2013-03-15

Toward a Better Understanding of Recent Warming of the Central West Antarctic Ice Sheet from Shallow Firn Cores

Jessica Williams
Brigham Young University - Provo

Toward a Better Understanding of Recent Warming of the Central West Antarctic Ice Sheet from Shallow Firn Cores

Jessica Williams

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

Summer B. Rupper, Chair
Barry R. Bickmore
Stephen T. Nelson
William F. Christensen

Department of Geological Sciences

Brigham Young University

March 2013

ABSTRACT

Toward a Better Understanding of Recent Warming of the Central West Antarctic Ice Sheet from Shallow Firn Cores

Jessica Williams
Department of Geological Sciences, BYU
Master of Science

Previous studies have shown significant warming through the 1990s in the West Antarctic Ice Sheet (WAIS); but the records used in those studies end in early 2000, preventing trend analysis into the latest decade. Fourteen new snowpits and firn cores were collected in 2010 and 2011, which have been combined with previous cores to extend the isotopic records over WAIS. Significance of these isotopic patterns across WAIS was determined and is used to re-evaluate the warming of the West Antarctic interior over recent decades.

We find that isotopic records longer than 50 years are needed to assess climate trends due to decadal variability. When assessed over periods greater than 50 years, there is a statistically significant warming trend over central WAIS. However, the isotopes in the 2000s are anomalously low in the isotopic records, which challenge the recent suggestion that the warming trend is accelerating. We attribute the isotopic low over the most recent decade to the coupling effect of anomalously low temperatures over central WAIS and associated increase in sea ice in the adjacent seas. This work strongly indicates that decadal variability and likely climate trends are both driven, at least in part, by atmospheric variability in the tropics as well as at high latitudes.

Keywords: climate variability, Antarctica, isotopes, ice core

ACKNOWLEDGEMENTS

I would like to express my deep appreciation and gratitude to my advisor, Dr. Summer Rupper, for the patient guidance and mentorship she provided to me, before applying to the Master's program, throughout my Master's Candidacy, and to the completion of this degree. I am truly fortunate to have had the opportunity to work with her. I would also like to thank my committee members, Drs. Barry Bickmore, Stephen Nelson, and William Christensen for the friendly guidance, and thought provoking suggestions that each of them offered to me.

Similarly, I'd like to recognize Dave Tingey for the lab training I received prior to and during my thesis that was crucial to my research work. I am also grateful for the commitment made by the students in the glaciology and climate labs who spent countless hours assisting me with the preliminary lab work. Finally, I'd be remiss if I didn't acknowledge the sacrifices made by my family and my friends who kept me sane over the last two years.

Furthermore, I gratefully acknowledge the funding that made my thesis work possible. The support for this research work was provided by the National Science Foundation Office of Polar Programs Grant #0944730.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. Introduction

1.1 Motivation and Background

[1] The mass balance of Antarctica is shifting as a result of the rapid warming of the coasts and the continental interior. This warming may release copious quantities of freshwater into the ocean by melting ice shelves and increasing iceberg calving rates, thereby altering thermohaline circulation (Comiso, 2000; Eisen et al., 2008; Schneider et al., 2006; and Schneider and Steig, 2008). Additionally, this input of water into the ocean would contribute to sea-level rise, in which the rate and amount of rise is still under debate. Indeed, the Intergovernmental Panel on Climate Change (IPCC) described sea-level rise as "one of the major long-term consequences of human-induced climate change" (Stocker et al., 2007). The Antarctic ice sheet has the largest potential impact with an estimated sea-level rise equivalent of 61.1 m of fresh water (Church et al., 2001). The West Antarctic Ice Sheet (WAIS), with a sea-level rise equivalent of roughly 5 m, has the greatest potential for contributing to sea-level rise in the near term as it is potentially unstable. This potential instability is due to the fact that WAIS is grounded largely below sea-level, where warming waters rapidly melt the ice shelves resulting in increased glacial flow which drains the ice sheet (Vaughan and Spouge, 2002; Steig et al., 2012; and Steig et al., 2013).

[2] Understanding regional patterns in temperature change across Antarctica is extremely important because this atmospheric variation in turn affects the mass balance of WAIS by changing the accumulation rate, continental surface melt, evaporation, sublimation, and the size of the sea ice buffer (Comiso, 2000). However, all but two of the continuous automated weather stations on WAIS are near the coast, providing little direct information on conditions in the continental interior (Steig et al., 2009). Borehole temperature data provides additional

information in the ice sheet interior, but these data are also limited spatially and are not resolved on annual time scales (Steig et al., 2013). This lack of weather station and borehole temperature data complicates understanding of climate variability and detection over WAIS (Schneider and Steig, 2008). Although this proves to be problematic, isotopes, which covary with atmospheric circulation, can be used as proxies for temperature in WAIS.

[3] The isotopic records from firn and ice cores are useful in quantifying the temperature at the precipitation site over WAIS, although there are limitations to the use of these cores as a complete paleoclimate record. Sublimation, erosion and redistribution by the wind after precipitation can scour or redeposit snow; this makes the surface less homogenous than the original precipitation (Schneider and Noone, 2007; Jouzel et al., 1997; Helsen et al., 2005; Eisen et al., 2008; and Magand et al., 2005). Preservation of all annual layers in previous cores drilled across WAIS from the US ITASE project indicate that the magnitude of this erosion is insufficient to remove the entire annual accumulation record (Steig et al., 2005; Schneider et al., 2006; and Schneider and Steig, 2008). In addition, none of these erosive events will change the isotopic composition of individual snow grains. However, these erosive events can mix the isotope record as well as introduce bias if there is a seasonal preference to snow removal (Masson-Delmotte et al., 2008). These biases are likely to be greatest in lower accumulation areas, and must be acknowledged when assessing patterns and trends in isotopes across a large region.

[4] Additional limitations are the spatial and temporal extent of firn and ice cores. A single ice core is representative only at a local scale (both spatially and temporally) due to high frequency variability in microrelief (sastrugi) across the ice sheet; but with multiple cores, a regional spatial and temporal map can be compiled (Steig et al., 2005; Frezzotti et al., 2005; and

Eisen et al., 2008). The ice core records from the ITASE project were used to generate isotope-temperature trends for WAIS over the past several hundred years. However, these cores do not extend into the 2000s.

1.2 Objectives

[5] The purpose of this research was to determine if the temporal warming trend observed in WAIS ice core records during the 1990s extends into the most recent decade. This study obtained high resolution depth-age relationships for a suite of new firn cores collected during the 2010-2011 Antarctic field season. These new isotopic records were combined with the ITASE cores to quantify the spatial and temporal isotopic patterns across WAIS; particularly to determine the significance of trends through the most recent decade. Lastly, atmosphere-ocean mechanisms driving the isotopic records were evaluated.

1.3 Previous Work

[6] The long term temporal warming trend of WAIS over the last few centuries, excluding the most recent decade, has been recorded in the spatial and temporal isotopic patterns of the ITASE ice cores. Determining a temperature trend from ice cores is permissible because in mid-high latitudes, there is a linear relationship between the mean annual isotope content of precipitation (δD and $\delta^{18}O$) and the mean annual temperature at the precipitation site (Jouzel et al., 1997; and Rozanski et al., 1992). This δ-T relationship is related to the distance from the open ocean (extent of sea ice coverage), latitude (controls solar radiation input), elevation, source region, transport path, time of precipitation, and post depositional alterations (Schneider and Steig, 2008; Magand et al., 2005; Frezzotti et al., 2005; Jouzel et al., 1997; Küttel et al., 2012; Noone and Simmonds, 2002; and Masson-Delmotte et al., 2008). As expected from the abundance of seasonally dependent geographical parameters influencing δD and $\delta^{18}O$, Schneider

et al. (2005) found that site-specific δ-T correlations in the WAIS region are strong on a seasonal basis, which reinforces the use of stable isotopes as temperature proxies for our region of interest.

[7] Using the isotopic composition of ice cores, in combination with passive infrared brightness measurements, Steig et al. (2009) found that between 1957 and 2006, West Antarctica warmed at a statistically significant rate of 0.17±0.06 ºC per decade, with warming strongest in winter and spring. However, using compiled Byrd Station air temperature data, Bromwich et al. (2012) found significant warming of West Antarctica between 1958 and 2010 at a rate of 0.47±0.23 ºC per decade with the strongest warming in austral spring. The two different methods used to calculate warming trends in WAIS differ by more than a factor of two. However, the results from both studies suggest that there has been significant warming in West Antarctica over the last 50 years.

[8] Regional changes in atmospheric circulation are required to explain the enhanced warming in West Antarctica (Kwok and Comiso, 2002; and Steig et al., 2009). These changes may be due to stratospheric ozone depletion and the radiative changes of rising atmospheric CO_2 concentrations on the Southern Annular Mode (SAM), which is the variability in atmospheric flow not associated with the seasonal cycle (Banta et al., 2008; Thompson and Solomon, 2002; Schneider et al., 2005; Schneider et al., 2006; Schneider and Noone, 2007; and Ding et al., 2012). However, recent studies have noted that the pronounced warming in the central tropical Pacific is related to a persistent pressure anomaly north of the Amundsen Sea Embayment, an increase in sea surface temperatures (SST), and negative anomalies in sea ice extent (Schneider and Steig, 2008; Steig et al., 2009; Steig et al., 2012; Ding et al., 2012; and Steig et al., 2013). Therefore, there is a debate on whether changes in atmospheric CO_2 and ozone concentrations

are driving the regional atmospheric circulation, or if atmospheric circulation is dominated by anomalous climate conditions of the tropical Pacific.

[9] Although there has been significant warming in West Antarctica, particularly over the last 50 years, there is little to no isotopic data to compare with this warming over the last decade. Therefore, using new high resolution cores to extend the isotope records to 2010-2011, significance of isotope-temperature trends including the 2000s were determined. Furthermore, evaluation of atmospheric circulation patterns driving WAIS precipitation was assessed using a combination of isotopic records and climate indices. The methods used to recover and analyze the new cores are discussed below.

2. Methods

[10] Fourteen cores were collected as part of the Satellite Era Accumulation Traverse (SEAT) at sites less than 100 km apart in transect (Table 1 and Figure 1) during two Antarctic field seasons (2010-2011 and 2011-2012). The site selection for the SEAT cores was specifically chosen because it crosses the WAIS ice divide, which provides a strong accumulation gradient and likely an isotopic gradient. Additionally, the study area is located strategically in central WAIS, between the Ross and Amundsen Sea Embayments, where most of the ice stream and ice shelf changes are occurring. Moreover, the SEAT cores are adjacent to the Byrd weather station, WAIS Deep Core, and two previous shallow ITASE cores; allowing for validation of the isotopes as a temperature proxy and placing the new cores in context of previous cores. Lastly, our cores inform regional reliability of the new WAIS Deep Core. Therefore, as part of the SEAT project, a combination of analyses on the ice cores were completed both in the field and in the Glaciology Laboratory at Brigham Young University, which will be discussed below.

2.1 Field Work

[11] For the five SEAT cores drilled during the 2010-2011 field season, the following procedure was used in the collection of firn cores and snowpit samples. For the upper ~2 m, samples were collected along a snowpit wall to avoid compaction and mixing of the softer layers that would accompany coring. Snow samples were collected with a fixed volume snow cutter along the snowpit wall at 2 cm resolution using a crossover pattern to reduce contamination from overlying snow (Eisen et al., 2008). This 2 cm resolution thickness was chosen to ensure that a minimum of seven samples were analyzed per year in order to annually resolve the isotopic records (Eisen et al., 2008). A firn core was then drilled from the bottom of the snowpit to approximately 17 m depth in roughly 80 cm increments (to a max depth of 20 m). Each core section was measured for bulk weight and length, to be used later in the firn density calculations. Eisen et al. (2008) noted that there is often some unrecoverable loss of core material in firn due to powdering. Thus, core sections with questionable integrity (surface sections drilled after the snowpit) were processed in the field. This processing included electrical conductivity measurements (ECM) along the core profile, ~2 cm sectioning of each core, and measurements of thickness, diameter, and weight for each 2 cm sample. Cores, core samples, and snowpit samples were bagged and placed in core tubes. Each core tube was then packed with snow and placed in insulated ice core boxes for shipping to the Glaciology Laboratory at Brigham Young University. Temperature loggers were placed in each core box, and were used to ensure temperatures remained below freezing for the duration of transport from the field to the lab freezer.

[12] The procedure for cores collected during the 2011-2012 field season was similar to that of the previous year with minor exceptions. To increase efficiency of drilling operations, the

core was drilled next to the pit wall. This allowed for simultaneous sampling of the snowpit and drilling of the core. Also, powdering of samples was not observed in any of the core sections or snowpit samples collected the previous year. Thus, only a bulk weight and length of core sections were deemed necessary in the field and all other measurements were done in the lab.

2.2 Lab Work

[13] Most of the following lab measurements were made in order to compile the seasonal data records necessary for determining the depth-age scales for the SEAT cores. Field samples were re-measured with higher precision calipers for thickness and diameter, to insure quality sampling for more accurate volume calculations. The snowpit and core samples were then weighed on a high precision balance; resulting in a cumulative density uncertainty of 10% for snowpit samples and 5% for firn cores samples. On uncut core sections, ECM measurements were collected, following which 2 cm sections were cut and then sampled for thickness, diameter, and weight (as described above). All of the samples were melted in double sealed bags, and immediately decanted into two pre-labeled 25mL antistatic scintillation vials with sealing caps. One vial was promptly stored in a -20 °C freezer while the other remained in the lab until isotopic work on the samples were completed, usually within a month.

[14] Isotopic analysis of the snowpit and firn samples was completed using a Los Gatos Research Liquid Water Isotope Analyzer (LWIA-24d), which analyzes $\delta^{18}O$ and δD simultaneously and has a precision of 0.2‰ and 0.6‰ respectively. Batch sample set-up used the procedure outlined in Nelson (2000) and Nelson and Dettman (2001). Memory correction was addressed by rejecting the first four injections of each sample; following which, the remaining four injections of each isotope run was drift corrected (procedure used in Nelson and Dettman, 2001) using in-house standards. The in-house standards (calibrated by Vienna Standard Mean

Ocean Water and Standard Light Antarctic Precipitation) have isotopic values within the range of our data, thus reducing the influence of memory. Additionally, a quality check sample of similar isotopic values to the WAIS samples (Steig et al., 2013) was used to determine the error in the drift corrected samples throughout a batch. The final isotopic composition of a sample was determined by taking the average of the drift corrected injections.

[15] To calculate the depth-age relationship in the firn cores, the three seasonal data described above were used to resolve any ambiguities in the records. Specifically, the isotopes, density, and ECM data were used in combination to identify the annual layers within each core. Using multiple seasonal proxies to determine the depth-age relationship increases the certainty in the depth-age scale (Banta et al., 2008). Assignment of the depth-age scale between winter and summer peaks, using linear interpolation, is detailed in Steig et al. (2005) and Küttel et al. (2012). We then used solute spikes associated with the Pinatubo and El Chichón eruptions to validate the depth-age scale and quantify the depth-age uncertainty. The final depth age uncertainty was determined to be <±1 year for the snowpit and core samples younger than 1991, while the uncertainty increased to ±1 year for the older core samples.

2.3 Isotopic Statistical Analyses

[16] Several statistical tools were used to determine the spatial patterns and temporal trends in the isotopic data. Based on our depth-age relationships, our ice core records all extend back to at least 1976. This is imperative as several studies have shown that at least a 20 year record is required to do meaningful statistical evaluations (Chapman and Walsh, 2007; and Comiso, 2000). Since the SEAT cores are all greater than 30 years, a spatial isotopic comparison was made with the geographical parameters of latitude, altitude and distance to the coast, using least squares regression (Shuman and Stearns, 2001; and Ding et al., 2010). These spatial tests

determine whether the SEAT cores were associated with the same atmospheric conditions. Once the spatial relationship between cores was established, temporal tests were performed over varying time frames, where temperature trends over the last decade were established with autocorrelated least squares regression and incorporated into the context of prior decades. The significance level p of reported autocorrelated least squares regression accounts for the degrees of freedom reduced by the quotient $(1 - r_1 r_2)/(1 + r_1 r_2)$, where r_i is the lag-1 autocorrelation of time series i. Additionally, several simple statistical relationships were established (i.e. standard deviation, variance, skewness, kurtosis, mean, etc.) within each SEAT 2010 isotope record.

[17] Another statistical relationship that assisted in the determination of a warming trend was firn core stacking. Stacking, or averaging, firn cores increases the signal to noise ratio, which allows the temporal isotopic records to become more spatially representative (Schneider and Noone, 2007; and Steig, 2005). In order to stack multiple firn core records, the cores need to be dated at high resolution with a high level of accuracy and precision (Steig, 2005; and Banta et al., 2008). Stacking is supported due to the large-scale covariance of temperature and isotope anomalies in this region, and also by the reduction of non-climate related noise when proxy records are combined (Schneider et al., 2006).

3. Additional Data and Analysis

[18] Although the spatial and temporal relationships can be determined for our SEAT cores, relating these cores into the context of recent climatic and geographical parameters require several additional datasets. Geographical parameters influencing spatial and temporal isotopic composition were addressed using sea ice data obtained from Carsey (1992). Byrd air temperature data and climate indices were used to assess warming trends in central WAIS and

the driving mechanisms of these trends in the isotope records (Bromwich et al., 2012; Mo et al., 2000; Reynolds et al., 2001; and Trenberth et al., 1997).

3.1 Sea Ice Analysis

[19] Sea ice extent influences the seasonal signature observed in the isotopic composition of precipitation. In general, during the austral winter, sea ice extent is at a maximum and the transport pathway of precipitation is lengthened. The lengthened transport pathway of austral winter results in decreased precipitation and negative isotopic anomalies at the core sites, as compared to austral summer. Here we compare our isotopic data to sea ice area over time to assess the relative influence of sea ice extent on our firn core data. The sea ice area data used in this study were compiled by Carsey (1992) with a bootstrap method for the Amundsen-Bellingshausen and Ross Sea Embayments. We performed a time series analysis for the sea ice data in order to quantify the trend in area over the past three decades. This analysis was done using an autocorrelated least squares regression and is used to determine if any trends in the isotopic data could be the result of trends in the sea ice. Autocorrelated correlation coefficients were also calculated between the two sea ice areas and the five SEAT isotope time series in order to assess the influence of sea ice variability on isotopic variability at our core sites.

3.2 Byrd Air Temperature Record

[20] Comparison between the Byrd air temperature record in central WAIS with the SEAT isotopic records are possible using the established 0.5‰/ °C conversion in Steig et al. (2013), and allows for a comparison between the Byrd air temperature data and the inferred warming trends from our isotopic data in our region. The air temperature data used in this study were compiled from Byrd Station by Bromwich et al. (2012), and covers the time period of 1957 to 2012. The monthly mean temperature data Bromwich et al. (2012) used to assemble this

record was derived mostly from weather station data, although occasional infilling of the data was required due to gaps in the station data. They used a combination of adjusted 2 m air temperature from ERA-40 and NCEP reanalyses and spatial interpolation of other Antarctic station observations to infill the missing data in the early to middle 1970s. Thereafter, infilling was from adjusted 2 m temperatures from the ERA-Interim reanalysis.

3.3 Climate Analyses

[21] Climate indices are a measure of the temporal variability of the coupled atmosphere-ocean system across a given region, and can provide insights into the climate variability giving rise to the isotopic variability in the cores. The climate indices used in this study are monthly averaged SAM, Southern Oscillation Index (SOI), and Niño3.4 data which are from NOAA's Climate Prediction Center. SAM is the difference of zonal mean sea-level pressure (SLP) at 40°S and 65°S, and is a proxy for average circumpolar westerly wind strength (Ding et al., 2012; Mo et al., 2000; and Steig et al., 2012). SAM has a base period from 1979 - 2000, whereas the data extends from January 1979 to the present. SOI is the SLP change between Tahiti and Darwin (Reynolds et al., 2001). SOI has a base period, for which the data has been standardized, from 1981- 2000 whereas the data extends from 1951 to the present. Niño3.4 is the SST from 5° North - 5° South and 170° - 120° West. Niño3.4 has a base period from 1981 - 2000, whereas the data extends from January 1982 to the present (Trenberth et al., 1997). The Niño3.4 region is a measure of the central Pacific SST variability (Ding et al., 2012; and Steig et al., 2012). Both SOI and Niño3.4 are associated with El Niño Southern Oscillation (ENSO) episodes, which are driven by changes in the tropical Pacific (Kwok and Comiso, 2002). Autocorrelated correlation coefficients were calculated between the three climate indices and the five SEAT isotope time

series to determine if isotopic variability over West Antarctica is linked to a given mode of climate variability.

[22] Although climate variability may drive isotopic composition, changes in the tropical Pacific may more fully be driving the isotopic variability in the cores during anomalous years. Using the anomalous years in the stacked SEAT record, composite records of the SAM, SOI, and Niño3.4 data were compiled for the overlap period of 1980-2010. This composite analysis infers whether anomalous years in the isotopic record were driven by one of the dominant modes of climate variability. The anomalous years were analyzed in the SAM, SOI, and Niño3.4 data; where the difference in the means of the anomalous years and the entire data period were calculated for each record. The difference in the means was then compared to zero using a two-tailed Student's t-test, to determine if the anomalous years in the SAM, SOI, and Niño3.4 data were significantly different (Steig et al., 2013).

4. Spatial Patterns in SEAT Isotopic Records

[23]Analysis of the spatial patterns in the SEAT isotopes helps determine whether the cores are influenced by the same changes in atmospheric circulation and would be expected to have similar isotopic compositions. This will allow for direct comparison of the isotopes between the cores, and supports the assumption that a stacked record is a reasonable representation of the region.

4.1 SEAT Isotopic Records

[24] Constructed $\delta^{18}O$ time series of the SEAT 2010 cores are shown in Figure 2. The shortest record covers 1976 to 2010 while the longest record extends to 1967. As seen in the isotopic records, there is a clear seasonal cycle imprinted on the isotopic composition. The peaks in the record are indicative of the warmer temperatures observed in austral summer, whereas the

troughs are indicative of the cooler temperatures of austral winter. Preservation of all annual layers in the SEAT cores was validated by solute volcanic horizons indicating that winds were not sufficient in removing the precipitation of entire years from the isotopic records. Additionally, the fairly smooth cyclical records of the SEAT cores indicate that precipitation removal (if any) from the core sites was not biased to a particular season. Moreover, several statistical relationships were established for each SEAT 2010 isotope record (Table 2). Although the means for each of the cores are similar, there are some distinct patterns within the mean isotopic composition that will be addressed further in the following section.

4.2 Geographic Effects on Isotopes

[25] There are several geographical parameters that can affect mean isotopic composition of the firn core records, including latitude, elevation, and distance to the ocean (Schneider and Steig, 2008; Magand et al., 2005; Frezzotti et al., 2005; Jouzel et al., 1997; and Masson-Delmotte et al., 2008).

4.2.1 Elevation

[26] The mean isotopic value for each of SEAT 2010 and SEAT 2011 cores were compared to the elevations at each of the core sites (Figure 3A). There is an extremely low, insignificant correlation (r = 0. 3418, p = 0.2317) between elevation and mean isotopes; indicating, at least for the number of cores used in the analysis, that there is not a strong linear relationship between the two parameters. However, elevation has been shown to play a strong role in isotopic patterns in many regions of the world, including Antarctica (Magand et al., 2005; and Masson-Delmotte et al., 2008). The lack of a clear relationship between elevation and isotopes may be due to the overwhelming continentality (distance from source) effect in this region (discussed in detail below). In general, however, these results most strongly suggest that

the elevation differences between the core sites are not a dominant control on the mean isotopes in central WAIS.

4.2.2 Latitude

[27] The latitude for each of the SEAT 2010 and SEAT 2011 cores were compared to the mean isotopic value at each core site (Figure 3B). A statistically significant correlation (r = 0.7097, p = 0.0045) exists for the SEAT cores. This is expected because both solar radiation and distance from the source region would impart a similar influence on isotopic composition and are directly related to latitude in this region. However, it is hard to extract the contributing importance of solar radiation versus distance from the coast (or source region) directly from the latitude data.

4.2.3 Sea Ice Area

[28] Distance from the open ocean is controlled not only by latitude, but also by sea ice extent. Indeed, variability in sea ice extent will change the distance of the cores to the moisture source. Here, sea ice areas are used as a means for integrating the extent of the sea ice over all possible source regions, thereby incorporating several potential precipitation transport pathways into the analysis. The mean monthly sea ice area time series for both the Amundsen-Bellingshausen and the Ross Sea Embayments are shown in Figure 4. The average trend for the Amundsen-Bellingshausen Sea Embayment shows a decrease in the sea ice area over the past thirty years; however, the Ross Sea Embayment shows the reverse. These results are consistent with previous studies highlighting the anticorrelation in sea ice trends between the Ross Sea and the Amundsen-Bellingshausen Sea (Cavalieri and Parkinson, 2008). In Figure 5, a correlation matrix indicates that the mean seasonal sea ice areas and mean seasonal isotopes are significantly correlated for the Amundsen-Bellingshausen Sea Embayment, for both the sea ice area and the

detrended sea ice area. Since both correlations are statistically significant, this indicates that the variability in sea ice is driving the high correlation with isotopic records. This correlation suggests that the transport pathway of precipitation in central WAIS comes across the Amundsen-Bellingshausen Sea, which agrees with Genthon et al. (2005).

[29] The statistically significant relationships between latitude and isotopes as well as sea ice area and isotopes, both strongly suggest that distance from the source plays an important role in determining the spatial and temporal patterns in the isotopes. This is illustrated further in Figures 1 and 2 where SEAT-10-4 is the closest to the coast and is the least negative (indicative of a warmer temperatures) whereas SEAT-10-6 is the furthest core inland and has the most negative isotopic mean (indicative of cooler temperatures). Although there is a spatial component resulting in the slight differences in mean isotopic composition for the SEAT cores, there is additionally a temporal component which is only partly explained by the changes in sea ice extent.

5. Temporal Trends in Isotopic Records

[30] The isotopic temporal trends in the SEAT and ITASE (Steig et al., 2005; Schneider et al., 2006; and Schneider and Steig, 2008) firn and ice cores can be used to infer temperature trends across WAIS; particularly to determine the significance of trends including the most recent decade. This inference makes the explicit assumption that the isotopes in this region are indeed a good proxy for temperature.

5.1 Stacked SEAT Record

[31] As noted above, averaging the ice core isotopic records can reduce the local noise and result in a single record representative of the larger region. However, the choice of averaging may affect the results. Therefore, two SEAT-2010 stacked records (Figure 6) were calculated

and compared in order to determine whether the averaging method would affect the results. The first stacked record is an equally weighted average of the annual SEAT 2010 isotopes (Figure 6A, black line). The second stacked record is weighted based on area (Figure 6A, red line), using the Thiessen Polygon perpendicular bisector method between the SEAT 2010 cores (i.e. cores that are clustered together are weighted less than cores that are further apart). Statistical comparison of the equal and area weighted records are shown in Figure 6B. There is a statistically significant correlation ($r = 0.9688$, $p = <0.0001$) between the weighted records. Thus the choice of averaging is unlikely to significantly affect interpretation of the results. Therefore, due to the simplicity of the equal weighted record, it will be used throughout the remainder of the analyses.

5.2 Statistical Analysis of Temporal Trends

[32] One of the questions posed earlier was whether the warming trend observed in previous studies (Steig et al., 2009; and Bromwich et al., 2012) continues into the latest decade; the response to this is best illustrated in Figures 7 and 8. Figure 7 shows the annually averaged SEAT cores excluding the 2000s; this was done so to be more comparable with the ITASE cores which terminate in the early 2000s. From this, we see a positive isotopic trend in most of the cores and in the stacked record. The SEAT isotopic records were transformed into temperature changes under the assumption that mean annual isotopic content of precipitation is linearly related to the annual temperature at the precipitation site in mid-high latitudes (Jouzel et al., 1997; and Rozanski et al., 1992). Here we use a predetermined conversion of 0.5‰ per °C for change in isotopes to change in temperature over WAIS (Steig et al., 2013). Although the warming inferred in the SEAT cores is larger than that of the previous studies using the ITASE cores, it is still well within the same order of magnitude (Steig et al., 2009; Thompson and

Solomon, 2002; Schneider et al., 2005; Schneider et al., 2006; Schneider and Noone, 2007; Steig et al., 2012; Ding et al., 2012; Bromwich et al., 2012 and Steig et al., 2013). However, the trends for the same cores when including the latest decade (Figure 8) are not statistically significant and vary between positive and negative isotopic trends. Therefore, including the latest decade drastically changes both the magnitude and possibly the sign of the trend over the last forty years. The time frame, therefore, can greatly influence the resulting isotopic and inferred temperature trends on these timescales.

[33] The influence of the chosen time frame on isotopic trends is further evident in Figures 9 and 10. Using autocorrelated least squares regression (Figure 9), analysis of the isotopic trend from the point shown on the graph to 2009 was performed (i.e. for SEAT-10-6 the slope at 1985 is the trend analysis from 1985 to 2009). While most of the cores have a negative isotopic trend throughout the analysis, very few of the cores have significant trends at the 95% confidence level. The exception is SEAT cores 3 and 4 which show large periods of statistically significant negative slopes. However, Figure 10 performs the trend analysis in the reverse direction, where the isotopic trend is from the oldest year in the record to the point shown on the graph (i.e. for SEAT-10-6 the slope at 1985 is the autocorrelated least squares regression from 1970 to 1985). This illustrates that most of the cores have statistically insignificant positive isotopic trends throughout the analyses. Thus, not only is the end date important when doing trend analysis, but also the start date used to analyze the time series records. Regardless, the stacked records in both Figures 9 and 10 only showed statistically significant positive trend over very limited time frames. This lack of statistically significant trends through much of the stacked record may be due to two reasons: (1) the decadal variability in the cores masks any trends in isotopes and, by proxy, temperature, or (2) there is no trend in isotope/temperatures over this

region. The following sections discuss both possible reasons for the lack of significant temperature trends in central WAIS.

5.3 Regional Record

[34] Extending the SEAT cores with the ITASE cores increases the record length and reduces the potential masking effect of decadal variability on the trend analysis. This temporally-extended regional record permits another evaluation of the central WAIS temperature trend. The regional record was compiled by stacking the SEAT 2010 cores with the ITASE cores that surround the SEAT site (Figure 11, bolded black line), including SEAT-10-1, SEAT-10-3, SEAT-10-4, SEAT-10-5, SEAT-10-6, ITASE-00-1, ITASE-00-2, ITASE-00-4, ITASE-00-5, ITASE-00-6, ITASE-01-1, ITASE-01-2, and ITASE-01-3. In addition to the full stacked record of the cores, partial stacks were made for every possible permutation of four different ITASE cores (the number of available cores for the earlier part of the record), resulting in 70 possible stacked records (Figure 11, faint black lines). The partial stacks were plotted as partially transparent lines, so the darker regions indicate the overlap of multiple partial stacks. However, the average of all the records is used as a representative regional record of central WAIS. This long term record is similar to the compiled ITASE record for all of WAIS in Steig et al. (2013); however, notable differences exist between the two regional records. Our central WAIS record shows that the 1990s are not as $\delta^{18}O$ enriched, the 1940s are much more $\delta^{18}O$ enriched, the 1850s are $\delta^{18}O$ enriched, and the early 1820s are not $\delta^{18}O$ enriched as compared to the WAIS record of Steig et al. (2013). Steig et al. (2013) attributed the upward isotopic trend of the last 50 years in the WAIS record to the anomalous 1990s. However, our cores do not have anomalous 1990s. An autocorrelated least squares regression was performed for the central WAIS isotopic data, including and excluding the 2000s data. For both time frames, the longer timescale shows

statistically significant warming at the 95% confidence level (without the anomalously high 1990s) that exceeds the extreme negative decadal variability of the 2000s. This indicates that a much longer time frame than the suggested minimum of 20 years is necessary to do meaningful trend analysis in this region. Additionally, long term isotopic trend analysis (including and excluding the 2000s) indicate that the isotopes in the 2000s were anomalously low, as the isotopes of the later 2000s extend substantially past the 95% confidence intervals. The anomalous 2000s are also evident in the long term warming trend for the regional record which is 0.136°C/ decade excluding the 2000s and 0.102°C/ decade including the 2000s.This longer record therefore illustrates two important things: there is a warming trend in the data that is only recognizable over a longer time frame, and the isotopes during the 2000s are anomalously low and may counter a recent suggestion that the warming trend over this region of central WAIS is accelerating (Bromwich et al., 2012).

[35] Although geographical parameters control isotopic composition of Antarctic precipitation spatially, temporal variability also influences the isotopes in the SEAT cores. Atmospheric circulation anomalies that contributed to changes in sea ice, sea surface temperature, sea-level pressure, source region, and precipitation transport path, should have also influenced the isotopic content of West Antarctica (Schneider and Steig, 2008; Magand et al., 2005; Frezzotti et al., 2005; Jouzel et al., 1997; Küttel et al., 2012; Masson-Delmotte et al., 2008; and Steig et al., 2013). These circulation anomalies that result in the climate trends, inferred from the isotopic records of central WAIS, have been associated largely with changes in the tropical Pacific (Küttel et al., 2012; Ding et al., 2012; and Steig et al., 2013) and will be discussed in the following section.

6. Climatic Drivers of WAIS Isotopes

[36] Since temporal isotopic patterns are driven by complex atmosphere-ocean interactions, comparison between these interactions and the SEAT cores were made. This included comparison between the isotopic composition and the Byrd temperature record, which is located within the same general area of central WAIS as the SEAT cores. Furthermore, tropical Pacific connections to the SEAT isotopic records were made using analysis of SST, SLP, and circumpolar westerly wind strength indices.

6.1 Temperature Comparison

[37] The SEAT isotopic records were transformed into relative temperature changes and compared to the compiled in-situ air temperatures measured at Byrd Station (Steig et al., 2013; and Bromwich et al., 2012). As evident in Figure 12, the magnitude of the change calculated over central WAIS closely mimics the observed air temperature change at Byrd Station over the period 1957 to about 2000. After 2000, the Byrd Station and SEAT records both show a general decrease in temperature. However, the magnitude of the change calculated for the SEAT records is nearly a factor of five larger than that observed at Byrd Station. This may in part be explained by the anomalous conditions of sea ice during the 2000s. In general, the sea ice area significantly increased in both the Amundsen-Bellingshausen and Ross Sea Embayments during the 2000s, which would give rise to a decrease in isotopic composition of precipitation in central WAIS. This coupled with the cooling temperatures observed at Byrd Station could have resulted in the anomalously low isotopes of the 2000s in the SEAT records. In addition, the evidence for decreasing regional isotopes, decreasing temperature at Byrd Station, and the increasing sea ice extent all suggest that the cooler temperatures of the 2000s is a spatially expansive change, and not a local or regional phenomenon.

6.2 Recent Climate Trend Associated with Tropical Pacific

[38] Recent climate trends in West Antarctica (inferred from isotopic records) are influenced by anomalous convection over the tropical Pacific which propagates to the poles through atmospheric Rossby waves (Steig et al., 2013). Using isotopic records as a proxy for climate information provides a longer and more spatially distributed record of climate change than the available observations (Schneider et al., 2005). Typical climate patterns connected with tropical Pacific variability are SOI and Niño3.4, which are associated with ENSO. However, the SAM index, which is the average circumpolar westerly winds, is not independent of tropical conditions as it is forced by tropical variability (Steig et al., 2012; and Ding et al., 2012). Therefore, the SOI and Niño3.4 climate indices are directly dependent on the tropical Pacific while SAM is indirectly dependent on changes in the tropics. In Figure 13, correlation of the annually and seasonally averaged climate indices with the stacked SEAT record was analyzed. The SEAT stacked record is negatively correlated with SLP (SOI) in austral spring at the 95% confidence level. Furthermore, a detrended analysis was performed due to the lack of trend in the SEAT stacked record versus a significant trend in some of the climate indices. This yielded a positive correlation at the 95% confidence level between the SEAT stacked record and the circumpolar westerly wind strength (SAM) in austral fall, indicating that the variability (not the trend) in circumpolar westerly wind strength is correlated to the stacked SEAT record. Moreover, this suggests that during transitional seasons, changes in circumpolar westerly wind strength and SLP may be the long term driving forces in SEAT isotopic composition. This is consistent with the sea ice-isotopic relationship suggested above as these are the seasons during which sea ice variability is greatest.

[39] There are statistically significant relationships between the climate indices and the stacked SEAT record for austral fall and spring; however, changes in the tropical Pacific may more fully be driving isotopic composition during anomalous years. In other words, many combinations of atmospheric circulation conditions may give rise to the average isotopes, but perhaps extreme years are more fully explained by a limited number of atmospheric circulation patterns. To test this, a composite analysis was performed where the anomalous isotopic years (± 0.5 standard deviation about the mean) were determined from the stacked SEAT record (Table 3). Comparison of the climate index mean over the anomalous isotopic years to the mean of the climate index over 1974-2010 (full coverage in SEAT individual records) was made using a student's t-test. The composite yielded a statistically significant difference in the means for circumpolar westerly wind strength (positive) in austral fall, and ENSO (SOI is positive, Niño3.4 is negative) in austral summer. Furthermore, the 2000s were anomalously high in SOI which may also have contributed to the anomalously low isotopes in the SEAT cores. Thus, over anomalous years austral fall and summer were the seasons where climate indices seem to be driving the isotopic composition in the SEAT records, while decadal variability may be attributed to SOI.

[40] The statistical comparisons of isotopic composition and climate indices suggests that central WAIS isotopes (and temperature) are influenced by tropically induced changes in the circumpolar westerly wind strength during austral fall and tropical sea-level pressure and sea surface temperature changes during austral spring-summer. Thompson and Solomon (2002) attributed climatic drivers during transitional seasons (austral fall and spring) to the gradient of strong winter and the weak summer mid-high latitude atmospheric circulation patterns (by default there is also a temperature gradient between winter and summer). Küttel et al. (2012) also

found that for the ITASE cores in our region, isotopic composition was strongly linked to large-scale atmospheric circulation (due to pressure anomalies over the Amundsen and Ross Seas), West Antarctic sea ice, and temperature during the fall. Steig et al. (2013) attributed the strong atmospheric Rossby wave response to the anomalous conditions of ENSO in the tropical Pacific. In conclusion, although circumpolar westerly wind strength is driving the isotopic composition in central WAIS, changes associated with ENSO (sea surface temperature, sea-level pressure, and by extension sea ice) in the tropical Pacific from radiative forcing associated with greenhouse gas concentrations are required to explain the warming trend of the region (Steig et al., 2009).

7. Conclusions

[41] Our sea ice area comparison and previous studies suggest that for this region in central WAIS, the transport pathway is dominated by storms originating from the Amundsen-Bellingshausen Sea Embayment (Genthon et al., 2005). Furthermore, the latitude and sea ice area data correlate significantly with the SEAT 2010 mean isotopes, indicating that distance to the coast significantly influences the spatial and temporal variability of the SEAT isotopes. Therefore, combining these geographical parameters with the similar variability and mean isotopic values found in the SEAT 2010 and 2011 cores, it is likely that the cores are seeing the same regional atmospheric circulation patterns; thus, isotopic changes are directly comparable between cores over temporal time scales of interest here.

[42] An unanticipated result was that the SEAT 2010 isotopic records showed anomalously low isotopic content and, by proxy, anomalously low temperatures over the 2000s. This is also evident in the Byrd air temperature record which is the closest station to our SEAT cores. The magnitude of isotopic temperature variability prior to 2000 mimics closely the

observed temperature warming at Byrd Station. However, while Byrd Station also recorded a decrease in temperature during the 2000s, the magnitude of cooling is about a factor of five larger in the SEAT records, given the assumption that the isotopes are a simple record of temperature. In reality, this anomalous cooling recorded in the SEAT isotopes is likely due to the coupling effect of anomalously high sea ice area and low temperatures over central WAIS. This extremely large decadal variability complicates trend analysis of the SEAT cores, and results in significant shifts in the apparent isotopic trends depending on the time frame analyzed. Thus, in this region of WAIS, assessing temperature or isotopic trends requires much longer records than often used. This may account for the wildly variable trends reported by different research groups (Bromwich et al., 2012; Steig et al., 2013; Steig et al., 2009; and Schneider at al., 2005). In other words, the differences in temperature trends reported from ice core analyses may not be entirely due to regional variability in recent temperature trends, but instead due, at least in part, to the different time periods over which the trend analysis is applied.

[43] To more accurately determine if there has been a significant warming trend in this region of WAIS given the large decadal variability, a longer stacked record of central WAIS was compiled from the ITASE cores surrounding our SEAT cores. This long stacked record is different from the record shown in Steig et al. (2013), in that their record compiles all of the ITASE cores and is representative of all of WAIS, while ours places central WAIS into context of this larger region. Our central WAIS record shows that in comparison to the WAIS record of Steig et al. (2013), the 1990s are not as $\delta^{18}O$ enriched, the 1940s are much more $\delta^{18}O$ enriched, the 1850s are $\delta^{18}O$ enriched, and the early 1820s are not $\delta^{18}O$ enriched. Steig et al. (2013) attributed the warming trend of WAIS to the upward trend of the last 50 years and particularly the anomalous 1990s. However, our central WAIS long record does not have anomalously high

isotopic composition during the 1990s, but instead had anomalously low isotopic composition during the 2000s, and yet a significant warming trend persists. This indicates that there is a long term warming trend in this region of WAIS despite anomalous conditions during the 2000s.

[44] Several climate indices have been used to determine the driving atmospheric forcings resulting in isotopic-temperature changes over WAIS. Seasonal climate indices were compared to the stacked SEAT record, which was positively correlated with the circumpolar westerly wind strength (SAM) in austral fall while SLP (SOI) and SEAT are negatively correlated in austral spring at the 95% confidence level. Additionally, during anomalous years in the SEAT isotopic record, circumpolar westerly wind strength was positively correlated with the stacked SEAT record in austral fall, while sea-level pressure was positively and sea surface temperature was negatively correlated with the stacked SEAT record in austral summer. Furthermore, decadal variability of SOI closely resembles that of the SEAT cores. Thus in central WAIS the isotopic composition is driven by tropically induced changes in the circumpolar westerly wind strength during austral fall and tropical sea-level pressure and sea surface temperature changes during austral spring-summer, with decadal variability attributed largely to sea-level pressure changes.

[45] This work indicates that longer records (>50 years) are needed to assess climate trends from ice core isotopes due to decadal variability in central WAIS. This decadal variability is likely driven, at least in part, by atmospheric variability at high latitudes and in the tropics. Shifts in high latitude variability are currently being driven by changes in greenhouse gas concentrations and stratospheric ozone (Banta et al., 2008; Thompson and Solomon, 2002; Schneider et al., 2005; Schneider et al., 2006; Schneider and Noone, 2007; Steig et al., 2009; and Ding et al., 2012) and shifts in the tropics are mainly due to the response of ENSO to greenhouse

gas concentrations (Schneider and Steig, 2008; Steig et al., 2009; Steig et al., 2012; Ding et al., 2012; and Steig et al., 2013). Therefore, the response of both the tropics and high latitudes to anthropogenic activities will impact the long term temperature trends and decadal variability over central WAIS in the near future.

8. References

Banta, J.R., McConnell, J.R., Frey, M.M., Bales, R.C., and Taylor, K., 2008, Spatial and temporal variability in snow accumulation at the West Antarctic Ice Sheet Divide over recent centuries: Journal of Geophysical Research, v. 113, p. 8, doi: 10.1029/2008jd010235.

Bromwich, D.H., Nicolas, J.P., Monaghan, A.J., Lazzara, M.A., Keller, L.M., Weidner, G.A., and Wilson, A.B., 2012, Central West Antarctica among the most rapidly warming regions on Earth: Nature Geoscience, doi:10.1038/ngeo1671.

Carsey, F.D., 1992, Microwave remote sensing of sea ice: Geophysical Monograph Series, v. 68, p. 1-462, doi:10.1029/GM068.

Cavalieri, D.J. and Parkinson, C.L., 2008, Antarctic sea ice variability and trends, 1979–2006: Journal of Geophysical Research, v. 113, p. 19, doi:10.1029/2007JC004564.

Chapman, W.L., and Walsh, J.E., 2007, A synthesis of Antarctic temperatures: Journal of Climate, v. 20, p. 4096-4117.

Church, J.A., Gregory, J.M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M.T., Qin, D., Woodworth, P.L., Anisimov, O.A., Bryan, F.O., Cazenave, A., Dixon, K.W., Fitzharris, B.B., Flato, G.M., Ganopolski, A., Gornitz, V., Lowe, J.A., Noda, A., Oberhuber, J.M., O'Farrell, S.P., Ohmura, A., Oppenheimer, M., Peltier, W.R., Raper, S.C.B., Ritz, C., Russell, G.L., Schlosser, E., Shum, C.K., Stocker, T.F., Stouffer, R.J., van de Wal, R.S.W., Voss, R., Wiebe, E.C., Wild, M., Wingham, D.J., and Zwally, H.J., 2001, Chapter 11: Changes in Sea Level, *in* Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K. and Johnson, C.A., eds., Climate change 2001: the scientific basis: Cambridge, UK, Cambridge University Press, p. 639-693.

Comiso, J.C., 2000, Variability and Trends in Antarctic Surface Temperatures from In Situ and Satellite Infrared Measurements: Journal of Climate, v. 13, p.1674-1696.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Hólm, E.V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N. and Vitart, F., 2011, The ERA-Interim reanalysis: configuration and performance of the data assimilation system: Quarterly Journal of the Royal Meteorological Society, v. 137, p. 553-597.

Dimarzio, J., Brenner, A., Fricker, H., Schutz, R., Shuman, C.A., and Zwally, H.J., 2007, GLAS/ICESat 500 m laser altimetry digital elevation model of Antarctica: Boulder, Colorado USA: National Snow and Ice Data Center. Digital Media.

Ding, M.H., Xiao, C.D., Jin, B., Ren, J.W., Qin, D.H., and Sun, W.Z., 2010, Distribution of delta O-18 in surface snow along a transect from Zhongshan Station to Dome A, East Antarctica: Chinese Science Bulletin, v. 55, p. 2709-2714.

Ding, Q., Steig, E.J., Battisti, D.S., and Wallace, J.M., 2012, Influence of the Tropics on the Southern Annular Mode: Journal of Climate, v. 25, p. 6330-6348.

Eisen, O., Frezzotti, M., Genthon, C., Isaksson, E., Magand, O., van den Broeke, M.R., Dixon, D.A., Ekaykin, A., Holmlund, P., Kameda, T., Karlof, L., Kaspari, S., Lipenkov, V.Y., Oerter, H., Takahashi, S., and Vaughan, D.G., 2008, Ground-based measurements of spatial and temporal variability of snow accumulation in East Antarctica: Reviews of Geophysics, v. 46, p. 39, doi:10.1029/2006RG000218.

Frezzotti, M., Pourchet, M., Flora, O., Gandolfi, S., Gay, M., Urbini, S., Vincent, C., Becagli, S., Gragnani, R., Proposito, M., Severi, M., Traversi, R., Udisti,R., and Fily, M., 2005, Spatial and temporal variability of snow accumulation in East Antarctica from traverse data: Journal of Glaciology, v. 51, p. 113-124.

Genthon, C., Kaspari, S., and Mayewski, P.A., 2005, Interannual variability of the surface mass balance of West Antarctica from ITASE cores and ERA40 reanalyses, 1958-2000: Climate Dynamics, v. 24, p. 759-770, doi: 10.1007/s00382-005-0019-2.

Helsen, M.M., van de Wal, R.S.W., van de Broeke, M.R., van As D., Meijer, H.A.J., and Reijmer, C.H., 2005, Oxygen isotope variability in snow from western Dronning Maud Land, Antarctica and its relation to temperature: Tellus B: Chemical and Physical Meteorology, v. 57, p. 423-435.

Jouzel, J., Alley, R.B., Cuffey, K.M., Dansgaard, W., Grootes, P., Hoffmann, G., Johnsen, S.J., Koster, R.D., Peel, D., Shuman, C.A., Stievenard, M., Stuiver, M., and White, J., 1997, Validity of the temperature reconstruction from water isotopes in ice cores: Journal of Geophysical Research, v. 102, p. 26, doi:10.1029/97JC01283.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebixuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., and Joseph, D., 1996, The NCEP/NCAR 40-year reanalysis project: Bulletin of the American Meteorological Society, v. 77, p. 437-470.

Küttel, M., Steig, E. J., Ding, Q., Battisti, D. S. and Monaghan, A. J., 2012, Seasonal climate information preserved in West Antarctic ice core water isotopes: relationships to temperature, large-scale circulation, and sea ice: Climate Dynamics, v. 39, p. 1841-1857.

Kwok, R., and Comiso, J.C., 2002, Southern Ocean Climate and Sea Ice Anomalies Associated with the Southern Oscillation: Journal of Climate, v. 15, p. 487-501.

Magand, O., Frezzotti, M., Pourchet, M., Stenni, B., Genoni, L., and Fily, M., 2005, Climate variability along latitudinal and longitudinal transects in East Antarctica: Annals of Glaciology, v. 39, p. 351-358.

Masson-Delmotte, V., Hou, S., Ekaykin, A., Jouzel, J., Aristarain, A., Bernardo, R.T., Bromwich, D., Cattani, O., Delmotte, M., Falourd, S., Frezzotti, M., Gallée, H., Genoni, L., Isaksson, E., Landais, A., Helsen, M.M., Hoffmann, G., Lopez, J., Morgan, V., Motoyama, H., Noone, D., Oerter, H., Petit, J.R., Royer, A., Uemura, R., Schmidt, G.A., Schlosser, E., Simões, J.C., Steig, E.J., Stenni, B., Stievenard, M., van den Broeke, M.R., van de Wal, R.S.W., van de Berg, W.J., Vimeux, F., and White, J.W.C., 2008, A Review of Antarctic Surface Snow Isotopic Composition: Observations, Atmospheric Circulation, and Isotopic Modeling: Journal of Climate, v. 21, p. 3359-3387.

Mo, K.C., 2000, Relationships between Low-Frequency Variability in the Southern Hemisphere and Sea Surface Temperature Anomalies: Journal of Climate, v. 13, p. 3599-3610.

Nelson, S.T., 2000, A simple, practical methodology for routine VSMOW/SLAP normalization of water samples analyzed by continuous flow methods: Rapid Communications in Mass Spectrometry, v. 14, p. 1044-1046.

Nelson, S.T., and Dettman, D., 2001, Improving hydrogen isotope ratio measurements for on-line chromium reduction systems: Rapid Communications in Mass Spectrometry, v. 15, p. 2301-2306.

Noone, D., and Simmonds, I., 2002, Associations between $\delta^{18}O$ of Water and Climate Parameters in a Simulation of Atmospheric Circulation for 1979-95: Journal of Climate,

v. 15, p. 3150-3169.

Reynolds, R.W., Rayner, N.A., Smith, T.M., Stokes, D.C., and Wang, W., 2001, An Improved In Situ and Satellite SST Analysis for Climate: Journal of Climate, v. 15, p. 1609-1625.

Rozanski, K., Araguas-Araguas, L., and Gonfiantini, R., 1992, Relation Between Long-Term Trends of Oxygen-18 Isotope Composition of Precipitation and Climate: Science, v. 258, p. 981-985.

Schneider, D.P., Steig, E.J., and van Ommen, T.D., 2005, High-resolution ice-core stable-isotopic records from Antarctica: towards interannual climate reconstruction: Annals of Glaciology, v. 41, p. 63-70.

Schneider, D.P., Steig, E.J., van Ommen, T.D., Dixon, D.A., Mayewski, P.A., Jones, J.M., and Bitz, C.M., 2006, Antarctic temperatures over the past two centuries from ice cores: Geophysical Research Letters, v. 33, p. 5, doi:10.1029/2006GL027057.

Schneider, D.P., and Noone, D.C., 2007, Spatial covariance of water isotope records in a global network of ice cores spanning twentieth-century climate change: Journal of Geophysical Research, v. 112, p. 15, doi:10.1029/2007JD008652.

Schneider, D.P., and Steig, E.J., 2008, Ice cores record significant 1940s Antarctic warmth related to tropical climate variability: Proceedings of the National Academy of Science, v. 105, p. 12154-12158.

Shuman, C.A., and Stearns, C.R., 2001, Decadal-Length Composite Inland West Antarctic Temperature Records: Journal of Climate, v. 14, p. 1977-1988.

Steig, E.J., Mayewski, P.A., Dixon, D.A., Kaspari, S.D., Frey, M.M., Schneider, D.P., Arcone, S.A., Hamilton, G.S., Spikes, V.B., Albert, M., Meese, D., Gow, A.J., Shuman, C.A., White, J.W.C., Sneed, S., Flaherty, J., and Wumkes, M., 2005, High-resolution ice cores from US ITASE (West Antarctica): development and validation of chronologies and determination of precision and accuracy: Annals of Glaciology, v. 41, p. 77-84.

Steig, E., Schneider, D., Rutherford, S., Mann, M., Comiso, J., and Shindell, D., 2009, Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year: Nature, v. 457, p. 459-462.

Steig, E.J., Ding, Q., Battisti, D.S., and Jenkins, A., 2012, Tropical forcing of Circumpolar Deep Water Inflow and outlet glacier thinning in the Amundsen Sea Embayment, West Antarctica: Annals of Glaciology, v. 53, p. 19-28.

Steig, E.J., Ding, Q., White, J.W.C., Küttel, M., Rupper, S.B., Neumann, T.A., Neff, P., Gallant, A., Mayewski, P.A., Taylor, K.C., Hoffmann, G., Dixon, D.A., Schoenemann, S., Markle, B., Fudge, T.J., Schneider, D.P., Schauer, A.J., Teel, R.P., Vaughn, B.H., Burgener, L., Williams, J., and Korotkikh, E., 2013, Recent climatic and glaciological changes in West Antarctica compared to the past 2000 years: Nature Geoscience.

Stocker, T., Qin, D., Plattner, G., Tignor, M., Allen, S., and Midgley, P., 21-24 June 2010, Workshop Report, *in* IPCC workshop on sea level rise and ice sheet instabilities, Kuala Lumpur, Malaysia: University of Bern, Bern, Switzerland, Intergovernmental panel on climate change, p. 1-227.

Thompson, D.W.J. and Solomon, S., 2002, Interpretation of recent Southern Hemisphere climate change: Science, v. 296, p. 895-899.

Trenberth, K.E., 1997, The Definition of El Niño: Bulletin of the American Meteorological Society, v. 78, p. 2771-2777.

Vaughan, D.G., and Spouge, J.R., 2002, Risk estimation of collapse of the West Antarctic Ice Sheet: Climatic Change, v. 52, p. 65, doi: 10.1023/A:1013038920600.

Core Name	Latitude (N)	Longitude (E)	Elevation (m)	Age Range (years)
SEAT-10-1	-79.383	-111.239	1790.7	1976-2010
SEAT-10-2	-79.407	-111.654	1771.8	NA
SEAT-10-3	-79.042	-111.547	1771.8	1975-2010
SEAT-10-4	-78.488	-111.698	1649.8	1970-2010
SEAT-10-5	-79.123	-113.041	1793.7	1978-2010
SEAT-10-6	-79.751	-114.552	1693.6	1968-2010
SEAT-11-1	-80.009	-119.423	1502.9	NA-2011
SEAT-11-2	-79.348	-116.290	1681.1	NA-2011
SEAT-11-3	-78.728	-114.732	1782.7	NA-2011
SEAT-11-4	-78.311	-113.788	1608.7	NA-2011
SEAT-11-5	-78.312	-113.793	1610.1	NA-2011
SEAT-11-6	-78.424	-115.292	1731.0	NA-2011
SEAT-11-7	-78.837	-116.307	1739.4	NA-2011
SEAT-11-8	-79.447	-117.963	1618.5	NA-2011
SEAT-11-9	-79.446	-117.969	1618.4	NA-2011

Table 1. Firn core data for the SEAT 2010 and 2011 cores (the depth-age analysis is not finished for the SEAT 2011 cores). Location data are in WGS-84 decimal degrees. NA = not available.

Core Name	Max	Mean	Min	Median	StDev	Variance	Skewness	Kurtosis
SEAT-10-1	-28.067	-33.876	-42.313	-34.015	2.103	4.424	-0.120	3.550
SEAT-10-2	NA	NA	NA	NA	NA	NA	NA	NA
SEAT-10-3	-25.436	-32.178	-40.681	-32.014	2.809	7.891	-0.378	2.875
SEAT-10-4	-24.364	-30.890	-39.744	-30.677	3.146	9.897	-0.232	2.275
SEAT-10-5	-27.112	-32.928	-39.309	-32.984	2.447	5.986	-0.076	2.462
SEAT-10-6	-28.783	-34.823	-45.545	-34.797	2.127	4.524	-0.476	4.898

Table 2. Isotopic core data for the SEAT 2010 cores. The analytical uncertainty associated with the isotopic measurement for each core is 0.2‰ for $\delta^{18}O$ and 0.6‰ for δD. NA = not available.

SAM Anomalies					
	Season				
SEAT Isotopes	Annual	DJF	MAM	JJA	SON
High	0.0209	0.2382	0.7127	-0.2497	-0.3455
Low	0.0371	-0.0351	-0.3753	0.2493	0.2291

SOI Anomalies					
	Season				
SEAT Isotopes	Annual	DJF	MAM	JJA	SON
High	-0.0102	0.5608	0.2695	-0.2215	-0.3965
Low	0.2906	0.1508	0.1977	0.2951	0.3535

Niño3.4 Anomalies					
	Season				
SEAT Isotopes	Annual	DJF	MAM	JJA	SON
High	-0.0517	-0.6333	-0.2694	0.1027	0.2425
Low	-0.1858	-0.0460	-0.1544	-0.2166	-0.2225

Table 3. Composite analysis of climate indices from SEAT 2010 anomalous years. Anomalous years were determined from the stacked SEAT record over the 1974 - 2010 time period. The difference in the means of the anomalous years and the entire data period were calculated for each record and compared to zero using a two-tailed Student's t-test. Statistically significant values at the 95% confidence level are highlighted, and are potentially driving West Antarctic precipitation. SAM, SOI, and Niño3.4 data are from NOAA's Climate Prediction Center, which are the average circumpolar westerly wind strength, changes in sea-level pressure, and the central Pacific SST variability, respectively. DJF = austral summer or December, January, February; MAM = austral fall or March, April, and May; JJA = austral winter or June, July, and August; SON = austral spring or September, October, and November.

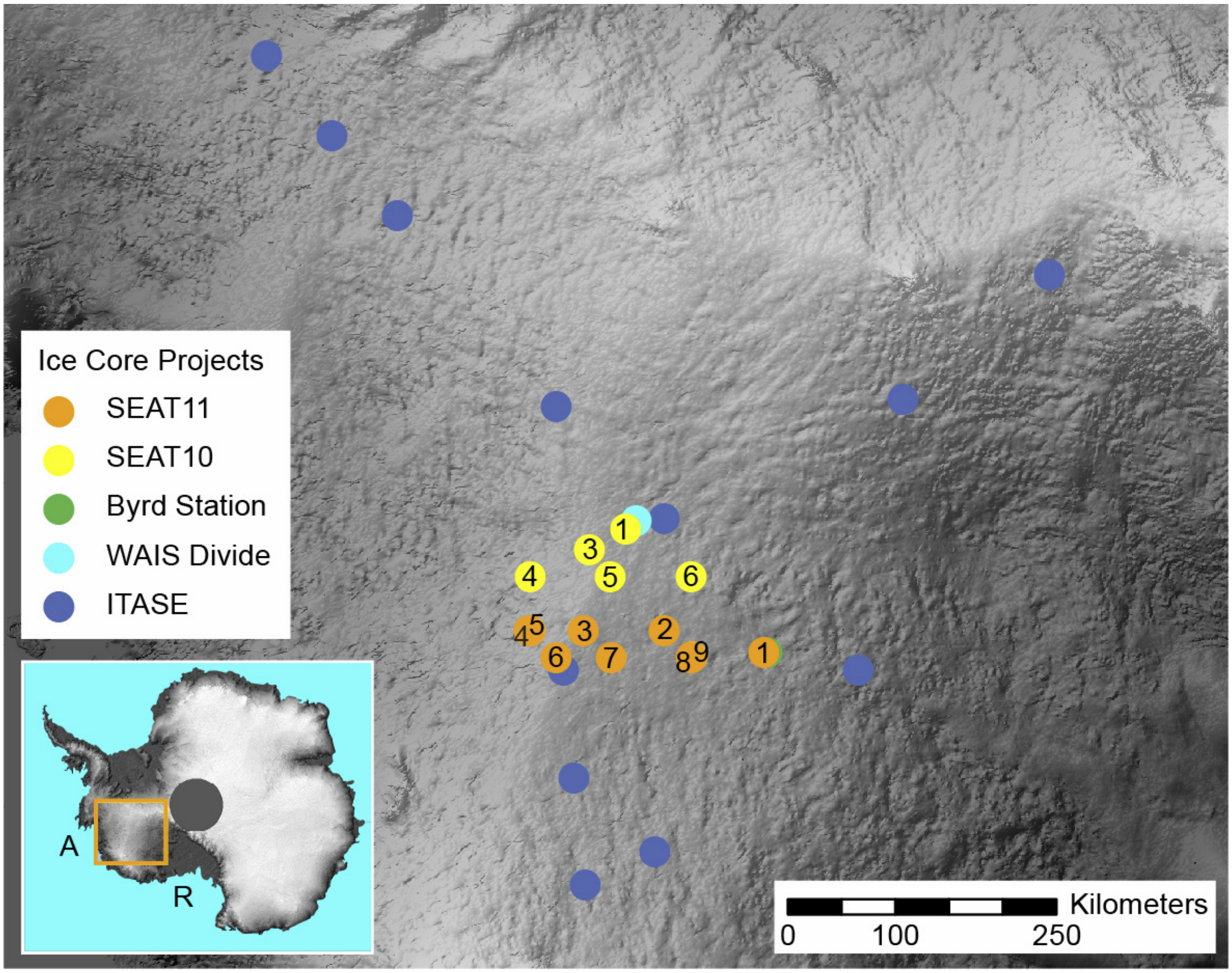

Figure 1. Map showing location of ice and firn cores in WAIS. SEAT 2010 cores are in yellow, SEAT 2011 cores are in orange, Byrd Station is in green, WAIS Divide Deep core is in light blue, and ITASE cores are in blue. SEAT-10-1 and ITASE-00-1 are at the same location and SEAT-11-1 is 3 km from current Byrd Station. SEAT-11-4 and SEAT-11-5 are 100 m apart; the same is also true for SEAT-11-8 and SEAT-11-9. In the inset map, A = Amundsen-Bellingshausen Sea, and R = Ross Sea. Shaded relief map distributed by NSIDC (Dimarzio et al., 2007).

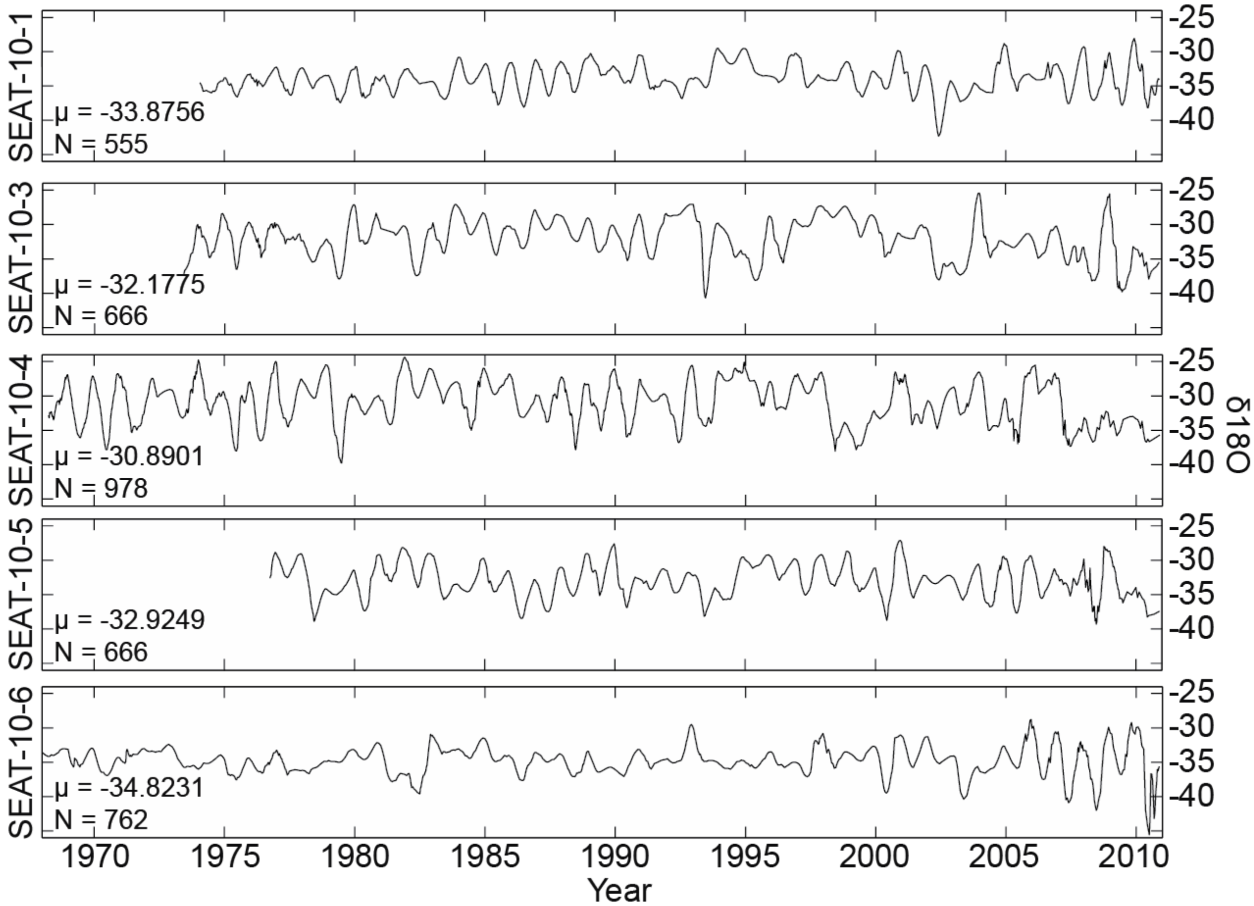

Figure 2. Time series of SEAT 2010 isotopic records. The analytical uncertainty associated with the isotopic measurement for each core is 0.2‰. Uncertainty associated with the age-depth scale is ±1 year at depth. N = number of samples in isotopic record while μ = the mean isotopic value.

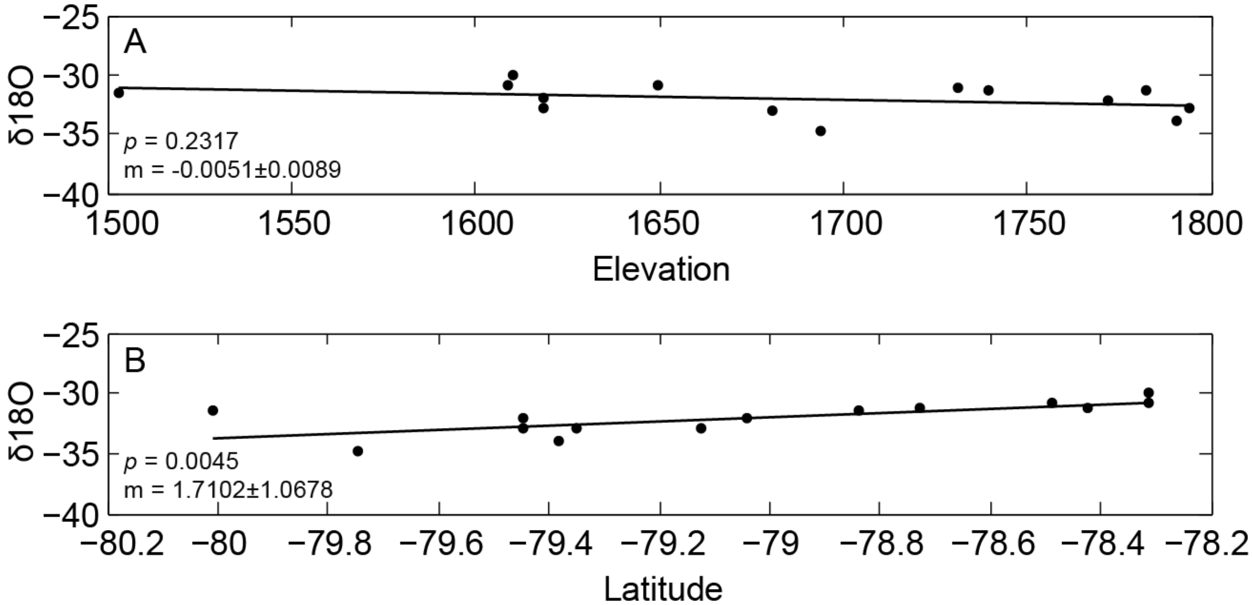

Figure 3. Relationships between geographical parameters and the SEAT cores. A) Comparison of the elevation at each core site and the mean oxygen isotopic value for each of the SEAT 2010 and SEAT 2011 cores. B) Comparison of the latitude at each core site and the mean oxygen isotopic value for each of the SEAT 2010 and SEAT 2011 cores. The latitude relationship is statistically significant at the 95% confidence level. For both plots the trend line (linear black line) along with the slope ± error and p-value for the predicted $\delta^{18}O$ are shown.

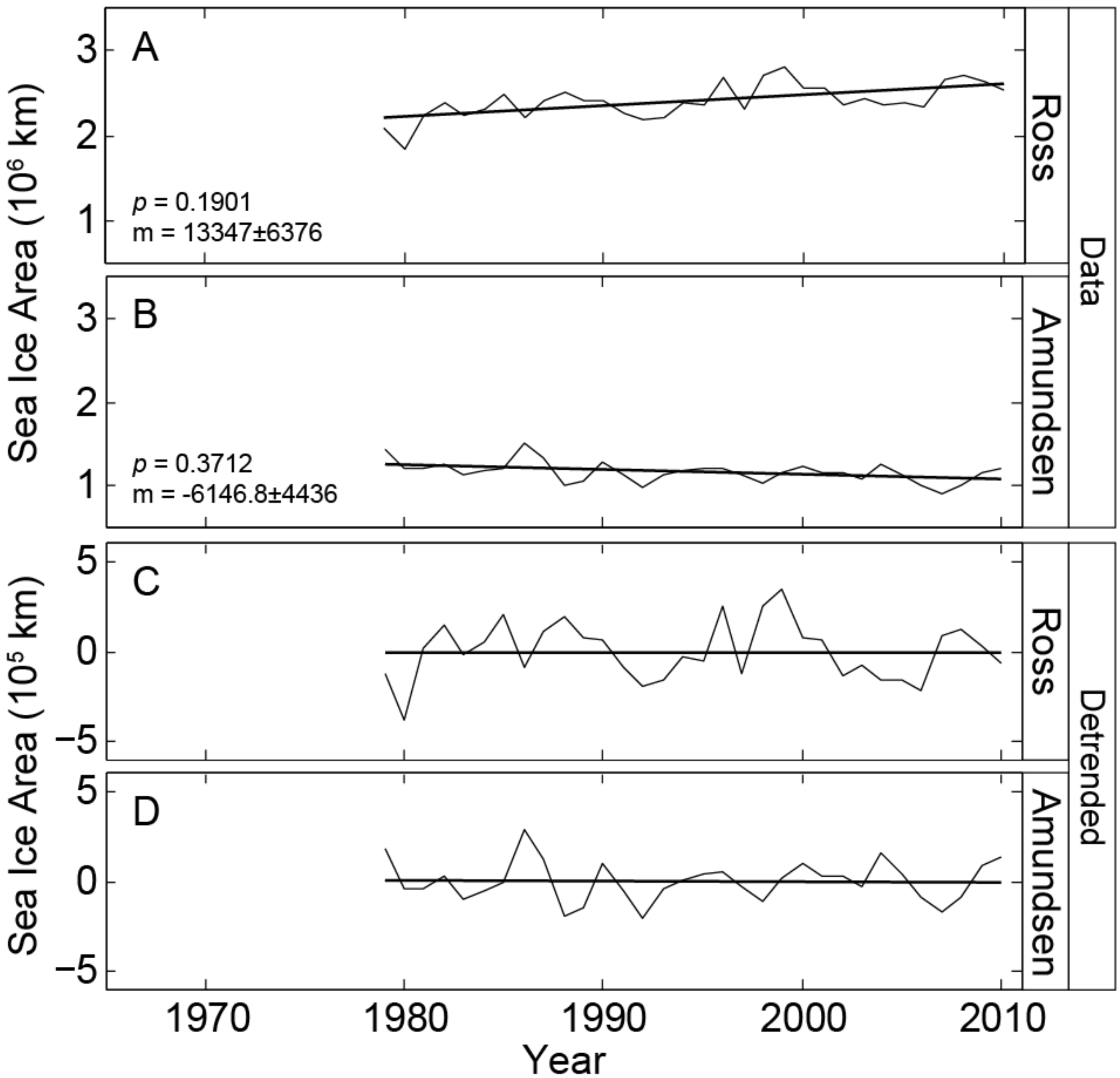

Figure 4. Time series of annual sea ice areas surrounding WAIS. The trend line (linear black line) for the predicted sea ice areas accounting for the autocorrelation in the time series are shown. Also shown are the slope ± error and p-value for the analyses. A) Bootstrap method for the compiled Ross sea ice data. B) Bootstrap method for the compiled Amundsen-Bellingshausen sea ice data. C) Detrended bootstrap method for the compiled Ross sea ice data. D) Detrended bootstrap method for the compiled Amundsen-Bellingshausen sea ice data. Sea ice data are from Carsey, 1992.

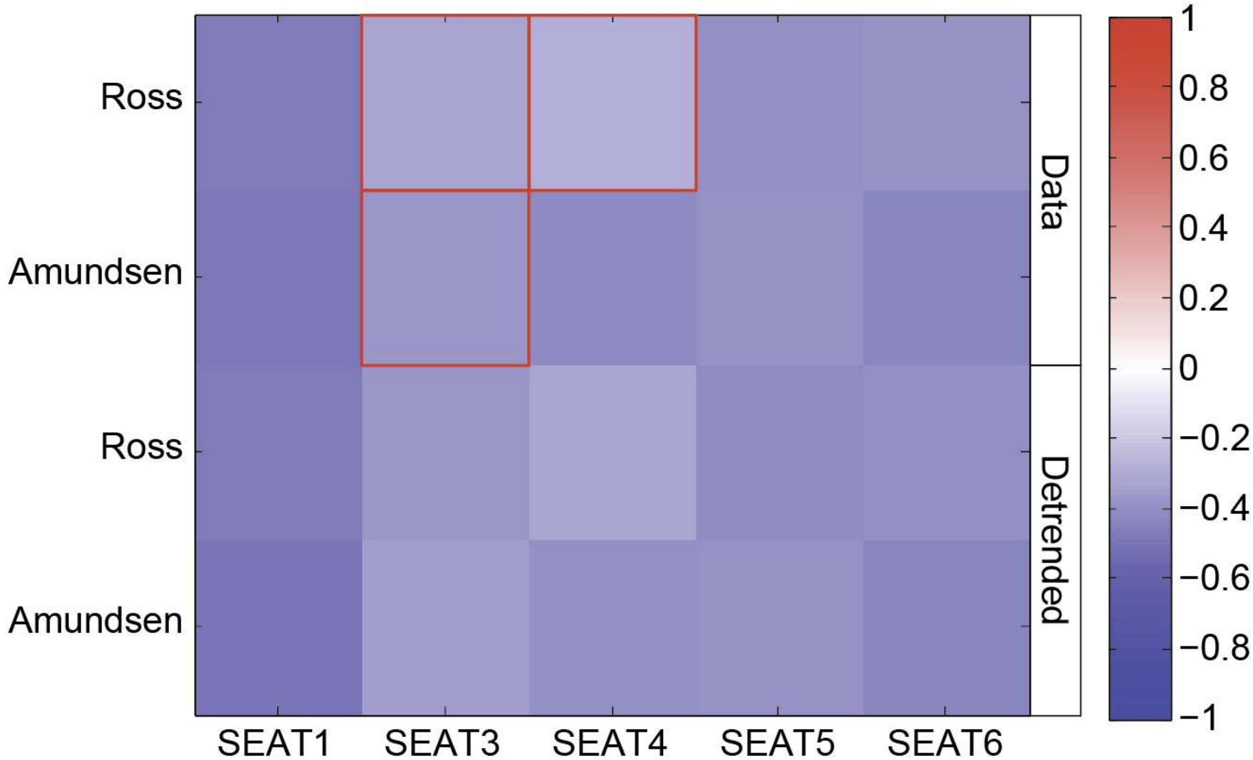

Figure 5. Correlation matrix between monthly sea ice area and SEAT 2010 isotopes. All relationships shown are statistically significant at the 95% confidence level except for the cells outlined in red. Data is compiled for both the Amundsen-Bellingshausen and Ross Sea Embayments using a bootstrap method. Sea ice data are from Carsey, 1992.

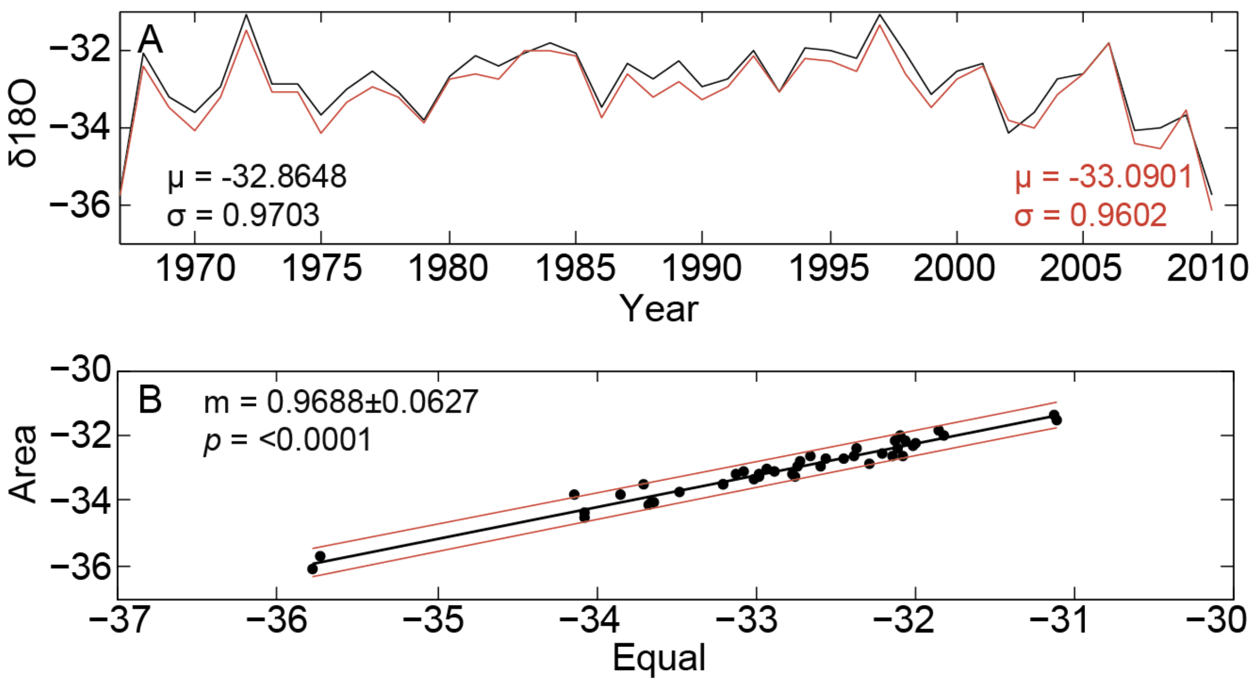

Figure 6. Annually resolved stacked records from the SEAT 2010 cores. A) The equal weighted record (black line) is a simple average of the five SEAT 2010 cores. The area weighted record (red line) is an average based on Thiessen Polygons using perpendicular bisectors between each of the SEAT 2010 cores (i.e. cores that are clustered together are weighted less than cores that are further apart). The mean and standard deviation for both weighted methods are plotted in their respective color. B) Autocorrelated least squares regression between the annual isotopic records of the equal and area weighted records where the trend line (linear black line) along with the slope ± error and p-value for the predicted $\delta^{18}O$ are shown.

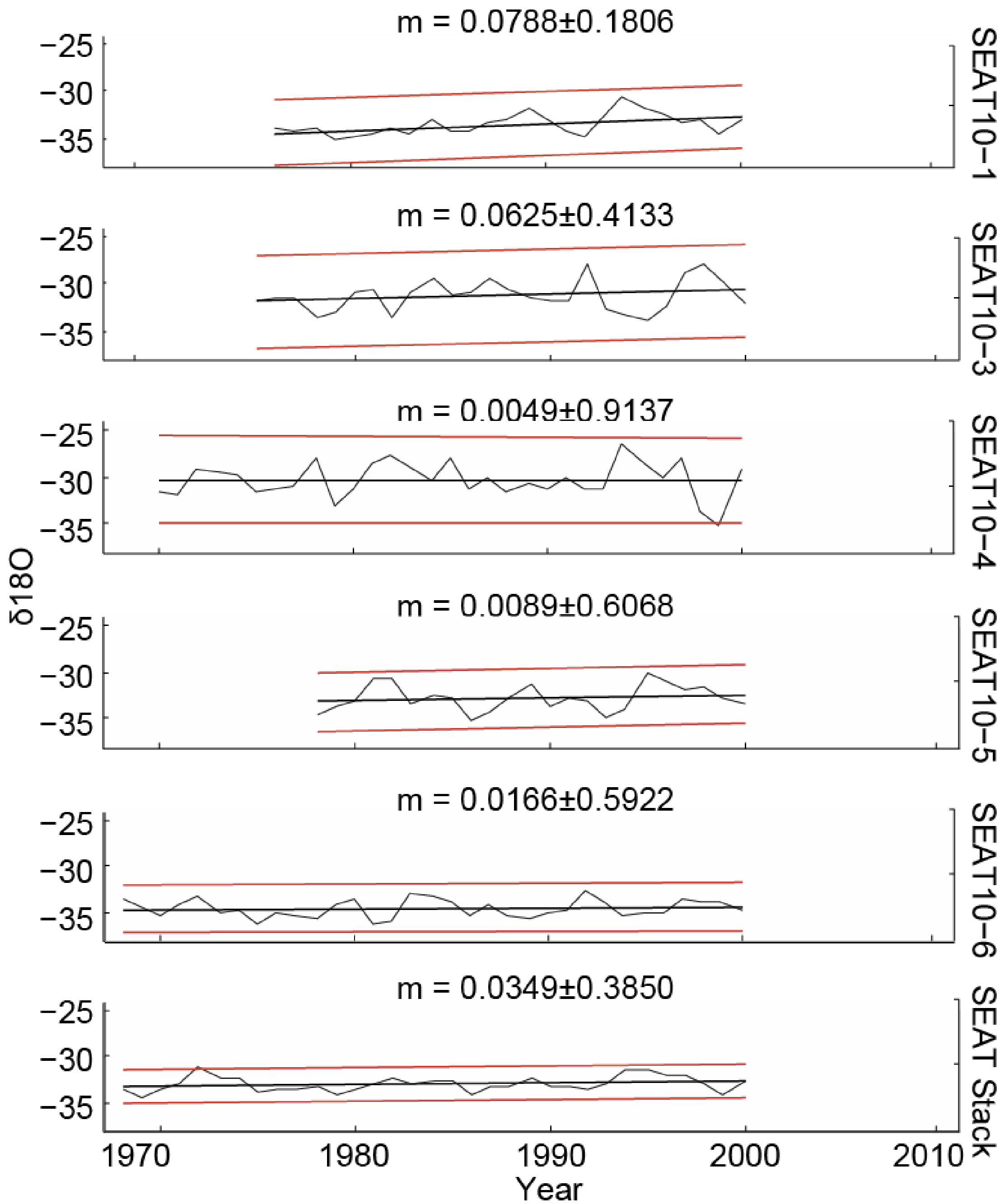

Figure 7. Trend of annually resolved SEAT 2010 isotopes excluding the 2000s (so as to be more comparable with the ITASE records). All of the SEAT cores show a positive trend that is not statistically significant at the 95% confidence level. The trend line (linear black line) and slope ± error for the predicted $\delta^{18}O$ accounting for the autocorrelation in the time series are shown.

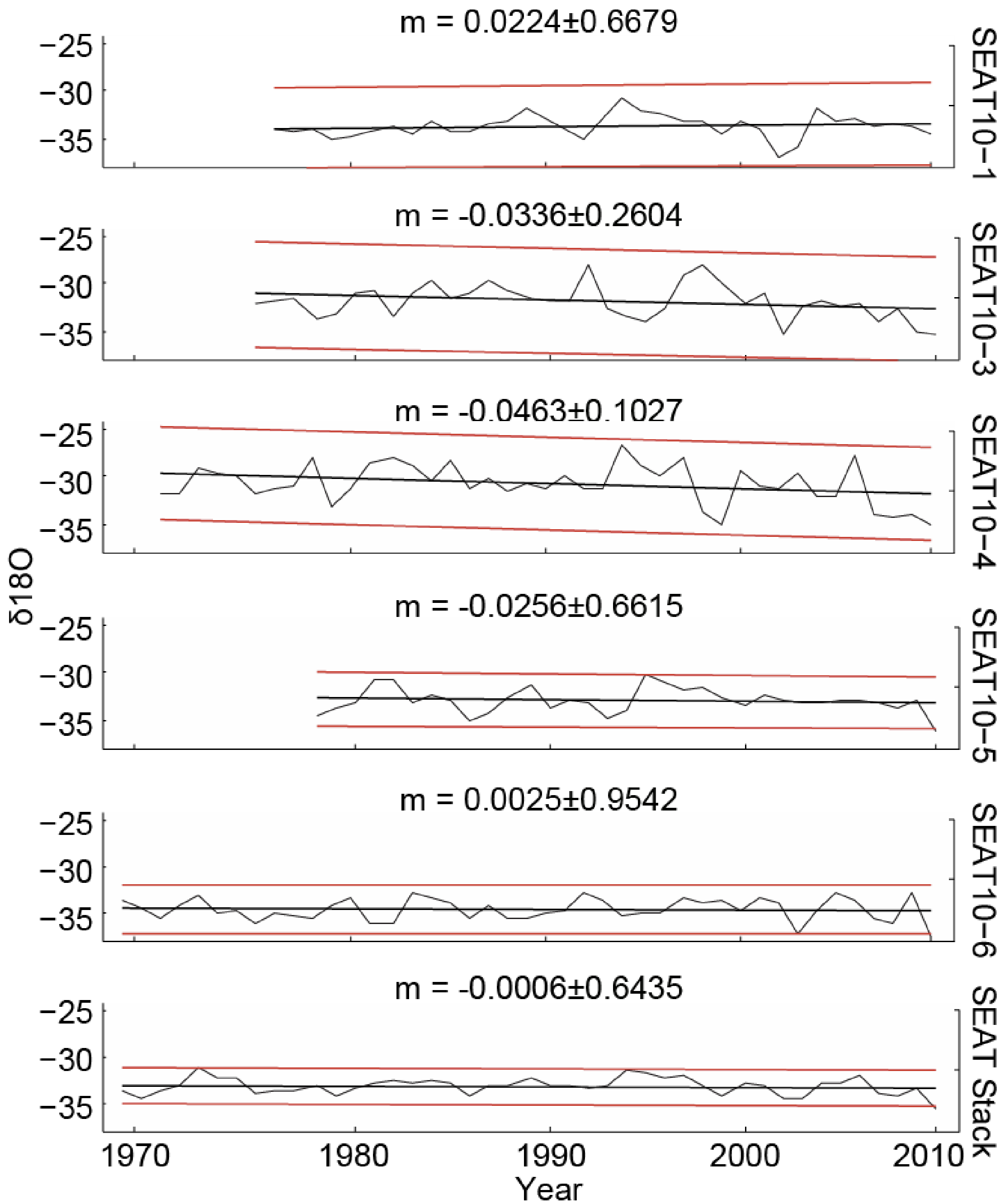

Figure 8. Trend of annually resolved SEAT 2010 isotopes including the 2000s. None of the SEAT cores have statistically significant trends at the 95% confidence level. Including the 2000s decreased the trend for all of the SEAT cores, and in most of the records, changed the directionality of the trend. The trend line (linear black line) and slope ± error for the predicted $\delta^{18}O$ accounting for the autocorrelation in the time series are shown.

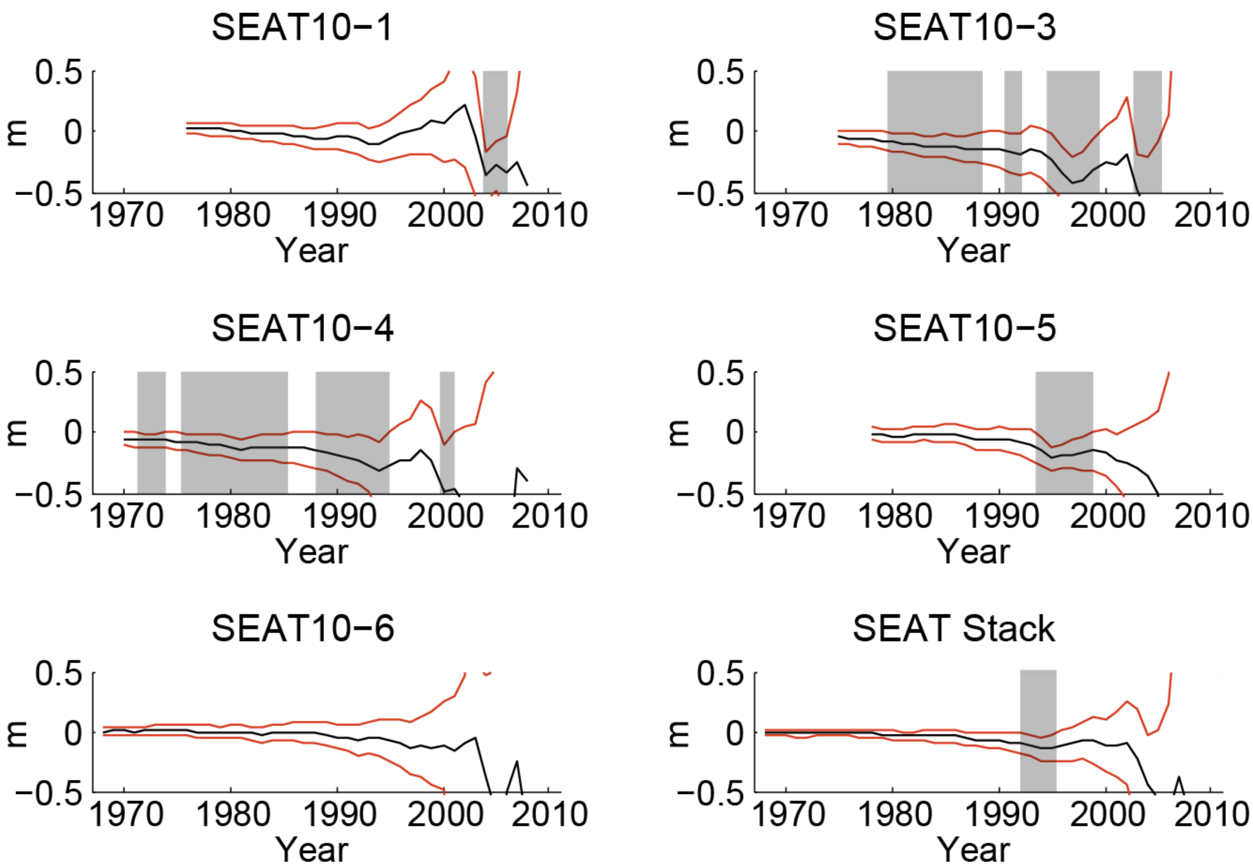

Figure 9. Slope to target of SEAT 2010 isotopes including the 2000s, where the slope is calculated from the most recent year in the record to the point shown on the graph (i.e. for SEAT-10-6 the slope at 1985 is the autocorrelated least squares regression from 1985 to 2009). The only time frames that are significantly different from zero at the 95% confidence level are shown in the grey shading.

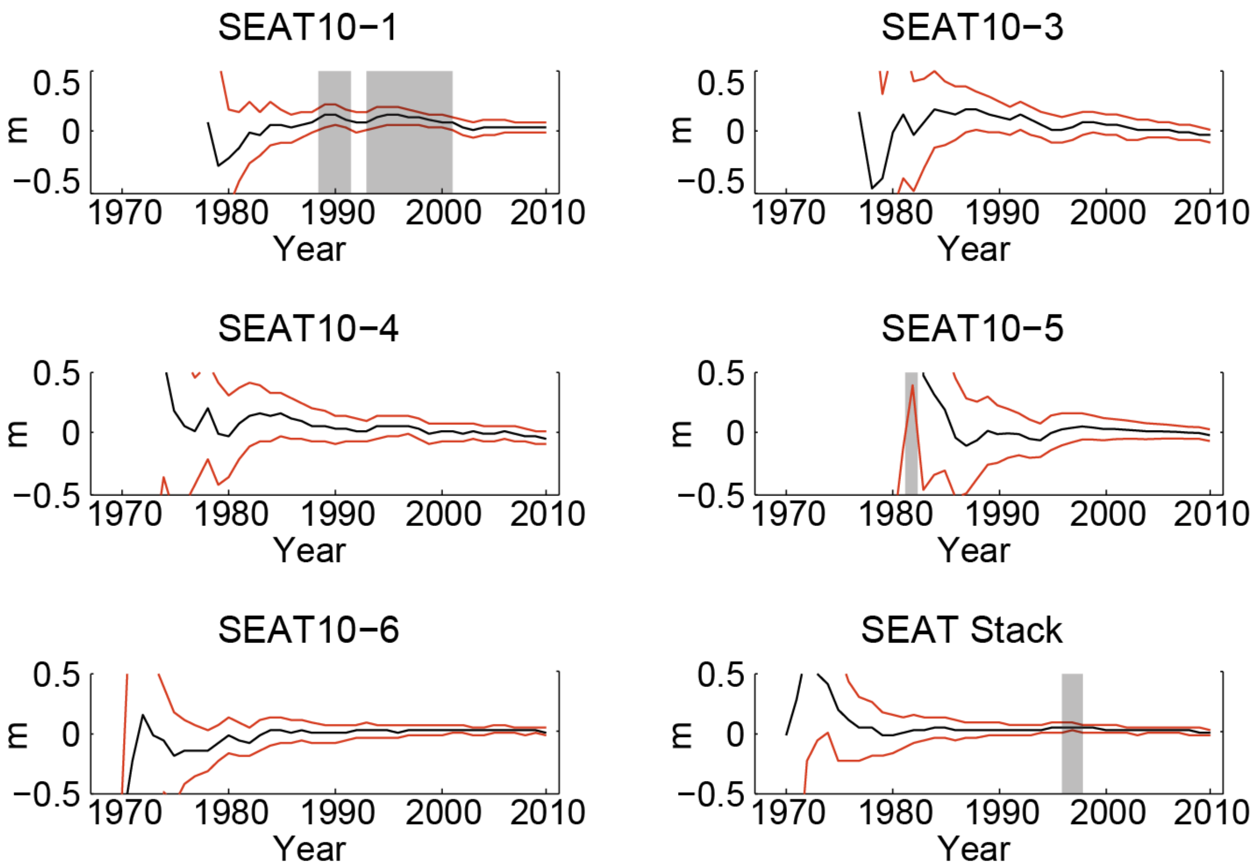

Figure 10. Slope to target of SEAT 2010 isotopes including the 2000s, where the slope is calculated from the oldest year in the record to the point shown on the graph (i.e. for SEAT-10-6 the slope at 1985 is the autocorrelated least squares regression from 1970 to 1985). The only time frames that are significantly different from zero at the 95% confidence level are shown in the grey shading. Note that the shaded regions, in general, are very different between Figure 9 and Figure 10.

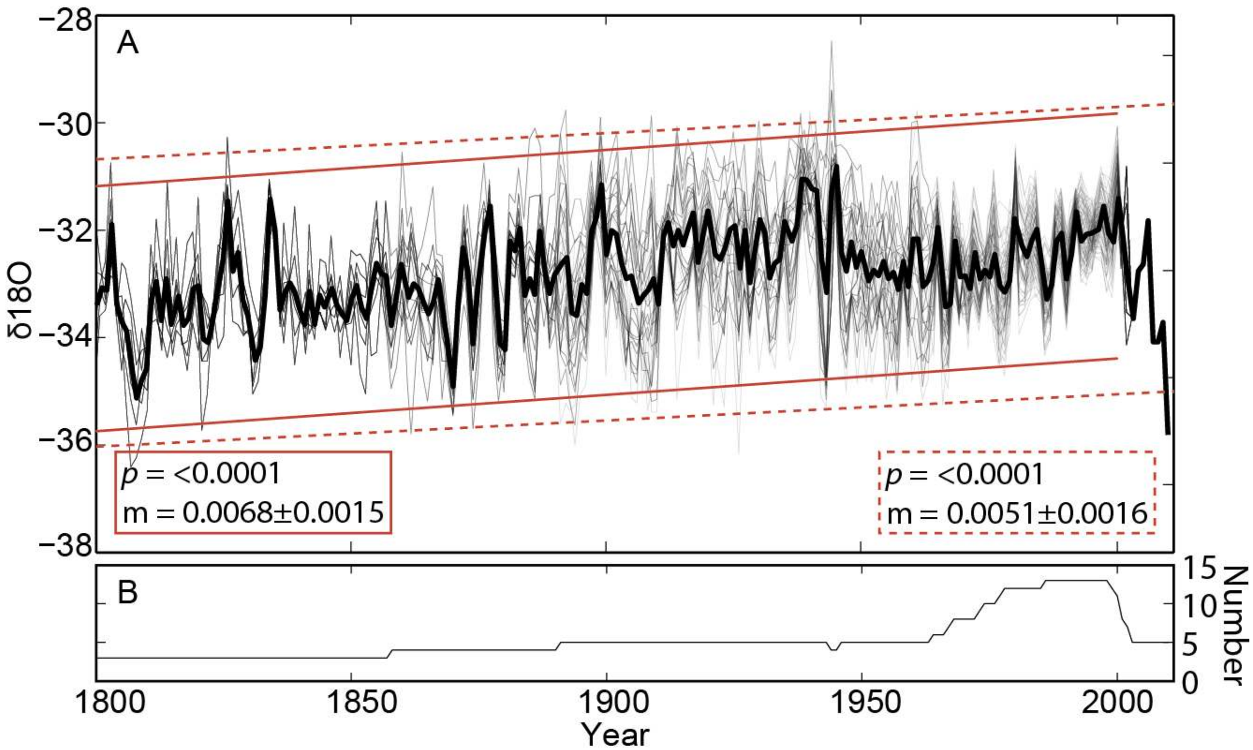

Figure 11. Regional isotopic record generated through combination of the annually resolved SEAT and ITASE records. A) The faint black lines are partial stacks or the possible combinations of combining just four ITASE cores. The bold black line is the full stack or combination of all SEAT and ITASE cores. The trend line (bold black line) along with the 95% confidence bands (red lines) for the predicted $\delta^{18}O$ accounting for the autocorrelation in the time series are shown. The solid red lines are for the time period 1800 to 2000, while the dotted red lines are for the time period 1800 to 2010. The slope ± error and p-values are shown for the time frame excluding the 2000s (boxed with solid red line) and for the time frame including the 2000s (boxed with dotted red line). ITASE data are from Steig et al. (2005), Schneider et al. (2006) and Schneider and Steig (2008). B) Number of cores used to compile the full stacked record in A.

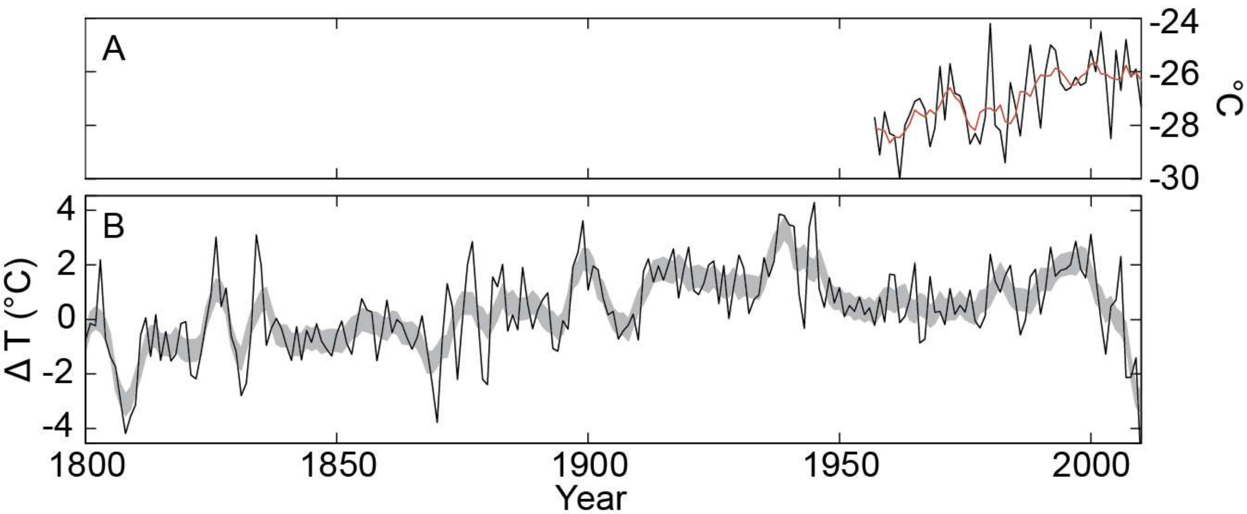

Figure 12. West Antarctica temperature and isotopic relationships. A) Temperature record compiled from Byrd Station in West Antarctica near the SEAT cores where the red line is the 5-year running mean. Temperature data are from Bromwich et al., 2012. B) Regional stacked converted temperature record of SEAT and ITASE cores where the grey shading is the standard error about the 5-year running mean. Relative temperature changes are shown using the conversion from Steig et al. (2013) and are only applicable over long time scales. Temperatures in both y-axes are to scale.

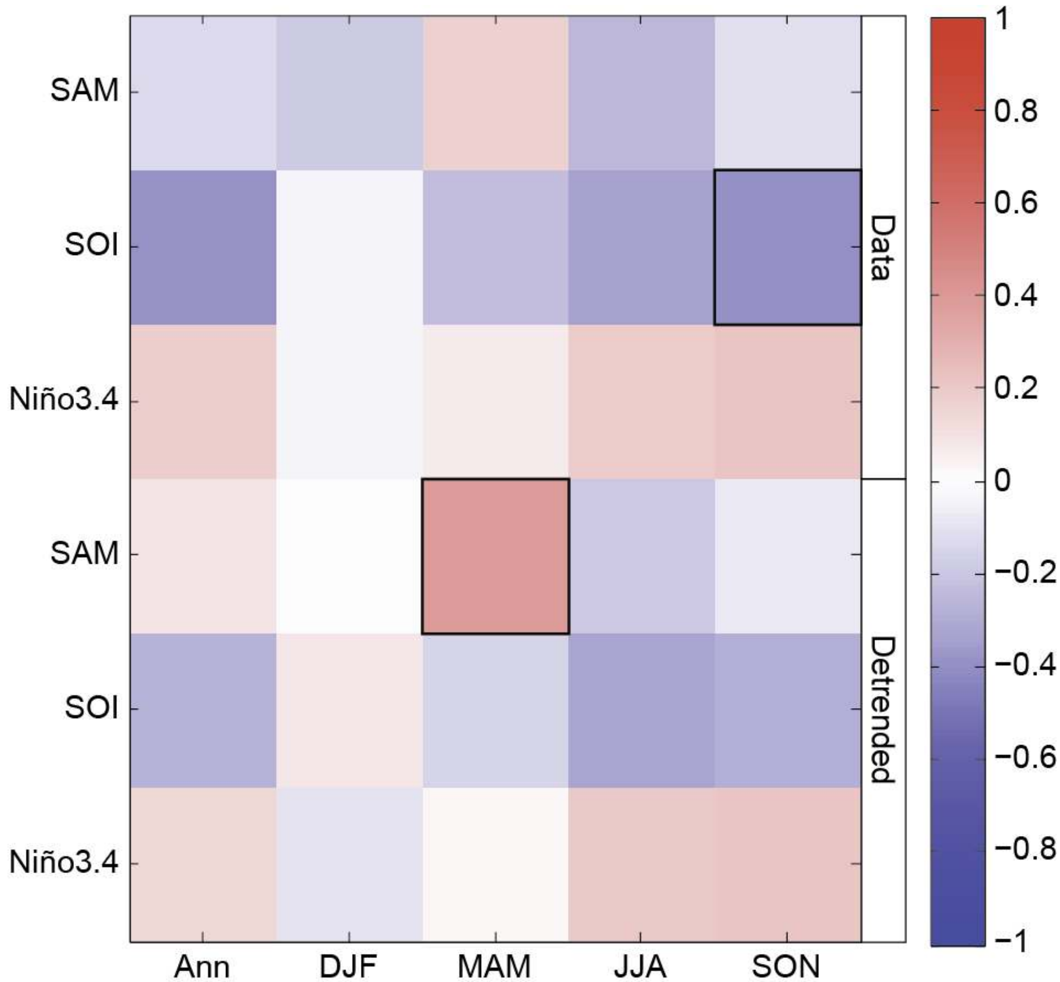

Figure 13. Correlation between the annual and seasonal climate index data with the annual SEAT stack data. Correlations outlined in black are statistically significant at the 95% confidence level. SAM, SOI, and Niño3.4 data are from NOAA's Climate Prediction Center, which are the average circumpolar westerly wind strength, changes in sea-level pressure, and the central Pacific SST variability, respectively.