer temperature series, (Kaufman et al.,2009). **b,** MF Penny Ice Cap. **c,** Stacked MF for the Devon 1972,73 cores. **d,** Devon 1999 core. **e,** Agassiz MF. The black shading showing the updated portion and older 1984, 87 deep core results shaded in grey. **f,** Prince of Wales MF.

3.3 The Holocene melt record from the Agassiz Ice Cap.

The Agassiz ice cap cores taken in 1984 and 87 are within 100 metres of each other and the core quality was high enough to track the melt features right through the Holocene (Koerner and Fisher,1990; Fisher et al.,1995). Recently the Agassiz time scale has been coordinated with the canonical chronology for Greenland ice cores (GICC05) (Vinther et al.,2008,2009). Twenty five year averages of the Agassiz $(MF_{84}+MF_{87})/2$ stack are presented in Fig. 4 on this time scale. The estimated error bars are also shown. They are the RMS values for the difference series $(MF_{84} - MF_{87})/2$. Signal and noise levels in ice core records are well understood (SOM-1). The deep core results are shaded light grey and the extension series in black. This melt record ends in the spring of 2009. Melt-percentage on Agassiz (and likely on Devon) in the most recent 25 years is the highest in 4200 years (see "line-1" Fig. 4). If the levels of melt since the mid-1990's (see line-2 in Fig. 5c) continue, then as "line-2" (Fig. 4) suggests, one has to look back 9000 years to find higher melt-percentages. The recent Arctic warming stands out as anomalous not only compared to the past century (Overland et al.,2008), but on much longer time scales(Kaufman et al.,2009; Axford et al.,2009; Fauria et al.,2009).

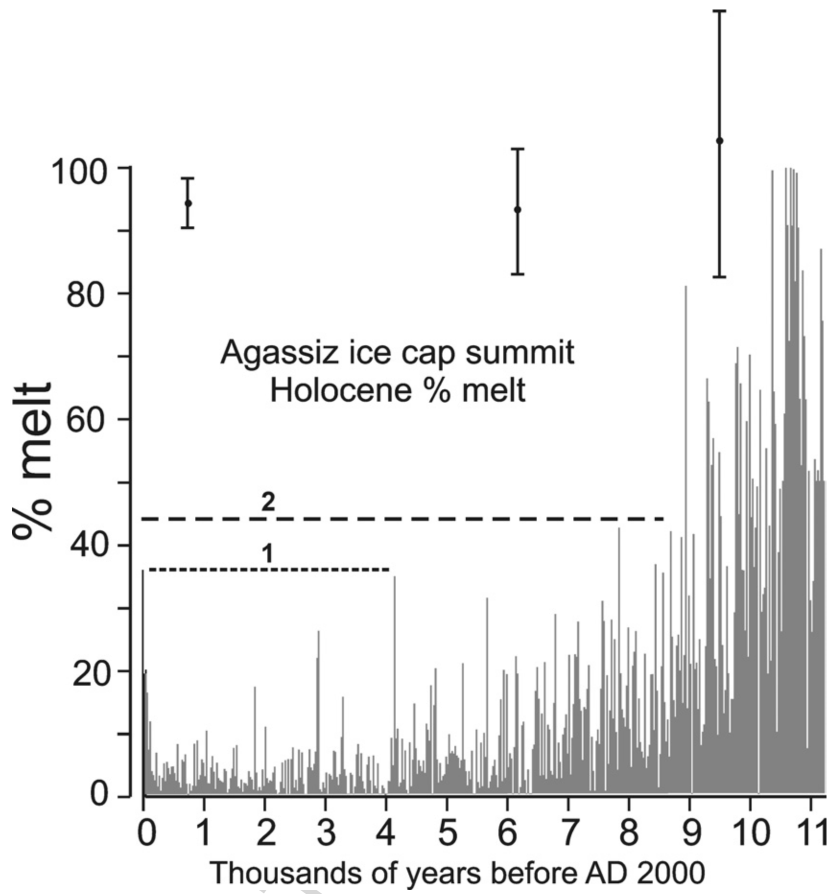

Figure 4 : The Holocene melt record from Agassiz Ice Cap 1984,87 cores (25 year averages) placed on the GICC05 time scale (Vinther et al.,2008). The estimates of error come from the rms value of the differences between the 1984 and 87 MF series. The " line-1" traces the most recent 25 year melt-percentage back 4200 years . The Agassiz melt percentage since the early 1990s ,"line-2" (also shown in Fig. 5c) can be traced-back 9000 years, to the early Holocene.

4. Discussion and Conclusions

Arctic warming amplification due to ice and snow albedo feedback is expected to be most pronounced in autumn, when sea-ice decline is greatest, and have little surface expression in summer (Serreze et al.,2009). Indications of summer warming aloft using re-analysis data have been reported, but the evidence is contested (Graversen et al.,2008). Our work suggests Arctic warming is taking place in summertime, at a faster rate than hemispheric trends, and this is most apparent in the sites north of 75° and above 1800 metres.

The change in 25 year average NH summer temperature (CRU-BADC,2008) from [1908-1883] to [2008-1983] is 0.7 C (Fig. 2e). Using the 25 year melt records for the same periods, the accumulation rates (Table 1) and transfer function (Fig. SOM-4), the temperature change for sites north of 75° is 2.2 C. Thus the MF-data suggests an Arctic amplification factor of ~3, which falls within model-predicted values (Holland and Bitz,2002) and which compares well with paleo-climate estimates(Miller et al.,2010).

Accelerating melt rates since the late 20th century find echoes in Greenland (Mote,2007) and in Svalbard glaciers (Kohler et al.,2007), indicating a general trend across the Arctic. The warming may be driven by increased pole-ward heat advection in response to rising global temperatures, but other factors may include, the reduced burden of radiation-scattering sulfate aerosols since the late 1980s, (which counteracts surface warming in the springtime), and suspected increases in tropospheric ozone concentration and black carbon aerosols, which contribute a net positive radiative forcing, particularly in spring and summer (Quinn et al,2008; Shindell and Faluvegi,2009).

In conjunction with much enhanced melt since early 1990s, is an increase in glacier surface mass loss, the highest since observations began in the early 1960's, Fig. 5a. Glacier mass losses for the past 5 years (2005 – 2009) from NW-Devon, Meighen, and Melville ice caps are 3 times greater than the average over the entire period of record (Burgess and Koerner,2009; Koerner,2005). This coincides with positive summer-temperature anomalies of 1.5–2 degrees for this region (CRU-BADC,2008) emphasizing that mass balance is driven primarily by summer warmth (Koerner,2005) and that glacier losses in this region are responding very sharply to rising temperatures. It is not surprising that the Devon and Agassiz MF series correlate well with the Devon net mass balance series (correlation coefficient of 0.83 using 4 year averages, 7 degrees of freedom) and with each other (0.93), Fig 5. The great increase in melt on Devon and Agassiz since the middle 1990s is mirrored in the net mass balance and, as has been shown here, this is unique in the context of many millennia. The ice core melt record puts these recent mass balance losses in context and suggests that Canadian Arctic ice caps are loosing mass faster than any time in the last 4000 years.

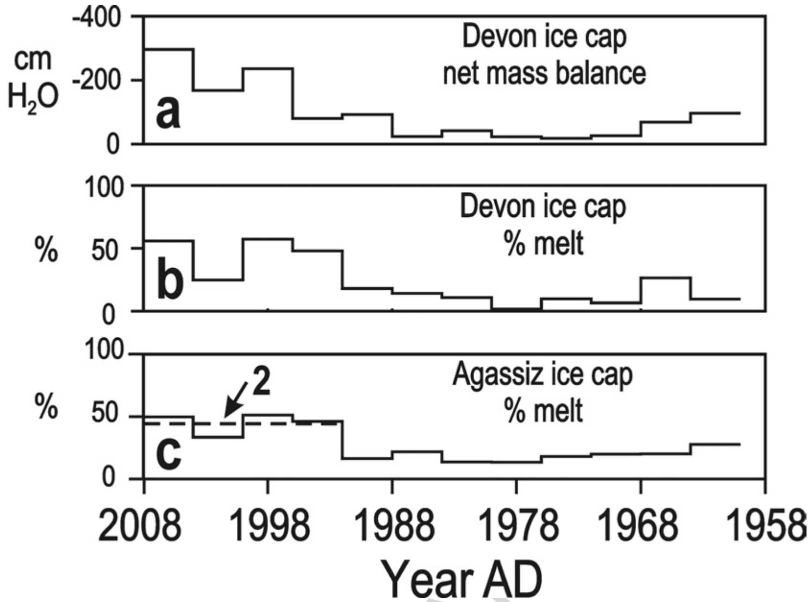

Figure 5: a, Four year averages of Devon Ice Cap measured net mass balance. **b**, The melt-percentage, MF, records from Devon. **c,** Agassiz MF. Line-2 gives the average over the most recent 16 years and is redrawn in Fig. 4.

References

Axford, Y., Briner, J.P., Cooke, C.A., Francis, D.R., Micheluttie, N., Miller, G.H., Smole, J.P., Thomas, E.K., Wilson, C.R., Wolfe, A.P., 2009. Recent changes in a remote Arctic lake are unique within the past 200,000 years. Proceedings of the National Academy of Sciences 106, 18443-18446.

Burgess,D.O., Koerner, R.M.,2009. Glacier mass balance observations for Devon Ice Cap NW sector, NU, Canada (updated to 2009). Spatially referenced data set, State and Evolution of Canada’s Glaciers, http://pathways.geosemantica.net/WSHome.aspx?ws=NGP_SECG&locale=en-CA, Geological Survey of Canada.

Fauria, M.M., Grinsted, A., Helama, S., Moore, J., Timonen, M., Martma, T., Isaksson, E., Eronen, M.,2009. Unprecedented low twentieth century winter sea ice extent in the Western Nordic Seas since A.D. 1200. Climate Dynamics 34,781.

Fisher, D.A., Koerner ,R.M., Paterson, W.S.B., Dansgaard ,W., Gundestrup, N., Reeh, N., 1983. Effect of wind scouring on climatic records from ice-core oxygen-isotope profiles. Nature 301, 205-209.

Fisher, D. A., Reeh, N., Clausen, H.B.,1985. Stratigraphic noise in time series derived from ice cores. Annals of Glaciology **7**, 76-83 .

Fisher, D. A., Koerner, R.M., 1994. Signal and noise in four ice-core records from the Agassiz Ice Cap, Ellesmere Island, Canada: details of the last millennium for stable isotopes, melt and solid conductivity. The Holocene 4,113-120.

Fisher, D.A. Koerner, R.M., Reeh, N., 1995. Holocene climatic records from Agassiz Ice Cap, Ellesmere Island, NWT, Canada. The Holocene 5, 19-24.

Fisher, D.A., Koerner, R.M., Bourgeois, J.C., Zielinski, G., Wake, C., Hammer, C.U., Clausen, H.B., Gundestrup, N., Johnsen, S., Goto-Azuma, K., Hondoh, T.,Blake, E., Gerasimoff, M.,1998. Penny Ice Cap, Baffin Island, Canada and the Wisconsinan Foxe Dome connection: two states of Hudson Bay ice cover. Science 279, 692-695.

Goto-Azuma, K. Koerner, R.M., Fisher, D.A., 2002. An ice core record over the last two centuries from Penny Ice Cap, Baffin Island, Canada. Annals of Glaciology 35, 229-235.

Graversen, R.G., Maurtsen, T.,Tjernström, M., Källén,E., Svensson, G. 2008. Vertical structure of recent Arctic warming. Nature 541,53.

Holland, M., Bitz, C., 2003. Polar amplification of climate change in coupled models. Climate Dynamics 21, 221-232.

Kaufman, D.S., Schneider, D.P., McKay, N.P., Ammann, C.M., Bradley, R.S., Briffa K.R., Miller, G.H., Otto-Bliesner, B.L., Overpeck, J.T., Vinther, B.M., Arctic Lakes 2k Project Members, 2009. Recent warming reverses long-term Arctic cooling. Science 325, 1236. doi:10.1126/science.1173983,1236-1239.

Kinnard, C., Zdanowicz, C.M**.,** Fisher D.A., Wake, C., 2006. Calibration of an ice-core glaciochemical (sea salt) record with sea-ice variability in the Canadian Arctic. Annals of Glaciology 44, 383-390.

Kinnard,C.,Koerner,R.M.,Zdanowicz,C.M.,Fisher,D.A.,Zheng,J.,Sharp,M.J., Nicholson,L., Lauriol, B., 2008. Stratigraphic analysis of an ice core from the Prince of Wales Icefield, Ellesmere Island, Arctic Canada, using digital image analysis: high-resolution density, past summer warmth reconstruction, and melt effect on ice core solid conductivity. Journal of Geophysical Research 113, D24120, doi:10.1029/2008JD011083.

Koerner, R.M., 1970.The mass balance of the Devon Ice Cap, Northwest Territories, Canada, 1961-66. Journal of Glaciology 9, 325-336.

Koerner, R.M.,1977. Devon Island Ice Cap: core stratigraphy and paleo-climate. Science 196, 15-18.

Koerner, R.M.., Fisher, D.A.,1990. A record of Holocene summer climate from a Canadian High Arctic ice core. Nature 343, 630-631.

Koerner, R.M., 2005. Mass balance of glaciers in the Queen Elizabeth Islands, Nunavut, Canada. Annals of Glaciology 42, 417-423.

Kohler, J., James, T.D., Murray, T., Nuth, C., Brandt, O., Barrand, N. E., Aas, H.F., Luckman, A., 2007. Acceleration in thinning rate on western Svalbard glaciers. Geophysical Research Letters 34, L18502, doi:10.1029/2007GL030681, 5 pages.

Miller, G. H., Alley, R.B., Brigham-Grette, J., Fitzpatrick, J.J., Polyak, L. Serreze, M.C.,White, J.W.C., 2010. Arctic amplification: Can the past constrain the future ? Quaternary Science Reviews 29, 1779-1790.

Mote, T. L., 2007. Greenland surface melt trends 1973–2007:Evidence of a large increase in 2007. Geophysical Research Letters 34,L22507, doi:10.1029/2007GL031976.

Overland, J. E., Wang, M., Salo S., 2008. The recent Arctic warm period. *Tellus* **60A,** 589-597.

Paterson, W. S. B., Koerner, R.M., Fisher, D., Johnsen, S.J., Clausen, H.B., Dansgaard, W., Bucher, P., Oeschger, H.,1977. An oxygen-isotope climatic record from the Devon Island ice cap, Arctic Canada. Nature 266, 508-511.

Quinn, P.K., Bates, T.S., Baum, E., Doubleday, N., Fiore, A.M., Flanner, M., Fridlind, A., Garrett, T.J., Koch, D., Menon, S., Shindell, D., Stohl, A.,Warren, S.G., 2008. Short-lived pollutants in the Arctic: their climate impact and possible mitigation strategies. Atmospheric Chemistry and Physics 8, 1723-1735.

Serreze, M. C., Barrett, A. P., Stroeve, J. C., Kindig, D. N., Holland, M. M., 2009. The emergence of surface-based Arctic amplification. The Cryosphere 3,11.

Shindell, D., Faluvegi, G., 2009. Climate response to regional radiative forcing during the twentieth century. Nature Geoscience 2, 294 .

University of East Anglia Climate Research Unit (CRU) CRU Data sets, Internet. British Atmospheric Data Centre, 2008. http://badc.nerc.ac.uk/data/cru .

Vinther, B.M., Clausen, H.B., Fisher, D.A., Koerner, R.M., Johnsen, S.J., Andersen, K.K., Dahl-Jensen, D., Rasmussen, S.O., Steffensen, J.P., A.M. Svensson, 2008. Synchronizing ice cores from the Renland and Agassiz ice caps to the Greenland ice core chronology. Journal of Geophysical Research 113(D08115), doi: 10.1029/2007JD009143 10 pages.

Vinther B.M., Buchardt S.L., Clausen H.B., Dahl-Jensen D., Johnsen S.J. Fisher D.A., Koerner R.M., Raynaud D., Lipenkov V., Andersen K.K., Blunier T., Rasmussen S.O., Steffensen J.P., A.M. Svensson, 2009. Holocene thinning of the Greenland ice sheet. Nature 461, doi:10.1038/nature08355: 385-387.

Acknowledgements . The late Roy Koerner (1932-2008) pioneered the use of melt features and did the stratigraphic observations of all the deep cores. D. Bass, B. Wang and A. Smetny-Sowa assisted with core updates. Logistical and financial support was provided by the Natural Science and Engineering Council, the Canadian Foundation for Climate and Atmospheric Science, the Polar Continental Shelf Project and the Canadian IPY office.

Supporting Online Material

Three SOM sections are available; SOM-1, SOM-2 and SOM-3

Correspondence and requests for materials should be addressed to fisher@nrcan.gc.ca.