Bull. Inst. fr. études andines
1993, 22 (1): 65-83

RECONSTRUCTING THE PALEO ENSO RECORDS FROM TROPICAL AND SUBTROPICAL ICE CORES

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Abstract

Interannual variability in climate is a major feature of the climate system, particularly in subtropical and tropical regions. It is essential to know if the interannual variability signature in the climate record is affected by a change in the mean state of the climate system. This goal can be met only by analyzing long records of interannual climate variability throughout intervals in the past when climate was different from today (e.g., Little Ice Age, Medieval Warm, last glaciation). This task is especially important as man may be inadvertently altering the mean state of global climate.

With the exception of the annual cycle, ENSO is the dominant global climate signal on time scales of a few months to a few years. It is associated with major dislocations of rainfall regimes in the tropics. Whereas the northern coastal desert regions of Peru experienced abnormally high precipitation, the southern highlands of Peru, where Quelccaya is located, experienced drought. Annual variations in the amount and chemical composition of precipitation accumulating on both polar and alpine (high elevation) glaciers produce laminations which allow precise dating of these stratigraphic sequences. This paper examines the interannual climate variability in the Quelccaya ice core records; (1) over the last 150 years where a limited amount of documentary data exist by which the ice core data can be evaluated and (2) the longer record covering the last 1500 years where independent evaluation becomes more difficult. The Quelccaya precipitation records derived from the ice cores are compared to the early history of man in South America. There is archeological evidence that, when compared to the Quelccaya net balance record over the last 1500 years, suggests that periods of flourishing highland cultures appear during periods when the mountains are wetter than average and that coastal cultures flourish when the mountains are drier than normal. These data suggest that there may exist longer period ocean/atmospheric links which yield «El Niño-like» precipitation responses on the longer term.

Key words: *Ice cores, Quelccaya, climatic variability, ENSO, tropical paleo climate.*

RECONSTRUCCIÓN DE LOS REGISTROS DE PALEO ENSO A PARTIR DE NÚCLEOS DE HIELO TROPICALES Y SUBTROPICALES

Resumen

La variabilidad interanual del clima es una característica mayor del sistema climático, particularmente en las regiones subtropicales y tropicales. Es esencial saber si la imprenta de la variabilidad interanual en el registro climático está afectada por un cambio en el estado promedio del sistema climático. Este objetivo solamente puede ser logrado analizando largos registros de variabilidad climática interanual a lo largo de intervalos en el pasado cuando el clima fue diferente al actual (ej. Pequeña Edad Glaciar, Calentamiento Medieval, última glaciación). Esta tarea es especialmente importante ya que el Hombre puede inadvertidamente alterar el estado promedio del clima global.

Con excepción del ciclo anual, ENSO es la señal climática global dominante a escalas de tiempo de pocos meses a pocos años. El está asociado con dislocaciones mayores del régimen de lluvia en los trópicos. Mientras que las regiones costeras desérticas del noroeste peruano experimentan precipitación anormalmente alta, las altiplanicies del sur del Perú, donde se ubica el Quelccaya, sufre sequía. Las

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variaciones anuales en la cantidad y composición química de las precipitación que se acumula tanto en los glaciares polares como alpinos (alta elevación) producen laminaciones que permiten un fechamiento preciso de estas secuencias estratigráficas. Este artículo examina la variabilidad climática interanual en los registros de los núcleos de hielo del Quelccaya; (1) sobre los últimos 150 años, en que existe una cantidad limitada de datos documentales con los que se pueden evaluar los datos de los núcleos de hielo y (2) el registro más largo, que cubre los últimos 1,500 años, en que la evaluación independiente se torna más difícil. Los registros de precipitación del Quelccaya, derivados de los núcleos de hielo, se comparan con la historia temprana del hombre en Sudamérica. Existe evidencia arqueológica que, cuando se compara con el registro del balance neto del Quelccaya en los 1,500 años, sugiere que los períodos de florecimiento de culturas de altura aparecen durante períodos en que las montañas fueron más húmedas que el promedio, y que las culturas costeras florecieron cuando las montañas fueron más secas que lo normal. Estos datos sugieren que pueden existir nexos océano/atmósfera de más largo período que producen respuestas de precipitación «tipo El Niño» de largo plazo.

Palabras claves: *Núcleos de hielo, Quelccaya, variabilidad climática, ENSO, paleoclima tropical.*

RECONSTRUCTION DES REGISTRES DE PALÉOENSO À PARTIR DE CAROTTES DE GLACE TROPICALES ET SUB-TROPICALES

Résumé

La variabilité interannuelle du climat est une des principales caractéristiques du système climatique, en particulier dans les régions tropicales et sub-tropicales. Il est essentiel de savoir si l'empreinte de la variabilité interannuelle dans le registre climatique est affectée par un changement dans l'état moyen du système climatique. Cet objectif ne peut être atteint qu'en analysant de longs registres de variabilité climatique interannuelle tout au long d'intervalles dans le passé, quand le climat était différent de l'actuel (ex. Petit Age Glaciaire, Réchauffement Médiéval, Dernière Glaciation). Ce travail est particulièrement important étant donné que l'Homme peut, sans le savoir, altérer l'état moyen du climat général.

À l'exception du cycle annuel, ENSO est le signal climatique global dominant à des échelles de temps qui vont de quelques mois à quelques années. Celui-ci est associé à des dislocations importantes du régime de pluie sous les tropiques. Tandis que les régions côtières désertiques du nord-est péruvien subissent des précipitations anormalement fortes, les régions des hauts plateaux du sud du Pérou, où se trouve le Quelccaya, connaissent la sècheresse. Les variations annuelles dans la quantité et composition chimique des précipitations qui s'accumulent aussi bien dans les glaciers polaires qu'alpins (forte élévation) produisent des laminations qui permettent une datation précise de ces séquences stratigraphiques. Cet article examine la variabilité climatique interannuelle dans les registres des carottes de glace du Quelccaya; (1) sur les 150 dernières années, où il existe une quantité limitée de documents qui permettent d'évaluer les informations contenues dans les carottes de glace et (2) le registre plus long, qui couvre les 1500 dernières années, où l'évaluation indépendante devient plus difficile. Les registres de précipitation de Quelccaya, tirés des carottes de glace, se comparent avec l'histoire ancienne de l'homme en Amérique du Sud. Une évidence arquéologique, comparée au registre du bilan net du Quelccaya au cours des 1500 dernières années, suggère que les cultures d'altitudes prospèrent au cours de périodes où les montagnes sont plus humides que la moyenne, et que les cultures côtières firent de même quand les montagnes furent plus sèches que la normale. Ces informations suggèrent qu'il peut exister des liens océan/atmosphère de plus longue durée qui provoquent des précipitatons «de type El Niño» à long terme.

Mots clés : *Carottes de glace, Quelccaya, variabilité climatique, ENSO, paléoclimat tropical.*

1. INTRODUCTION

The El Niño/Southern Oscillation (ENSO) phenomenon is without doubt, one of the most striking sources of large-scale variability in the modern climate. However, the degree to which the characteristics observed during the 20th century of this phenomenon is a function of the mean climate conditions of this period is a key issue. Predictions of future climatic oscillations whether dominated by anthropogenic perturbations or not, demand greatly increased knowledge and understanding of the natural climate variability. Reliable meteorological observations for climate reconstruction are limited or absent for many regions of the Earth prior to 1850. This is especially true for tropical South America. Ice sheets and ice caps are widely recognized as libraries of atmospheric history from which past climatic and environmental conditions may be extrapolated. Ice core records from ice caps such as Quelccaya can provide long-term records of El Niño/Southern Oscillation and monsoon variability from the regions where most of the Earth's population is concentrated.

The 1500-year record from the Quelccaya is most critical in light of recent (1991) observations of the Quelccaya ice cap. An expedition to Quelccaya in 1991 found that the paleoclimatic record once preserved in the ice cap is undergoing alteration due to recent warming conditions which result in the percolation of meltwater through the upper firn layers (Thompson *et al.*, in press). Thus, the valuable archives preserved for centuries in this low latitude, high altitude ice cap are in imminent danger of destruction if the current warming trend in this region continues.

2. ACQUISITION OF THE ICE CORES

Research programs were conducted on the tropical Quelccaya ice cap (Fig. 1a) in the Peruvian Andes (13-56-S; 70-50-W) between 1974 and 1984. Quelccaya covers 55 km^2, has a summit elevation of 5670 meters (Fig. 1b) and a mean annual temperature of -3-C. The maximum ice thickness at the summit is 164 m and the underlying bedrock is a relatively flat ignimbrite flow. On average roughly three meters of snow (1.15 m of water equivalent) accumulate on the summit each year. There is a consistent annual precipitation cycle during which 80 to 90% of the snow falls from November to April (Thompson *et al.*, 1984a). This distinct seasonality in precipitation results in the deposition of dry season dust bands which are preserved in the ice stratigraphy (Fig. 2).

The high summit elevation and remoteness of Quelccaya made it impossible to use a conventional ice core drilling system. Therefore, a portable, lightweight, solarpowered drill was designed specifically for this program, the first major ice core drilling project to use solar power. In 1983 this system successfully recovered two ice cores from the summit area of Quelccaya (Fig. 1c). The two parallel cores were drilled and analyzed similarly to provide an independent verification of the time scale and to ensure an uninterrupted physical and chemical stratigraphic record. The first core extended 163.6 meters to the bedrock and is henceforth referred to as Core 1. The second core, henceforth Summit Core, extended 154.8 meters to some undetermined distance above the bedrock. Summit Core drilling terminated after penetration of an unconformity consisting of dust layers inclined 18- from the horizontal (Thompson *et al.*, 1985). The solar powered drill system made it possible to obtain these cores without contaminating the pristine environment or the core samples.

The individual core sections averaged 2 meters in length and were 9 cm in diameter. A laboratory tent was established where the cores were cut and placed into plastic bags. After melting, each sample was transferred to a high density polyethylene bottle which was sealed with wax. The Summit Core was cut into 2704 samples while Core 1 was cut into 2803 samples for which insoluble particulates, oxygen isotopic ratios ($\delta^{18}O$) and liquid conductivity were measured. Approximately 1500 samples were also cut for total Beta radioactivity and chemical measurements.

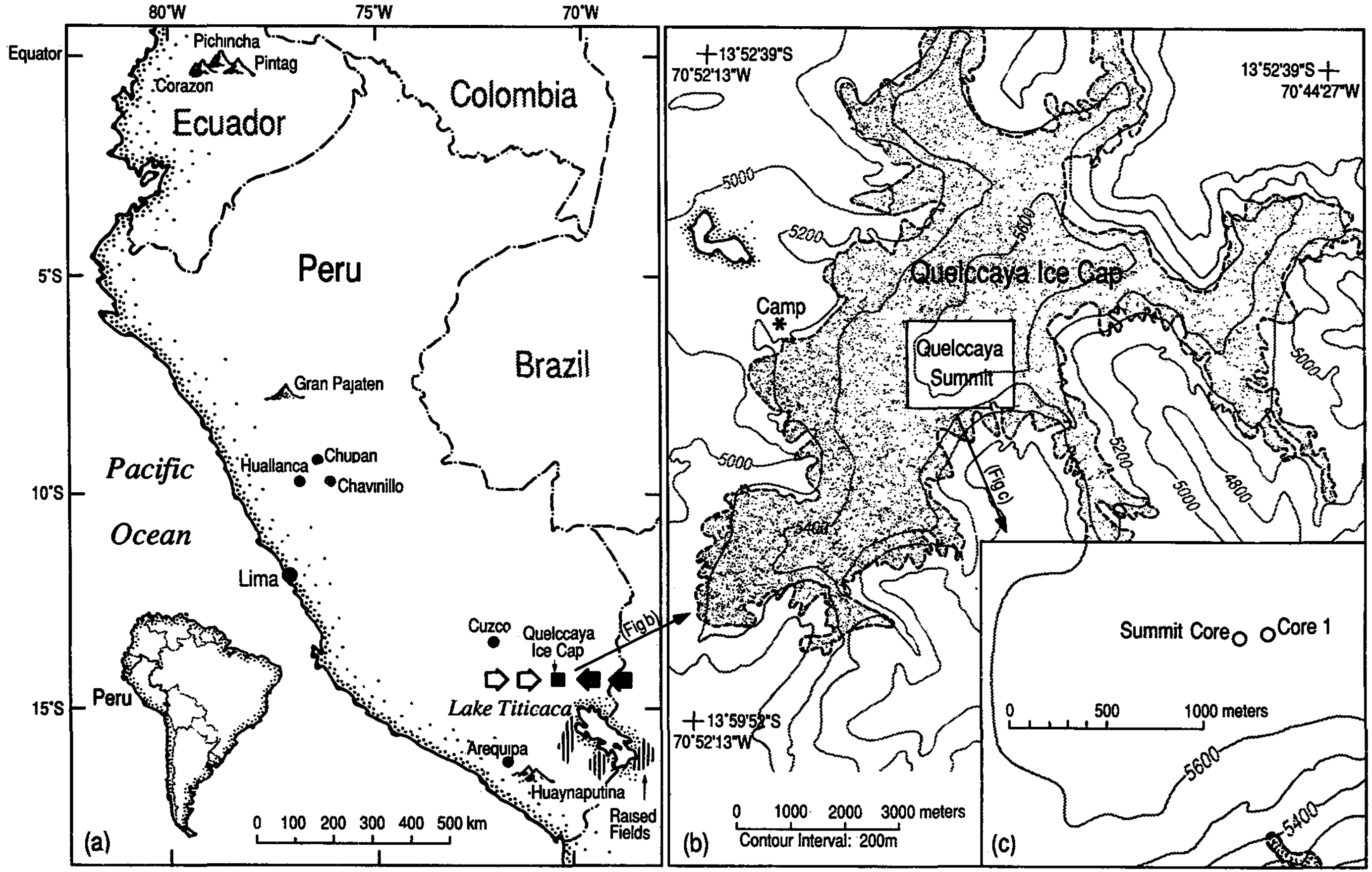


Fig. 1 - (a) Map of the location of the Quelccaya ice cap in Peru. Dominant wind direction is illustrated for the wet season (dark arrows) and the dry season (open arrows). Flood and drought areas associated with the 1982-83 El Niño are shaded; (b) shows the topography of the ice cap and (c) illustrates the locations of the two deep ice cores drilled in 1983.

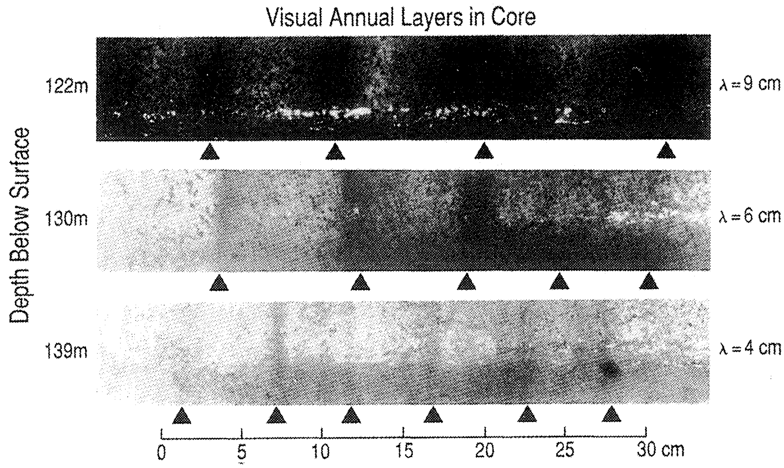


Fig. 2 - The three representative core sections from different depths show the distinct annual dry-season dust layers (triangles) used for initial dating of the core. The average thickness (λ) of the annual layers in each section is given and illustrates the layer thinning that occurs with depth.

3. LABORATORY ANALYSES OF THE ICE CORES

The bottled samples were returned to The Ohio State University where they were kept frozen until analysis. All sample preparations and handling were conducted under Class 100 clean room conditions. Routine analyses consisted of the concentration and size distribution for insoluble particles with diameters ≥ 0.63 μm, liquid conductivity, and $\delta^{18}O$ (Thompson *et al.*, 1986; 1988).

3. 1. Particulate analyses

Particulate concentrations were measured using two Model TA II Coulter Counters which electronically separate particles into 14 size ranges between 0.63 and 16.0 μm in diameter. The annually-averaged particulate data are presented in this paper in two size ranges: (1) total particle concentrations with diameters ≥ 0.63 μm and ≤ 16 μm, (2) the large particle fraction with diameters ≥ 1.59 μm and ≤ 16 μm. Thompson (1977) presents a complete discussion of the Coulter technique for particulate analysis including the sample preparation and handling procedures.

3. 2. Liquid conductivity analyses

Electrolytic conductivity, measured under Class 100 clean room conditions using an Altex RC-16C Conductivity Bridge, furnishes an excellent estimate of the soluble impurities in the meltwater. Conductivity measurements, reported in microSiemens per centimeter

($\mu S\ cm^{-1}$), have an accuracy within 1% of the reading. All laboratory measurements were conducted under temperature conditions of 21°C plus or minus 1°C and with replicate analyses to insure reproducibility.

3. 3. Oxygen isotopic analyses

The oxygen isotopic analyses are reported as $\delta^{18}O$, the relative difference in the oxygen isotopic abundance ratio ($^{18}O/^{16}O$) of the sample and that of Vienna Standard Mean Ocean Water (V-SMOW). $d^{18}O$ is expressed in per mil (o/oo) and is calculated as

$$\delta^{18}O = [(^{18}O/^{16}O)\ \text{sample} - (^{18}O/^{16}O)\text{standard}]/(^{18}O/^{16}O)\text{standard}.$$

Grootes *et al.* (1989) were able to explain quantitatively both the large seasonality in $\delta^{18}O$ and the substantially depleted values. The most important factors appear to be (1) variations in air mass stability over the Amazon Basin, (2) elevation of the Quelccaya summit, and (3) seasonal changes over Quelccaya.

4. CONSTRUCTING THE TIME SCALE

The utility of ice core analyses hinges upon accurate dating of the stratigraphic sequence. The first step is to establish the average annual accumulation as well as the range of interannual variability in accumulation for the drill site. Next the potential of various physical and chemical properties for dating must be assessed. To accomplish these objectives the net annual accumulation was measured each year from 1976 to 1984 along an array of poles also used to determine ice motion. In addition, pits were excavated and samples were collected to study the seasonality of the chemical and physical properties of the snow deposited in the intervening year. The seasonality of the variations in the soluble and insoluble particulate concentrations and oxygen isotopic ratios was confirmed by comparison with the known accumulation measured along the stake network. On Quelccaya the least negative oxygen isotopic ratios, highest concentrations of both insoluble and soluble dust, and the visible dust layers occur during the dry season which is May through October.

The dating of the upper firn layers in the ice cap was further confirmed by comparison with known time-stratigraphic horizons associated with well documented atmospheric thermonuclear tests (Picciotto & Wilgain, 1963; Lambert *et al.*, 1977). These were identified by the measurement of total Beta radioactivity in pit and shallow core samples collected on Quelccaya in field seasons preceding the acquisition of the long cores in 1983 (Thompson, 1980; 1991). In addition, prior to the deeper drilling the age of ice at the bottom of the ice cap was estimated to range from 600 to 1300 years. These estimates were derived from flow-model calculations (Thompson *et al.*, 1982) using three different expressions for the vertical strain rate. In addition, the ice cap was assumed to be 180 meters thick and in steady state with an annual accumulation rate of 1.24 m (in ice equivalent) that is independent of time.

Ultimately, the most accurate time scales for ice cores are based upon the integration of high resolution (8 to 12 samples per year) records of chemical constituents and/or physical properties which exhibit a distinct seasonal variation in their flux (Thompson *et al.*, 1986; Hammer, 1989). On Quelccaya the visible annual dust layers (Fig. 2) allowed rapid and highly accurate dating of the ice core in the field (Thompson *et al.*, 1985). This initial time scale, based solely upon visible stratigraphic features, was later refined using the seasonal variations in $\delta^{18}O$, concentrations of insoluble particulates, and liquid conductivity. In addition, the availability of two parallel ice core records further enhanced the accuracy of the time scale as the second core provided information unavailable from the first core when problem areas arose. Such problem areas may result, for example, when the core is broken into sections during drilling or when core recovery is not complete. The quality and recovery of the cores on Quelccaya was excellent and did not present a problem. However, the cores were retrieved in 1.5 to 2-meter increments and therefore core breaks existed every 150 to 200 cm along the length of the core. It was here that the records from two parallel cores became extremely valuable.

Figure 3 illustrates the use of multiple parameters for time scale construction. The 50-year period from A.D. 1775 to 1825 is simply illustrative. The Quelccaya ice cores have been dated to A.D. 1500 with an estimated uncertainty of ± 2 years, including an absolute date of A.D. 1600 where ash from the Huaynaputina eruption was identified (Thompson *et al.*, 1986). The dating of the lower sections of both cores, based solely on the visible dust layers recorded in the field, has an estimated uncertainty of ± 20 years (Thompson *et al.*, 1986). The time scale development has been discussed more extensively elsewhere (Thompson *et al.*, 1985; 1986).

The identification of annual layers using both the visible dust layers and the seasonal variations in $\delta^{18}O$ and particulates made it possible to estimate the annual net accumulation on the ice cap summit (Thompson *et al.*, 1985). The observed annual layer thicknesses (in ice equivalent) varied from 1.2 meters at the top of the core to 0.01 meters at the base. Although the thicknesses of these annual layers could be determined throughout the cores, they do not represent the thicknesses originally deposited at the ice cap surface due to thinning and stretching as new snow accumulates on the surface and as the ice flows outward from the center. Thompson *et al.* (1985) provide a discussion of the method by which the vertical strain rate was estimated and used to calculate the initial layer thickness, or net annual accumulation. These reconstructed layer thicknesses provide a time history of the net accumulation on the summit of the ice cap.

5. DISCUSSION OF THE DATA

The annual averages represent each thermal year from A.D. 470 to 1980 as reflected in the cores drilled in 1983. The thermal year is defined as that time from one dry season dust layer to the next dry season dust layer and is approximately from July through the following June. The annual averages for 1980 to 1984 are derived from snow pit samples collected during field seasons in each of those years. The period from A.D. 1475 to 1984 represents that portion of the cores for which a sufficient numbers of samples were cut from each annual layer so that both visible dust layers and seasonal variations in particulate concentrations, conductivity, and $\delta^{18}O$ could be used for time scale construction. The ice cores are absolutely dated at A.D. 1600 (Fig. 4) where ash from the Huaynaputina eruption has been identified (Thompson *et al.*, 1986). The cores are dated to A.D. 1500 with an estimated uncertainty of ± 2 years and for the bottom of the Core 1 the authors' best estimate of potential timescale error is ± 20 years.

The Quelccaya records have provided a variety of new information for this region of South America where both proxy and meteorological data are sparse. Much of the value of these records stems from their annual resolution and accurate time scale. It was quickly

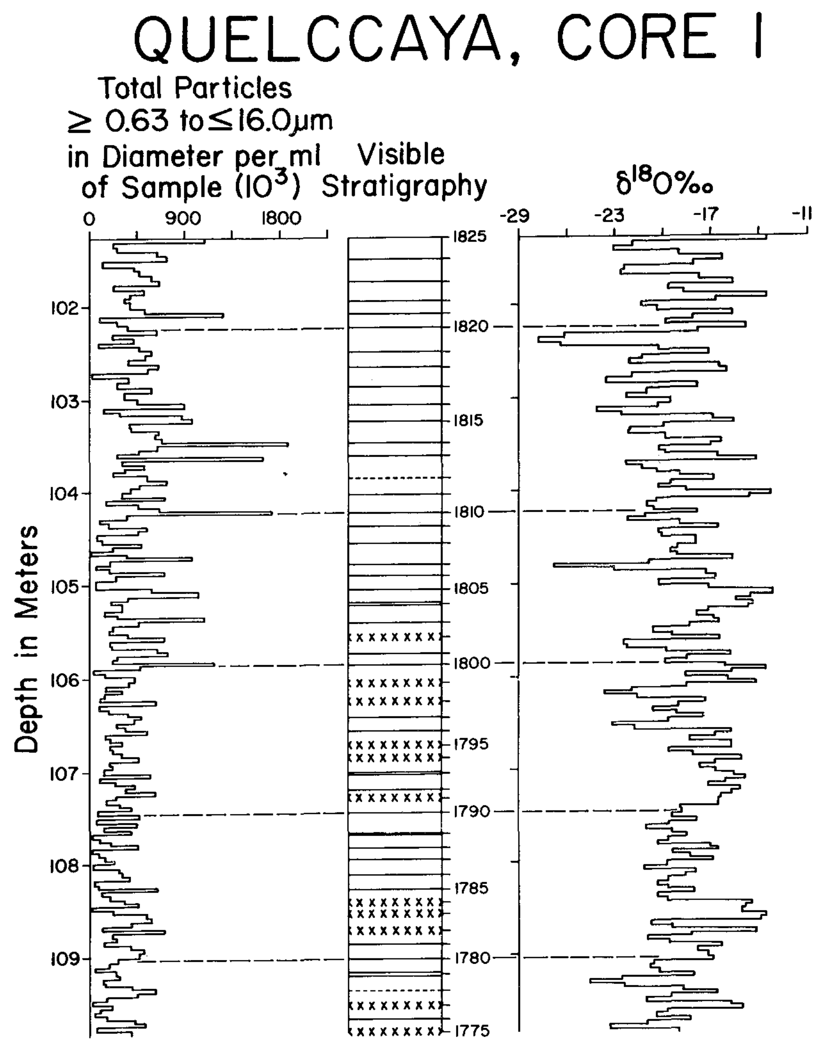
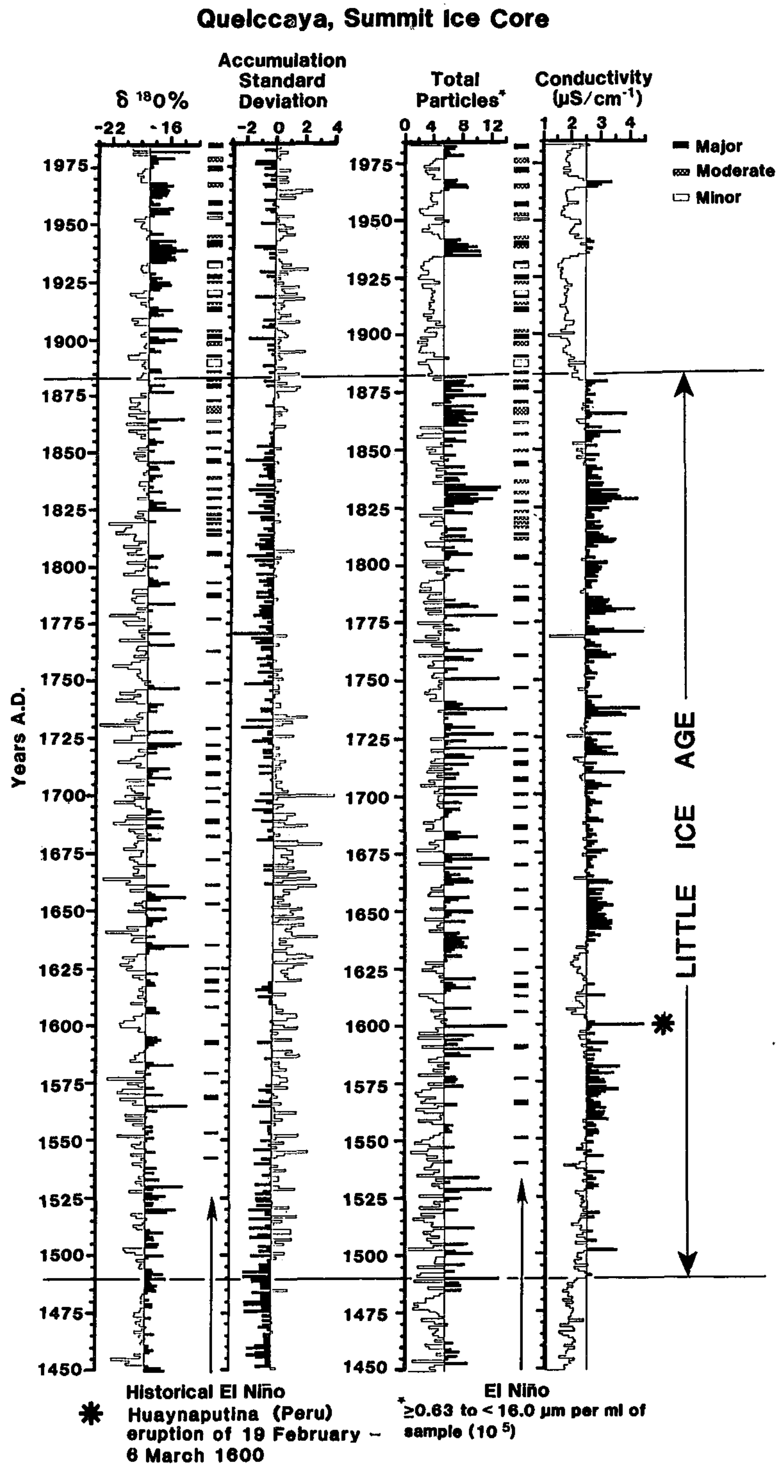


Fig. 3 - A section of Core 1 representing A.D. 1775 to 1825 and illustrates the seasonally varying parameters used to date the core. Shown are insoluble particle concentrations (0.63 ≥ diameter ≤ 16.0 µm) per milliliter of sample, visible stratigraphic features and oxygen isotopic ratios. For stratigraphy, a single solid line represents a normal dry-season dust layer, a single dashed line and a doubledashed line represent very light and light dust layers, respectively. Series of x's symbolize diffused dry-season layers.

Fig. 4 - The annual records of δ18O, net accumulation, insoluble particulates, and liquid conductivities for the Summit Core for A.D. 1450 to 1983. Included is the historical El Niño record from Quinn & Neal (1992). For accumulation 1σ equals 34 cm. The Little Ice Age (LIA) stands out clearly and is characterized by increased soluble and insoluble particulate concentrations and decreased (more negative) δ18O. The LIA appears to have been a major climate event in South America. The large dust event at A.D. 1600 was produced by the eruption of Huaynaputina (Peru) from February 19 to March 6, 1600.


Quelccaya, Summit Ice Core
δ ¹⁸O%
Accumulation Standard Deviation
Total Particles*
Conductivity (μS/cm⁻¹)
-22 -16
-2 0 2 4
0 4 8 12
1 2 3 4
Major
Moderate
Minor
Years A.D.
1975
1950
1925
1900
1875
1850
1825
1800
1775
1750
1725
1700
1675
1650
1625
1600
1575
1550
1525
1500
1475
1450
LITTLE ICE AGE
Historical El Niño
Huaynaputina (Peru) eruption of 19 February – 6 March 1600
El Niño
*≥0.63 to < 16.0 μm per ml of sample (10⁵)

recognized that the annual accumulation layers were frequently thinner during major El Niño events (Thompson *et al.*, 1984b). Southern Peru generally experiences drought conditions in association with major El Niño events. Thus, the annual accumulation record may make it possible to extend Quinn & Neal's (1992) historical El Niño record beyond A.D. 1525.

The Quelccaya records have provided the first strong evidence for a tropical response to the most recent Neoglacial cooling referred to as the Little Ice Age (LIA) from approximately A.D. 1450 to 1880 (Thompson *et al.*, 1986). The $\delta^{18}O$ record (Fig. 4) reveals a marked ^{18}O depletion ($\delta^{18}O$ more negative) and elevated concentrations of both soluble and insoluble particulates during the LIA. The increased dust concentrations do not result from reduced net accumulation. Figure 4 reveals that the high dust concentrations in the first half of the LIA were correlative with above-average net accumulation, while during the latter half, the dust concentrations remained high although net accumulation was below the long-term average. These records also provide evidence of rapid changes, on the order of a few years to a few decades. The transition into the LIA appears to have occurred within several decades while the termination of the LIA appears to have occurred abruptly (within several years) around A.D. 1880 (Thompson & Mosley-Thompson, 1987).

Figure 5 illustrates the decadal averages of insoluble dust concentrations, conductivity and $\delta^{18}O$ for the entire 1500-year record. Note that the LIA stands out prominently as the isotopically lightest (coolest) period in the entire record. On the other hand, elevated LIA dust concentrations are diminished by two major insoluble dust peaks each lasting about 130 years and centered at A.D. 920 and 600. These major dust events may reflect changes in pre-Incan agricultural practices in the Lake Titicaca region (Thompson *et al.*, 1988). The accumulation records from Quelccaya appear to provide a proxy for Lake Titicaca water levels and possibly for precipitation in the highlands of the southern Andes. The ice core records suggest that changes in the water level of Lake Titicaca were strongly linked to changes in the agricultural practices of people in the surrounding area.

The precipitation in the highlands of Southern Peru appears to be inversely related to that along the northern Peruvian coast. Frequently when it is dry in the southern highlands it is wet along the northern coast and vice versa. Changes in the precipitation regime along the northern coast (inferred from the Quelccaya records) offer a possible explanation for a drastic, broad spectrum transformation of the prehistoric Mochica culture on the north coast of Peru (Shimada *et al.*, 1991; Thompson, 1992).

5. 1. 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 & Montecinos (1993, this volume) and Ropelewski & Halpert (1987), show that the rainfall in the Altiplano region may only be weakly related to the Southern Oscillation. However, only one station, La Paz, was used to characterize the long term precipitation on the Altiplano and given the regional variability of precipitation in the tropics more long term records are needed. Quelccaya, situated in southern Peru, experienced a major drought associated during the 1982/1983 El Niño. This

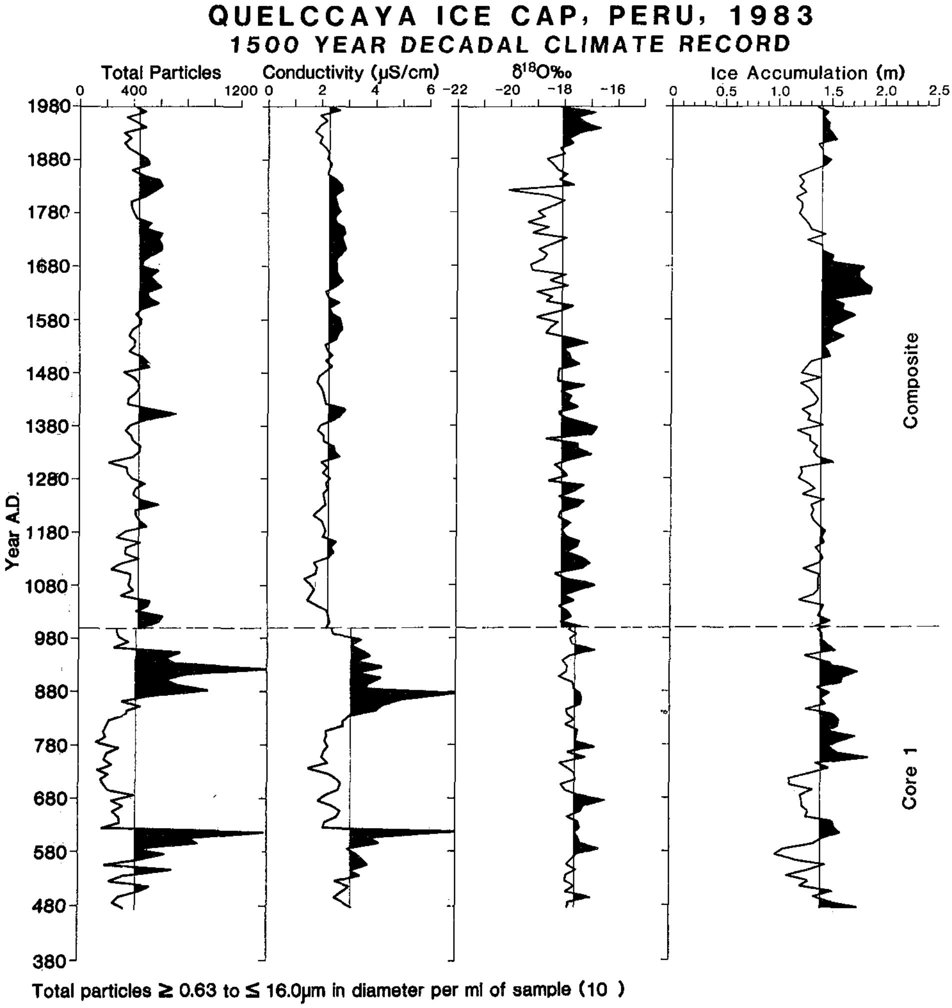


Fig. 5 - The decadal averages from A.D. 470 to 1980 for the concentrations of insoluble particles (0.63 ≥ diameter ≤ 16.0 μm) per ml sample, liquid conductivity, $\delta^{18}O$, and net accumulation. The composite record from A.D. 1000 to 1980 is the average for both cores while only Core 1 is used for A.D. 470 to 1000 as the Summit Core contained a discontinuity at 153.68 m (A.D. 745).

is apparent in Figure 6, which contrasts the ice cap margin in 1978 (a non-ENSO year) with the margin at the same location during the 1982 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.

To assess the utility of the Quelccaya record for extracting a long ENSO chronology, the character of the more recent accumulation can be compared with both observational and historical data. Figure 7 illustrates the annual records of the Southern Oscillation index (SOI),

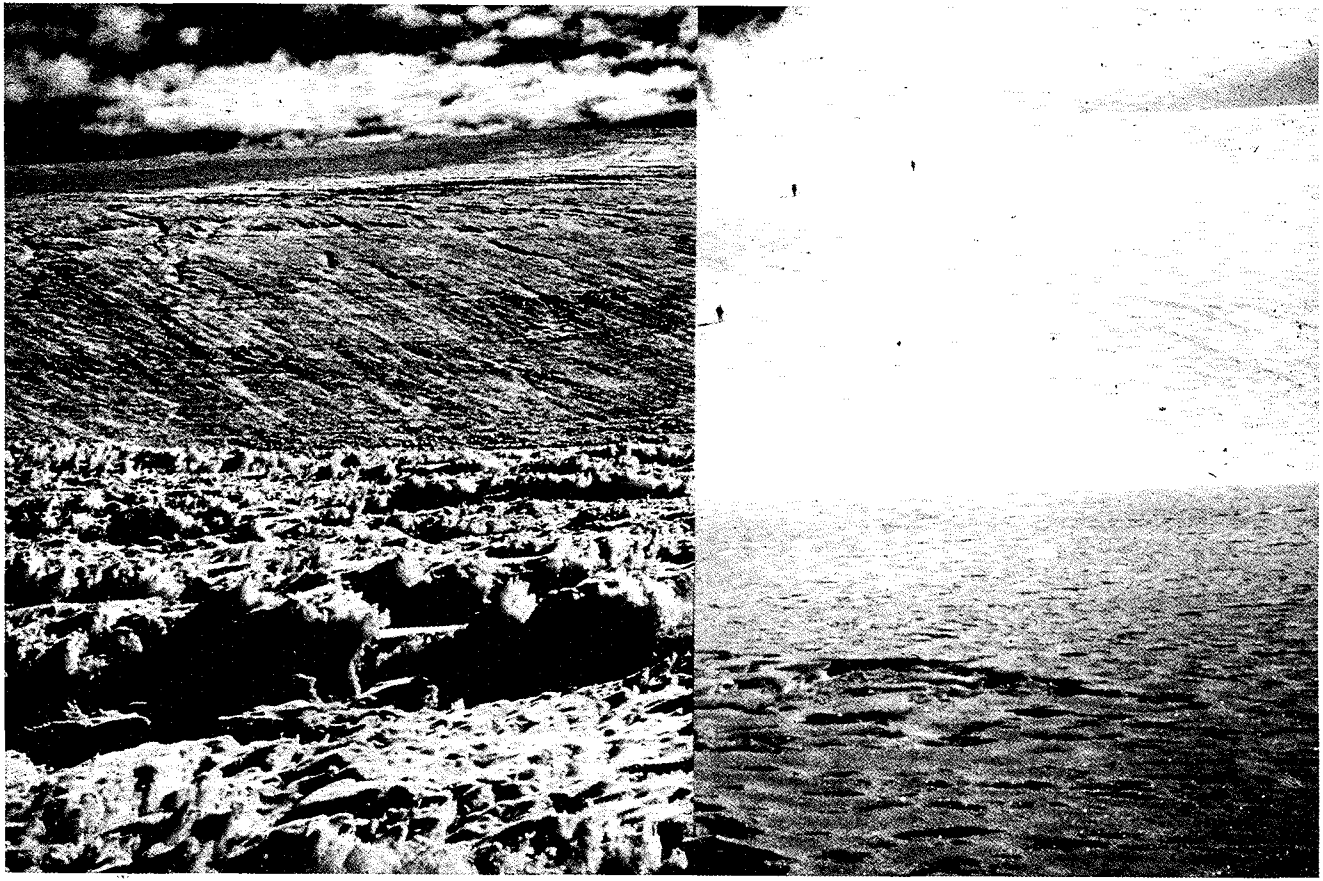


Fig. 6 - Photo. Right is margin of Quelccaya ice cap in early July 1978 during normal year. Left is same area in early July 1983 during the longest El Niño in the last century.

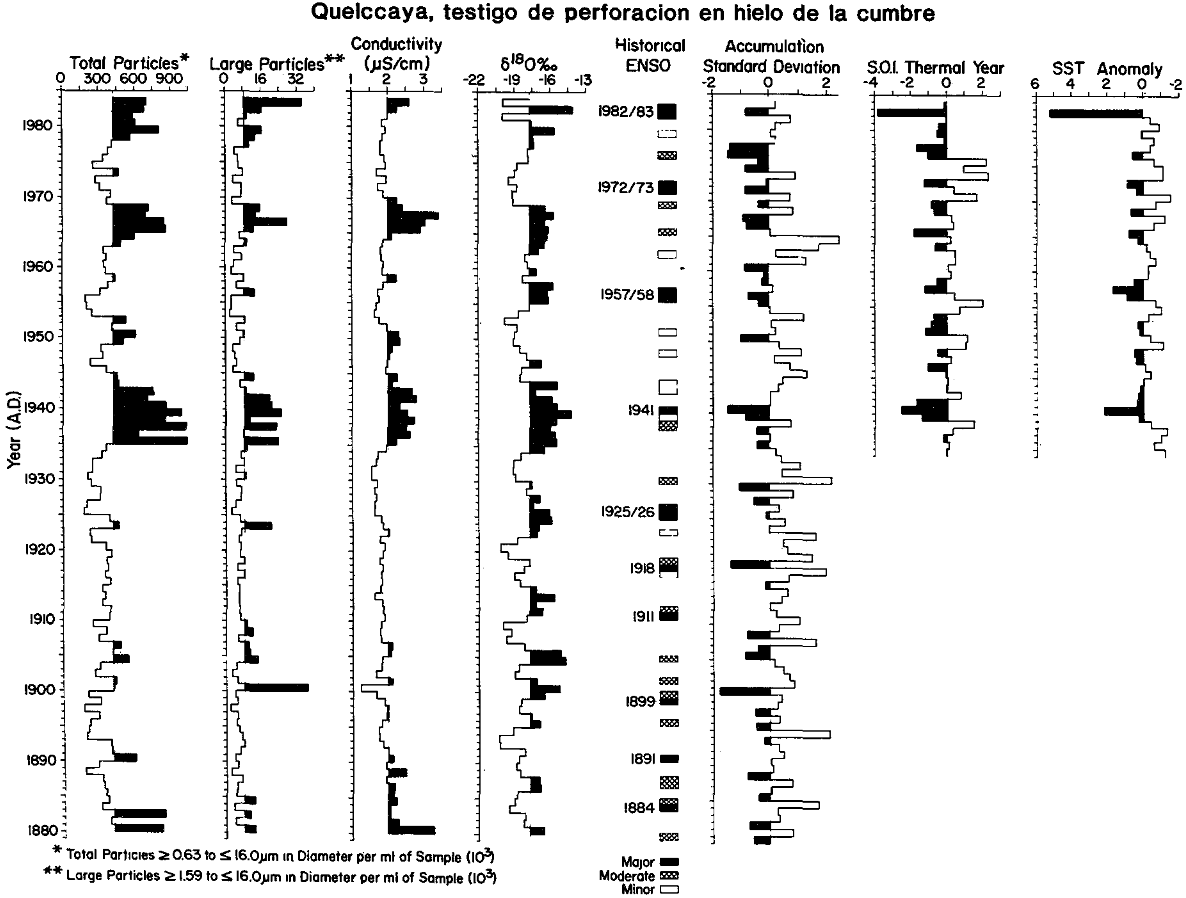


Fig. 7 - Annual averages of particulate concentrations, liquid conductivity, ∂18O, and net accumulation for 1880 to 1984 are compared with two common ENSO indicators: the Southern Oscillation Index (SOI) and the Sea Surface Temperature (SST) anomalies from Puerto Chicama, Peru (after Quinn *et al.*, 1987).

sea surface temperatures (SST), and the historical record of major, moderate and minor El Niño phases (Quinn *et al.*, 1987). The 1982/1983 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 7 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 of the ice-core record in order to extract a longer ENSO history (Thompson *et al.*, 1992).

In situ observations on the Quelccaya ice cap during both the 1976 and 1982/1983 El Niño events reveal a marked change in the general climatic patterns. For example, net accumulation was substantially reduced (Fig. 7) and net radiation receipt increased (Thompson *et al.*, 1984b). Figure 4 suggests that similar climatic conditions probably characterized most of the earlier ENSO events. Michaelsen and Thompson (1992) calibrated the ice core record with long ENSO instrument records. In these comparisons the ice core proxy records showed significant levels of correspondence with the instrumental record.

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.

Instrumental records of ENSO phases rarely extend more than 100 years in length. Quinn & Neal (1992) 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 phase are not uniform as demonstrated by the large 1982/1983 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. Studies have shown that El Niño events are oscillatory, but not truly periodic (Wright, 1977; Hamilton & Garcia, 1986; Quinn *et al.*, 1987; Quinn & Neal, 1992). The ice-core records suggest that ENSO phases fluctuate substantially in both frequency and intensity. The major ENSO phase (1982-1983) focused attention upon this phenomenon and once again spurred a great effort to determine its predictability

(Rasmusson & Carpenter, 1982; Cane, 1983; Cane & Zebiak, 1985; Kiladis & Díaz, 1986; Yarnal & Díaz, 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.* (1987) and Quinn & Neal (1992) for the period A.D. 1450 to 1984 A.D. Figure 4 illustrates changes in the concentrations of insoluble and soluble particulates, $\delta^{18}O$ and net annual accumulation, along with the occurrences of major, moderate and minor El Niño events. As in the 20th century (Fig. 7), El Niño events were generally associated with Fig 8 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 recorded in isotopic and chemical composition of moisture sources which dominate this area of the tropical Andes.

5. 2. Low frequency «El Niño-like» events

The longer precipitation record for southern Peru derived from the Quelccaya A_n record provides valuable information which can be related to the early history of man in this region of South America. Figure 8 presents the decadal trends in accumulation from A.D. 470 to 1980. Currently, ENSO events may be associated with droughts in the southern Peruvian highlands (Fig. 1a) and floods in the coastal desert areas of northern and central Peru and southern Ecuador (Thompson *et al.*, 1984b). The Quelccaya net balance record for the last 1500 years has been integrated with archaeological evidence (Shimada *et al.*, 1991). These data strongly suggest that flourishing 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.

6. SUMMARY

The Quelccaya ice cap is situated in a region where the climate exhibits a high degree of interannual variability. Here the preservation of seasonal variations in chemical and physical constituents, make possible 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 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 accomplished this were discussed briefly. In addition, evidence was presented for the potentially strong impact of high-frequency climatic variability upon the human activities as expressed in archaeological records.

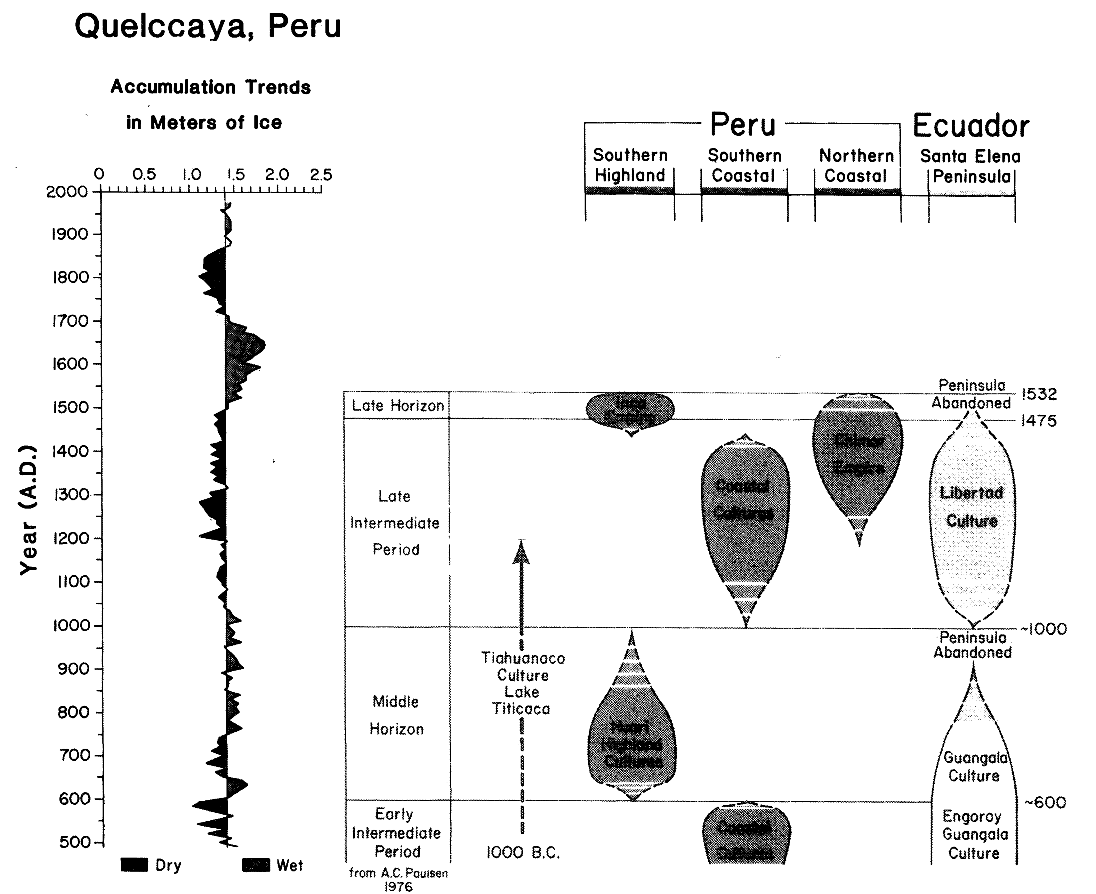


Fig. 8 - Quelccaya decadal accumulation trends in meters of ice core presented as a composite of Core 1 and Summit core records. Wet and dry periods are noted. On the right the periods of the rise and fall of coastal and highland cultures of Ecuador and Peru are illustred (taken mainly from Paulsen, 1976).

The Quelccaya ice cap records also reinforce the importance of low-frequency oscillations in tropical accumulation over the last 1500 years 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. 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.

A few select high-altitude glaciers and ice caps still have preserved within them an annual-resolution climate and environmental record of the past. High priority should be given to recovery of these ice cores for if the current warming continues, these records will soon be lost to humanity.

Acknowledgments

The success of the Quelccaya ice cap program results directly from the unselfish collaboration by the many scientists and support personnel who participated in the ten field programs. The support provided by ElectroPeru, the Inter-American Geodetic Survey and the Polar Ice Coring Office was essential to conducting the project and is gratefully acknowledged. The particulate and conductivity measurements were made by M. Davis. Many graduate and undergraduate students contributed to the program and their efforts are appreciated. This project was supported by NSF grants ATM7515513A02, ATM78-1609A01, ATM81-05079A02 and ATM82-13601A02. The NSF Division of Polar Programs supported the 1974 field program (GV41411) and the development of the solar powered drill. The Quaternary Isotope Laboratory (Univ. of Washington) oxygen isotope study was supported by NSF grants DPP-8019756 and DPP-8400574 and that of the Geophysical Institute (University of Copenhagen) by the Danish Natural Science Research Council. The preparation and publication of this data volume was supported by NOAA. We thank K. Doddroe for preparing the text and J. Nagy for illustrations. This is contribution number 831 of the Byrd Polar Research Center.

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