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Temporal trends in West Antarctic accumulation rates: evidence from observed and simulated records

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Temporal Trends in West Antarctic Accumulation Rates: Evidence From Observed and Simulated Records

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ABSTRACT

Temporal Trends in West Antarctic Accumulation Rates: Evidence From Observed and Simulated Records

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Reconstructed snow accumulation rate observations from five new firn cores show a statistically significant negative trend in accumulation rates over the past four decades across the central West Antarctic ice sheet. A negative temporal trend in accumulation is unexpected in light of rising surface temperatures and simulations run by GCMs. Both the magnitude of the mean accumulation rates and the range of interannual variability observed in the new records compares favorably to older records, suggesting that the new accumulation rate records may serve as a regional proxy for recent temporal trends in West Antarctic accumulation rates. The observed negative trend is likely the result of changes in the Southern Hemisphere involving changes in both large scale atmospheric circulation patterns driven by changes in tropical Pacific sea surface temperatures and high-latitude internal atmospheric dynamics, dominated by changes in the austral fall season. The well-documented positive trend in the Southern Annular Mode causes a low pressure center to form over the Amundsen Sea, which in turn produces lower accumulation rates across the western portion of the West Antarctic ice sheet. The new accumulation rate records are compared to several models/reanalyses to test the skill of simulated accumulation rate predictions. While the models/reanalyses and the new observations agree well in both mean and variability, the simulated records do not capture the full negative trend observed in the reconstructed records.

Keywords: Antarctica, West Antarctica, WAIS Divide, Accumulation rate, Southern Annular Mode, SAM, firn core, ice core

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Table of Contents

List of Tables

List of Figures

1. Introduction

1.1 Scientific significance

Earth's polar regions play a critical role in climate processes by regulating many climate systems, including ocean circulation, surface albedo and especially global sea level. The Intergovernmental Panel on Climate Change (IPCC) has described sea-level rise as "one of the major long-term consequences of human-induced climate change" (Stocker et al., 2007). Of the various factors influencing global sea level, changes to the volume of the Greenland and Antarctic ice sheets—which contain a sea-level rise equivalent of 7.2 m and 61.1 m of fresh water respectively—have the largest potential impact and the greatest associated uncertainty (Church et al., 2001). The West Antarctic Ice Sheet (WAIS) alone has a sea rise potential of roughly 5 m (Vaughan and Spouge, 2002).

Thomas et al., (2004) reported that large glaciers along the Amundsen Sea sector of WAIS are contributing significantly to global sea level rise, with an annual discharge equal to 0.2 mm of sea-level rise per year. Additionally, their report noted that discharge in this region of WAIS is likely to increase in the future (Thomas et al., 2004); however, in order to accurately predict future changes to WAIS discharge, it is necessary to accurately quantify the mass-input across the surface of the ice sheet.

Mass is added to WAIS by snow precipitation. Iceberg calving and basal melting of ice shelves are the primary processes for mass-removal, though sublimation and surface melting do play a limited role (van den Broeke et al., 2006). Because snowfall is the primary means of adding mass to WAIS—and thus a key component in modeling any mass balance changes—more accurate accumulation reconstructions allow for more accurate predictions of the ice sheet's past, present and future response to climate change. Citing this link between accumulation and the physical modeling of ice sheet behavior, many recent studies have stressed the importance of obtaining accurate accumulation records from WAIS (Banta et al., 2008; Neumann et al., 2008).

Despite the importance of quantifying precipitation over WAIS, actually collecting accurate accumulation rates (here defined as total precipitation minus evaporation, sublimation and wind-scouring) is a challenging task at best (Eisen et al., 2008). A variety of methods are commonly used to measure accumulation rate, including firn and ice cores, snow pits, stake farms, ground-penetrating radar and remote-sensing; however, each of these methods suffer from numerous uncertainties (Eisen et al., 2008), as well as temporal and spatial limitations. For example, a firn/ice core provides excellent temporal records of accumulation rate for a given location, but is severely limited spatially (most shallow firn cores are less than 10 cm in diameter). Genthon et al. (2005) showed that small-scale variability can account for up to 90% of the interannual variability seen in ice cores. Because of this large degree of small-scale spatial variability found in all Antarctic accumulation rate records, a single core is unlikely to be representative of the larger region. Conversely, remote-sensing data provides excellent spatial coverage but is temporally limited (essentially restricted to the previous three decades). Simulated precipitation generated by meso-scale climate models and global climate reanalyses can also provide spatial and temporal accumulation estimates; however, reanalyses rely to some extent on field observations and remote-sensing data, and meso-scale model boundary conditions are often determined by those same reanalyses data—thus introducing the observational uncertainties into the models and reanalyses.

The spatial limitations of firn cores can be compensated for in part by collecting multiple cores from a given region and averaging the resulting accumulation rate observations together

(Genthon et al., 2005), providing a regional accumulation rate estimate. This method eliminates much of the small scale variability inherent in all Antarctic ice cores (Genthon et al., 2005). Over a dozen accumulation rate records have been reconstructed from ice/firn cores collected across WAIS during various US-ITASE expeditions (Figure 1; Kaspari et al, 2004; Kreutz et al., 1999; Kreutz and Mayewski, 1999; Kreutz et al., 2000); however, this collection of records suffers from relatively low spatial density and even the most recent of the accumulation rate records do not extend beyond the early 2000s.

1.2 Objectives

The main objective of this study is to accurately and precisely define the spatial and temporal patterns of accumulation across an area that straddles the central WAIS ice divide. The study will be conducted using a compact network of five high-temporal-resolution firn cores collected during the 2010-2011 Antarctic field season. These five new accumulation rate records fill both a temporal and spatial gap in this key region of central WAIS, allowing for a statistically rigorous examination of recent accumulation rates.

1.3 Previous Work

GCM projections of future changes to Antarctic accumulation rate suggest that precipitation will increase as temperatures continue to rise (Manabe and Stouffer, 1980; Thompson and Pollard, 1997). Temperatures over the Antarctic ice sheet are cold enough that, even in predictions for the end of the 21st century, melt rates around the ice sheet margins do not increase markedly (Krinner et al., 2007); thus, the simulated changes to accumulation rate are due mainly to changes in snow deposition. Increasing accumulation rates would lead to a growth in the volume of the ice sheets and a decrease in the rate of sea-level rise (Oerlemans, 1982). Corresponding with these GCM predictions, recent observations have shown that surface temperatures over WAIS have been increasing by more than 0.1 ˚C per decade since 1957 (Steig et al., 2009). Following the Clausius-Clapeyron relation, these rising air temperatures could lead to an increase in precipitation due to the higher saturation vapor pressure of the air mass.

Despite the GCM predictions and the observed temperature increase, studies using reanalysis data, meso-scale modeling, and in-situ/remote sensing observations have not yet shown the expected increase in accumulation rate across WAIS (Monaghan et al., 2006). For example, using isochronous ice layers identified at depth in the ice sheet by airborne radar, Siegert and Paine (2004) showed that there has been little change in accumulation rates over West Antarctica for the past 3100 years. This observation is supported by the findings of Monaghan et al. (2006), who created a continent-wide map of accumulation covering five decades (1955-2004), using a synthesis of observed accumulation rates (1955-1984) and output from ERA-40 reanalysis precipitation fields (1985-2004). They show that relative to the regional 50-year mean of the compiled accumulation record, WAIS appears to have experienced periods of both positive and negative changes to accumulation. From the mid-1990s to 2004 trends in accumulation were variable across WAIS, but the dominant signal is a trend towards decreasing accumulation rates; however, none of the trends were shown to be significant (Monaghan et al., 2006).

One of the factors complicating the assessment of accumulation rate changes are the non-climatic factors that create complex spatial variability in accumulation rates (Kaspari et al., 2004). Reviewing a series of WAIS ice cores collected during US-ITASE expeditions, Kaspari et al. (2004), showed that accumulation rates are highly variable from year to year and that correlation between individual cores is generally low. A variety of large-, meso-, and small-scale topographic features contribute to the observed temporal and spatial variability of accumulation.

In particular, cores collected on the leeward side of WAIS divide have lower accumulation rates than windward cores (Kaspari et al., 2004). Superimposed on this large-scale pattern is variability due to meso-scale undulations (wavelength > 20 km). Cores collected downstream from such undulations may show periods of sustained above- or below-average accumulation rates since deeper portions of the ice/firn cores may have been deposited on the crests or troughs of the undulations (Kaspari et al., 2004). Additionally, small-scale wind-driven features like sastrugi can affect the interpretation of the uppermost part of firn cores, but these perturbations tend to be eliminated as the layers are buried (Kaspari et al., 2004; Gow, 1965).

In order to determine if any changes have occurred in WAIS accumulation rates over the most recent decades, observations should be made using a closely-spaced network of high-resolution cores that extend through the period of significant WAIS surface warming and that were collected from a region not complicated by meso-scale topographic features on the surface of the ice sheet. Five new firn cores meeting these requirements were collected from a region of WAIS during the 2010-2011 summer field season. The field and laboratory methods used to recover and analyze these cores will be discussed below.

2. Methods

2.1 Field Methods

The Satellite Era Accumulation Traverse (SEAT) 2010-2011 was conducted by a six-person team traveling from the WAIS Divide Deep Core camp. Five cores were collected at sites ~70 km apart, ranging across the ice divide (Fig. 1). A study by Morse et al. (2002) identified a strong accumulation gradient perpendicular to the divide, with relatively high accumulation (>250 mm water equivalent [w.e.].) on the coastal slope of the divide and low accumulation

(~150 mm w.e.) on the pole-ward slope. SEAT-10-1 was collected at the same site as the ITASE-00-1 core, which was recovered during the US-ITASE 2000 expedition at a site that lies roughly along the strike of the divide. SEAT-10-3 and SEAT-10-5 were also collected near the summit of the divide. SEAT-10-4 and SEAT-10-6 were recovered further from the summit of the divide, in areas of high and low accumulation respectively.

At each site a snow pit was dug through the uppermost layers of snow and firn to a depth where the firn was dense enough to remain intact during drilling (~1.5 m). Density measurements were collected from each of the snow pits with 2 cm vertical resolution. The firn cores were drilled in ~80 cm sections beginning at the base of the snowpits. Because the youngest firn at several of the core sites was poorly compacted, the upper 1 to 2 meters were sampled in-field. This sampling process for each section included obtaining electrical conductivity measurements (ECM), dividing the sections into ~4 cm samples, and recording length, diameter and mass measurements for each of these samples.

2.2 Laboratory Methods

The remaining core sections were shipped to the Climate Dynamics Lab at Brigham Young University. Temperatures were maintained at -20 C throughout transit. Ice core storage and processing took place in a walk-in freezer at -20° C. Three to four ECM runs were recorded along each section at a sample-collection rate of 2 cm/s. The sections were then cut into ~2 cm samples, and each sample was weighed and volume-measured for density calculations. Cumulative uncertainties for the density calculations are 10% for snowpit samples and 5% for firn cores samples.

Isotopic analysis ($\delta^{18}O$ and δD) of the melted samples was conducted using a Los Gatos Liquid Water Isotope Analyzer (LWIA-24d). Analytical uncertainties for $\delta^{18}O$ and δD are 0.2‰ and 0.6‰, respectively.

Time-scales at seasonal resolution were developed for each core by counting the peaks and troughs in the seasonal signal of the $\delta^{18}O$ and δD records. These preliminary age-depth scales were verified and refined by comparing the isotopic profiles to the ECM and density profiles. Additionally, the anion concentration of each sample was measured using a Dionex ICS-90 Ion Chromatography System. The resulting solute data were used as a third independent proxy of time. A prominent peak in the sulfate record was found in each of the five records and identified as aerosol deposition resulting from the 1991 Pinatubo eruption. A study by Cole-Dai et al. (1997) observed that the majority of Pinatubo sulfate was deposited between 1992 and 1994, which corresponded well with the estimated depth of the 1993 annual layer in all of the SEAT-10 cores. From the top of each core to the depth of the 1991 Pinatubo sulfate peak the maximum uncertainty in age is < ±1 year; the maximum age uncertainty at depths below the sulfate peak is estimated to be ±1 year.

Water-equivalent annual accumulation rate records were reconstructed by multiplying the density of each sample by the sample thickness and then summing the results of all samples pertaining to a single year, according to the method described in Cuffey and Paterson (2010):

$$\dot{b} = \frac{\rho_{firn} \times h_{year}}{\rho_{water}} \qquad (1)$$

where $\dot{b}$ is the mean annual accumulation rate in water equivalent (w.e.) cm/yr, ρ is the density of the firn sample in g/cm^3 and h_{year} is the thickness of the annual firn layer.

3. Results and Discussion: Trends in SEAT-2010 Accumulation Rate

Here we discuss the accumulation rate findings of the SEAT-2010 field campaign. A comparison between the firn cores SEAT-10-2010 and ITASE-00-1 (collected at the same location) will be made to establish the validity of the methods used to reconstruct the SEAT-2010 accumulation rate records. The findings of a rigorous statistical analysis testing the temporal trends in accumulation rate will also be discussed. The results from a study of the topography of the core sites and the isotopic patterns of the recovered cores will be presented in order to establish that the observed accumulation rate trends are not due to topographic irregularities or local temperature change. Finally, a comparison between the SEAT-2010 accumulation rate records and previous US-ITASE SMB records will be described, and possible causes behind the negative accumulation rate trend discussed.

3.1 SEAT-2010 Accumulation Rate

Figure 2 shows the reconstructed annual accumulation rates (w.e. mm/yr) for the five new firn cores collected during the SEAT 2010-2011 field season. The records from each core cover differing timespans, with the longest record (SEAT-10-6) extending back to 1966 and the shortest record (SEAT-10-5) extending to 1976. As shown in Figure 3, the results from these new cores agree well with previous observations, showing a general decrease in accumulation rate with increasing distance from the coast (Kaspari et al., 2004). Additionally, there is low correlation between cores over the 1976-2010 period of overlap ($r < 0.36$, p-value > 0.035) and individual cores show large variation in annual accumulation rates ($\sigma > 50.9$ w.e. mm/yr). Contrasting with the lack of significant accumulation trends reported in other studies (Kaspari et al., 2004; Monaghan et al., 2006), the results from each of the SEAT cores show a statistically significant decreasing trend in accumulation, ranging from a maximum decrease of -72 mm to a minimum of -15 mm w.e. per decade. The statistical significance of these trends will be discussed in Section 3.3.

3.2 SEAT-10-1 and ITASE-00-1

The two firn cores SEAT-10-1 and ITASE-00-1 were collected from the same core site, providing an opportunity to compare the two records and establish whether or not the SEAT-2010 cores are comparable to previous US-ITASE cores collected from WAIS (Figure 4). Analysis of the two accumulation rate records reveals similar mean accumulation rates (222 mm/yr w.e. and 238 mm/yr w.e., respectively) and standard deviations (53.3 mm/yr w.e. and 66.5 mm/yr w.e., respectively). A simple two-tailed t-test fails to reject the null hypothesis that the difference in means between the overlapping period of both cores is 0 (two-sided $p = 0.33$). This close agreement of both the mean accumulation rate and interannual variability suggests that the methods used to reconstruct accumulation rates for the SEAT-2010 cores yield results that are directly comparable to previous observations. Importantly, the new data from SEAT-10-1 suggests that since at least the early 1990s, the site has been experiencing an extended decline in accumulation rates.

The favorable comparison between the SEAT-2010 and ITASE-00-1 accumulation rate results and previous accumulation rate studies in the region provides greater confidence in the reliability of these new data, and that the new cores will contribute to our knowledge of accumulation rates in this region of WAIS.

3.3 Statistical Analysis of Temporal Trends in Accumulation Rate

The salient finding of this study is the decreasing accumulation rate trend seen in all of the new ice cores. In order to evaluate the statistical significance of the SEAT-2010 accumulation rate results, two different averaged or "stacked" records were created. Genthon et al., (2005) showed that spatially averaging a number of accumulation rate records together reduces the amount of small-scale perturbations (SSP; noise due to wind redistribution, sublimation, etc.). Additionally, the study showed that using spatial averages increases the fraction of common variability between accumulation rate observations and simulated accumulation rates (see Section 4; Genthon et al., 2005). The first stacked record is a straight average of the five accumulation rate records. The second stacked record is a weighted average, where a 5-year moving-average of each firn cores' standardized accumulation rate record was used to obtain residuals from the record. The variance of the residuals from the standardized record was then used as an inverse weight in the weighted average. Figure 5 shows both the straight and weighted stacked records for the SEAT-2010 firn cores. The difference between the two stacked records is minimal, so the straight stacked record was used for comparison in the rest of the study.

To determine whether or not the observed accumulation trends are statistically significant, both an ordinary least squares (OLS) regression model and a regression model accounting for the autocorrelated errors was fit to each of the five standardized accumulation records and to the straight and weighted stacked records. Table 1 shows the resulting statistics and p-values for each of the records. All of the records, including both the straight and weighted stacked records, show statistically significant negative trends in accumulation rate for the total length of each record (maximum one-sided $p = 0.040$). Additionally, all of the records except SEAT-10-5 show a statistically significant negative trend in accumulation rate when only the period 1980-2010 is considered (maximum one-sided $p = 0.046$). Thus the negative trends in both stacked records are statistically significant regardless of the period of observation, suggesting that the observed decrease in accumulation is a true regional trend and not a function of noise within the system.

Table 1. Statistical significance of accumulation trends (non-significant p-values in red).				
Core/Period	OLS Model		Autoregressive Model	
	t-statistic	p-value	t-statistic	p-value
SEAT Stack	-6.96	<.0001	-6.96	<.0001
Stack from 1980	-5.35	<.0001	-5.35	<.0001
Stack from 1990	-3.24	0.0044	-4.78	0.0001
SEAT-10-1	-2.69	0.0109	-3.8	0.0006
SEAT-10-1 from 1980	-2.48	0.0193	-3.61	0.0012
SEAT-10-1 from 1990	-0.23	0.8216	-0.23	0.8216
SEAT-10-3	-4.52	<.0001	-4.52	<.0001
SEAT-10-3 from 1980	-2.79	0.0092	-3.71	0.0009
SEAT-10-3 from 1990	-2.15	0.0446	-2.15	0.0446
SEAT-10-4	-5.17	<.0001	-7.23	<.0001
SEAT-10-4 from 1980	-3.45	0.0017	-5.2	<.0001
SEAT-10-4 from 1990	-3.84	0.0011	-3.84	0.0011
SEAT-10-5	-2.14	0.0402	-3.64	0.001
SEAT-10-5 from 1980	-1.88	0.0698	-3.33	0.0026
SEAT-10-5 from 1990	-0.84	0.413	0.38	0.7098
SEAT-10-6	-3.21	0.0025	-5.2	<.0001
SEAT-10-6 from 1980	-2.08	0.0464	-2.08	0.0464
SEAT-10-6 from 1990	-1.1	0.2852	-1.1	0.2852

The analysis above takes into account the analytical uncertainties in the density measurements; however, it fails to account for two different types of uncertainty associated with assigning dates to the various peaks in the isotopic records: peak identification uncertainty and date identification uncertainty.

Peak identification uncertainty was addressed by assigning to each peak a probability that it represents a true summertime maximum. Generally, annual maximums are easily identified (note SEAT-10-5 in Figure 6D); however, some potential peaks are abnormally shaped or spaced, and identifying the true number of years over a given portion of the record can prove difficult. A probability ranging from 0 to 1 was assigned to each 2 cm sample, with a value of 0 indicating a 0% probability, and a value of 1 indicating a 100% probability that the sample is associated with a summer maximum. The vast majority of the samples were clearly not peaks, and were assigned a value of 0; samples corresponding to a clear annual mid-summer peak were given a value of 1; samples associated with possible mid-summer peaks were assigned a value between 0 and 1. A number of realizations are then drawn from a Bernoulli distribution for each sample. Samples where any of the realizations are equal to 1 are treated as possible mid-summer peaks, and annual accumulations can be obtained by summing the accumulations between these peaks.

An assumption in counting seasonal cycles in isotopic records is that the peaks (or troughs) are occurring at the same time each year (i.e., the summer-time maximum in $\delta^{18}O$ of any given year is assumed to occur on 1 January). In reality, the $\delta^{18}O$ summer maximum could occur several weeks before or after January 1, leading to the second type of uncertainty associated with the dating method: date identification uncertainty (Steig et al., 2005). Based on the shape of each peak, a range of plausible dates is identified within which the actual January 1 date is expected to occur among 90% of similar peaks.

After accounting for peak identification and date identification uncertainty, 1000 accumulation rate time series for each of the five SEAT-2010 firn cores were generated using the sample realizations and the peack morphology. Additionally, for each generated set of five series (SEAT-10-1, SEAT-10-3, SEAT-10-4, SEAT-10-5 and SEAT-10-6), a stacked accumulation rate record was created as described previously. The significance of the trend in accumulation rate was then analyzed using the approach described at the beginning of this section. Table 2 shows the percentage of the 1000 accumulation rate time series generated for each firn core and the stacked record that displayed a significant negative trend. Despite the range of plausible accumulation rate time series for any one core site (Figure 7), there is still very strong evidence for a downward trend in accumulation rate in each of the firn cores and the stacked record.

Table 2. Percent of possible accumulation series with significant (two-sided) test for trend.						
	SEAT-1	SEAT-3	SEAT-4	SEAT-5	SEAT-6	Average Accumulation
Percent Significant	99.90%	100%	100%	97.00%	99.70%	100%

3.4 Topographic and Temperature effects on Accumulation Rate

Many different factors can influence the surface mass balance of WAIS and potentially explain the trends in accumulation rate seen. For example, changes to precipitation, sublimation/evaporation, topographic irregularities and temperature can all impose a trend in accumulation rate. The hypothesis we put forth is that the observed trends in accumulation rate from the SEAT-2010 records is due to shifts in atmospheric circulation and associated changes in precipitation rates. Before the negative accumulation rate trend can be attributed to a change in atmospheric circulation patterns, the potential effect of other factors must be ruled out. The following two sections will investigate the effect of topography and temperature on accumulation rate results from the SEAT-2010 area.

3.4.1 Topographic Effects

The interpretation of accumulation rates from ice core records can be influenced by the ice sheet topography upstream of the core site, where past undulations that existed on the surface of the ice sheet can be manifested at depth in the core as prolonged periods of above- or below-average accumulation (Kaspari et al., 2004). All five SEAT-2010 cores were collected on or near (distance <75 km) the ice divide, where flow rates are low and surface undulations minimal. Analysis of the topography of the ice sheet upstream from each ice core site was conducted using a DEM generated by the National Snow and Ice Data Center (NSIDC) (Dimarzio et al., 2007) according to the methods described by Kaspari et al (2004). Figure 8 shows the five SEAT-2010 core sites plotted on a 2 m contour map generated from the NSIDC DEM. Both SEAT-10-1 and SEAT-10-5 were collected near the centerline of the divide and the surface slope upstream of the sites is minimal, suggesting that any changes in accumulation seen at these sites is not a function of upstream topography. SEAT-10-3 and SEAT-10-6 were collected roughly 24 km and 72 km from the divide centerline respectively. Like SEAT-10-1 and SEAT-10-5, the topography upstream of SEAT-10-3 and SEAT-10-6 is relatively smooth and has a shallow slope. SEAT-10-4 is the furthest from the divide centerline (~73 km) and the upstream topography is slightly more complex, including a ~10 km undulation. The coastward crest of this undulation is 9 km upstream from the core site, and the DEM shows that the maximum difference between the crest and trough heights is <6 m. If this undulation has been a stable feature through time, it is possible that the accumulation rate record for SEAT-10-4 has been affected by the undulation; however, because the ice sheet flow rate near the divide is so slow (Rignot et al., 2011), it is unlikely that the 22 m core contains snow/ice old enough to have been significantly affected by the undulation. Additionally, as shown in Section 3.2, even when the record from SEAT-10-4 is excluded from the stacked SEAT-2010 accumulation rate time-series the negative accumulation trend persists, suggesting that the presence of undulations upstream of SEAT-10-4 has not seriously affected the accumulation rate results.

3.4.2 Temperature Effects

There is no coherent, statistically significant, trend in isotopes across the study region from 1976 to 2010 (Figure 6). Certainly there is no evidence of a negative trend in isotopes (and by correlation, a negative trend in temperature) which might explain the decrease in accumulation rates. Additionally, previous studies of the larger WAIS region have shown that temperatures are increasing (Steig et al., 2009), which would, assuming a simple relationship between temperature and precipitation, be expected to lead to an increase in accumulation rate. Both the SEAT-2010 isotopic data and work done by Steig et al. (2009) suggest that the negative trend in accumulation rate cannot be attributed directly to local or regional temperature trends alone.

3.5 Additional Evidence

Two additional lines of evidence exist that agree with the negative trend in accumulation rates observed in the SEAT-2010 cores. The first line of evidence comes from the Gravity Recovery and Climate Experiment (GRACE) satellites, which have been in operation since 2002, mapping spatial and temporal changes to Earth's gravity field. The gravity measurements are spatial averages termed "mascons" (from 'mass concentrations'). Observations from the two mascons (620, 630) that correspond to the SEAT-2010 study area show a negative mass anomaly beginning before 2004 and continuing to 2010 (personal communication, Luthcke, 2012). The rate of ice flow in the region near WAIS divide is too low to account for all of the decrease in mass (Rignot et al., 2011); therefore it is reasonable to assume that the observed negative mass anomaly is due in part to a decrease in accumulation rate. It should be noted that the period of observations for the GRACE data (2003-2010) is much shorter than the period covered by the SEAT-2010 cores.

The second line of evidence comes from the deuterium-excess (d-excess) records calculated from the isotopic analysis of the SEAT-2010 cores. Deuterium-excess is often assumed to be a proxy for moisture source region conditions (Fernandoy, et al., 2011). The d-excess records from all of the core sites and a stacked average of the five records show a statistically significant negative trend in d-excess. Fernandoy et al. (2011) show that a negative trend in d-excess corresponds most with either a cooling of the moisture source region or a pole-ward migration of the source region. It is therefore possible that this shift in d-excess reflects a change in atmospheric circulation that affects the central WAIS accumulation rates.

While significant uncertainty may attend each of these three lines of evidence (SEAT-2010 accumulation rate record, GRACE data, and the d-excess record), taken together they present a compelling case for decreasing accumulation rates across the SEAT-2010 study area over the past two decades.

3.6 SEAT-2010 and US-ITASE Accumulation Rates

The SEAT-2010 accumulation rate records are compared to WAIS accumulation rate observations collected during previous expeditions to ascertain whether the decrease in accumulation rates is spatially restricted to only a small area of WAIS or is indicative of a larger, regional trend. In order to determine if the five new SEAT-2010 cores serve as a reliable proxy for the greater WAIS region, a simple stacked record (hereafter referred to as SEAT10) was created from the overlapping portions (1976-2010) of the five SEAT-2010 accumulation rate records and compared to two stacked records created from a similar average of cores collected during the US-ITASE expeditions to WAIS (Figure 1): the first stacked ITASE record (ITASE, hereafter) consists of accumulation rate records from 16 core sites recovered from across a wide area of WAIS; the second record consists of the accumulation rate records from 8 core sites located in a more restricted area in central WAIS (this record will be referred to hereafter as CW). The cores incorporated into CW (ITASE-00-1, ITASE-00-3, ITASE-01-1, ITASE-01-2, CWA-D, RIDS-A, RIDS-B and RIDS-C) were chosen based on their proximity to SEAT10 (generally less than 250 km distant) and their distribution along the accumulation gradient that crosses the divide.

In terms of both magnitude of accumulation and interannual variability, SEAT10 agrees more closely with CW than with ITASE. The mean accumulation rate for SEAT10 is 260.3 w.e. mm/yr compared to 221.6 w.e. mm/yr for ITASE, and the difference between the two means is statistically significant (two-sided $p = 0.0005$). In contrast, the mean accumulation rate for CW during 1976-1993 was 268 w.e. mm/yr, only ~8 mm higher than the mean rate observed in SEAT10, and the differences are not statistically significant. However, several difficulties arise when comparing these different stacked records. Because averaging a larger pool of records together tends to decrease noise, much of the difference in interannual variability between SEAT10 and the two other records can likely be explained by a difference in sample size. Additionally, the removal of just one core from any of the stacked records leads to a significant change in mean accumulation rate and the standard deviation, suggesting that the resulting means of the stacked records are highly dependent on the locations/number of cores included. Nevertheless, the close agreement between SEAT10 and CW suggest that it is possible that the SEAT-2010 accumulation rate records may correlate to a larger region.

Both Kaspari et al. (2004) and Monaghan et al. (2006) noted negative trends in accumulation rate observations from WAIS, as observed in this study as well; however, those trends were not significant. If the new SEAT-2010 records are truly representative of the larger region, the significance of the negative accumulation rate trend observed in the new findings may simply indicate that the US-ITASE cores were not collected recently enough to capture the significance of the negative trend.

3.7 Relationship between SEAT-2010 Accumulation Rates and Southern Hemisphere Climate Patterns

One possible cause of the decreasing trends in accumulation rate could be a change to atmospheric circulation patterns affecting precipitation over Antarctica. The Southern Annular Mode (SAM) is the dominant mode of atmospheric variability in the high latitudes of the Southern Hemisphere (Marshall, 2003) and is defined as either the first empirical orthogonal function of sea level pressure, or as the difference in normalized zonally averaged anomalies between 40˚S and 65˚S (Ding et al., 2012).

Numerous studies have described a positive shift in the SAM (Figure 9) since the mid-1970s, e.g. Thompson et al. (2011). Genthon et al., 2003 linked the positive phase of the SAM to lower mean sea-level pressure (MSLP) over the Amundsen Sea area, and showed that this zone of low pressure leads to lower precipitation rates over western WAIS (nearer the Ross ice shelf) and higher precipitation rates over eastern WAIS (nearer the Antarctic Peninsula; Figure 10). As the duration of positive SAM phases increases, low pressure conditions over the Amundsen Sea should occur more often/persist longer, leading to the sustained periods of low accumulation across western WAIS observed in the SEAT-2010 accumulation rate records. MSLP output from ERA-Interim support this hypothesis, showing a pronounced shift from higher pressures over the Amundsen Sea area during the SEAT-2010 high accumulation rate decade (mid-1970s to mid-1980s) to lower pressure during the most recent, low accumulation rate decade (Figure 11).

It is also possible that the change in SEAT-2010 accumulation rates is not due to internal dynamics at high latitudes, but instead linked by teleconnections to changes in tropical climate. In particular, recent work by Ding et al. (2012) has shown that the atmospheric pattern generally identified as the SAM may not be a zonally symmetric pattern driven by internal dynamics at high latitudes as is generally assumed, but rather a zonally asymmetric pattern driven by variations in tropical SST. The study concludes that a true SAM pattern can only be said to exist during the austral summer and that atmospheric variations over the WAIS region during the colder months are in fact due to SST anomalies in the central tropical Pacific (Ding et al., 2012). Figure 11 shows that negative trends in MSLP over the Amundsen Sea of the coast of WAIS are occurring during the entire year, with the largest negative trend happening in the fall months. Because this anomaly occurs during the entire year, it is most likely being driven by both changes to tropical Pacific SST changes year-round and high latitude variability (SAM related variability) during the summer months, which in turn suggests that the observed decrease in accumulation rates in the SEAT-2010 records are being caused by larger scale changes to climate patterns at lower latitudes, and internal variability of atmospheric dynamics at high latitudes.

4. Simulated versus Observed Accumulation Rates across Central WAIS

Because accumulation rate is an important component of ice sheet mass balance it is critical that highly skilled regional climate models be developed. Many different meso-scale models have been developed to accurately simulate Antarctic climate, but it is important to determine whether these models are capable of capturing the magnitude and variability of precipitation over the ice sheet. To validate the skill of such models and the various climate reanalyses, they must be compared to observational data, such as the SEAT-2010 accumulation rate records.

The reconstructed accumulation rate time-series from the five individual SEAT-2010 cores and the stacked SEAT record were compared to the accumulation output generated from two regional climate models (RACMO2.1/ANT and Polar MM5), NASA's Modern-Era

Retrospective Analysis for Research and Applications (MERRA), ERA-40 and ERA-Interim climate reanalyses generated by ECMWF. The models/reanalyses utilize different methods for calculating accumulation rate (Bromwich et al., 2011). MERRA, ERA-40, ERA-Interim and the Polar MM5 output used in this study make use of a simple precipitation minus evaporation formula (P – E) that does not take into account various ablation processes such as horizontal transport and sublimation of blowing snow. RACMO2.1/ANT uses a more complex formula to calculate accumulation rate that includes the above-mentioned ablation processes. The implications of including/excluding horizontal snow transport and blowing snow sublimation will be discussed later. Figure 12 shows each of these simulation accumulation rate records plotted against time. It should be noted that all of these models and reanalyses operate on different horizontal grid spacing. Because of the differences inherent in each model/reanalysis, direct comparison between the individual models and the individual/ firn cores was beyond the scope of this study. Rather, the regionally-averaged trends in the model/reanalyses output are compared to the regionally-averaged trends seen in the stacked SEAT record. The area over which the regional averages were calculated corresponds to the SEAT-2010 study area (77˚S to 81˚S latitude, 116˚W to 120˚W longitude).

4.1 Model/Reanalyses Descriptions

As described by Lenaerts et al. (2012), RACMO2.1/ANT is a regional atmospheric climate model that merges the dynamics of the High Resolution Limited Area Model (HIRLAM) and the physical processes of the European Centre for Medium-Range Forecasts (ECMWF) model. The model has been optimized to simulate the climate conditions of large ice sheets. RACMO2.1/ANT has a horizontal grid spacing of 27 km and is forced at its boundaries by ERA-Interim. RACMO2.1/ANT covers the period 1979-2010.

Polar MM5 is a regional atmospheric model based on the fifth-generation Pennsylvania State University-National Center for Atmospheric Research (PSU-NCAR) Mesoscale Model, which has been optimized for climate modeling over ice sheets by the Byrd Polar Research Center at The Ohio State University (Bromwich et al., 2004). Polar MM5 has a 60 km horizontal resolution and its boundary conditions are forced by both ERA-40 and NCEP-II (Monaghan et al., 2006b). Polar MM5 covers the period 1979 to 2001.

MERRA is a climate reanalysis developed by NASA to address deficiencies found in the hydrological cycle as represented by other climate reanalyses (Reineker et al., 2011). MERRA utilizes the 3DVAR data assimilation analysis algorithm and has a ½˚ latitude by ⅔˚ longitude horizontal grid resolution (Reineker et al., 2011). The MERRA output used in this study covers the period 1979 to 2010.

ERA-40 is a 45-year reanalysis conducted by ECMWF (Uppala et al., 2005). Salient improvements over the previous ERA-15 reanalysis are a higher horizontal resolution (2.5˚ latitude by 2.5˚ longitude) and more observations, including operational data provided by NCEP and the Japan Meteorological Agency, and *in situ* and satellite data from NCAR (Uppala et al., 2005). Numerous studies (Bromwich and Fogt, 2004; Monaghan et al., 2006) have shown that the full record of ERA-40 SMB output shows a strong positive trend due to the incorporation of remote sensing observations after 1978. Bromwich and Fogt (2004) reported that it is only after 1978 that ERA-40 reaches a high level of skill; thus this study restricts the use of ERA-40 to the period 1978-2001.

As reported by Dee et al. (2011), one goal of the ERA-Interim reanalysis was to prepare for a replacement atmospheric reanalysis for ERA-40. ERA-Interim offers a higher horizontal resolution than its predecessor, with a 1.5˚ latitude by 1.5˚ longitude grid. Relative to ERA-40, the newer reanalysis shows better skill at representing the hydrological cycle and has better temporal consistency on multiple time-scales (Dee et al., 2011). ERA-Interim includes the period from 1979 to 2012 and is being continuously extended forward (Dee et al., 2011; ECMWF website: ERA-Interim data portal). The ERA-Interim and ERA-40 data were obtained from the ECMWF Data Server.

4.2 Simulated and observed accumulation rate results over central WAIS

Table 3. Statistical comparison of stacked SEAT-2010 record and five simulated accumulation rate time-series. Section **A** shows the correlation coefficient (r) and the associated p-value for each record. Section **B** shows the resulting two-tailed p-values from a simple t-test comparing the mean accumulation rate of each record.

A	SEAT Stack		MERRA		ERA-INT		ERA-40		RACMO		Polar MM5	
	r	p-value	r	p-value	r	p-value	r	p-value	r	p-value	r	p-value
SEAT Stack	1	0	0.13	0.55	0.20	0.37	0.12	0.58	0.09	0.68	0.12	0.57
MERRA			1	0	0.85	>0.01	0.71	>0.01	0.73	>0.01	0.77	>0.01
ERA-INT					1	0	0.88	>0.01	0.77	>0.01	0.91	>0.01
ERA-40							1	0	0.81	>0.01	0.84	>0.01
RACMO									1	0	0.75	>0.01
Polar MM5											1	0

B	SEAT Stack	MERRA	ERA-INT	ERA-40	RACMO	Polar MM5
	p-value	p-value	p-value	p-value	p-value	p-value
SEAT Stack	1	0.79	0.53	>0.01	0.28	0.42
MERRA		1	0.30	>0.01	0.15	0.53
ERA-INT			1	>0.01	0.55	0.13
ERA-40				1	>0.01	>0.01
RACMO					1	0.07
Polar MM5						1

Despite the differences in horizontal resolution and model formulations, Fig. 12 shows that all of the models are in good agreement with each other for the period of overlap, 1979-2001, with similar periods of higher than average accumulation rates (for example, the early 1990s) and lower accumulation rates (the mid-1990s). Tables 3a shows that all of the models/reanalyses are highly correlated with each other (r > 0.71), but are not significantly correlated with SEAT10, suggesting that the models/reanalyses are consistent amongst themselves but do not accurately capture the observed interannual variability in accumulation rate. However, Table 3b shows that , with the exception of ERA-40, there is no significant difference in mean accumulation rates between the models/reanalyses and SEAT10, suggesting that the models/reanalyses do accurately capture the observed magnitude of accumulation rate. This suggests that despite a variety of horizontal grid sizes and differing model complexity, no one model/reanalyses (aside from ERA-40) stands out as being more or less skilled at simulating accumulation rates over the SEAT-2010 study area. It should be noted that the comparisons made in Table 3 include only the period of overlap between SEAT-2010 and the models/reanalyses (1979-2001)

A multi-model ensemble mean of the five simulated accumulation rate records was created for the period 1979 to 2010 by averaging together all models/reanalyses that overlap over a given period. The IPCC Fourth Assessment Report described the many difficulties in simulating climate behavior over Antarctica, especially when comparing output from reanalyses, GCMs and regional climate models (Lemke et al., 2007). Using a multi-model ensemble mean helps account for the range of accumulation-rate values simulated by the different models/reanalyses. Figure 13 shows the model ensemble plotted against the stacked SEAT-2010 record, each with their respective 95% confidence intervals. During the 1980s and early 1990s the stacked model record agrees well in both magnitude and variance with the SEAT-2010 observations; however, the model ensemble mean does not show the sharp negative trend in accumulation rate seen in the SEAT-2010 stacked record after ~1995.

Ascertaining in a quantitative way why the models/reanalyses do not reflect the observed trend in accumulation rate is the subject of future work; however, we offer here several possible explanations for the discrepancies. The models/reanalyses may not be capturing changes in storm frequency/intensity associated with changes in large-scale circulation patterns that have occurred over the past few decades. Additionally, they may not be capturing the full magnitude of shifts in large-scale circulation patterns. Another possibility is that increases in sublimation due to circulation changes may not be accurately captured. As mentioned earlier, some of the models/reanalyses do not take into account horizontal snow transport/blowing snow sublimation when calculating accumulation rates, which may lead to differences between simulated and observed accumulation. However, any trends in wind transport/sublimation would also lead to trends in direct evaporation, and no such temporal trends in evaporation are found in the simulation evaporation, suggesting that the inclusion of additional ablation processes in the model/reanalysis schemes would not have a large effect on the simulated accumulation rates. Indeed, RACMO2.1/ANT, which does include these ablation processes in its calculation of accumulation rate does not show a higher negative trend in accumulation rate than the other models/reanalyses.

5. Conclusions

The negative accumulation trend observed in all of the SEAT-2010 cores may be unexpected in light of increasing temperatures across WAIS and GCM simulations of future precipitation over WAIS which predict increasing annual accumulation rates in response to higher surface temperatures. The combined mean of the five SEAT-2010 cores suggests that on average, accumulation rates have been decreasing across the region by 3.8 w.e. mm/yr, with major declines in accumulation rates beginning in the mid-1990s. Statistical analysis shows that the negative trend is statistically significant at the 95% confidence interval for all five cores and the stacked record.

Comparisons with cores collected during the US-ITASE expeditions show that the magnitude and interannual variability of accumulation rates reconstructed from the SEAT-2010 cores agree well with the previous records. However, it is difficult to determine over how large an area the SEAT-2010 accumulation rate records are truly representative. When comparing the stacked SEAT-2010 record to averages of the US-ITASE cores the addition or subtraction of even one core in either group has a large influence on the resulting mean accumulation rate and can change the comparison of means between stacked records from significance to insignificance. This suggests that the magnitude/interannual variability of the stacked records is highly dependent on the selection of cores. At minimum, the SEAT-2010 record demonstrates that a sizable area of central WAIS has experienced a period of decreasing accumulation rates since 1995.

The decrease in accumulation rates cannot be easily explained by a regional trend in temperature as evidenced by isotopic analysis of the cores. No clear trend exists in any of the isotope records, suggesting that temperature trends have not significantly affected the study area over the past ~3 decades. Additionally, the upstream topography of SEAT-10-1, SEAT-10-3, SEAT-10-5 and SEAT-10-6 (all of which are located near the divide) is characterized by low surface slopes and a lack of meso-scale surface undulations. This suggests that the accumulation rate records from these cores are not due to topographic irregularities. Surface undulations may exist upstream of SEAT-10-4, but due to the short period of time the core covers, these undulations are unlikely to have affected the reconstructed accumulation rates. Thus, the trends in accumulation rate are mostly likely due to atmospheric circulation changes over the past decades.

From 1979 to 1990s, the mean accumulation rate of the stacked SEAT-2010 record agrees well with the simulated output of MERRA, RACMO, Polar MM5, and ERA-Interim; however, none of the models/reanalyses accurately simulate the interannual variability observed in the SEAT-2010 records. Excluding ERA-40, none of the models exhibit more skill than the others at simulating temporal changes in accumulation rate over the SEAT-2010 study area. Additionally, after 1995 the observed and simulated accumulation rate records diverge sharply. The large negative trend seen in the cores is not present in any of the models/reanalyses.

The most likely explanation for the decreasing accumulation rate is changes in atmospheric circulation patterns influencing central WAIS. Since the 1970s, a positive trend in the SAM index (visible in the summer/fall months) has led to lower pressures over the Amundsen Sea (seen in all seasons) and decreasing snowfall over western WAIS. If the negative trend in accumulation rates in the SEAT-2010 cores is indeed the result of the year-round negative trend in MSLP (this study) and the positive trend in the SAM (Ding et al, 2012), then this may suggest that low precipitation caused by two factors: 1) changes to tropical Pacific SSTs that affect atmospheric circulation patterns at higher latitudes, and 2) changes to internal atmospheric dynamics at high latitudes (as evidenced by the positive trend in the SAM) during the summer months, and that both these high and low latitude changes may account for the decrease in accumulation rates observed in the SEAT-2010 study area. If this theory is correct, the negative trend in the SLP and geopotential heights should be inducing higher-than-average accumulation rates over eastern WAIS (as identified by Genthon et al. (2003); however, published accumulation rate records that extend through the 2000s are lacking in that region.

Though the negative trend in accumulation rates is statistically significant, the cores do not cover a long enough period (<50 yrs) to determine if this is a long-term trend towards lower accumulation across central WAIS. It is entirely possible that long-term temperature increases will eventually cause an increase in precipitation, but that the observed temperature increases over WAIS are not yet large enough to have exceeded the natural, long-term variability in accumulation rates; or, it is possible that due to global/regional circulation patterns, an increase in temperature will not lead to a uniform accumulation rate increase over WAIS. Ding et al. (in press) and Steig et al. (submitted) suggest that the warm-month trends (related to the SAM) may be due to anthropogenic forcings. If this theory is correct and high-latitude dynamics are indeed responsible for the observed decline in accumulation rates in the SEAT-2010 cores, future accumulation rates over central WAIS may continue to decrease as greenhouse gases continue to rise. In addition, models will have to correctly capture the trends and variability in the tropical pacific in order to accurately capture trends and variability in WAIS accumulation.

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7. Figures

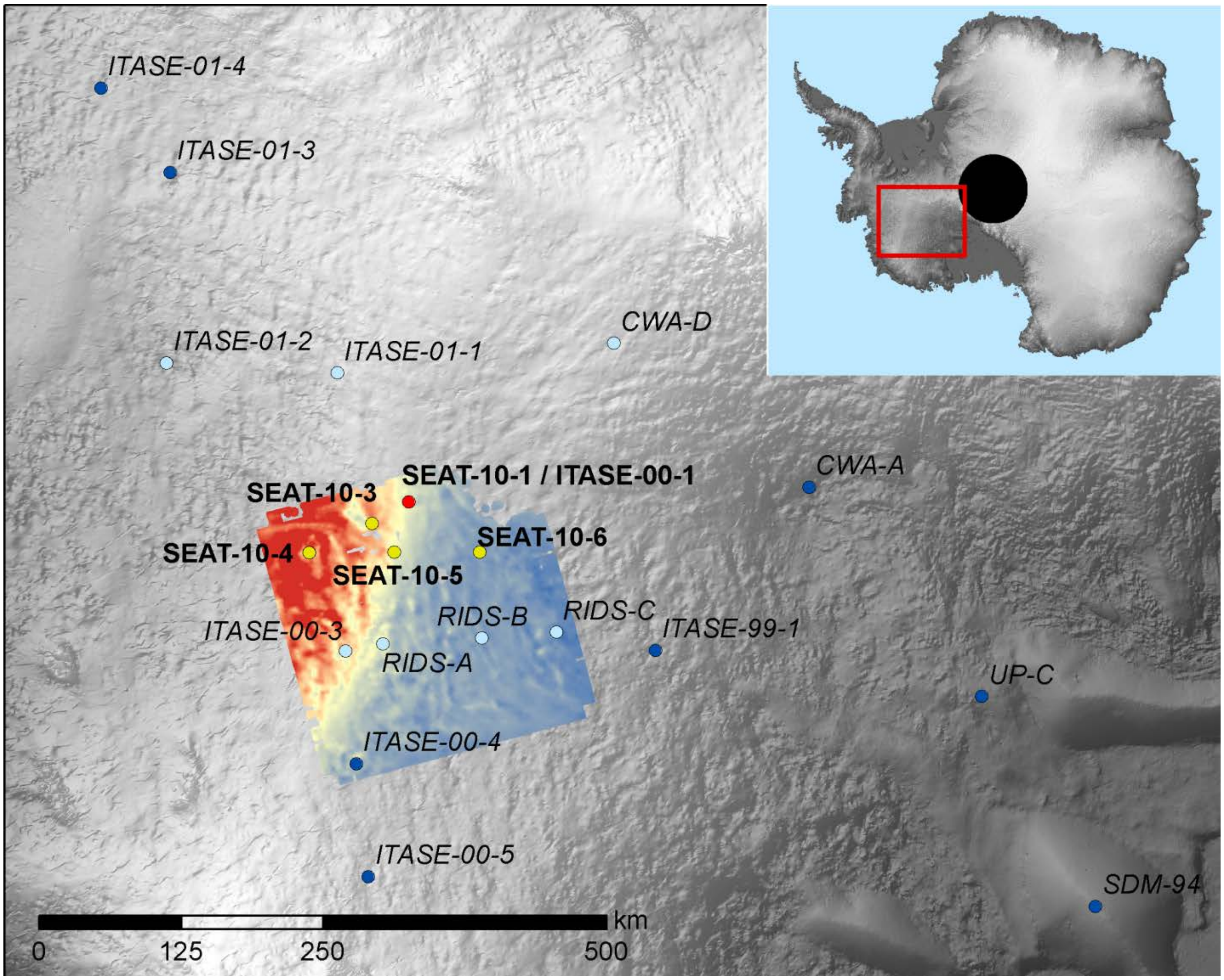

Figure 1. Map showing central WAIS and the SEAT-2010 field area. The red point marks the location of SEAT-10-1 (this study) and ITASE-00-1 (3.6). Yellow points mark the other four SEAT-2010 ice core locations (this study). Blue points (dark and light) mark cores recovered during previous studies. The new ice core data (SEAT) are compared to these previously published data (see Section 3.6). In particular, the ITASE accumulation rate stacked record includes all blue points and the ITASE-00-1. The Central WAIS (CW) accumulation rate stacked record includes the light blue points and ITASE-00-1. The colored section of the map is modified from Morse et al. (2002) and shows the accumulation gradient across WAIS divide from high (red) to low (blue). DEM generated by the National Snow and Ice Data Center (Dimarzio et al., 2007)

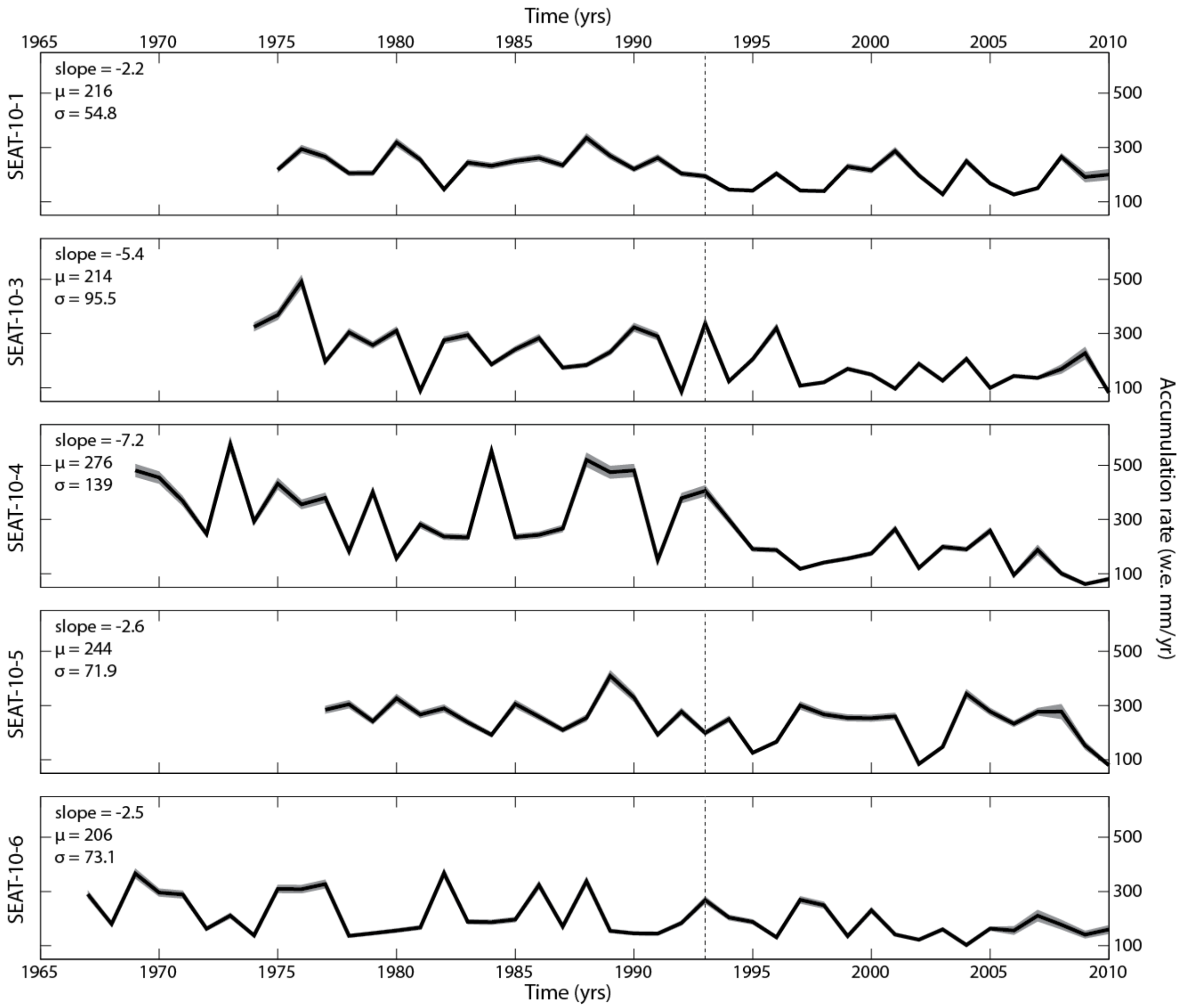

Figure 2. Reconstructed annual accumulation rates (water equivalent mm/yr). The analytical uncertainty associated with the density measurement for each record is represented by the gray band (10% for snowpit samples, 5% for core samples). Uncertainty associated with the age-depth scale is ±1 year at depth. The dotted line marks the year (1993) correlated with the 1991 Pinatubo eruption. Note that all five records show a statistically significant (95% confidence level) negative trend in accumulation rate.

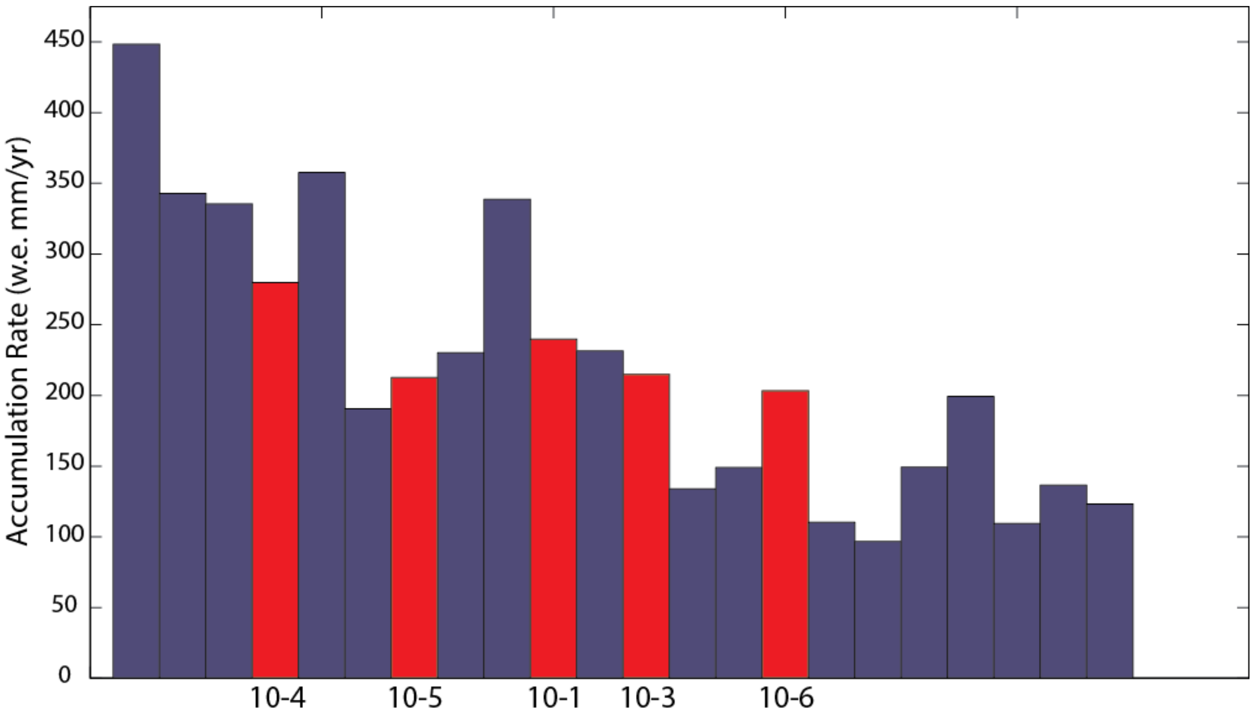

Figure 3. Mean accumulation rate (w.e. mm/yr) for 17 US-ITASE cores and the five new SEAT-2010 cores, arranged by increasing distance from coast (left to right). Note that the SEAT-2010 cores fit the general trend of decreasing accumulation rate with increasing distance from moisture source.

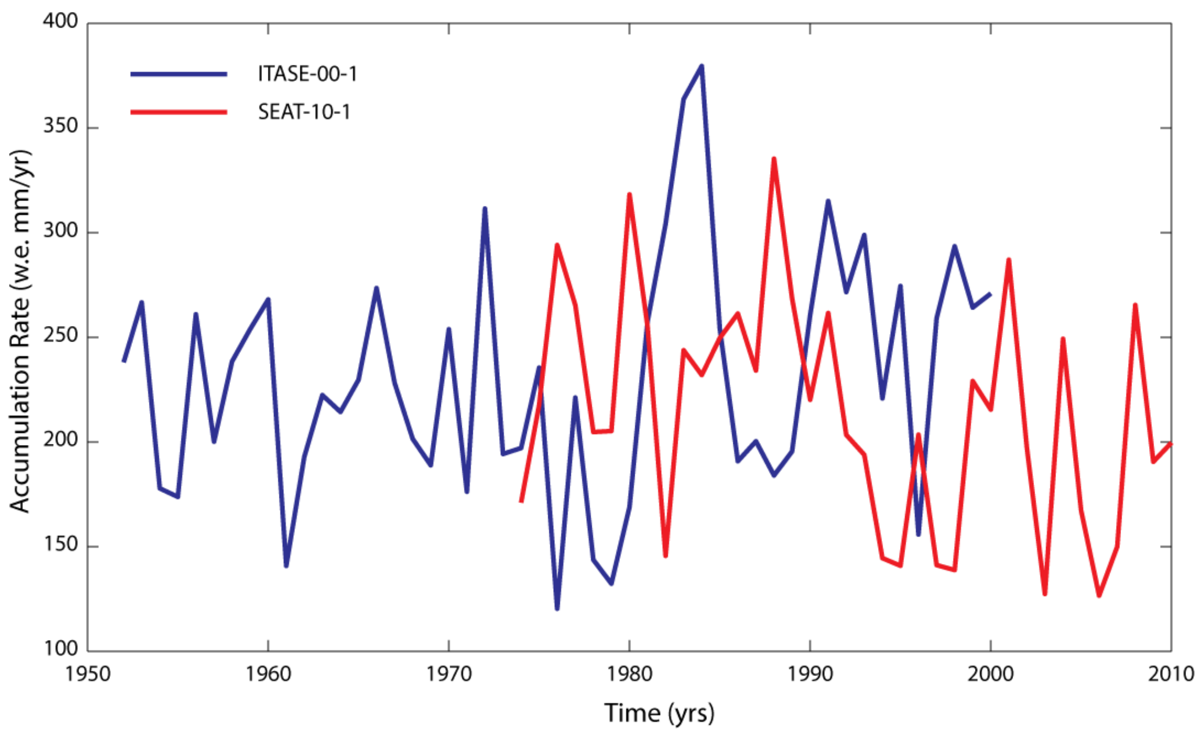

Figure 4. Accumulation rate (w.e. mm/yr) for both ITASE-00-1 and SEAT-10-1, which were collected at the same location. During the period of overlap the two cores display similar magnitudes and ranges of interannual variability in accumulation rates.

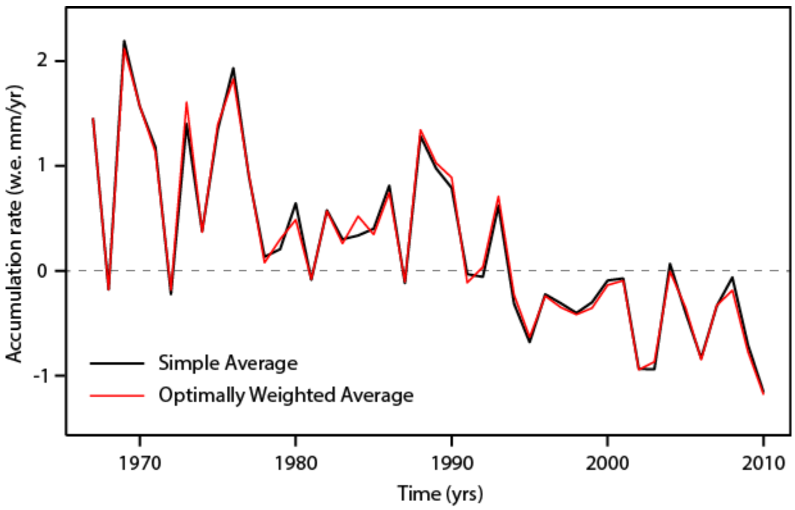

Figure 5. Normalized average of the five SEAT-2010 cores for the period of overlap (1979-2010), and the optimally weighted average. The two different stacked records show little difference, so the straight average was used in the discussion.

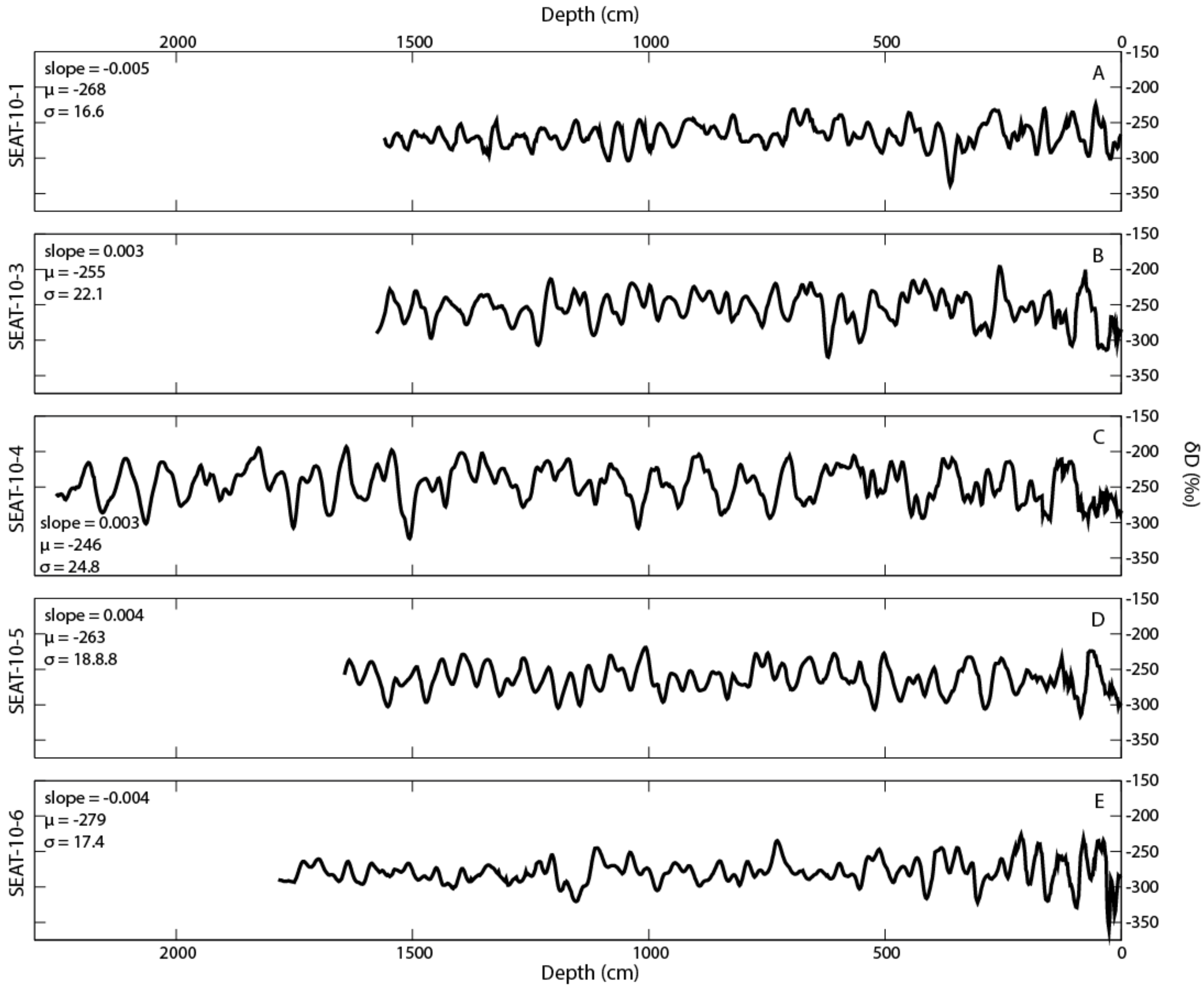

Figure 6. Isotopic data for the five SEAT-2010 cores. There are no significant isotopic trends in any of the isotopic records, suggesting that local temperature has not changed appreciably over this time period.

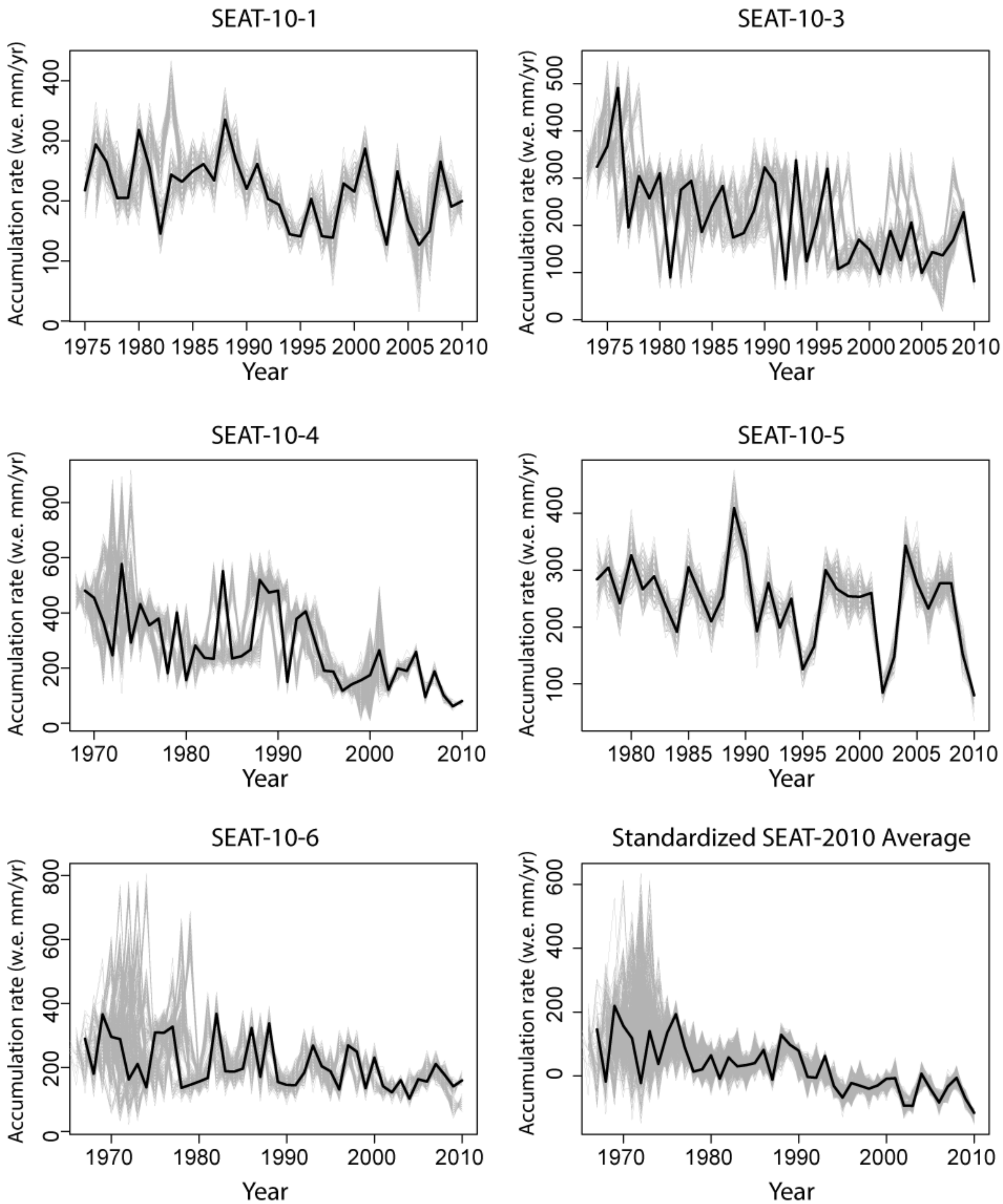

Figure 7. Reconstructed accumulation rate (w.e. mm/yr) for each SEAT-2010 core and the stacked record (black) and 1000 possible accumulation rate series based on dating uncertainty (gray). Note that the negative trend persists in all of the cores for nearly all of the possible accumulation rate series (see Table 2).

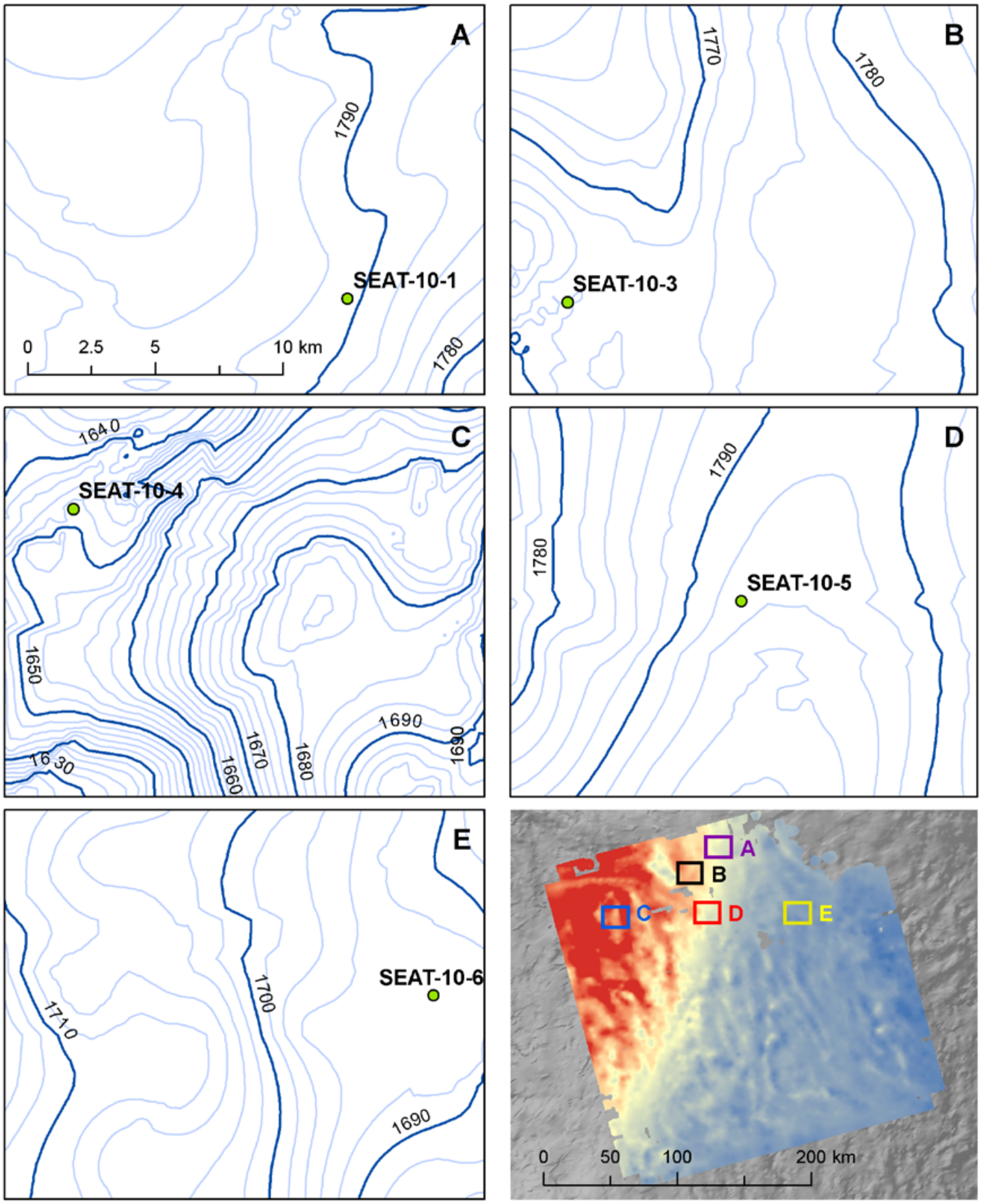

Figure 8. Contour plots showing the topography around the five SEAT-2010 core sites (A to E). The lower left-hand image shows the accumulation map from Morse et al. (2002) as described in Figure 1. SEAT-10-1, SEAT-10-3, SEAT-10-5 and SEAT-10-6 show no signs of upstream undulations that might influence the accumulation rate record. A possible undulation exists upstream of SEAT-10-4, but the core is too short and regional flow rates too slow for the resulting accumulation rate record to be biased. Note that the scale in A to E are the same.

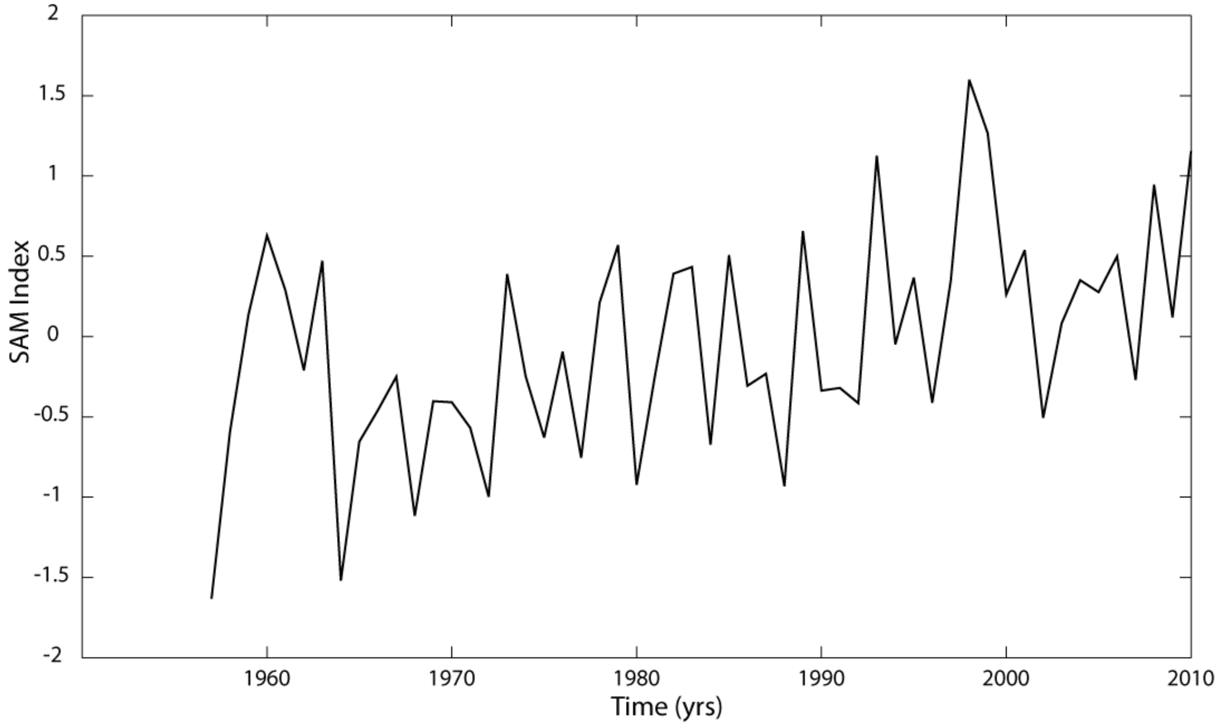

Figure 9. Southern Annular Mode (SAM) index from Marshall (2003). The positive phase of the SAM corresponds to lower pressures over Amundsen Sea. Since the mid-1970s the SAM has shown a trend towards increasing positive phase.

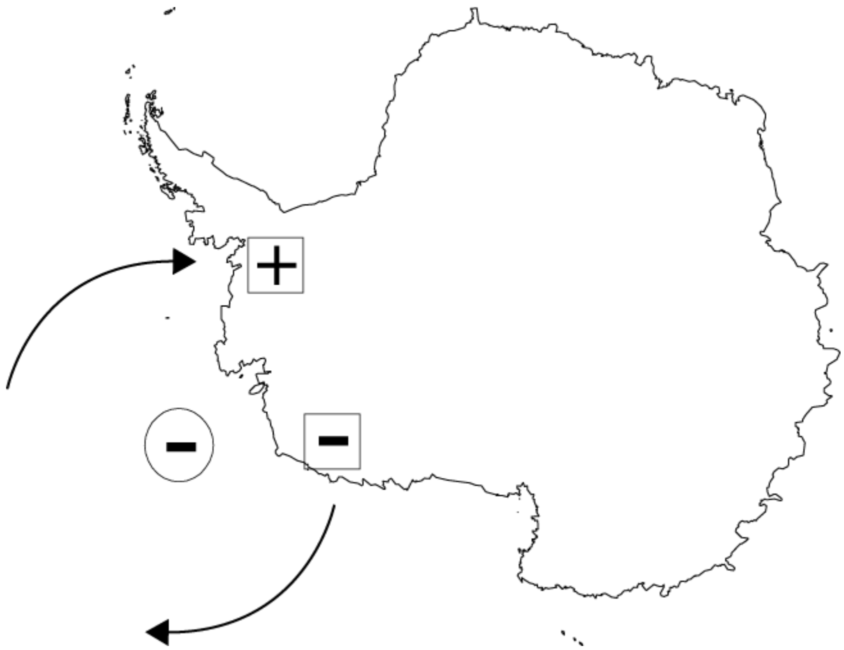

Figure 10. Conceptual image modified from Genthon et al. (2005) showing the effect a low pressure center (minus sign in circle) over the Amundsen Sea has on accumulation rates over WAIS. The low pressure center is associated with the positive phase of the SAM and results in lower accumulation rates over western WAIS (minus sign in square) and higher accumulation rates over eastern WAIS (plus sign in square). As the duration of the positive SAM phase has increased, so too has the duration of the low pressure system over the Amundsen Sea.

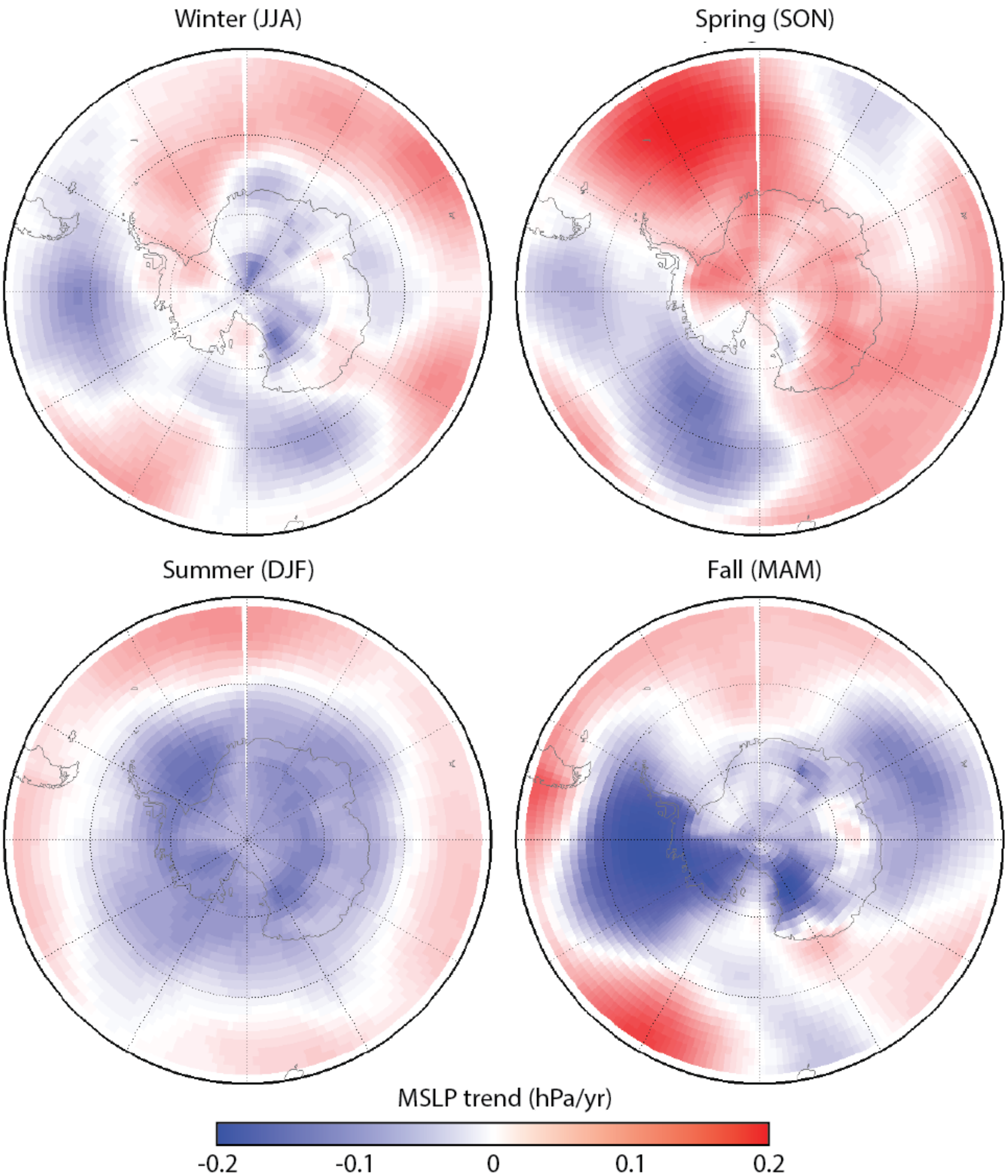

Figure 11. Mean sea-level pressure (MSLP) trends in hPa for DJF (A), MAM (B), JJA (C) and SON (D). Note the negative trends present in all seasons, indicating adecrease in MSLP occurring in all seasons. This decrease is dominated by the fall season (MAM). MSLP from ERA-Interim provided by ECMWF.

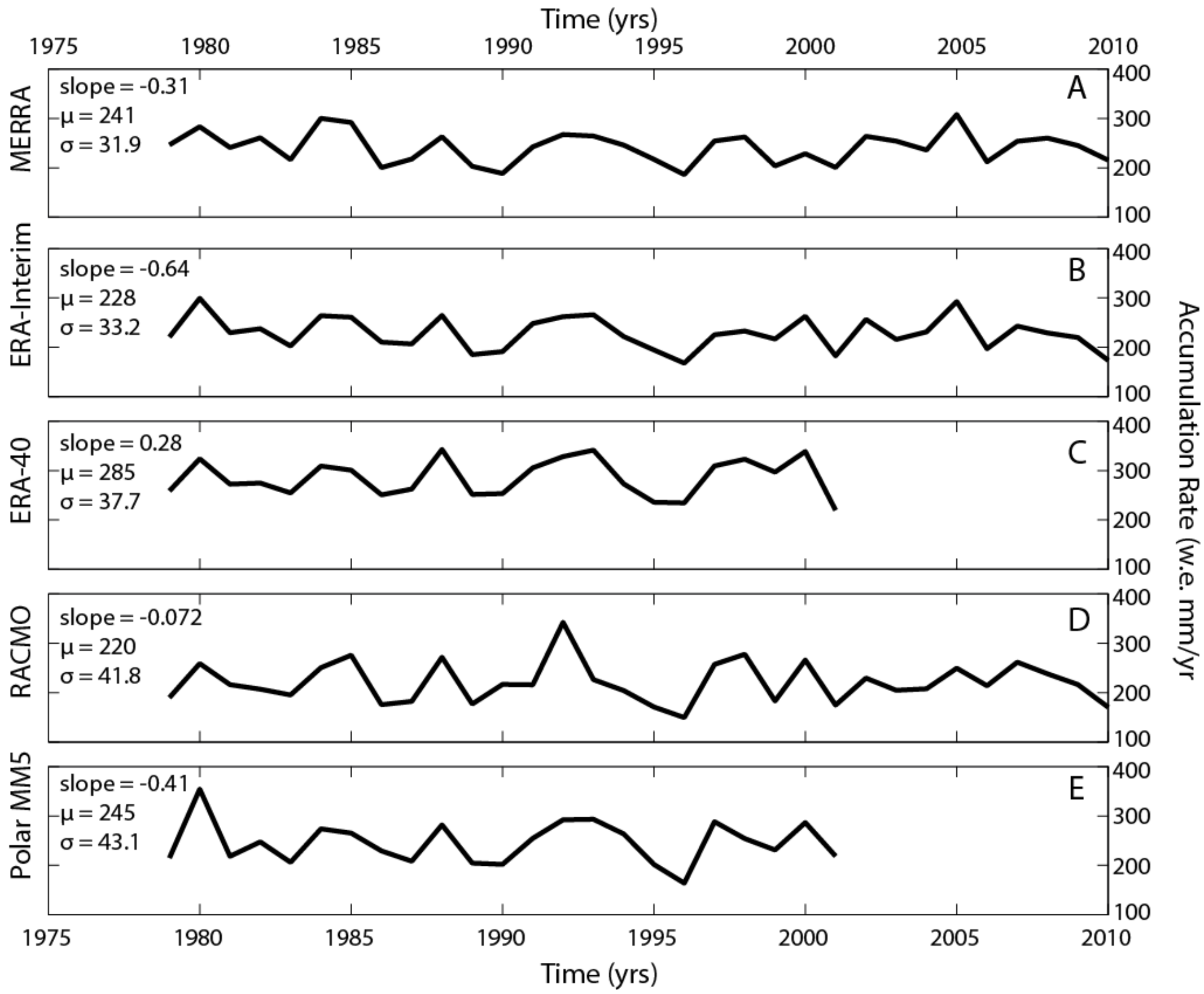

Figure 12. Accumulation rates (w.e. mm/yr) simulated for the SEAT-2010 area by three reanalyses (A,B,C) and two regional climate models (D,E). Note that the magnitude and interannual variability of all of the models/reanalyses are in general agreement. None of the models display a significant trend (positive or negative) in accumulation.

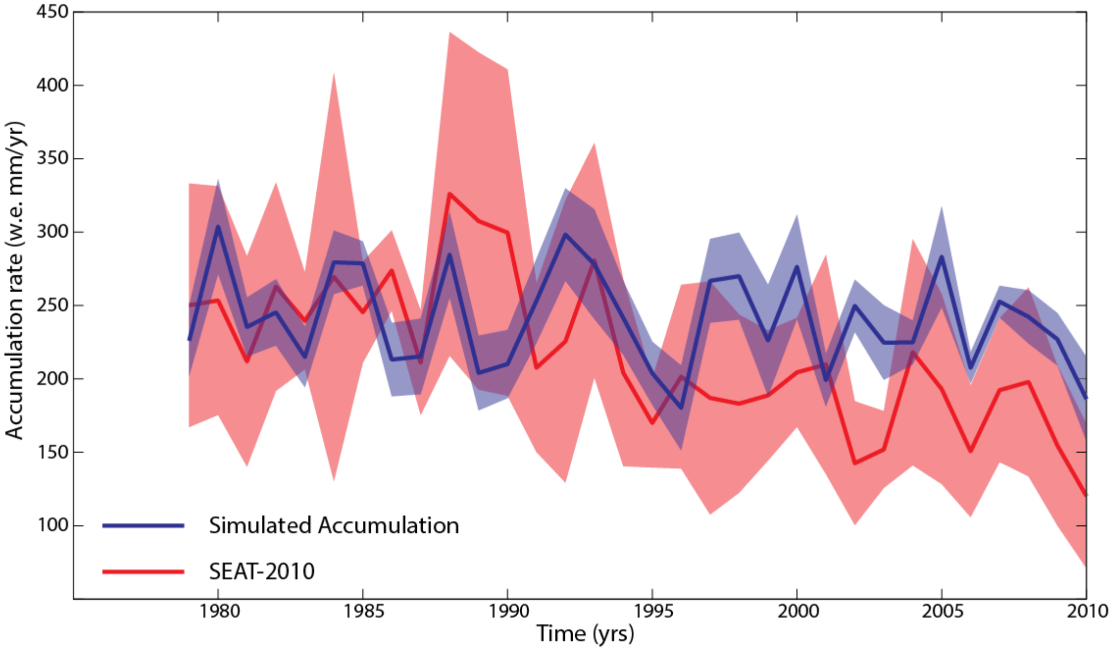

Figure 13. Observed (red) and simulated (blue) accumulation rates (w.e. mm/yr) for the SEAT-2010 study area. Both the observed and simulated time series agree in magnitude and variability, but the simulated record does not capture the large decrease in accumulation rate seen after 1995 in the SEAT-2010 cores. The blue and red bands around each time series mark the 95% confidence intervals.