High variability of Greenland surface temperature over the past 4000 years estimated from trapped air in an ice core

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[1] Greenland recently incurred record high temperatures and ice loss by melting, adding to concerns that anthropogenic warming is impacting the Greenland ice sheet and in turn accelerating global sea-level rise. Yet, it remains imprecisely known for Greenland how much warming is caused by increasing atmospheric greenhouse gases versus natural variability. To address this need, we reconstruct Greenland surface snow temperature variability over the past 4000 years at the GISP2 site (near the Summit of the Greenland ice sheet; hereafter referred to as Greenland temperature) with a new method that utilises argon and nitrogen isotopic ratios from occluded air bubbles. The estimated average Greenland snow temperature over the past 4000 years was −30.7°C with a standard deviation of 1.0°C and exhibited a long-term decrease of roughly 1.5°C, which is consistent with earlier studies. The current decadal average surface temperature (2001–2010) at the GISP2 site is −29.9°C. The record indicates that warmer temperatures were the norm in the earlier part of the past 4000 years, including century-long intervals nearly 1°C warmer than the present decade (2001–2010). Therefore, we conclude that the current decadal mean temperature in Greenland has not exceeded the envelope of natural variability over the past 4000 years, a period that seems to include part of the Holocene Thermal Maximum. Notwithstanding this conclusion, climate models project that if anthropogenic greenhouse gas emissions continue, the Greenland temperature would exceed the natural variability of the past 4000 years sometime before the year 2100.

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1. Introduction

[2] Greenland surface temperature is a key parameter for Greenland ice sheet mass balance, and thus for global sea-level and ocean circulation [*Hanna et al.*, 2008; *van den Broeke et al.*, 2009]. Recent rapid warming and subsequent ice-melt in Greenland is estimated to account for 4–23% of global sea level rise for the period of 1993–2005 [*van den Broeke et al.*, 2009]. However, the Greenland temperature trend diverges from the global trend in the last 168 years, which raises the possibility that much of the trend is due to natural variability, and makes it more difficult to attribute the recent warming in Greenland to increasing anthropogenic greenhouse gases in the atmosphere [*Box et al.*, 2009; *Chylek et al.*, 2006, 2010]. For example, according to observed temperature records, Greenland underwent a 33% larger warming in 1919–1932 than the warming in 1994–2007 [*Box et al.*, 2009], and recent decadal average temperature is similar to that of the 1930s–1940s [*Chylek et al.*, 2006; *Box et al.*, 2009]. A deviation of the Greenland temperature from the global average temperature trend is likely caused by regional climate variability via modes such as the North Atlantic Oscillation/Arctic Oscillation (NAO/AO) and the Atlantic Multi-decadal Oscillation (AMO) [*Hanna et al.*, 2008; *Long*, 2009; *Chylek et al.*, 2010]. These twentieth century oscillations are thought to be induced by the internal variability of climate system [*Ting et al.*, 2009]. As our understanding of climate variability is limited by relatively short observational records, it is critical to develop a longer precise temperature record with tight age control.

[3] Several methods have been developed to reconstruct Greenland's temperatures, such as the oxygen isotopes of ice in ice cores ($\delta^{18}O_{ice}$) [*Stuiver et al.*, 1995; *Jouzel et al.*, 1997; *White et al.*, 1997; *Johnsen et al.*, 2001; *Masson-Delmotte et al.*, 2005; *Vinther et al.*, 2006, 2009] and borehole thermometry [*Cuffey and Clow*, 1997; *Dahl-Jensen et al.*, 1998], but these methods have several drawbacks [*Jouzel et al.*, 1997; *White et al.*, 1997; *Masson-Delmotte et al.*, 2005; *Dahl-Jensen et al.*, 1998]. The measured ice core parameter $\delta^{18}O_{ice}$ is known to be affected not only by local temperature changes but also by changes in moisture source regions, moisture transport pathways and precipitation seasonality [*Jouzel et al.*, 1997; *White et al.*, 1997; *Masson-Delmotte et al.*, 2005]. Borehole thermometry is accurate but rapidly loses temporal resolution with increasing age into the past, owing to heat diffusion in ice sheets [*Dahl-Jensen et al.*, 1998].

[4] A new method [*Kobashi et al.*, 2008a, 2008b; *Kobashi et al.*, 2010] has been developed to reconstruct surface

temperature variability for relatively stable climates such as the Holocene through simultaneous, high-precision analyses of δ^{15}N and δ^{40}Ar in trapped air in ice cores with tight chronological control (see auxiliary material).[1] This method, which is independent of $\delta^{18}O_{ice}$, builds on the methodology of quantifying the magnitude of abrupt climate changes [*Severinghaus et al.*, 1998; *Kobashi et al.*, 2007]. An advantage of this method is that the reconstructed surface decadal temperatures are physically constrained and are not subject to bias from seasonal temperature swings, as gas diffusion averages out any surface temperature variability that is shorter than a few decades [*Severinghaus et al.*, 1998]. A caveat is that our method reconstructs past local surface temperature changes, which may have been affected by reported elevation changes of the Greenland Ice Sheet [*Vinther et al.*, 2009] (see later discussion). Another potential drawback of our method is that it measures snow temperature, not free-tropospheric air temperature, and these can differ radically due to strong near-surface inversions that are common during times of low wind speed at Greenland Summit. Although the surface snow temperature is an important variable for surface mass balance of the Greenland Ice Sheet [*Franco et al.*, 2011], it is possible that the strength of these inversions has changed over time, which would make our record less relevant to the study of regional climate dynamics. The strength of inversions may be decreased by cloud cover, which retards radiative cooling of the surface, or high winds that break up the inversions by turbulent mixing.

2. Methods

[5] The samples and gas analyses (δ^{15}N and δ^{40}Ar) have been described in detail elsewhere [*Kobashi et al.*, 2008a]. The GISP2 ice core from the Summit region of central Greenland (72° 36′N, 38° 30′W; 3200 m.a.s.l.) was used for this study. The method for the temperature reconstruction relies on the fact that gases in firn (unconsolidated snow) layers fractionate according to the depth and temperature gradient (ΔT) at the top and bottom of the layer [*Severinghaus et al.*, 1998] (see auxiliary material). Information about past depths and ΔTs at the time of air bubble trapping in the ice sheet can be retrieved by measuring δ^{15}N and δ^{40}Ar in the occluded air in ice cores [*Severinghaus et al.*, 1998; *Kobashi et al.*, 2008a]. Then, the surface temperature history can be reconstructed by integrating the ΔTs over time [*Kobashi et al.*, 2008b, 2010] with a firn densification/heat diffusion model [*Goujon et al.*, 2003] (see auxiliary material). This method also incorporates the complementary constraint offered by borehole temperature measurements; the gas isotopes primarily record decadal-to-centennial frequencies whereas the borehole method records lower frequencies.

3. Past 4000 Years of Reconstructed Greenland Temperature

3.1. Prior Work: The Last 1000 Years

[6] The past 1000 years of Greenland's snow surface temperature were reconstructed with high temporal resolution (~10 years) and precision ($1\sigma = 0.48$°C) and persistent multi-decadal to multi-centennial temperature fluctuations were reported [*Kobashi et al.*, 2010] (Figure 1, middle). The record is characterised by a warm period in the 11th and 12th centuries (the Medieval Warm Period), a long-term cooling toward the coldest period in the 17th and 18th centuries (the Little Ice Age), and the observed recent warming [*Kobashi et al.*, 2010]. The Greenland temperatures of the past 1000 years were found to be significantly correlated with Northern Hemispheric (NH) temperatures (r = 0.35–0.44; depending on different NH temperature reconstructions) with an amplitude 1.4–2.3 times larger than the NH temperature likely owing to polar amplification [*Kobashi et al.*, 2010].

3.2. Past 4000 Years

[7] To extend the reconstruction to the last 4000 years (Figure 1, bottom), we followed the methodology used for the past 1000 years but with a lower sample resolution of ~20 years [*Kobashi et al.*, 2010] (see auxiliary material). The reconstructed temperature record is consistent with the observed borehole temperature profile [*Alley and Koci*, 1990; *Clow et al.*, 1996] within an observational uncertainty of ±0.05°C [*Vinther et al.*, 2009] above 1500 m borehole depth (Figure 2). The average Greenland temperature for the past 4000 years was found to be −30.7°C with a standard deviation of 1.0°C. The temperature decreased by approximately 1.5°C (a linear regression coefficient) over the past 4000 years, and the multi-millennial trend is similar to the temperature reconstruction produced using a borehole temperature inversion technique [*Dahl-Jensen et al.*, 1998] (Figure 3). We note that δ^{40}Ar was affected by the gas loss process during bubble closure in the firn and/or during storage [*Kobashi et al.*, 2008a], which necessitated a correction that nonetheless had a minimal effect on reconstructed temperature variation (see auxiliary material). Interestingly, the multi-centennial variation in the temperature history is broadly similar to known European climatic epochs [*Lamb*, 1977] (Figure 3). The temperature record starts with a colder period in "the Bronze Age Cold Epoch". After a warm period in "the Bronze Age Optimum", a 1000-year cooling was initiated during "the Iron Age Cold Epoch". A relatively long warming, spanning "the Iron/Roman Age Optimum", "the Dark Ages", and "the Medieval Warm Period" continued for ~1300 years. Finally, a cooling trend towards the coldest period of the past 4000 years, "the Little Ice Age", ended with the recent warming (Figure 3).

[8] The Greenland temperature reconstruction shows clear multi-centennial to multi-millennial fluctuations with spectral peaks at 333, 210, 174, 114, 87, 72.7, 64.5, 58.8, 54.1, 49.4, and 47.1 years with a 90% significance level (Figure S1). Oscillations with 87-year and 210-year periods may correspond to the Suess and Gleissberg solar cycles [*Wanner et al.*, 2008], suggesting a possible solar influence on Greenland snow temperature. *Vinther et al.* [2009] derived elevation changes in the Greenland ice-sheet for the Holocene using the $\delta^{18}O_{ice}$ of six Greenland ice cores (Figure 3). According to their study, the elevation of the GISP2 site decreased by 70 m from 2000 B.C.E. to 0 C.E. (Figure 3). Assuming an empirical lapse rate of 0.6–1.0°C per 100 m, the 70 m decline in elevation may have induced a 0.4–0.7°C temperature increase. As the temperature actually

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL049444.

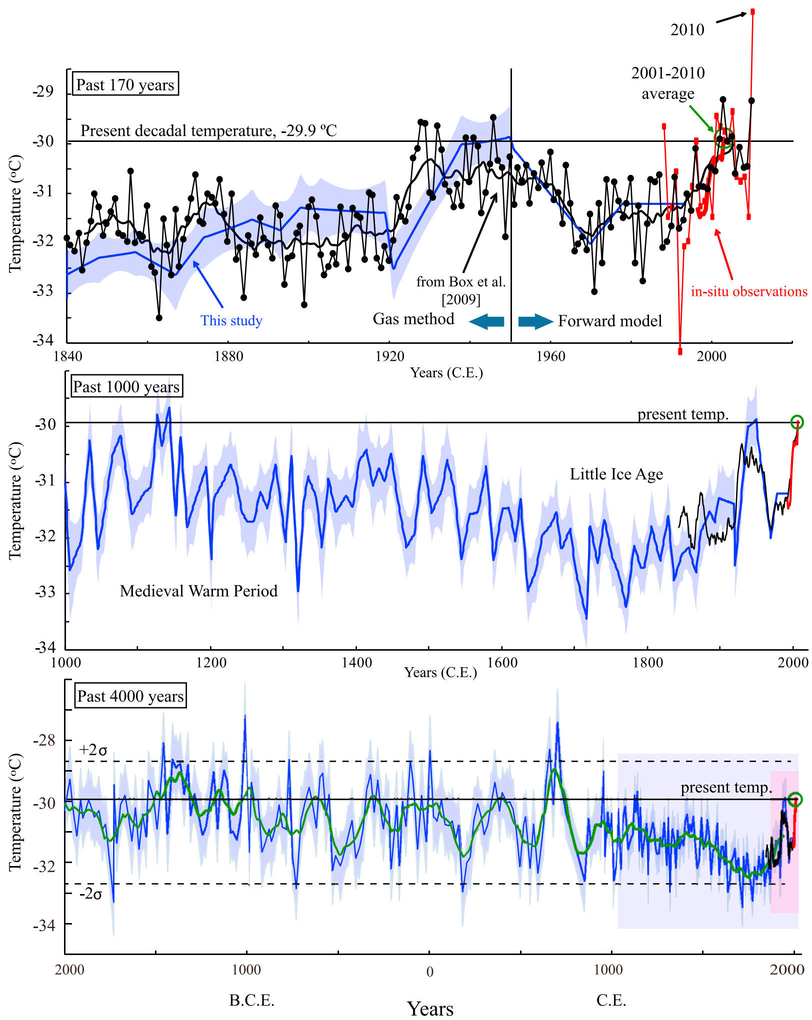

Figure 1. (top) Reconstructed Greenland snow surface temperatures for the past 4000 years and air temperature over the past 170 years (1840–2010) from three records. The thick blue line and blue band represents the reconstructed Greenland temperature and 1σ error, respectively (this study). The reconstruction was made by two different methods before and after 1950. The "gas method" is as described in section 2, and the "forward model" is described by *Kobashi et al.* [2010]. Thick and thin black lines are the inversion-adjusted reconstructed Summit annual air temperatures and 10-year moving average temperatures, respectively [*Box et al.*, 2009]. Thin and thick red lines are the inversion adjusted annual and 10-year moving average AWS temperature records, respectively [*Stearns and Weidner*, 1991; *Shuman et al.*, 2001; *Steffen and Box*, 2001; *Vaarby-Laursen*, 2010]. (middle) Past 1000 years of Greenland temperature. Thick blue line and band are the same as above. Black and red lines are the Summit [*Box et al.*, 2009] and AWS [*Stearns and Weidner*, 1991; *Shuman et al.*, 2001; *Steffen and Box*, 2001; *Vaarby-Laursen*, 2010] decadal average temperatures as above. (bottom) Past 4000 years of Greenland temperature. Thick blue line and band are the same as above. Thick green line represents 100-year moving averages. Black and red lines are the Summit [*Box et al.*, 2009] and AWS [*Stearns and Weidner*, 1991; *Shuman et al.*, 2001; *Steffen and Box*, 2001; *Vaarby-Laursen*, 2010] decadal average temperature, respectively. Blue and pink rectangles are the periods of 1000–2010 C.E. (Figure 1, middle) and 1840–2010 C.E. (Figure 1, top), respectively. Present temperature is calculated from the inversion adjusted AWS decadal average temperature (2001–2010) as −29.9°C (Figure 1, top). Present temperature and $\pm 2\sigma$ are illustrated by lines in the plots. Green circles are the current decadal average temperature as above (−29.9°C, 2001–2010).

cooled during this period (Figure 3), the elevation change should have worked to dampen the cooling trend.

4. Comparison With Oxygen Isotopes of Ice

[9] Oxygen isotopes of ice ($\delta^{18}O_{ice}$) have long been employed as a local temperature proxy [*Jouzel et al.*, 1997], because of the fact that the $\delta^{18}O$ of meteoric water and local temperatures show a strong spatial covariation (0.72‰/°C; r^2 = 0.96, n = 50 in Greenland) [*Masson-Delmotte et al.*, 2005]. However, this measure is also affected by changes in moisture source regions, moisture transport pathways and precipitation seasonality such that the application of this metric to temporal variation is more difficult [*Jouzel et al.*, 1997; *White et al.*, 1997; *Masson-Delmotte et al.*, 2005]. With a local temperature record in hand, it should be possible to evaluate the fidelity of $\delta^{18}O_{ice}$ as a temperature proxy. Three ice cores (GISP2, GRIP, and NGRIP) have

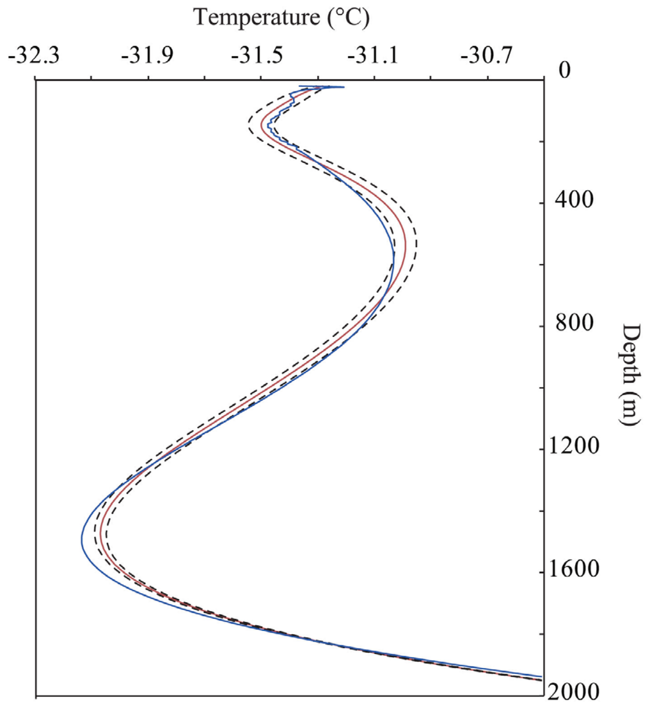

Figure 2. Borehole temperature reconstruction (red) and observation (blue). Dotted lines are 1σ error bands (standard deviation).

been obtained from near the topographic summitt of the ice sheet and the ridge area of the Greenland ice sheet. GISP2 is located ~30 km west of GRIP, and NGRIP is located ~310 km northwest of GISP2 and GRIP. The $\delta^{18}O_{ice}$ of GISP2, GRIP, and NGRIP show slightly decreasing trends [*Stuiver et al.*, 1995; *Vinther et al.*, 2006] over the past 4000 years (Figure 3). Although GISP2 is geographically much closer to GRIP, the correlation (r = 0.40, p < 0.01) of the $\delta^{18}O_{ice}$ of these two sites is not as high as the correlation (r = 0.65, p < 0.01) between GRIP and NGRIP (Figure 3). However, it should be noted that the borehole temperature profile above 1300 m for GISP2 [*Alley and Koci*, 1990; *Clow et al.*, 1996] is consistently warmer than that of GRIP [*Johnsen et al.*, 1995] by ~0.3°C, providing evidence of a temperature difference for geographically close locations.

[10] The correlations between the temperature and the $\delta^{18}O_{ice}$ of the three Greenland Summit ice cores with a 100-year running mean (GISP2 [*Stuiver et al.*, 1995], GRIP [*Vinther et al.*, 2006], and NGRIP [*Vinther et al.*, 2006]) were found to be r = 0.41 (p < 0.01), 0.51 (p < 0.01), and 0.57 (p < 0.01), respectively; these correlations explain 16 to 32% of the variance in temperature. It is noteworthy that multi-centennial fluctuations in $\delta^{18}O_{ice}$, especially for NGRIP, correlate well with the temperature variations (Figure 3). The observation that the slope of the NGRIP $\delta^{18}O_{ice}$ vs. temperature is 0.18 ‰/°C (linear regression coefficient) lower than the modern spatial slope of 0.72‰/°C in Greenland [*Masson-Delmotte et al.*, 2005] is partly explained by the low correlation. Importantly, the NGRIP $\delta^{18}O_{ice}$ has a higher correlation (r = 0.57, p < 0.01) with temperature than those with GISP2 (r = 0.39, p < 0.01) or GRIP (r = 0.51, p < 0.01). This can be explained by the fact that the NGRIP site is located at a higher northern latitude than the GISP2 and GRIP sites so that it is downstream from them with respect to a common air mass flow that brings intense seasonal snowfall. Therefore, as previous studies have inferred [*Johnsen et al.*, 2001; *Masson-Delmotte et al.*, 2005], the NGRIP $\delta^{18}O_{ice}$ is less susceptible to seasonal storm activity and snowfall that obscures temperature signals, making NGRIP $\delta^{18}O_{ice}$ more sensitive to temperature change.

5. Placing the Present Temperature Into Historical and Future Context

5.1. Present Greenland Temperature

[11] To place the Greenland temperature proxy reconstruction into a historical context, we incorporate two additional Summit temperature records. One record is obtained from a compilation of Summit Automatic Weather Station ~2 m surface air temperature (SAT) observations (hereafter AWS or in-situ record) that spans 23 years (1987–2010). The AWS were situated within 20 km of the GISP 2 coring site and within 25 m elevation of the ice sheet topographical summit (Figure 1, top, red line). The series begins in May 1987 with Automatic Weather Station data after *Stearns and Weidner* [1991]. *Shuman et al.* [2001] merge this record with data from the Greenland Climate Network (GC-Net)

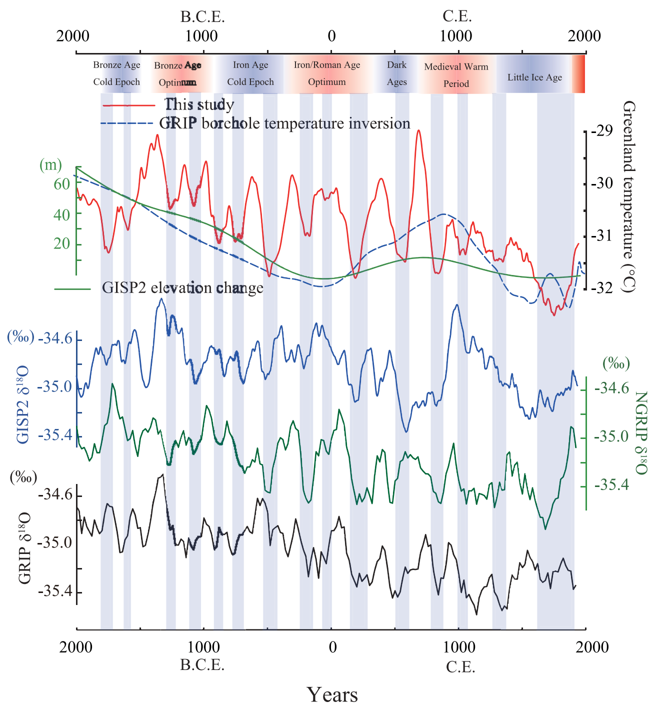

Figure 3. Greenland temperature and oxygen isotopes (GISP2, GRIP, and NGRIP) for the past 4000 years. From the top, the Greenland temperatures from this study are presented as a 100-year running mean (red), with the GRIP borehole temperature inversion (blue dashes) [*Dahl-Jensen et al.*, 1998] and the GISP2 elevation change (green) [*Vinther et al.*, 2009]. $\delta^{18}O_{ice}$ of GISP2 (blue) [*Stuiver et al.*, 1995], NGRIP (green) [*Vinther et al.*, 2006], and GRIP (black) [*Vinther et al.*, 2006] are 100-year running means with GISP2 additionally smoothed by a 20-year running mean.

AWS data [*Steffen and Box*, 2001] to produce the first 12 years of this compilation. Gaps before June 1996 are in-filled using daily passive microwave emission brightness temperatures. GC-Net data then comprise the period spanning June 1996 to December 2003 with gaps in-filled by Danish Meteorological Institute (DMI) Summit AWS data [*Vaarby-Laursen*, 2010]. The DMI data exclusively form this data series from January 2004 through December 2010.

[12] A second Summit air temperature series comes from a 171 year (1840–2010) spatial/temporal reconstruction based on an optimal combination of meteorological station records and regional climate model output [*Box et al.*, 2009] (hereafter "reconstructed Summit temperature"; Figure 1, top). The reconstruction is re-sampled onto a 5 km grid. The extracted time series is from the average of values from a 5 km radius area centered at 72.583 N, 38.450 W. The position corresponds to the Summit station and is within 2 km of the core site. The correlation coefficient with the AWS record for the 23 overlapping complete years (1988–2010) is r = 0.63. The reconstruction underestimates the extremes such as the 1991–1992 Pinatubo cooling [*Box*, 2002] and the 2010 high temperature (Figure 1, top).

[13] Before the two records are combined with the 4000-year temperature record, it is necessary to make an adjustment, as firn temperatures are colder than air temperatures by 0.2°C to 2.6°C in Greenland [*Steffen and Box*, 2001] as a result of the surface radiative cooling and inversion as noted above. As the mean difference between the decadal average reconstructed Summit temperatures and the reconstructed Greenland temperature for the 1845–2005 period is 1.75°C, the AWS and reconstructed Summit temperatures are reduced by 1.75°C (Figure 1).

5.2. Verifying the Reconstructed Temperature With Observation

[14] An overlapping period (1845–1993) between the reconstructed Greenland temperature and the Summit temperature (a 10-year running mean) [*Box et al.*, 2009] is used to validate the 4000-year reconstructed Greenland temperature. It is found that the two records agree within the uncertainties of both estimates (r = 0.67, p < 0.01; Figure 1, top). This overlap interval includes the mid-20th century warm decades (1930s–1950s) and a subsequent cooling. The reconstructed Summit temperature for 1840–2010 is highly correlated with the whole Greenland Ice Sheet annual temperature from *Box et al.* [2009] (r = 0.92, p < 0.01) but with a 22% higher standard deviation for the whole Ice Sheet temperature, indicating that the reconstructed Greenland temperature for the past 4000 years should be a good proxy for the whole Greenland Ice Sheet temperature trend. We note that our Greenland temperature reconstruction comprises decadal average temperatures from the Summit area, which may not be strongly correlated with melting around the ice sheet margin that occurred in the past.

5.3. Present Temperature in the Context of the Past 4000 Years

[15] The current decadal surface temperature at Summit (2001–2010) is calculated to be −29.9 ± 0.6°C from the inversion- adjusted AWS record (Figure 1), and is illustrated in the 4000 year context (Figure 1). The current decadal average surface temperature at the summit is as warm as in the 1930s–1940s (Figure 1, top), and there was another similarly warm period (−29.7 ± 0.6°C) in the 1140s (Figure 1, middle) (Medieval Warm Period), indicating that the present decade is not outside the envelope of variability of the last 1000 years. Excluding the last millennium, there were 72 decades warmer than the present one, in which mean temperatures were 1.0 to 1.5°C warmer, especially in the earlier part of the past 4000 years [*Dahl-Jensen et al.*, 1998; *Wanner et al.*, 2008]. During two intervals (~1300 B.P. and ~3360 B.P.) centennial average temperatures were nearly 1.0°C warmer (−28.9°C, the 97 percentile) than the present decade (Figure 1, bottom). From the above observations, we conclude that the current decadal mean snow temperature in central Greenland has not exceeded the envelope of natural variability of the past 4000 years.

[16] This conclusion differs somewhat from the result of a recent reconstruction of Arctic summer air temperature over the past 2000 years, which indicates that a long cooling trend over the last 2000 years ended with a pronounced warming during the twentieth century [*Kaufman et al.*, 2009]. Possible reasons for the differences are numerous, and include at a minimum 1) our record is a mean-annual temperature, not a summer temperature, and variability is minimal in summer but highest in winter [*Box*, 2002]; 2) differences between air and snow temperature may be influenced by changes in cloud cover and wind speed, which affect the strength of the near-surface inversion; and 3) our site is not necessarily representative of the whole Arctic, and may respond in opposite ways to annular mode fluctuations.

5.4. Future Context

[17] Although somewhat speculative, it is of interest to ask when Greenland snow temperature will exceed the envelope of variability found in the last 4000 yr given current projections. We define an upper bound of the natural variability over the last 4000 years as the value (−28.7°C) derived from two standard deviations (2.0°C) above the average (−30.7°C) of Greenland temperatures over the period (Figure 1). The future projections based on the IPCC emission scenarios (SRES; B1, A1B, and A2) by IPCC AR4 models (MPI, HADCM3, and HADGEM1; chosen for better performances of Greenland climate reconstructions [*Franco et al.*, 2011]) indicate that annual average warming at Greenland Summit will exceed 2–4°C above the 1970–1999 period by 2070–2099 [*Franco et al.*, 2011]. The average reconstructed Summit temperature of the 1970–1999 period is −31.4°C so that the values of 2–4°C above the 1970–1999 period at Greenland Summit are −29.4°C to −27.4°C, indicating a possibility of exceeding the upper bound (−28.7°C) of the natural variability by 2100.

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