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Glacial Records of Global Climate: A 1500-Year Tropical Ice Core Record of Climate

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A general discussion is given of climate variability over the last 1500 years as interpreted from two ice cores from the Quelccaya ice cap, Peru. The possible role of climatic variability in prehistory over this period is discussed with emphases on (1) relationships between climate and the rise and decline of coastal and highland cultures; (2) the possible causes of two major dust events recorded in the Quelccaya ice cores around AD 920 and AD 600; and (3) implications of climatic variation for the occupation and abandonment of the Gran Pajaten area. The remarkable similarity between changes in highland and coastal cultures and changes in accumulation as determined from the Quelccaya ice cores implies a strong connection between human activities and climate in this region of the globe. Two ice cores drilled to bedrock from the 6047 masl col of Huascarán in the Cordillera Blanca, Peru in 1993 offer the potential of an annual to decadal climatic and environmental record which should allow the study of human–climate and human–environmental relationships over 10,000+ years. The 1991 and 1993 evidence from the Quelccaya ice cap indicates that recent and rapid warming is currently underway in the tropical Andes. Thus many of the unique glacier archives are in imminent danger of being lost forever.

KEY WORDS: climate variability; ice core; Quelccaya ice cap; raised fields; tropical; El Niño–Southern oscillation; "recent warming."

INTRODUCTION

The historical record of human activities in pre-Spanish South America is scant and incomplete, and the process of piecing it together is hampered by the lack of written language from this period. Archaeologists,

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through excavations of sites of pre-Hispanic civilizations in Ecuador and Peru, have been able to unearth information concerning the chronology and activities of civilizations in these regions. Another piece of the historical puzzle, however, can be provided by a non-archeological source. Recently, ice fields in the Andes have yielded records of climatic events which may prove to have played a major role in human activities.

Each summer from 1976 to 1984 field programs were conducted on the Quelccaya ice cap (13° 56'S, 70° 50'W, 5670 masl on the easternmost rise of the Andes before descending into the Amazon basin) with the ultimate goal of establishing a climatic record from an ice core for at least the last 1000 years. In 1983 the objective was reached with the successful recovery of two ice cores, one to bedrock and containing 1500 years (core 1) and a second, containing 1350 years (summit core). The decadal precipitation record derived from these cores is presented in Thompson et al. (1985), while a climatic record of the last 1000 years, including the period incorporating the Little Ice Age, is reviewed in Thompson et al. (1986).

These cores, when drilled in the field on the Quelccaya ice cap, were logged and sectioned according to the visible stratigraphy, melted by passive solar heating, bottled, and shipped to the Ice Core Research Laboratory at The Ohio State University. The Quelccaya cores were analyzed for microparticle concentration and size distributions using TAII Coulter Counters; in addition analyses were conducted for liquid conductivity and particle characterization. Oxygen isotope analyses of core 1 were performed at the University of Washington and analyses of the summit core at the University of Copenhagen. In 1993 two ice cores were drilled to bedrock on the 6047 masl col of Huascarán (9° 06' 40.8"S: 77° 36' 52.7"W). Core 1 (160.3 meters in length) was returned as 2750 bottled water samples while core 2 (166.1 meters in length) was returned frozen to the freezers at The Ohio State University (OSU). The Huascarán cores are currently being analyzed for microparticle concentration and size distribution, chemistry (both anions and cations), oxygen isotopes and Beta radioactivity at the new ice core research facilities at OSU. Establishment of the time scale for the Quelccaya cores is reviewed in Thompson, et al. (1986). Of the two cores, core 1 is best suited for analysis of the pre-AD 1000 period, as it contains a continuous, undisrupted record, while the record of the summit core is interrupted by a discontinuity at 153.7 meters, or AD 745, which prevents continuous dating below that point. It should be noted that the time scale becomes less precise deeper in the cores, as several years are contained in one sample, as opposed to the top of the core, where seven to eight samples can be contained in one year. This is due to the thinning of the annual layers with depth; at the surface the thicknesses of the annual layers range up to 1.24 m (ice equivalent) and at the base the annual layers average 1 cm.

In this paper possible relationships between the ice core climate records over the last 1500 years and three very diverse pieces of archeological evidence are examined. These include: (1) the possible relationship between precipitation and the rise and fall of coastal and highland cultures as documented by studies of the Santa Elena Peninsula, Ecuador, and coastal and highland sites in Peru; (2) the possible relationship of two major dust events in the two Quelccaya ice cores around AD 920 and AD 600 to man and climate (Thompson et al., 1988); and (3) possible implications of climate to the occupation and abandonment of the Gran Pajaten. The position of the Quelccaya ice cap and the new Huascarán sites relative to the Santa Elena Peninsula, the Gran Pajaten and the raised fields around Lake Titicaca as well as the locations of the other archeological sites are illustrated in Fig. 1.

South America is rich in archeological evidence of many advanced cultures for which there are no written records. Figure 1 shows the distribution of archeological sites in Peru taken from the Mapa Fisico Politico compilado por el Instituto Geografico Militar Del Peru, 1970. These sites fall into two main groups, coastal cultures and highland cultures. Figure 2 illustrates the decadal averages from AD 470 to 1980 of total dust, conductivity, of $\delta^{18}O$ and net balance (in meters of ice equivalent) for the Quelccaya cores. In Fig. 3 decadal accumulation trends in meters of ice are presented as the composite of core 1 and summit core records. This profile very clearly illustrates marked dry periods from AD 540 to 610, AD 650 to 730, AD 1040 to 1490, and AD 1720 to 1860, and wet periods from AD 760 to 1040 and AD 1500 to 1720. It is important to note that under present climate conditions of El Niño-Southern Oscillation (ENSO) events coastal Ecuador and coastal Peru suffer from heavy rains, while the highlands of southern Peru, where the Quelccaya ice cap is located, generally experience drought conditions (Thompson et al., 1984; Lam and del Carmen, 1986). It is remarkable that Paulsen (1976) reported a similar seesaw relationship in the longer term archeological records documenting the rise and fall of coastal cultures of Peru and Ecuador. In Fig. 3, the cultural record (dating based largely on highly refined ceramic sequences and some C^{14} measurements) from Peru and Ecuador are presented. Paulsen discussed the fact that highland and coastal cultures seemed to flourish out of phase with each other, i.e., highland cultures flourished when coastal cultures were in decline and *vice versa.* Since both the prehistoric coastal and highland civilizations were largely agrarian based and both the coastal areas (due to dependence on a limited water supply) as well as the high plateau areas (being the upper limits of agriculture) are very climatically

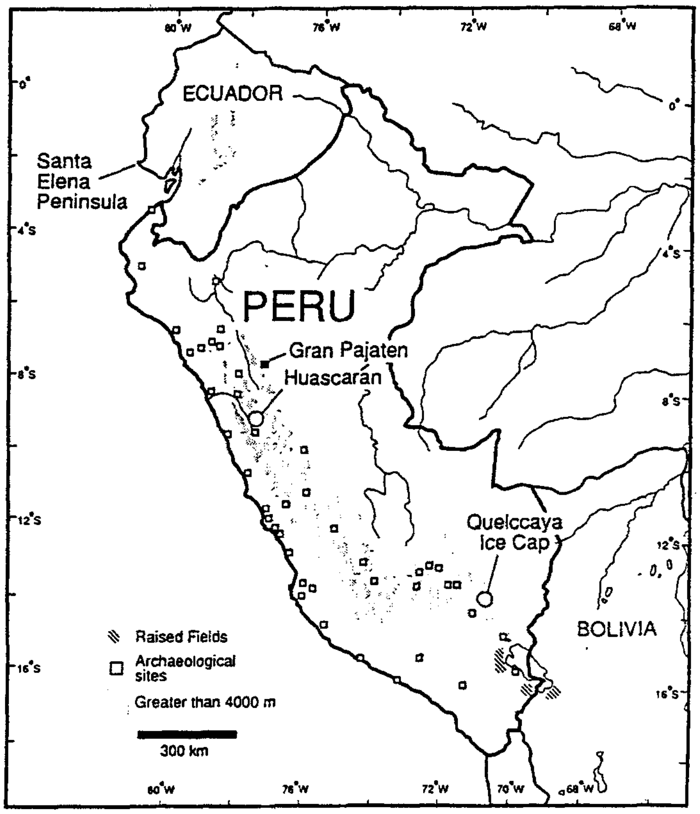

Fig. 1. Location of the Quelccaya ice cap and Huascarán relative to the Santa Elena Peninsula, Ecuador, the Grand Pajaten and raised fields around Lake Titicaca, Peru. The map also presents other archeological sites in Peru relative to elevation. The sites fall into two main groups, coastal and highland.

sensitive (Cardich, 1985), it is likely that climate played an important role in the survival of these cultures. However, the exact role which climate variability has played as a dominant independent variable in prehistoric Andean culture changes is much debated (Paulsen, 1984; Stahl, 1984).

The comparison of the records of accumulation from the Quelccaya ice cores and the archeological history demonstrates that highland cultures flourished during wet periods on the Bolivian-Peruvian plateau; coastal cultures flourished when the highlands were dryer. If we assume that the same seesaw relationship which exists presently during ENSO events (Thompson et al., 1984; Thompson, 1992, 1993) may also hold over the longer periods

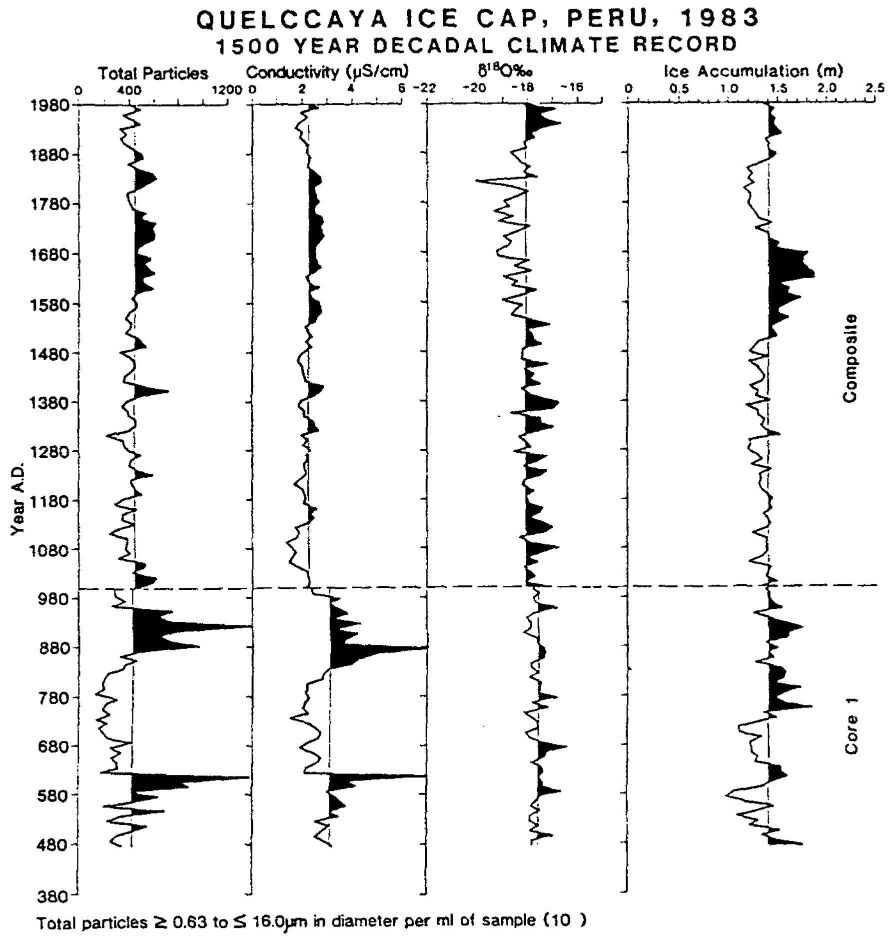

Fig. 2. Profiles of decadal averages from AD 470 to 1980 of total particles (≥ 0.63 to ≤16.0 μm in diameter per ml of sample × 10^3), conductivity, $\delta^{18}O$ and net accumulation (meters of ice equivalent). The dust events of AD 920 and 600 are dominant in the microparticle and conductivity profiles.

of El Niño-like ocean and atmospheric circulation patterns, then we would expect to see wetter coastal conditions during these periods of highland drought. The fact that coastal cultures flourished during the dryer highland periods implies that this seesaw relationship does exist over longer time periods. The new Huascarán ice cores should shed additional light on the potential relationship.

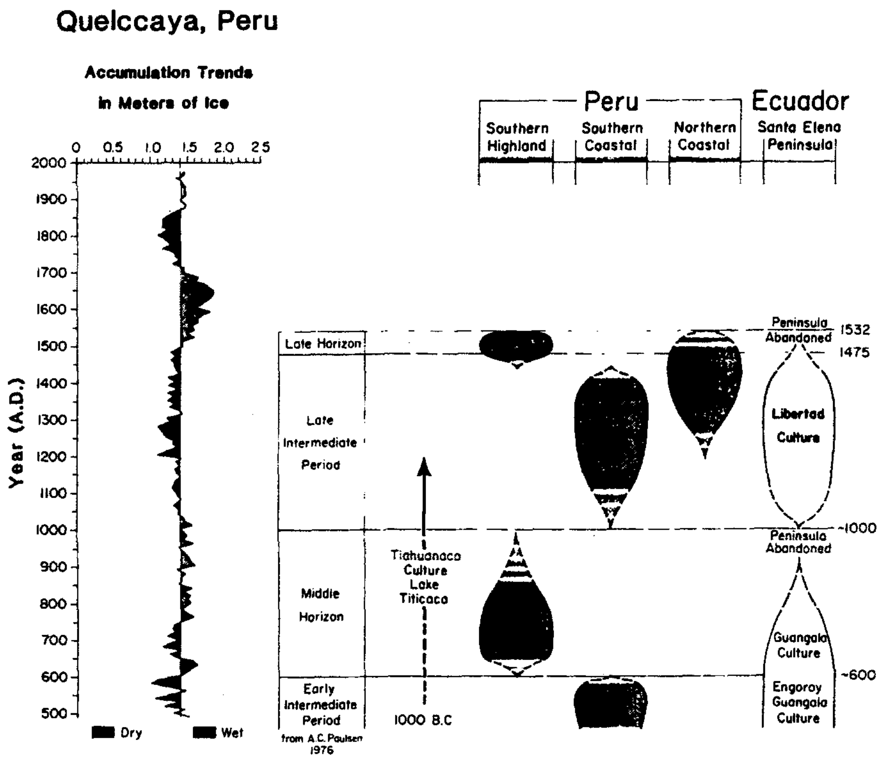

Fig. 3. Decadal accumulation trends in meters of ice presented as a composite of core 1 and summit core records. Wet and dry periods are indicated. On the right the periods of the rise and fall of coastal and highland cultures of Ecuador and Peru are indicated (taken mainly from Paulsen, 1976).

The ice core records provide evidence of the possible impact of humans on the prehistoric environment of the highlands of southern Peru. Pre-AD 1000 decadal averages of microparticle concentration (MPC), liquid conductivity (C) and precipitation profiles for both cores are shown in Fig. 4. Two major events depicted by insoluble and soluble particle profiles are dramatically apparent in both Figs. 2 and 4. The core 1 profiles show these two peaks to have their greatest intensities around AD 920 and AD 600, and depict periods of deposition which were sustained for approximately 60 and 130 years, respectively. The magnitudes are striking, for in no other part of the core do events of these intensities occur over such long time periods. It should be noted that although the estimated error in the time scale increases toward the bottom on each core, the AD 920 event in both cores occurs at the same time on these two independently derived time scales and adds validity to the dating of the prehistoric sections of the Quelccaya cores.

The cause of these anomalous events between AD 500 and AD 1000 cannot be definitively determined. Several possibilities can be ruled out based on combinations of the various core parameters, or on examination of the particles. For example, southern Peru is dotted with several volcanoes which have been active over the past several centuries. Although Quelccaya is located in the vicinity of these volcanos, only one, Huaynaputina, appears to have left an obvious mark on the ice cap since the dominant easterly winds in this region tend to carry volcanic ash toward the Pacific. A major eruption which occurred in AD 1600 deposited a layer of ash over a wide area of southern Peru. A description of the eruption's record in the Quelccaya ice cores can be found in Thompson et al. (1986).

Dust particles from melted ice samples were observed by reflected light microscope and scanning electron microscope equipped with an X-ray energy dispersive system. Micrographs of representative samples are shown in Fig. 5. The particles appear to be ordinary wind-blown dust, a minor number of diatoms and a few large, dark vesicular volcanic shards—essentially the same types of particles which occur throughout the entire lengths of the cores. The pre-AD 1000 microparticle samples show no in-

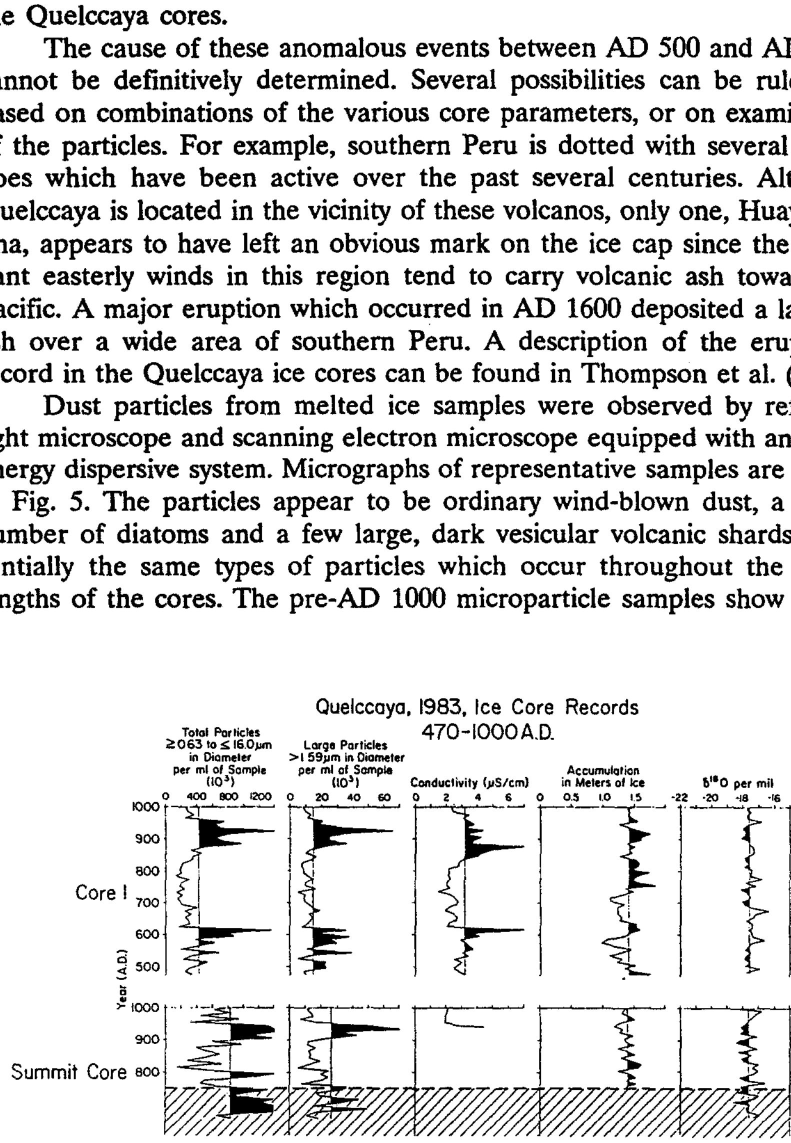

Fig. 4. Decadal variations of total microparticles (>0.63 μm and 1.59 μm diameter), liquid conductivities, net accumulation, and $\delta^{18}0$ for the period from pre AD 1000 span for core 1 and summit core. The dashed line in summit core at 152.8 meters or AD 745 is a discontinuity in the core which prevents continuous dating of the record below that point.

crease in volcanic material. Although a historical record of volcanic eruptions prior to AD 1500 is nonexistent for this area, unusually elevated levels of volcanic activity during these two remarkable periods can effectively be discounted.

The occurrences of two short, separate climatic events marked by lower temperatures and increased storm activity similar to the Little Ice Age (LIA) (which has been established to have been the most significant climatic event in the last 1000 years in southern Peru in Thompson et al., 1986) is likewise not a plausible explanation. The conditions which distinguish the LIA in this region include increased particulates and conductivity, and overall lower $\delta^{18}O$ values. Although, as during the LIA, influx of soluble and insoluble particulates increased dramatically during these earlier events, $\delta^{18}O$ values do not become more negative.

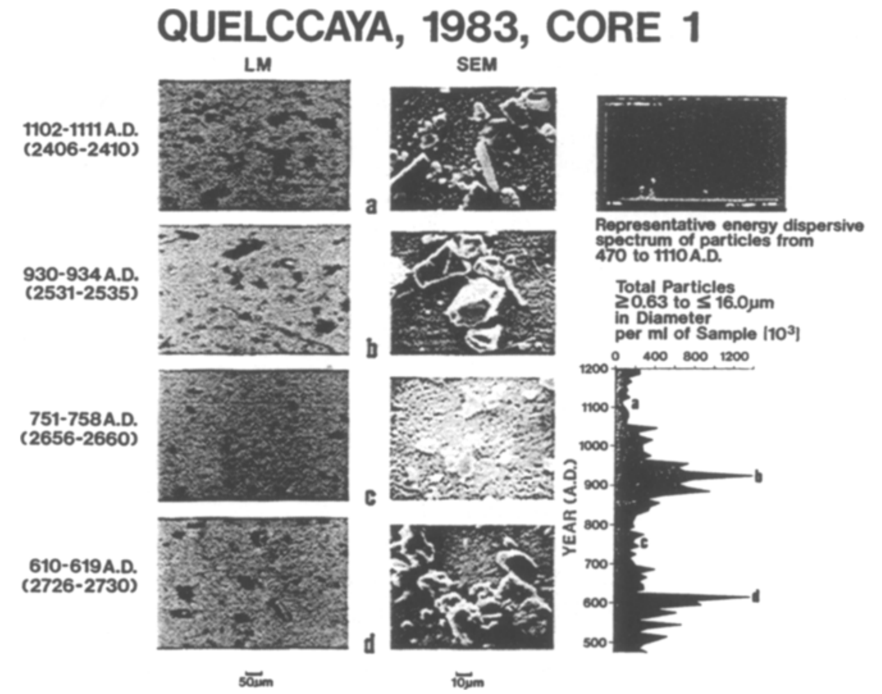

Fig. 5. Illustrates the morphology both from light microscope (LM) and scanning electron microscope (SEM) and elemental composition of characteristic particles for the periods 1102-1111 AD, 930–934 AD, 751–758 AD and 610–619 AD.

Drought conditions have been observed to cause increased particle concentrations and conductivities in several areas of the ice cores. The most notable of recent droughts occurred from 1935 to 1945, an episode which is discernible in both cores (Thompson and Mosley-Thompson, 1987). The reconstructed accumulation record from AD 500 to AD 1000, however, rules out the possibility that dry conditions were the cause of the two events. As Figs. 2 and 4 illustrate, both occur simultaneously with wet periods in the record.

Most of the major natural causes of perturbations in the records of the Quelccaya ice cores can therefore be eliminated as explanations for these unusual features. Drought, volcanic activity, and neoglacial episodes are all present at various times in the record, but the combinations of necessary perturbations which mark their occurrences are absent between AD 500 and AD 1000. Another theory, based on anthropogenic activity is therefore proposed to explain them.

Over many years raised fields with distinctive patterns have been observed around the edges of Lake Titicaca, about 300 km to the south of the ice cap. These fields cover at least 202,796 acres at elevations of 3800-3850 masl, and are the most extensive of their kind in South America (Smith et al., 1968). They may have been used in pre-Incan times for agriculture, although the technique for cultivating the land had been abandoned before the Spanish conquest. For a number of years archaeologists have attempted to date their construction, but even today the results are not conclusive. However, most investigators seem to agree that the fields were abandoned by AD 1400, during the initial rise of the Inca Empire. It is believed that these fields were constructed to reclaim marshlands for cultivation or to protect farmland from occasional inundation by rainfall or rise in river or lake levels (Smith et al., 1968; Denevan, 1970). The possibility exists that utilization of these fields may have introduced soluble and insoluble material into the atmosphere which was deposited on the ice cap. If so, the cores would provide valuable evidence for determining the dates these fields were in use. Further investigation of the soils from the fields and the ice core dust and pollen content yielded no conclusive linkages (Thompson et al., 1988).

These major peaks, on the other hand, may not have been artificially induced. Other major climatic events have been reported in this same time frame. Nials et al. (1979), Moseley et al. (1981), Moseley (1983), and Shimada (1981) have presented archeological and anthropological evidence for a severe ENSO episode tentatively placed at AD 1100 ± 100 and another significantly greater and potentially much longer event around AD 500 ± 200. The large dust events, around AD 920 lasting 60 years and the AD 600 event lasting 130 years, if climatically induced, would have to involve meteorological and oceanographic variations quite different from those characteristic of recent ENSO events. Moreover the two periods in the Quelccaya cores are associated with periods of increased precipitation in southern Peru which is opposite to what would be expected based upon modern analogues of ENSO events (Thompson et al., 1984, 1992).

Finally, the climatic record provided by Quelccaya may have implications for reconstructing the histories of so-called "lost" civilizations in the Andes. For example, according to preliminary information from American and Peruvian archaeologists, the Gran Pajaten, a prehistoric city, was established sometime between AD 500 to AD 1500, during the period for which the Quelccaya ice cores provide a detailed record of climate for this part of the world. It is extremely interesting that this site, which once supported a dense human habitation, is currently in a "cloud forest" 2620 m above sea level, a place of almost perpetual rain (584 cm/year), dense jungle and no human habitation. As demonstrated earlier, the Quelccaya ice core records show that alternating drought and wet periods have occurred over the last 1500 years in the Andes. It is most probable that the Gran Pajaten, as well as other cities in the area, along with terraced fields, were built and occupied during periods of drought such as from AD 540 to 610, AD 650 to 730, and AD 1040 to 1490 (Fig. 3). During these intervals reduced amounts of precipitation may have produced conditions more conducive to human occupation and cultivation of the normal crops of potatoes, oca (oxalis tuberosa), olluco (ullucus tuberosus), quinoa (chenopodium quinoa), and cañihua (chenopodum pallidaule) (Smith et al., 1968). In fact the humid jungle conditions may be a relatively recent phenomenon of the last century when conditions in the high Andes have been wetter than average (Fig. 3). This concept is supported by the fact that in spite of the current extreme humidity of the surrounding rain forest many of the ancient structures are in remarkably good condition.

CONCLUSIONS

The possible role of climate variability in human prehistory in Ecuador and Peru has been examined in light of the proxy climatic records obtained from the two Quelccaya ice cores. The coastal and highland cultures of the region were both largely agrarian and were located in particularly climatically sensitive zones. The coastal cultures were very dependent on a reliable water supply and the highland cultures, being located at the upper limits of agriculture, were sensitive to precipitation and temperature.

Correlations have been established between the shifts of cultural activity between highland and coastal civilizations in the region and the accumulation record reconstructed from the ice cores. This record may also provide a key to determining the succession of habitation and abandonment of sites of so-called 'lost' civilizations uncovered by archaeologists, such as the Gran Pajaten. Two major dust events centered on AD 920 and AD 600 provide evidence of the possible impact of man on the pre-Hispanic environment of the altiplano in southern Peru. The acquisition and analysis of additional ice cores north and south of Quelccaya will provide a very detailed history of climate variability in this part of the world. This detailed climate record in conjunction with the wealth of prehistory archeological data should allow determination of the role climate played in the prehistorical development of man in South America. Two new 1993 ice cores drilled from Huascarán in the Cordillera Blanca of the North Central Andes promise new and exciting climate and environmental records spanning the past 10,000+ years which will allow long-term examination of the human–environmental and the human–climate relationship in this part of the world.

There exists a growing body of evidence for recent and rapid warming in the tropics and particularly in the tropical Andes of South America. Recent studies (Thompson et al., 1993) demonstrate that the record which was recovered from the Quelccaya ice cap in 1983 is no longer being preserved, as melting is now taking place at the summit drill sites and water is moving vertically through the ice cap, destroying the archives of the past. Brecher and Thompson (1993), further demonstrate that not only is the glacier climate archive being destroyed, but in fact the whole ice cap is undergoing a drastic and accelerating rate of retreat. These data illustrate that climatic change is currently underway in the tropical Andes which will, should it persist, undoubtedly test the abilities of today's cultures to adapt to rapid climatic change.

Obtaining records of climate changes for the past is essential to our understanding of how the Earth's climate might change in the future. It is important to obtain a broad distribution of records both spatially and with altitude, as the climate of the earth changes. Unfortunately, as a result of the current warming trend, many of the low-latitude, high elevation glaciers are retreating and may soon disappear. While complete wastage of these ice masses may not occur for decades, increased free-water flow is destroying their structure, and therefore the information they contain. Thus, there is a pressing need to obtain high quality ice cores from these glaciers and ice caps as soon as possible.

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