Rapid recent warming on Rutford Ice Stream, West Antarctica, from borehole thermometry

B. E. Barrett,[1] K. W. Nicholls,[2] T. Murray,[1] A. M. Smith,[2] and D. G. Vaughan[2]

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[1] The Antarctic Peninsula has warmed faster than the global average rate of warming during the last century. Due to limited availability of long term meteorological records, the geographical extent of this rapid warming is poorly defined. We collected borehole temperature measurements in the upper 300 m of Rutford Ice Stream, West Antarctica, and employed an inverse modeling scheme with a heat diffusion-advection equation to determine the recent surface temperature history of the borehole position. Our results reveal recent warming of 0.17 ± 0.07°C (decade)$^{-1}$ since 1930. This result suggests that, at least in an attenuated form, the rapid warming observed over the Antarctic Peninsula extends as far south as Rutford Ice Stream. This result agrees with other recent results that show a warming trend across much of the West Antarctic Ice Sheet. **Citation:** Barrett, B. E., K. W. Nicholls, T. Murray, A. M. Smith, and D. G. Vaughan (2009), Rapid recent warming on Rutford Ice Stream, West Antarctica, from borehole thermometry, *Geophys. Res. Lett.*, *36*, L02708, doi:10.1029/2008GL036369.

1. Introduction

[2] The Antarctic Peninsula warmed dramatically (~0.56°C (decade)$^{-1}$) during the last half-century, as indicated by meteorological records of mean annual temperature [*Turner et al.*, 2005]. This warming exceeds the global average warming of 0.06 ± 0.02°C (decade)$^{-1}$ during the 20th Century [*Intergovernmental Panel on Climate Change*, 2001], and is in contrast with East Antarctica, which shows limited or no warming trend [*Vaughan et al.*, 2003]. The geographic extent of the peninsula's rapid warming is difficult to determine because of the sparsity of meteorological records, and there are few estimates of surface temperature change for West Antarctica south of the Antarctic Peninsula. However, *Steig et al.* [2008] show a warming of 0.17 ± 0.06°C (decade)$^{-1}$ averaged over the West Antarctic Ice Sheet. We have used borehole temperature measurements from Rutford Ice Stream (Figure 1) to infer decadal scale trends in its recent surface temperature history and provide some insight into the distribution of surface warming in West Antarctica.

1.1. Borehole Thermometry

[3] Borehole temperature measurements can be used to infer recent surface temperature history because surface temperature fluctuations diffuse downwards through the subsurface, primarily by conduction. Surface temperature histories have been estimated from vertical temperature profiles in both frozen [e.g., *Lachenbruch and Marshall*, 1986] and unfrozen ground [e.g., *Pollack et al.*, 1998]. Applying the technique to an ice column requires the consideration of vertical advection due to surface accumulation, basal melting and strain thinning in addition to heat conduction. Different implementations of the technique have been used to determine surface temperature histories on millennial [*Dahl-Jensen et al.*, 1998], centennial [*van de Wal et al.*, 2002], and decadal [*Nicholls and Paren*, 1993] scales, and to determine geothermal heat flow at the bed of an ice sheet [*Engelhardt*, 2004].

1.2. Rutford Ice Stream

[4] Rutford Ice Stream drains approximately 10% of the West Antarctic Ice Sheet from a drainage basin of about 49,000 km^2 into Ronne Ice Shelf [*Doake et al.*, 2001]. The ice stream flows toward the south–east with a speed of 300–400 m a^{-1} between the Ellsworth Mountains to the south–west and Fletcher Promontory to the north–east (Figure 1b).

[5] Rutford Ice Stream is close to having a net flux balance [*Doake et al.*, 2001] and is therefore in a state of dynamic equilibrium. However, recent estimates of surface elevation change from satellite altimeter data show that the drainage basin is thickening by ~8 cm a^{-1} [*Vaughan et al.*, 2008]. The source of precipitation for this region is most likely the Bellingshausen and Amundsen seas [*Doake et al.*, 2001], which also have a strong influence over the Antarctic Peninsula [*Vaughan et al.*, 2003]. It is therefore plausible that Rutford Ice Stream will have similar climatic changes to the Antarctic Peninsula, some 500 km to the north.

2. Method

[6] In February 2005, we installed a thermistor string in a hot-water drilled borehole located near the middle of the ice stream, approximately 35 km upstream from the grounding line (S78°08.4′ W83°55.2′). The string contained ten 3K3A Betatherm thermistors spaced at 31.5 m intervals between 15 m and 300 m depth. These thermistors were calibrated prior to deployment and their resistance was measured 24 months after installation, thus allowing sufficient time for the borehole temperatures to recover from the drilling operation. We estimate the accuracy of the measured temperatures to be ±0.01°C.

2.1. Forward Model

[7] The evolution of the temperature field within a dry ice pack can be described by the following equation

$$\rho \frac{\partial T}{\partial t} = \nabla \cdot (\rho \kappa \nabla T) - \nabla \cdot (\rho T U) \quad (1)$$

[1] School of the Environment and Society, Swansea University, Swansea, UK.

[2] British Antarctic Survey, Cambridge, UK.

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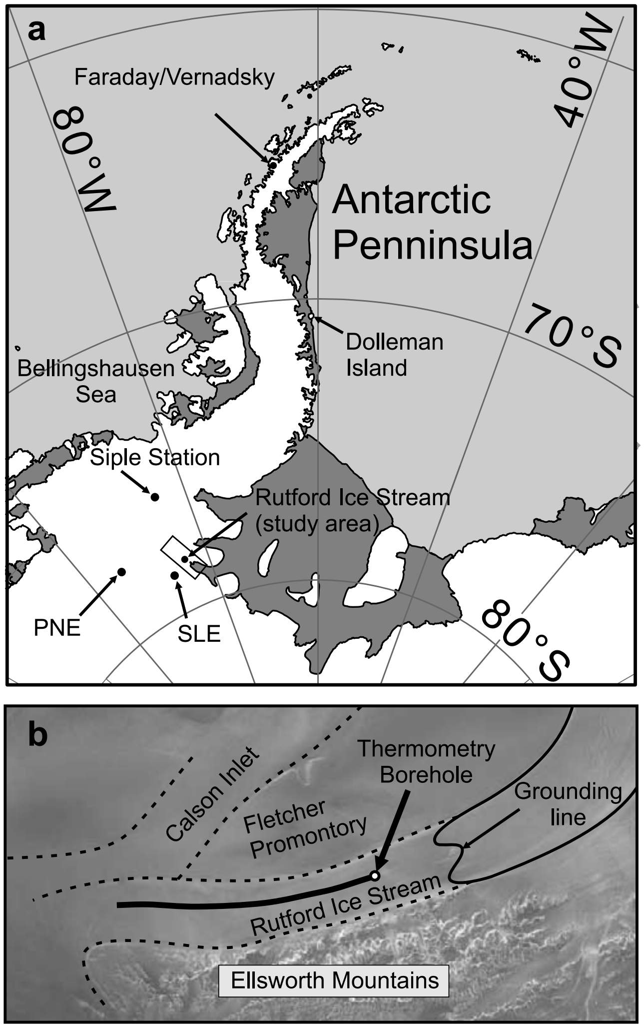

Figure 1. Location map. (a) The Antarctic Peninsula showing the Siple and Faraday meteorological stations, Dolleman Island, the Subglacial Lake Ellsworth (SLE) and Pine Island Glacier basin (PNE) sites and our Rutford Ice Stream borehole location. (b) Rutford Ice Stream showing the thermometry borehole, and the 100 km flow line upstream of the borehole (bold line).

where ρ is the ice density, T is the temperature, κ is the thermal diffusivity and U is the three-dimensional velocity field. By assuming T is constant in horizontal directions, equation (1) can be written

$$H^2 \frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2} + \left(\frac{\partial \kappa}{\partial \rho} \frac{\partial \rho}{\partial x} + \frac{\kappa}{\rho} \frac{\partial \rho}{\partial x} + x\dot{H}H - wH \right) \frac{\partial T}{\partial x} \quad (2)$$

where H is the ice column thickness, $\dot{H}$ is the time rate of change in H, x is the depth scaled by H (x = 0 at the ice surface, x = 1 at the bed), and w is the vertical velocity of the ice column (a function of x). Equation (2) is a second-order non-linear partial differential equation which we solved numerically using a fully implicit discretization.

[8] The boundary conditions for the model were the ice surface and bed temperatures. The bed temperature was fixed at −2°C, the approximate pressure melting point beneath 2200 m of ice, but we assumed that the base was not melting at an appreciable rate. Surface temperature varied as a function of time. The model also required inputs of the vertical density profile (assumed to be constant through time), the thermal diffusivity (a function of the density and ice temperature), the ice thickness (assumed to be constant through time), and the vertical velocity profile of the ice. The vertical velocity profile of the ice is determined from the density profile, surface accumulation and basal melt rates, and the rate of change in ice thickness.

[9] Density profiles have been measured on Rutford Ice Stream by seismic refraction surveys [*Smith*, 1997]. These profiles show little geographic variation, and good agreement with shallow ice-core and snow-pit densities where available.

[10] The snow accumulation on the ice stream was measured by *Doake et al.* [1987] between 1983 and 1984. They found a near linear increase in accumulation rate with elevation, from ~0.40 Mg m^{-2} at 300 m elevation to ~0.70 Mg m^{-2} at 600 m elevation. We used an elevation profile of the ice stream from BEDMAP [*Lythe et al.*, 2001], and the ice stream's present flow velocity profile to estimate the accumulation rate history. The current velocity at the borehole position is ~377.3 m a^{-1} [*Murray et al.*, 2007]. We supplemented this velocity measurement with InSAR data (E. King, personal communication, 2008) to determine how contemporary velocities vary over the length of the ice stream. We assumed that the ice stream velocities and accumulation pattern have not changed significantly over the duration of the modeled surface temperature history.

[11] The forward model defined by equation (2) was used to calculate the evolution of the ice column's temperature using a predefined surface temperature history. A steady state thermal profile was calculated by modeling 1000 years with a constant surface temperature. We then applied 1000 years of changing surface temperature. Present day accumulation and flow velocity are well constrained from ~100 km upstream of the drill location (further upstream, conditions are complicated by convergence and a change in flow direction), which corresponds to ~300 years of displacement. However, including 1000 years of surface temperature variability in the model enables the steady-state starting condition to be forgotten. We truncated the final surface temperature histories to the most recent 300 years.

2.2. Inverse Model

[12] We used an inversion scheme to find surface temperature histories that produce ice column temperature profiles with a close fit to our measured temperatures. The fit between modeled temperatures and our data was defined as their root mean squared (RMS) difference.

[13] The inversion started with a constant surface temperature history, chosen randomly between −27.5°C and −26°C (encompassing the entire range of measured temperatures) and defined with a temporal resolution of 15 years. This surface temperature history was updated by changing the temperature at a randomly chosen temporal point. The updated surface temperature history was adopted if the forward model produced an improved fit to the measured data, otherwise it was rejected and a different random alteration was tested. The inversion continued until the model fit could not be improved.

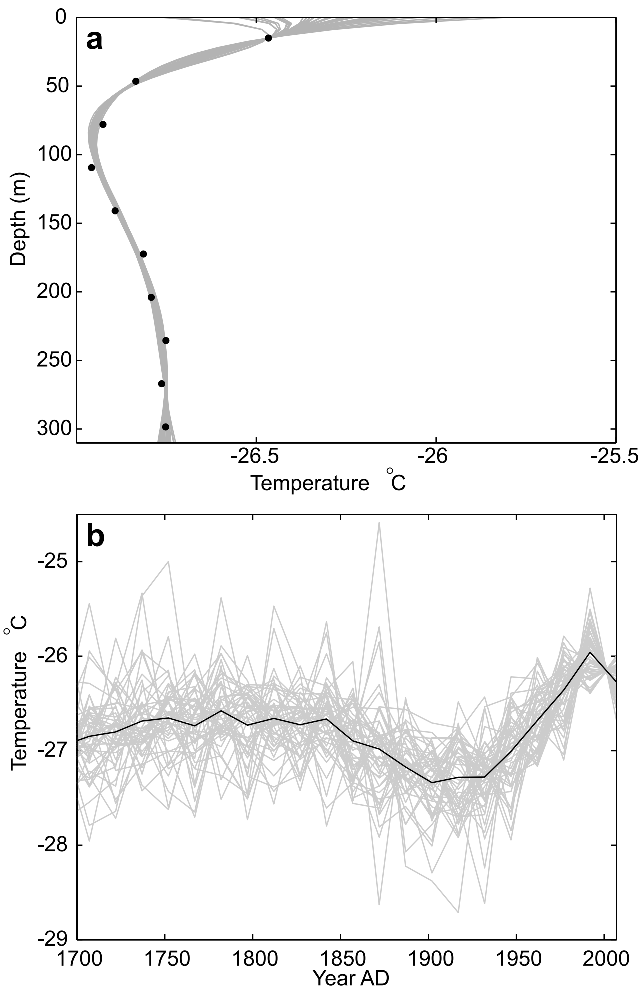

Figure 2. Thermometry inversion results. (a) Vertical profile of temperature measured in 2007 (dots) with the forward modeled thermal profile from each of 50 inversions. (b) The surface temperature history for the geographic drill location from the 50 inversions (gray lines) and the mean of these results (black line).

[14] The inversion result is the surface temperature history of the ice column as it flowed downstream over the last 300 years. However, this includes the effects of both climate and the changing geographic location of the ice column with time. To obtain the surface temperature history at the geographic location of the borehole, we corrected the inversion results using the spatial trend in present day surface temperature along the flow line. This trend was obtained from the Advanced Very High Resolution Radiometer (AVHRR) data from the period 1982 to 2000 from a grid with ∼12.5 km spacing [*King and Comiso*, 2003], and interpolated to the flow line. AVHRR temperatures may suffer from a lack of direct calibration, however we use only the spatial trend.

3. Results

[15] Our measured vertical temperature profile from Rutford Ice Stream is shown in Figure 2a; it is characterized by temperatures of −26.8°C at 300 m depth, decreasing to a temperature minimum of −27.0°C at 110 m depth, and increasing to a temperature maximum of −26.5°C at 15 m depth. We performed 50 inversions on these data (Figure 2).

[16] Each inversion result displays a broadly consistent pattern. The mean of the 50 inversions represents the most probable 300 year surface temperature history at the borehole location (Figure 2b). The results suggest a decrease in surface temperatures during the 19th Century and a faster warming over the most recent 75 years. The warming trend is ∼1.3 ± 0.5°C over these 75 years (the error is derived from the standard deviation of the 50 inversions at the beginning and end of the warming trend); a rate of ∼0.17 ± 0.07°C $(\text{decade})^{-1}$.

4. Discussion

[17] Our research shows that Rutford Ice Stream, ∼500 km south of the Antarctic Peninsula, has been warming since ∼1930. Prior to this there may have been a period of cooling, which is a similar result to that presented by *Nicholls and Paren* [1993] from Dolleman Island (Figure 1). The fact that rapid warming has occurred at Rutford Ice Stream is consistent with new estimates of average warming across West Antarctica [*Steig et al.*, 2008]. We also looked for other evidence of temperature trends south of the Antarctic Peninsula in order to improve our knowledge of the distribution of warming in West Antarctica.

[18] A 19 year long meteorological surface temperature record exists for Siple Station (Figure 1a) between 1979 and 1997 [*Shuman and Stearns*, 2001, 2002], which shows a strong warming trend of 1.1 ± 0.55°C $(\text{decade})^{-1}$ (one sigma confidence limit), but this trend must be interpreted with caution because the time series is short [*Vaughan et al.*, 2003].

[19] In the absence of continuous meteorological data, satellite-borne measurements (e.g. AVHRR) can provide regular surface temperature measurements over large areas. However the temporal coverage of AVHRR data does not extend far enough into the past to be useful for multi-decadal surface temperature histories. Furthermore, AVHRR is only effective during cloud free conditions, which may limit the possibility of calculating an annual average temperature.

[20] 10-m temperatures are often used as a proxy for mean temperature over the most recent few years because seasonal fluctuations in temperature decay in amplitude with depth. These fluctuations are effectively absent below 20 m depth [*Paterson*, 1994], but *Morris and Vaughan* [1994] showed that corrections for seasonal fluctuations, based on the time of year and measurement depth, can be used to make use of 10-m temperatures.

[21] We measured a 10-m temperature of −29.4 ± 0.1°C at the PNE camp (Figure 1a; S77°34.23′ W95°55.70′) on the Pine Island Glacier drainage basin on December 30th 2004. The same location was visited on January 4th 1958 and a 10-m temperature of −29.87 ± 0.01°C was measured [*Anderson*, 1958; *Bohlander and Scambos*, 2001]. The corrections described by *Morris and Vaughan* [1994] are not required here because the measurements were made at the same depth and time of year. These values have a difference of +0.5 ± 0.1°C over 47 years, corresponding to a change of +0.11 ± 0.02°C $(\text{decade})^{-1}$.

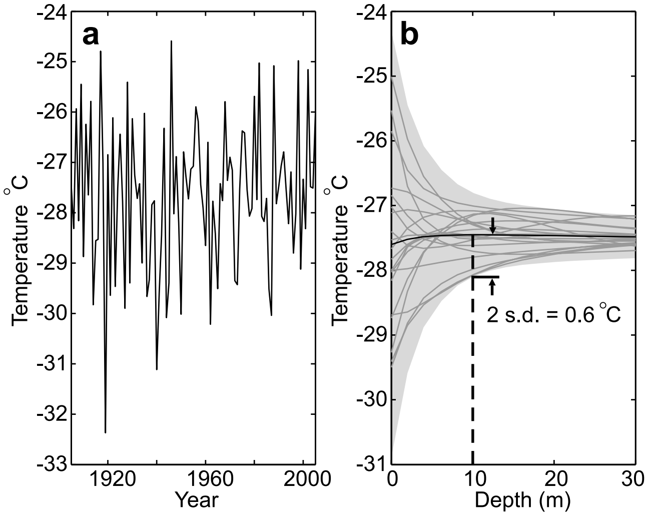

Figure 3. Precision of 10-m temperatures for decadal scale surface temperature trends. (a) One example of a surface temperature history with a constant mean of −27.5°C and an inter-annual variability with 1.5°C standard deviation. (b) Twenty examples (from 100) of modeled temperature profiles (gray lines), and the mean temperature profile (black line) with two standard deviations (gray shape). For 10-m temperature measurements, the mean value of the surface temperature history can be estimated with ±0.6°C precision (two standard deviations; 95% confidence).

[22] At Subglacial Lake Elsworth (SLE) (Figure 1a; S78°58.679′ W90°30.712′) we measured a 20-m temperature of −31.9 ± 0.2°C in December 2007. This station is between Stations 660 and 690 of the Sentinel Range to Marie Byrd Land IGY Traverse where 10-m temperatures were measured in January 1958 [*Anderson*, 1958; *Bohlander and Scambos*, 2001]. A linear interpolation of these 10-m temperatures to the location of our 20-m temperature gives −32.01 ± 0.01°C. Because the depth of our temperature was not the same as the IGY temperatures, it is necessary to correct the IGY temperature for seasonal effects (Our temperature is at 20-m and therefore not sensitive to seasonal effects). The corrected temperature for 1958 is −31.6 ± 0.1°C; a difference of −0.3 ± 0.2°C over 50 years, or a change of −0.06 ± 0.04°C (decade)$^{-1}$.

[23] Inter-annual variability in mean annual surface temperatures means that 10-m and 20-m temperatures may not accurately represent the average temperature over the most recent few years, and that the difference between a pair of 10-m or 20-m temperatures may not give a good indication of decadal trends, except where those changes are substantial. We investigated this using our forward model for a 100 year surface temperature history with a constant mean and an inter-annual variability with a standard deviation of 1.5°C (the largest inter-annual variability reported by *Vaughan et al.* [2003] from Antarctic meteorological stations). We ran the forward model 100 times and measured the distribution of modeled temperatures at 10-m depth (Figure 3). We found that the 10-m temperatures had a standard deviation of 0.3°C. We conclude that for an inter-annual variability with a standard deviation of 1.5°C, measured 10-m temperatures should be within ±0.6°C (two standard deviations; 95% confidence) of the underlying decadal trend in surface temperatures. Similarly, we found that measured 20-m temperatures should be within ±0.4°C of the underlying trend. Therefore, a difference between a pair of 10-m temperatures of ±0.85°C and a difference between a 10-m and a 20-m temperature of ±0.72°C is possible from inter-annual variability alone. For our pair of temperatures from PNE that span 47 years, a measured decadal warming or cooling trend would need to exceed ±0.18°C (decade)$^{-1}$ to be statistically significant. Similarly, from our data at SLE, only a decadal warming or cooling trend that exceeds ±0.14°C (decade)$^{-1}$ would be statistically significant.

5. Conclusions

[24] There is limited information available about the surface temperature history south of the Antarctic Peninsula, but we have shown that borehole thermometry is a practical method for obtaining multi-decadal surface temperature histories. Our results quantify the warming at Rutford Ice Stream as 0.17 ± 0.07°C (decade)$^{-1}$ since 1930. This shows that the rapid warming that has been observed on the Antarctic Peninsula has also occured, more slowly, at Rutford Ice Stream.

[25] 10 or 20-m temperatures can provide average temperatures of the most recent few years and we have presented repeat measurements spanning ~50 years from PNE and SLE. The temperature differences observed at these two sites are both small enough to be caused entirely by inter-annual variability, and we conclude that there has not been any warming trend at these sites large enough to be detected by the data.

[26] We have increased the known geographical extent of recent warming to Rutford Ice Stream, 500 km south of the Antarctic Peninsula. Further borehole thermometry in other locations south of the peninsula and across West Antarctica would allow the geographical distribution and rates of rapid warming to be more completely determined.

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References

Anderson, V. H. (1958), USNC-IGY Antarctic glaciological data: Field work 1957 and 1958, *Rep. 825 Part II*, Ohio State Univ. Res. Found., Columbus.

Bohlander, J., and T. Scambos (2001), Thermap Antarctic '10 Meter' Temperature Data, http://www.nsidc.org/data/thermap/antarctic_10m_temps/, Natl. Snow and Ice Data Cent., Boulder, Colo.

Dahl-Jensen, D., K. Mosegaard, N. Gundestrup, G. D. Clow, S. J. Johnsen, A. W. Hansen, and N. Balling (1998), Past temperatures directly from the Greenland Ice Sheet, *Science*, *282*, 268–271, doi:10.1126/science.282.5387.268.

Doake, C. S. M., R. M. Frolich, D. R. Mantripp, A. M. Smith, and D. G. Vaughan (1987), Glaciological studies on Rutford Ice Stream, Antarctica, *J. Geophys. Res.*, *92*, 8951–8960.

Doake, C. S. M., H. F. J. Corr, A. Jenkins, K. Makinson, K. W. Nicholls, C. Nath, A. M. Smith, and D. G. Vaughan (2001), Rutford Ice Stream, Antarctica, *Antarct. Res. Ser.*, *77*, 221–235.

Engelhardt, H. (2004), Ice temperature and high geothermal flux at Siple Dome, West Antarctica, from borehole measurements, *J. Glaciol.*, *50*, 251–256.

Intergovernmental Panel on Climate Change (2001), *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton et al., 881 pp., Cambridge Univ. Press, Cambridge, U. K.

King, J. C., and J. C. Comiso (2003), The spatial coherence of interannual temperature variations in the Antarctic Peninsula, *Geophys. Res. Lett.*, *30*(2), 1040, doi:10.1029/2002GL015580.

Lachenbruch, A. H., and B. V. Marshall (1986), Changing climate: Geothermal evidence from permafrost in the Alaskan Arctic, *Science*, *234*, 689–696, doi:10.1126/science.234.4777.689.

Lythe, M. B., D. G. Vaughan, and the BEDMAP Consortium (2001), BEDMAP: A new ice thickness and subglacial topographic model of Antarctica, *J. Geophys. Res.*, *106*, 11,335–11,351.

Morris, E. M., and D. G. Vaughan (1994), Snow surface temperatures in West Antarctica, *Antarct. Sci.*, *6*, 529–535.

Murray, T., A. M. Smith, M. A. King, and G. P. Weedon (2007), Ice flow modulated by tides at up to annual periods at Rutford Ice Stream, West Antarctica, *Geophys. Res. Lett.*, *34*, L18503, doi:10.1029/2007GL031207.

Nicholls, K. W., and J. G. Paren (1993), Extending the Antarctic meteorological record using ice-sheet temperature records, *J. Clim.*, *6*, 141–150.

Paterson, W. S. B. (1994), *The Physics of Glaciers*, 3rd ed., Butterworth-Heinemann, Oxford, U. K.

Pollack, H. N., S. Huang, and P. Shen (1998), Climate change record in subsurface temperatures: a global perspective, *Science*, *282*, 279–281, doi:10.1126/science.282.5387.279.

Shuman, C. A., and C. R. Stearns (2001), Decadal-length composite inland West Antarctic temperature records, *J. Clim.*, *14*, 1977–1988.

Shuman, C., and C. R. Stearns (2002), Decadal-Length Composite West Antarctic Air Temperature Records, http://www.nsidc.org/data/nsidc-0097.html, Natl. Snow and Ice Data Cent., Boulder, Colo.

Smith, A. M. (1997), Seismic investigations on Rutford Ice Stream, West Antarctica, Ph.D. thesis, Open Univ., Milton Keynes, UK.

Steig, E. J., D. P. Schneider, S. D. Rutherford, M. E. Mann, J. C. Comiso, and D. T. Shindell (2008), Warming of the Antarctic ice sheet surface since the 1957 International Geophysical Year, *Nature*, in press.

Turner, J., S. R. Colwell, G. J. Marshall, T. A. Lachlan-Cope, A. M. Carleton, P. D. Jones, V. Lagun, P. A. Reid, and S. Iagovkina (2005), Antarctic climate change during the last 50 years, *Int. J. Climatol.*, *25*, 279–294.

van de Wal, R. S. W., R. Mulvaney, E. Isaksson, J. C. Moore, J. F. Pinglot, V. A. Pohjola, and M. P. A. Thomassen (2002), Reconstruction of the historical temperature trend from measurements in a medium-length borehole on the Lomonosovfonna Plateau, Svalbard, *Ann. Glaciol.*, *35*, 371–378.

Vaughan, D. G., G. J. Marshall, W. M. Connolley, C. Parkinson, R. Mulvaney, D. A. Hodgson, J. C. King, C. J. Pudsey, and J. Turner (2003), Recent rapid regional climate warming on the Antarctic Peninsula, *Clim. Change*, *60*, 243–274.

Vaughan, D. G., H. F. J. Corr, A. M. Smith, H. D. Pritchard, and A. Shepherd (2008), Flow-switching and water piracy between Rutford Ice Stream and Carlson Inlet, West Antarctica, *J. Glaciol.*, *54*, 41–48, doi:10.3189/002214308784409125.

B. E. Barrett and T. Murray, School of the Environment and Society, Swansea University, Singleton Park, Swansea SA2 8PP, UK. (b.e.barrett@swansea.ac.uk)

K. W. Nicholls, A. M. Smith, and D. G. Vaughan, British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK.