A 308 year record of climate variability in West Antarctica

Elizabeth R. Thomas,[1] Thomas J. Bracegirdle,[1] John Turner,[1] and Eric W. Wolff[2]

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[1] We present a new stable isotope record from Ellsworth Land which provides a valuable 308 year record (1702–2009) of climate variability from coastal West Antarctica. Climate variability at this site is strongly forced by sea surface temperatures and atmospheric pressure in the tropical Pacific and related to local sea ice conditions. The record shows that this region has warmed since the late 1950s, at a similar magnitude to that observed in the Antarctic Peninsula and central West Antarctica; however, this warming trend is not unique. More dramatic isotopic warming (and cooling) trends occurred in the mid-nineteenth and eighteenth centuries, suggesting that at present, the effect of anthropogenic climate drivers at this location has not exceeded the natural range of climate variability in the context of the past ~300 years.
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1. Introduction

[2] The Antarctic Peninsula and West Antarctica have both warmed dramatically in recent decades, with some records suggesting that these are among the most rapidly warming regions on Earth [*Bromwich et al.*, 2013]. Although climate models suggest large natural climate variability over West Antarctica [*Hawkins and Sutton*, 2012], instrumental records from West Antarctica and the Antarctic Peninsula are sparse, and the lack of long-term records is hindering our ability to evaluate modeling results and place these recent changes in a longer-term context. Recent studies, exploiting the linear relationship between local temperature and stable isotopes in precipitation at middle and high latitudes [*Dansgaard*, 1964], have improved our understanding of climate variability in the northern Antarctic Peninsula [*Mulvaney et al.*, 2012] and continental West Antarctica [*Schneider and Steig*, 2008; *Steig et al.*, 2013]. However, the climate in the coastal region, especially in the area closest to some of the largest and fastest flowing outlet glaciers in the region, is still largely unknown.

2. Method and Data

[3] Deuterium (δD) data are presented from the Ferrigno ice core (F10) drilled on the Bryan Coast, West Antarctica, during the austral summer 2010/2011. Stable isotopes in precipitation are widely used as a proxy for temperature; however, the relationship between δD and temperature is poorly defined in this region. The F10 record is significantly correlated ($r = 0.44$, $P = 0.01$) with ERA-Interim temperature (t850, 1979–2009), and we observe that the pattern of correlation with atmospheric pressure and sea surface temperatures (SSTs) is similar for both observational δD and local temperature from reanalysis; however, we do not assume that δD is a quantitative temperature proxy. F10 was drilled using an electomechanical drill (without drilling fluid) to a depth of 136 m on a three-way ice divide between the Ferrigno glacier and the Pine Island glacier (74.57°S, 86.90°W, 1354 m above sea level) in December 2010 (Figure 1b).

[4] The record was measured using a Los Gatos Liquid Water Isotope Analyzer (model LWIA-DLT 100) with estimated analytical precision of ±1‰. Internal standards were calibrated against international standards Vienna Standard Mean Ocean Water 2 and Vienna Standard Light Antarctic Precipitation 2. The record was dated using the summer maxima in non-sea-salt sulfate measured with ion chromatography, using a reagent-free Dionex ICS-2500 anion and IC 2000 cation system. Samples were measured at 5 cm resolution, corresponding to approximately 14 samples per year, with annual averages calculated for January–December. Eight major volcanic eruptions (1963, 1932, 1913, 1883, 1836/1837, 1822, 1815, and 1809/1810) are clearly visible in the sulfate record and match the annual layer counted ages to within 1 year. The estimated dating error for 2010–1810 is ±3 months; the estimated error for 1810–1702 is ±1 year (no independently dated volcanic tie points available). Seasonal snowfall (from automatic weather station and ERA-Interim data [*Dee et al.*, 2011]) is evenly distributed at this site, suggesting minimal precipitation bias. All correlations presented in this study are carried out using detrended data with the significance levels for Pearson's correlation calculated using the two-tailed *t* test.

3. Result and Discussion

3.1. Rapid Warming Since 1957

[5] The annual average deuterium record (δD) from F10 (Figure 1) reveals that there has been an isotopic warming in Ellsworth Land, observed as an increase in δD of $2.7 \pm 0.2‰\ dec^{-1}$ since 1957, statistically significant at the 99% confidence level. This is consistent with water isotope trends observed in southern Palmer Land (Gomez ice core) [*Thomas et al.*, 2009] and continental West Antarctica [*Schneider and Steig*, 2008; *Steig et al.*, 2009] (Figure 2) and a warming observed in instrumental records [*Bromwich et al.*, 2013]. However, the recent isotopic warming trend is not the largest in the 308 year record. Larger 50 year warming trends occurred in the middle to late eighteenth century [+4.1‰ dec^{-1}(1740–1789)] and the mid-nineteenth century [+3.8‰ dec^{-1}(1888–1839)] with several equally large cooling trends. Overall, there is no significant trend in the δD record since 1702 A.D.

[1]British Antarctic Survey, Cambridge, UK.
[2]Department of Earth Sciences, University of Cambridge, Cambridge, UK.

Corresponding author: E. R. Thomas, British Antarctic Survey, Cambridge CB4 0ET, UK. (lith@bas.ac.uk)

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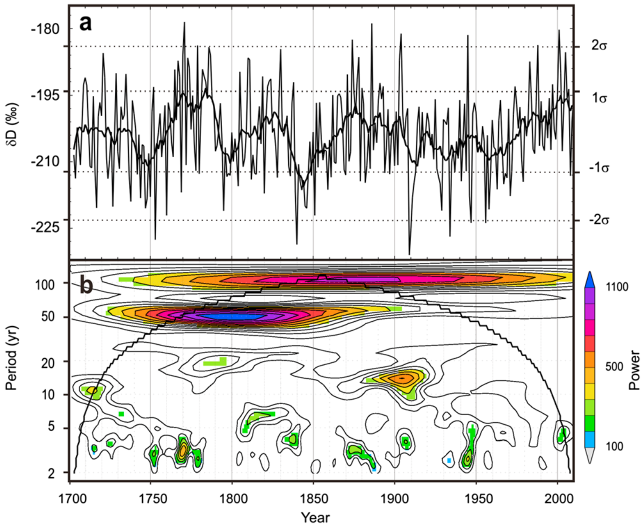

Figure 1. (a) Ferrigno (F10) annual average δD (January–December) and running decadal mean (thick line). Horizontal dashed lines represent one and two standard deviations (σ) above and below the mean. (b) Order 6 Mortlet wavelet analysis of the detrended annual average δD. Black line indicates the cone of influence; color shading indicates >95% confidence levels.

[6] Wavelet analysis of the detrended δD reveals strong temporal variance in the 40–60 year domain prior to 1880, fluctuating between cold and warm decades approximately every 25 years, but a marked reduction in multidecadal variability during the twentieth century (Figure 1b). This suggests that at this site, a large amount of the isotopic warming since the late 1950s occurred during a period of reduced multidecadal variability and has not yet taken the system outside its natural range. This is consistent with a recent study from continental West Antarctica [West Antarctic Ice Sheet (WAIS) divide core, Figure 2], suggesting that the anomalous δ^{18}O values and trends of recent decades are not unprecedented [*Steig et al.*, 2013]. However, on the Antarctic Peninsula, the James Ross Island ice core revealed that the high rate of warming over the past century is unusual [*Mulvaney et al.*, 2012]. The warming there has been ongoing since ~1920s and is shown to be climatically distinct from the climate signal seen in West Antarctic ice cores [*Abram et al.*, 2013].

3.2. What Is Driving the Recent Isotopic Warming?

[7] F10 δD has been correlated with 500 hPa geopotential height (z500) from ERA-Interim (1979–2009) [*Dee et al.*, 2011] to reveal a band of statistically significant correlations (>95% confidence) extending from the Antarctic Peninsula to the tropical Pacific (Figure 3a). Atmospheric circulation anomalies provide a corridor for enhanced northerly (onshore) flow, drawing warm moist air to the ice core site. F10 δD has been correlated with 2 m wind fields from ERA-Interim (Figure 3b) to confirm that warm (less negative δD) years are associated with strengthening of the meridional winds (onshore northerlies) between ~50–70°S, ~100–140°W (contours in Figure 3b). This pattern is maintained in the longer reanalysis data sets, including GISS [*Hansen et al.*, 2010] (1880–2004) and the Twentieth Century Reanalysis Data [*Compo et al.*, 2011] (1878–2008) (despite the absence of observations in these longer data sets), suggesting that the relationship may be maintained during the twentieth century. Recent model ensembles of the Southern Hemisphere climate variability have shown that during the past 500 years, the mechanisms linking climate in the Pacific with that of coastal West Antarctica have remained stable [*Wilmes et al.*, 2012].

[8] The pattern of correlations with z500 and winds at F10 are comparable with those observed at Byrd Station [*Bromwich et al.*, 2013] and the Gomez ice core, where warm years are associated with enhanced northerly (onshore) flow. Seasonal analysis of a suite of δ^{18}O records from the International Trans-Antarctic Scientific Expedition ice cores from West Antarctica determined that for all seasons, above-normal δ^{18}O values are generally related to enhanced meridional (onshore) flow [*Küttel et al.*, 2012]. Correlating the ERA-Interim 2 m meridional winds from the region of greatest correlation with F10 (110–120°W, 65–70°S) with 2 m temperatures (Figure 3c) demonstrates that increased northerly flow is accompanied by increased 2 m temperatures across the whole of West Antarctica, Ellsworth Land, and the southeastern Antarctic Peninsula (red shading in Figure 3c). Although there is no trend in meridional winds during the reanalysis period [coincident with the small trend in δD (+0.1‰ yr^{-1}) and 2 m temperatures (+0.002°C), 1979–2009], this suggests that meridional winds in the Amundsen Sea may be the common driver influencing interannual temperature variability at F10 and the wider West Antarctic region.

3.3. The Role of Tropical SSTs

[9] The winter and spring warming in continental West Antarctica has been linked to sea surface temperature (SST) changes in the tropical Pacific [*Schneider and Steig*, 2008; *Steig et al.*, 2009; *Ding et al.*, 2011] close to the South Pacific Convergence Zone (SPCZ). F10 δD is positively correlated with SSTs [*Reynolds et al.*, 2002] in the tropical Pacific and the Southern Ocean (contours in Figure 3a). The highest correlations are in the central Pacific ($r > 0.6$, 1981–2009), at the western edge of the SPCZ (~100–140°W, ~10–20°S; SST1 in Figure 3a), with smaller but statistically significant correlations in the subtropical SPCZ region north of New Zealand (~170°W, 30°S; SST2 in Figure 2a) and the Pacific sector of the Southern Ocean (~130°W, ~60°S; SST3 in Figure 3a).

[10] It has been shown that SST anomalies under areas of strong tropical convection have a significant influence on the atmospheric circulation in the Amundsen Sea region, through the generation of a large-scale atmospheric wave train [*Lachlan-Cope and Connolley*, 2006; *Ding et al.*, 2011]. Rossby waves forced from deep convection anomalies over the tropical Pacific on interannual time scales are believed to be related to El Niño–Southern Oscillation (ENSO); however, changes in the tropical Pacific that are not directly related to ENSO can also influence the high-latitude circulation [*Ding et al.*, 2011]. F10 is poorly correlated with the Southern Oscillation Index, suggesting that interannual variability at this site is not directly related to ENSO. The atmospheric teleconnection at F10 is better explained by the second mode of covariability between z200 and SSTs presented in *Bromwich et al.* [2013], which involves an SST forcing in the subtropical SPCZ region (SST2 in Figure 3a) that is not related to ENSO.

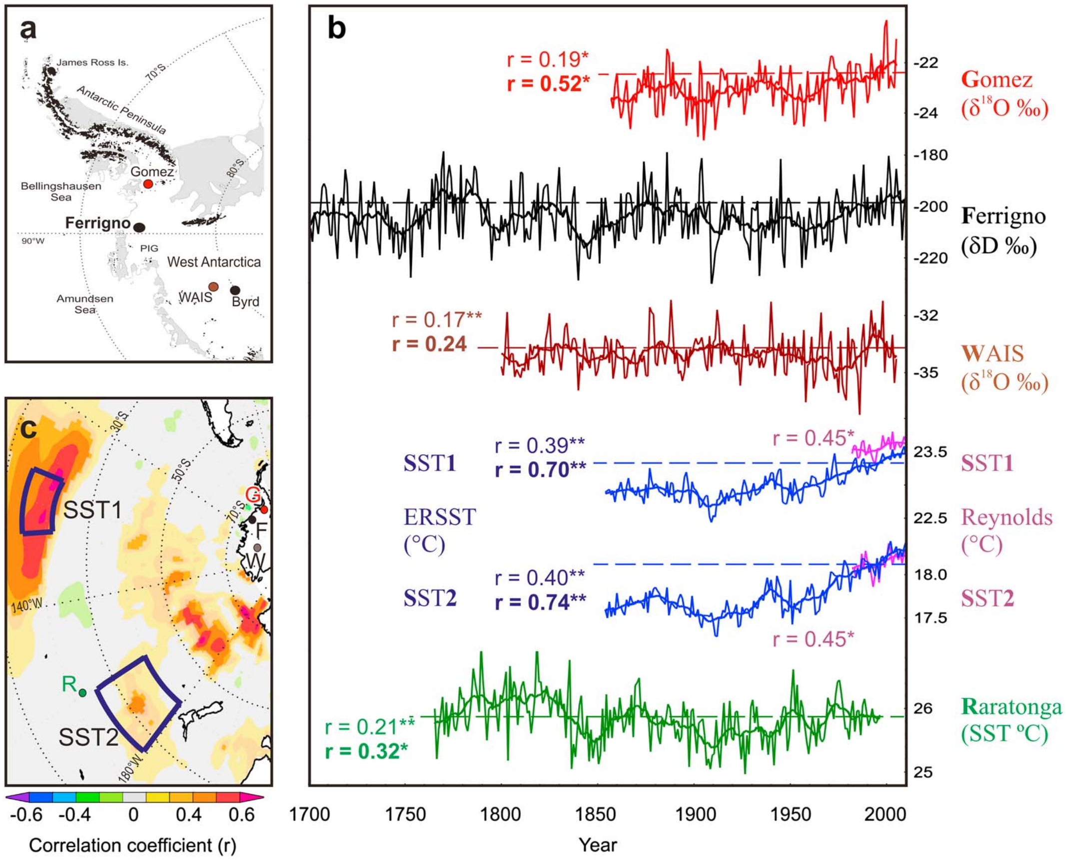

Figure 2. (a) Map with key locations. (b) Time series referred to in the text as annual average (thin lines) and running decadal means (thick lines) with correlation coefficients for each record with F10 δD (bold indicates decadal correlations, single asterisk indicates >90% confidence, and double asterisk indicates >95% confidence). Gomez $\delta^{18}O$ (red). Ferrigno δD (black). WAIS $\delta^{18}O$ (brown). SSTs from ERSST.v3 (blue) and Reynolds (pink) from SST zone 1 and SST zone 2. Rarotonga SST reconstruction (green). Horizontal dashed lines indicate the record average from 1980 to 2005 (1980–1997 for Rarotonga). (c) Correlation plot of annual average δD and annual average SSTs [*Reynolds et al.*, 2002] with record locations. Annual averages calculated for January–December; blue boxes in Figure 2c indicate the area averaged for SST1 and SST2, and darker shading indicates >95% confidence levels.

[11] To explore the teleconnection between F10 δD and the climate in the Pacific over longer time scales, we compare F10 with available reconstructions and proxy records from the central and west Pacific (Figure 2). Oceanographic data are extremely sparse (adding uncertainty to the SST reconstructions); however, using the extended SST reconstruction from NCDC (ERSST.v3) [*Smith et al.*, 2008], we observe significant correlations in regions SST1 and SST2 (especially on the decadal scale) extending back to 1854 (Figure 2). In addition, a proxy record of SSTs from a coral growing at Rarotonga [*Linsley et al.*, 2000], in the Cook Islands (21.5°S, 159.5°W), is close to our zone of positive correlation with SSTs (SST2 in Figure 3a). There is a significant correlation ($r = 0.32$, 1765–1995, >90% confidence) (the full SST record is not used due to an unusual excursion in the coral SST prior to 1765 [*Linsley et al.*, 2000]) between the decadal average coral-derived SSTs and decadal δD at F10, both exhibiting several synchronous warm and cold periods over the past 240 years, further supporting the tropical teleconnection over longer time scales.

3.4. Relationship With Sea Ice

[12] Sea ice extent in the Bellingshausen Sea has decreased in recent decades [*Turner et al.*, 2009], and it has been estimated that this may account for ~80% of the spring warming on the Peninsula and ~20–30% of the inland warming in West Antarctica [*Schneider et al.*, 2011]. Negative anomalies in sea ice extent and the length of the sea ice season in the Amundsen and Bellingshausen Seas have been related to the warming trends observed in previous West Antarctic reconstructions [*Steig et al.*, 2009; *Küttel et al.*, 2012].

[13] There is a significant (>95% confidence) negative correlation between F10 δD and both winter sea ice extent [*Cavalieri et al.*, 1996; *Meier et al.*, 2006] ($r = -0.37$) and winter sea ice concentrations (Figure 3b) [*Comiso*, 1999] ($r = -0.54$) in the Amundsen and Bellingshausen Seas, greatest during the sea ice maximum in September. The region of greatest significance corresponds to the region of significant correlation between F10 δD and meridional flow (dashed contours overlain in Figure 3b), between ~100°W and ~140°W. A reduction in sea ice concentration has been shown to directly alter water isotopes through an injection of relatively enriched water vapor, with some studies speculating that water isotopes reflect changes in sea ice rather than temperature [*Bromwich and Weaver*, 1983]. However, seasonal studies of water isotope records from West Antarctica suggest that both water isotopes and temperature are influenced by sea

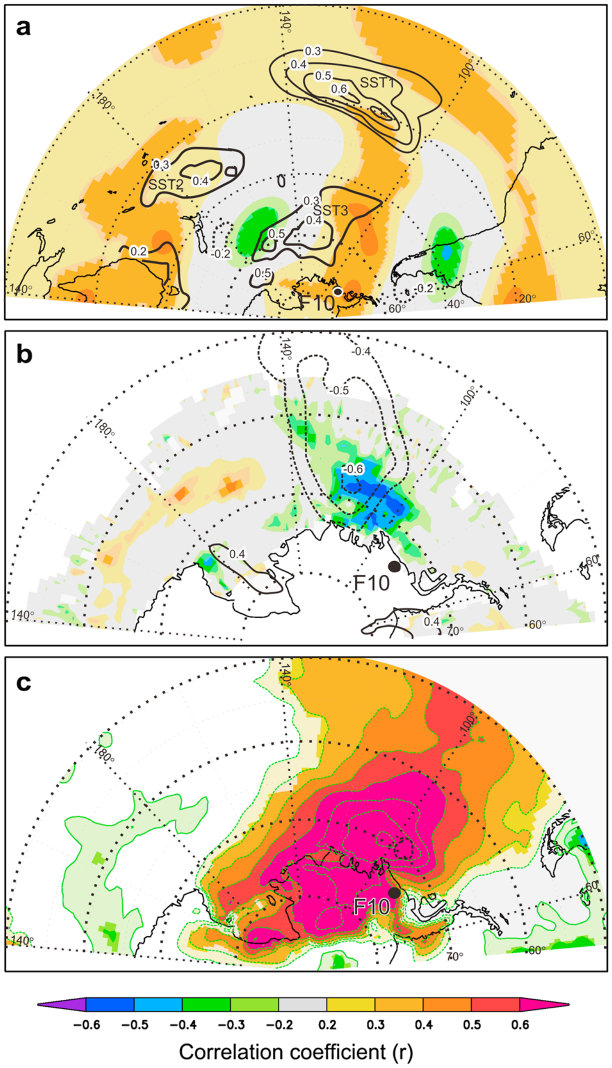

Figure 3. (a) Correlation plot of annual average F10 δD with annual average 500 hPa (z500) geopotential heights (colored shading) and annual average SSTs [*Reynolds et al*., 2002] (contours) from 1981 to 2009. (b) Correlation plot of annual average F10 δD with September sea ice concentration (colored shading) and annual average surface meridional (v) winds (contours) from ERA-Interim (1979–2009). (c) Correlation plot of annual average meridional winds (110–120°W, 70–65°S) with annual average 2 m temperatures from ERA-Interim (1979–2009). Annual averages calculated for January–December; darker shading indicates >95% confidence levels, and dashed contours indicate negative correlations.

ice variations which are themselves driven by atmospheric circulation [*Küttel et al*., 2012].

4. Conclusions

[14] The new isotope record from Ellsworth Land, West Antarctica, is ideally placed to capture climate variability in the region surrounding some of the fastest flowing and largest glaciers in West Antarctica. Climate variability at this site is influenced by subtropical high pressure and SST anomalies in the central and west Pacific. Reanalysis data has been used to demonstrate the influence of meridional winds on surface temperatures at the F10 site and across the wider West Antarctic region. Pacific SST reconstructions and coral data have been used to verify that the tropical teleconnection extends beyond the instrumental period.

[15] Our results show that the large isotopic warming (~2.7‰ dec^{-1}) since the 1950s is not unusual, with equally large warming and cooling trends observed several times over the past 308 years. This is consistent with a study from continental West Antarctica [*Steig et al*., 2013] which concluded that this recent warming is not unprecedented in the context of the past 2000 years. The record reveals a reduction in multidecadal variability during the twentieth century and suggests that the warming since the late 1950s has not yet taken the system outside its natural range. This is not inconsistent with the exceptional recent global warming, during which approximately 20% of the observationally covered Earth's surface still does not show 100 year trends that are significantly larger than internal variability [*Karoly and Wu*, 2005].

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