GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L01706, doi:10.1029/2007GL032529, 2008

Click Here for Full Article

A doubling in snow accumulation in the western Antarctic Peninsula since 1850

Elizabeth R. Thomas,[1] Gareth J. Marshall,[1] and Joseph R. McConnell[2]

Received 31 October 2007; revised 20 November 2007; accepted 6 December 2007; published 12 January 2008.

[1] We present results from a new medium depth (136 metres) ice core drilled in a high accumulation site (73.59°S, 70.36°W) on the south-western Antarctic Peninsula during 2007. The Gomez record reveals a doubling of accumulation since the 1850s, from a decadal average of 0.49 m_{weq} y^{-1} in 1855–1864 to 1.10 m_{weq} y^{-1} in 1997–2006, with acceleration in recent decades. Comparison with published accumulation records indicates that this rapid increase is the largest observed across the region. Evaluation of the relationships between Gomez accumulation and the primary modes of atmospheric circulation variability reveals a strong, temporally stable and positive relationship with the Southern Annular Mode (SAM). Furthermore, the SAM is demonstrated to be a primary factor in governing decadal variability of accumulation at the core site (r = 0.66). The association between Gomez accumulation and ENSO is complex: while sometimes statistically significant, the relationship is not temporally stable. Thus, at decadal scales we can utilise the Gomez accumulation as a suitable proxy for SAM variability but not for ENSO. **Citation:** Thomas, E. R., G. J. Marshall, and J. R. McConnell (2008), A doubling in snow accumulation in the western Antarctic Peninsula since 1850, *Geophys. Res. Lett.*, *35*, L01706, doi:10.1029/2007GL032529.

1. Introduction

[2] The Antarctic Peninsula region has experienced dramatic changes in climate over the past 50-years, the period of observational record: annual temperatures have increased faster than elsewhere in the Southern Hemisphere and many ice shelves fringing the Peninsula have disintegrated [e.g., *Vaughan et al.*, 2003]. Contemporaneous changes in the regional atmospheric circulation have also been observed: in particular the Southern Annular Mode (SAM) has become more positive during austral summer and autumn [*Thompson and Solomon*, 2002; *Marshall*, 2003]. The resultant increasing westerlies are believed to be primarily responsible for enhanced summer warming in the north-east Peninsula [*Marshall et al.*, 2006] and resultant surface melt on the northern sections of the Larsen Ice Shelf [*van den Broeke*, 2005], which in turn played a key role in their subsequent collapse [e.g., *Scambos et al.*, 2000].

[3] Antarctic precipitation is a difficult parameter to measure directly, primarily because of problems with blowing snow. A recent synthesis of available data suggests no significant change in snowfall across the continent as a whole since the 1950s [*Monaghan et al.*, 2006]. However, proxy indicators do suggest an increase in the Peninsula. *Turner et al.* [2005] reported that the number of days with precipitation — based on synoptic observations of 'present weather' — at Faraday station, in the north-western Peninsula, increased at a rate of 12.4 days dec^{-1} between 1950–99. In addition, model data reveal an upward trend in regional precipitation for the period 1980–2004 [*van den Broeke et al.*, 2006] while satellite altimeter data indicate an increase in elevation in the western Peninsula for 1992–2003, thought to be due to greater snowfall [*Davis et al.*, 2005; *Wingham et al.*, 2006]. A recent Empirical Orthogonal Function (EOF) analysis of gridded Peninsula accumulation data from model forecasts [*Miles et al.*, 2008] revealed that the predominant trend for the 1979–2001 period is in the second EOF in autumn: this is highly correlated with the SAM, and the trend has resulted in more (less) accumulation in the central and southern (north-eastern) regions of the Peninsula.

[4] The records mentioned previously rarely exceed 50 years in length. However, longer time-scale precipitation data obtained from snow accumulation in ice cores can be employed to set the recent upward trend in a longer temporal framework. In this paper we present a 150-year record of annual net accumulation from a new ice core obtained from the western Antarctic Peninsula. We examine the trends and variability in accumulation at this location and compare it with that at other ice core sites in the region. Peninsula precipitation is predominantly associated with synoptic-scale cyclonic activity [e.g., *Turner et al.*, 1995] so we also relate the accumulation record to the primary modes of regional atmospheric circulation variability.

2. Data

[5] The new accumulation record is derived from a medium depth ice core drilled at a high accumulation site (Gomez) on the south-western Antarctic Peninsula (73.59°S, 70.36°W, 1400 m a.s.l.). The core was drilled in January 2007 using an electromechanical, 104 mm diameter drill to a depth of 136 m. Although the drill-site is not situated on an ice divide, ground penetrating radar data from a 20 km radius shows very little accumulation variability across the region to the depth of the core: therefore, we assume that the accumulation change is not an artefact of topographic changes. The lengths of ice core were cut to 550 mm and packed in the field into polythene layflat tubing (to avoid contamination) and insulated boxes for transport to the UK. Subsequently, continuous longitudinal samples with a cross section of 34 × 34 mm were cut and transported to the Desert Research Institute, for trace element analysis. The samples were analysed at very high resolution (~10 mm, average 90 samples per year) using the

[1]British Antarctic Survey, Cambridge, UK.
[2]Desert Research Institute, Reno, Nevada, USA.

0094-8276/08/2007GL032529$05.00

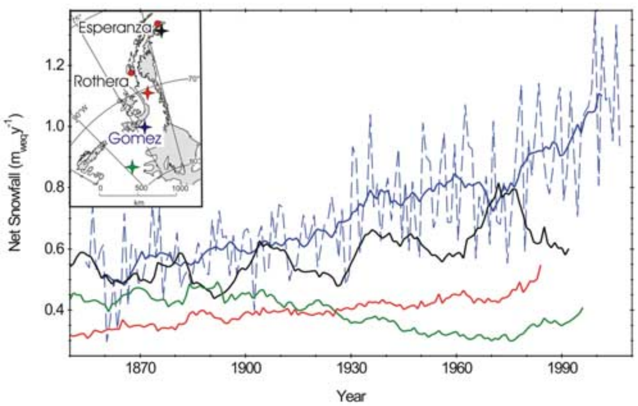

Figure 1. Annual accumulation at Gomez (dashed blue) and running decadal mean accumulation at Gomez (solid blue), Dyer Plateau (red), James Ross Island (black) and ITASE01_05 (green) in meters of water equivalent per year (m_{weq} y^{-1}) between 1850 and 2006. Inset map shows locations of core sites and stations referred to in the text.

Continuous Flow Analysis with Trace Elements-Dual (CFA-TED) method adapted from *McConnell et al.* [2002, 2007] for a broad range of elements and chemical species.

[6] Clear annual cycles in concentration are observed in nearly all the elements and chemical species analysed. The annual accumulation record was derived using two methods: a winter-winter value determined from the minima of hydrogen peroxide (H_2O_2) and a summer-summer value based on maxima in non-sea salt sulphate (nssS). While the annual cycles in H_2O_2 and nssS concentration are very similar, the timing of the summer maximum in nssS is likely more consistent from year to year. Data from the European Centre for Medium Range Weather Forecasts (ECMWF) 40-year reanalysis (ERA-40) [*Uppala et al.*, 2005] indicate a summer minimum in accumulation in this region: thus, there is less chance of incorrectly assigning accumulation to the wrong year than if winter-winter data were used. Annual thicknesses are converted to water equivalents based on the ice core density and corrected for ice thinning using a simple Nye model that assumes a linear vertical strain rate through the total depth of the core [*Nye*, 1963]. 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 $\ll$1 year from 1875 to 2006.

3. Results and Discussion

[7] The annual accumulation at Gomez is plotted in Figure 1 as meters of water equivalent accumulation per year (m_{weq} y^{-1}). For the entire record the mean annual accumulation is 0.72 m_{weq} y^{-1} with a standard deviation of 0.20 m_{weq} y^{-1}, indicating considerable variability in the regional climate (cf. the quasi-cyclic inter-annual accumulation variability in Figure 1). Annual accumulation has more than doubled in the last 150 years: the mean for 1855–1864 was 0.49 m_{weq} y^{-1} while for 1997–2006 it was 1.10 m_{weq} y^{-1}. At the beginning of the record annual accumulation is relatively stable until about 1930 when it begins to increase steadily. Following a slight reduction in accumulation in the late 1960s, the most rapid increase occurs in the latter part of the record with the mean accumulation rate from the mid-1970s onwards increasing to 0.95 m_{weq} y^{-1}. Note that for the post-1980 period even the lowest annual accumulation values are still greater than the highest accumulation values from the first half of the record (1855–1924). Analysis of temporal changes in the standard deviation of annual accumulation reveals that the inter-annual variability jumped markedly at about 1930 and has generally kept increasing since.

[8] In Figure 1 the Gomez record is compared with other ice core accumulation records in the region: James Ross Island, in the north-east of the Antarctic Peninsula (64.2°S, 57°W, 1600 m a.s.l) drilled in 1998 [*Aristarain et al.*, 2004; *Miles et al.*, 2008]; Dyer Plateau, on the spine of the Peninsula (77.80°S, 64.52°W, 2002 m a.s.l.) obtained in 1988 [*Thompson et al.*, 1994]; and ITASE01_5, drilled in West Antarctica, south-west of the base of the Peninsula (77.06°S, 89.13°W, 1246 m a.s.l) in 2001 [*Miles et al.*, 2008].

[9] The doubling of accumulation in the last 150 years appears to be unique to the Gomez site. However, there is also a similar general increase, albeit at a much smaller rate, in accumulation at Dyer Plateau. Using de-trended data there is no correlation between annual accumulation at the two locations, located some 400 km apart, but at decadal time-scales $r = 0.34$ ($p < 0.01$). Thus it seems likely that accumulation at Dyer Plateau has continued to increase in the period following the drilling there. The James Ross Island record also demonstrates an overall accumulation increase during the period 1850–1999 but exhibits marked decadal variation not observed in the other records. At the ITASE01_05 site accumulation has apparently decreased over the last 150 years. However, it is worth noting that the surface topography surrounding the site may have impacted this accumulation record [*Kaspari et al.*, 2004]. Thus it seems that there has been a steady increase in accumulation in the central-southern ice core sites relative to sites both to the north and south-west, as also indicated by the analysis of *Miles et al.* [2008]. High resolution regional climate model data indicate that during 1980–1993 the very strong increase in annual accumulation observed in the ice core is limited to the Gomez region itself and the Peninsula immediately south of it (N. van Lipzig, personal communication, 2007).

[10] To help understand the changes in climate responsible for the increase in accumulation at Gomez we correlated the annual summer-summer accumulation for 1958–2006 with 500 hPa geopotential height data obtained from ERA-40 for 1958–2001 supplemented by ECMWF operational model data to 2006 (Figure 2). The 500 hPa level was chosen for analysis as it is the lowest standard level above the Antarctic continent and thus will not be affected by spurious trends caused by changes in Antarctic orography between ERA-40 and the ECMWF operational model. The monthly 500 hPa data were weighted according to the annual cycle of precipitation at the Gomez site, as determined from the most recent ECMWF data. Note that all statistics are computed from de-trended data. The ERA-40 model is known to be more reliable at high southern latitudes after 1979, when satellite sounder data were assimilated regularly [*Marshall*, 2003; *Bromwich and Fogt*, 2004]: however, a near facsimile of the spatial pattern of correlations shown in Figure 2 is obtained for the 1979–2006 period — correlations are higher but the regions of

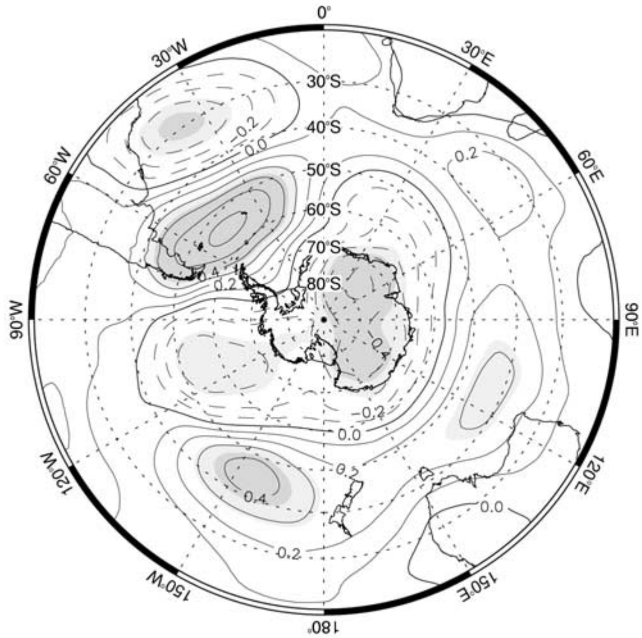

Figure 2. Correlation between annual summer-summer accumulation from the Gomez core and 500-hPa geopotential height derived from ECMWF data for 1958–2006. The 500-hPa data have been weighted according to the annual cycle of accumulation at Gomez from recent ECMWF data. Negative contours (0.1 interval) are dashed. Regions where correlations are significant at <5% level and <1% level are shaded light and dark grey, respectively. Both datasets were de-trended before calculating the correlation coefficient and autocorrelation was accounted for when computing the significance.

statistical significance are similar — and therefore we can be confident that the pattern is temporally stable for at least the past 50 years. Given that the correlations in Figure 2 have a maximum magnitude of ~0.6 — explaining approximately one third of the total variance in annual accumulation at the Gomez site — it seems likely that we can attribute much of the inter-annual variability seen in Figure 1 to natural internal regional climate variability.

[11] Nevertheless, there are two principal spatial patterns in Figure 2 that can be related to known modes of atmospheric circulation variability. The first comprises the strong negative correlations over the Antarctic continent (minimum < −0.56), particularly East Antarctica, together with the ring of positive correlations to the north, with the exception of the south-east Pacific. This spatial pattern is very reminiscent of the pressure anomalies associated with a positive phase of the SAM. Using an observation-based annual SAM index available from 1957 onwards [*Marshall*, 2003], the correlation between it and the Gomez accumulation record is 0.41 (significant at <1% level). The regression coefficient reveals that an increase of one in the SAM index is associated with an accumulation increase of 0.05 m_{weq} y^{-1}. Using this value and computed linear trends in the SAM and Gomez accumulation, we estimate that 28% of the 0.46 m_{weq} y^{-1} increase in the latter during 1957–2006 is due to the contemporaneous positive trend in the annual SAM.

[12] Moreover, using decadal running means the correlation coefficient increases to 0.66, indicating that SAM variability is a primary factor driving Gomez accumulation at decadal timescales, consistent with model results that indicate a positive precipitation coupling to SAM in this region [*van den Broeke and van Lipzig*, 2004] *Marshall et al.* [2006] showed that temperatures in the north-east Peninsula are more strongly dependent on the SAM than those on the western side. Thus, the much stronger relationship between Gomez accumulation and temperatures at Esperanza in the north-east (see Figure 1), 1300 km from Gomez ($r = 0.76$, $p < 0.01$, period = 1951–2006) compared to that at Rothera in the central west Peninsula, 700 km from the core site ($r = 0.42$, $p < 0.05$, period = 1978–2006) is also indicative of a strong SAM signal contained within the annual accumulation variability at Gomez.

[13] The second primary spatial pattern seen in Figure 2 is a wave-train of four alternate regions of positive and negative correlation across the South Pacific and into the South Atlantic, each of which is statistically significant at <5% level. The couplet of low and high pressure anomalies centred at 60°S, 115°W and 54°S, 45°W, respectively, will result in strong northerlies that will advect warm maritime air from the South Pacific towards the Gomez region, where the steep coastal topography will cool it as it is forced to rise and lead to orographic precipitation. The wave-train in Figure 2 is similar to the Pacific-South American (PSA) teleconnection pattern through which the El Niño-Southern Oscillation (ENSO) signal propagates into high southern latitudes [e.g., *Mo and Higgins*, 1998]. Indeed, accumulation variability in parts of West Antarctica is known to be influenced significantly by ENSO [e.g., *Cullather et al.*, 1996; *Genthon et al.*, 2005].

[14] We investigated the relationship between Gomez accumulation and ENSO variability by utilising the Southern Oscillation Index (SOI), a commonly employed measure of the strength and phase of ENSO. Monthly SOI data from 1866–2005 were acquired from the Climatic Research Unit, University of East Anglia [*Ropelewski and Jones*, 1987] and annual values created as the mean of 12 monthly values. The pattern of the correlation in Figure 2 is such that it resembles the height anomalies associated with the La Niña phase of ENSO [cf. *Turner*, 2004, Figure 3b], and therefore we would expect a positive relationship between Gomez accumulation and the SOI. However, there is no significant relationship over the entire 1866–2005 period ($r = 0.08$) or for the recent period on which Figure 2 is based ($r = 0.10$). Investigation of temporal changes in the relationship between Gomez accumulation and the SOI using correlations based on running 21-year periods reveals that there are four short periods when it is statistically significant at <10% level. Nonetheless, there are periods when the relationship is reversed, particularly in the 1970s. An equivalent plot (not shown) to Figure 2 for the 21-year period when the correlation is most negative (1963–83) reveals that the wave-train has disappeared, with only one of the four centres seen in Figure 2 still existent. Thus, there is no consistent ENSO signal in the Gomez accumulation — as also shown for accumulation in West Antarctica [*Frey et al.*, 2006] — highlighting the need for caution in interpreting circulation patterns from short data sets.

[15] The marked temporal variability in the Gomez accumulation-ENSO relationship can be related to the findings of *Lachlan-Cope and Connolley* [2006]; they used GCM experiments to demonstrate that natural variability in the region encompassed by the PSA wave-train can cause the high-latitude response to tropical changes with apparently similar forcings to vary markedly. Finally, we note that the change from a negative to positive relationship between Gomez accumulation and the SOI is centred on ~1985, slightly earlier than when the sign of the relationship between ENSO and accumulation in Marie Byrd Land, West Antarctica abruptly reversed in 1990 [*Cullather et al.*, 1996]. *Fogt and Bromwich* [2006] suggested that this shift was due to a change from an out-of-phase relationship between ENSO and the SAM during the austral spring in the 1980s to an in-phase relationship in the 1990s.

4. Conclusions

[16] The new ice core record from the Gomez site has revealed a doubling of accumulation on the southwestern Antarctic Peninsula since the 1850s. Inter-annual variability in accumulation has also increased markedly. Comparison with published regional accumulation records reveal that this rapid increase is the largest recorded, and that the central and southern Peninsula has experienced a greater accumulation rise than areas to the north and south-west.

[17] A strong, temporally stable relationship between Gomez accumulation and the SAM is shown to exist. Recent trends in the SAM are estimated to be responsible for more than a quarter of the ~0.5 m_{weq} y^{-1} accumulation increase at Gomez over the past 50 years. SAM variability is revealed as the principal factor governing decadal variability of accumulation at the ice core site. The association between Gomez accumulation and ENSO is more complex: although there are short periods when a statistically significant relationship exists, overall the correlation varies considerably in magnitude and even sign. Such changes have also been observed in West Antarctica [*Cullather et al.*, 1996; *Frey et al.*, 2006] and this study further emphasises the need for caution when attempting to use Antarctic accumulation from the South Pacific sector as a simple proxy for ENSO variability.

[18] These initial studies reveal that the Gomez site is sensitive to hemispheric-scale circulation patterns. Future work will include a comparison of Gomez accumulation against statistical reconstructions of the SAM that are of similar temporal length to the ice core [e.g., *Jones and Widmann*, 2003] Furthermore, it is expected that investigation into additional parameters and analysis of intra-annual variability will reveal additional useful proxies in the new Gomez ice core.

[19] **Acknowledgments.** We would like to thank those who helped in the field (P. Waite-Shores) and with the ice core analysis at the Desert Research Institute laboratories (R. Banta, R. Edwards and D. Pasteris), R. Mulvaney for providing data, and two anonymous reviewers for their comments. This work was funded by the UK Natural Environment Research Council and the U.S. National Science Foundation (NSF) through grants OPP-0538427 and OPP-9904294.

References

Aristarain, A. J., R. J. Delmas, and M. Stievenard (2004), Ice-core study of the link between sea-salt aerosol, sea-ice cover and climate in the Antarctic Peninsula area, *Clim. Change*, *67*, 63–86.

Bromwich, D. H., and R. L. Fogt (2004), Strong trends in the skill of the ERA-40 and NCEP-NCAR reanalyses in the high and midlatitudes of the Southern Hemisphere, 1958–2001, *J. Clim.*, *17*, 4603–4619.

Cullather, R. I., D. H. Bromwich, and M. L. van Woert (1996), Interannual variations in Antarctic precipitation related to El Niño–Southern Oscillation, *J. Geophys. Res.*, *101*, 19,109–19,118.

Davis, C. H., Y. Li, J. R. McConnell, M. M. Frey, and E. Hanna (2005), Snowfall-driven growth in East Antarctic Ice Sheet mitigates recent sea-level rise, *Science*, *308*, 1898–1901.

Fogt, R. L., and D. H. Bromwich (2006), Decadal variability of the ENSO teleconnection to the high-latitude South Pacific governed by coupling with the Southern Annular Mode, *J. Clim.*, *19*, 979–997.

Frey, M. M., R. C. Bales, and J. R. McConnell (2006), Climate sensitivity of the century-scale hydrogen peroxide (H_2O_2) record preserved in 23 ice cores from West Antarctica, *J. Geophys. Res.*, *111*, D21301, doi:10.1029/2005JD006816.

Genthon, C., S. Kaspari, and P. A. Mayewski (2005), Interannual variability of the surface mass balance of West Antarctica from ITASE cores and ERA40 reanalyses, 1958–2000, *Clim. Dyn.*, *24*, 759–770.

Jones, J. M., and M. Widmann (2003), Instrument- and tree-ring-based estimates of the Antarctic Oscillation, *J. Clim.*, *16*, 3511–3524.

Kaspari, S., P. A. Mayewski, D. A. Dixon, V. B. Spikes, S. B. Sneed, M. J. Handley, and G. S. Hamilton (2004), Climate variability in West Antarctica derived from annual accumulation-rate records from ITASE firn/ice cores, *Ann. Glaciol.*, *39*, 585–594.

Lachlan-Cope, T., and W. Connolley (2006), Teleconnections between the tropical Pacific and the Amundsen-Bellingshausen Sea: Role of the El Niño/Southern Oscillation, *J. Geophys. Res.*, *111*, D23101, doi:10.1029/2005JD006386.

Marshall, G. J. (2003), Trends in the Southern Annular Mode from observations and reanalyses, *J. Clim.*, *16*, 4134–4143.

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

McConnell, J. R., G. W. Lamorey, S. W. Lambert, and K. C. Taylor (2002), Continuous ice-core chemical analyses using inductively coupled plasma mass spectrometry, *Environ. Sci. Technol.*, *36*, 7–11.

McConnell, J. R., A. J. Aristarain, J. R. Banta, P. R. Edwards, and J. C. Simões (2007), 20th Century doubling in dust archived in an Antarctic Peninsula ice core parallels climate change and desertification in South America, *Proc. Natl. Acad. Sci. U. S. A.*, *104*, 5732–5748.

Miles, G. M., G. J. Marshall, J. R. McConnell, and A. J. Aristarain (2008), Recent accumulation variability and change on the Antarctic Peninsula from the ERA-40 reanalysis, *Int. J. Clim*, in press.

Mo, K. C., and R. W. Higgins (1998), The Pacific–South American Modes and tropical convection during the Southern Hemisphere winter, *Mon. Weather Rev.*, *126*, 1581–1596.

Monaghan, A. J., et al. (2006), Insignificant change in Antarctic snowfall since the International Geophysical Year, *Science*, *313*, 827–831.

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

Ropelewski, C. F., and P. D. Jones (1987), An extension of the Tahiti-Darwin Southern Oscillation index, *Mon. Weather Rev.*, *115*, 2161–2165.

Scambos, T. A., C. Hulbe, M. Fahnestock, and J. Bohlander (2000), The link between climate warming and break-up of ice shelves in the Antarctic Peninsula, *J. Glaciol.*, *46*, 516–530.

Thompson, D. W. J., and S. Solomon (2002), Interpretation of recent Southern Hemisphere climate change, *Science*, *296*, 895–899.

Thompson, L. G., D. A. Peel, E. Mosley-Thompson, R. Mulvaney, J. Dai, P. N. Lin, M. E. Davis, and C. F. Raymond (1994), Climate change since AD 1510 on Dyer Plateau, Antarctic Peninsula: Evidence for recent climate change, *Ann. Glaciol.*, *20*, 420–426.

Turner, J. (2004), The El Niño–Southern Oscillation and Antarctica, *Int. J. Climatol.*, *24*, 1–31.

Turner, J., T. A. Lachlan-Cope, J. P. Thomas, and S. R. Colwell (1995), The synoptic origins of precipitation over the Antarctic Peninsula, *Antarct. Sci.*, *7*, 327–337.

Turner, J., T. Lachlan-Cope, S. Colwell, and G. J. Marshall (2005), A positive trend in western Antarctic Peninsula precipitation over the last 50 years reflecting regional and Antarctic-wide atmospheric circulation changes, *Ann. Glaciol.*, *41*, 85–91.

Uppala, S. M., et al. (2005), The ERA-40 re-analysis, *Q. J. R. Meteorol. Soc.*, *131*, 2961–3012.

van den Broeke, M. R. (2005), Strong surface melting preceded collapse of Antarctic Peninsula ice shelf, *Geophys. Res. Lett.*, *32*, L12815, doi:10.1029/2005GL023247.

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

van den Broeke, M. R., W. J. van de Berg, and E. von Meijgaard (2006), Snowfall in coastal West Antarctica much greater than previously assumed, *Geophys. Res. Lett.*, *33*, L02505, doi:10.1029/2005GL025239.
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, *Clim. Change*, *60*, 243–274.
Wingham, D. J., A. Shepherd, A. Muir, and G. J. Marshall (2006), Mass balance of the Antarctic ice sheet, *Philos. Trans. R. Soc. London, Ser. A*, *364*, 1627–1635.

G. J. Marshall and E. R. Thomas, British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK. (lith@bas.ac.uk)
J. R. McConnell, Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512, USA.