Investigating snow accumulation variability on the Antarctic Peninsula using Ground Penetrating Radar

- A tool for interpreting ice core records

Elizabeth R. Thomas

June 2008

Scientific Report in support of Loan 824
"Identifying a Southern Annular Mode signal in Antarctic Peninsula accumulation"

British Antarctic Survey
High Cross, Madingley Road
Cambridge
CB3 0ET
lith@bas.ac.uk

Abstract

In this study Ground Penetrating Radar (GPR) has been used to investigate snow accumulation variability in the southwestern Antarctic Peninsula to aid the interpretation of a new ice core record. The GPR revealed homogeneity in the observed isochrones to a depth of 150 meters, encompassing the depth of the ice core (136 meters), over a 20 km radius from the central drill site. The GPR records have been used to validate accumulation records that reveal a doubling in snowfall in the southwestern Peninsula since 1850 allowing us to infer that this is a true climate signature and not a result of topography changes or flow.

Background

The British Antarctic Survey (BAS) core-funded Antarctic Climate ChangE and Non-linear Teleconnections (ACCENT) project aims to investigate the primary atmospheric and oceanic links between Antarctic climate and the rest of the Global Earth System. Some of the changes in Antarctic climate have been very marked: over the last 50 years the Antarctic Peninsula has experienced greater warming in near surface temperatures than anywhere else on Earth [*Vaughan et al.*, 2003]. A component of this warming has been linked to a recent positive trend in the Southern Annular Mode (SAM), also called the Antarctic Oscillation. The SAM is the principal mode of atmospheric circulation variability in the Southern Hemisphere: essentially it comprises a ring-like or annular structure with synchronous pressure anomalies of opposite sign in mid- and high southern latitudes. Variability in the SAM has had a significant impact on Antarctic near-surface temperatures [*Thompson & Solomon*, 2002; *Kwok & Comiso*, 2002]. In the more recent period pressures have been lower over Antarctica and higher in the Southern Hemisphere extra-tropics (a positive SAM). This has resulted in stronger westerly winds across the northern Peninsula during summer, reducing the blocking effect of the Peninsula barrier and allowing greater eastward advection of warmer air masses over it. Thus the increasing SAM has led to rapid regional summer warming on the east coast of the northern Peninsula and the resultant collapse of the Larsen Ice Shelf [*Marshall et al.*, 2006]. In contrast, in East Antarctica the positive trends in the SAM have led to a reduction in temperatures [*Thompson & Solomon*, 2002].

Ice cores are the principle data-source for historical Antarctic climate beyond the last 50 years, the period of instrumental record. Preliminary studies, utilising ~20 years of climatologically reanalysis data, suggest that accumulation variability from the south-western Antarctic Peninsula may contain a strong signal of the SAM, as also observed in ice core chemistry variability in East Antarctica [*Goodwin et al.*, 2004]. As part of the ACCENT project a medium depth ice core was drilled in this region to set the observed regional circulation changes in a longer temporal framework.

Survey Procedure

In January 2007 a 136-meter ice core was drilled at a site called Gomez (~73.6°S, ~70.4°W) in the southwest Antarctic Peninsula (Fig.1) using an electromechanical, 104 mm diameter drill.

The Pulse Ekko 100 system has been found to work well for the continuous trace of internal reflecting horizons in Antarctic firn to a depth of 100 m. Traditionally ice core sites are chosen on the top of an ice divide where flow is essentially zero, however this core site was selected for its predicted sensitivity to changes in regional atmospheric circulation and the SAM [*van den Broeke and van Lipzig*, 2004] and will have to be corrected for ice thinning and flow. In addition, previous studies [e.g. *King et al.*, 2004] have demonstrated that small-scale changes in topography can lead to significant changes in accumulation via an effect on near-surface winds and resultant net snow transport. Therefore, the Pulse Ekko 100 was used to enhance interpretation of the new ice core by investigating the accumulation variability and possible influence of flow and topographic changes.

It was originally proposed that we run two 30 km transects, both originating at the drill site. The first was to extend northwest toward the English Coast and the second to the southeast toward the highest point in the region. However, 20 km was the limit of travel that could safely be achieved in one day (with only a half travel unit) and thus it was decided that a better spatial coverage of accumulation could be achieved by running additional transects over a shorter distance (Fig. 1).

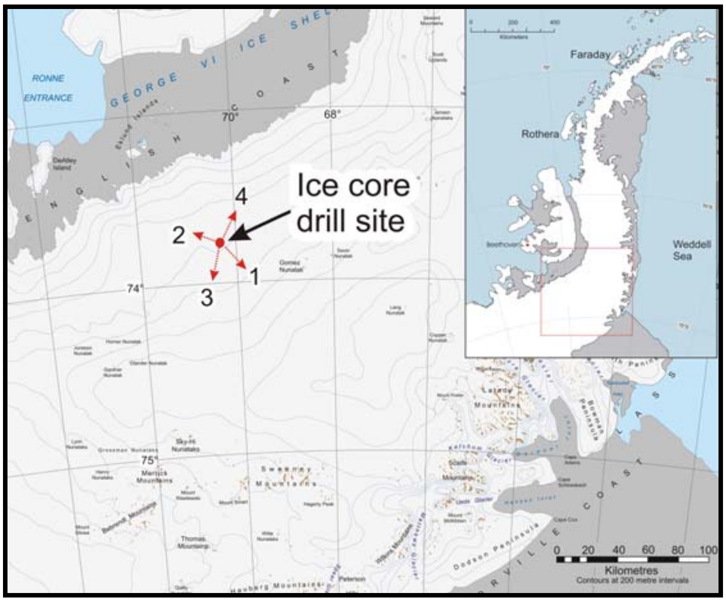

Figure 1. Location of the ice core site, near Gomez Nunatak on the southwestern Peninsula. GPR transects (20 km) are shown as red arrows originating from the drill site. Shorter (2 km) transects were run long the same routes.

In January 2007 a total of three transects of 20 km length (labelled 1,3 and 4, Fig 1), one transect of 15 km length ((2 in Fig. 1) stopped short due to skidoo failure) and four transects of 2 km length were run from the central drill site. The equipment was transported using linked skidoos, with the antenna transducer unit fixed to a small sled in tow using an approximate traverse speed of 10 km/hr. A safe traverse was established using linked skidoo to the furthest point on the traverse and the radar line run on the return route to the drill site. We used precise global positioning system (GPS) data every 5 km to locate our position and elevation.

The 20 km transects (and the 15 km transect) were recorded using the 100 MHz antenna with the aim of recovering horizons to a depth of over 200 meters to encompass the total length of the ice core. The 2 km transects were retrieved using the 200 MHz antenna to give a higher resolution record to concentrate on the upper section of the ice core.

GPR transect number	Lat	Long	MHZ	Transect Distance	Direction from drill site
1	74:07,13.5'S	70:09,43.5'W	100	20	SE
2	73:57,51.1'S	71:04,47.2'W	100	15	NE
3	74:10,22.1'S	70:36,20.8'W	100	20	SW
4	73:49,07.5'S	70:28,34.0'W	100	20	NE
5	73:58,40.6'S	70:38,47.0'W	200	2	NW
6	73:59,27.0'S	70:32,21.7'W	200	2	NE
7	74:00,34.8'S	70:36,56.7'W	200	2	SE
8	73:59,53.5'S	70:40,08.6'W	200	2	SW

Table 1. Location and distance of GPR transects.

Interpretation

Processing of the GPR data from the Gomez site was carried out using Reflex W software for windows. Two-dimensional analysis has been carried out to filter the data and obtain a visual representation of accumulation variability and isochrones disturbances.

The ice core has been analysed using trace element analysis to determine annual layers in non-sea salt sulphate and hydrogen peroxide for dating purposes. The temporal length of the core is 152 years, encompassing 1855-2006 and the estimated uncertainty in the dating is ±1 year from 1855 to 1875 and <<1 year from 1875 to 2006. This dating allows us to put a calendar date to the observed layers in the GPR record.

Results

The GPR transects reveal continuous reflections, which are generally accepted to result from layers of isochronous deposition of snow and can reveal much about the dynamics of the ice sheet [*Vaughan et al.*, 1999]. There are several internal horizons clearly visible in the uppermost 100 m, which are thought to result from density variations related to depositional processes [*Paren and Robin*, 1975]. The homogeneous nature of the isochrones (Fig. 2 and Fig. 3) reveal that very little accumulation variability exists at this site and therefore we can conclude that topographic disturbances will not affect the accumulation record.

In order to assess the potential merits of using the snow accumulation record from the Gomez ice core as a proxy for the SAM the degree of thinning, as a result of ice flow from the ice divide, must be corrected for. GPS measurements, taken in January 2005 and repeated again in January 2007, reveal that the ice is flowing west from the ice divide at a rate of approximately 60 m yr^{-1}. In order to assess the extent of thinning as a result of flow at the ice core drill site, we investigated the layer compression in GPR transects 1 and 7 (20 km and 2 km southeast of the ice core drill site).

Strong horizons in the GPR records were selected using the layer pick mode in reflex W to extract the depths and distances. The thinning between layers was determined by calculating the distance between layers at the start of the GPR transect (20 km from the drill site) and at the end of the GPR transect (the location of the ice core drill site). The thinning was converted into an estimated horizontal strain rate based on the age of the layers (determined from the ice core) and the velocity of the ice (60 m y^{-1}).

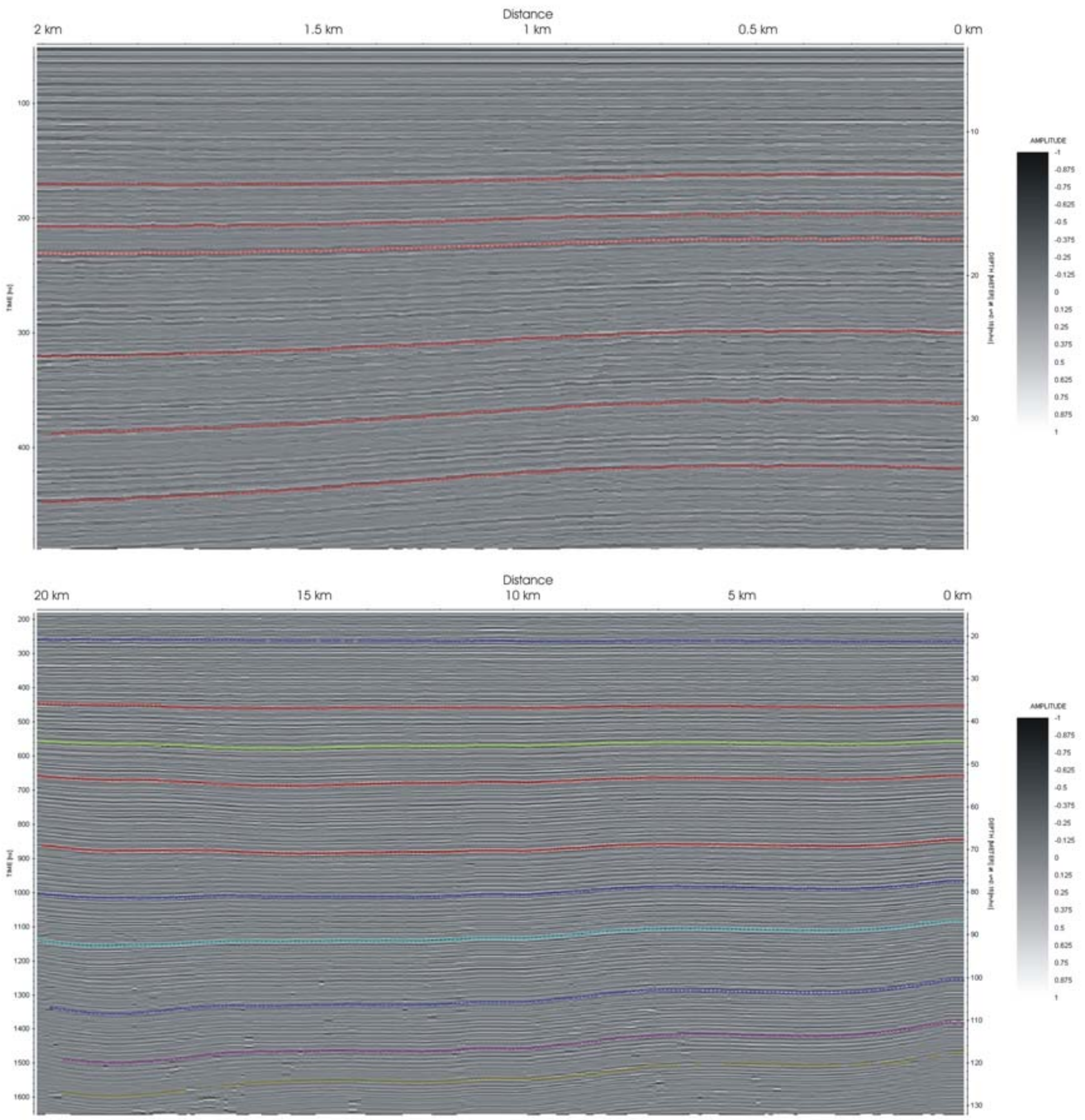

Figure 2. Radar layers from GPR transect 7 (top) and GPR transect 1 (bottom). The ice core drill site is located at distance 0 km. Layer pick data shown were used to calculate the accumulation variability and amount of layer thinning.

The average horizontal stain rate determined from the two GPR transects southwest of the drill site (transects 1 and 7) is 0.0014 m yr^{-1}. The same method was applied to the GPR transects that were perpendicular to the direction of flow, northeast to southwest of the ice core drill site (Fig. 3), to show a considerably smaller horizontal strain rate of just 0.00009 m yr^{-1}.

Layer age	Layer Depth	Thinning between picked layers	Horizontal strain rate
Calculated from GPR transect 7 (2 km)			
2001	12.992	0.1722	0.001783
1999.39	15.7638	0.1605	0.002876
1998.46	17.472	0	0
1993.7	24	0.576	0.002667
1990.1	28.928	0.384	0.001866
1986.67	33.536	0.2365	0.0000198
Calculated from GPR transect 1 (20 km)			
1976.211	44.16	0.9101	0.001937
1968.378	52.32	0.28	0.000349
1955.016	66.24	3	0.005028
1945.072	76.6	0.736	0.001293
1935.588	86.48	0.44	0.000575
1922.84	99.76	0.28	0.000479
1913.088	109.92	0.387	0.000771
1904.717	118.64	0.031	0.000027
		Average	0.001405

Table 2. Horizontal strain rate calculated from picked layers from GPR transect 1 and 7. The layer depth is the depth of the layer at the drill site. The layer age is determined from the annual layer counting from the Gomez ice core.

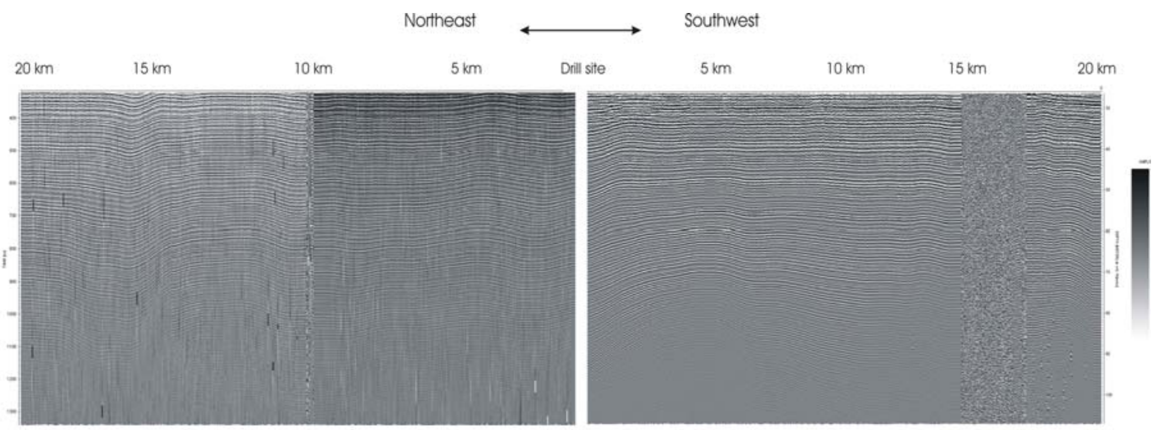

Figure 3. GPR transects 4 (right) and 3 (left) combined to show 40 km continuous horizons northwest and southeast of the ice core drill site. Missing data between 15 km and 17 km (right) due to battery failure.

The estimated horizontal strain rate has been applied to the snow accumulation record from the ice core (Fig. 4); calculated using the annual layers of non-sea salt sulphate and hydrogen peroxide and converted to meters of water equivalent based on density. The standard method of estimating thinning in ice cores that are less than 10% of the ice sheet thickness (as is the case for Gomez) is the Nye model, that assumes a linear vertical strain rate through the total depth of the core [*Nye*, 1963]. This method has also been applied to the ice core accumulation record (black curve in Fig. 4) to show a very similar degree of thinning, adding confidence to this method of GPR derived thinning.

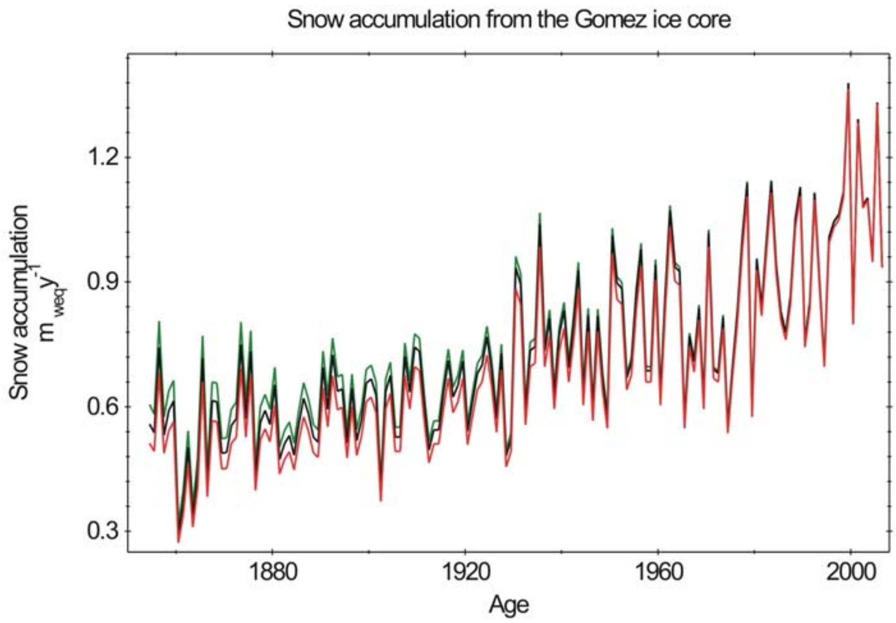

Figure 4. Snow accumulation record at Gomez between 1855 and 2006. The record with no thinning applied (red), Nye thinning applied (black) and thinning estimate from GPR layers (green).

Conclusions

Mass balance observations from high-accumulation coastal regions in Antarctica and rare and even more so if they provide a time series of accumulation to study temporal variability. The new ice core is an important contribution to both mass balance modelling and regional climate history. The GPR data has been an invaluable tool in the interpretation of this new and important ice core and has been used to validate the climate record by revealing only a small degree of accumulation variability and estimated thinning over the total length of the ice core record and allowed us to infer that topography has had very little effect on the accumulation at this site. This has enabled us to confidently report that snow accumulation in this region has more than doubled since the 1850s, which is significantly correlated to changes in the Southern Annular Mode (SAM) and has been accelerating since the 1970's [*Thomas et al.*, 2008].

These are just the initial findings and it is hoped that further proxies for regional circulation and the SAM will be found in the chemistry and the isotope records of the ice core. Therefore the spatial variability obtained by the GPR transects will also be used to validate these additional study results.

Publications from this work

Elizabeth R. Thomas, Gareth J. Marshall, Joseph R. McConnell, (2008), A doubling in accumulation in the western Antarctic Peninsula since 1850, *Geophysical Research Letters, 35*, L01706, doi:10.1029/2007GL032529

References

Goodwin, I. D., T. D. Van Ommen, M. A. J. Curran and P. A. Mayewski, (2004), Mid latitude winter climate variability in the South Indian and southwest Pacific regions since 1300 AD, *Climate Dynamics, 22*, 783-794

King, J. C., P. S. Anderson, D. G. Vaughan, G. W. Mann, S. D. Mobbs, and S. B. Vosper, (2004), Wind-borne redistribution of snow across an Antarctic ice rise, *Journal of Geophysical Research, 109*, doi:10.1029/2003JD004361

Kwok, R., Comiso, J., (2002), Spatial patterns of variability in Antarcti surface temperatures: Connections to the Southern Hemisphere Annular Mode and the Southern Oscillation, *Geophysical Research Letters, 29*, 1705

Marshall, G. J., Orr, A., van Lipzig, N.P.M., King, J.C, (2006), The impact of a changing Southern Hemisphere Annular Mode on Antarctic Peninsula summer temperatures, *Journal of Climate, 19*, 5388–5404

Nye, J. F., (1963), Correction factor for accumulation measured by the thickness of the annual layers in an ice sheet, *Journal of Glaciology, 4*, 785-788

Paren, J. G., and Robin, G, (1975), Internal reflections in polar ice sheets, *Journal of Glaciology, 14*, 251-259

Thompson, D. W. J. S., S., (2002), Interpretation of recent southern hemisphere climate change, *Science, 29*, 895-899

van den Broeke, M., R., and van Lipzig, N.P.M., (2004), Changes in Antarctic temperature, wind and precipitation in response to the Antarctic Oscillation, *Annals of Glaciology, 39*, 119–126

van den Broeke, M. R., van de Berg, W.J., van Meijgaard. E, (2006), Snowfall in coastal West Antarctica much greater than previously assumed, *Geophysical Research Letters, 33*, doi:10.1029/2005GL025239

Vaughan, D. G., Corr, H. F. J., Doake, C. S. M. & Waddington, E. D., (1999), Distortion of isochronous layers in ice revealed by ground-penetrating radar, *Nature, 398*, 323-326

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