Spatial and temporal variability in snow accumulation at the West Antarctic Ice Sheet Divide over recent centuries

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Received 7 April 2008; revised 21 July 2008; accepted 19 August 2008; published 10 December 2008.

Ice cores collected in 2000 (ITASE 00-1) and 2005 (WDC05A, WDC05Q) from the West Antarctic Ice Sheet Divide (WAIS Divide) project site were used to investigate the spatial and temporal variability in accumulation. The ice cores were dated based on annual layer counting of multiple glaciochemical measurements resulting in bottom depth ages for WDC05A, WDC05Q, and ITASE 00-1 of 1775, 1521, and 1653 A.D., with mean annual accumulation rates of 0.200, 0.204, and 0.221 m\textsubscript{eq} a\textsuperscript{-1}, respectively. Small-scale spatial variability (SSV) was determined using an analysis of variance of accumulation in the ice core array, thereby quantifying the uncertainty in individual accumulation records. Results indicate that the spatial variability was 0.030 m\textsubscript{eq} a\textsuperscript{-1}, or approximately 15% of the average annual accumulation. An accumulation record representative of the WAIS Divide local area over recent centuries was developed using a principal component analysis to identify the coherent accumulation signal. The WAIS Divide local record exhibited 14% interannual variability (1 standard deviation of the mean) with the SSV reduced to 0.017 m\textsubscript{eq} a\textsuperscript{-1}. Correlations of the WAIS Divide local accumulation record with atmospheric indices (e.g., Antarctic Oscillation) exhibited periods when the records oscillate in and out of phase. Thus, reconstructing local and global atmospheric indices from WAIS Divide accumulation records over recent centuries may prove problematic.


1. Introduction

Developing high-resolution regionally representative long-term accumulation records from ice cores which can go back thousands of years are fundamental to better understanding the role of Antarctica in the context of global climate change. Accurate historical records of net accumulation, defined as precipitation minus evaporation, are especially important in the west Antarctic region, which is undergoing significant changes in mass balance and glacier dynamics [Överbeck et al., 2006; Davis et al., 2005; Scambos et al., 2000]. While previous studies have shown that there has not been a significant change in snowfall over the continent for the past 50 years [Monaghan et al., 2006], studies have also indicated that certain regions of the Antarctic ice sheet such as the West Antarctic ice sheet and peninsula, have seen an increase in annual accumulation [Kaspari et al., 2004; Mosley-Thompson et al., 1999], in some cases doubling since 1850 [Thomas et al., 2008]. Using radar depth-age scales, Neumann et al. [2008] found that accumulation in central West Antarctica decreased approximately linearly across the ice divide, however, accumulation rates in polar regions have been shown to vary significantly over short distances [Spikes et al., 2004; McConnell et al., 2000a]. Hence, more spatially representative historical accumulation records are necessary to further investigate accumulation variability in west Antarctica.

Temporal variability in Antarctic accumulation has been linked with past climate conditions. For example, accumulation rates have been correlated with the El Niño–Southern Oscillation (ENSO), however, these correlations can be highly variable in strength and sign [e.g., Frey et al., 2006; Kaspari et al., 2004; Bromwich et al., 2000]. Van den Broeke and van Lipzig [2004] used a climate model to demonstrate that the Antarctic Oscillation (AAO) can strongly affect Antarctic accumulation, though the effects vary spatially.

In this study, we examine the temporal and spatial trends of accumulation at the West Antarctic Ice Sheet Divide project site area (WAIS Divide) over recent centuries, and explore links between accumulation and atmospheric
processes. High-resolution trace element glaciochemical records were used to develop two new accumulation records from WAIS Divide as well as a reanalysis of accumulation from a previously collected nearby ice core (International Trans-Antarctic Scientific Expedition (ITASE) 00-1). To gain a more complete understanding of the climatic processes affecting WAIS Divide, a locally representative accumulation record was developed from the array of three ice cores and compared with atmospheric indices. The uncertainty in the WAIS Divide local accumulation record due to the effects of small-scale spatial variability was quantified using an analysis of variance.

2. Methods

Two ice cores were collected in 2005 using a 10 cm electromechanical drill from the West Antarctic Ice Sheet Divide project site (WAIS Divide), located between the Pine Island–Thwaites and Ross drainage basins: WDC05A and WDC05Q (hereafter also referred to as WAIS cores; Figure 1 and Table 1). The ice cores, approximately 1 km apart, were analyzed to 70 m and 130 in depth, respectively, corresponding to the past 230 and 484 years. Following standard procedures, the ice cores were measured, weighed and processed in the field in order to calculate density profiles. The WAIS ice cores were shipped to the National Ice Core laboratory (NICL), Denver, CO where they were cut and then shipped to the Desert Research Institute (DRI), Reno, NV for laboratory analysis. Both the NICL and DRI facilities maintained a constant ambient temperature of −20°C or below while storing the ice cores prior to laboratory analysis. An additional 105 m deep ice core located 20 km to the northwest (ITASE 00-1) was collected in 2000 [Kaspari et al., 2004]. We reanalyzed the ITASE 00-1 core at the Desert Research Institute using the same laboratory methodology as the WAIS cores, which differs from the previous studies.

In order to obtain high-fidelity, high-resolution glaciochemical records, the ice cores were analyzed using the Continuous Flow Analysis–Trace Elements Dual (CFA-TED) methodology (adapted from McConnell et al. [2002]). The CFA-TED analytical system allows for (1) very high depth resolution (approximately 0.01 m water equivalent per sample corresponding to an average of ~21 samples per year for these ice cores); (2) measurements of a broad spectrum of elemental and chemical species (>20); (3) exact depth coregistration of all measurements; and (4) very low detection limits (detection limits for some elements are in the low parts per quadrillion range).

Developing accurate accumulation records from ice cores requires accurate identification of annual layers. Previous studies have demonstrated that several glaciochemical parameters exhibit seasonal cycles [e.g., Banta and McConnell, 2007; Frey et al., 2006; Dixon et al., 2005; McConnell et al., 1998]. However, accumulation rates of individual years may differ by as much as 50% depending on the seasonal characteristics of the parameter used to develop the depth-age scale [Anklin et al., 1998]. Consistent layer identification is best accomplished when robust seasonal indicators, such as the midwinter H2O2 concentration minima or the summer non–sea salt sulfur (nssS) concentration maxima, are combined with multiple annually varying parameters to resolve any ambiguities [e.g., Banta and McConnell, 2007; Frey et al., 2006; McConnell and Bales, 2004]. The use of multiple parameters is especially important if the total accumulation for a given year is low or if the chemical seasonal signal is dampened for one or more years.

The WAIS and ITASE 00-1 ice cores were dated using annual layer identification based on multiple seasonal markers, with nssS to sodium ratio (nssS/Na) as the primary indicator. Seasonal cycles of hydrogen peroxide were not well preserved below the top 12 m. The nssS/Na annual cycle covaries in time with well known seasonal tracers such as hydrogen peroxide and dust tracers, with maxima occurring during the summer and minima occurring midwinter [Dixon et al., 2005; McConnell and Bales, 2004]. Where the nssS/Na annual layers were ambiguous (e.g., a low accumulation year, a doublet peak in one year, or due to

Table 1. Summary of Ice Core Accumulation Records

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude (°S)</th>
<th>Longitude (°W)</th>
<th>Elevation (m)</th>
<th>Mean Annual Accumulation (m_wet a⁻¹)</th>
<th>Time Span (years)</th>
<th>Coefficient of Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>WDC05A</td>
<td>79.463</td>
<td>112.125</td>
<td>1759</td>
<td>0.200 ± 0.034</td>
<td>1775 – 2005</td>
<td>0.18</td>
</tr>
<tr>
<td>WDC05Q</td>
<td>79.468</td>
<td>112.086</td>
<td>1759</td>
<td>0.204 ± 0.035</td>
<td>1521 – 2005</td>
<td>0.19</td>
</tr>
<tr>
<td>ITASE 00-1</td>
<td>79.383</td>
<td>111.239</td>
<td>1791</td>
<td>0.221 ± 0.041</td>
<td>1653 – 2000</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Symbol ± represents the range (1 σ) of the annual values.
volcanic fallout), annual layers of sea salt and dust tracers were used to aid in dating the ice cores (e.g., Mg, Sr, Ca, Al, Ce).

Additional cores from across the Antarctic ice sheet were previously analyzed and dated using this methodology. Owing to very high accumulation rates at these other sites, there was minimal ambiguity in the dating (e.g., Gomez accumulation rate = 0.72 m\text{weq}\ a^{-1} [Thomas et al., 2008], James Ross Island accumulation rate = 0.57 m\text{weq}\ a^{-1} [McConnell et al., 2007]). Accumulation records from other high accumulation sites are also known to a high level of confidence (e.g., Law Dome accumulation rate = 0.7 m\text{weq}\ a^{-1}, updated from Palmer et al. [2001]). The glaciochemical records from these sites were used for comparisons to reduce uncertainties in the WAIS and ITASE 00-1 depth-age scales. The depth-age scale was verified in each ice core using nssS and conductivity peaks that are associated with known volcanic eruptions. The final dating uncertainty for the three ice cores was estimated to be less than one year.

A seventh-order polynomial depth-density model was fit to the field generated density measurements to convert snow depth to annual accumulation in water equivalent (reported in m\text{weq}\ a^{-1}). An additional 30 m ice core (WDC05E; T. Sowers, personal communication, 2008) and 3 m snow pit samples (Science Coordination Office, personal communication, 2008) were collected in the immediate area of the WDC05Q core. These additional density profiles were used to help constrain the WAIS depth-density curve in the shallower depths where the density measurement uncertainties are greatest. The ITASE 00-1 depth-density profile was also generated from field measurements of that ice core as well as from a nearby 1 m snow pit using an eighth-order polynomial model. Because the WAIS and ITASE 00-1 ice cores were less than 4% of the ice sheet thickness, they were not corrected for vertical strain rates or ice flow. While not incorporated here, thinning is estimated to be no more than 3.0% of the annual layer thickness at a depth of 130 m using a Dansgaard Johnsen model (E. Waddington, personal communication, 2008).

3. Results

On the basis of the multiparameter dating, the bottom depths of the WDC05A, WDC05Q, and ITASE 00-1 cores were determined to be 1775, 1521, and 1653 A.D., respectively, with mean annual accumulation rates ($\pm$1 standard deviation) of 0.200 $\pm$ 0.036, 0.204 $\pm$ 0.038, and 0.221 $\pm$ 0.046 m\text{weq}\ a^{-1}, respectively (Table 1 and Figure 2). The difference in accumulation between the two WAIS records is largely due to the difference in length of the records. Over the common 229 year period, the accumulation rates for both cores were 0.200 m\text{weq}\ a^{-1}. The resulting accumulation records of all three ice cores were approximately normally distributed (Chi squared analysis).

An increasing trend of $\approx$-0.005 m per 100 years was identified over the length of the ITASE 00-1 accumulation record (accounting for autocorrelation [Santer et al., 2000]; Mann-Kendall analysis, statistically significant at the 95% confidence level [CL]). A lesser decreasing trend was identified in the WDC05Q record ($\approx$-0.004 m per 100 years or $\approx$-10% over the length of the record, 95% CL incorporating autocorrelation), though much of the decrease occurred between 1650 and 1725 (average accumulation was 0.215 and 0.198 m\text{weq}\ a^{-1} for pre 1650 and post 1725, respectively). Prior to 1650 and after 1725, no significant trends were identified in WDC05Q. This matches the finding that the WDC05A accumulation record (which only goes back to 1775) did not exhibit a trend. While not included here, the estimated 3% thinning over 130 m snow depth accentuates the decreasing trend in the WDC05Q record to approximately $\approx$-13% and reduces the increasing trend in the ITASE 00-1 record to below statistical significance.
The temporal variability, defined here as the coefficient of variation (CV = standard deviation/mean), was 0.18, 0.19 and 0.21 for WDC05A, WDC05Q, and ITASE 00-1, respectively (Table 1). While higher CVs were identified for short periods, long-term trends in temporal variability were not present over the length of the records. For example, the coefficient of variation at ITASE 00-1 for the 1725–1750 period was 0.17, 0.25 for the 1750–1775 period, and 0.17 from 1775 to 1800. The WAIS cores exhibited lesser fluctuations in CVs, with the maxima/minima occurring during different time periods. Thus, short-term fluctuations in temporal variability are likely caused from local small-scale spatial variability rather than regional-scale atmospheric processes.

4. Discussion

4.1. Temporal Variability

The measured accumulation rates for the WAIS and ITASE 00-1 cores agree well with previous west Antarctica accumulation maps [e.g., Arthern et al., 2006; Monaghan et al., 2006], as well as with previously reported accumulation rates for the ITASE 00-1 core [Frey et al., 2006; Kaspari et al., 2004]. The difference in accumulation between the WAIS and ITASE 00-1 cores is also in agreement with radar accumulation studies [e.g., Neumann et al., 2008] who found an approximately linear decreasing trend in accumulation across the West Antarctic ice divide. The increasing trend in accumulation over the length of the core at ITASE 00-1 matches closely with the previously reported accumulation record (7% versus 8%, respectively for the 1653–2000 period) and is consistent with other ITASE accumulation records and high-frequency events, such as the El Niño–Southern Oscillation with a 3- to 5-year periodicity, may be substantially reduced. Quantifying the SSV allows error bars to be placed on annual accumulation records, resulting in more meaningful comparisons with atmospheric processes. Using an approach described by McConnell et al. [2000b], we calculated the SSV for the WAIS Divide local area using the WAIS and ITASE 00-1 ice cores. For two adjacent ice cores, X and Y, the annual accumulation time series was defined as $X(t) = P(t) + e_X(t)$ and $Y(t) = P(t) + e_Y(t)$, respectively; where $P(t)$ was the coherent accumulation signal common to both ice cores and $e(t)$ was the incoherent signal composed of spatial variability and methodological noise. The variability in the accumulation signal of the two adjacent cores was separated into a coherent and incoherent component, defined here as $Var(P) = r_{xy}Var(X)$ and $Var(e) = (1 - r_{xy})Var(X)$; where $r_{xy}$ was the correlation coefficient between X and Y. $Var(X) = variance of X(t)$ and $Var(e) = Var(e) [McConnell et al., 2000b; Fisher et al., 1985]$. $Var(P)$ was calculated using the average of all possible $r_{xy}$ values between sites, and $Var(e)$ was calculated using the mean squared variance from an analysis of variance. SSV was reported as $Var(e)^{0.5} (m_{\text{eq}} a^{-1})$. For the 1775–2000 period common to the three ice cores, small-scale spatial variability was 0.030 $m_{\text{eq}} a^{-1}$, accounting for 61% of the annual variance which is equivalent to ~15% of the annual accumulation rate. Previous studies have reported similar SSVs in polar regions, ranging between 0.029 and 0.040 $m_{\text{eq}} a^{-1}$ [Banta and McConnell, 2007; McConnell et al., 1997, 2000b].

4.2. Spatial Variability

Small-scale spatial variability (SSV), defined here as the incoherent signal due to blowing snow or sastrugi, has significant implications for ice core record interpretations, especially at sites where the SSV may constitute a significant percentage of the annual accumulation such as WAIS Divide. For instance, correlations between accumulation records and high-frequency events, such as the El Niño–Southern Oscillation with a 3- to 5-year periodicity, may be substantially reduced. Quantifying the SSV allows error bars to be placed on annual accumulation records, resulting in more meaningful comparisons with atmospheric processes. Using an approach described by McConnell et al. [2000b], we calculated the SSV for the WAIS Divide local area using the WAIS and ITASE 00-1 ice cores. For two adjacent ice cores, X and Y, the annual accumulation time series was defined as $X(t) = P(t) + e_X(t)$ and $Y(t) = P(t) + e_Y(t)$, respectively; where $P(t)$ was the coherent accumulation signal common to both ice cores and $e(t)$ was the incoherent signal composed of spatial variability and methodological noise. The variability in the accumulation signal of the two adjacent cores was separated into a coherent and incoherent component, defined here as $Var(P) = r_{xy}Var(X)$ and $Var(e) = (1 - r_{xy})Var(X)$; where $r_{xy}$ was the correlation coefficient between X and Y. $Var(X) = variance of X(t)$ and $Var(e) = Var(e) [McConnell et al., 2000b; Fisher et al., 1985]$. $Var(P)$ was calculated using the average of all possible $r_{xy}$ values between sites, and $Var(e)$ was calculated using the mean squared variance from an analysis of variance. SSV was reported as $Var(e)^{0.5} (m_{\text{eq}} a^{-1})$. For the 1775–2000 period common to the three ice cores, small-scale spatial variability was 0.030 $m_{\text{eq}} a^{-1}$, accounting for 61% of the annual variance which is equivalent to ~15% of the annual accumulation rate. Previous studies have reported similar SSVs in polar regions, ranging between 0.029 and 0.040 $m_{\text{eq}} a^{-1}$ [Banta and McConnell, 2007; McConnell et al., 1997, 2000b].

4.3. Local Accumulation

An accumulation record generated from an array of ice cores is more representative of the accumulation patterns for the region than a record from a single ice core because of the reduced impact of SSV. An accumulation record of the WAIS Divide project area was created from an array including WDC05A, WDC05Q, and ITASE 00-1 (hereafter referred to as the WAIS Divide local record). We did not...
include other ice cores further away as they were likely influenced by different hydrologic processes and/or were analyzed using different methodologies. For example, the Gomez core, located 1200 km from WDC05Q, experienced a doubling in accumulation over recent centuries [Thomas et al., 2008]. The WAIS Divide local record was generated from a principal component analysis (first eigenvector) using annual data for those years common to the ice cores. While the mean accumulation rates are very similar in the three ice cores, the annual data were normalized \( Z = \text{observation/mean} \) to ensure records with higher accumulation did not overly influence the composite record. The WAIS Divide local mean accumulation (1775–1999) was \( 0.207 \text{ m eq a}^{-1} \) and varied by approximately 14% of the mean (1 standard deviation). It did not exhibit a statistically significant linear trend (95% CL, accounting for autocorrelation).

[18] The WAIS Divide local accumulation record generally agreed with the European Centre for Medium-Range Weather Forecasts reanalysis (ECMWF ERA-40) in the post satellite era (Spearman rank correlation, \( r_s = 0.36 \), 90% CL; 1985–1999; Figure 3). Note that Spearman rank correlation coefficients \( (r_s) \) were used here in place of Pearson’s \( r \) correlations because a Pearson’s \( r \) correlation is neither robust nor resistant, making it highly sensitive to data points with large leverage. ECMWF ERA-40 precipitation data from the modern satellite era (post-1979) have higher degrees of confidence than presatellite data [Bromwich et al., 2007; Bromwich and Fogt, 2004; Marshall, 2003]. ECMWF has also issued a statement that “1979–2001 [is] the period with the best and most time-consistent product quality for the globe as a whole” (http://www.ecmwf.int/research/era). Hence, presatellite comparisons with ECMWF ERA-40 were not included in this study. The comparison also highlighted the uncertainty in the ECMWF ERA-40 data prior to 1985 where \( r_s \) was not significant (90% CL; 1980–1985; Figure 3). While this is in the postsatellite era, Bromwich et al. [2007] point out that the bias correction scheme adjustment between and pre- and postsatellite data did not fully adjust until 1985.

[19] The SSV of the WAIS Divide local record was reduced by \( n^{-0.5} \), or to 0.017 m\(_{eq}\) a\(^{-1}\), where \( n \) is the number of cores in the array. Arrays with more ice cores would further reduce the SSV (e.g., four ice core records are necessary to reduce the impact of SSV by 50%; nine ice cores are required to reduce it to 0.010 m\(_{eq}\) a\(^{-1}\) or less than 5% of the average annual accumulation). Alternatively, SSV can also be reduced by temporal averaging (versus spatial). Multiyear filters dampen the incoherent noise, however, they also reduce the high-frequency coherent signal [van der Veen and Mosley-Thompson, 1999]. For example, averaging 4 years of annual accumulation from a single ice core will also reduce the SSV by 50%, however, this temporal average will also smooth out any 3- to 4-year periodicities. Longer decadal- and millennial-scale averages further reduce the noise (e.g., important for examining glacial versus interglacial periods), but such long averages also reduce the 5- to 7-year coherent signal, thereby preventing meaningful comparisons with many atmospheric processes (e.g., El Niño–Southern Oscillation). Hence, a balance is necessary between reducing incoherent noise and preserving higher-frequency information. Here, a three-point running average filter was applied to the annual WAIS Divide local accumulation record (hereafter referred to as the filtered WAIS Divide local record; Figure 3). The improved signal-to-noise ratio in the filtered record was reflected by higher correlation coefficients of accumulation rates between sites (Table 2b). For this study, a three-point running average filter was the shortest filter width which (1) sufficiently preserved high-frequency events and (2) allowed identification of the coherent signal.

**Table 2b.** Correlation Matrix (Pearson’s \( r \)) for 1775–1999 of Normalized Average Annual Accumulation, Three-Point Filter Applied\(^a\)

<table>
<thead>
<tr>
<th></th>
<th>WDC05Q</th>
<th>WDC05A</th>
<th>ITASE 00-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>WDC05Q</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WDC05A</td>
<td>0.73</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>ITASE 00-1</td>
<td>0.61</td>
<td>0.54</td>
<td>1.00</td>
</tr>
</tbody>
</table>

\(^a\)All correlations are significant at the 99% confidence level.
Following Kuhns et al. [1997], a signal-to-noise variance ratio $F$ was calculated as $F = r_{xy} / (1 - r_{xy})$. A high $F$ ratio denotes a high degree of coherent signal between the ice cores, while an $F$ ratio below 1 indicates that the variance in the ice core records are largely composed of incoherent signals. The average $F$ ratio for the filtered WAIS accumulation records was 1.67, confirming that the common coherent precipitation signal can be readily identified. In addition, the SSV of the filtered WAIS Divide local record was reduced to 0.007 m$_{weq}$ a$^{-1}$, or about 3% of the mean accumulation.

4.4. Comparison to Atmospheric Circulation Processes

The Antarctic Oscillation (AAO), also known as the Southern Hemisphere annular mode (SAM), is commonly defined as the first principal component of 850 hPa geopotential height anomalies from 20S to the South Pole [Thompson and Wallace, 2000; Thompson and Solomon, 2002]. The AAO accounts for 33% of the variance, while the second (SA1) and third (SA2) principle components explain 11% and 9%, respectively [Thompson and Wallace, 2000]. The AAO, SA1, and SA2 indices used in this study (as reported by Thompson and Wallace [2000]) were generated from the National Center for Atmospheric Research/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data. Similar to the ECMWF ERA-40 data, NCEP/NCAR reanalysis atmospheric pressure data have a much higher level of confidence in the post satellite era [Bromwich et al., 2007; Bromwich and Fogt, 2004; Marshall, 2003]. Hence, for this study, we examined the role of the AAO and subsequent modes over the entire length of the record, but primarily focused on the 1970s to present by calculating running decadal-scale Spearman rank correlations (three-point running average filter applied to all data sets).

Figure 4. Comparison of the filtered WAIS Divide local accumulation record with the three dominant modes of atmospheric variability (AAO, SA1, SA2) and the Southern Oscillation Index (SOI) using decadal-scale Spearman rank correlations (three-point running average filter applied to all data sets). Dashed lines indicate 95% confidence level.

Using the 1958–1999 period, only the SA1 was found to be significantly correlated with the filtered WAIS accumulation record ($r_s = 0.37$, 95% CL, three-point running average filter applied to all data sets). Correlations on decadal scales demonstrated that the filtered AAO was highly anticorrelated with the filtered WAIS Divide local accumulation record in the 1960s and early 1970s, followed by periods of positive correlations in the late 1970s to early 1980s and then switched back to anticorrelated in the mid 1980s to present (Figure 4). The correlation switched signs four times over the length of the record. Hence, while the overall correlation for 1958–2000 was negative, the relationship goes in and out of phase several times, even during the postsatellite period, where there is a higher degree of confidence in the atmospheric reanalysis data. The phase
reversal was even more pronounced in the comparison between the filtered SA1 and the filtered WAIS accumulation record, switching from \( r_s < -0.60 \) (1976–1986, 95% CL) to \( r_s > 0.80 \) (1986 to present, 99% CL). The filtered SA2 exhibited a generally positive correlation with accumulation, though there are periods where the correlation drops to zero (e.g., 1980–1990).

[24] Previous studies have seen similar phase reversals between accumulation rates in west Antarctica and atmospheric processes [e.g., Mayewski et al., 2004]. Bromwich et al. [2000] and Cullather et al. [1996] found that net precipitation just outside of the WAIS region was positively correlated with the Southern Oscillation Index (SOI) from 1980 to 1990 and anticorrelated with the SOI in the 1990s. Kaspari et al. [2004] did not find this relationship within the ITASE 00-1 ice core, but reported an overall anticorrelation between SOI and accumulation. Comparing the filtered WAIS Divide local accumulation record to the filtered SOI, we found a negative correlation \( (r_s = -0.31, 99\% \text{ CL} \) for 1867–1998; \( r_s = -0.43 \) for 1958–1998, 99% CL; Figure 4). However, similar to the filtered AAO, the decadal-scale correlations switched signs multiple times throughout the record. For example, the correlation to the filtered SOI was highly negative \( (r_s = -0.75, 95\% \text{ CL}) \) from 1990 to present with no statistically significant correlation in the 1980s (95% CL). Consistent with Kaspari et al. [2004], the filtered SOI was anticorrelated during periods of prolonged El Nino events (1940–1942 and 1991–1995). This is also consistent with Frey et al. [2006], who reported that the first principal component of accumulation from a 20 ice core array in west Antarctica showed correlations of both signs with SOI during the 1911–1993 period.

5. Conclusion

[25] Three multicentury high-resolution accumulation records from the West Antarctic Ice Sheet (WAIS) Divide area presented here were developed using multiparameter annual layer counting. A WAIS Divide local accumulation record was generated from the array of ice cores, with an average accumulation rate of 0.207 m\( _{eq} \) a\(^{-1} \), varying approximately 14% of the mean (1 standard deviation). The small-scale variability (SSV), which inhibits correlations to geophysical processes, was determined to be 0.030 m\( _{eq} \) a\(^{-1} \) or \( \sim 15\% \) of the annual accumulation for an individual ice core, but was reduced to 0.017 m\( _{eq} \) a\(^{-1} \) (8% of the accumulation rate) in the WAIS Divide local accumulation record. The SSV quantified here is consistent with previous studies, suggesting that it is likely driven by local-scale physical processes common to polar regions (e.g., sastrugi). Hence, caution is warranted when interpreting high temporal resolution records from a single ice core in the WAIS Divide area.

[26] The reduced SSV in the local WAIS Divide accumulation record allowed for more meaningful comparisons between large climate indices and accumulation, though additional ice cores may be necessary to sufficiently reduce the SSV impacts depending on the application of the accumulation records. The relationship between atmospheric variability and accumulation in the WAIS Divide area is neither simple nor consistent in time. Temporal correlations between the WAIS Divide local accumulation record and atmospheric indices, such as the Antarctic Oscillation and subsequent modes (SA1 and SA2), varied in strength and exhibited periods where the relationship switched signs several times over recent decades. Consequently, reconstructing long-term records of high-frequency geophysical processes from accumulation records at WAIS Divide may prove problematic.

[27] Acknowledgments. This research was supported through funding from the National Science Foundation, grants OPP 9904294, OPP 0338427, OPP 0636929, and OPP 9814810. We would like to thank R. Edwards, T. Cox, A. Ellis, and C. Fox for their assistance in the DRI ultra-trace ice core laboratory.

References


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