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Ice core evidence for significant 100-year regional warming on the Antarctic Peninsula

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[1] We present a new 150-year, high-resolution, stable isotope record (δ^{18}O) from the Gomez ice core, drilled on the data sparse south western Antarctic Peninsula, revealing a ~2.7°C rise in surface temperatures since the 1950s. The record is highly correlated with satellite-derived temperature reconstructions and instrumental records from Faraday station on the north west coast, thus making it a robust proxy for local and regional temperatures since the 1850s. We conclude that the exceptional 50-year warming, previously only observed in the northern Peninsula, is not just a local phenomena but part of a statistically significant 100-year regional warming trend that began around 1900. A suite of coupled climate models are employed to demonstrate that the 50 and 100 year temperature trends are outside of the expected range of variability from pre-industrial control runs, indicating that the warming is likely the result of external climate forcing. **Citation:** Thomas, E. R., P. F. Dennis, T. J. Bracegirdle, and C. Franzke (2009), Ice core evidence for significant 100-year regional warming on the Antarctic Peninsula, *Geophys. Res. Lett.*, *36*, L20704, doi:10.1029/2009GL040104.

1. Introduction

[2] The Antarctic Peninsula has experienced considerable warming in the last 50 years [*Vaughan et al.*, 2003; *Turner et al.*, 2005], resulting in widespread retreat of marine glacier fronts [*Cook et al.*, 2005] and disintegration of floating ice shelves on the east coast [*Scambos et al.*, 2000, 2004]. Changes in atmospheric circulation [*van den Broeke and van Lipzig*, 2004], most notably the Southern hemisphere Annular Mode (SAM) [*Marshall et al.*, 2006] and regional changes in sea surface temperatures and sea ice extent [*Meredith and King*, 2005] appear to drive interannual temperature fluctuations at the coastal stations in the Antarctic Peninsula. However, temperature trends on the Antarctic continent are less well defined. *Kwok and Comiso* [2002] report a statistically insignificant cooling trend over continental Antarctica from 1982 to 1998, inferred from Advanced Very High Resolution Radiometer (AVHRR) instruments, while *Schneider et al.* [2006], in a synthesis using 200 year ice core records from the continent revealed a slight warming of about 0.2 °C per century since ~1880. A new reconstruction approach by *Steig et al.* [2009] suggests that the warming trend observed in the Antarctic Peninsula since 1957 extends south to the Antarctic continent and into West Antarctica, where temperatures are reported to be increasing by 0.17°C per decade. Ice core reconstructions from this region reveal a warming trend of 1.0 °C per century during the period 1900–1999, based on a stack of several West Antarctic ice cores [*Schneider and Steig*, 2008]. Understanding the extent to which the extreme warming at stations in the north of the Antarctic Peninsula is a localized phenomena or if this is representative of regional changes, especially in its southward extent toward the sensitive west Antarctic region, is of vital significance in model validation and ultimately prediction of future climate change.

[3] Instrumental records from this remote region are short, rarely exceeding 50 years in length and generally confined to coastal sites. Ice cores, however, provide a wealth of climate information that extends beyond the instrumental period making them a valuable tool for interpreting climate trends, such as those observed in the Antarctic Peninsula, on a longer temporal framework. In this paper we present a 150-year high resolution stable isotope record, a proxy for past temperatures, from the data sparse region of the south-western Antarctic Peninsula. We use the data to investigate the regional extent of the reported warming and its statistical significance.

[4] The isotopic composition, expressed as δ^{18}O, is the relative difference in the ratio of the heavy to light isotopes of oxygen, ^{18}O/^{16}O, between a sample and the standard Vienna Standard Mean Ocean Water (SMOW). The linear relationship between local temperature and stable isotopes in precipitation at mid- and high-latitudes [*Dansgaard*, 1964] has been used to reconstruct past temperature from Antarctic ice cores over decades, centuries and millennia [*EPICA Community Members*, 2004; *Jouzel et al.*, 2007].

2. Data and Methods

[5] The new ice core, known as Gomez, was drilled in 2007 to a depth of 136 metres in a high accumulation site on the south-western Antarctic Peninsula (73.59°S, 70.36°W, 1400 masl) [*Thomas et al.*, 2008]. Samples of 7 cm length were cut for isotope analysis, equal to approximately 12 samples per year at the base of the core, with higher temporal resolution in more recent years. Samples of the melted ice (1.6 mL) were used for the stable isotope analysis using an automated CO_2-H_2O oxygen isotope equilibration system and subsequent CO_2 δ^{18}O analysis by dual-inlet isotope ratio mass spectrometry on a modified VG SIRA series II analyser. All results are reported with respect to VSMOW-SLAP. Analytical precision of ±0.07‰ (2σ) is estimated using data from 480 replicate analyses of the internal laboratory standard (NTW) that were run at random amongst batches of the Gomez ice samples.

[6] The annual average δ^{18}O was calculated using the seasonal cycle in δ^{18}O and verified using the winter minima

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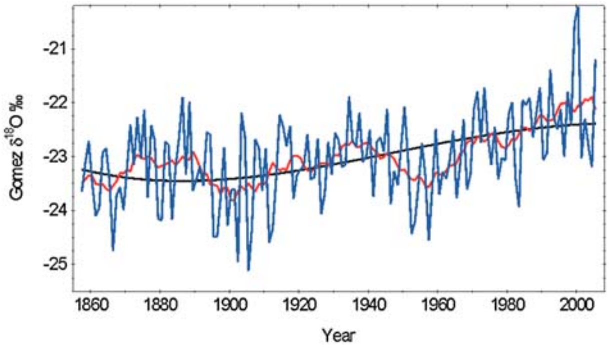

Figure 1. Gomez annual average δ^{18}O (blue), running decadal mean (red) and nonlinear trend (black). The running decadal mean is derived using an 11-point Gaussian window filter.

in hydrogen peroxide (H_2O_2), a photochemical species with a minima that corresponds to the winter solstice, and the summer maxima in non sea salt sulphate (SO_4^{2-}) [*Thomas et al.*, 2008]. Ice core and meteorological years all run July–June. The estimated error in determining the annual averages is ±1 month (2005–1885) and ±2–3 months (1884–1856) due to lower temporal resolution. The estimated error in the annual average δ^{18}O is ±1.6%, based on comparison with previous ice cores from Palmer Land [*Peel et al.*, 1988] during the period of overlap (1915–1992, $r = 0.88$, $p < 0.01$).

[7] We are using a temporal gradient of 0.5 ± 0.1 ‰ per °C to convert δ^{18}O to temperature, based on the calibration between the δ^{18}O with site temperatures from the European Centre for Medium Range Weather Forecasts (ECMWF) (1980–2005). Similar values are achieved when using instrumental records over the same time period from the two closest stations, Rothera (0.53 ‰ per °C) and Faraday (0.55‰ per °C) and is in agreement with temporal gradients from an isotopically enabled general circulation model (GCM), using 100-year CO_2 forced trends [*Sime et al.*, 2008]. The authors note that the temporal gradient may change through time and that a change in seasonality may alter the reported trends.

[8] The statistical significance of trends in the δ^{18}O record are tested using the empirical mode decomposition (EMD) approach [*Huang et al.*, 1998; *Huang and Wu*, 2008; *Franzke*, 2009] to decompose the time series into a finite number of components, the intrinsic mode functions (IMF's), and a residual which we interpret as a trend. The EMD approach is used to extract physically meaningful modes and nonlinear trends from nonlinear and non-stationary time series that cannot be captured by a linear least-square fit. The IMFs and the trends are tested against three different null models to test the statistical significance; 1) white noise, where we assume that all measurements are uncorrelated; 2) a First-Order Autoregressive Process (AR(1)) [*Franzke*, 2009] which allows for short-range correlation of the data and 3) a fractionally differenced process [*Percival et al.*, 2001] which is a long-range correlated process and exhibits trend-like behaviour over finite periods. For the white noise null model we only estimate the variance of Gomez time series, for the AR (1) we estimate the lag-1 auto-correlation value and variance, and for the fractional differenced model we estimate the long-range dependency parameter d by the Detrended Fluctuation Analysis [*Koscielny-Bunde et al.*, 1998].

3. Results and Discussion

[9] The annual average δ^{18}O, together with a running decadal mean, is plotted in Figure 1. There is a shift to less negative δ^{18}O values since the 1850s from a decadal average value of −23.5 ‰ during 1857–1866 to −22.0 ‰ in the most recent decade. Over the whole period this trend represents a warming of ∼0.14 ± 0.06 °C decade^{-1}. EMD analysis reveals that most of the variance (∼75%) is at the intra-decadal time scale but there is significant variance at inter-decadal time scales.

[10] The δ^{18}O exhibits a nonlinear trend (Figure 1), cooling slightly in the period 1857 through 1900, followed by a pronounced warming after 1900, that is statistically significant at the 2.5% level against all three null models. This is in agreement with trends observed in borehole temperature profiles from the Antarctic Peninsula [*Nicholls and Paren*, 1993] and the Rutford ice stream, west Antarctica [*Barrett et al.*, 2009]. Similar behaviour has been found in EMD analysis of the SAM [*Franzke*, 2009], the principal mode of variability in the southern hemisphere, suggesting that the SAM has a strong influence on the Gomez temperature record. Precipitation (and hence δ^{18}O contained therein) at the Gomez site is dominated by synoptic-scale storm activity from the Bellingshausen Sea [*Turner et al.*, 1997; *Thomas and Bracegirdle*, 2009] and thus the intensified westerly winds associated with the positive phase of the SAM in recent decades, will enhance transport of warm maritime air to the site due to the blocking effect of the mountainous Antarctic Peninsula. This mechanism was demonstrated in the Gomez accumulation record as a dramatic increase in snowfall since the 1960s that is strongly correlated to the SAM [*Thomas et al.*, 2008]. Indeed, comparison of δ^{18}O with the SAM index [*Marshall*, 2003] reveals that approximately a third of the variability in annual mean surface temperatures at the site (1957–2005) may be attributed to changes in the SAM.

[11] The largest warming has occurred since the 1950s, coincident with the start of the instrumental records. During this period the annual average surface temperature at the Gomez site, estimated using the isotope composition, has increased at a rate of 0.055 ± 0.02 °C year^{-1}, with four of the warmest years in the 150-year record occurring in the last decade.

[12] A study using satellite-derived temperatures to investigate interannual variations hypothesized that the Gomez region, with its relatively low elevation and location west of the topographic divide, would be influenced by the same air masses that govern climate over the west coast of the Peninsula [*King and Comiso*, 2003]. This coherent region of high interannual temperature variability extends south into southern Palmer Land (south of the Gomez site) and north through the South Shetland Islands. The regional link was demonstrated in previous ice cores studies from the Palmer Land plateau [*Peel et al.*, 1988] and for this site using trajectory paths from ECMWF reanalysis data (1980–2001) [*Thomas and Bracegirdle*, 2009].

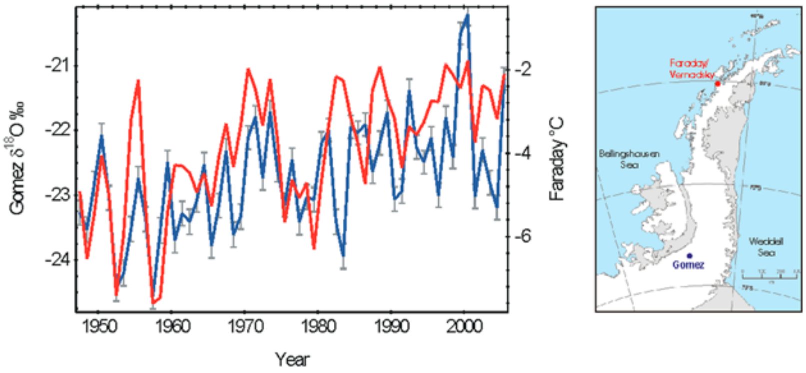

Figure 2. Comparing Gomez δ^{18}O and Faraday temperatures. Gomez annual average δ^{18}O (blue) and Faraday annual average temperature (red), both calculated from winter to winter (July–June). Gomez δ^{18}O error estimated from comparison with other Palmer land ice cores. Insert map showing locations of the two sites.

[13] Despite the complex relationship between local orography and synoptic scale activity and in contrast to previous ice core records from the north and east Antarctic Peninsula [*Peel et al.*, 1988; *Thompson et al.*, 1994; *Vaughan et al.*, 2003], the Gomez δ^{18}O record appears to capture both local and regional temperature variability. The annual average isotopic composition is not only strongly correlated with satellite-derived annual mean site temperatures [*King and Comiso*, 2003] ($r = 0.77$, $p < 0.01$ (1989–1999)), confirming δ^{18}O is representative of local temperature, but also the annual average temperatures at Faraday/Vernadsky station (Figure 2) almost 600 km north of the ice core site. Regardless of the precipitation bias in the ice core such that the annual isotope record is a composite of only days when there was precipitation at Gomez, the δ^{18}O record captures annual ($r = 0.44$, $p < 0.01$) and decadal ($r = 0.70$, $n = 5$) variability at the north west coast station and exhibits comparable warming trends; 0.055 ± 0.02 °C yr^{-} and 0.054°C yr^{-1} respectively (1955–2005).

[14] The relatively short time period available from the Gomez ice core means that statistical approaches cannot unequivocally show if the warming is due to intrinsic climate variability or external forcing by anthropogenic (e.g., greenhouse gas emissions) and/or other factors. A previous ice core from the Dyer Plateau, ~300 km north east of the Gomez site, concluded that the most recent two decades of the record (1968–1988) were the warmest of the last five centuries [*Thompson et al.*, 1994], suggesting that the observed warming at Gomez is outside of the range of natural variability. However, the Dyer Plateau record is poorly correlated with the instrumental records and does not capture the magnitude of the warming observed during the same period at Faraday/Vernadsky [*Thompson et al.*, 1994; *Vaughan et al.*, 2003]. Therefore, in the absence of additional longer records, we complement our comparison with simple stochastic models by comparing the trend observed in the Gomez ice core with data from phase three of the Coupled Model Intercomparison Project (CMIP3), available as part of the Intergovernmental Panel on Climate Change (IPCC) Assessment Report Four (AR4). Unforced pre-industrial control data for 20 different coupled climate models (summarised in Table 1) were downloaded, comprising an all-model total of 8338 years.

[15] Both the 50 and the 100 years trends observed in the Gomez ice core are larger than the 99th percentile of the frequency distribution of respective trends simulated in individual runs of the CMIP3 pre-industrial control runs. Figure 3 shows the frequency distribution of 50-year trends of surface temperature at Gomez, interpolated to the Gomez location from the gridded climate model data. The 95th percentile of the distribution is 0.022 °C yr^{-1}, which is below the 1955–2005 trend of 0.055 ± 0.02 °C yr^{-1} derived from the Gomez ice core. A similar analysis of 100 year trends (not shown) also shows the 95th percentile of trends derived from the CMIP3 pre-industrial control runs (0.009 °C yr^{-1}) to be less than observed (0.024 ± 0.01 °C yr^{-1} between 1905 and 2005). Assuming that the models accurately capture the full range of natural variability, which is difficult to verify in Antarctica, then this suggests that the observed warming is very unlikely to have occurred in the absence of external natural and/or anthropogenic climate forcing. An important caveat is that the CMIP3 climate models may under-estimate the range of unforced variability, which would reduce the

Table 1. CMIP3 Climate Model Data Used for the Trend Frequency Analysis

Model ID	Number of Years in Control Run	Number of Different 20c3m Ensemble Runs Used
BCCR BCM2	250	1
CCCMA CGCM3	1001	5
CNRM CM3	500	1
CSIRO Mk3	380	3
GFDL CM2.0	500	3
GFDL CM2.1	500	3
GISS EH	400	5
GISS ER	500	9
IAP FGOALS1	350	3
INM CM3	330	1
IPSL CM4	69	1
MIROC (hires)	100	1
MIROC (medres)	500	3
ECHO-G	341	5
MPI ECHAM5	506	4
MRI CGCM2	350	5
NCAR CCSM3	230	8
NCAR PCM1	950	4
UKMO HadCM3	341	2

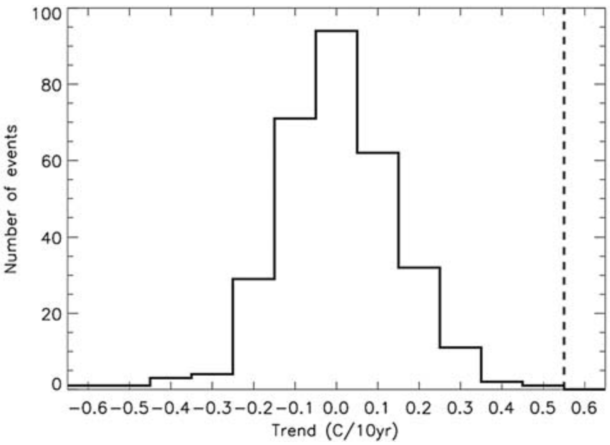

Figure 3. Frequency distributions of 50-year annual mean surface temperature linear trends (°C per decade) at Gomez derived from the CMIP3 climate model data archive. The panel shows 50% overlapping trends in unforced pre-industrial control runs (sample size 308). The vertical dashed line shows the trend derived from the Gomez core between 1947 and 2005. The model data used are summarised in Table 1.

significance of the above result. Therefore more research is required to reach a firm conclusion.

4. Conclusions

[16] The Gomez δ^{18}O record reveals that the rate of surface temperature increase in the south western Antarctic Peninsula is similar to that observed at Faraday/Vernadsky station on the north west coast, warming by as much as $\sim$2.7°C since the 1950s. The strong correlation between Faraday surface temperatures and Gomez δ^{18}O (1947–2006) confirm that the Gomez record may be considered a proxy for local and regional temperatures on the western Antarctic Peninsula. Therefore the statistically significant 100-year warming trend observed at Gomez, starting around 1900, and the exceptional warming since the 1950s (both of which are outside of the expected range of natural variability estimated from CMIP3 climate models), represent regional changes that extend at least as far south as the Gomez site (74°S).

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