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The climate signal in the stable isotopes of snow from Summit, Greenland: Results of comparisons with modern climate observations

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Abstract. Recent efforts to link the isotopic composition of snow in Greenland with meteorological and climatic parameters have indicated that relatively local information such as observed annual temperatures from coastal Greenland sites, as well as more synoptic scale features such as the North Atlantic Oscillation (NAO) and the temperature seesaw between Jakobshaven, Greenland, and Oslo, Norway, are significantly correlated with $\delta^{18}O$ and δD values from the past few hundred years measured in ice cores. In this study we review those efforts and then use a new record of isotope values from the Greenland Ice Sheet Project 2 and Greenland Ice Core Project sites at Summit, Greenland, to compare with meteorological and climatic parameters. This new record consists of six individual annually resolved isotopic records which have been average to produce a Summit stacked isotope record. The stacked record is significantly correlated with local Greenland temperatures over the past century ($r = 0.471$), as well as a number of other records including temperatures and pressures from specific locations as well as temperature and pressure patterns such as the temperature seesaw and the North Atlantic Oscillation. A multiple linear regression of the stacked isotope record with a number of meteorological and climatic parameters in the North Atlantic region reveals that five variables contribute significantly to the variance in the isotope record: winter NAO, solar irradiance (as recorded by sunspot numbers), average Greenland coastal temperature, sea surface temperature in the moisture source region for Summit (30°–20°N), and the annual temperature seesaw between Jakobshaven and Oslo. Combined, these variables yield a correlation coefficient of $r = 0.71$, explaining half of the variance in the stacked isotope record.

1. Introduction

One of the great strengths of ice cores as proxies for past environmental conditions is that they can provide not only the long timescale necessary to view the large changes of the past glacial periods but also the high temporal resolution needed to look at socially relevant timescales, that is, subannual to decadal changes in climate and environmental conditions. In the past the focus in ice-core research, particularly for stable isotopes, has been mostly on the long timescales, with less emphasis on the recent record and even less on the Holocene. Given our growing understanding of human impact on the global environment and climate system, one of the primary goals of the new Summit cores from the Greenland Ice Core Project (GRIP) and the Greenland Ice Sheet Project 2 (GISP2) was to take fuller advantage of the rich density of information available in the cores. In particular, there was an emphasis on determining how the isotopic signal records the recent climatic conditions of central Greenland and how those climate conditions can be related to the climate of the North Atlantic region. Despite the great potential for using isotopic data from ice cores to look at climate changes of the past few centuries, these data have been largely ignored and/or dismissed in studies of recent climate change. This is due in part to a lack of high-resolution isotopic data from the upper parts of cores and in part to a lack of emphasis on understanding the nature of the isotopic signal and what it records. Recently, several papers have addressed this issue, using data from the new GISP2 and GRIP cores in the Summit region as well as other isotopic data, mostly collected and analyzed by the Danish and Canadian groups, which have recently become available for public distribution via the World Data Centers A for Paleoclimatology and Glaciology (Boulder, Colorado). In this paper we will review those efforts, which uniformly point toward the conclusion that annually resolved isotopic data from Greenland ice cores do contain useful climatic information. We will then take a first look at the climate signals found in the

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stacked isotopic record from the Summit region. A total of six cores in the Summit region were drilled, sampled, and measured with sufficient temporal detail to calculate annual isotopic values. We have for the first time the capability to stack isotopic records and thus to greatly decrease the isotopic noise which is present in a single record, focusing attention on the common signal present in a suite of cores. The stacked record is described in a companion paper by *Johnsen et al.* [this issue]. Here we will compare this record to records of climate change in the region in order to determine what climatic signals are present in the isotopic composition of Greenland snow from the Summit region.

2. Stable Isotope Ratios of Greenland Snow and Regional North Atlantic Climate: An Overview of Recent Results

Several recent studies have linked the isotopic composition of snow ($^{18}O/^{16}O$ and/or D/H, expressed as $\delta^{18}O$ and δD) in the Summit area with climatic indicators or climate proxies in the North Atlantic region. These include the North Atlantic Oscillation (NAO), which is the atmospheric pressure oscillation between Iceland and the Azores [*Walker*, 1924; *van Loon and Rogers*, 1978; *Moses et al.*, 1987; *Rogers*, 1984; *Barlow et al.*, 1993; *White et al.*, 1996], regional Greenland temperatures [*Fisher et al.*, 1996], the temperature seesaw, which is an opposition in atmospheric temperatures between western Greenland (Jakobshaven) and western Scandinavia (Oslo) [*van Loon and Rogers*, 1978; *Barlow et al.*, 1993], and solar activity [*Stuiver et al.*, 1995]. The results of these studies are reviewed below. Our focus here will be on these newer studies as they all examine data from the Summit area. We will later use the relationships found in these studies between these climatic parameters and the isotopic record of central Greenland as a beginning point in examining the climate signals in the stacked isotopic record from Summit.

The North Atlantic Oscillation is a unifying atmospheric feature with associated variability in sea surface temperature (SST) and land surface temperatures in the North Atlantic region. The NAO denotes a sea level pressure contrast between the Icelandic Low and Azores High, specifically the tendency of these two centers of action to strengthen or weaken together [*Walker*, 1924; *van Loon and Rogers*, 1978; *Moses et al.*, 1987]. The NAO index is defined as the normalized monthly mean sea level pressure difference between Akureyri, Iceland, and Ponta Delgada, Azores [*van Loon and Rogers*, 1978; *Rogers*, 1984]. Sea level pressure difference in the North Atlantic is strongest in the winter, and generally the NAO is discussed in terms of its winter character.

Investigations of the NAO by *van Loon and Rogers* [1978], *Rogers and van Loon* [1979], *Lamb* [1977], *Kelly et al.* [1987], and *Moses et al.* [1987] indicate two distinctly different atmospheric and oceanic temperature regimes for the two extreme modes of the NAO. The temperature seesaw, or tendency for air temperatures in western Greenland to be warmer when air temperatures in western Scandinavia are cooler (and vice versa), describes this opposition of temperatures in the region. Intensification of the "normal" mode of the NAO (deep Icelandic Low, strengthened Azores High) has associations with the Greenland below (GB; Greenland colder) mode of the temperature seesaw as well as with stronger westerly winds and higher than normal SSTs for large parts of the North Atlantic Drift (Figure 1a). Stronger zonal westerlies are also associated with warmer temperatures in England and northern Europe. Intensification of the "reverse" mode of the NAO has associations with the Greenland above (GA; Greenland warmer) mode of the temperature seesaw, as well as with weaker westerlies, stronger meridional winds, and lower SSTs in parts of the North Atlantic Drift (Figure 1b). Stronger meridional winds are also associated with warmer temperatures along the west Greenland coast.

The link between stable isotope ratios from snow in central Greenland and the NAO was originally established in the GISP2 core [*Barlow et al.*, 1993] through association with the seesaw in winter temperatures between Jakobshaven, Greenland, and Oslo, Norway. Using the high-resolution isotopic record, which contains at least eight samples per annual layer, Barlow et al. compared the isotopic values of snow averaged annually as well as the lowest isotopic values (isotope "winters") and the highest values (isotopic "summers") with the temperature seesaw. The focus was on the strong GA and GB years taken from the winter seesaw values of *van Loon and Rogers* [1978] for the years 1840–1970. Within this time period, there were 23 GA winters and 26 GB winters. A one-tailed t-test showed high statistical significance for annual and winter as well as summer signals. The isotopic signal from the GISP2 site responds in agreement with the west Greenland (Jakobshavn) side of the temperature seesaw. It should be noted that the temperature seesaw is not well defined in coastal temperature stations on east Greenland. This suggests that while there is some regional coherence in the coastal Greenland temperatures, part of the variability in atmospheric temperatures in Greenland is different from the western to the eastern sides of the ice sheet. An investigation of storm tracks, cyclogenesis, atmospheric circulation patterns, and automatic weather station (AWS) records suggests that precipitation arrives in central Greenland primarily from both the southeast and southwest/west [*Barlow*, 1994; *Barlow et al.*, this issue]. This observation suggests that the isotopic composition of snow should respond to both the average coastal temperatures and the temperature pattern described by the temperature seesaw, a suggestion that will be supported by the results of the multiple linear regression analysis of the stacked isotope record described in the second part of this paper.

In a different approach to relating the stable isotopes in the GISP2 core to climate change, *White et al.* [1996] examined the power spectrum of the annually averaged δD values and compared the periodicities found in the isotopic record with oscillations found in records of climate change. The isotopic record at GISP2 exhibits many statistically significant oscillations. White et al. identified several which can also be found in other annually resolved isotopic records from Greenland, including sites in southern Greenland (Dye 3) and northern Greenland (Camp Century). These periods, in years, are 4.5, 6.3, 7.5, 9.8, 12.2, and 16. These oscillations were filtered from the isotopic time series and then plotted against similarly filtered oscillations from (1) the NAO, which has its strongest oscillation at 7.6 years, (2) sunspots, with a strong oscillation at 11–12 years, and (3) the $\delta^{18}O$ record from corals, which has a strong oscillation at 4.6 years and which is a proxy of the El Niño–Southern Oscillation (ENSO). The results of this study found no statistical coherence, or similarity in the temporal pattern of the amplitudes, for the isotopic signal versus ENSO, either for the pressure indices or isotopic values from corals.

There was also no coherence between the 11-year cycle of sunspot numbers and the 11-year cycle found in the GISP2

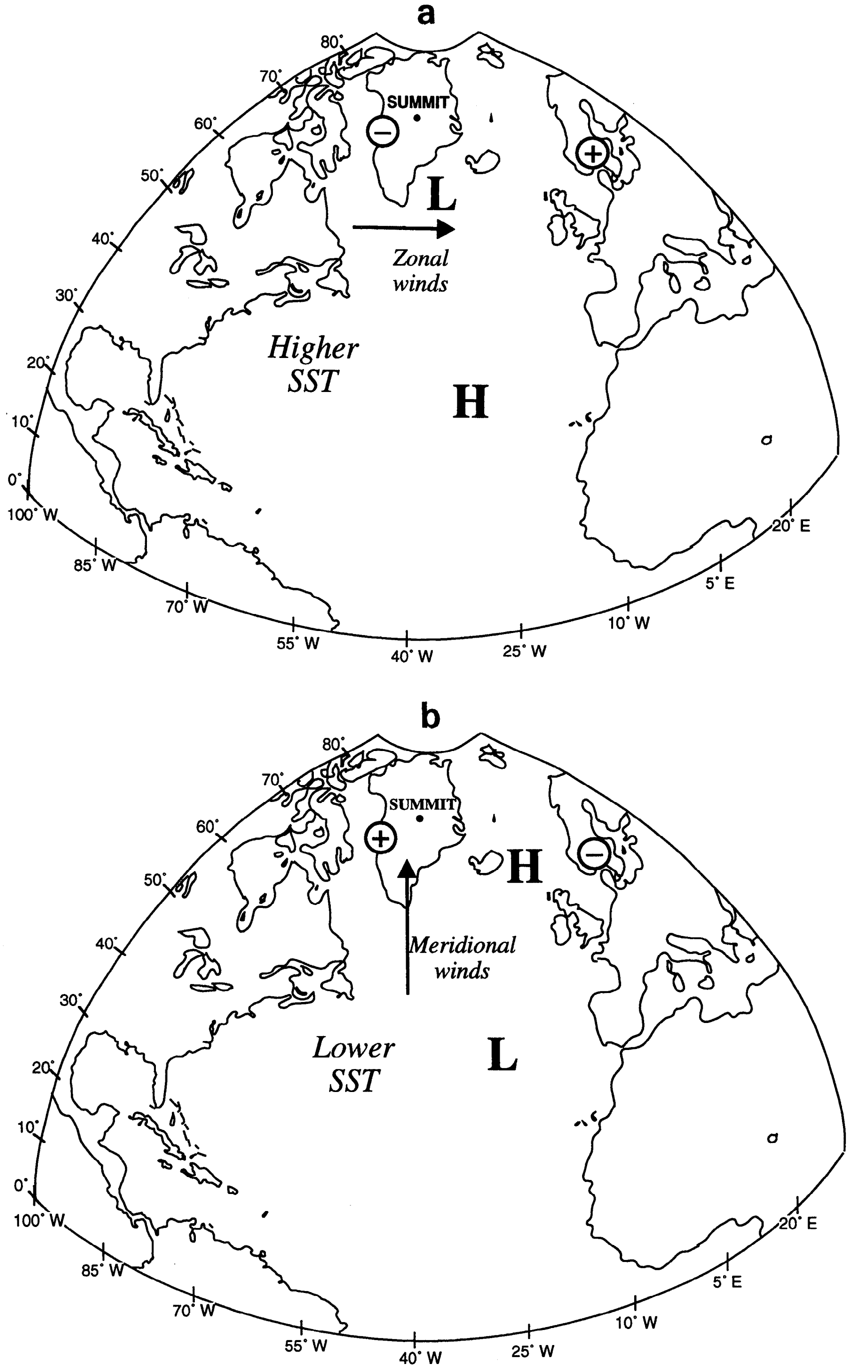

Figure 1. (a) Diagram of Greenland below (GB) mode of the temperature seesaw. In this end-member, Jakobshavn, Greenland, is relatively cold (marked by a minus sign) and Oslo, Norway, is relatively warm (marked by a plus sign). Accompanying oceanic and atmospheric phenomena, all associated with extreme normal mode of the NAO, are also noted: zonal winds with lower pressure north and higher pressure south and higher sea surface temperatures in the western North Atlantic. The ice-core sites for GRIP and GISP2 are marked (Summit). The diagram is a compilation of observations of *van Loon and Rogers* [1978], *Rogers and van Loon* [1979], *Lamb* [1977], *Kelly et al.* [1987], and *Moses et al.* [1987]. (b) As in Figure 1a, but for Greenland above (GA) mode of the temperature seesaw (extreme reverse mode of the NAO).

isotopic record. Comparison of these two time series filtered to isolate the 11-year component showed a slight correspondence, as the strongest sunspot minima tended to occur in phase with the strongest isotope minima. This correspondence was not compelling evidence, however, that isotopes and sunspots are linked. A different conclusion was reached by *Stuiver et al.* [1995], who compared the GISP2 isotopic record with sunspots for much of the Holocene. Their conclusion was that sunspots and isotopes did indeed appear to show common variance over this longer time period. Stuiver et al. also noted that volcanic

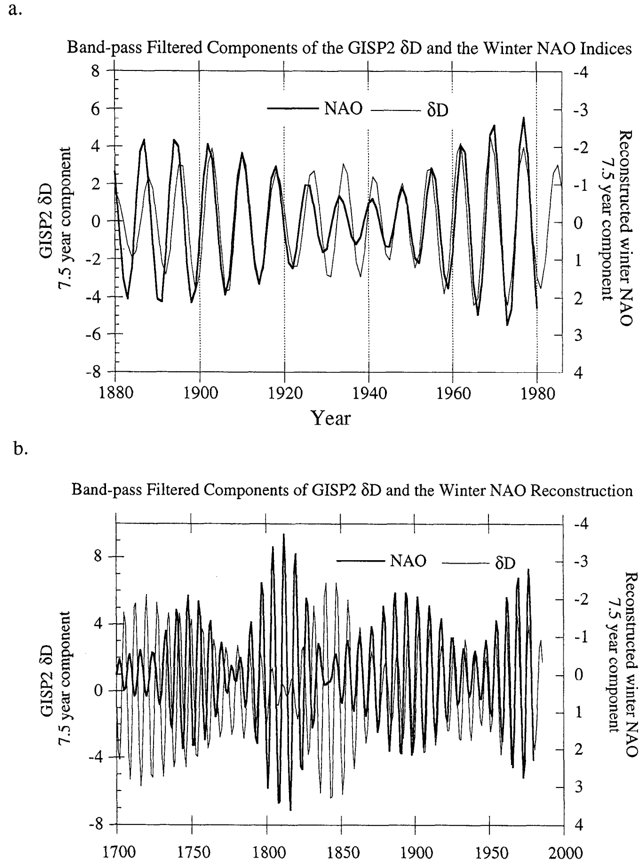

Figure 2. (a) Comparison of time series of δD values from the GISP2 ice core (thin line) and winter NAO indices (thicker line) which have been band-pass filtered at 7.5 years to isolate this oscillation in both records [from *White et al.* 1996]. In the isotope data this is one of many significant oscillations. In the NAO data this oscillation is significant and is the strongest in the power spectrum. Note that both the phase and amplitude of the two time series are very similar, implying that they are responding to the same forcing or that this oscillation in the isotope record is forced by the NAO oscillation. (b) As in Figure 2a, except the winter NAO indices are inferred from tree ring indices [*Cook et al.*, 1997]. The match for these two series is again excellent in the 1900s, but both the phasing and particularly the amplitude deviate in the previous 2 centuries. The implications of this are discussed in the text.

events appear to have an impact on the isotopic record, with evidence of lower $\delta^{18}O$ (cooling) corresponding with volcanic eruptions. They separated the volcanic events by size using indices of explosivity and showed that larger eruptions tended to be associated with larger $\delta^{18}O$ drops.

White et al. [1996] did find strong statistical coherence between the 7.6-year oscillations in the isotopic and NAO records. In addition, the temporal patterns of these oscillations, when filtered from the individual records, match well for the past 100 years. This is shown in Figure 2a. One drawback of comparing the isotope values with NAO indices is that the length of the NAO record is relatively short. In order to extend the NAO record, a record of winter NAO indices derived from tree rings [*Cook et al.*, 1997] was also filtered for the 7.6-year oscillation and then compared with the 7.6-year oscillation filtered from the isotope time series. While all three filtered records were very similar for the period 1880 to the present, the correspondence between the tree ring NAO proxy and the isotope series was not good between 1700 and 1880. This is shown in Figure 2b. White and coworkers speculated that this finding could mean that the NAO had a different behavior prior to 1880, at least in the nature of the oscillations in the indices, and that this difference could be driven by a different climate mode during the Little Ice Age or by anthropogenic influences in climate which began to manifest themselves in the late 1800s. Of course, the result could also mean that one or both of the climate proxies did not track the 7.6-year oscillation in the NAO as well prior to 1880 for reasons having to do with the proxy record and not the climate system. Nonetheless, the apparent difference in behavior between 1700–1880 and 1880 to the present in the isotopic record and the tree ring NAO record does raise some important issues for this study. First, it reinforces the importance of using long records of climate change to establish a baseline behavior in the climate system, even if they are proxy records with the accompanying caveats in interpretation, and second, it raises the point that calibrating proxy records with historical observations of climate carries some risk that uniformitarianism may not apply and thus the proxy may not be correctly interpreted beyond the period of historical observations.

One of the most exhaustive studies to date of the climate information in stable isotope ratios in Greenland ice cores is that of *Fisher et al.* [1996]. In this study, isotope records from about 20 ice cores were used, each with isotopes measured at subannual (>8 samples per year) resolution. Regional chronologies of isotope ratios covering the last few centuries were constructed for southern Greenland, central west Greenland, central east Greenland, and northern Greenland, as well as for the Canadian island sites Aggasiz, Ellesmere, and Devon.

For each region, isotope records from several individual cores were stacked in order to reduce noise. *Fisher et al.* [1996] discuss in detail the issue of noise in the isotopic times series from individual cores. Noise in this sense is defined as isotopic variability due to postdepositional processes which can alter the original isotopic signal in the snow. These processes include unevenness in drifting or sastrugi, wind scouring, summer melting and penetration of the melt into the lower layers, and vapor diffusion, which redistributes the isotopic gradients occurring naturally due to seasonal changes in the isotopic composition of snow.

The signal to noise ratio (S/N = (signal variance)/(noise variance)) for a single isotopic profile in Greenland varies with accumulation and latitude [*Fisher et al.*, 1985]. For Greenland, S/N appears to be smallest in the Summit area. The frequency distribution of both the noise and signal variances in the ice cores depends on the variable. For example, noise in snow accumulation time series is concentrated in the higher frequencies. Such noise can be reduced in a single time series by averaging over relatively short time steps. For isotopic time series, however, vapor diffusion tends to smooth out the higher-frequency variability and transfer it to the lower frequencies, reddening the spectrum. This means that longer averaging times, of the order of a decade or more, are needed to smooth out the noise in individual isotopic time series. The necessity for long averaging times has been observed when comparing isotopic records from Greenland, although such averaging is also required when cores are separated by large distances over which climate is not correlated on the subdecade timescale [e.g., *Dansgaard et al.*, 1975].

A better way to reduce noise in time series which have been reddened is to average many single time series from a specific region. Such an average depends on well-dated individual records and has been used to great advantage by the tree ring community, for example, in producing regional chronologies. It is expected that the noise level in such stacked chronologies should be lower and thus the correlations with meteorological and climatological variables should improve. This improvement is demonstrated by *Fisher et al.* [1996] and is also shown later in this work when we examine the stacked isotope time series from the Summit area.

Fisher et al. used the regional, stacked isotope records to examine the geographical patterns of correlations and to examine how well the stacked isotope records match the meteorological data from the four long coastal Greenland stations, Jakobshaven, Godthab, Upernavik, and Angmagssalik, as well as the average of eight Iceland stations. The linear correlations between stacked isotope records and the individual meteorological stations were nearly all statistically significant at the 99% confidence level. The stacked record from central west Greenland, which contains the Summit site, was particularly well correlated with coastal temperatures, with correlation coefficients of nearly 0.5 for all of the comparisons. They noted that temperature time series from meteorological stations at high latitudes are generally not highly correlated and that one cannot expect to explain much more variance than that observed between ice-core sites and coastal meteorological stations so far (500–1000 km) distant from each other.

To better use the regional information in the isotopic time series, *Fisher et al.* [1996] used the empirical orthogonal function (EOF) techniques to examine regional covariance through time. They calculated the geographic eigenvalues and vectors using standard techniques [e.g., *Kutzbach*, 1967]. The first two eigenvectors of the isotopic and coastal temperature time series taken together explain an impressive 47 and 17% of the variance, respectively. The components of the first eigenvector are all of the same sign, indicating that the temperatures and stacked isotopic time series vary in phase and share about 50% common variance, reinforcing the concept of a strong link between atmospheric temperature and stable isotopes in snow. The second eigenvector separates the coastal temperature sites from the stacked ice-core series from all regions, suggesting that about 17% of the variance in the isotope stacks and coastal temperatures is out of phase. The separation between the ice-core sites and coastal sites may be indicating the importance of altitude in the climate of the region; the ice-core sites form Greenland are generally from 1 to 3 km in altitude, and the Summit sites are at roughly 3 km.

Finally, *Fisher et al.* [1996] examined the last 3000 years of isotopic records from several sites in Greenland and Canada, averaging the annual isotopic values over 50 years to reduce the noise. They noted that there are clear Little Ice Age coolings apparent in the Canadian cores. In the Greenland cores, only the Dye 3 (southern Greenland) and Camp Century (northwestern Greenland) cores show signs of a Little Ice Age. Using EOF analysis on this longer data set, they further noted that the first eigenvector of the isotope series appears to separate central Greenland from the rest of Greenland and the Canadian sites and that the second eigenvector, as with the annual time series, separates the lower elevation sites from the higher elevation sites.

3. Analysis of the New Stacked Isotope Record From Summit

3.1. Description of the Data

Isotopic data were measured on six ice cores collected at the GISP2 and GRIP sites between 1987 and 1993. A complete description of the GRIP ice cores used to make the stacked isotopic record is given by *Johnsen et al.* [this issue]. The GISP2 core is described by *Grootes et al.* [1993]. While these records extend from the late 1980s back several millennia, our focus here will be on the last 200 years, with particular emphasis on the last century. This is the time period for which climate observations are available. The six individual isotopic records are presented in Figure 3. Five of the records are from the GRIP site and one is from the GISP2 site. Annually averaged isotopic values are presented. To make these averages, the ice cores were initially sampled with high temporal detail, generally with six to 10 samples per annual layer, in order to well define the average annual isotopic composition of the ice and potentially provide subannual values. Stable isotopes ratios ($^{18}O/^{16}O$ and/or D/H, expressed as $\delta^{18}O$ and δD) were measured on the individual samples. The cores were then dated using the observation that isotope ratios change from one season to the next, defining an annual oscillation. These oscillations in the isotopes along with other annually oscillating parameters are used to define annual layers, which are then counted back from a known, dated surface to yield years. On the basis of the dating established for the individual cores, the isotopic delta values for the subannual segments are then averaged to yield the annual delta value. The original dating of the GRIP cores is described by *Johnsen et al.* [this issue]. The original dating of the GISP2 core is described by *Meese et al.* [1994].

The dating of individual cores by counting "annual" oscillations is known to contain some error. Annual isotopic oscillations are smoothed by vapor diffusion in the firn, a process which dampens the annual isotopic oscillations and makes the task of defining annual layers more difficult. Extra years may be added by mistake, and years may be missed. Combining several annually oscillating parameters, such as visual stratigraphy, electroconductivity, and chemical measurements, may improve the dating, although these potential annual markers do occasionally disagree, and we have as yet no way of determining which, if any, is the best dating tool. Thus the dating of a single ice core will always have some uncertainty. As the purpose of this study is to compare annually resolved isotopic data with annually observed climate data, dating errors in the individual ice cores will lead to uncertainty in the isotope-climate comparison.

The advantage of having six ice cores from one region lies not only in reducing the noise in the composite record [*Johnsen et al.*, this issue; *Fisher et al.*, 1996] but also potentially in the ability to better date the composite record. Here we attempted to cross date the individual cores using the tree ring cross-dating technique in which years with prominent high or low isotopic values are identified and then the best cross dating is found by adding or deleting years at different points in the individual time series. For the time period examined here, 1772–1987, no compelling case can be made for adjusting the dating of any individual core. While prominent isotopic lows and highs are occasionally offset between the individual cores, in some cases with five cores agreeing and one core offset by a year or two, there was no case in which adjusting the dating of

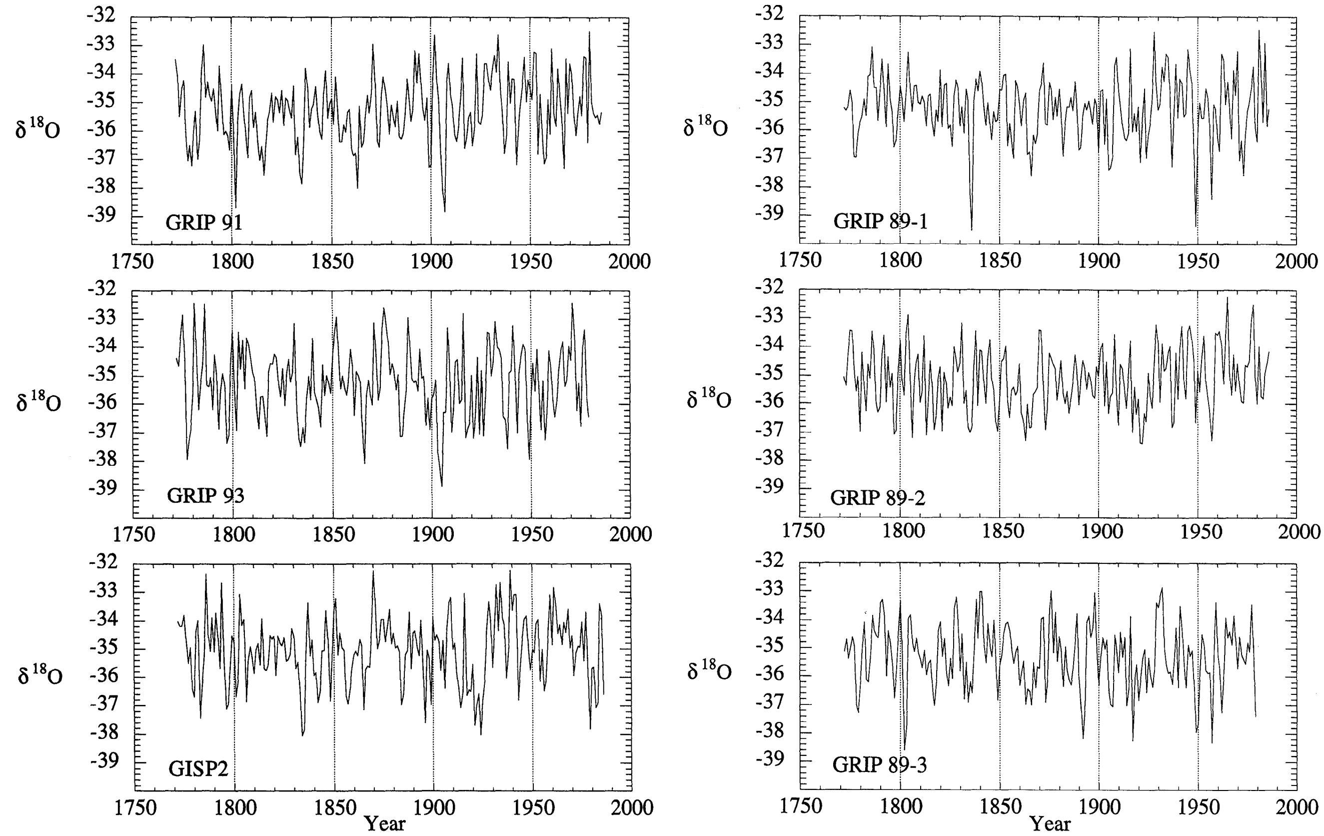

Figure 3. Time series of $\delta^{18}O$ values from five GRIP ice cores and the GISP2 ice core. Annual average isotope values are shown. The methods for dating the cores and determining the annual averages are described in the text. The GRIP data are from *Johnsen et al.* [this issue]. The GISP2 data are from *Grootes et al.* [1993] and *Stuiver et al.* [1995].

an individual core by a year or two resulted in an alignment of several prominent isotopic lows or highs. With only six cores to compare, we argue that adjusting the dating of an individual core would require such a compelling improvement. The dating uncertainty is not known exactly; we estimate it to be no more than 1 or 2 years for the last 200 years.

The cross-correlation matrix for the six cores for the time period 1770–1987 is shown in Table 1. Also included in this table is the stacked isotope record, which is the simple average of the six isotopic records. The correlation coefficients between the individual isotopic records range from 0.41 to 0.55 and average 0.50. Thus an average of about 25% of the variance in the annual isotopic values is common from one individual core to the next. The average correlation coefficient between the individual records and the stacked record is 0.66 (0.60–0.75), indicating that about 45% of the variance (r^2) in any individual

Table 1. Correlation Matrix: Summit Ice-Core Isotope Ratios and Coastal Greenland Temperatures

	GRIP 89-1	GRIP 89-2	GRIP 89-3	GRIP 91	GRIP 93	GISP2	Stacked Isotopes	Jakobshaven	Godthab	Angmagssalik	Uppernavik	Average Coastal Temperature, °C
GRIP 89-1	1							0.16*	0.25*	0.42*	0.22*	0.27*
GRIP 89-2	0.552	1						0.23*	0.37*	0.43*	0.2*	0.33*
GRIP 89-3	0.464	0.478	1									
GRIP 91	0.551	0.517	0.474	1				0.17*	0.3*	0.48*	0.2*	0.29*
GRIP 93	0.529	0.532	0.55	0.486	1			0.19*	0.32*	0.54*	0.19*	0.31*
GISP2	0.516	0.549	0.408	0.496	0.443	1		0.26*	0.39*	0.63*	0.3*	0.4*
Stacked Isotopes	0.646	0.667	0.603	0.642	0.668	0.75	1	0.17*	0.27*	0.44*	0.2*	0.29*
Jakobshaven	0.387	0.398	0.114	0.239	0.288	0.465	0.408	1				
Godthab	0.409	0.429	0.135	0.333	0.318	0.439	0.447	0.931	1			
Angmagssalik	0.398	0.399	0.189	0.345	0.355	0.429	0.459	0.661	0.669	1		
Uppernavik	0.354	0.301	0.152	0.250	0.289	0.465	0.391	0.838	0.743	0.649	1	
Average coastal temperature, °C	0.425	0.411	0.172	0.316	0.350	0.502	0.471	0.914	0.861	0.878	0.907	1

*Slopes of the delta-temperature relationships (permil/degree).

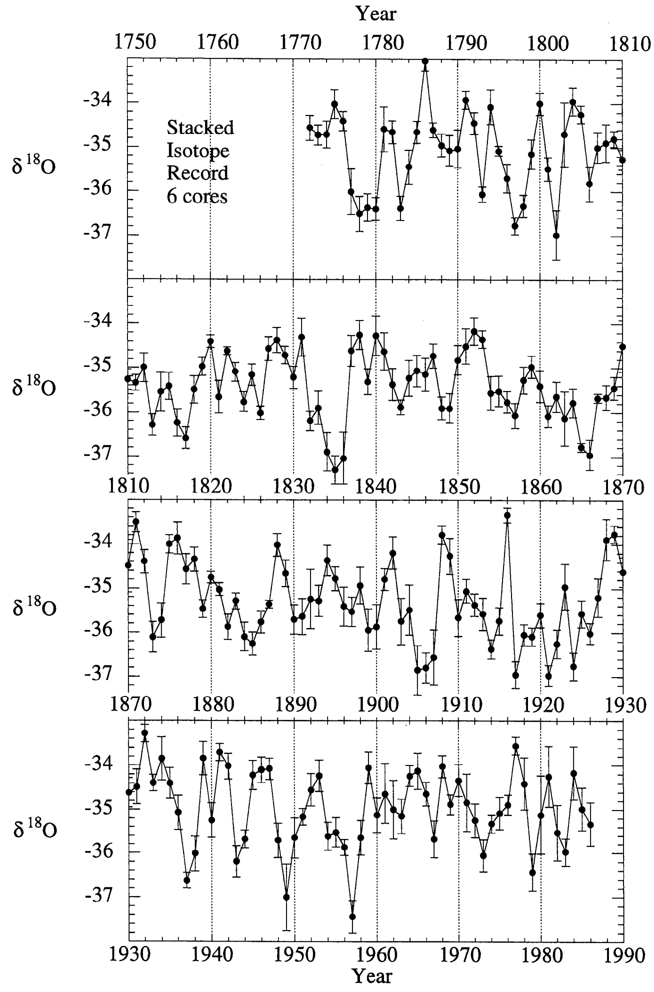

Figure 4. The stacked isotopic record from Summit, Greenland, consisting of GRIP and GISP2 ice cores. The stacked record is the simple average of the six individual cores. Error bars are standard deviation of the mean (1σ). The trends in the isotopic values are described in detail in the text.

record is captured in the stacked record. The reasons for the differences between individual records include dating uncertainties, the variable impact of postdepositional processes such as vapor diffusion and redistribution and redeposition of surface snow by winds, and original differences in the isotopic composition of snow from one site to another. A full discussion of the cause of noise in the individual and stacked isotopic records is given by *Johnsen et al.* [this issue]. We stress here that one of the issues that must be faced in ice-core research if annually resolved data are to be used is to find some way of better dating the records. This is one of the few times that we have had so many annually resolved isotopic records to work with from one site, so this issue has not been directly faced in the past. In tree ring work, for example, about 40 cores from a total of 20 trees are used to build a chronology in which missing years in any individual core are pinpointed to the year. With only six cores we cannot do that and thus must accept some level of dating uncertainty which will, when records are stacked, erode somewhat the signal recorded in the isotopes.

The stacked isotopic record is shown in Figure 4. Error bars representing standard deviations of the mean are shown, calculated for each individual year from the six $\delta^{18}O$ values of the individual cores. The average uncertainty in the mean value is about ±0.3‰. This is only about 5% of the maximum amplitude of the signal in the isotopic record and a factor of 3 larger than the uncertainty in the measurements. The uncertainties are nearly equal throughout the record, with two exceptions. First, the period around 1900 has higher standard deviations, driven mainly by GRIP 89-3, which disagrees consistently with the other five cores during this period by as much as 2–3‰. Second, the standard deviations are higher during the last few decades (1960–1987). This most likely reflects the additional uncertainty due to the uneven smoothing from one core to the next of the isotopic signals by vapor diffusion in the upper meters of the snow and firn.

Beginning in 1770, the stacked isotopic record exhibits relatively large variability, 2–3‰, on short timescales, 3–4 years. Beginning in 1805, the record becomes smoother and is characterized by slow isotopic declines and faster isotopic increases. Some of these increases are quite prominent, for example, the 3‰ increase between 1836 and 1837, the 2‰ increase between 1873 and 1875, and the 3‰ increase between 1907 and 1908. These are substantial isotopic changes when translated into theoretical temperature changes: 3°–4.5°C. For comparison, the $\delta^{18}O$ shift at the immediate end of the Younger Dryas was 5–6‰. This sawtooth pattern continues into the early 1900s. In 1916 a strong and well-defined isotopic peak of 3–4‰ is observed. This isotopic peak is seen in all of the individual records. Between 1920 and 1930 the isotopic composition rises strongly by over 3‰. This feature is significant in that a large shift is also observed in most climate records of the region at this time (e.g., average hemispheric temperatures). Between 1930 and 1987 the isotopic composition exhibits a slow decline from an average value of −34 to about −35‰ at the top of the record. Several large isotopic dips occur in the 1930s, 1940s, and 1950s. There is no significant trend over the length of the record suggesting recent warming, nor is there a significant reflection of the colder temperatures during the end of Little Ice Age.

3.2. Comparison With Climate and Climate Proxies

3.2.1. Comparison with coastal temperatures. On the basis of both theoretical considerations and observations, stable isotope ratios of polar snows are commonly interpreted in terms of temperatures [*Dansgaard*, 1964]. This approach depends on several key assumptions but is generally accepted as a very good first-order interpretation. The current state of thinking on this isotope thermometer is reviewed by *Jouzel et al.* [this issue]. As a first step in examining the climate signal contained in the stacked record from Summit, we compare the isotopic values with observed temperatures in Greenland. Unfortunately, there is no long record of temperature observations from central Greenland, and the only long records are from coastal sites. There is some reason to expect that sea level sites in Greenland may be somewhat climatically different from the high-altitude, midcontinental Summit site, as evidenced, for example, by the results of *Fisher et al.* [1996] discussed earlier. This long-distance comparison is all that is possible, however, and so we pursue it. Table 1 gives the correlation matrix for isotopes versus atmospheric temperatures. The six individual isotopic records and the four long temperature records from coastal Greenland (Jakobshaven, Godthab, Upernavik, and Angmagssalik) are included along with the stacked isotopic record and the average coastal temperature from the four stations. The correlation coefficients

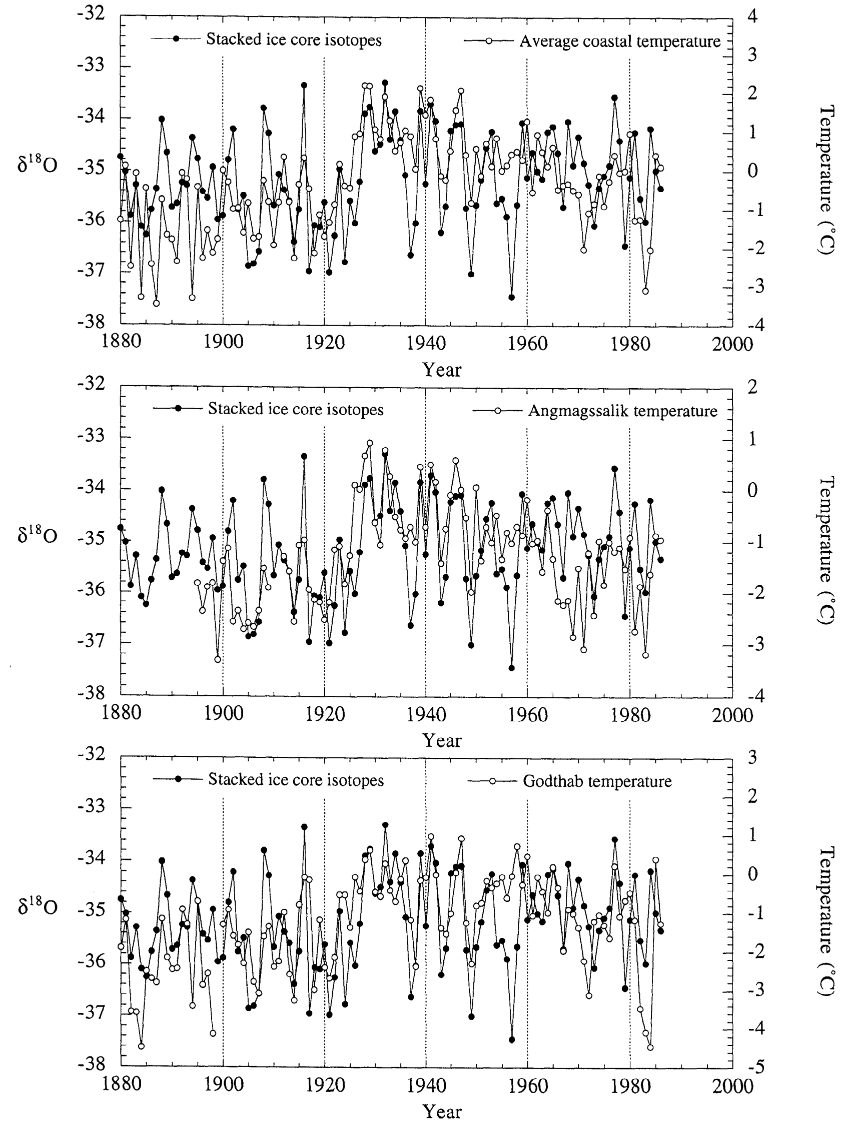

Figure 5. Comparisons of the stacked isotope record from Summit, Greenland, versus observations of mean annual temperatures measured at four meteorological stations on the coast of Greenland. Also shown is the stacked isotope record versus the simple average of the four temperature records. Note that the general trends in the isotope and temperature records are very similar: a sharp rise in the 1920s [see *Rogers*, 1985] followed by a slow decline toward the present.

for the individual cores and individual meteorological stations range from $r = 0.47$ to 0.11. In general, the GISP2 core and the stacked record have the highest correlations. It is worth noting that isotopic values from one of the six individual cores (GRIP 89-3) are not significantly correlated with any of the temperatures records from the coastal sites. This is the core in which the isotopic values deviated from the other cores significantly in the early 1900s. All of the other cores are significantly correlated with temperatures at all of the coastal sites. This reinforces the first-order interpretation of isotopes as temperatures but also illustrates the importance of analyzing more than one core when focusing on annual or near-annual timescales. The stacked isotopic record versus the average Greenland coastal temperature has a linear correlation coefficient of 0.471, which is significant at $p = 0.0001$.

Figure 5 shows the comparisons of the stacked isotopic record versus the four individual coastal temperature stations as well as versus the average temperature for the period 1880–1987. The isotopic record captures the sharp warming of about 3°C observed in the 1920s. The slow but prominent cooling of 2°–3°C between the 1930s and 1987, an Arctic trend which deviates from the global trend for the 1970s and 1980s, is also reflected in the isotopic record. The sharp isotope drops in the mid 1900s in the stacked isotopic record from central Greenland are not evident as colder years in the average observed temperatures from the coast. It does appear that the Godthab temperature observations contain some of the these coolings, although not all. The low isotope years in the late 1950s, for example, are not seen as corresponding cold years in any of the coastal temperatures.

Marked by asterisks Table 1 are the slopes of the delta-temperature relationships. The slopes for the GRIP 89-3 core and temperatures are not given as they are not statistically significant. The values of the slopes range from a low of

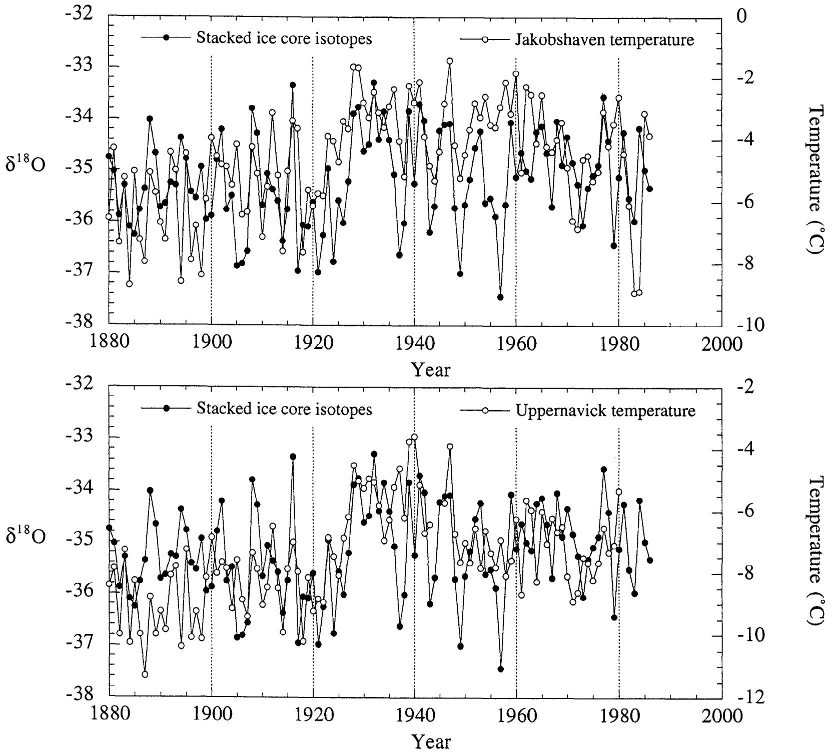

Figure 5. (continued)

0.16‰/°C to a high of 0.54‰/°C. The slope of the stacked isotopic record versus the average coastal temperature is 0.29‰/°C, which is roughly half that of the spatial slope of 0.67‰/°C [*Dansgaard*, 1964; *Johnsen et al.*, 1989]. The difference may be real, reflecting the difference between the temporal and spatial isotope-temperature relationships [see *Jouzel et al.*, this issue], but more likely the difference is due to the long distance and altitude difference between the ice-core site and the meteorological stations.

3.2.2. Comparison with other records of climate change. The stacked isotopic record is next compared with a number of records of climatic observations in the North Atlantic region including atmospheric pressures (from many individual locations as well as the pressure patterns represented by the NAO), atmospheric temperatures (from many individual locations as well as the seesaw between Jakobshaven and Oslo), and sea surface temperatures compiled from the Comprehensive Ocean-Atmosphere Data Set (COADS) data set. Also compared with the stacked isotopic record is the sunspot number record, the ENSO record [*Wright*, 1989], an ENSO proxy record from coral $\delta^{18}O$ [*Dunbar et al.*, 1994], a record of the winter NAO reconstructed from tree rings [*Cook et al.*, 1997] records of drought in the midwestern United States [*Cleaveland and Duvick*, 1992], and observations of relative humidities over the North Atlantic from the COADS data set. The midwestern drought records were added because of the prominent isotope lows in the mid 1900s, all of which occur during years of strong midwestern drought. All records were compared using the period 1900–1987, except for the ocean SST and humidity records, which in some cases covered only the last half of this time period. A total of 40 meteorological/climatological records were used.

A total of 13 correlations were found which are significant at the 95% level or higher. These are given in Table 2 and fall into two basic categories: atmospheric pressures and pressure patterns (from Iceland and the Azores, from the annual average NAO, the winter NAO, and the spring NAO) and temperatures and temperature patterns (from all four individual coastal Greenland sites, plus the average temperature seesaw between Jakobshaven and Oslo, the winter seesaw, and the spring seesaw). The individual ice-core isotope records were also compared to these climatological variables. In all cases, except for the comparison with coastal temperatures mentioned earlier, the correlations with the stacked record were higher than the correlations with individual records. Figure 6a shows plots of the stacked isotope record versus Iceland and Azores sea level pressure. Figure 6b shows the stacked isotopic record versus annual, winter (December-January-February

Table 2. Comparison of Climate Variables With the Stacked Isotopic Record: Linear Correlations

Variable	Correlation Coefficient	Probability of Chance Correlation, %
Iceland sea level pressure	0.256	1.68
Azores sea level pressure	0.248	2.03
Annual average NAO	0.279	0.88
Winter (DJF) NAO	0.240	3.12
Spring (MAM) NAO	0.236	2.80
Jakobshaven temperature	0.408	0.01
Godthab temperature	0.447	0.01
Angmagssalik temperature	0.459	0.01
Uppernavik temperature	0.391	0.02
Average coastal temperature	0.471	0.01
Annual average seesaw	0.343	0.11
Winter (DJF) seesaw	0.304	0.42
Spring (MAM) seesaw	0.329	0.19

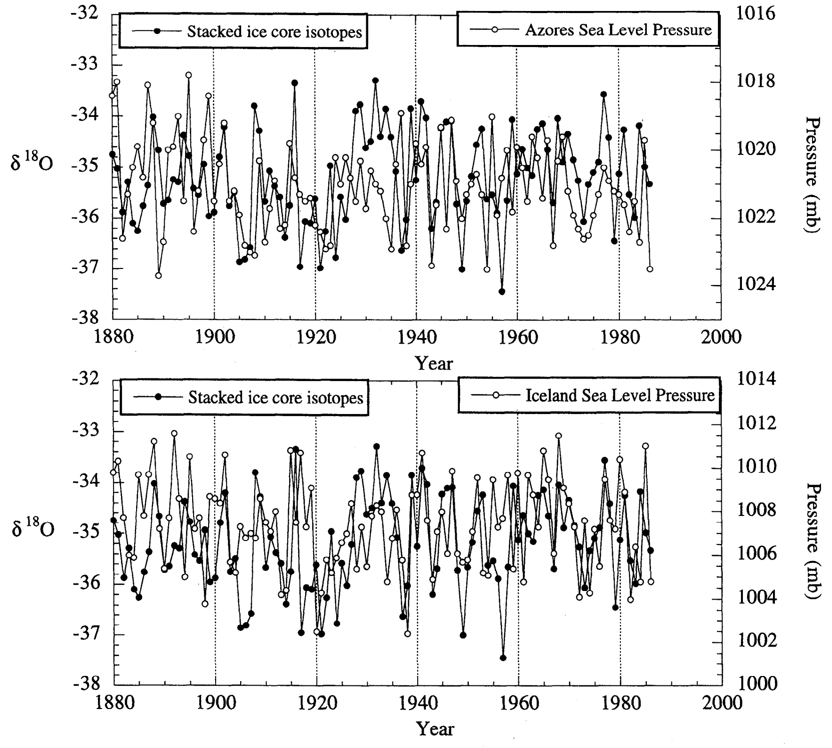

Figure 6a. Comparison of the stacked isotope record from Summit with sea level pressures measured in Iceland and the Azores. These sites are used in calculating the North Atlantic Oscillation index. Note that the pressures at Azores are inverted. The correlations between the isotope and pressure records are significant at the 95% confidence level. The correlation coefficients are given in Table 2.

(DJF)), and spring (March-April-May) (MAM)) NAO indices. The pressures and NAO indices do not exhibit a large shift in the 1920s. Much of the correlation between the isotopes and the pressures appears to be driven by the year to year changes. Figure 7 shows the stacked isotope record compared with the temperature seesaw values for the annual, winter (DJF), and spring (MAM) periods. The two seasonal seesaw indices as well as the annual average seesaw agree with the isotopic record in the general trend of rapid warming (and isotopic increase) in the 1920s followed by slow, steady cooling (and isotopic decrease) in the 1930s to 1980s. Interestingly, the seasonal seesaw indices also contain several large, rapid cooling events in the 1900s which correspond with the isotopic lows in this period. This is particularly evident in the winter seesaw, which is the season in which this temperature pattern is the most pronounced [*van Loon and Rogers*, 1978; *Barlow et al.*, 1993].

3.2.3. Comparison with combinations of records of climate change. As a final step in comparing the stacked isotopic record with the climate records, the stacked isotopic record is compared using the simple technique of stepwise multiple linear regression with the suite of climate records used in the individual correlation tests described above. Our goal here is to investigate whether the isotopic record is responding to a combination of climate variables, as opposed to being strongly tied to a single variable. In this test we use the period 1900–1987, as many of the climatic/meteorological variables tested do not extend beyond this time period. Using an approximate 95% confidence limit ($F = 4$ to enter the regression), five variables enter significantly into the multiple linear regression: average Greenland coastal temperature, winter NAO, the annual temperature seesaw between Jakobshaven and Oslo, insolation changes (as measured by sunspot numbers), and SST (30°–20°N). Combined, these variables explain about 50% of the variance in the isotopic record (combined $r = 0.71$). The multiple regression equation is

$$\delta D = -71‰ + 0.22 * T_{\text{seesaw}} + 1.36 * T_{\text{SST}} + 0.58 * T_{\text{coast}} - 0.01 * \text{Sun} - 0.038 * \text{NAO}$$

This same exercise was repeated with the individual isotope records. Only the GRIP 89-2 record was significantly correlated with all of the five variables at the same confidence limit ($F = 4$ to enter the regression). In this case the combined correlation coefficient was slightly lower, $r = 0.68$. For the other cores, fewer variables entered at this confidence limit. For example, average coastal temperature, winter NAO, and sunspots entered the stepwise regression with GRIP 89-1, and only average coastal temperatures entered with GISP2. Lower confidence limits ($F = 2$–1 to enter) were required to have more variables enter the regression. No variables other than the five listed above for the stacked record were significantly correlated with any of the individual records in the stepwise regressions. This result argues that stacking the isotope records does indeed improve the potential for climatic reconstructions from isotope data in ice cores.

The success and significance of this result are tempered somewhat by the fact that the time period of comparison is limited due to the shorter length of the SST record. There are, however, 60 years of SST data from this latitude band. Figure 8a shows the isotopic values reconstructed from a combination of these variables plotted versus the measured stacked record.

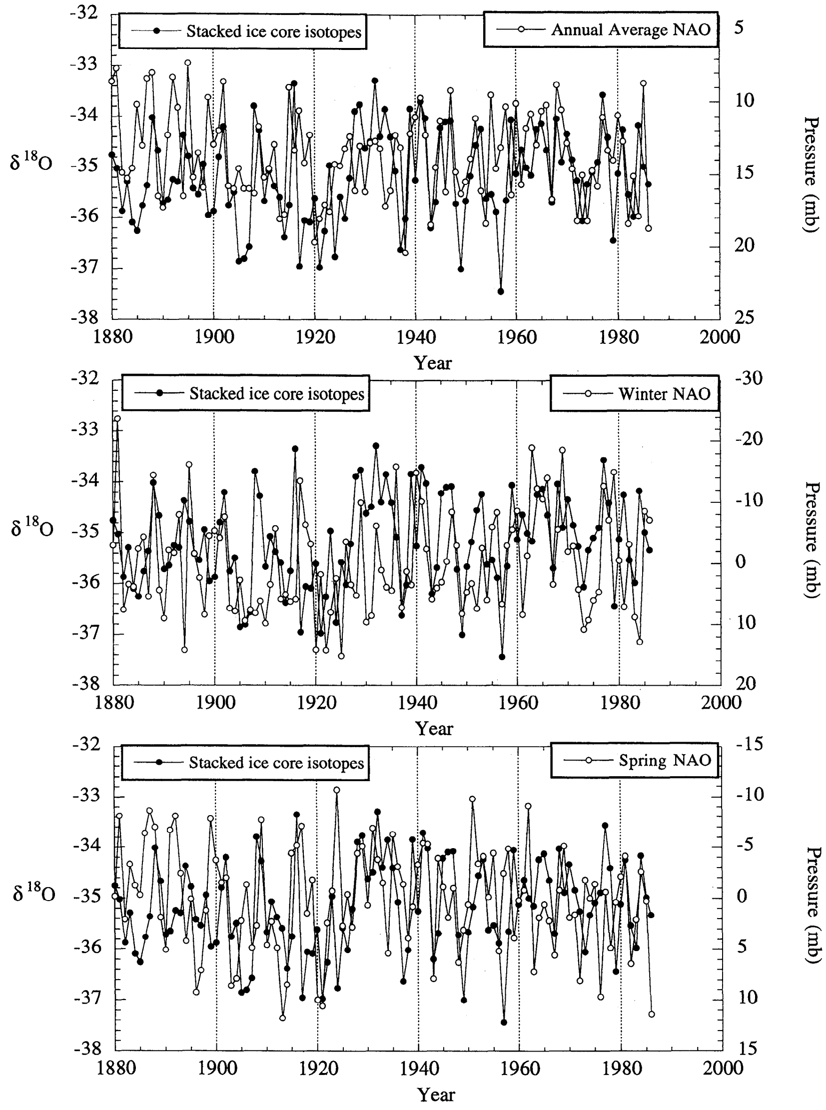

Figure 6b. Comparison of the stacked isotope record from Summit with indices of the North Atlantic Oscillation in air pressure. Shown are the annual average NAO, the average winter (DJF) index, and the average spring (MAM) index. The correlations between the isotope and NAO records are all significant at the 95% confidence level. The correlation coefficients are given in Table 2.

The correspondence is quite good. The predicted values capture nearly all of the variations in the stacked record and match well the extreme changes in the late 1940s and mid 1950s. To determine how good the fit would be without the sea surface temperatures and to extend the time period of the comparison, the sea surface temperatures are removed from the regression in Figure 8b. In this case the remaining variables enter the multiple linear regression with lower significance ($F = 2$ to enter). This combination of four variables, winter NAO, sunspots, average Greenland coastal temperature, and the annual temperature seesaw between Jakobshaven and Oslo, captures about 35% of the variance ($r = 0.60$) in the stacked isotopic record for period 1900–1987. The predicted isotope values track the decadal trends in the stacked record very well but do not appear to contain the extremes, for example, the low isotope values in the early 1940s and mid-1950s.

The appearance of sunspots and sea surface temperatures in the multiple linear regression deserves some comment, as these variables were not highly correlated themselves with the stacked isotope record. Both of these records, however, are correlated with the stacked isotope record at the 90% confidence level. The correlation with the sunspot record is driven primarily by the correspondence between the relatively strong sunspot maxima and the strong isotope lows in the 1930s, 1940s, and 1950s. These years also appear as marked deviations in the winter seesaw record, so the meaning of the correlation with sunspots in these years is difficult to assess. When the full stacked isotopic record from 1770 to 1987 is compared with the sunspot record, the correlation is not significant at the 10% confidence level and the correlation coefficient drops to a value of 0.061. However, when sunspots are removed from the multiple linear regression described above for the period 1900–1987, the amount of variance explained in the stacked isotopic record decreases from 35 to 20% (total $r = 0.451$, down from 0.597). The same result is observed when the time period of comparison is lengthened to begin in 1880 and 1860.

It is possible that the correlation with sunspots is a clue that climate in central in Greenland is correlated or connected with

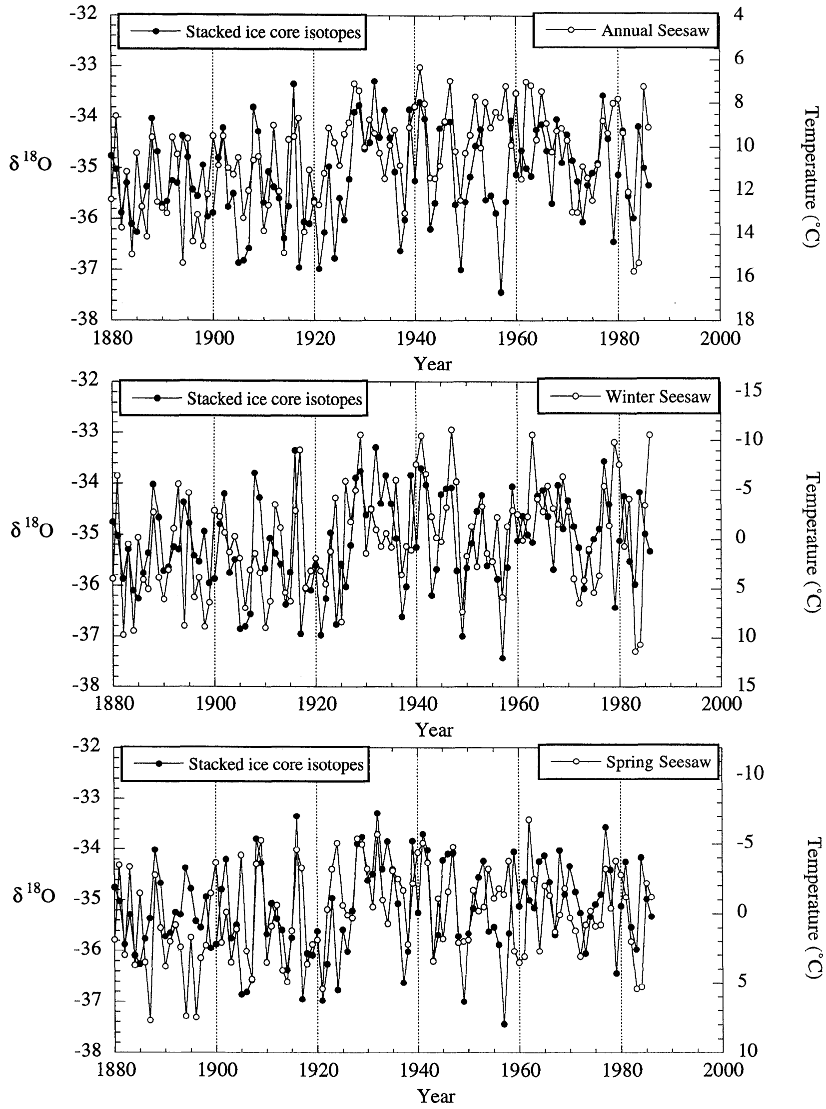

Figure 7. Comparison of the stacked isotope record from Summit with indices of the temperature seesaw in the North Atlantic region, which is the tendency for air temperatures between Jakobshavn, on the west coast of Greenland, and Oslo, Norway, to fluctuate in opposite directions. The correlations between the isotope and seesaw records are all significant at the 95% confidence level. The correlation coefficients are given in Table 2.

precipitation in the North American midwest. Significant droughts occurred in this region in the 1930s, 1940s, and 1950s, although the dominant frequency in the drought records is 22 years, not the 11-year frequency which dominates the sunspot record. To examine this possibility, we compared the stacked isotopic record with the Palmer Drought Severity Index (PDSI) for June reconstructed from tree rings in Iowa [*Cleaveland and Duvick*, 1992] as well as rainfall records from several cities in the midwestern United States. While there does appear to some relationship between low isotope ratios and low PDSI values, the correlation between these two records is not significant unless the records are first smoothed and the low-frequency information is removed from both records.

The correlation with sea surface temperatures in the 20°–30°N longitude band is interesting in that the slope is positive (0.7‰/°C). This region of the North Atlantic is thought to be the source region for moisture for snow in central Greenland [*Johnsen et al.*, 1989]. In general, if the source region for moisture warms, this will increase the temperature gradient between the moisture source and the ice sheet, which in turn will result in lower isotope ratios and more negative delta values. In effect, the delta values of snow on the ice sheet appear "colder" when the moisture source region is warmer. Thus the expected slope of a linear relationship between the temperature at the moisture source region and the isotopic composition of snow is negative. The observed positive slope implies a climate connection between the moisture source region and central Greenland. This connection is implied in the work of *Fisher et al.* [1996] discussed earlier, in which 17% of the variance in the stacked ice-core records from all of Greenland was out of phase with the coastal temperatures. Unfortunately, the short length of the SST record prohibits us from further speculation on this point. We can note, however, that as one moves north, the correlation coefficients between the stacked isotope record and SSTs drop steadily to values of 0.06 at about 45°N and then increase again to values about −0.15 at

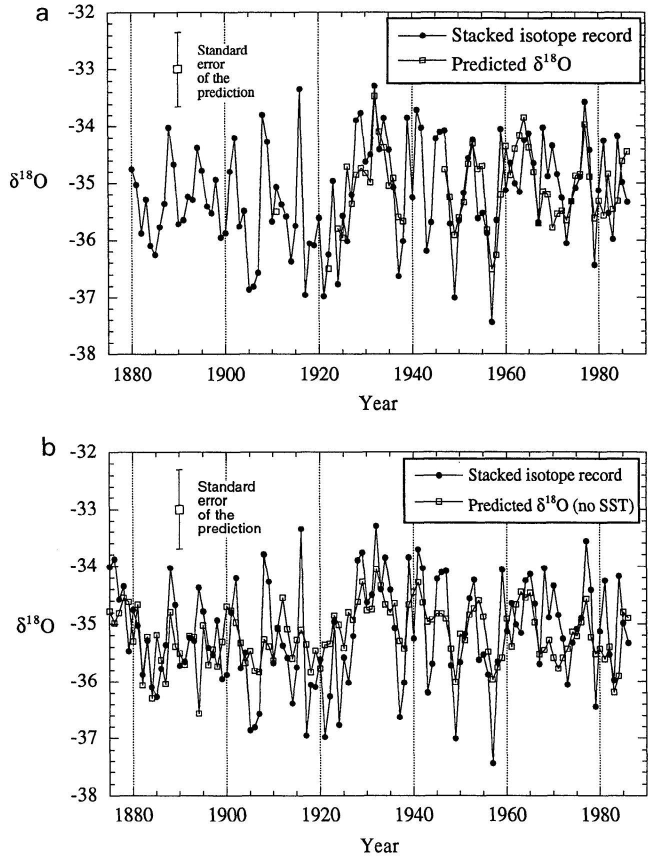

Figure 8. (a) Comparison of the stacked isotope record from Summit with isotope values predicted from a multiple linear regression of the isotope values with the following variables: winter NAO, sunspots, average Greenland coastal temperature, sea surface temperatures (SST 30°–20°N), and the annual temperature seesaw between Jakobshavn and Oslo. The combined correlation coefficient is $r = 0.71$. All of these variables enter significantly into the multiple linear correlation at $F = 4$. Note that missing years are due to the lack of SST data. The standard error of the estimated $\delta^{18}O$ is shown. (b) As in Figure 8a, except that SST has been removed from the multiple linear regression. All variables enter the multiple linear correlation at $F = 2$. The total correlation coefficient is $r = 0.60$.

60°–70°N. In the more northerly latitudes the slopes shift from positive to negative. This is consistent with the temperature pattern for SSTs expected from the presence of a north-south pressure oscillation, in other words, the NAO. This appears to be an area worthy of more sophisticated statistical approach than that attempted here.

In an attempt to determine how robust the multiple linear correlation of atmospheric temperatures, pressures, and sunspots with the stacked isotopic record is, we changed the length of the time period tested and also added and removed individual isotopic and climatic records. When each of the individual isotope records is removed and the multiple linear regression is recalculated, there was no significant change in the results, even when the GRIP 89-3 record was removed. The comparison period used was changed by steps of 10 years back to a record length of 1875–1987. Prior to this time the data required to reconstruct the seasonal NAO do not exist. Four of the five variables listed above (winter NAO, sunspots, average Greenland coastal temperature, and the annual temperature Seesaw between Jakobshaven and Oslo) continue to be significantly correlated with the stacked isotope record. The SST values do not cover a long enough period of time to contribute significantly beyond the 1900–1987 time period. No other climatic/meteorological variables entered the multiple linear regression.

Finally, some comment is needed concerning the coefficients of the multiple linear regression, particularly that of the effect of average coastal temperatures on the stacked isotope record. The coefficient which emerges from the stepwise regression is 0.58‰/°C. The error on this slope is estimated to be about ±0.16. This is a temporally derived slope and close to the classic, spatially derived slope for Greenland of 0.67‰/°C. It is significantly closer than was found earlier for the simple linear regression between average coastal Greenland temperatures and the stacked isotopes record, 0.29‰/°C, also a temporally derived slope. It is tempting to speculate that the impact of temperature in the temporal sense derived from the simple linear regression with coastal temperatures is low because of competing factors such as the temperature seesaw, the NAO, solar insolation, and sea surface temperatures. When the impacts of these factors are removed in the stepwise regression, the effect of coastal temperature change on the isotopes is similar to that found in the spatial sense and also from simple theory. At this time we can only draw attention to this observation and note that it should be considered when examining the isotope paleothermometer. We stress that we are limited in what can be inferred from this result by the problem that the temperatures are measured at the coast, hundreds to thousands of kilometers from the ice-core sites in central Greenland. Coastal sites will be affected by the proximity of the ocean, both as a buffer to temperature change and, with fluctuations in the extent of sea ice from one year to the next, as an amplifier of temperature change. Thus determining the significance of a comparison of isotopes in central Greenland with temperature observations on the coast is a difficult exercise that awaits better models linking regional climate and isotopes in polar snow.

4. Conclusions

Inherent in every ice core is a trade-off between high temporal resolution and longevity of the record; the higher the accumulation rate of snow, the shorter the potential record but the higher the temporal resolution. Ever since the pioneering work of W. Dansgaard, stable isotope ratios in ice cores have been viewed in terms of temperatures, opening the door to many new land-based records of paleotemperature changes. While much of the focus on this paleotemperature proxy outside of the ice-coring community has been on the handful of deep ice cores that provide longevity of record, it has long been argued that an equally rich record of climate change could be found in the upper layers of ice sheets and ice caps, a record with annual to subannual resolution for hundreds to thousands of years. As human impacts on the Earth have become increasingly apparent and increasingly powerful, the need to understand the climate record in the isotopic composition of recent snow has become more pressing. At the Summit site in central Greenland, two groups, GRIP and GISP2, labored for several years to collect two deep cores and in the process collected a total of six cores covering the last few millennia with subannual resolution. These cores provide us with a unique opportunity to reduce the noise commonly found in high-resolution isotopic records by stacking or averaging the individual records to produce a cleaner record of the isotopic composition of snow falling at Summit. Here we have compared this stacked isotope record to a variety of meteorological and climatic variables, including both very local records such as temperatures from coastal sites in Greenland, and to records which capture broader scale patterns of atmospheric temperature changes and pressure changes.

The results have confirmed what recent studies have asserted, that isotopes in ice cores reflect not only local Greenland temperatures but also the broader scale climatic conditions in the North Atlantic region. The stacked stable isotope record at Summit is significantly correlated with several meteorological and climatological variables, including average coastal Greenland temperatures, the east-west seesaw in air temperatures in the North Atlantic region, and the north-south North Atlantic Oscillation in atmospheric pressures. A full 50% of the variance ($r = 0.71$) in the stacked isotopic record can be explained by a combination of these variables along with solar irradiance (as observed in the sunspot record) and sea surface temperatures in the moisture source region for Summit. This result demonstrates that the stable isotopic composition of Greenland snow is responding to regional climate change and not just local meteorological changes at the top of an isolated ice sheet. This is perhaps most strongly supported by the observation that despite the fact that the temperature seesaw and the NAO are themselves highly correlated ($r = 0.5$ for winter NAO and winter seesaw), significant aspects of these oscillations which are not intercorrelated are found in the isotopic record. This result also indicates that since the stable isotopic composition of Greenland snow appears to be responding to the broad scale climate of the North Atlantic region, these values should be good diagnostic variables in testing models such as general circulation models which attempt to model the full spectrum of climate on large scales.

Perhaps the most frustrating aspect of making these comparisons is that we have no record of temperature observations from the Summit area which extends far enough back in time to make direct comparisons of isotopes and temperatures. We cannot know whether the correlations found here with the stacked isotope record are the result of correlations between Summit temperatures and the broader climatic patterns of the North Atlantic region or whether the isotopic composition indeed integrates the history of the air masses reaching Summit and thus the climatic history of the broader region. At this point we can be fairly sure that the Summit region will not be unique in its correlations with the broader-scale features of North Atlantic climate. The results from the stacked isotopic records at Summit indicate clearly the need for similar multicore efforts in other areas.

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