Spatial and Temporal Characteristics of the Little Ice Age: The Antarctic Ice Core Record

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ABSTRACT

Recently, ice core records from both hemispheres, in conjunction with other proxy records (e.g., tree rings, speleothems and corals), have shown that the Little Ice Age (LIA) was spatially extensive, extending to the Antarctic. This paper examines the temporal and spatial characteristics of the dust and $\delta^{18}O$ information from Antarctic ice cores. Substantial differences exist in the records. For example, a 550-year record of $\delta^{18}O$ and dust concentrations from Siple Station, Antarctica suggests that warmer, less dusty conditions prevailed from A.D. 1600 to 1830. Alternately, dust and $\delta^{18}O$ data from South Pole Station indicate that opposite conditions (e.g., cooler and more dusty) were prevalent during the LIA. Three additional Antarctic $\delta^{18}O$ records are integrated with the Siple and South Pole histories for a more comprehensive picture of LIA conditions. The records provide additional support for the LIA temperature opposition between the Antarctic Peninsula region and East Antarctica. In addition, periods of strongest LIA cooling are not temporally synchronous over East Antarctica. These strong regional differences demonstrate that a suite of spatially distributed, high resolution ice core records will be necessary to characterize the LIA in Antarctica.

INTRODUCTION

The broad spectrum of chemical and physical data preserved within ice sheets and ice caps provide a multifaceted record of both the climatic and environmental history of the earth. Over the last three decades, ice cores have provided new details about the magnitude, direction, and rate of climatic change during the last 160,000 years. These histories serve as comprehensive case studies that can improve our understanding of future changes in the global environment.

Clarification of the course of future climatic changes requires understanding the origin of the natural variability within the environmental system on time scales ranging from decades to centuries [IGBP, 1989]. The Holocene record (~last 10,000 years) offers the temporal and spatial detail necessary to characterize that variability. The last several thousand years of the Holocene provide the best opportunity to study decadal- and centennial-scale processes as it is the period (1) most relevant to human activities, both present and future; (2) of extremes within the Holocene warm period including the "Little Ice Age" period from A.D. 1450–1880; (3) of maximum data coverage; (4) for which multi-proxy reconstructions are possible; (5) when annual and decadal resolution is possible so that leads and lags in the system can be studied; and (6) when causes of these changes remain undetermined. In the last decade ice cores have been recognized increasingly as sources of very highly resolved paleoenvironmental time series. Here we examine the characteristics of the most recent neoglacial period or Little Ice Age as it is preserved in Antarctic ice cores.

ANTARCTIC ICE CORE RECORDS

The histories discussed below originated from different areas of the Antarctic (Figure 1) which are characterized by quite disparate net balances, mean annual temperatures, surface climatologies, and ice flow regimes. Dating of ice core records is the first, critical step in paleoclimatic reconstruction and dating precision varies widely among these records. The net annual accumulation and temperature of a site, as well as the sample sizes selected for individual analyses,

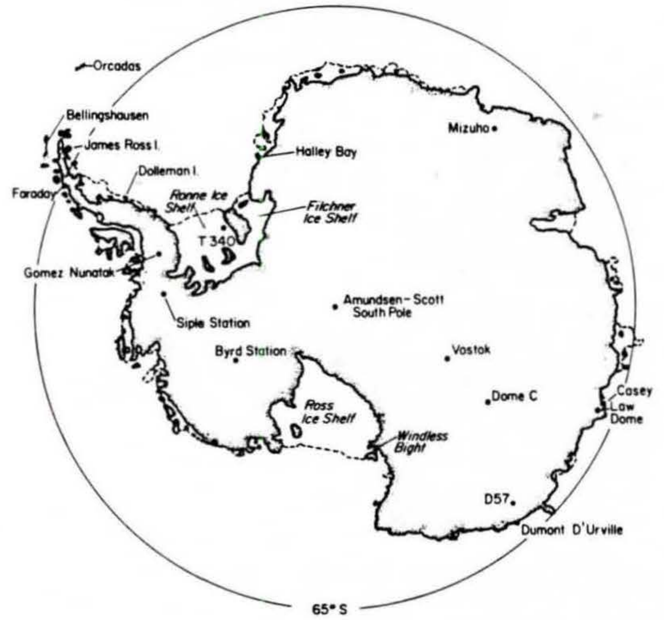

Figure 1. Core sites and meteorological stations discussed in the text.

limit the time resolution possible. To examine the last 500 years as recorded in Antarctic ice cores, annual- to decadal-time resolution is essential and the precision of the time scale is a major consideration. Data drawn from other authors are presented as faithfully as possible with respect to time, and any annual or decadal averages presented were calculated from the time series as originally published. The reader is encouraged to review the original records if more specific information is desired.

Siple Station (75°55'S; 84°15'W; 1054 masl). A 550-year record of the concentrations of dust, $\delta^{18}O$, and SO_4^{2-} was obtained from a 302-meter core drilled in 1985/86 at Siple Station (Figure 1). This core was cut into 5757 samples each for microparticle concentrations and $\delta^{18}O$ and into 3492 samples for SO_4^{2-} analyses. The small sample size (and thus large number of samples) was necessary to isolate seasonal signals for establishing the best possible time scale. Both $\delta^{18}O$ and SO_4^{2-} records exhibit excellent seasonality throughout the entire 302 meters [Mosley-Thompson et al., 1990] and were used to produce the time scale which has an estimated error of 10 years at A.D. 1417 (2%).

South Pole Station (90°S; 2835 masl). A 101-meter core drilled at South Pole in 1974 was cut into 5218 samples for the analysis of microparticle concentrations [Mosley-Thompson and Thompson, 1982] which were used to establish a 911-year record. The core was also cut into 1024 samples for $\delta^{18}O$ analyses at the University of Copenhagen. The $\delta^{18}O$ samples were cut to approximate a single year as defined by the current accumulation rate coupled with a steady state calculation of layer thinning with depth. Therefore, the $\delta^{18}O$ record does not contribute to the refinement of the time scale. The $\delta^{18}O$ data have been converted into a time series using the time–depth relationship derived from the particulate record. The $\delta^{18}O$ data from 1974 to 1982 were obtained from a pit 4 km from the station [Mosley-Thompson et al., 1985].

A second isotopic record available from South Pole consists of a very detailed (~900 samples), continuous deuterium (δD) record for the last 100 years with an estimated accuracy of ±5 years. The annual averages for A.D. 1887–1977 and the smoothed curves used in this paper are reproduced from Jouzel et al. [1983].

Dome C (74°39'S; 124°10'E; 3240 masl). The low net annual accumulation (~37 mm H_2O eq.) at Dome C (Figure 1) precludes establishing an annually resolved record. The most detailed $\delta^{18}O$ records of the last 1000 years for Dome C are from the upper 100 m of two cores drilled in 1978 and 1979 [Benoist et al., 1982]. Due to the large variability in net accumulation, a high level of smoothing was required to reduce the noise. Smoothing with filter band widths of 512 and 170 years precluded extraction of a detailed record.

T340: Filchner–Ronne Ice Shelf (~78°60'S; 55°W). A 100-meter core was drilled in 1984 at site T340 on the Filchner–Ronne Ice Shelf (Figure 1) by the German Antarctic Research Program [Graf et al., 1988]. Net annual accumulation at T340 is ~155 mm H_2O equivalent. The core was dated using the seasonal variations in $\delta^{18}O$ preserved in much of the core. The quality of the $\delta^{18}O$ record, and thus the time scale, was compromised by partial melting in the upper part of the core. Essentially, 479 annual layers were identified by $\delta^{18}O$ and of these, 80 were expressed as small maxima or shoulders on larger peaks. In addition, 5 m of core were unavailable. Extrapolating from surrounding sections led to the addition of 41 years, representing this 5-m section. Thus, a total of 520 years was estimated for the core which gives an age of A.D. 1460 for the bottom. No estimate of accuracy was given for the dating of T340.

Law Dome (66°44'S; 112°50'E; 1390 masl). The Australian National Antarctic Research Expedition recovered a 473-meter ice core (BHD) in 1977 from the summit of the Law Dome. The net annual accumulation at the site of core BHD is ~800 mm H_2O and the annual layers thin to approximately 110 mm H_2O eq. at 450 m. Pit studies and total Beta radioactivity profiles confirm the annual character of the well-preserved $\delta^{18}O$ signal. The upper 28 m (1950–1977) were cut into roughly 10 samples per year to verify the seasonality of the $\delta^{18}O$ record. Below 28 m, $\delta^{18}O$ was measured in selected sections and the results were extrapolated over intervening core sections. Recognizing that this introduces some uncertainty in the dating, Morgan [1985] suggests a dating accuracy of ±10%.

Mizuho Core (70°41.9'S; 44°19.9'E; 2230 masl). A 150-meter core was drilled at Mizuho Station by Japanese Antarctic Research Expeditions between 1970 and 1976 [Watanabe et al., 1978]. Mizuho is situated in the Antarctic coastal zone (Figure 1) in a region dominated by katabatic winds.The mean annual accumulation is ~450 mm H_2O equivalent, but removal of material by wind produces hiatuses in the annual record making reconstruction of a continuous $\delta^{18}O$ record from the 150-m core impossible. No obvious seasonal cycles in $\delta^{18}O$ were found. Principally, the core was dated by matching prominent isotope features to similar features in the upper part of the Camp Century, Greenland core which were assumed to be correlative. Thus, it is impossible to assess the quality of the time scale, but the error is likely to be higher than for other cores considered here.

SURFACE TEMPERATURE AND $\delta^{18}O$: A.D. 1945-1985

Annual $\delta^{18}O$ averages, like surface temperatures, exhibit interannual variability in response to large-scale circulation changes which control the frequency, duration, intensity, and seasonality of precipitation from cyclonic storms. In addition, ice core records contain glaciological noise superimposed upon the input signal by both surface and post-depositional processes. The climatological utility of an ice core record as an environmental proxy depends upon whether or not it reflects larger- or regional-scale climatic trends. This assessment for Antarctic ice core records is hindered by the poor availability of long meteorological observations [DOE, 1987].

Comparison of $\delta^{18}O$ and surface temperatures provides a crude estimate of the larger-scale representativity of the ice core record although there are weaknesses in this approach [see Peel et al., 1988 for discussion]. Mosley-Thompson [1992] provides a more extensive discussion of the comparison of $\delta^{18}O$ annual averages and meteorological observations for the period of overlap: A.D. 1945–1985. Essentially, conditions at Siple Station reflect those prevailing in the Peninsula more frequently than those prevailing over the polar plateau. In general trends in surface temperatures in the Peninsula are "out of phase" with those in East Antarctica. Likewise, the annual $\delta^{18}O$ records from Siple and South Pole are out of phase suggesting that trends in the $\delta^{18}O$ records are consistent with trends in surface temperatures.

THE RECORDS SINCE A.D. 1500

The most recent widespread Neoglacial episode (approximately A.D. 1500–1880), evident in reconstructed Northern Hemisphere temperatures [Groveman and Landsberg, 1979] and proxy records [Lamb, 1977; Grove, 1988], is commonly referred to as the Little Ice Age (LIA). Figure 2 illustrates the five Antarctic ice core $\delta^{18}O$ histories with sufficient time resolution and precision to examine environmental conditions over continental Antarctica during the last 480 years. A record from the Quelccaya ice cap [Thompson et al., 1986], located at 14°S at 5670 meters on the Altiplano of the southern Peruvian Andes, is included as it closely resembles Northern Hemisphere temperatures reconstructed by Groveman and Landsberg [1979].

For the records in Figure 2, the Mizuho time scale is the least precise while that for Siple is the most precise. Partial melting makes assessing the Filchner-Ronne T340 time scale difficult; however, if approximately 20 years were missing from the upper part of T340, the major warm and cool events would correspond fairly well with those at Siple. Such errors are possible as the upper part of the core was affected by melting and contained most of the missing core sections for which extrapolations were used. In addition, the T340 $\delta^{18}O$ record was adjusted for increasing continentality (^{18}O depletion) with depth in the core due to northward ice shelf movement and was finally smoothed with an unspecified filtering function [Graf et al., 1988].

Only selected sections of the Mizuho and Law Dome cores were analyzed. This discontinuous sampling results in a smoothed appearance. By contrast, the South Pole, Siple, and Quelccaya records were continuously analyzed, are annually resolved, and thus exhibit a higher degree of variability. To facilitate comparison, a 48-point (or 48 year) Gaussian filter was used to smooth the annual data for presentation in Figure 2. The horizontal line is the time series average for each core and values below the mean, interpreted as cooler than average temperatures, are shaded.

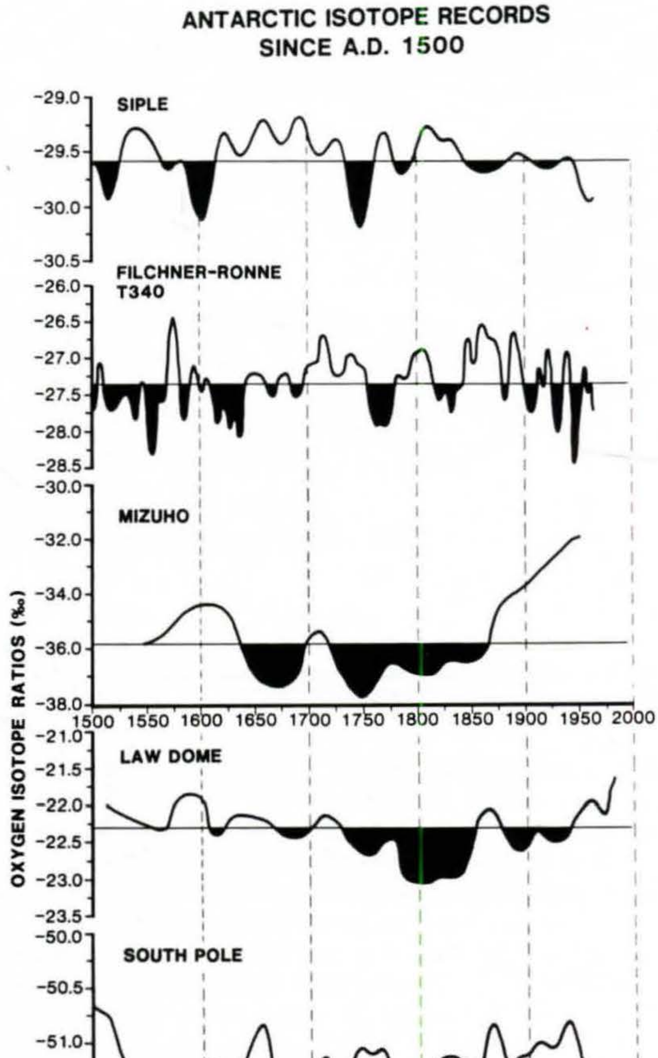

Figure 2. Isotope records for A.D. 1500 to the present for these locations: Siple, T340, Mizuho, Law Dome, and South Pole. A comparable record for Quelccaya Ice Cap, Peru is included. Each time series mean is illustrated by the horizontal line. Isotopic values below the mean suggest cooler than normal temperatures and are shaded.

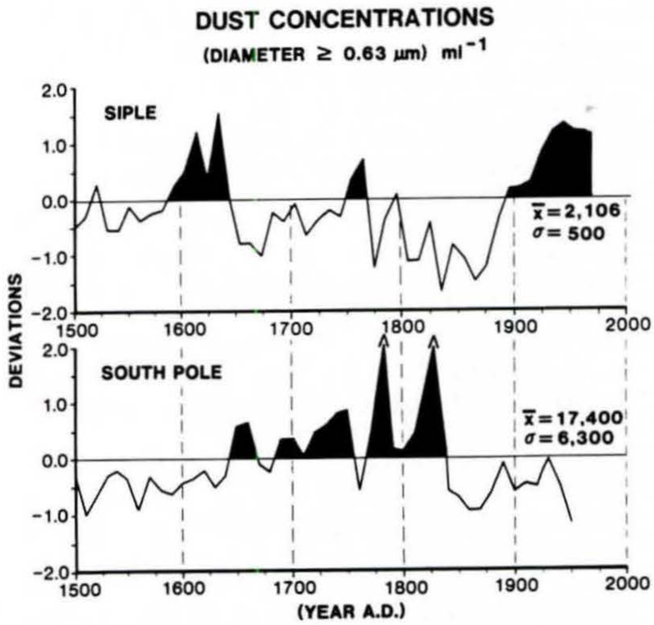

Figure 3. The 10-year unweighted averages of dust content for Siple and South Pole ice core are compared. Microparticle (diameter ≥ 0.63 μm) concentrations per mL are shown as standardized deviations from their respective time series means.

The records from East Antarctica suggest cooler conditions during much of the LIA while the Siple record indicates warmer conditions for much of that period. Core T340 also suggests warmer conditions from A.D. 1650 to 1830 with a brief cool event at ~A.D. 1760. Clearly, in the last 300 years the T340 record most closely resembles that from Siple, particularly the downward trend in the last century.

Figure 2 reveals several spatial differences. First, Mizuho and Law Dome show the strongest similarity, with coldest conditions between A.D. 1750 and 1850. Although conditions were cooler than average at South Pole from A.D. 1550 to 1800, this period is punctuated by warmer and cooler events with the coldest period in the mid- to late 1500s. Using the empirical $\delta^{18}O$-temperature relationship of Aldaz and Deutsch [1967], the "isotopically inferred" temperature depression in the late 1500s may have been ~0.5°C. A smoothed δD history from Dome C (not shown) also suggests cooler conditions from A.D. 1200 to 1800; however, because significant noise necessitated high-level smoothing, further time resolution is impossible [Benoist et al., 1982].

These records indicate that a warming trend has prevailed in East Antarctica since A.D. 1850 while cooling has clearly dominated at Siple and T340. The T340 record supports the suggestion that the longer-term trends in the Siple $\delta^{18}O$ history may reflect similar conditions for much of the Peninsula region. The opposition between the $\delta^{18}O$ records at Siple and those in East Antarctica is consistent with the currently observed opposition in surface temperatures [Mosley-Thompson, 1992]. Since A.D. 1975 these trends appear to have reversed, with cooling dominating over the Plateau and warming over the Peninsula.

The dust concentrations in cores from Siple and South Pole suggest further differences. Figure 3 illustrates the 10-year unweighted averages of particulate concentrations (diameters ≥0.63 μm) per milliliter sample for both cores. Concentrations above the time series mean for each core are shaded. From A.D. 1630 to 1880 dust concentrations at Siple are below average. A brief dust event around A.D. 1750 is associated with a negative (cooler) excursion in $\delta^{18}O$ (Figure 2). From A.D. 1880 to the present dust concentrations at Siple have increased while a cooling trend has prevailed (Figure 2). In contrast, at South Pole dust deposition was higher from A.D. 1650–1850. Note that the coldest temperatures at South Pole preceded the increase in dust by 100 years.

CONCLUSIONS

The records of $\delta^{18}O$ and dust concentrations from Siple Station suggest warmer and less dusty atmospheric conditions from A.D. 1600 to 1830 which encompasses much of the Northern Hemisphere Neoglacial period, the Little Ice Age. Dust and $\delta^{18}O$ data from South Pole, supported by the $\delta^{18}O$ results from Law Dome and Mizuho, indicate that opposite conditions (e.g., cooler and more dusty) were prevalent over the East Antarctica Plateau.

The similarity between the $\delta^{18}O$ records from South Pole and Quelccaya is intriguing. The excellent correspondence between the Quelccaya $\delta^{18}O$ record and Northern Hemisphere reconstructed temperatures has been demonstrated [Thompson et al., 1986]. The similarity between the South Pole and Quelccaya $\delta^{18}O$ records, as well as the elevated dust concentrations, suggests the possibility of large-scale upper atmospheric teleconnections between the South American Andes and the high East Antarctica Plateau which warrant investigation beyond the scope of this paper.

Meteorological data from 1945 to 1985 show that the Peninsula–East Antarctica Plateau temperature opposition prevailing during much of the last five centuries is consistent with the present spatial distribution of surface temperature trends. There is some observational evidence suggesting that under present conditions stronger zonal westerlies are associated with cooler conditions on the polar plateau and warmer conditions in the Peninsula region [Rogers, 1983]. The physical processes controlling these spatial relationships must identified and better understood; however, the observational data base necessary for this assessment is lacking. These regional differences demonstrate that a suite of spatially distributed, higher resolution ice core records will be necessary to characterize more fully paleoenvironmental conditions since A.D. 1500 in Antarctica.

ACKNOWLEDGMENTS

We acknowledge all those who participated in both the field and laboratory aspects of this program. We especially thank Drs. C. C. Langway, Jr. and Willi Dansgaard for making available their unpublished $\delta^{18}O$ data from the 1974 South Pole ice core. This work was supported by NSF grant DPP-841032A04 to The Ohio State University. This is contribution 725 of the Byrd Polar Research Center.

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