Twentieth-Century Surface Temperature Trends in the Western Ross Sea, Antarctica: Evidence from a High-Resolution Ice Core

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ABSTRACT

A 125-yr ice core record of climate from the Whitehall Glacier ice divide provides exceptionally high-resolution stable isotope data from the northwest margin of the Ross Sea, Antarctica. This is the only proxy data available to extend the instrumental record of temperature in this region, where little is known about climate variability over the past two centuries. Using ECMWF Interim Re-Analysis (ERA-Interim) data, this study develops a precipitation-weighted $\delta^{18}O$-temperature transfer function of 0.62‰ °C^{-1}, which is comparable to other proximal ice cores, such as Taylor, Talos, and Law Domes. Reconstructed mean annual temperatures show no significant change between 1882 and 2006. However, a decrease in cold season [April–September (AMJJAS)] temperatures of $-1.59° \pm 0.84°$C decade^{-1} (at 90% confidence) is observed since 1979. This cooling trend is in contrast to a surface temperature record from Ross Island (Scott Base) where significant spring warming is observed. It is also coincident with a positive trend in the southern annular mode, which is linked to stronger southerly winds and increased sea ice extent and duration in the western Ross Sea.

1. Introduction

Although the Antarctic ice sheet plays a pivotal role in the global ocean and atmospheric circulation systems and their response to warming climates, there are few long-term observations of surface temperature across the continent. This is particularly true for areas poleward of the Antarctic Peninsula because of the sparsity of scientific bases and problems associated with satellite measurements of surface temperature (Mayewski et al. 2009). Given rapid changes in surface mass balance (Rignot et al. 2008), sea ice extent and concentration (Comiso et al. 2011), and the spatial and seasonal variability in temperature trends (Schneider et al. 2011) across West Antarctica, there is a pressing need for a better understanding of climate variability and the forcings that underlie these changes.

Analyses of surface temperature trends across West Antarctica find significant increases over the past 50 years, with the largest observed warming in the austral spring since the late 1970s (Chapman and Walsh 2007; Monaghan et al. 2008; Steig et al. 2009; Schneider et al. 2011). However, this trend is not spatially coherent and lower sea surface temperatures and increased sea ice extent in the western Ross Sea are asynchronous with the Bellinghausen and Amundsen Sea coasts (Comiso et al. 2011). This has been linked to changes in the phase of the Southern Hemisphere annular mode (SAM), which has shown a positive trend since the mid-1960s (Marshall et al. 2006) and an increased covariability between SAM and ENSO (Fogt and Bromwich 2006). Both the positive

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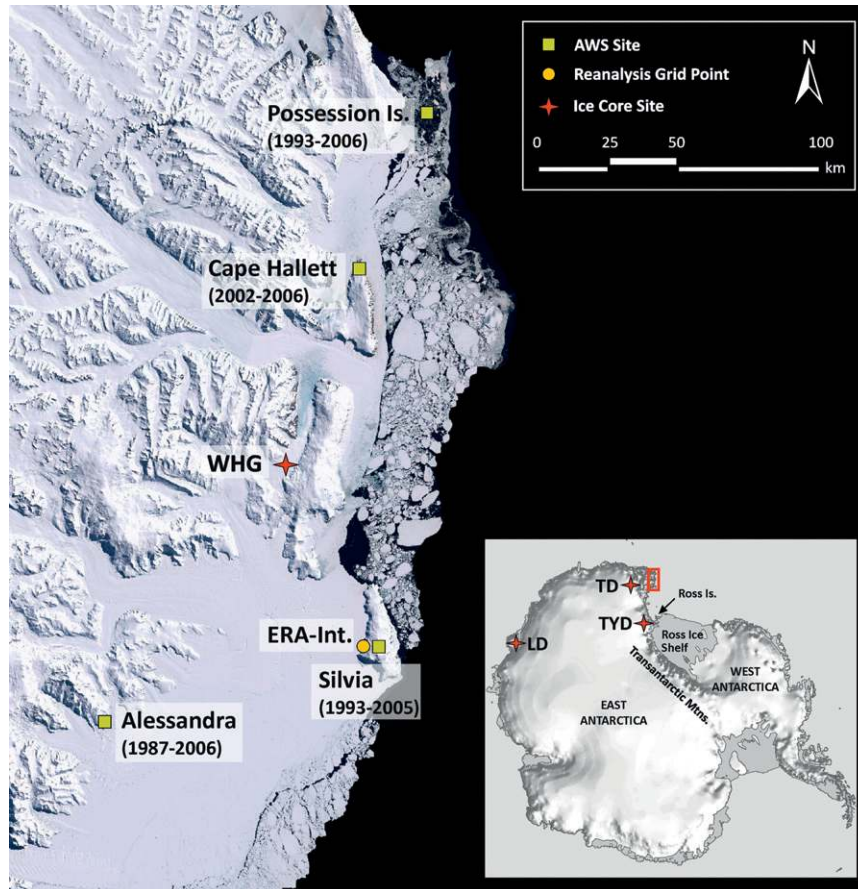E-mail: k.sinclair@gns.cri.nz

FIG. 1. Landsat Image Mosaic of Antarctica (LIMA) showing the WHG site, along with the locations of nearby AWS sites and the closest ERA-Interim grid point. The inset map (courtesy of Australian Antarctic Division) shows the spatial extent of the LIMA imagery (box), ice core sites discussed in the text (TYD = Taylor Dome, TD = Talos Dome, and LD = Law Dome), and Scott Base on Ross Island.

phase of the SAM and ENSO (La Niña events) result in a deeper Amundsen Sea low and therefore stronger meridional (southerly) flow along the western margin of the Ross Sea and wind-driven sea ice advance (Stammerjohn et al. 2008; Markle et al. 2012).

There are only two long-term meteorological time series in the Ross Sea region that span more than 50 years: Scott Base and McMurdo Station at Ross Island (Fig. 1). To date, there have been no proxy data available to extend the instrumental record of temperature along the western Ross Sea coastline. To address the need for high-resolution terrestrial climate records for the Ross Sea region, the New Zealand contribution to the International TransAntarctic Scientific Expedition (ITASE) has extracted a series of low-elevation coastal ice cores in areas of high accumulation. These records offer an unprecedented view of climate variability in this sector of Antarctica and extend the temperature

record beyond the timeframe covered by instrumental observations (Mayewski et al. 2005; Bertler et al. 2004, 2011). These ice cores also will provide insight into the latitudinal variability of climate forcings along the Ross Sea coast, and the way that climate is modulated by decadal-scale shifts in the dominant modes of atmospheric circulation.

In this study we consider isotope–temperature relationships at a high-resolution ITASE site, the Whitehall Glacier (WHG). This site is located in northern Victoria Land (72°54′S, 169°5′E) at 400 m above mean sea level (MSL) on a flat ice divide approximately 12 km from the nearest seasonally open water (Fig. 1). We present the complete stable isotope stratigraphy from the record spanning 125 years from 1882 to 2006 and develop an isotope–temperature calibration to reconstruct annual and seasonal temperatures for the 125-yr span of the ice core record.

2. Data

The WHG core was drilled to a depth of 105 m in 2006/07, shipped frozen to New Zealand, and processed using a continuous melter system (Osterberg et al. 2006). A total of 6081 samples were analyzed for $\delta^{18}O$ and δD at the National Isotope Centre, GNS Science, with an analytical precision of 0.1‰ and 1.0‰, respectively. All results are reported with respect to Vienna Standard Mean Ocean Water (VSMOW) and normalized to internal standards.

This study also employs gridded European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) data, available at 1.5° resolution from 1989 onward (Dee et al. 2011). Figure 1 shows the locations of the closest ERA-Interim grid point and automatic weather station (AWS) sites near WHG. For the time period that all AWS sites concurrently measured surface temperature (1 May 2002–31 December 2005) we find a coherent temperature signal across the region and highly correlated daily temperatures ($n = 1706$, $r > 0.92$, and $p < 0.01$).

3. Isotope and accumulation chronology

Ice core $\delta^{18}O$ data are presented in Fig. 2. The upper two years of data are from snow pits at the site, sampled at 5-cm resolution for density and stable isotopes in November 2006. The mean density of each section of ice core was found using dual energy x-ray absorptiometry (DEXA) to establish a water equivalent scale for the record (Kroger et al. 2006). The age model is established by direct counting of annual isotope cycles; 1 January each year is defined to coincide with summer $\delta^{18}O$ maxima and winter $\delta^{18}O$ minima were set at 1 August based on the temperature record from the closest AWS site, Cape Hallett (Fig. 1). Dates between the summer maxima and winter minima are assigned using a linear accumulation versus time relation, with a mean annual sample resolution of 47 yr^{-1} (ranging from 22 to 105 samples per year). The high-resolution nature of the record affords an unequivocal annual-layer count, but there is some uncertainty in the age model at time scales of less than one month.

The low-elevation topography of the Ross Sea region and the proximity of the site to the circumpolar trough results in frequent and intense cyclonic activity as low pressure systems track around the coast into the Ross Sea region (Simmonds et al. 2003). This produces a strong synoptic-scale control on temperature variability and high annual snow accumulation relative to both the interior of the continent and at sites further south along the Ross Sea coast (Bromwich and Wang 2008). The
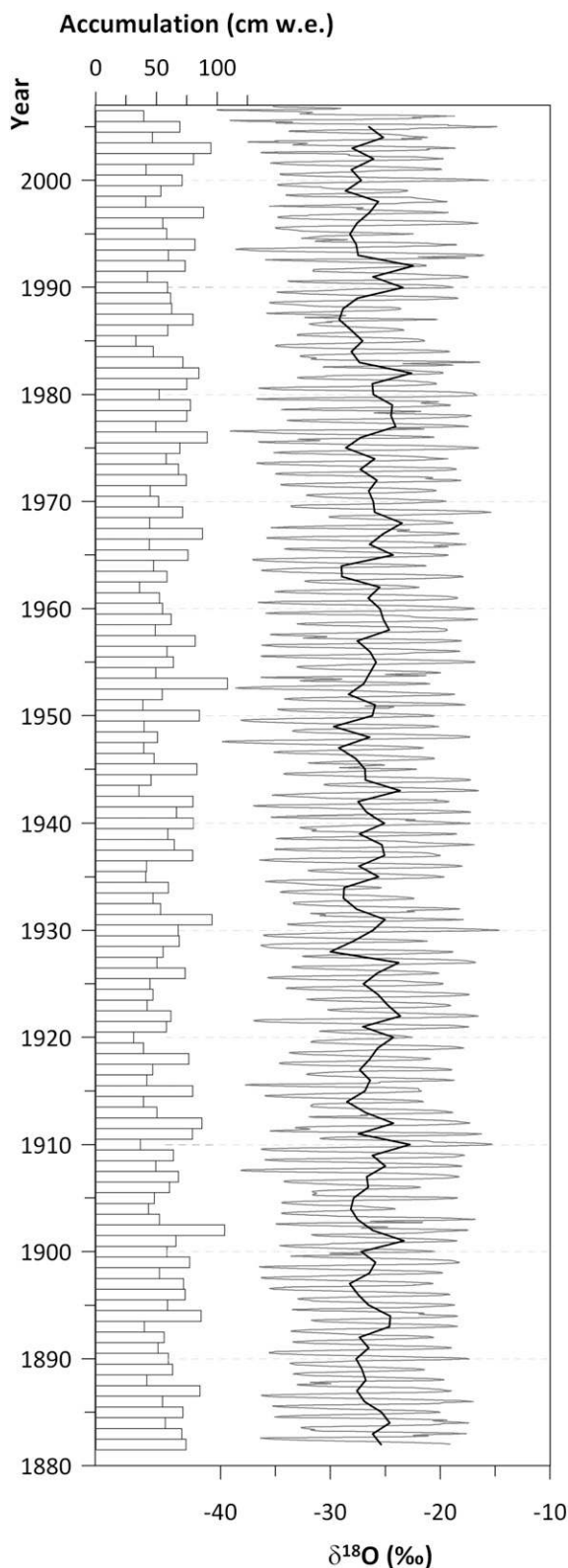

FIG. 2. The WHG ice core annual accumulation and $\delta^{18}O$. Diffusion-corrected $\delta^{18}O$ (see text for details) is shown by the gray line, and the 1882–2006 mean is shown by the black line.

mean annual accumulation from the ice core record is 61 cm of water equivalent (w.e.) yr^{-1}, which is of comparable resolution to the Law Dome ice core (64 cm w.e. yr^{-1}), (Fig. 1; van Ommen and Morgan 1997), making these sites complementary records of coastal–Antarctic Holocene climate variability. Although there is a high degree of interannual variability in accumulation ($1\sigma = 16.5$ cm w.e.), there is no significant long-term trend in accumulation at this site (Fig. 2).

A series of four snow pits were sampled at the site in November 2006 to assess the local variability in the stable isotope signal (Bull 2009). All snow pits demonstrate a high degree of consistency in the subseasonal variation in δD and $\delta^{18}O$. Although the coastal nature of this site makes it susceptible to strong katabatic winds, there is no indication that the winter signal is lost from the record because of wind erosion and all winter isotope minima are preserved in the record (Fig. 2). In addition, the ice core was logged and inspected for summer melt layers and there is no evidence that surface melt compromised the integrity of the record. This is supported by the temperature record from the Cape Hallett AWS, which is at an elevation of 0.5 m MSL (~400 m lower than the ice core site). This records daily temperatures above 0°C on only 28 days between May 2002 and December 2006 (1.6% of the time) with an average of 0.77°C. For this reason we expect the WHG site to have surface temperatures consistently below 0°C.

4. Precipitation seasonality

An important consideration in reconstructing temperature from stable isotope ratios is to establish if there is a seasonal bias in snowfall, as this will skew the annual isotope signal toward the season of highest precipitation (Charles et al. 1995; Vinther et al. 2010). The 40-yr ECMWF Re-Analysis (ERA-40) and ERA-Interim data have been previously shown to adequately reflect annual and subseasonal precipitation variability in the high southern latitudes after the incorporation of satellite measurements in 1979 (Monaghan et al. 2006; Bromwich et al. 2011) and have been used to reconstruct airmass pathways associated with precipitation at East Antarctic ice core sites (Scarchilli et al. 2010) and on the Antarctic Peninsula (Thomas and Bracegirdle 2009). Here, we investigate the ability of this dataset to reproduce accumulation at the WHG site by comparing total deposition recorded in the ice core record with annual ERA-Interim snowfall. For the first decade of ERA-Interim data (1989–99), reanalysis snowfall and ice core accumulation have no significant relationship, but from 2000 to 2005 the data are highly correlated ($r = 0.99$; $p < 0.01$) and the mean absolute difference in
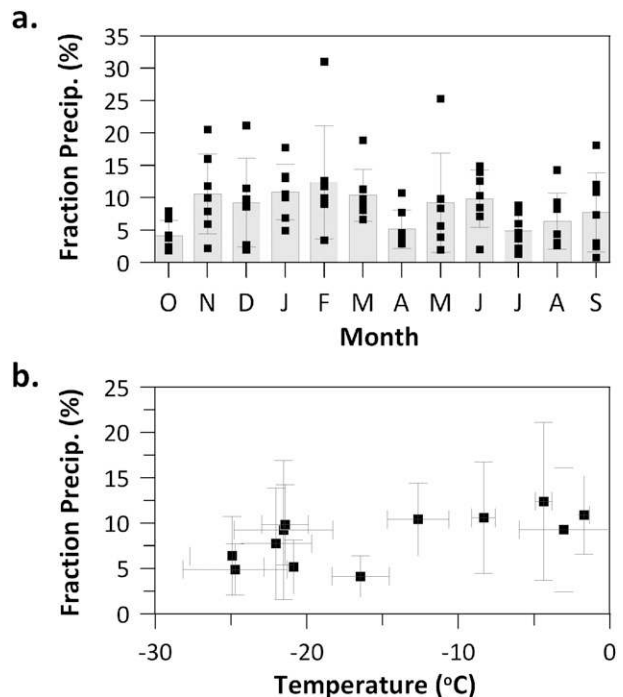

FIG. 3. (a) Monthly (October–September) ERA-Interim snowfall (2000–06) expressed as a fraction of the total annual accumulation along with mean values (gray bars) for this time period. (b) Mean monthly ERA-Interim snowfall and temperatures (2000–06). Error bars in both plots are one standard deviation around the mean.

accumulation is 6.7 cm w.e. yr^{-1}. The improved ability of ERA-Interim data to predict accumulation at the ice core site from 2000 onward is most likely due to the incorporation of additional AWS records into the reanalysis dataset and the improved parameterization of snowfall in the reanalysis data (Fig. 1; Dee et al. 2011).

In general, Antarctic precipitation is weighted toward periods with above-average atmospheric temperatures (Helsen et al. 2006; Marshall 2009), but the frequency of synoptic-scale storms plays a significant role in coastal areas because low pressure centers advect warm, moist air across the continent in all seasons (Sinclair et al. 2010; Nicolas and Bromwich 2011). As shown in Fig. 3a, months of April, July, August, and October bring only 4%–6% of the annual accumulation at WHG and all other months account for between 8% and 12% of precipitation. We find a significant relationship between mean monthly temperature and accumulation (Fig. 3b; $R^2 = 0.46$; $p = 0.02$). However, there is a considerable amount of interannual variability so that, although there is a tendency for more accumulation to occur in warmer months, high precipitation can occur in any month and is strongly influenced by the strength and frequency of large storm systems.

TABLE 1. Characteristics of ice core sites in proximity to the WHG.

	Elev (m MSL)	Distance to coast (km)	Mean temperature (°C)	Mean accumulation (cm w.e. yr^{-1})	$\delta^{18}O$–T slope (‰ °C^{-1})	References
Taylor Dome	2374	120	−43	6.7 ± 0.7	0.50*	Steig et al. (1998, 2000)
Talos Dome	2315	250	−41	8.7 ± 0.8	0.60	Stenni et al. (2002)
Law Dome	1390	100	−22	64.0	0.44	van Ommen and Morgan (1997)

* Converted from published dD–T slopes.

5. Isotope–temperature transfer function

Early work by Dansgaard (1964) showed that stable isotope ratios are primarily controlled by temperature-dependent fractionation processes between the evaporation site and the condensation site, so that in many areas there is a linear relationship between stable isotope ratios and surface temperature T. Provided that the isotope–temperature gradient stays consistent through time (e.g., Sime et al. 2009), this relationship can be used to reconstruct atmospheric temperature. For a series of Antarctic ice cores, Masson et al. (2000) find a $\delta^{18}O$–T slope of 0.81‰ °C^{-1} (converted from δD) and Masson-Delmotte et al. (2008) assessed the entire Antarctic stable isotope dataset, obtaining a conversion slope of 0.79‰ °C^{-1} (converted from δD) but note local slopes may vary by more than 20%. In addition, three deep ice cores have been drilled in East Antarctica within 250 km of the coast at Taylor, Talos, and Law Domes (Fig. 1). All three ice cores report lower isotope–temperature conversion slopes than the continent-wide average, ranging 0.44‰–0.60‰ °C^{-1} (Table 1).

To study seasonally resolved variations in the WHG isotope record it is necessary to account for water vapor diffusion in the firn column, which progressively smooths the signal and leads to a loss in seasonal amplitude with depth. This alters the apparent isotope–temperature calibration and introduces seasonally variable trends in the firn zone. We apply a diffusion correction procedure similar to that used by van Ommen and Morgan (1997) for fixed diffusion length in solid ice, but with modifications for use in the firn zone where a depth-varying diffusion length is necessary. We first compute the effective diffusion length at depth in the firn column (Cuffey and Steig 1998) using the local site parameters at WHG (density profile, mean temperature, and atmospheric pressure). This gives an integrated total diffusion length of 6.3 cm of ice equivalent, which is reached at 33-m depth (ca. 31-yr age) in the firn column. This is similar to diffusion length values observed in high accumulation cores from Law Dome, although lower than frequently adopted values of approximately 8 cm. The depth-varying diffusion length, derived as above, is then used to

deconvolve the isotope signal as in van Ommen and Morgan (1997), but computed piecewise through the firn column. Isotope variations with high spatial frequencies (short wavelengths) in ice are attenuated by diffusion to the point where reconstruction is not possible. We limit the reconstruction to wavelengths in ice longer than 33 cm by applying a low-pass filter in the deconvolution process.

To investigate the relationship between the seasonal cycle in stable isotopes and temperature at the WHG site, mean monthly temperatures are weighted by precipitation to account for the bias introduced by sub-seasonal precipitation variability. Figures 4a and 4b show the 2000–06 (September–August) cycle of monthly mean ERA-Interim temperatures and diffusion-corrected $\delta^{18}O$ and the least squares regression of these data, which results in an R^2 of 0.91 ($p < 0.01$; $n = 12$) and a linear fit described by

$$\delta^{18}O = 0.62T - 18.27.$$

To test the ability of the isotope–temperature transfer function to model temperature at the site, we compare reconstructed temperatures from diffusion-corrected ice core $\delta^{18}O$ to ERA-Interim surface temperature record for 2000–06. As shown in Fig. 4c, there is a close fit between modeled temperatures and reanalysis data. The strength of this relationship suggests that temperature is a dominant control on stable isotope ratios at the site rather than storm pathways, which can also impart a different stable isotope signal at a site because of variations in source region conditions and factors such as topography along storm pathways (Jouzel et al. 1997). However, as 2005 and 2006 isotope data from snow pits at the site have a higher variability in $\delta^{18}O$ than the ice core record because of the preservation of noise from individual storm events (Fig. 2), the relative influence of temperature and moisture trajectories is the focus of future investigation.

Given the strong linear isotope–temperature relationship at the site, we use this transfer function to reconstruct both summer [December–February (DJF)] and cold season [April–September (AMJJAS)] temperatures.
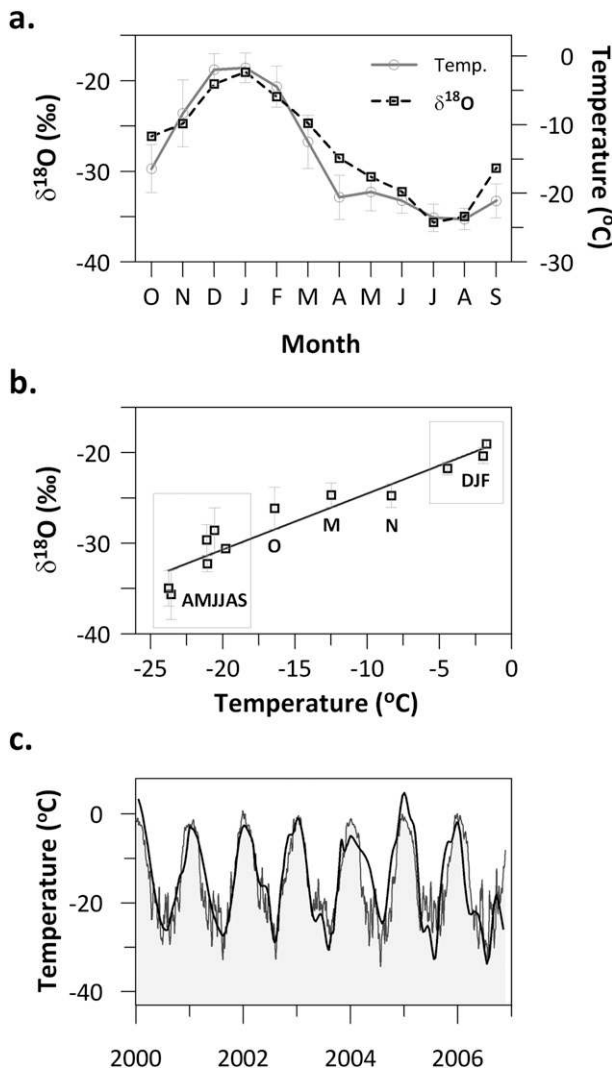
FIG. 4. (a) Mean monthly (October–September) cycle of ice core $\delta^{18}O$ and ERA-Interim temperature (2000–06). Error bars for temperature are one standard deviation around the mean. (b) Least squares regression of mean monthly $\delta^{18}O$ and temperature. The residuals from the regression model for each month are shown as error bars around $\delta^{18}O$. The summer (DJF) and cold season (AMJJAS) are delineated and the intermediate months, October (O), March (M), and November (N), are also marked. (c) Reconstructed site temperature (black line) and 7-point smoothed ERA-Interim daily temperatures (shaded plot) for 2000–06.

The long cold season at the site, with mean monthly temperatures of below $-20°C$ (Fig. 4a), is used in the temperature reconstruction rather than the conventional JJA austral winter because of the uncertainties in the ice core age model, particularly once the diffusion correction has removed some of the high-frequency seasonal isotopic variability.

At Scott Base on Ross Island, located approximately five degrees south of WHG (Fig. 1), a significant spring warming of $+0.41° \pm 0.39°C$ decade^{-1} is observed since 1958. This trend increases to $+0.64° \pm 0.69°C$ decade^{-1} since 1979 (Schneider et al. 2011). At WHG, there is no significant trend in summer or cold season temperatures since 1958. There is, however, a decrease in cold season temperatures of $-1.59° \pm 0.84°C$ decade^{-1} at 90% confidence ($p = 0.07$) since 1979 and no significant change in summer temperatures (Fig. 5).

Using the transfer function described above, we also reconstruct mean annual and seasonal temperatures for the 125-yr duration of the ice core record and find no significant trends between 1882 and 2006. In addition, we do not observe any significant changes in annual accumulation either over the 125-yr span of the ice core or since 1979. This may be in part due to the fact that more precipitation occurs in warmer months (Fig. 3b), so the accumulation budget is less sensitive to changes in winter temperatures. It is also possible that increased sea ice cover limits the evaporation from high-latitude source regions, so that decreasing surface temperatures (and increasing sea ice cover) result in less moisture availability.

6. Discussion and summary

A seasonal temperature reconstruction from the WHG ice core in the northwestern Ross Sea shows a cooling trend in months with mean temperatures of $-20°C$ and below (AMJJAS) since 1979. This indicates that the overall warming across West Antarctica over the past 50 years is not reflected at the northwestern margin of the Ross Sea. Furthermore, while this warming trend has been coincident with reduced sea ice extents in many areas (Comiso and Nishio 2008), the Ross Sea is one of the few regions experiencing a significant positive trend in sea ice extent and a negative trend in sea surface temperatures (Comiso et al. 2011). This is linked to a trend toward a more positive SAM since the mid-1960s, which promotes stronger southerly flow along the western margin of the Ross Sea and wind-driven sea ice advance (Thompson and Solomon 2002; Marshall et al. 2006; Stammerjohn et al. 2008).

The results of this study suggest that positive sea ice extent anomalies in the region adjacent to the WHG site, and cooler more vigorous meridional circulation in cooler months, may also be linked to lowered continental surface temperatures. However, we report a reconstruction from one ice core and additional data are required to investigate whether this is a regional cooling response. Furthermore, the temperature trends reported here are not observed at Scott Base on Ross Island where a significant spring warming has been observed (Schneider et al. 2011). For this reason, we suggest
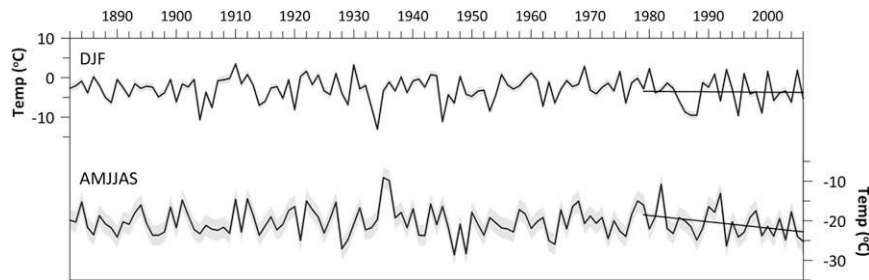
FIG. 5. Mean summer (DJF) and cold season (AMJJAS) reconstructed temperatures from 1882 to 2006. The line of best fit for data from 1979 onward is shown for comparison with the Scott Base temperature record (see text for details). The shaded area represents the error associated with the seasonal residual from the temperature–isotope regression model.

further investigation into the variability in terrestrial temperature to identify the latitudinal response to SAM and ENSO-driven climate variability along the western Ross Sea coast.

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