29 Paleoenvironmental conditions in Antarctica since A.D. 1500: ice core evidence

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29.1 Antarctic ice core records

The previous chapter described the paleoclimatic records available from ice cores in the Antarctic Peninsula region. This paper synthesizes the records available for the East and West Antarctica Ice Sheets (Figure 29.1). The histories summarized in this chapter come

Figure 29.1 The map illustrates core sites and meteorological stations discussed in the text.

from different areas which are characterized by a broad spectrum of net balances, mean annual temperatures, surface climatologies and ice flow regimes. Section 29.1.2 focuses upon the different ice cores and discusses the strengths and limitations of each record for the synthesis of environmental conditions since A.D. 1500. The following section provides an overview of the dating of ice core records which is the first, critical step in paleoclimatic reconstruction.

29.1.1 Dating the ice cores

As discussed in Chapter 1, ice cores may be dated using numerous techniques (Hammer 1978) ranging from seasonally varying parameters such as dust and $\delta^{18}O$, identification of discrete well-dated events, and modeling techniques. 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.

Johnsen (1977) demonstrated that the seasonal $\delta^{18}O$ signal will be smoothed gradually by diffusion during the firnification process and may not be preserved at depth when accumulation rates are below ~250 mm H_2O equivalent. In these regions other seasonally varying constituents such as insoluble particulates (MPC) sulfate (SO_4^{2-}) nitrate (NO_3^-) and direct current (D.C.) conductivity may be used. Ultimately, the net annual accumulation and temperature of a site limit the time resolution.

This may be illustrated using records from two very different places: Siple Station (75°55′S; 84°15′W; 1054m asl) and Amundsen-Scott South Pole Station (90°S; 2835m asl). Microparticle (insoluble) concentrations were analyzed in 5218 samples representing the entire length of a 101 meter ice core drilled in 1974 at South Pole. A 911 year time scale was produced using a single parameter, insoluble dust concentrations (Figure 2 in Mosley-Thompson and Thompson 1982). The time scale error at 101 meters was estimated as ~90 years or ± 10%. The low net annual accumulation at South Pole (~80mm H_2O equivalent) precludes the use of seasonal $\delta^{18}O$ and δD variations for dating at depths exceeding about 20 meters (Figure 29.2 in Jouzel *et al.* 1983). In contrast, the high net annual accumulation at Siple (560 mm H2O equivalent) and moderately low temperatures (MAT:-24°C) preserve the seasonal $\delta^{18}O$ signal which exhibits strong spatial reproducibility (Figure 29.2). Sulfate concentrations also exhibit a well preserved and spatially reproducible annual signal (Dai *et al.* 1990). Thus, using a combination of $\delta^{18}O$ and SO_4^{2-}, coupled with SO_4^{2-} identification of several volcanic events which serve as time-stratigraphic markers (e.g. Figure 29.3) the estimated accuracy of the time scale for the 302 meter Siple core is ± 10 years at A.D. 1417 or ± 2%. This 5-fold increase in precision illustrates the importance of net annual accumulation for obtaining highly resolved time scales.

The precision of the time scale also depends upon the sample size selected for individual analyses. The cores used in this synthesis were drilled at different locations (Figure 29.1) and were analyzed by different groups using a variety of techniques and sampling schemes. Therefore, the reader is encouraged to review the original records if more specific information is desired.

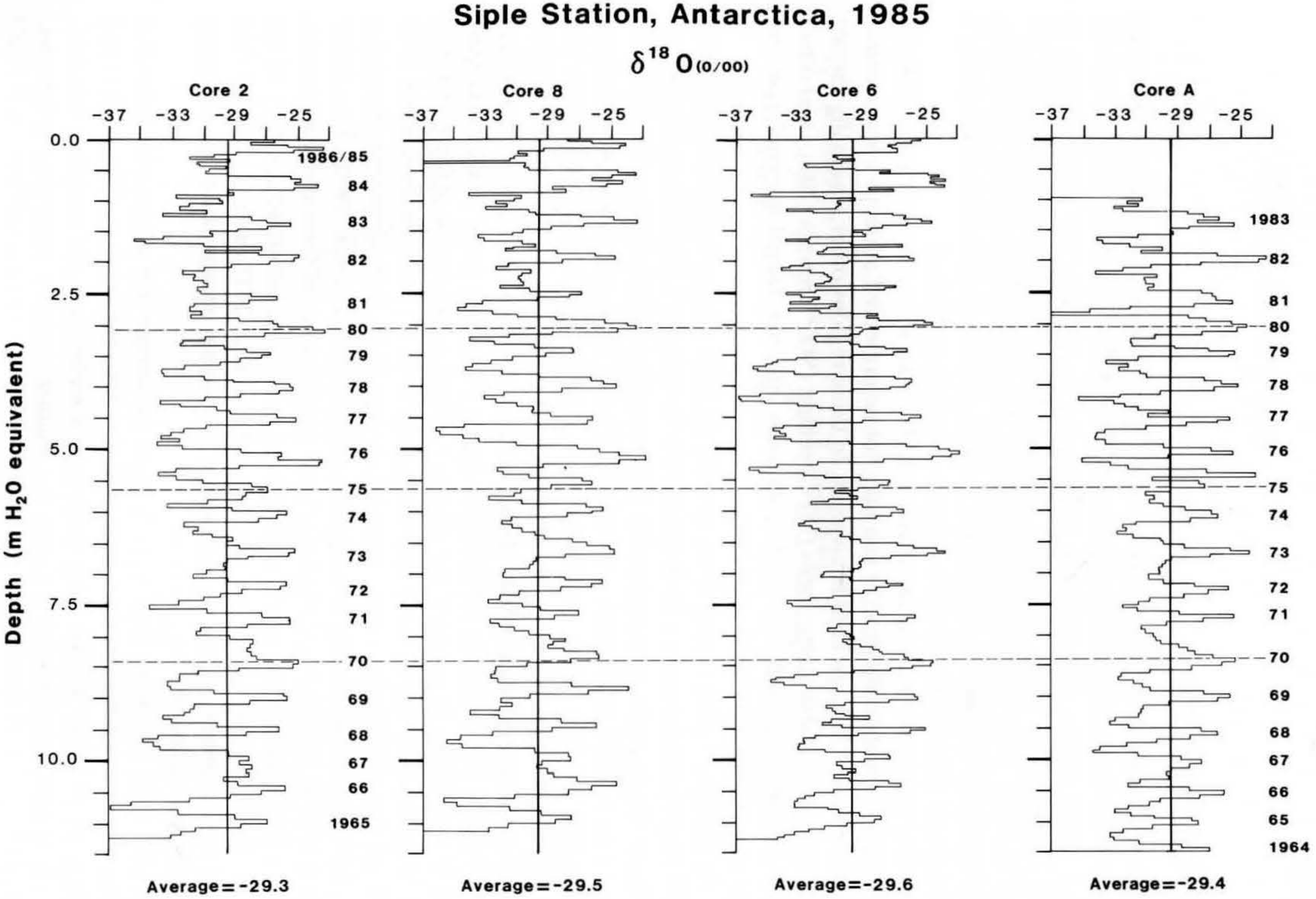

Figure 29.2 Four oxygen isotope records representing A.D. 1965-1985 at Siple Station illustrate the high degree of reproducibility of the annual signal used to date the deeper (302m) core. These shallow cores surround the deeper drill hole (see Mosley-Thompson *et al.*, 1990 for map).

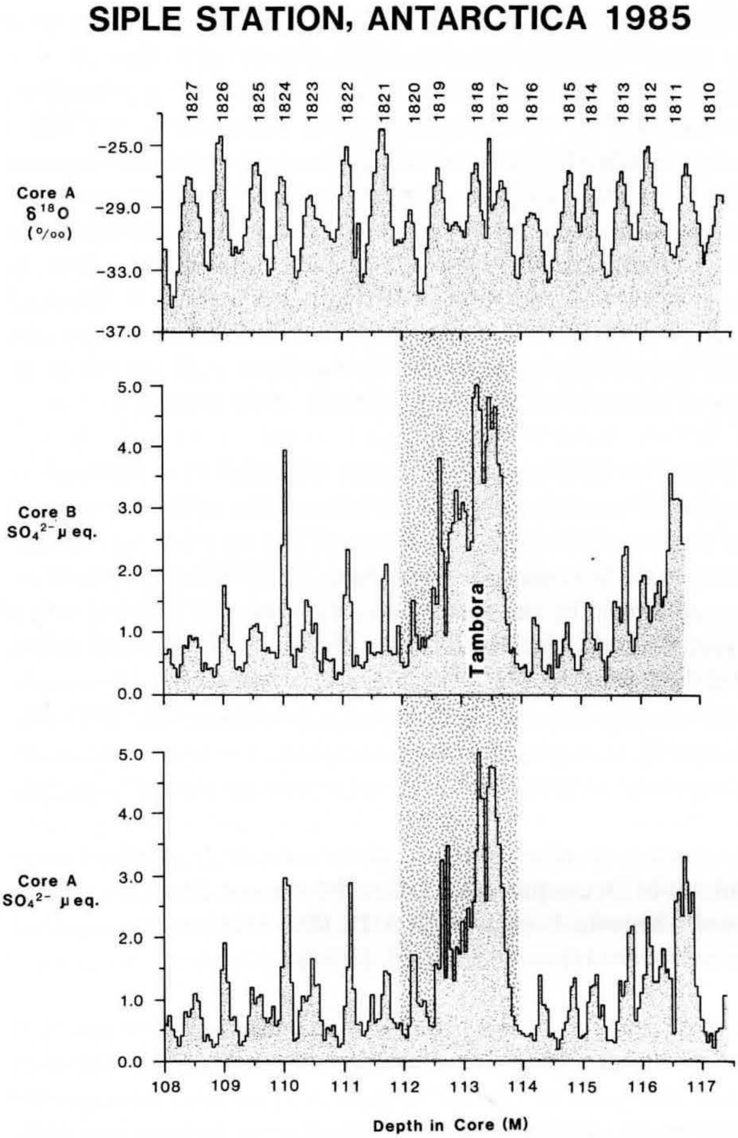

Figure 29.3 The sulfate concentrations (μeq. l^{-1}) in two parallel cores (A and B) from Siple Station exhibit an excellently preserved seasonal signal which is combined with the $\delta^{18}O$ record to produce the time scale. The SO_4^{2-} records reveal the eruption of Tambora (A.D. 1815) which serves as a time-stratigraphic marker, further confirming the time scale.

29.1.2 Description of the ice core records

Siple Station (75°55′S; 84°15′W; 1054m asl) 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 29.1). Siple lies between the Antarctic Peninsula region which is characterized by a complex near-surface wind regime (Schwerdtfeger and Amaturo 1979) and the high inland polar plateau. To the east of the Peninsula the continental character of the meteorological regime leads to a very cold Antarctic coastal belt while maritime conditions prevail to the west. It is likely that the Siple region is not dominated consistently by a single meteorological regime, but is a sensitive region of transition. This will be explored in more detail in Section 29.3.

The 302 meter Siple 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 (Figure 29.3) throughout the entire 302 meters and were used to produce the time scale previously discussed (Section 29.1.1). To create the annual records the $\delta^{18}O$ and particulate concentration values were averaged over individual annual layer thicknesses. The weight of each sample in the annual average was a function of its contribution to the thickness of the annual unit.

South Pole Station (90°S; 2835m asl) 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 by averaging over the annual layers in a pit 4 kilometers from the station (Mosley-Thompson *et al.* 1985). The net annual accumulation at South Pole is ~80 mm H_2O equivalent.

A second isotopic record is available from South Pole. Jouzel *et al.* (1983) produced 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 (124°10'E; 74°39'S; 3240m asl) The low net annual accumulation (~37 mm H_2O eq.) at Dome C (Figure 29.1) precludes establishing an annually resolved record. The most detailed $\delta^{18}O$ records of the last 1000 years for Dome C (Figure 29.1) are from the upper 100 meters 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. Benoist *et al.* (1982) conclude that the smoothed curves suggest generally cooler conditions from A.D. ~1200-1800.

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 29.1) 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 meters of core were unavailable. Extrapolating from surrounding sections lead to the addition of 41 years, representing this 5m section. Thus, a total of 520 years were estimated for the core which gives an age of A.D. 1460 for the bottom (Graf *et al.* 1988). No estimate of accuracy was given for the dating of T340. Due to the movement of the ice shelf, the ice in the core did not accumulate at a single location. Graf *et al.* (1988) attempted to correct the $\delta^{18}O$ record for the increasing continental effect down the length of the core since the ice at depth originated in a less maritime location.

Law Dome (66°44'S; 112°50'E; 1390m asl) 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 ~800mm H_2O and the annual layers thin to approximately 110mm H_2O eq. at 450 meters. Pit studies and total Beta radioactivity profiles confirm the annual character of the well-preserved $\delta^{18}O$ signal. The upper 28 meters (1950-1977) were cut into roughly 10 samples per year to verify the seasonality of the $\delta^{18}O$ record. Below 28 meters, $\delta^{18}O$ 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 (70°41.9'S; 44°19.9'E; 2230m asl) 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 29.1) 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. These hiatuses make the reconstruction of a continuous $\delta^{18}O$ record from the 150 meter 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.

29.2 The contemporary setting

Despite its zonal symmetry, the Southern Hemisphere atmospheric circulation is characterized by interannual variability larger than that in the Northern Hemisphere (Trenberth 1984). The distribution of storm tracks and preferred regions of blocking are tied to the planetary waves, and thus to the position of the mean jet stream. Rogers (1983) found that interannual temperature variability at a site reflects similar variability in the longitudinal positions of the upper level waves and associated surface cyclones. Positions of these features are controlled partially by the distribution of Antarctic sea ice and hence, by sea surface temperatures (Carleton 1984; Trenberth 1984). Thus, the high interannual temperature variability results from large-scale changes from year to year in the position of the jet stream and preferred storm tracks which control the penetration of warm air to the Antarctic interior.

Figures 29.4 and 29.5 illustrate the longest and most complete mean annual Antarctic surface temperature records expressed as departures from their respective time series means.

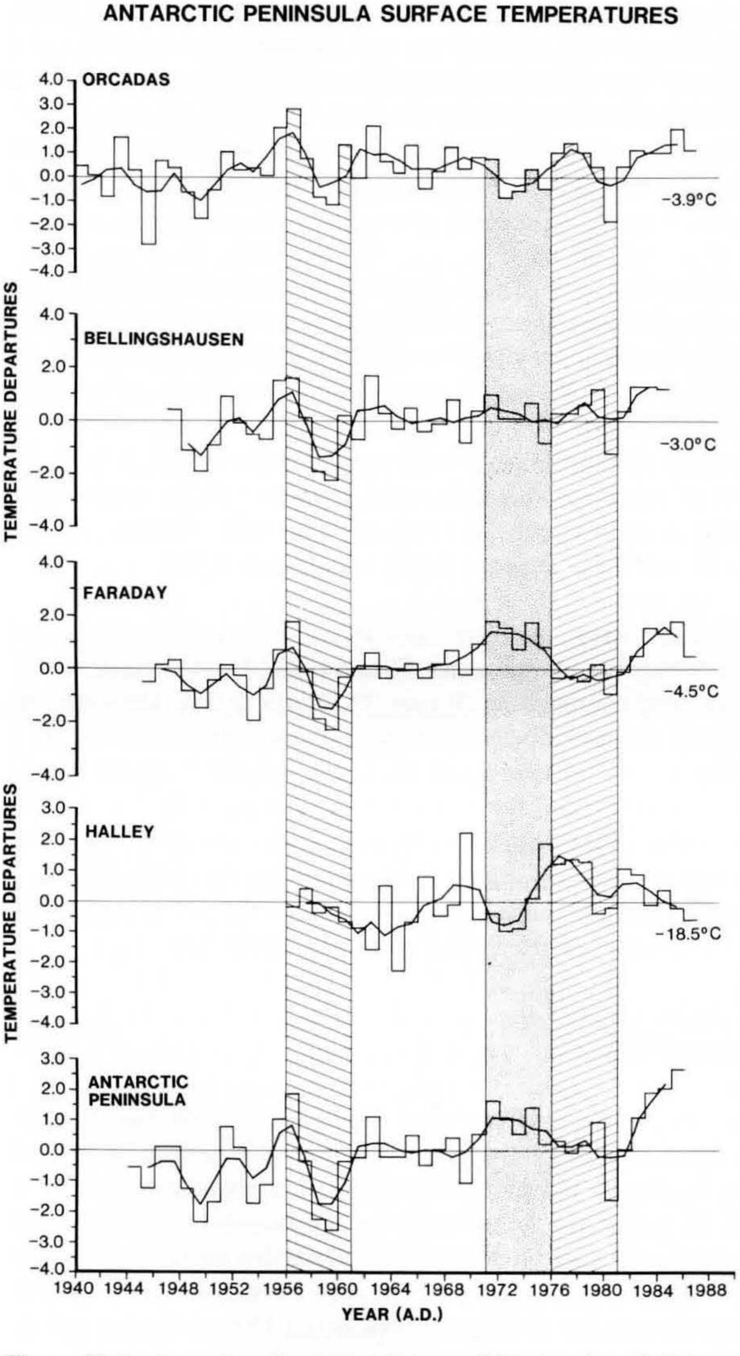

Figure 29.4 Annual surface temperatures (histogram) and three-year unweighted running means (solid line) are illustrated for Halley Bay and the following Antarctic Peninsula stations: Islas Orcadas, Bellingshausen, and Faraday. Composite temperatures for the Antarctic Peninsula are included (Limbert, 1984; Peel *et al.*, 1988).

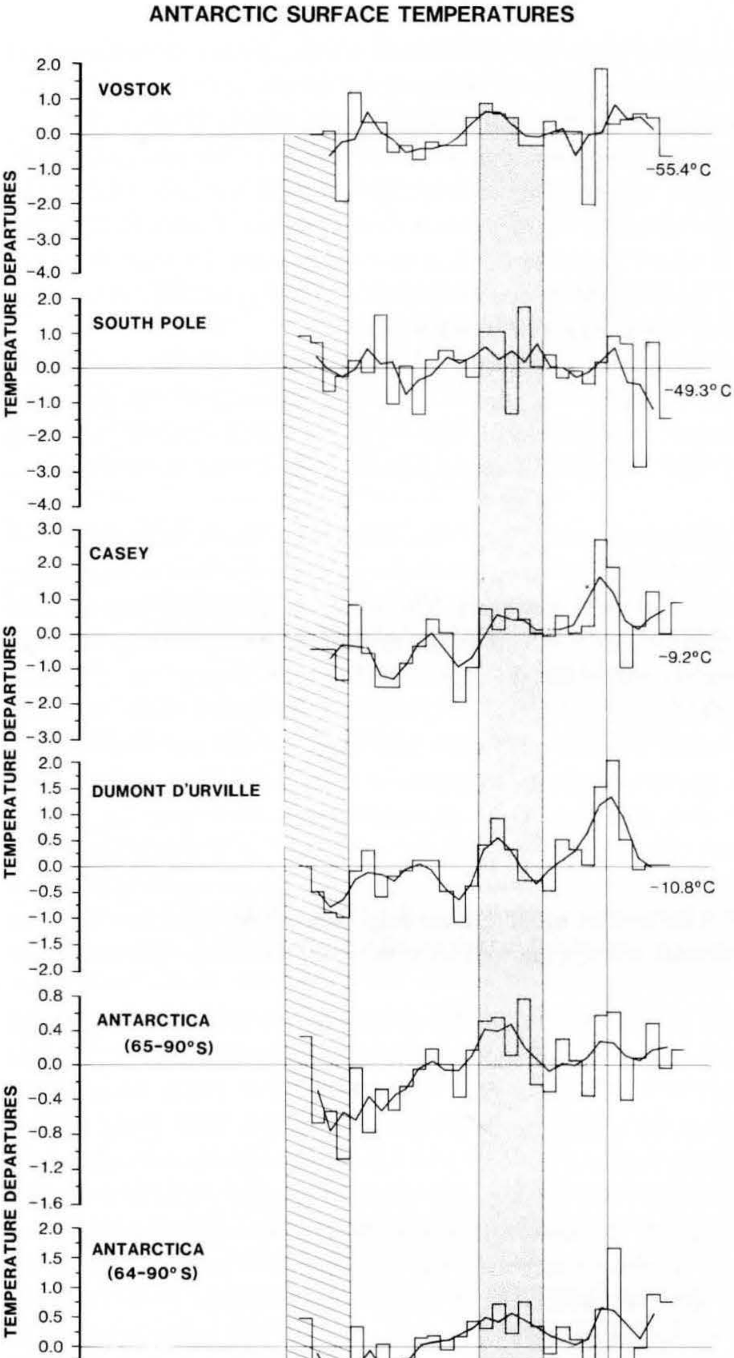

Figure 29.5 Annual surface temperatures (histogram) and the three-year unweighted running means (solid line) are illustrated for the following Antarctic stations: Vostok, Amundsen-Scott South Pole, Casey, and Dumont D'Urville. Two continental composites are included: Antarctic (65°-90°S) temperature trends (Raper *et al.*, 1984); Antarctic (64°-90°S) temperature trends (Hansen and Lebedeff, 1987).

To highlight trends in each record the three-year unweighted running mean is shown as a solid line and three periods of persistent multi-year temperature trends are shaded for later discussion. In Figure 29.4 stations from the Antarctic Peninsula region (Figure 29.1) are shown with the Antarctic Peninsula composite compiled by Limbert (1984) and updated by Peel *et al.* (1988). Islas Orcadas and Bellingshausen represent the northern end of the Peninsula while Faraday is characteristic of the western coastal region. Halley Bay, on the extreme eastern edge of the Weddell Sea, characterizes the colder, more continental regime to the east of the Peninsula. The temperature regime at Halley Bay is generally out of phase with that on the western side of the Ronne-Filchner Ice Shelf.

Figure 29.5 shows the most complete temperature records from East Antarctica. On the high polar plateau are Vostok and South Pole while Casey and Dumont D'Urville are along the Wilkes Land Coast. Included is a synthesis for (65°-90°S) derived from areal averaging (Raper *et al.* 1984; DOE 1987) and a spatially averaged trend analysis for 64° to 90°S (Hansen and Lebedeff 1987).

The main trends in the continental-scale composites (Figure 29.5) are reflected in the Peninsula composite (Figure 29.4) with the exception of the prominent warming trend since 1980 in the Peninsula region (excluding Halley Bay). This similarity arises partially because the continental-scale composites contain some areal bias toward the Peninsula region where the longer and more complete records exist (see Figure 29.2 in both Raper *et al.* 1984 and Hansen and Lebedeff 1987). Further, they are biased toward coastal conditions as only three inland stations (Amundsen-Scott, Vostok and Byrd) have long records and observations ended at Byrd in 1970. The greater similarity to trends at Casey and Dumont D'Urville illustrates this bias. If South Pole and Vostok are characteristic of the high polar plateau (above 2500 meters) then much of the areal extent of East Antarctica may not be represented well in the composite records. All three composites suggest a broad warming trend from the late 1950s to the early 1970s followed by moderate cooling. Since 1980 there has been no strong trend except in the Peninsula where a marked warming is evident at all stations (Figure 29.4) except Halley Bay.

The only long temperature record, Islas Orcadas (1903-1985) has been shown to be unrepresentative of both the Antarctic mean temperature series and the Southern Hemisphere (0°-60°S) composite for 1957-1983 (Jones *et al.* 1986; Raper *et al.* 1984). Much of the dissimilarity arises from a significant change in the temperature field in 1970. From 1957 to 1970 the temperature relationship between Orcadas and Faraday was consistent with colder temperatures at Faraday. However, this relationship reversed (Figure 29.4) in 1970. An analysis of the sea level pressure field led Schwerdtfeger (1976) to conclude that stronger and more frequent winds from the northwest increased the advection of warmer maritime air from the southeastern Pacific along the west coast of the Peninsula. Rogers' (1983) analysis suggested that a shift in the preferred location of surface cyclones and upper-level waves occurred. Comparison of the records in Figures 29.4 and 29.5 reveals that this warm event of the early 1970s affected a much larger area than the west coast of the Peninsula.

Antarctic temperature records reveal two other periods of persistent (multi-year) and geographically extensive temperature trends: 1975-1980 and 1955-1960. The spatial patterns of these trends are not simple and appear to change with time; that is, the temperature relationship between specific station pairs is not temporally consistent. For example, the 1970-1975 warm period, discussed above, which was so prominent at Faraday (Figure 29.4;

stipple) is present in all the composites, as well as Dumont D'Urville, Casey and Vostok (Figure 29.5). It is nearly absent at South Pole and Bellingshausen. Alternately, Halley Bay and Islas Orcadas exhibit cooler temperatures. It is interesting that the cooling trend in the late 1970s was prominent only where warming was pronounced earlier in the decade. This consistent spatial pattern may indicate that the consecutive warming and cooling throughout the decade was part of a large-scale circulation pattern which exhibited long-term persistence.

The spatial characteristics of the temperature pattern for the cooler period from 1955-1960 (Figure 29.4, hatched pattern) are different from those of the 1975-1980 cool period. Along the entire north-south axis of the Peninsula cooler temperatures were prevalent, but did not extend across the ice shelf to Halley Bay. The cooling was modest at Amundsen-Scott and Vostok, but more pronounced at Dumont D'Urville.

This discussion highlights the large-scale spatial differences in surface air temperatures which should be reflected in paleorecords reconstructed from $\delta^{18}O$ variations in ice cores. Such spatial differences may result from minor shifts in preferred locations for large-scale circulation features (Rogers 1983). Winter mean surface temperature trends in Antarctica have been linked to slow (multi-year) variations in atmospheric long waves (van Loon and Williams 1977) suggesting that mid-latitude large-scale circulation plays a significant role in the spatial variability of temperature over the continent. A more detailed discussion of the characteristics of the Antarctic meteorological regime is given by Schwerdtfeger (1984) and the precipitation regime is reviewed by Bromwich (1988).

29.3 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) as previously illustrated (Figures 29.4 and 29.5). The only long and complete interior record is from South Pole. Vostok is of equal length but has three missing annual averages (Figure 29.5).

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 (Peel, this volume). For example, the implicit assumption that accumulation occurs evenly throughout the year may introduce a bias. Precipitation falls throughout the year at Siple in association with persistent cyclonic activity, but the distribution throughout the year is unknown. On the other hand, winter (March to October) is the principal accumulation season at South Pole. The limitations of $\delta^{18}O$ as a proxy of condensation temperature are recognized as other factors such as distance from the source (e.g., sea ice extent, Bromwich and Weaver 1983) storm track trajectory and isotopic composition of the source also contribute to $\delta^{18}O$ at the deposition site. The relationships among these controlling factors are complex and their relative importance varies with geographic location.

Multi-year field programs are required to quantify the $\delta^{18}O$-air temperature relationship. For the ice cores discussed here, such studies have been conducted only at South Pole. Aldaz and Deutsch (1967) collected precipitation for $\delta^{18}O$ analyses between November 1964 and October 1965 and combined these results with upper air (50 kPa) temperature observations. They formulated an empirical mean annual temperature-$\delta^{18}O$ relationship ($\delta^{18}O = 1.4(T°C)+4.0$) which encompassed the majority of their observations. Using a similar approach, but with δD derived from pit studies for 1957-1978, Jouzel *et al.* (1983) found that mean annual deuterium values were best correlated ($r= 0.57$) with temperatures just above the inversion. This is consistent with the observation that precipitation forms just above the surface inversion (Miller and Schwerdtfeger 1972). For the purposes of this paper the $\delta^{18}O$ record is assumed to provide a proxy history for the condensation temperature of the precipitation at each core site. Thus, the classical interpretation of $\delta^{18}O$ for polar ice sheets is adopted, that is more (less) negative ratios imply cooler (warmer) condensation temperatures.

Figure 29.6 illustrates the $\delta^{18}O$ records for the only Antarctic ice cores (exclusive of the Peninsula, see previous chapter) analyzed in sufficient detail to provide meaningful annual averages for the period of overlap with meteorological observations. These are the South Pole δD record (Jouzel *et al.* 1983) the Law Dome $\delta^{18}O$ record (Morgan 1985) and the Siple $\delta^{18}O$ record (Mosley-Thompson *et al.* 1990, in press). The time scale accuracy of these cores has been discussed (Section 29.1.2). The 1974 South Pole $\delta^{18}O$ record is not included as it was cut into samples only approximating individual years (in the section on the South Pole Station) and thus, the 'annual' values lack the precision necessary for comparison with measured annual average temperatures; however, the record is quite appropriate for examination of longer trends. Figure 29.6 also illustrates two of the previously discussed temperature composites, the Peninsula and 65-90°S, respectively.

The large interannual variability makes it impossible to compare individual years among the three ice core records (Figure 29.6); however, the use of a three-sample unweighted running mean (solid line) highlights multi-year trends. Precise comparison of these records may be complicated by minor dating errors which could shift features several years in either direction. South Pole and Law Dome show remarkable similarity for sites of such disparate physical climatology (high plateau versus coastal). Nevertheless, both records reflect the same broad trends: an 'isotopic warm event' from 1955-1958, a subsequent cooling trend with little interannual variance throughout the early 1960s, and a warming trend since 1965. On the other hand, 2-3 year warm and cool events at Siple appear out of phase with those at South Pole and Law Dome, particularly prior to 1965. Only two longer trends characterize both South Pole and Siple: (1) the warming of the later 1960s which was also characteristic of the Peninsula (Figure 29.6) and a modest cooling from the mid-1940s to the mid-1950s. The latter was not characteristic of the Peninsula which experienced modest warming.

The large scale features in the Siple $\delta^{18}O$ record compare well with isotopic histories from James Ross Island, Dolleman Island, and Gomez Nunatak (Mosley-Thompson *et al.* 1990; Peel, this volume). This suggests that conditions at Siple may reflect those prevailing in the Peninsula area more frequently than over the high plateau.

There is observational evidence that temperature trends in the Peninsula area are generally 'out of phase' with those over the East Antarctica Plateau which is consistent with the South Pole and Siple records. Using factor analysis Rogers (1983) examined the spatial variability of

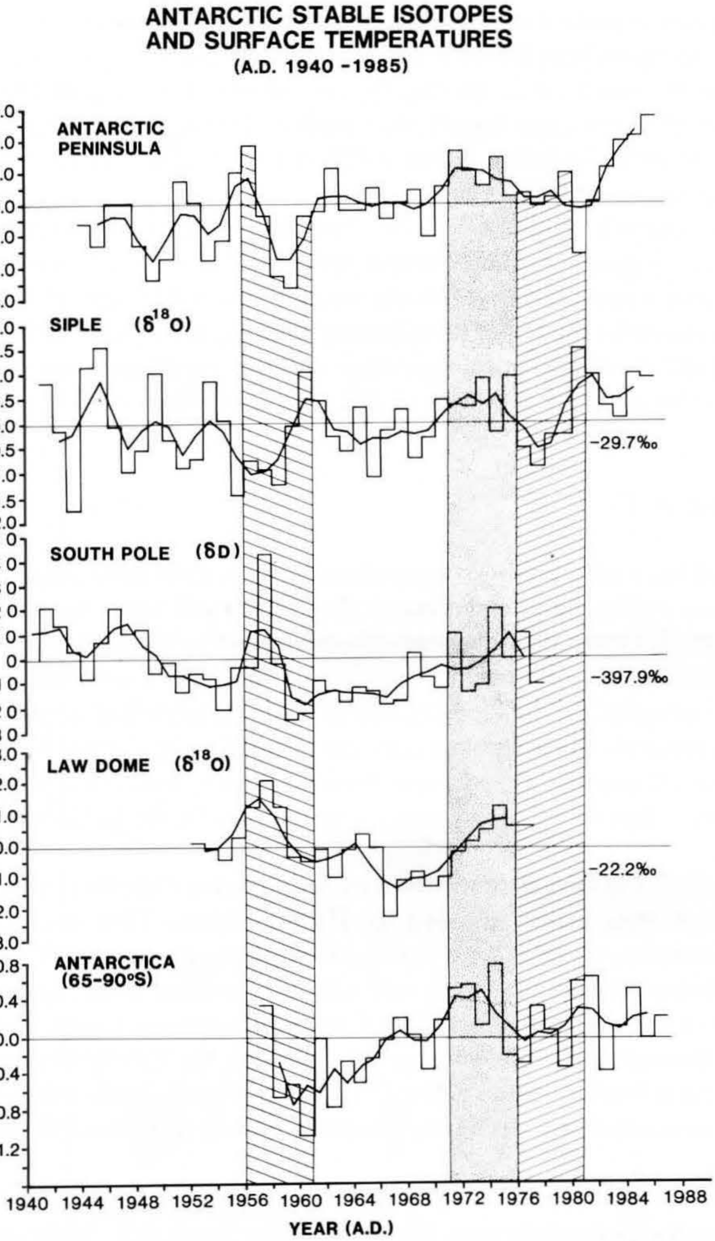

Figure 29.6 Stable isotope records for Siple ($\delta^{18}O$) South Pole (δD) and Law Dome ($\delta^{18}O$) are compared with the Antarctic Peninsula and continental (65-90°S) composites for A.D. 1940-1985.

seasonal mean temperature departures and reported an opposition in temperature anomalies between continental stations and those on or near the Antarctic Peninsula in all seasons but spring. For 1958 to 1980 the strength of the zonal westerlies (estimated from height differences across six pairs of mid-latitude and Antarctic stations) was strongly tied to the Peninsula-continent temperature opposition pattern in winter and summer. Rogers found that in years when zonal westerlies are strongest, temperatures are anomalously cold at South Pole and anomalously warm in the Peninsula area. Previously, Swanson and Trenberth (1981) reported an opposition in the long-term temperature trends (1957-1979) between the northeast sector (roughly 0°-90°E; including South Pole) and the rest of the continent including much of West Antarctica and the Peninsula.

A principal components analysis (Raper *et al.* 1984) of the spatial characteristics of Antarctic annual and winter temperatures (1957-1983) support the Swanson and Trenberth results: that is, negative loadings (a cooling trend) in the sector between 40°E and 30°W and positive loadings (warming trend) for the rest of the continent including the Peninsula. These data illustrate the regional differences that exist over Antarctica and explain why no single meteorological record provides a consistent picture of Antarctic temperature trends.

29.4 The records since A.D. 1500

The most recent widespread Neoglacial episode (approximately A.D. 1500-1880) evident in both 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 29.7 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 (Figure 29.7) as it closely resembles Northern Hemisphere temperatures reconstructed by Groveman and Landsberg (1979).

For the records in Figure 29.7, 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 (Figure 29.7) 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 Gaussian filter was used to smooth the annual data (Figure 29.7). The horizontal line is the time series average for each core and values below the mean, inferred as cooler than average temperatures, are shaded.

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.

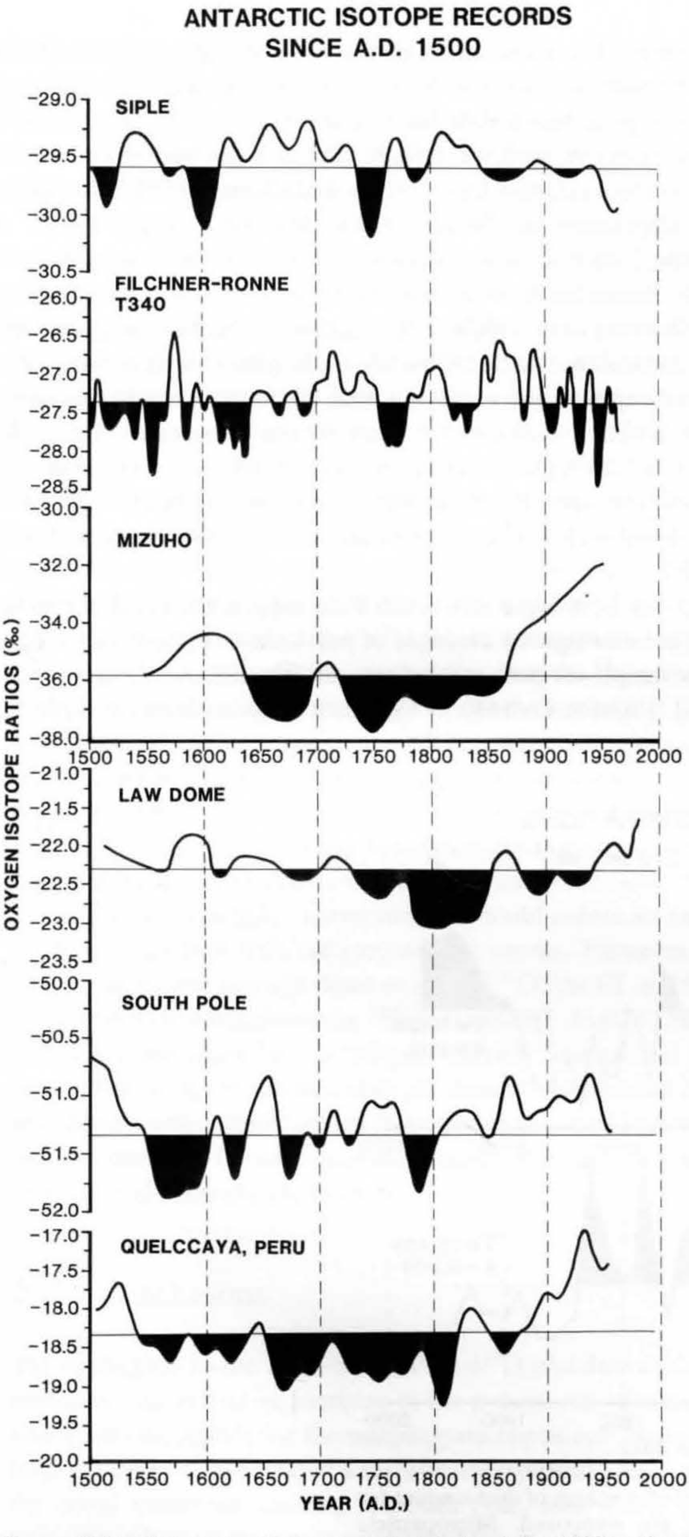

Figure 29.7 The Antarctic isotope records for A.D. 1500 to the present: Siple, T340, Mizuho, Law Dome, and South Pole. A comparable record for Quelccaya Ice Cap, Peru is included. Each time series mean is illustrated by the horizontal line. Isotopic values below the mean suggest cooler than normal temperatures and are shaded.

Figure 29.7 reveals several interesting 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 (Section 3.). Since A.D. 1975 these trends appear to have reversed with cooling dominating over the Plateau and warming over the Peninsula (Figure 29.6).

The dust concentrations in cores from Siple and South Pole suggest further differences. Figure 29.8 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

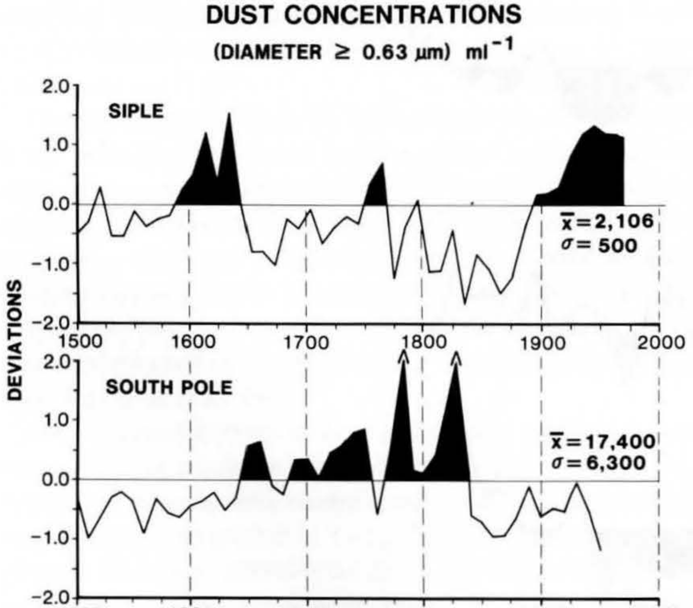

Figure 29.8 The 10-year unweighted averages of dust content for Siple and South Pole ice core are compared. Microparticle (diameter ≥ 0.63μm) concentrations per ml are shown as standardized deviations from their respective time series means.

below average. A brief dust event around A.D. 1750 is associated with a negative (cooler) excursion in $\delta^{18}O$ (Figure 29.7). From A.D. 1880 to the present dust concentrations at Siple have increased while a cooling trend has prevailed (Figure 29.7). 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.

Every ice core extending back to the last glacial stage has exhibited a positive relationship between increased dust deposition and cooler temperatures as inferred from $\delta^{18}O$ (Thompson and Mosley-Thompson 1981; DeAngelis *et al.* 1987). A similar relationship has been demonstrated for a prominent Neoglaciation event on the Quelccaya Ice Cap in Peru (Thompson *et al.* 1986). The dust concentration-$\delta^{18}O$ relationship at Siple and South Pole supports this; e.g., reduced dust deposition during warmer conditions (less negative average $\delta^{18}O$) and increased dust deposition during cooler conditions. Thus, the insoluble particulate concentrations further support an inverse relationship between environmental conditions at Siple and South Pole during the last 500 years. Most of the broad temperature trends in the Peninsula region are reflected in the Siple $\delta^{18}O$ record (note the A.D. 1945-1955 exception) suggesting that the Siple region, possibly including much of the Antarctic Peninsula area, was characterized by warmer conditions from A.D. 1620-1830 than in the current century.

As previously discussed, the $\delta^{18}O$ record is interpreted strictly in terms of temperature and other factors may account for, or contribute to, the ^{18}O enrichment. For example, increased storm frequency during winter might enrich the annual $\delta^{18}O$ average (making it less negative) as storms tend to be associated with warmer than average temperatures. More frequent and/or intense cyclonic activity could increase warm air advection to the continent and possibly suppress sea ice extension. Parkinson (1990) examined sea ice limits using ship reports from early exploratory voyages to the Antarctic. The records, which are admittedly scanty and temporally discontinuous, showed no definitive evidence of sea ice extension. An increase in Cl^- and SO_4^{2-} concentrations could reflect an enhanced oceanic contribution as might be expected with reduced sea ice extent. However, from A.D. 1600 to 1830, the interval of greater warmth (least negative $\delta^{18}O$) the Cl^- and SO_4^{2-} concentrations in the Siple core are not elevated above the 480-year average. Figure 29.9 illustrates the 10-year averages of net accumulation for the 580-year record. The annual layers were converted to water equivalent using the measured depth-density relationship and were corrected for thinning with depth using a simple steady state model discussed by Bolzan (1984). A.D. 1600-1830 was not characterized by increased net balance although shorter intervals (several decades) of increase and decrease are evident.

29.5 Conclusions

The opposition in the Siple-South Pole $\delta^{18}O$ and dust records during much of the last five centuries may reflect an increase in the persistence of atmospheric and oceanic conditions which are responsible for the temperature opposition observed in the instrumental records. Rogers (1983) demonstrated a statistically significant relationship between intensification of the zonal westerlies, cooling at South Pole, and warming in the Peninsula region. It is unknown whether the intensification of the westerlies leads to cooling over the high polar plateau or vice versa.

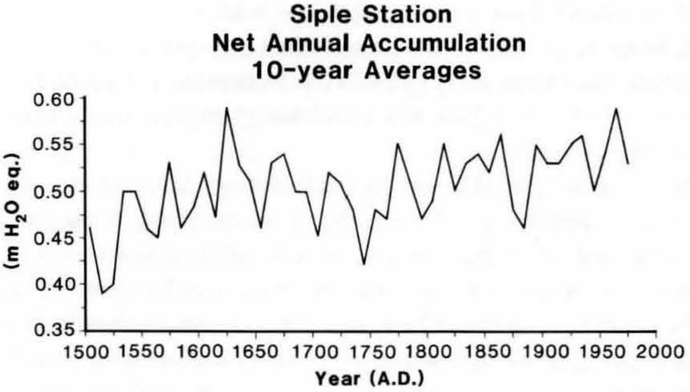

Figure 29.9 The 10-year unweighted averages of annual layer thicknesses for Siple are based upon the $\delta^{18}O$ time scale and converted to water equivalent. The thicknesses, which have been adjusted for thinning with depth, do not reveal major changes in net accumulation over the 480 year record.

The dissimilar dust concentrations probably reflect two different transport pathways from lower latitudes where the South American Altiplano and the South African Desert are the principal sources of dust. Observations at South Pole (Hogan *et al.* 1984) indicate the terrestrial (Al and Si) component of the aerosol mass is associated with an upper tropospheric or lower stratospheric source layer. Intensified westerlies at lower latitudes could entrain more material higher into the atmosphere and thus, increase the source of dust for the South Pole.

No similar aerosol studies have been conducted at Siple (accumulation rate $0.56 m^{-1}$ H_2O eq.) where frequent and severe storms dominate throughout the year. However, it is more likely that particulates deposited at Siple have a lower tropospheric pathway associated with the passing cyclonic systems. Precipitation is an excellent mechanism for removal of entrained dust and thus lower tropospheric air reaching this region should be very clean (Hogan 1975). The microparticle analyses support this (Mosley-Thompson *et al.* 1990). If increased cyclonic activity along the periphery of the continent accompanied the postulated stronger westerlies, then the lower atmosphere should be cleansed further, leading to the low concentrations characterizing A.D. 1630 to 1880 (Figure 29.8). If this postulated increase in cyclonic activity resulted in more frequent storms at Siple, and hence increased net balance, the decrease in particulates could actually be accompanied by a net accumulation increase. However, as Figure 29.9 illustrates, the 480-year net accumulation record does not show an increase between A.D. 1650 and 1890, the interval of lowest dust deposition.

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 warrants further investigation beyond the scope of this paper.

The 480-year records of δ^{18}O and dust concentrations from Siple 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 δ^{18}O data from South Pole, supported by the δ^{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.

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 temperatures. 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. The physical processes controlling these spatial relationships must identified and better understood; however, the observational data base necessary for this assessment is currently 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.

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