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Reconstructing interannual climate variability from tropical and subtropical ice-core records

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Abstract

The patterns and sources of interannual, decadal, and century-scale climatic and environmental variability are of greatest relevance to human activities. Ice-core records from tropical and subtropical ice caps provide unique information about the chemical and physical character of the atmosphere. Annual variations in the amount and chemical composition of precipitation accumulating on these ice caps produce annual laminations which allow precise dating of these stratigraphic sequences. The thickness of an annual lamination reflects the net accumulation, while the physical and chemical constituents (e.g., dust, isotopes, ions) record local atmospheric conditions during deposition. In this chapter interannual climate variability is reconstructed from ice cores on the tropical Quelccaya ice cap, Peru, and the subtropical Dunde ice cap, China.

Except for the annual cycle, the El Niño/Southern Oscillation (ENSO) is the dominant signal in the global climate system on time scales of months to several years. Associated with major dislocations of rainfall regimes in the tropics and subtropics, ENSO events leave signatures in the physical and chemical character of the annually accumulated layers. Variations in annual layer thicknesses, microparticle concentrations, conductivities, and oxygen isotopic ratios are examined for the last 150 yr when limited documentary data exist for evaluation and calibration. When the 1500-yr Quelccaya net balance record is integrated with archaeological evidence, it appears that oceanic/atmospheric linkages which produce ENSO-like precipitation responses may dominate for longer periods. A comparison of decadally averaged net balance on Quelccaya with that on the Dunde ice cap, from A.D. 1600 to 1980 indicates the existence of

low-frequency teleconnections across the Pacific Basin through the Walker Circulation.

Introduction

This chapter evaluates the history of interannual climatic and environmental variability in the southern Andes of Peru as recorded in the Quelccaya ice cap. Interannual variability is a major feature of the global climate system. Since human activities may be inadvertently altering the mean state of the climate system, it is essential to determine whether interannual variability is closely linked to changes in the mean state. Urgency arises from the likelihood that human activities are more sensitive to interannual variability than to the slower changes in the system's mean state.

Characterizing the relationship between interannual variability and changes in the longer-term mean requires long records of climatic variability which encompass times when the climate was different from today (e.g., Little Ice Age, Medieval Warm Period, Last Glacial Stage). Ice-core data provide a multifaceted record of past variations in the Earth's climate and environment. Seasonal variations in precipitation amount and chemical composition produce laminations in both polar and alpine (high elevation) glaciers. Such seasonal variations allow these stratigraphic sequences to be dated precisely (Thompson et al. 1984a), a prerequisite for discerning the interannual character of the record.

This chapter examines the interannual climate variability preserved in ice core records from the Quelccaya ice cap (13°56′S, 70°50′W) (Fig. 16.1) located in the southern Andes of Peru. Here two ice cores, one 154.8-m core (henceforth summit core) containing a record of 1350 yr and a 163.6-m core (henceforth core 1) containing a record of 1500 yr, were recovered in 1983. These records are examined over two time intervals. The first focuses upon the last 150 yr when limited documentary data exist for evaluation and calibration of the record. The second interval is the last 1500 yr for which independent evaluation of the record is very limited. Finally, the decadally averaged net accumulation record from Quelccaya is compared with that from the subtropical Dunde ice cap, China. For two such widely separated regions there is a remarkable similarity in the net accumulation trends over the last 400 yr, although Dunde appears to lag Quelccaya by several decades.

Recent variations: A.D. 1850 to 1984

The Quelccaya ice cap record

Figure 16.2 presents the annual averages of microparticle concentrations (MPC), liquid conductivities (LC), net accumulation (A_n), and oxygen isotopic ratios ($\delta^{18}O$) from A.D. 1850 to 1984. Both LC and MPC (Fig. 16.2) clearly show that elevated concentrations of both soluble and insoluble material characterized the

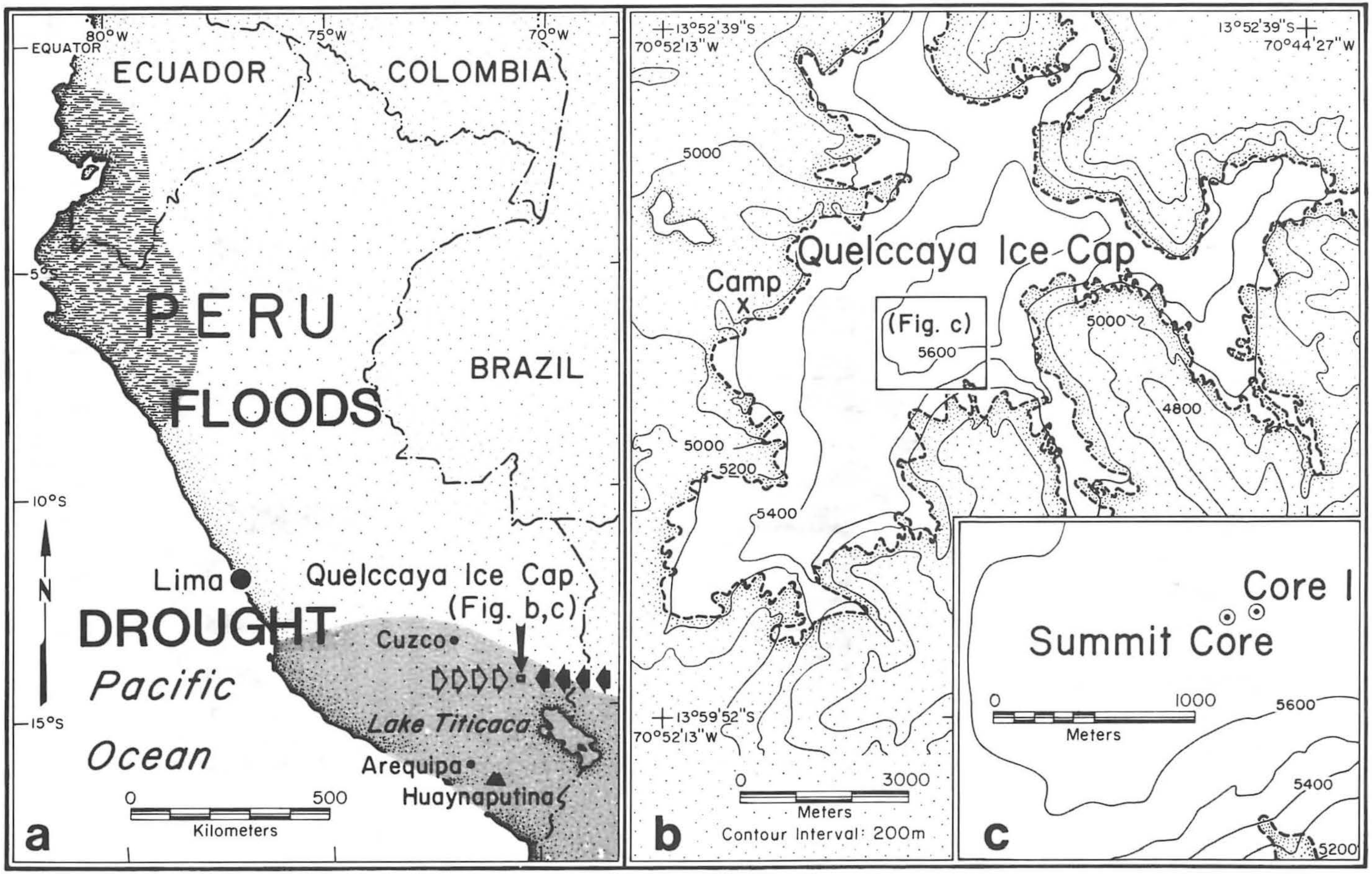


Fig. 16.1 The location of (a) the Quelccaya ice cap relative to precipitation patterns associated with the 1982–83 ENSO event; (b) the topography of ice cap, and (c) the locations of two deep cores drilled in 1983. Droughts occur in the south of Peru while floods occur in the north. The prevailing winds over Quelccaya during the southern hemisphere summer are from the east (shown by the solid arrows) and in the southern hemisphere winter are from the west (shown by open arrows).

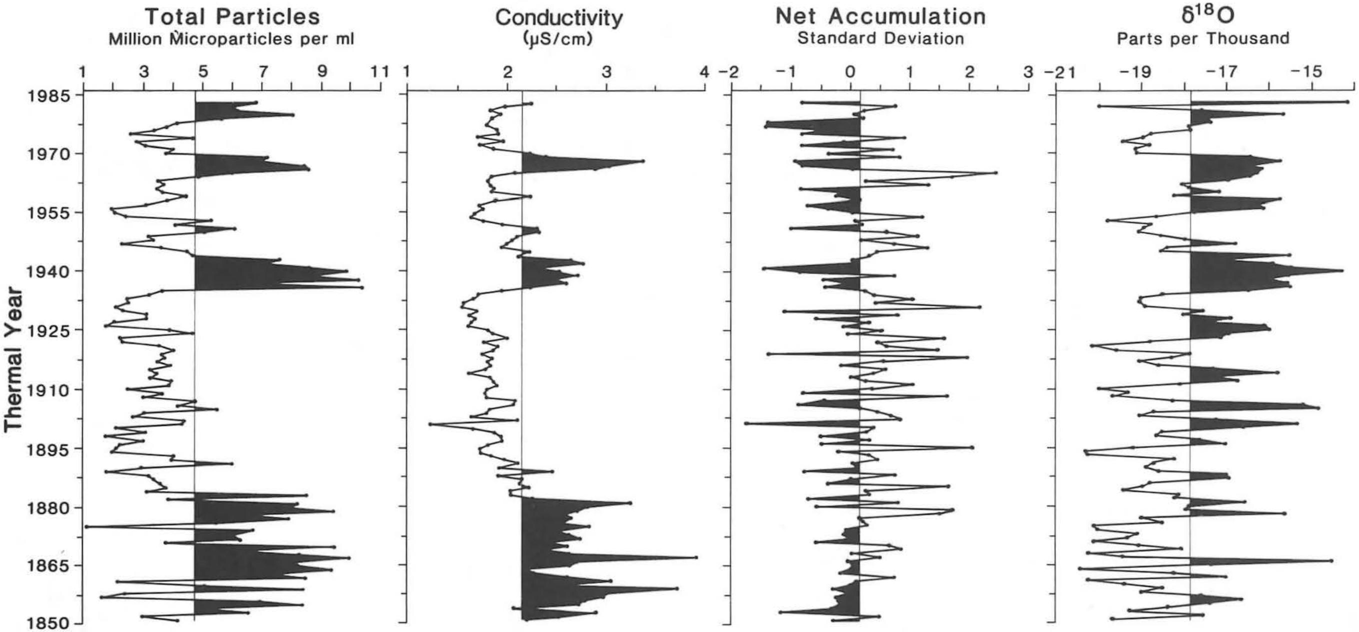


Fig. 16.2 Annual (July–June) averages for particulate concentrations, liquid conductivities, net accumulation and oxygen isotopic ratios from A.D. 1850 to 1984 on the Quelccaya ice cap, Peru. The average (solid line) for that period is included for each parameter.

end of the Little Ice Age (LIA) (Thompson et al. 1986). Most notable is the abrupt concentration decrease from 1882 to 1884 (Thompson and Mosley-Thompson 1987). From 1884 to 1935 the average concentrations of both insoluble dust and soluble materials are below their 1850–1984 averages with the exception of a minor peak in 1891. Greatly elevated concentrations of soluble and insoluble particulates occur from 1935 to 1945, synchronous with the most severe drought recorded in southern Peru prior to 1950 (Newell 1949). Since 1950 there have been four periods of elevated dust concentrations (1951–1954, 1959–1960 [minor], 1965–1970, 1980–1984) with low concentrations during intervening times. Note that from 1980 to 1984 insoluble particles were more highly concentrated than soluble material.

The oxygen isotopic ratios ($\delta^{18}O$) (Fig. 16.2) exhibit a higher frequency of variation than the particulate concentrations. Over much of this period (A.D. 1880–1984) the variability appears somewhat quasi-periodic with an average periodicity of ~ 12 yr. From A.D. 1880 to 1940 the mean $\delta^{18}O$ values gradually increase to a maximum (least negative) in the early 1940s. From the 1940s to late 1970s there has been a gradual decrease (more negative) in the mean $\delta^{18}O$ values, consistent with the northern hemispheric temperature cooling trend from the 1940s to the mid-1970s. These trends are most evident when the annual data are averaged decadally (see Thompson et al. 1986). There is also a gradual change in the frequency and amplitude of $\delta^{18}O$. Prior to A.D. 1882 more negative (depleted in $\delta^{18}O$) values occurred more frequently and with a shorter periodicity. During this interval (1850–1880) there were more years with $\delta^{18}O$ around $-20‰$ and decadal averages prior to 1880 were consistently lower.

It has been shown previously (Thompson et al. 1986; Thompson and Mosley-Thompson 1989; Thompson 1992) that more negative oxygen isotopic values characterized the entire LIA period from A.D. 1530 to 1880. Thompson et al. (1986) demonstrated that decadally averaged $\delta^{18}O$ values closely reflect the Northern Hemisphere decadally averaged temperatures (Landsberg 1985) from A.D. 1580 to 1980. Thus, less negative $\delta^{18}O$ values appear to represent warmer temperatures while the more negative oxygen isotopic values represent cooler temperatures. However, the reader is reminded that on an annual basis $\delta^{18}O$ may be altered by other factors such as (1) variations in the ^{18}O depletion as water vapor is transported over the Amazon Basin and the air masses rise up the Andes; (2) seasonal and annual variations in snow intensity; and (3) seasonal changes in sublimation of snow on the ice cap surface (Grootes et al. 1989). The longer records (centuries) of $\delta^{18}O$, MPC, and LC reveal that periods of less negative $\delta^{18}O$ values such as during the 1935 to 1945 drought, are consistently correlated with increased concentrations of both insoluble and soluble particulates.

The net accumulation record (Fig. 16.2) reveals a marked increase in the annual variability of both amplitude and frequency beginning abruptly in 1878. In fact, reduced variability and small amplitudes in A_n are characteristic only of the transitional period near the end of the LIA (1850–1878). These striking differences in the frequency and/or amplitude of all four environmental parameters are thought to directly reflect concomitant changes in the circulation regime from the LIA period to the post-LIA period (Thompson et al. 1986). The net accumulation record (A_n) shows a general increasing trend from lower values more characteristic of the latter half of the LIA (A.D. 1720 to 1860). This increasing trend in A_n peaked in the 1930s and has decreased since (Thompson et al. 1985). The interpretation of A_n from 1967 to present must be made cautiously as these values are derived from layers above the firn/ice transition where density determinations are less reliable. The relationship between the ice core A_n record and the observational record is discussed further in the next section.

Complementary observational and historical records

Past observations of the elevation, spatial distribution, and type of cultivation in southern Peru provide a qualitative measure of the prevailing environmental conditions. Many historical records reveal the elevation limits of cultivation at different times during the past few centuries and document the changes in climatic conditions in the high Andes of Peru. Cardich (1985) reports several such observations.

Of particular note for the time span under discussion are the observations made by a German-Swiss naturalist, J.J. von Tschudi, during his travels in Peru from 1838 to 1842. While ascending the narrow Rimac Valley, about two leagues (~ 10 km) above San Mateo, von Tschudi came to the village of Chicla at 3750 m elevation where he recorded: 'Here, barley is grown in a few protected ravines, but it does not mature and is cut green for forage. This is the last place in the valley where the soil is cultivated' (von Tschudi 1847, in Nuñez 1973, p.50). Cardich (1985) reports that he has visited Chicla twice to observe present conditions. He notes: 'The village remains the same, although the trail that passed through it in von Tschudi's time has become a principal road to the highlands. Today, however, in contrast to 150 years ago, potatoes and other hardy cultigens grow on the slopes extending well above the village. More sensitive grains also mature, including barley, habas, and even wheat, whose thermal requirements are higher. The limit of cultivation in the valley has also been displaced upward several kilometers and is now between Bellavista and Casapalca, where the altitude is 4000 m. This represents an increase of more than 200 m in the elevation at which crops can be grown successfully.'

These historical observations are consistent with and support the inferences drawn from the Quelccaya ice-core records; specifically, that climatic conditions prior to 1880 were characterized by cooler temperatures (more negative $\delta^{18}O$), drought conditions (lower A_n), and increased atmospheric dustiness. Undoubtedly both colder temperatures and reduced precipitation would have contributed to the observation of poor crops and a lower elevation limit of cultivation in the Peruvian highlands at this time. However, since roughly 1880 the ice-core data suggest milder temperatures and increased precipitation which

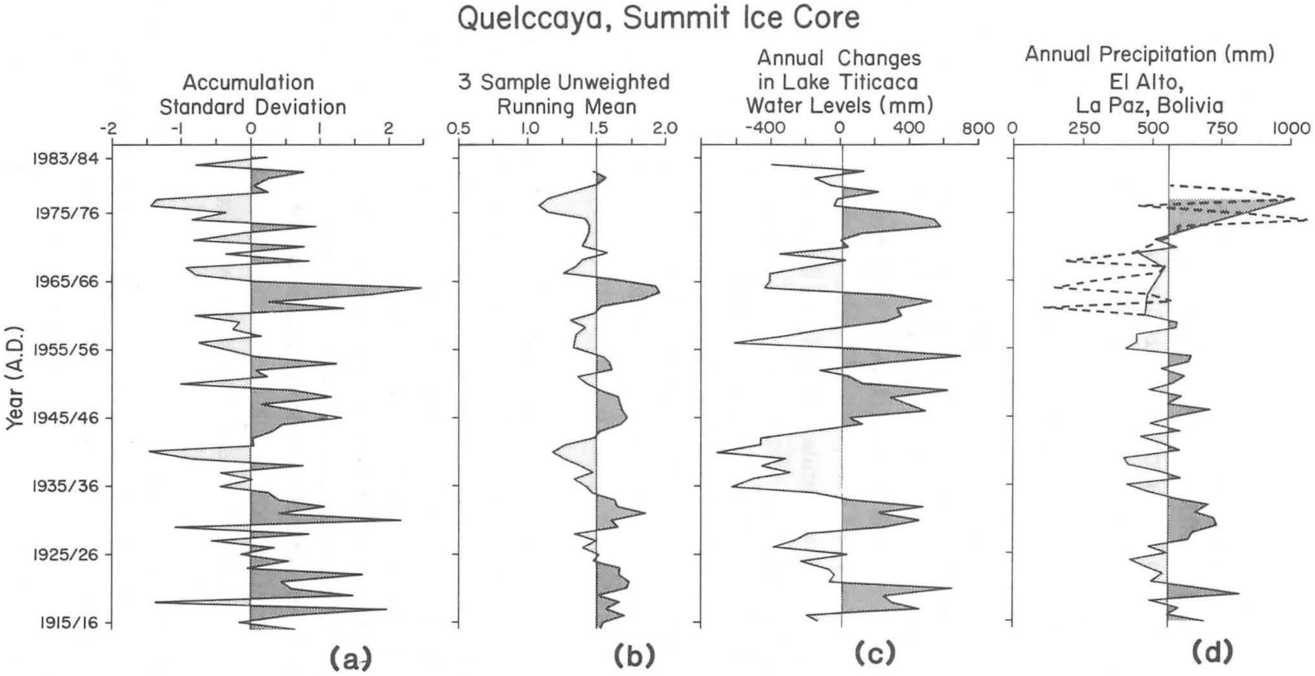


Fig. 16.3 The records from 1915 to 1984 for (a) standardized net annual accumulation (A_n) on the Quelccaya ice cap and (b) the three-sample running mean of A_n are compared with (c) annual changes in Lake Titicaca water levels (mm) and (d) annual precipitation (mm) at El Alto, La Paz, Bolivia. The dashed line indicates years with incomplete precipitation records.

again are consistent with Cardich's recent observations of more diverse crops and higher cultivation limits.

Further evidence supports the reliability of the A_n record as a proxy for paleoenvironmental conditions on the Altiplano of southern Peru. Lake Titicaca, the world's highest freshwater lake (3812 m a.s.l.), covers an area of 8446 km^2 and is located 300 km south of Quelccaya. Streams originating on the north side of the ice-cap flow into the Amazon, while streams originating on the south side flow into Lake Titicaca. Water level in Lake Titicaca has been monitored since 1914, and its fluctuations should be consistent with changes in the net accumulation on the Quelccaya ice cap, if indeed the ice cap is recording regional precipitation variations.

The Quelccaya A_n record for 1915 to 1984 (Fig. 16.3a,b) has been compared with the annual changes in Lake Titicaca water levels (mm) (Fig. 16.3c) and the annual precipitation (mm) at El Alto, La Paz, Bolivia (Fig. 16.3d). The greatest drought of this century, 1935 to 1945 (Newell 1949), is associated with a 5-m drop in the mean water level in Lake Titicaca. Similarly, at this time the Quelccaya ice cap recorded very low accumulation, elevated dust concentrations (both soluble and insoluble), and less negative $\delta^{18}O$ (Fig. 16.2). Prior to 1970 major increases in Lake Titicaca water levels were associated with above average net accumulation on Quelccaya. Since 1970 the relationship appears to have reversed for some unknown reason. In general decreases in A_n, coupled with increases in particulate concentrations (soluble and insoluble), may, however, provide reasonable proxies with which to reconstruct major drought events from the longer ice core records.

From 1915 to 1961 (data sets are complete) the coefficient of determination (R^2) between the three-sample running mean of A_n (Fig. 16.3b) and changes in Lake Titicaca water level is 0.304, very close to the R^2 (0.325) between annual precipitation at La Paz, Bolivia, and changes in Lake Titicaca water levels (Thompson et al. 1988). Table 16.1 demonstrates that the three-sample running mean of A_n on Quelccaya is most strongly correlated ($R^2 = 0.324$) with annual changes in Lake Titicaca water levels in the subsequent year (T + 1). This probably reflects the time lag between precipitation on the ice cap and runoff into Lake Titicaca. As expected, the annual precipitation (mm) at El Alto near La Paz is equally well correlated with the annual changes in Lake Titicaca water levels in the current year (T).

The relatively low R^2, even for the best correlations, between changes in annual water levels in Lake Titicaca and the measured precipitation at La Paz and A_n on Quelccaya arises because lake level is dependent also upon other factors such as evaporation, surface discharge, and groundwater flow into and out of the lake (Street-Perrott and Harrison 1985). Nevertheless, these results suggest that for the period of comparison (1915–1961) the A_n record from Quelccaya provides a reasonable estimate of regional precipitation and is comparable in quality to instrumental observations (La Paz) in the region. Thus, the longer A_n

Table 16.1 *Coefficients of determination (R^2) for the 1915 to 1961 records of: Quelccaya net accumulation (annual and three-year running mean), changes in water levels in Lake Titicaca, and measured precipitation at El Alto, Bolivia.*

	Bal Dev	Lake T	Lake T(+1)	Lake (T + 2)	El Alto	Bal 3 s.r.m.
Bal Dev	1.000	0.160	0.138	0.014	0.116	0.172
Lake T	0.160	1.000	–	–	0.325	0.302
Lake T(+1)	0.138	–	1.000	–	0.235	0.324
Lake T (+2)	0.014	–	–	1.000	0.22	0.230
El Alto	0.116	0.325	0.235	0.22	1.000	0.124
Bal 3 s.r.m	0.172	0.302	0.324	0.23	0.124	1.000

Bal Dev, Net accumulation (standard deviation);
Lake T, Annual changes in Lake Titicaca water levels (mm);
Lake T(+1), Lake Titicaca record (1 year lag);
Lake T(+2), Lake Titicaca record (2 year lag);
El Alto, Annual precipitation (mm) El Alto, La Paz, Bolivia;
Bal 3 s.r.m., Three sample, unweighted running mean of Quelccaya net accumulation (m ice equivalent).

records from Quelccaya should provide unique and otherwise unavailable information about the hydrological history in this region of southern Peru.

El Niño/Southern Oscillation events

Except for the annual cycle, El Niño/Southern Oscillation (ENSO) is the dominant signal in the global climate system on time scales of a few months to a few years. It is associated with major dislocations of rainfall regimes in the tropics during which the northern coastal desert regions of Peru and Ecuador experience abnormally high precipitation and the southern highlands of Peru and northern Bolivia experience drought (Fig. 16.1). Quelccaya, situated in southern Peru, experienced a major drought associated during the 1982/83 El Niño. This is apparent in Figure 16.4 which contrasts the ice cap margin in 1978 (a non-ENSO year) with the margin at the same location during the 1983 ENSO. In this section a preliminary evaluation is made of the potential record of ENSO events as recorded in the Quelccaya ice cap by concomitant changes in microparticle concentrations, liquid conductivity levels, oxygen isotopic ratios, and net accumulation over the period where the most complete instrumental and historical documentation exist.

Annual pit studies from 1975 to 1984 on Quelccaya demonstrate that the two major ENSO events which occurred during this time were associated with substantially reduced net accumulation (Fig. 16.5). The annual variations in the

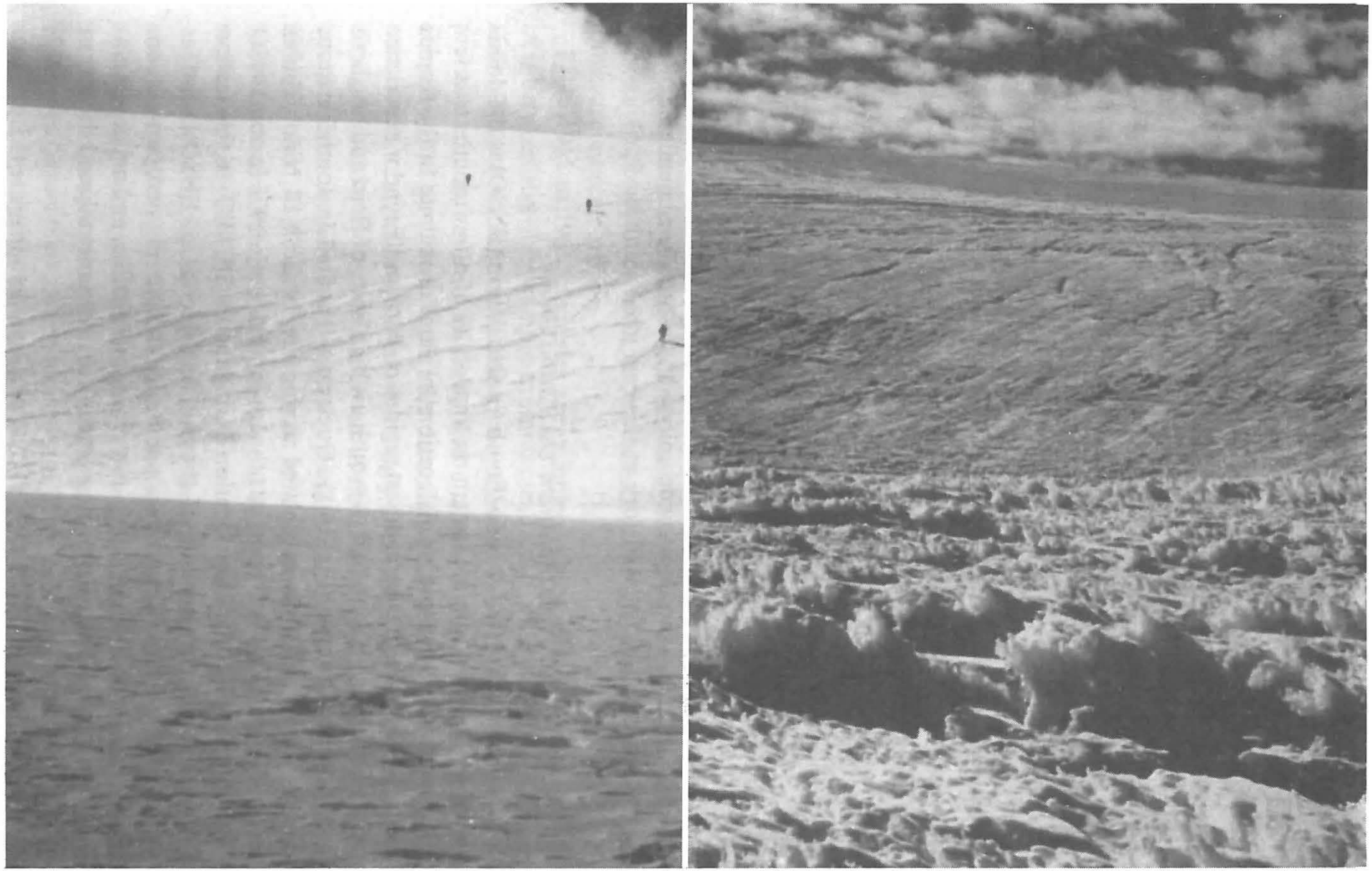


Fig. 16.4 The impact of the 1983 El Niño on the margin of Quelccaya ice cap. The left photograph was taken in a "normal" year (July 1978) while the photograph on the right, which was taken in July 1983, clearly shows the effect of widespread melting.

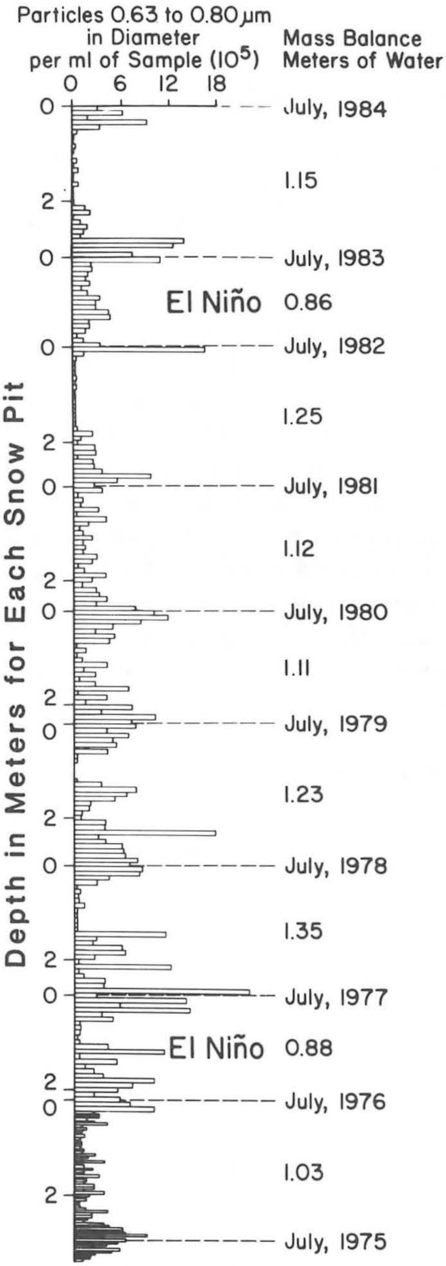


Fig. 16.5 Particle concentrations (0.63 μm $\leqslant$ diameter $\leqslant$ 0.80 μm) and net annual accumulation were determined from successive pits excavated each year from 1976 to 1984 on the Quelccaya ice cap. The El Niño years of 1976–77 and 1982–83 exhibit marked reductions in net mass accumulation.

particulate concentrations (0.63 μm ≤ diameter ≤ 0.80 μm) are evident with the greatest concentrations associated with the dry season from May to August each year. The dashed line (Fig. 16.5) represents the July snow surface, and thus, the separation between consecutive July surfaces reflects net accumulation between consecutive thermal years (July to subsequent June). Snow layer thicknesses are converted to water equivalent thicknesses using the vertical density profile. Figure 16.5 reveals that the El Niño years of 1976–77 and 1982–83 exhibit marked reductions in net accumulation.

To assess the utility of the Quelccaya record for extracting a longer ENSO chronology, the character of the more recent accumulation can be compared with both observational and historical data. Figure 16.6 illustrates the annual records of the Southern Oscillation index (SOI), sea surface temperatures (SST), and the historical record of major, moderate and minor El Niño phases (Quinn et al. 1987). The 1982–83 El Niño is recorded on Quelccaya by increased particulate deposition, elevated conductivity levels (more soluble material), less negative $\delta^{18}O$, and substantially reduced net accumulation. Figure 16.6 clearly shows that many (although not all) of the historical El Niño phases are associated with less negative $\delta^{18}O$, increased concentrations of dust (soluble and insoluble), and reduced net accumulation. The relationship among the ice-core parameters and the ENSO indicators (SOI and SST) has been explored statistically in an initial effort to develop a transfer function which might be applied to the older part

Table 16.2 *Autocorrelations and cross correlations Thermal Years: A.D. 1936–1983*

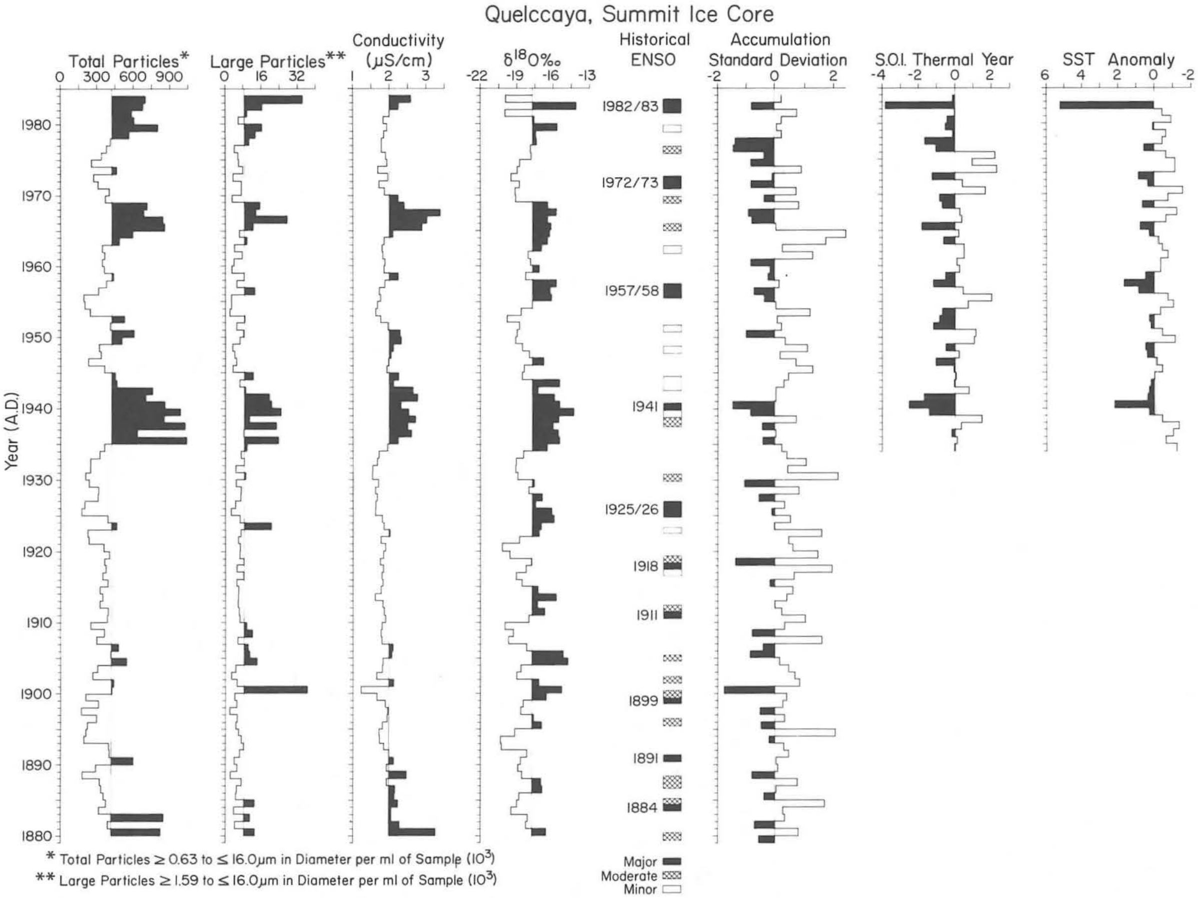
a. Correlation of T_t and:

k	T_{t+k}	I_{t+k}	D_{t+k}	A_{t+k}	C_{t+k}	P_{t+k}
0	1.00	−0.73	0.36	−0.18	0.03	0.11
1	0.10	0.02	0.03	0.03	−0.02	0.06
2	−0.22	0.18	0.08	0.01	−0.04	0.01
3	−0.06	−0.02	0.17	0.04	−0.05	0.22
4	−0.06	0.02	0.08	0.16	−0.04	0.08
5	−0.09	0.09	0.08	−0.26	−0.06	0.09

b. Correlation of I_t and:

k	I_{t+k}	T_{t+k}	D_{t+k}	A_{t+k}	C_{t+k}	P_{t+k}
0	1.00	−0.73	−0.32	0.20	−0.14	−0.23
1	0.14	−0.22	−0.18	0.03	−0.06	−0.30
2	−0.18	0.24	−0.19	0.07	−0.16	−0.22
3	−0.15	0.15	−0.20	0.03	−0.06	−0.18
4	−0.06	0.08	−0.13	−0.17	0.01	−0.18
5	0.18	−0.00	−0.11	0.19	0.11	0.07

The following symbols are used above:
T, sea surface temperature (SST); I, Southern Oscillation index (SOI); D, oxygen isotope ratio ($\delta^{18}O$); A, annual accumulation (A_n); C, liquid conductivity (LC); P, concentration of large particles; t, thermal year; k, lead time in thermal years.



* Total Particles ≥ 0.63 to ≤ 16.0μm in Diameter per ml of Sample (10³)

** Large Particles ≥ 1.59 to ≤ 16.0μm in Diameter per ml of Sample (10³)

Fig. 16.6 Annual (July–June) averages of particulate concentrations, liquid conductivity, δ ^{18}O, and net accumulation from 1880 to 1984 are compared with two common ENSO indicators: the Southern Oscillation Index (SOI) and the sea surface temperature (SST) anomalies from Puerto Chicama, Peru (Quinn et al. 1987). Note SST increases toward the bottom.

of the ice-core record in order to extract a longer ENSO history (Thompson et al. 1987).

Autocorrelations and cross correlations between the ice core parameters, SST, and SOI are given in Table 16.2 (a, b) for lead times ranging from 0 to 5 yr. In general, SOI is more strongly correlated with the ice-core variables than SST; however, the strongest single correlation ($R = 0.36$) is between SST and $\delta^{18}O$. This is logical as the ocean surface waters are ultimately the source of the moisture for the accumulating snowfall. As might be expected, there are strong correlations between SST and SOI ($R = -0.73$), conductivity levels and particle concentrations ($R = 0.69$), particle concentrations and $\delta^{18}O$ ($R = 0.56$), and conductivity levels and $\delta^{18}O$ ($R = 0.44$). All correlations were for 1936 to 1983 during which all six parameters were available. A correlation coefficient (R) of at least ± 0.29 is required to consider the relationship as statistically different from zero at a 5% significance level.

In situ observations on the Quelccaya ice cap during both the 1976 and 1982–83 El Niño events reveal a marked change in the general climatic patterns. For example, net accumulation was substantially reduced (Fig. 16.5) and net radiation receipt increased (Thompson et al. 1984b). Figure 16.6 suggests that similar climatic conditions probably characterized most of the earlier ENSO events.

The substantial concentration increases in both soluble and insoluble particles per unit volume of water is a direct result of the reduction in net accumulation. Even under conditions of constant particulate flux the reduced net accumulation would concentrate the material. However, it is certain that there was an associated increase in the flux of particles due to the increased dryness on the Altiplano of southern Peru during most of the ENSO events. Increased surface sublimation due to higher radiation receipt would also tend to concentrate the particles, especially during the dry season.

The reduction in net accumulation is the primary mechanism responsible for the less negative mean oxygen isotope values. Under normal conditions 80% of the snow falls on the ice cap during the wet season, when $\delta^{18}O$ values are most negative. In addition, increased sublimation due to longer periods of surface exposure to radiation between snowfalls leads to an enrichment of ^{18}O in the surface snow, producing annual mean $\delta^{18}O$ values which are less negative (Grootes et al. 1989). Thus, the physical mechanisms by which ENSO events are recorded in the Quelccaya ice cap are very clear. Unfortunately, other climatic processes, such as the 1935 to 1945 drought, also may produce similar variations in the ice-core parameters and hence complicate the detection of the short term ENSO events from the record at a single site.

Longer-term variability: A.D. 450 to 1984

El Niño/Southern Oscillation events

One of the records potentially available in ice cores taken from tropical and subtropical glaciers is a long-term record of El Niño/Southern Oscillation (ENSO) phases in the equatorial Pacific (Thompson et al. 1984b). Instrumental records of ENSO phases rarely extend more than 100 yr in length. Quinn et al. (1987) used historical documentation to extend the El Niño record back to the arrival of the Spanish in South America. These historical records are based largely on evidence obtained along the west coast of northern South America and from the adjacent Pacific Ocean waters. Unfortunately, the record is much less reliable prior to 1800. In addition, the effects of El Niño phases are not uniform as demonstrated by the large 1982–83 El Niño in which storms moved down the entire coastal area of Peru although the intensity and magnitude of the flooding was not uniform. This is consistent with the large spatial variability in El Niño frequency and intensity reported by Waylen and Caviedes (1986). Studies have shown that El Niño events are oscillatory, but not truly periodic (Wright 1977; Quinn et al. 1978, 1987; Hamilton and Garcia 1986; Quinn and Neal 1992). The ice-core records suggest that ENSO phases fluctuate substantially in both frequency and intensity. The recent major ENSO event (1982–83) focused attention upon this phenomenon and once again spurred a great effort to determine its predictability (Rasmusson and Carpenter 1982; Cane 1983; Rasmusson and Wallace 1983; Cane and Zebiak 1985; Kiladis and Diaz 1986; Yarnal and Diaz 1986). Bradley et al. (1987) demonstrated that the global characteristics of both warm and cold phases of ENSO affect both temperature and precipitation in the Northern Hemisphere.

The Quelccaya records may be compared with the historical El Niño reconstruction by Quinn et al. (1978, 1987) for the period A.D. 1450 to 1984. Figures 16.7 and 16.8 illustrate changes in the concentrations of insoluble (left) and soluble (right) particulates along with occurrences of major, moderate and minor El Niño events. Figures 16.9 and 16.10 illustrate the changes in $\delta^{18}O$ (left) and net annual accumulation (right) along with occurrences of major, moderate and minor El Niño events. As in the 20th century (Fig. 16.6), El Niño events were generally associated with reduced accumulation, higher concentrations in the insoluble and soluble dust, and less negative $\delta^{18}O$. However, as in the 20th century, similar variations may be produced by non-ENSO related events. Thus, reconstructing the ENSO history will require complementary records from more than one Peruvian ice cap. Most preferable is to extract a very high resolution history from several appropriate ice caps situated in northern Peru where the response to major ENSO phases should be in opposition to that on the Quelccaya ice cap. A number of potential ice caps and glaciers may exist in the Cordillera Blanca (Fig. 16.11).

Linkages with archaeological records

The historical record of man's activities in pre-Spanish Peru is limited, and the process of piecing it together is hampered by the lack of written records. Archaeological sites in Peru may be assigned to either coastal or highland cultures (Fig. 16.12). Civilizations in both areas were largely agrarian and both developed in very climatically sensitive regions (Cardich 1985), where they

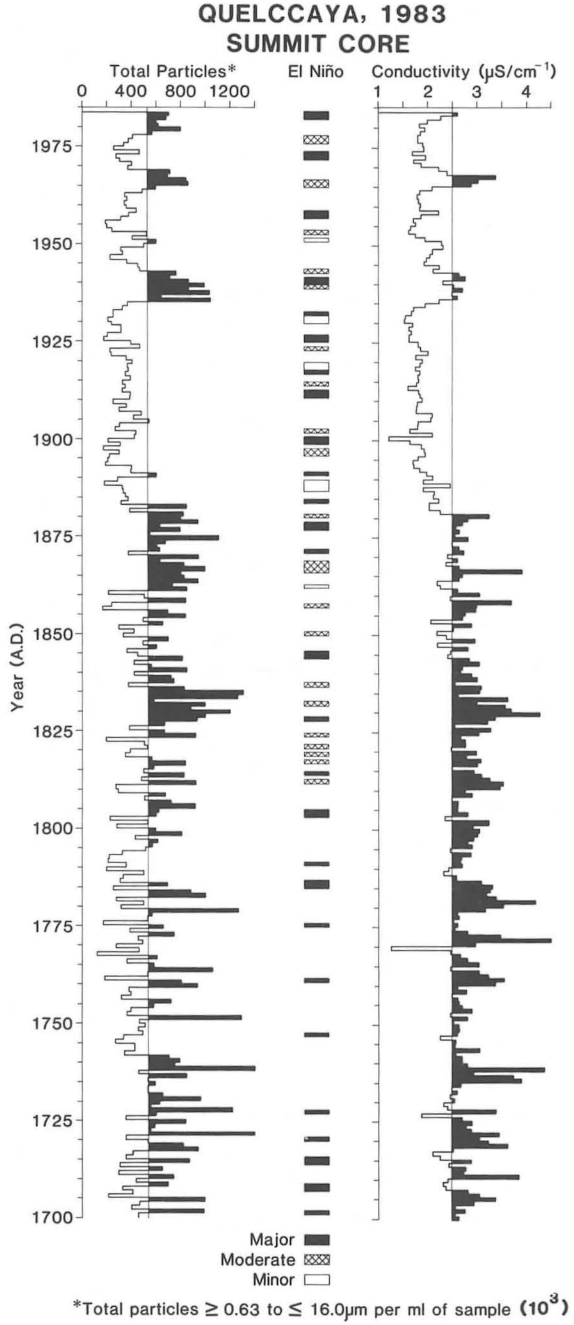


Fig. 16.7 Annual (July–June) averages of particulate concentrations ($0.63\ \mu m \leqslant$ diameter $\leqslant 16.0\ \mu m$) and liquid conductivities from A.D. 1700 to 1984 are illustrated along with the historical record of El Niño occurrences (Quinn et al. 1987).

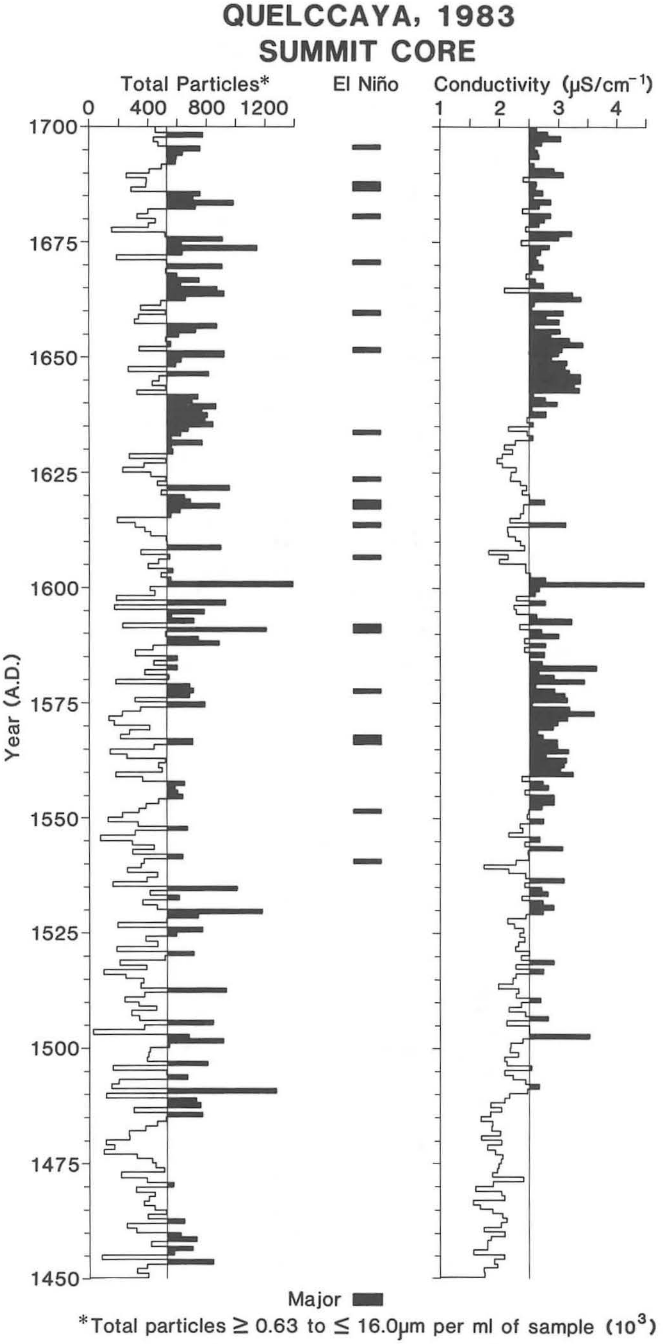


Fig. 16.8 Annual (July-June) averages of particulate concentrations (0.63 μm $\leqslant$ diameter $\leqslant$ 16.0 μm) and liquid conductivities from A.D. 1450 to 1700 are illustrated along with the historical record of El Niño occurrences (Quinn et al. 1987).

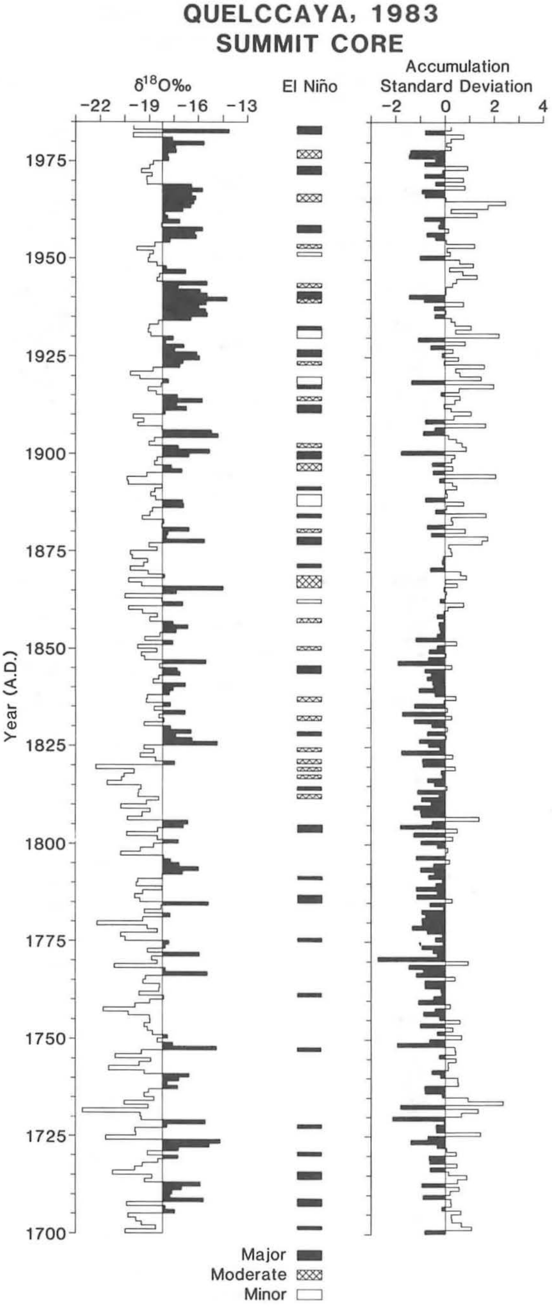


Fig. 16.9 Annual averages of δ^{18}O and standardized net accumulation from A.D. 1700 to 1984 are illustrated along with the historical record of El Niño occurrences (Quinn et al. 1987).

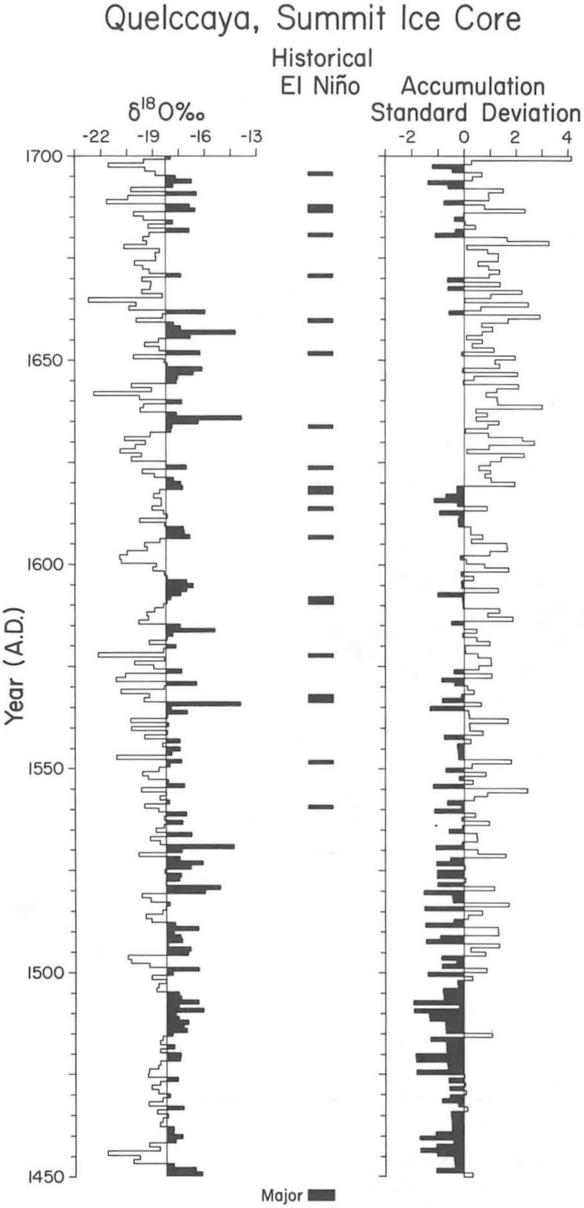


Fig. 16.10 Annual averages of $\delta^{18}O$ and standardized net accumulation from A.D. 1450 to 1700 are illustrated along with the historical record of El Niño occurrences (Quinn et al. 1987).

depended heavily upon water availability. Along the coast agriculture depended upon water from the rivers originating in the Andes. On the Altiplano agriculture extended to the upper limit of both temperature and water availability.

The longer precipitation record for southern Peru derived from the Quelccaya A_n record provides valuable information which can be related to the early

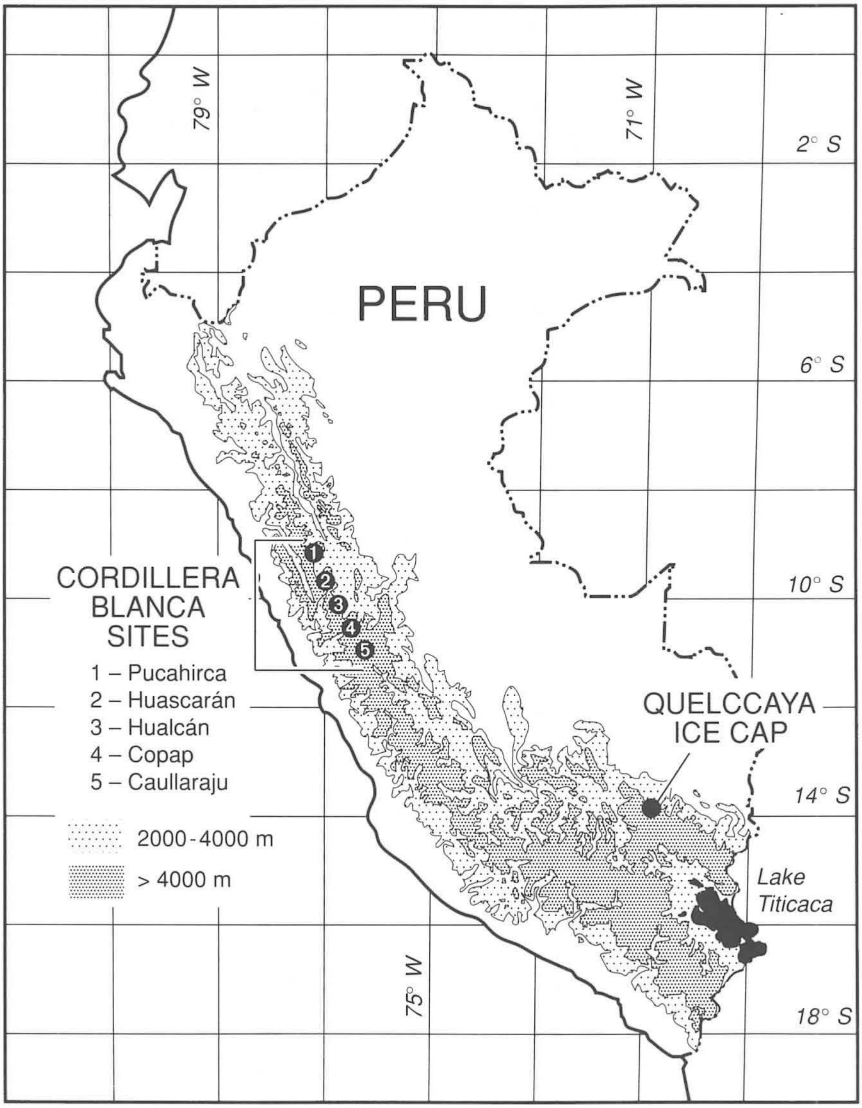


Fig. 16.11 Major archaeological sites in Peru are shown relative to elevation and the Quelccaya ice cap. These sites fall into two main groups, coastal and highland. Potential drill sites for additional ice core records in the Cordillera Blanca are shown.

history of man in this region of South America. Figure 16.12 presents the decadal trends in accumulation from A.D. 470 to 1980. Currently, ENSO events are associated with droughts in the southern Peruvian highlands (Fig. 16.1) and floods in the coastal desert areas of northern and central Peru and southern Ecuador (Thompson et al. 1984b; Lam and Del Carmen 1986). The Quelccaya net balance record for the last 1500 yr has been integrated with archaeological evidence (Shimada et al. 1991). These data strongly suggest that flourishing

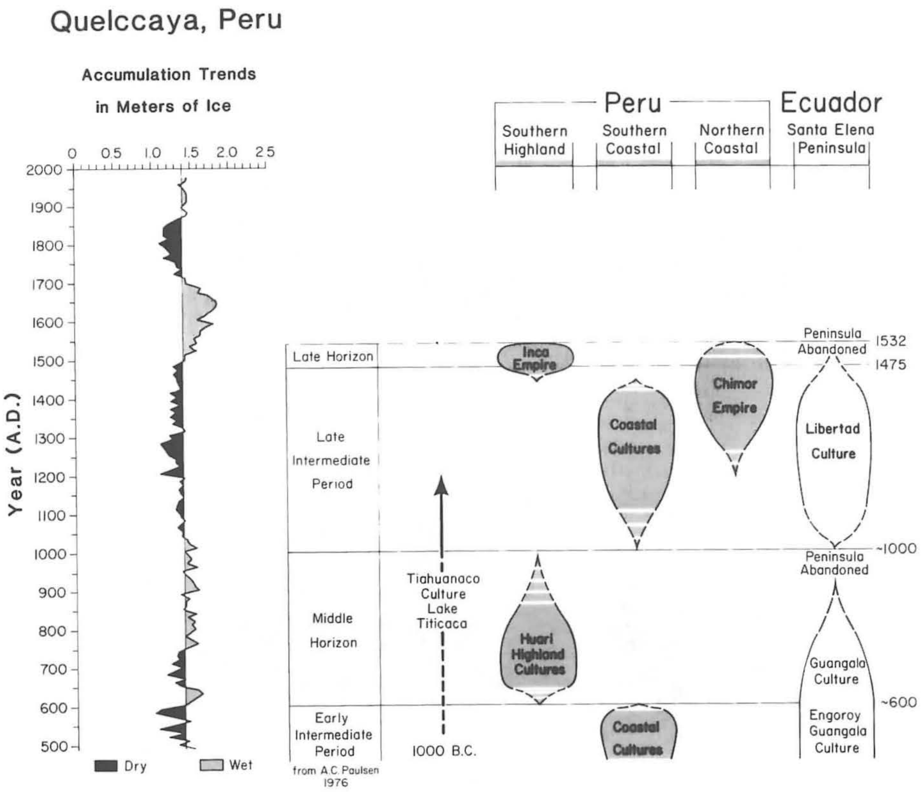


Fig. 16.12 Decadal accumulation (precipitation) trends which are a composite of A_n from core 1 and summit core are shown. Major wet (lighter gray) and dry (darker gray) periods are indicated. On the right, the rise and fall of coastal and highland cultures in Ecuador and Peru (after Paulsen 1976) are shown.

highland cultures appear when moisture conditions in the mountains are above normal and that coastal cultures flourish when the mountains are drier than normal. These data suggest that longer-term ocean/atmosphere linkages similar in character to shorter-term ENSO phases may have persisted over many decades and created conditions similar to those currently associated with brief (1–2 yr) ENSO phases.

Paulsen (1976) reported a similar relationship in the longer-term archaeological records associated with the rise and fall of coastal cultures in Peru and Ecuador. She noted that highland and coastal cultures seemed to flourish out of phase, i.e., highland cultures flourished when coastal cultures declined and vice versa. The cultural record, dated primarily using highly refined ceramic sequences and some ^{14}C measurements, is included in Figure 16.12 for comparison with the net accumulation record from Quelccaya. Assuming that the same seesaw relationship that currently exists during ENSO events (Thompson et al. 1984b) could have persisted over longer time intervals, wetter coastal conditions would be expected during periods of highland drought. The fact that

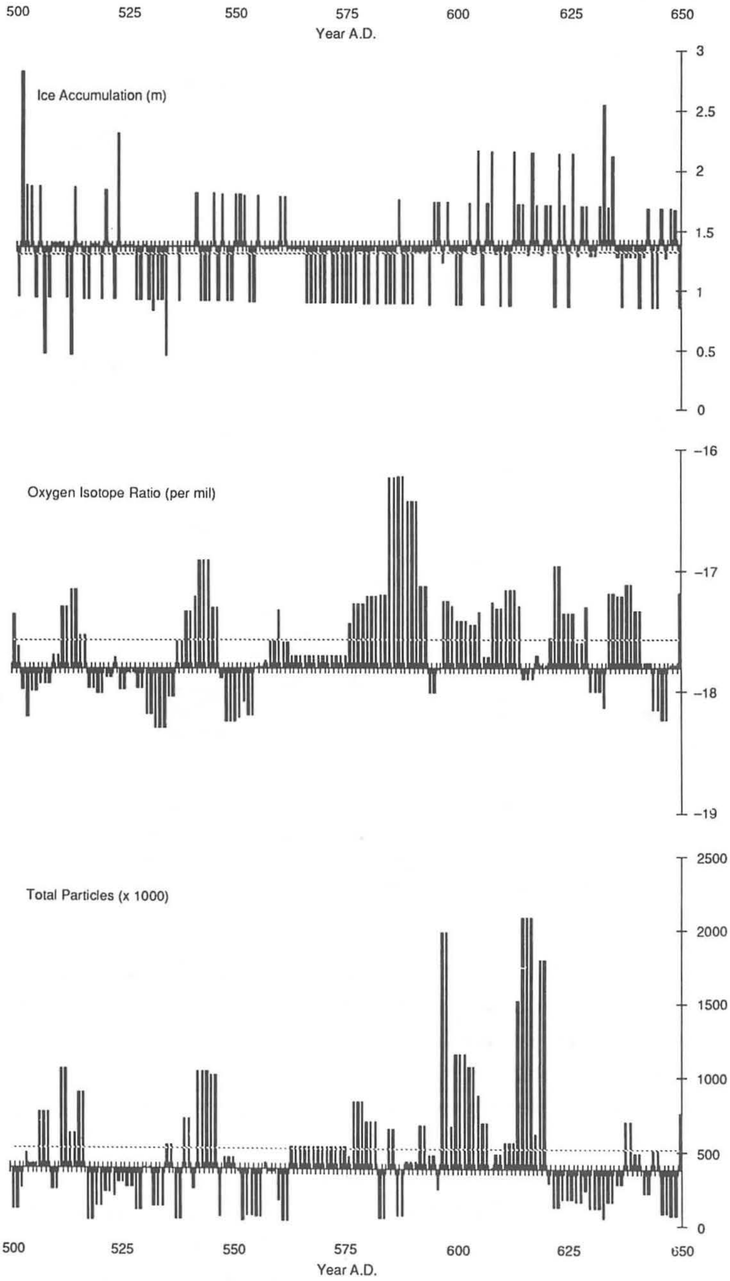


Fig. 16.13 Net annual accumulation, δ^{18}O, and particulate concentrations (0.63 μm $\leqslant$ diameter $\leqslant$ 16.0 μm) are displayed around their respective long-term means (A.D. 500–1984). The dashed lines are their respective short-term (A.D. 500–650) means. (After Shimada et al. 1991.)

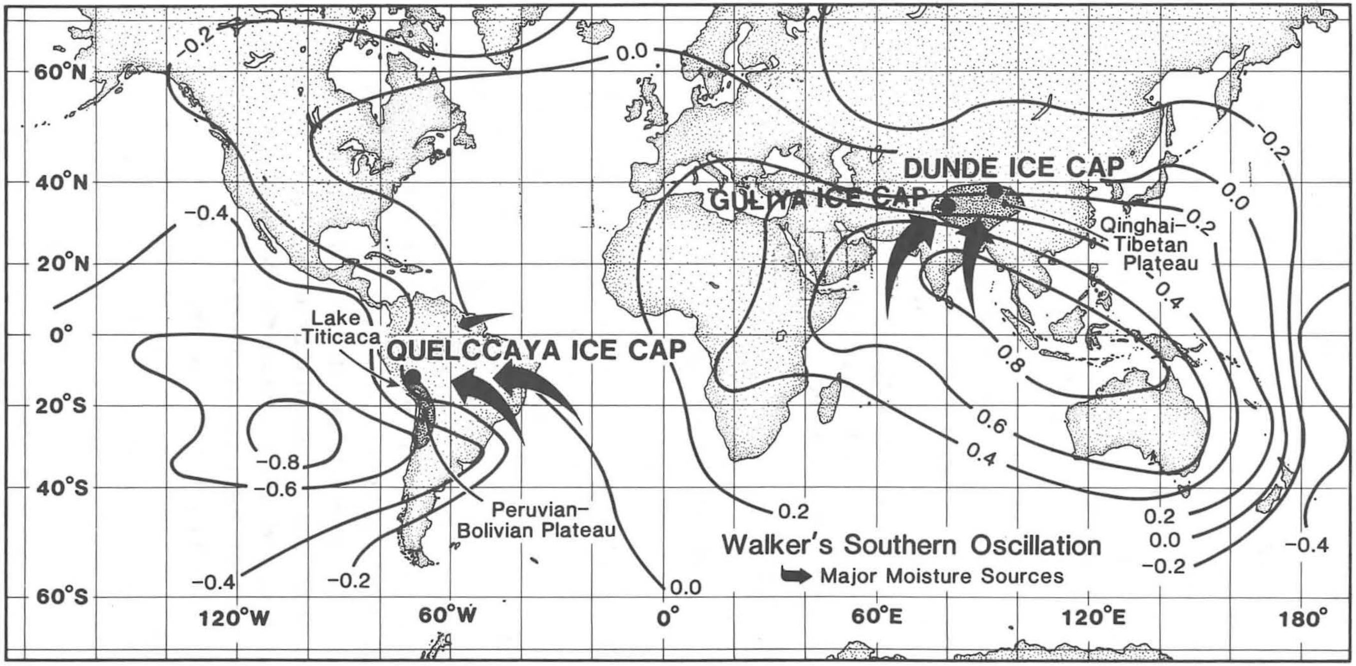


Fig. 16.14 The position of the Quelccaya ice cap (south of the equator) and the Dunde ice cap (north of the equator) relative to Walker's Southern Oscillation.

coastal cultures flourished when the highlands were drier implies that ENSO-like oceanic and atmospheric circulation patterns may have persisted for extended periods of time.

Several other examples of this relationship between climate and cultural development may be drawn from the earlier part of the Quelccaya record. Figure 16.13 illustrates large variations in A_n, $\delta^{18}O$, and particulate concentrations from A.D. 500 to 650. Precipitation appears to have decreased 30% during a major drought from A.D. 563 to 594. It seems intuitive that such an abrupt change in water availability could produce major environmental stresses within Andean cultures. Further evidence for this cultural dependence upon climate arise from the fact that this extended drought between A.D. 500 and 600 is contemporaneous with major relocations of the Mochica and other Andean cultures which produced rapid and far-reaching internal transformations (Shimada et al. 1991). It is likely that these relocations resulted from the inhabitants' attempts to control life-giving water sources. Finally, encompassed in this time interval is a large dust event from A.D. 600 to 620, which is believed to reflect the impact of prehistoric agricultural activities on the environment of the Altiplano (Thompson et al. 1988).

Linkages between South America and Asia

Additional ice-core evidence from the Dunde ice cap in China indicate that decadally averaged net accumulation trends on the Qinghai-Tibetan Plateau are quite similar to those in the southern Andes of Peru from A.D. 1600 to 1980. Although these areas are on opposite sides of the Pacific Ocean basin, they should be related physically through the Walker Circulation (Fig. 16.14).

Figure 16.15 illustrates a preliminary comparison of decadally averaged net accumulation from A.D. 1610 to 1980 for Quelccaya and Dunde ice caps (Thompson et al. 1989, 1990; Thompson 1992). Over the last 400 yr these records show a remarkable similarity in net balance for such widely separated areas. This is consistent with the physical linkage (teleconnection) between these areas which has been recognized since the turn of the century. The ENSO phenomenon perturbs the ocean/atmosphere system of the Pacific Basin episodically and is related to anomalous weather patterns covering much of the globe (Rasmusson and Wallace 1983; Nicholls 1987; Enfield 1989; Kiladis and Diaz 1989). The comparisons in Figure 16.15 support the hypothesis that these teleconnections exist, not only for high frequency events such as ENSO, but also for lower frequency events which may persist for centuries.

Summary

The Quelccaya (Peru) and Dunde (China) ice caps are situated in regions where the climate exhibits a high degree of interannual variability. Here the preservation of seasonal variations in chemical and physical constituents, make possible

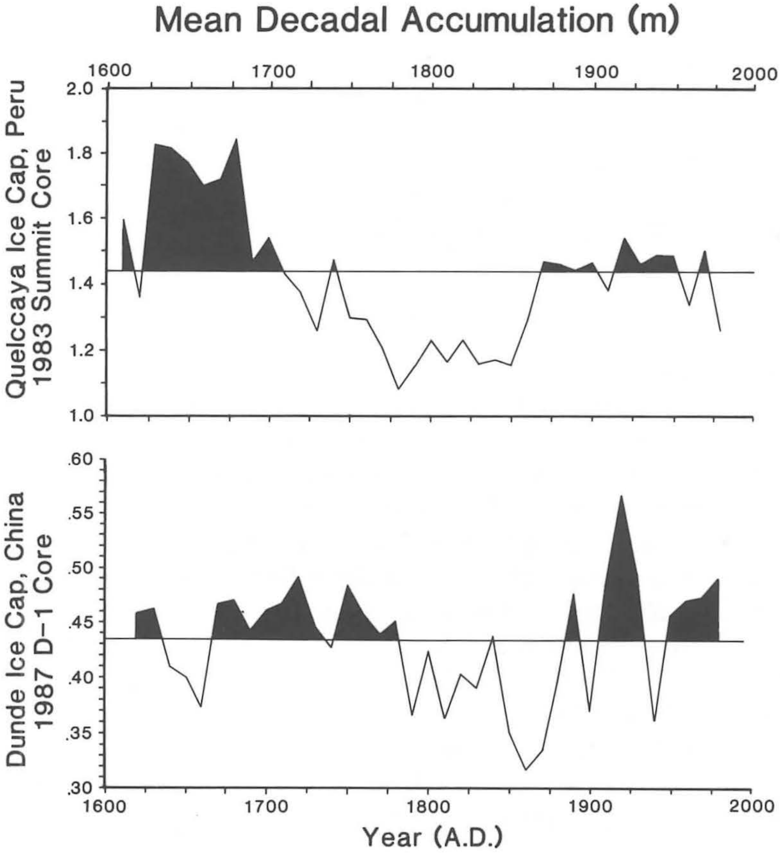


Fig. 16.15 The decadally averaged net accumulation (~A.D. 1600–1980) for the composite of two cores from the Quelccaya ice cap is compared with that from core D-1 on the Dunde ice cap, China.

very precise dating of the annual precipitation layers. Thus, the analyses of cores drilled in these ice caps provide unparalleled opportunities to construct multifaceted paleorecords of both the high- and low-frequency changes of the climate system and the regional environment. The potential for extracting much longer ice core records of the largest ENSO events has been presented and strategies for accomplishing this were discussed briefly. In addition, evidence was presented for the potentially strong impact of high frequency climatic variability upon human activities as expressed in archaeological records.

The Quelccaya ice cap records also reinforce the importance of low frequency oscillations in tropical accumulation over the last 1500 yr in southern Peru. The records from these high-elevation, low- and mid-latitude sites allow the documentation of low frequency oscillations as well as provide a new perspective on tropical teleconnections in space and time. Currently, a new ice core drilling program is planned for glaciers in the Cordillera Blanca at 8°S (Fig. 16.11). These sites are much closer to the zone of maximum ocean/atmosphere response to ENSO events and thus, when coupled with the Quelccaya records, they should provide much clearer proxies for paleo-ENSO events along the coast of South America. Coupling these South American records with those anticipated from the Tibetan Plateau (Dunde and Guliya ice caps) should provide both additional understanding of the physical linkages across the Pacific Basin and a record of the major ENSO events for the last few centuries.

Acknowledgments

We acknowledge with great appreciation the efforts of the many individuals, Peruvian, Chinese and American, who participated in the numerous field programs. Mary Davis conducted the particulate and conductivity analyses at The Ohio State University and the oxygen isotope analyses were conducted at the University of Washington by P. Grootes and at The Geophysical Laboratory of the University of Copenhagen by N. Gundestrup. The Peruvian program was a cooperative effort with colleagues from ElectroPeru. The Chinese program was a cooperative effort with colleagues from the Lanzhou Institute of Glaciology and Geocryology. This work and the many field programs associated with it were supported by the NSF Office of Climate Dynamics and Division of Polar Programs (ATM75-15513A02; ATM78-1609A01; ATM81-05079A02; ATM82-13601A02; ATM85-19794; ATM89-16635); The National Geographic Society (3323-86); and NOAA (NA89AA-D-AC197). J. Nagy produced the figures and K. Doddroe typed the mansucript. Byrd Polar Research Center Contribution No. 774.

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