ONE-HALF MILLENNIA OF TROPICAL CLIMATE VARIABILITY AS RECORDED IN THE STRATIGRAPHY OF THE QUELCCAYA ICE CAP, PERU

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Abstract. For many geographical regions reliable meteorological observations (i.e., temperature and precipitation) and accurate documentation of environmental conditions (i.e., drought, volcanic activity) prior to 1850 are scarce or absent. However such records, whether based upon observations or proxy information, are essential for the reconstruction of past environmental histories. Ice sheets and ice caps have long been recognized as libraries in which the history of the atmosphere is preserved. However, climatic events which most greatly affect the tropical and subtropical regions may not be manifested strongly in the polar regions and thus may not be well recorded in polar ice sheets. Therefore it is essential to secure proxy climatic records from nontemperate tropical ice caps that record paleoclimatic histories unavailable from other proxy sources. This paper presents a 500-year record of tropical climate variability that was extracted from an ice core at the summit of the Quelccaya ice cap. The last 500 years was selected for discussion because the annual layers in the core were sufficiently large so that 2 to 10 samples could be cut from each annual layer. This allowed the record to be resolved on an annual basis. The final time scale is based upon a combination of annual stratigraphic indicators including visible dust layers, microparticle concentrations, conductivity, and oxygen isotope ratios. The time scale has been independently verified since it spans the historical time period that starts with the arrival of the Spanish in 1532. Possible teleconnections are discussed with emphasis on both the Little Ice Age and several very abrupt climatic events. Emphasis is placed on the discussion of unusual periods of climate (A.D. 1590 to 1630, A.D. 1800 to 1840, and A.D. 1915 to 1940) that appear to have had global significance. Finally, data are given that show the annual values of particle concentrations for total particles (diameters greater than or equal to 0.63 μm), large particles (diameters greater than or equal to 1.59 μm), liquid conductivity, oxygen isotope ratios, and the standard deviation of accumulation from A.D. 1485 to 1984.

Introduction

During the last two decades ice cores extending to bedrock have been obtained from the Greenland and Antarctic ice sheets as well as from other high latitude glaciers. Analyses of these cores, particularly the ratios of the stable isotopes of oxygen ($\delta^{18}O$) and hydrogen (δD), the concentration of insoluble microparticles, and concentrations of entrapped CO_2 and methane, have produced extraordinary paleoclimatic records for the polar regions [Langway et al., 1985; Jouzel et al., 1987; Barnola et al., 1987]. The abundance of high latitude records contrasts sharply with the gap in similar information from the tropics. Therefore the opportunity to apply ice core paleoclimatic techniques to the low latitude, high altitude glaciers merits particular attention.

Low and middle latitude ice fields, which are restricted to plateaus of gentle topography, are most desirable for acquiring these records as the effect of ice flow on the stratigraphic record is minimized. Additionally, summit elevations should be sufficiently high so that low temperatures preclude significant melting and percolation. Ice caps located in areas dominated by marked seasonal variations in weather patterns generally contain a distinct seasonality that may be preserved in the visible and (or) chemical stratigraphy. The length of the climatic record that can be extracted is a function of the ice cap thickness, net balance, and ice temperature [Thompson et al., 1979].

The Quelccaya ice cap (13°56′ S., 70°50′ W.) is situated in the easternmost glaciated mountain chain of the Peruvian Andes (Figure 1). The ice cap covers approximately 55 km², has a summit elevation of 5670 m, and lies on top of a gently undulating ignimbrite plateau.

Each summer between 1976 and 1984 research was conducted on the Quelccaya ice cap with one central objective: to recover an ice core to bedrock from which a 1000-year climatic history for tropical South America could be reconstructed. In 1983 one core, 155 meters in length containing 1350 years of recorded history, and a second core, 163.6 meters in length containing 1500 years of climatic history, were recovered [Thompson et al., 1985].

The lack of historical records from the southern hemisphere, particularly South America, has hindered attempts to describe global changes in climate from the historical record. Precipitation records are one of the most difficult paleoclimatic records to obtain. In Peru the longest historically recorded precipitation records cover only the past several decades. However, appropriately selected ice caps offer the best opportunity to obtain proxy precipitation records. The Quelccaya records have extended that record to A.D. 470 and illustrate that there have been significant changes in precipitation over the last 1500 years [Thompson et al., 1985, 1986, 1988, in press]. The Quelccaya records also provide other annually resolvable histories of climate variations such as major droughts, El Niño-Southern Oscillation events, volcanic activity, and possibly temperatures [Thompson et al., 1984a, b; Thompson et al., 1986]. For example, there was a 140-year drought from A.D. 1720 to 1860 when accumulation was 15 percent below the 1500-year average. On the other hand during a 220-year period, from A.D. 1500 to 1720, accumulation was 20 percent higher than the 1500-year average.

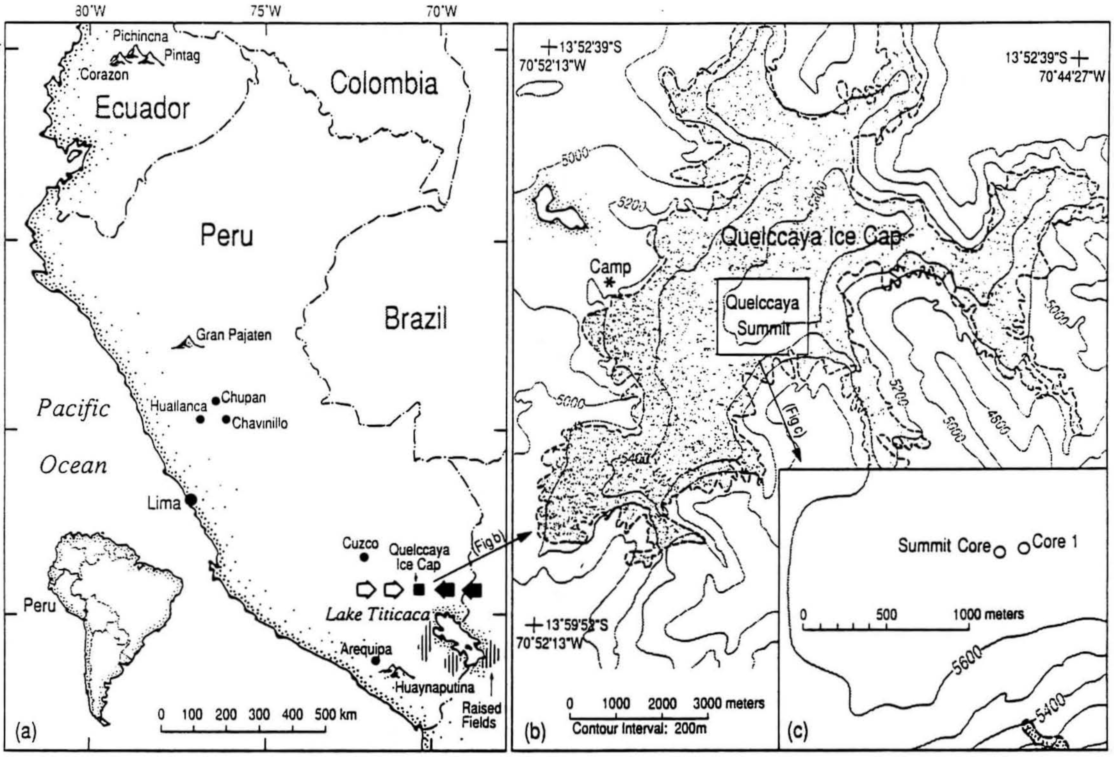

Fig. 1(a). Location of the Quelccaya ice cap in Perú. Dark arrows indicate dominant wet season wind directions and open arrows indicate dominant dry season wind direction. 1(b) shows ice cap topography and 1(c) illustrates the location of the two deep ice cores drilled in 1983.

Study Area

Each year from 1976 to 1984, for periods extending from 3 to 8 months, hourly temperature records were obtained at the Quelccaya summit using automatic weather stations (RIMCO Mark III). Daily mean temperature ranges from −5 °C in southern winter to −2 °C to −3 °C in summer. Surface heat-budget studies, including lysimetric measurements and bulk aerodynamic estimates based on data collected during the dry ablation period (May through September), indicate that there is essentially no energy available for evaporation and melting.

Under current meteorological conditions the thickness of the layer accumulating at the summit each year should reflect the regional precipitation. A 1500-year net balance record has been reconstructed from these ice cores and provides a well-dated precipitation history with excellent temporal resolution (annual to decadal) for southern Peru [Thompson et al., 1985]. This reconstructed net balance record represents a complex integration of local and large-scale climate variations. The wet season typically extends from November to April when the sun is nearly in the zenith. The high Peruvian-Bolivian Altiplano, as well as the lower atmosphere, is heated by intense solar radiation before noon when cloudiness is minimal.

To the south and west along the axis of the Andes a greater proportion of the annual total precipitation falls in the wet season and accounts for slightly more than 80 percent of the annual precipitation in the area of Quelccaya. This seasonality of precipitation leads to the distinct annual stratigraphy preserved in the ice. Three representative core sections (Figure 2) show the distinct annual dust layers used to date these cores. Note the thinning of the annual layers that occurs with depth. Annual-layer thicknesses (ice equivalent) ranges from 1.2 m at the surface to 0.01 m at the base.

Methods

The time scale is based on the integration of visible dust layers, annual layers in oxygen isotopes, microparticles, and annual conductivity. The presence of two ice-core records allows better resolution of time scale, especially in problem areas that may arise in either core such as when the core is broken into sections during drilling. On average individual core sections were 2 m in length and 8 cm in diameter. Selected core sections were analyzed in the field for both liquid and solid conductivity. Six thousand samples were collected for microparticle and oxygen isotope analyses and 1500 samples for total Beta radioactivity and chemical measurements.

The very accurate dating of the Quelccaya ice cap cores results directly from the use of multiple stratigraphic features that exhibit seasonal variability. Age estimates for the bottom of the ice cap were derived initially from flow-model calculations [Thompson et al., 1982], which depended heavily upon initial assumptions and boundary conditions. Fortunately, the visible annual dust layers were used to date core in the field. The visible stratigraphy was complemented by the preservation of annual variations in microparticle concentrations, conductivity levels, and oxygen isotope ratios. The development of a time scale has been discussed more extensively elsewhere [Thompson et al., 1986]. The Quelccaya cores have been dated to A.D. 1500 with an estimated uncertainty of plus or minus 2 years and an absolute date of A.D. 1600 where ash from the Huaynaputina eruption has been identified.

The analysis of microparticle concentrations and size distribution [Thompson, 1977] is conducted under Class 100 clean room conditions using two Model TA II Coulter Counters, which electronically separate particles into 15 size ranges between 0.4 and 16 μm in diameter. The microparticle concentration data are presented as total particles (diameter greater than

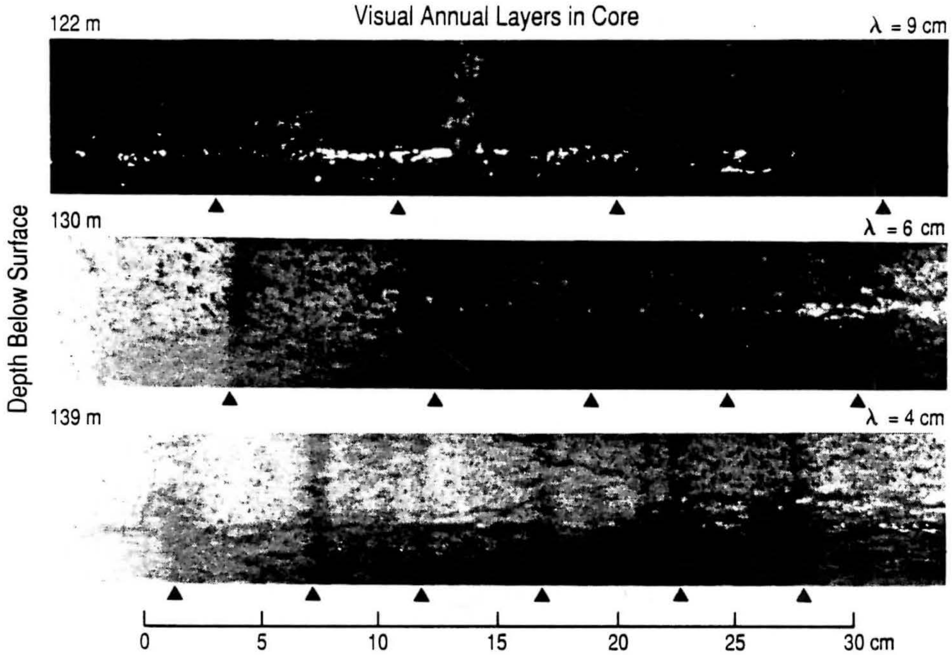

Fig. 2. Three representative core sections show the distinct dry season dust layers (triangles) used to date the cores. The average thickness of these (λ) annual layers is shown and the annual layer thinning with depth is evident.

or equal to 0.63 μm) per milliliter (mL) sample. Electrolytic conductivity, measured under Class 100 clean room conditions using an Altex RC-16C Conductivity Bridge, furnished an excellent estimate of the soluble impurities in the meltwater. Conductivity measurements, in microsiemens cm^{-1}, have an accuracy within 1 percent of the reading. All measurements were conducted under temperature conditions of 21 °C plus or minus 1 °C and with replicate analyses to insure reproducibility. The oxygen isotope ($\delta^{18}O$) analyses were conducted at the University of Copenhagen (Denmark) for summit core and at the University of Washington for Core 1. The oxygen isotope results are expressed as $\delta^{18}O$, the relative difference in isotopic abundance ratio $^{18}O/^{16}O$ between the sample and the Vienna Standard Mean Ocean Water (V-SMOW) expressed in per mil (°/oo). Control samples for interlaboratory comparison indicate a maximum difference of only 0.30 °/oo.

Overview of the Annual Climatic Variability for the Last 500 Years From the Summit Core

The analyses of two ice cores from a southern tropical ice cap provides a record of climatic conditions over 1500 years for a region where other proxy records are nearly absent. Decadal variations in microparticle concentration (total particles greater than or equal to 0.63 to 16.0 μm and large particles greater than 1.59 μm in diameter per milliliter of sample), conductivity, oxygen isotopic ratios, and net accumulation for the past 1000 years are presented in Figure 3. The accumulation record is from core 1 [Thompson et al., 1985]. The "Little Ice Age" (LIA) stands out clearly as an increase in dust from 1490 to 1880 and a decrease in the $\delta^{18}O$ values from 1520 to 1900 as a major climatic event in tropical South America.

Figure 3 gives the longer time perspective for the annual averages (Figure 4) of microparticle concentrations, conductivity, accumulation and $\delta^{18}O$ measurements for the last 500 years. The field dating of the core was independently verified; hence this portion of the summit core record can be discussed with greatest confidence.

The most significant climatic event evident in all the ice core parameters in tropical South America over the last 1500 years is the LIA, which is distinctly recorded in several ice core parameters between A.D. 1490 to 1880 [Thompson et al., 1986]. The LIA is recorded in the northern hemisphere from the early 1500's to the late 1800's and is characterized by colder temperatures and expanded glaciers. The dates of the LIA, determined from historical and proxy climate records, span ranges from A.D. 1430 to 1900. The timing of the LIA is apparently dependent upon both the location and the observed parameter.

As is illustrated in Figure 4, the records from the summit of the Quelccaya ice cap show that the LIA was characterized by: (1) an overall increase in particulates (both insoluble and soluble) starting around A.D. 1490 and ending abruptly in A.D. 1880, (2) an initial increase in net accumulation (A.D. 1500–1720) followed by a marked dry period (A.D. 1720–1860), and (3) more negative $\delta^{18}O$ values beginning in the 1520's and ending around A.D. 1880. Although inferences about temperature from $\delta^{18}O$ must be made cautiously, Thompson et al. [1986] demonstrated that the northern hemisphere mean decadal temperature departures from the 1881–1975 mean (compiled by Groveman and Landsberg [1979] from long temperature series including Manley's central England temperature record back to 1658 and from proxy data including freeze records and tree rings before 1658) and the Quelccaya summit core $\delta^{18}O$ record are related remarkably well. Note in both Figures 3 and 4 that the LIA event is evident as a perturbation in all five ice core parameters. Figure 4 illustrates that the initial increases in conductivity, large particles, and accumulation began 30 years before the decrease in the $\delta^{18}O$ signal.

During the LIA in southern Peru microparticles and conductivities increased as much as 30 percent above their respective averages for the entire core. Increases in particulates may reflect increased atmospheric impurities and (or) decreased accumulation. However, the accumulation history (Figure 4) from Quelccaya is well documented [Thompson et al., 1985] and indicates that the increase in particulates at the onset of the LIA must reflect increased atmospheric loading because the period A.D. 1500

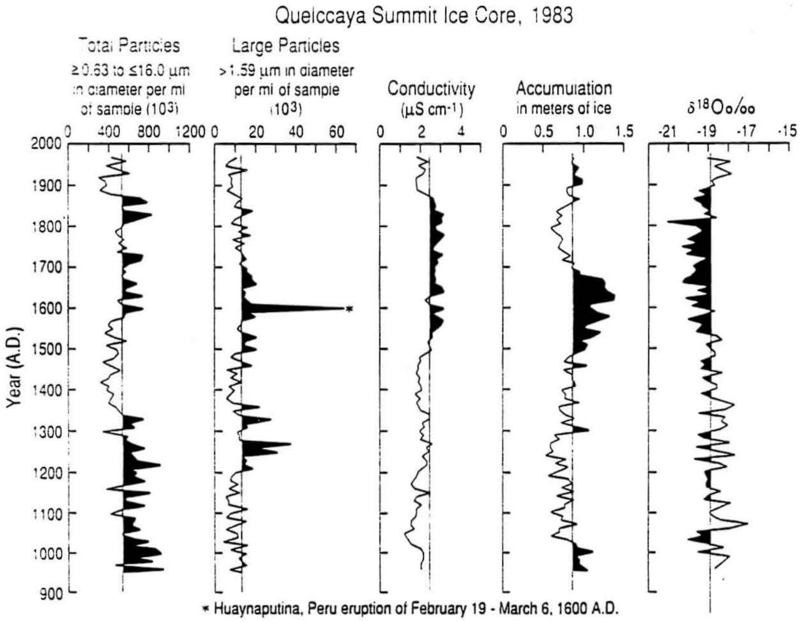

Fig. 3. Decadal variations in microparticle concentrations (total particles <0.63 μm and greater than 1.59 μm diameter), liquid conductivities, net accumulation, and $\delta^{18}O$ over the last 1000 years [Thompson et al., 1986]. The solid line represents the 1000 year averages. The "Little Ice Age" appears as the largest climatic event in the last 1000 years in tropical South America.

to 1720 was an extremely wet period. Similarly, A.D. 1720 to 1860 is a very dry period, and yet both the particles and conductivities remain unchanged from previous wet period values. These data suggest that the variations in concentrations of microparticles and conductivity cannot be explained solely by changes in the rate of snow accumulation. The preliminary scanning electron microscope and light microscope analysis of insoluble particles show no significant change in the type of particles deposited during the LIA; thus it is most likely that the increase is a result of more vigorous winds across the high altiplano of southern Peru, at least during the first half of the LIA. Tradition increased aridity may have contributed to the high particle concentration during the latter half of the LIA.

Historical Documentation and Its Relationship to the Ice Core Climate Record

Since historical and prehistory coastal and highland civilizations in Peru, Ecuador, and Bolivia were largely agrarian based, and since 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 sensitive [Cardich, 1985], it is likely that climate played an important role in the survival and economical well being of these cultures. The role that climate variability has played as a dominant independent variable in prehistoric Andean culture changes is much debated [Stahl, 1984; Paulsen, 1976, 1984].

Here we look at specific historically documented aspects of the recent climate in this area of South America to examine how it is related to the ice core climatic records. As the Inca and pre-Inca cultures had no written language there is not a written documentation of South American climate prior to the arrival of the Spanish in 1532. Even in the historical period from 1532 to the present, good documentation is largely missing prior to 1850.

The chronicles and other writings during the 16th century contain references to the characteristics of the environment. These can be compared with the present environmental conditions as well as with present and past Quelccaya ice core proxy climatic data. For example, snow capped peaks are reported in sectors, such as the Sierra del Norte of Peru, where none exist today [Cardich, 1985]. Other references to subsistence cultivation in the high mountains, such as those of the Visitador Garci Diez de San Miguel in 1567 concerning the residents on the margins of Lake Titicaca, state: "Everyone has his own fields in which are grown potatoes, quinoa *(Chenopodium quinoa Wild.)*, and canagua *(Chenopodium pallidicaule Hellen)*, and where neither wheat nor maize are planted because they do not mature; during most years their food freezes and they go to the coast for food, taking for exchange sheep and wool." [Diez de San Miguel 1964].

The ice core data (Figure 4 and Table 1) indicate that A.D. 1565 to 1578 was characterized by very low isotopic values suggesting colder temperatures and by relatively high precipitation. Thus these ice core data support the descriptive historical data of this period.

Two centuries ago the botanist Hipólito Ruiz visited the upper Marañón during one of his trips to Peru [Cardich, 1985]. Referring to the settlements of Chavinillo and Chupán in the Department of Huánuco (fig. 1), Ruiz stated that they occupy elevated zones where the climate is very cold. Concerning Chupán, a village on the right side of the Marañón at an altitude of 3450 m, he remarked that it is in a region of natural pasture where only potatoes were grown, and these were confined to sheltered portions of the terrain below the village [Ruiz 1940]. Cardich reports that today the climate is milder, and agriculture is possible considerably above the town. In addition barley, habas *(Vicia faba L)*, oca *(Oxalis tuberosa Mol.)*, olluco *(Ullucus tuberosus Lozan.)*, wheat, and even maize are also raised in the vicinity of the town. Natural pastures in this area, suitable only for grazing, have been substantially displaced upward.

The ice core records show that indeed two centuries ago southern Peru was in the extremes of the LIA climate characterized by more negative oxygen isotope values (estimated at 1-5 °C colder temperatures) and drought. Undoubtedly, both colder temperatures and lower precipitation

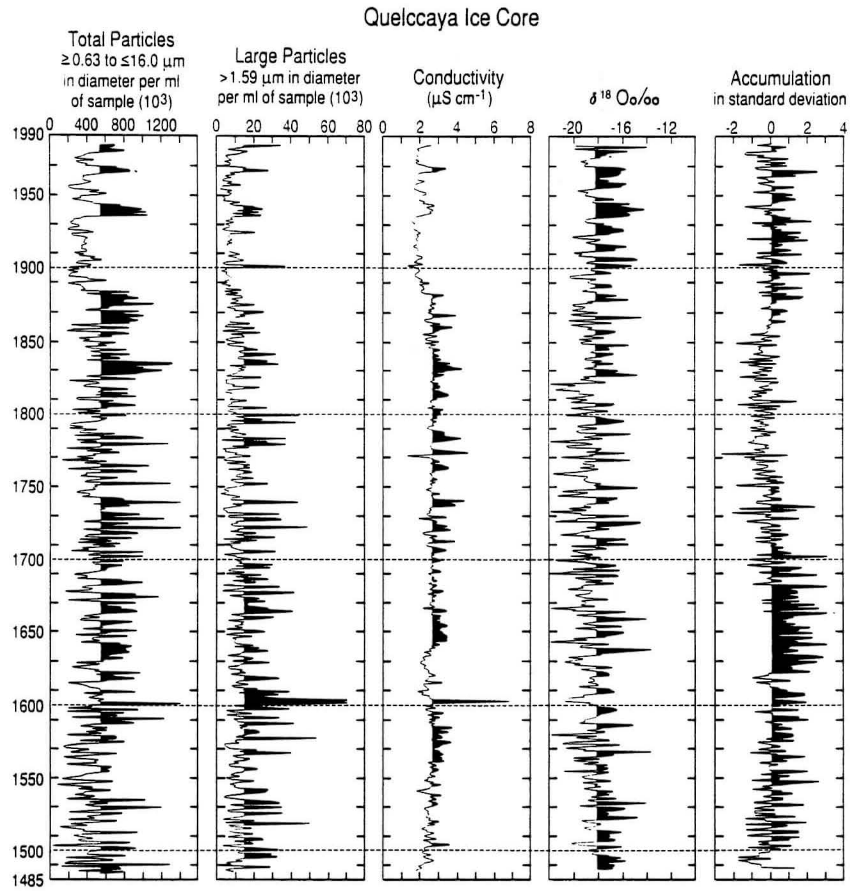

Fig. 4. Illustrates annual variations in microparticle concentrations (total particles greater than or equal to 0.63 to less than or equal to 16.0 μm and large particles greater than or equal to 1.59 μm in diameter, per mL of sample), conductivity, oxygen isotope ratios, and accumulation in standard deviation for the last 500 years. The Little Ice Age (A.D. 1500 to 1880) stands out clearly and is characterized by increased soluble and insoluble dust and decreased $\delta^{18}O$. It appears to have been a major climatic event in tropical South America. The large dust event, centered on A.D. 1600, was produced by the February 19 to March 6 eruption of Huaynaputina, Perú.

would have contributed to the poor crops in the highlands of southern Peru during this period of time. The ice core data reveal less negative oxygen isotope values (milder temperatures) and more precipitation during the last 100 years.

Middendorf [1974] reported nearly a century ago that Huallanca in the highlands of Huánuco at 3500 m elevation "is surrounded by puna, covered only by grass." At present this village is encircled by eucalyptus trees and by cultivated fields, which produce good crops of potatoes, barley, and other cultigens. Both forest and fields extend well above the settlement.

The ice core proxy climate record shows an abrupt termination of the LIA around A.D. 1880. Prior to that time the climate was predominantly cold and dry, but shortly after 1880 milder and wetter conditions prevailed and have characterized the last 100 years. Again the climatic conditions suggested by the ice core data are consistent with the historical description.

More recently the greatest historically recorded drought in southern Peru occurred from 1933 to 1945. The drought resulted in a large drop in Lake Titicaca water levels over this period [Newell, 1949] and is evident in the precipitation record from El Alto in Bolivia. Lake Titicaca, the highest large lake in the world (3812 meters above sea level), covers 8446 km². From 1933 to 1945 water levels dropped almost 5 m [Newell, 1949, p. 10–17] causing extreme difficulties for the Peruvian Corporation that operated a fleet of steamboats. The lake was closed to traffic for several years, and installations were abandoned because of the shallowing.

Excellent evidence of this drought is preserved in the Quelccaya ice core records. From 1934 to 1945 (Figure 4) note the reduced accumulation, the increase in the concentration of both large and small particles, and higher conductivities. In association with this drought the $\delta^{18}O$ ratios are less negative than those associated with the wetter conditions, which prevailed several decades prior to and since that time. The substantial increase in particle concentration and conductivities probably result from the increased dryness of the Altiplano in association with the drought.

Hastenrath [1981] reports that further north, in the Ecuadorian Andes, the documentation of former ice conditions is exceptional for the tropics as it spans several centuries in varying detail. Over the last 100 years there has been a gradual upward displacement of the snow line in the Andes near Quito. Glaciation during the 1500's and the first half of the 1700's was more intense than at present. In particular, east of Pintag (Figure 1) there are indications that a portion of the eastern Cordillera, which rises to little more than 4400 m, may have been perennially snowcapped during the 1500's. Pichincha and Corazán had a perennial snow/ice cover in the 1500's,

TABLE 1. Annual Averages of Dust Concentrations, Conductivity, Oxygen Isotopes, and Ice Accumulation as Deviations From the Mean, Quelccaya Summit Ice Core, 1475-1984

[The Quelccaya summit core average annual values of small particles (diameter greater than or equal to 0.63 μm and less than or equal to 0.80 μm), total particles (diameter greater than or equal to 0.63 μm) and large particles (diameter greater than or equal to 1.59 μm) per mL of sample, conductivity in $\mu S\ cm^{-1}$, oxygen isotopes in parts per thousand ($\delta^{18}O$) and ice equivalent accumulation (percent of as standard deviation, σ = 0.34 m) for each thermal year from A.D. 1475-1984. Values for years 1980-1984 are based on snowpit samples collected during field seasons in each of those years. The period from A.D. 1475-1984 represents that portion of the core for which sufficient numbers of samples existed so that the annual visible dust layer time scale could be confirmed with annual microparticle, conductivity, and oxygen isotope data. The ice core data are dated to A.D. 1500 with an estimated uncertainty of plus or minus 2 years and an absolute date of A.D. 1600 where ash from the Huaynaputina eruption has been identified.]

Year	Samples		Particle Concentrations per Milliliter Sample			Electrical Conductivity ($\mu S\ cm^{-1}$)	$\delta^{18}O$	Accumulation (ice equivalent) Percent of Standard Deviation
			.63-.80 μm*	>.63 μm*	>1.59 μm*			
1984-1983	1	29	310,720.	701,720.	34,300.	2.60	−19.93	0.236
1983-1982	1	19	370,780.	681,080.	16,380.	2.26	−14.11	−.796
1982-1981	1	30	288,860.	599,680.	9,700.	1.99	−19.99	.774
1981-1980	1	27	418,780.	615,700.	5,920.	1.83	−17.58	.236
1980-1979	15	23	512,449.	801,436.	16,413.	1.94	−15.65	.058
1979-1978	24	30	361,637.	566,449.	13,500.	1.85	−17.42	.237
1978-1977	31	38	270,300.	412,235.	10,710.	1.79	−17.36	−1.386
1977-1976	39	44	267,463.	378,820.	4,260.	1.79	−17.89	−1.457
1976-1975	45	51	240,706.	337,306.	5,757.	1.90	−17.82	−.382
1975-1974	52	59	171,430.	258,448.	6,188.	1.92	−18.76	−.816
1974-1973	60	70	324,545.	467,971.	7,920.	1.69	−18.99	.915
1973-1972	71	80	197,702.	276,404.	3,700.	1.96	−19.49	−.104
1972-1971	81	88	180,730.	310,418.	7,195.	1.72	−18.80	−.821
1971-1970	89	98	274,250.	405,124.	7,210.	1.87	−19.15	.738
1970-1969	99	105	236,037.	371,070.	3,370.	2.23	−19.13	−.379
1969-1968	106	114	456,283.	717,440.	15,705.	2.40	−16.43	.825
1968-1967	115	120	442,020.	693,677.	13,793.	3.39	−15.74	−.924
1967-1966	121	127	562,534.	845,777.	27,594.	3.03	−16.44	−.807
1966-1965	128	134	549,363.	861,391.	12,531.	2.89	−16.17	.043
1965-1964	135	145	392,404.	600,253.	6,540.	2.09	−16.28	2.467
1964-1963	146	153	317,765.	490,980.	9,830.	1.85	−16.46	1.747
1963-1962	154	162	241,783.	349,263.	4,295.	1.80	−16.95	.250
1962-1961	163	173	222,660.	367,858.	7,665.	1.82	−18.05	1.311
1961-1960	174	182	203,929.	346,360.	4,133.	1.87	−17.87	−.830
1960-1959	183	189	236,869.	364,540.	2,911.	1.85	−17.15	−.182
1959-1958	190	197	279,806.	442,017.	8,326.	2.24	−18.25	−.249
1958-1957	198	206	254,342.	381,624.	4,811.	1.88	−15.74	.149
1957-1956	207	214	170,808.	315,505.	12,800.	1.72	−16.23	−.726
1956-1955	215	221	123,740.	194,060.	2,757.	1.76	−16.12	−.374
1955-1954	222	230	124,544.	203,233.	2,647.	1.67	−17.73	.037
1954-1953	231	240	145,094.	245,948.	1,950.	1.63	−18.65	1.212
1953-1952	241	246	313,257.	529,470.	8,130.	1.77	−19.77	.083
1952-1951	247	255	274,236.	410,560.	4,773.	1.96	−18.76	.208
1951-1950	256	260	358,468.	606,072.	7,844.	2.30	−18.99	−1.007
1950-1949	261	270	311,206.	508,002.	6,246.	2.33	−19.08	.600
1949-1948	271	279	198,624.	319,827.	3,084.	2.11	−18.52	1.144
1948-1947	280	287	194,925.	336,223.	4,053.	2.05	−17.96	.182
1947-1946	288	296	130,067.	231,073.	4,711.	1.98	−16.77	.733
1946-1945	297	306	231,336.	363,060.	3,202.	1.93	−18.38	1.301
1945-1944	307	314	293,355.	451,483.	12,178.	2.25	−18.55	.462
1944-1943	315	321	309,557.	465,751.	6,209.	2.11	−15.48	.302
1943-1942	322	329	474,075.	760,995.	8,763.	2.65	−17.26	.016
1942-1941	330	338	449,411.	710,747.	19,289.	2.77	−15.90	.023
1941-1940	339	343	550,016.	861,656.	20,184.	2.31	−15.46	−1.457
1940-1939	344	349	595,868.	986,512.	24,488.	2.53	−14.27	−.847
1939-1938	350	359	533,634.	858,790.	10,386.	2.72	−15.53	0.742
1938-1937	360	366	683,080.	1,029,171.	22,469.	2.49	−16.00	−.446
1937-1936	367	374	419,858.	642,595.	8,075.	2.61	−15.56	.009
1936-1935	375	382	633,727.	1,038,517.	23,577.	2.24	−15.48	−.428
1935-1934	383	388	225,724.	365,228.	9,532.	1.95	−16.48	.243
1934-1933	389	396	206,158.	325,990.	6,913.	1.71	−18.46	.402
1933-1932	397	405	124,338.	248,338.	8,511.	1.67	−19.03	1.062

TABLE 1. Annual Averages of Dust Concentrations, Conductivity, Oxygen Isotopes, and Ice Accumulation as Deviations From the Mean, Quelccaya Summit Ice Core, 1475–1984

Year	Samples		Particle Concentrations per Milliliter Sample			Electrical Conductivity (μS cm^{-1})	$\delta^{18}O$	Accumulation (ice equivalent) Percent of Standard Deviation
			.63–.80 μm*	>.63 μm*	>1.59 μm*			
1932-1931	406	412	135,166.	249,194.	4,520.	1.55	−19.07	.416
1931-1930	413	422	115,722.	207,460.	9,026.	1.54	−18.92	2.184
1930-1929	423	427	115,068.	235,216.	4,632.	1.70	−17.54	−1.092
1929-1928	428	436	177,464.	313,200.	6,924.	1.62	−18.02	.815
1928-1927	437	442	182,640.	311,433.	6,873.	1.67	−16.90	−.582
1927-1926	443	449	110,983.	203,617.	4,591.	1.63	−17.47	.314
1926-1925	450	456	103,266.	175,994.	2,637.	1.62	−16.11	−.124
1925-1924	457	463	197,051.	391,003.	6,417.	1.81	−15.96	.527
1924-1923	464	470	244,089.	466,180.	20,246.	1.86	−16.94	−.044
1923-1922	471	479	124,300.	224,491.	6,913.	2.02	−17.14	1.599
1922-1921	480	487	135,253.	234,575.	5,740.	1.77	−18.78	.448
1921-1920	488	494	228,257.	355,983.	6,606.	1.90	−20.19	.598
1920-1919	495	504	245,740.	403,078.	6,448.	1.85	−19.58	1.471
1919-1918	505	509	181,684.	363,344.	8,144.	1.75	−17.85	−1.369
1918-1917	510	516	249,680.	374,749.	5,171.	1.85	−18.28	1.980
1917-1916	517	526	189,482.	348,214.	8,242.	1.80	−19.09	.565
1916-1915	527	530	251,615.	393,315.	4,975.	1.82	−18.60	−.174
1915-1914	531	537	201,851.	325,777.	5,903.	1.78	−17.29	.608
1914-1913	538	542	192,344.	349,812.	5,820.	1.61	−15.78	.398
1913-1912	543	548	170,880.	326,710.	5,617.	1.82	−17.33	−.015
1912-1911	549	555	238,671.	393,774.	6,074.	1.86	−16.74	.240
1911-1910	556	563	205,015.	389,213.	6,385.	1.90	−18.04	1.056
1910-1909	564	568	152,288.	251,860.	9,556.	1.80	−20.00	.360
1909-1908	569	573	218,080.	363,444.	12,200.	1.78	−19.33	−.807
1908-1907	574	580	190,206.	299,951.	5,526.	1.79	−19.70	1.626
1907-1906	581	585	296,560.	481,912.	10,240.	2.10	−18.24	−.414
1906-1905	586	589	239,680.	418,100.	10,880.	2.07	−15.20	−.876
1905-1904	590	593	276,655.	548,140.	14,105.	1.82	−14.82	.150
1904-1903	594	599	183,250.	308,113.	4,753.	1.80	−18.70	.468
1903-1902	600	605	184,330.	268,077.	2,807.	1.65	−19.03	.687
1902-1901	606	611	255,515.	439,710.	5,170.	2.11	−17.22	.856
1901-1900	612	615	206,733.	428,653.	36,300.	1.22	−15.33	−1.766
1900-1899	616	619	132,440.	210,875.	4,230.	1.66	−16.59	.400
1899-1898	620	625	197,277.	313,017.	5,103.	1.88	−18.50	.268
1898-1897	626	628	98,220.	176,573.	2,047.	1.94	−18.68	−.522
1897-1896	629	634	155,163.	299,660.	5,380.	1.95	−17.64	.322
1896-1895	635	639	128,548.	225,016.	4,840.	1.81	−16.99	−.489
1895-1894	640	645	106,697.	212,683.	6,033.	1.72	−19.17	2.070
1894-1893	646	650	116,412.	194,260.	7,116.	1.73	−20.33	−.222
1893-1892	651	654	162,615.	400,415.	8,050.	1.84	−20.28	.305
1892-1891	655	659	253,320.	403,872.	6,344.	1.99	−18.19	.479
1891-1890	660	663	401,660.	602,865.	4,000.	2.12	−18.69	.044
1890-1889	664	668	188,920.	292,448.	5,304.	1.92	−18.91	.094
1889-1888	669	670	41,810.	181,410.	2,320.	2.47	−18.60	−.797
1888-1887	671	674	144,495.	323,685.	7,225.	1.92	−16.99	.765
1887-1886	675	678	217,367.	335,460.	4,960.	2.15	−16.92	.026
1886-1885	679	682	178,490.	354,525.	4,680.	2.13	−18.81	−.392
1885-1884	683	690	223,783.	376,595.	12,910.	2.23	−18.97	1.658
1884-1883	691	693	194,240.	317,593.	3,693.	2.04	−19.43	.264
1883-1882	694	699	558,972.	847,776.	10,976.	2.04	−18.11	0.314
1882-1881	700	703	216,095.	388,225.	4,170.	2.27	−18.24	−0.721
1881-1880	704	708	457,290.	821,600.	12,885.	3.26	−16.55	.825
1880-1879	709	714	469,607.	799,310.	13,827.	2.82	−17.88	−.574
1879-1878	715	720	646,847.	943,803.	7,363.	2.72	−17.96	1.733
1878-1877	721	726	407,297.	631,043.	11,750.	2.58	−15.62	1.499
1877-1876	727	731	481,480.	794,584.	10,228.	2.66	−19.01	.144
1876-1875	732	735	295,855.	552,080.	6,460.	2.56	−18.50	.234

TABLE 1. Annual Averages of Dust Concentrations, Conductivity, Oxygen Isotopes, and Ice Accumulation as Deviations From the Mean, Quelccaya Summit Ice Core, 1475-1984—Continued

Year	Samples		Particle Concentrations per Milliliter Sample .63-.80 μm*	Particle Concentrations per Milliliter Sample >.63 μm*	Particle Concentrations per Milliliter Sample >1.59 μm*	Electrical Conductivity (μS cm⁻¹)	$\delta^{18}O$	Accumulation (ice equivalent) Percent of Standard Deviation
1875-1874	736	740	519,408.	1,111,904.	19,844.	2.84	−20.15	.281
1874-1873	741	745	421,896.	671,636.	9,928.	2.51	−20.05	−.071
1873-1872	746	749	380,960.	608,635.	5,225.	2.64	−19.09	−.117
1872-1871	750	754	371,812.	629,372.	9,988.	2.75	−19.34	−.030
1871-1870	755	757	241,813.	375,867.	8,987.	2.41	−20.15	−.596
1870-1869	758	762	571,368.	948,668.	24,656.	2.62	−19.07	.639
1869-1868	763	767	379,188.	631,780.	18,336.	2.38	−18.07	.873
1868-1867	768	771	531,550.	828,195.	11,520.	2.64	−20.28	.016
1867-1866	772	776	674,392.	998,716.	15,244.	3.93	−19.45	.501
1866-1865	777	780	546,170.	802,075.	9,575.	2.72	−14.51	−.044
1865-1864	781	785	564,748.	827,528.	9,124.	2.65	−17.33	.061
1864-1863	786	790	588,280.	938,788.	6,960.	2.20	−20.47	.021
1863-1862	791	794	491,495.	731,115.	6,460.	2.27	−18.23	−.185
1862-1861	795	799	481,560.	854,168.	17,348.	2.62	−16.98	.749
1861-1860	800	804	154,116.	220,156.	5,352.	3.07	−20.28	.109
1860-1859	805	807	327,093.	506,773.	3,767.	2.47	−19.41	−.019
1859-1858	808	811	403,305.	841,010.	19,935.	3.72	−18.51	−.321
1858-1857	812	816	140,768.	244,648.	13,428.	3.01	−18.98	−.027
1857-1856	817	820	117,465.	166,330.	2,675.	2.99	−17.58	−.249
1856-1855	821	824	359,415.	695,840.	22,975.	2.78	−16.66	−.213
1855-1854	825	829	447,748.	841,300.	7,248.	2.73	−17.38	−.177
1854-1853	830	833	300,645.	493,295.	13,740.	2.08	−18.36	−.319
1853-1852	834	837	359,310.	657,520.	14,590.	2.91	−19.29	−1.184
1852-1851	838	841	200,110.	299,240.	7,715.	2.53	−17.57	.477
1851-1850	842	845	303,065.	419,820.	4,075.	2.20	−19.69	−.306
1850-1849	846	849	126,485.	338,315.	7,660.	2.39	−18.55	−.642
1849-1848	850	854	369,132.	697,984.	14,336.	2.98	−19.49	.041
1848-1847	855	857	255,273.	492,520.	4,880.	2.22	−19.29	−.674
1847-1846	858	860	392,770.	602,940.	6,360.	2.84	−15.57	−1.914
1846-1845	861	865	161,644.	364,616.	15,240.	2.49	−18.38	.284
1845-1844	866	870	197,464.	451,204.	15,952.	2.43	−17.30	−.796
1844-1843	871	874	512,385.	814,200.	21,840.	2.86	−17.12	−.554
1843-1842	875	878	241,495.	421,985.	11,075.	3.06	−18.41	−.720
1842-1841	879	882	365,360.	561,405.	12,855.	2.72	−18.78	−.494
1841-1840	883	886	381,480.	850,420.	31,205.	2.68	−16.80	−.464
1840-1839	887	889	167,873.	424,293.	20,460.	2.91	−17.54	−1.035
1839-1838	890	893	464,275.	724,710.	11,100.	3.02	−17.78	−.404
1838-1837	894	899	385,070.	748,873.	10,880.	2.56	−19.13	.441
1837-1836	900	903	190,150.	378,110.	20,105.	3.09	−19.21	−.035
1836-1835	904	908	440,364.	830,324.	26,612.	3.06	−17.73	−1.245
1835-1834	909	912	656,505.	1,310,820.	19,380.	2.62	−18.72	.092
1834-1833	913	916	708,140.	1,260,275.	32,730.	3.62	−16.83	−1.745
1833-1832	917	920	352,840.	575,965.	6,480.	2.99	−18.41	.263
1832-1831	921	924	572,120.	994,300.	15,480.	3.57	−18.13	−1.259
1831-1830	925	928	528,735.	875,865.	10,795.	3.69	−19.32	−.529
1830-1829	929	933	758,784.	1,197,904.	14,512.	4.27	−17.71	.083
1829-1828	934	936	660,173.	994,620.	10,800.	3.36	−16.46	−.714
1828-1827	937	941	510,580.	928,100.	11,096.	3.21	−17.40	.036
1827-1826	942	944	391,433.	666,647.	7,393.	2.55	−16.40	−1.039
1826-1825	945	948	242,710.	377,850.	4,355.	3.28	−14.85	−0.682
1825-1824	949	952	417,860.	664,540.	23,605.	3.04	−19.35	−.208
1824-1823	953	955	510,707.	915,767.	7,987.	2.67	−18.73	−1.761
1823-1822	956	960	93,752.	189,060.	4,156.	2.76	−19.54	.303
1822-1821	961	964	198,745.	496,780.	5,170.	2.75	−18.61	−.925
1821-1820	965	967	283,147.	526,393.	4,347.	2.47	−17.46	−.903
1820-1819	968	973	172,767.	381,800.	9,453.	2.98	−22.22	.396
1819-1818	974	977	204,075.	340,835.	7,530.	2.78	−19.93	−.157

TABLE 1. Annual Averages of Dust Concentrations, Conductivity, Oxygen Isotopes, and Ice Accumulation as Deviations From the Mean, Quelccaya Summit Ice Core, 1475–1984

Year	Samples		Particle Concentrations per Milliliter Sample			Electrical Conductivity (μS cm^{-1})	$\delta^{18}O$	Accumulation (ice equivalent) Percent of Standard Deviation
			.63–.80 μm*	>.63 μm*	>1.59 μm*			
1818-1817	978	981	287,815.	557,450.	22,660.	3.07	−20.55	−.129
1817-1816	982	985	527,315.	832,275.	11,665.	3.01	−20.69	−.694
1816-1815	986	989	334,510.	576,675.	5,010.	2.50	−21.57	−.433
1815-1814	990	994	233,936.	500,952.	4,232.	2.93	−19.52	.071
1814-1813	995	997	528,820.	826,913.	8,240.	3.09	−19.64	−1.108
1813-1812	998	1,001	298,805.	476,395.	8,275.	3.25	−19.68	−.238
1812-1811	1,002	1,006	614,580.	919,444.	8,204.	3.53	−18.43	−.946
1811-1810	1,007	1,010	138,620.	267,085.	8,575.	3.46	−19.18	−.556
1810-1809	1,011	1,013	150,347.	287,633.	6,487.	2.75	−20.76	−1.276
1809-1808	1,014	1,016	336,780.	672,440.	15,933.	2.90	−18.95	−1.008
1808-1807	1,017	1,020	253,605.	502,690.	7,205.	2.49	−19.43	−.989
1807-1806	1,021	1,029	468,867.	720,538.	7,949.	2.62	−20.35	1.374
1806-1805	1,030	1,031	690,110.	913,350.	5,270.	2.60	−16.66	−.519
1805-1804	1,032	1,036	367,788.	619,104.	5,604.	2.61	−16.95	−1.822
1804-1803	1,037	1,042	306,513.	599,467.	26,773.	2.81	−18.49	.501
1803-1802	1,043	1,045	123,600.	221,567.	5,880.	2.35	−20.38	−1.278
1802-1801	1,046	1,048	292,027.	532,800.	5,607.	3.23	−18.52	.296
1801-1800	1,049	1,052	137,375.	279,865.	10,130.	2.93	−17.24	−.983
1800-1799	1,053	1,056	410,700.	595,180.	7,885.	3.07	−18.74	−.308
1799-1798	1,057	1,062	381,300.	805,747.	44,197.	3.03	−19.55	.110
1798-1797	1,063	1,065	239,213.	425,887.	9,680.	2.95	−20.74	.002
1797-1796	1,066	1,070	314,124.	607,996.	15,132.	2.82	−18.14	−1.176
1796-1795	1,071	1,073	355,147.	567,200.	24,107.	2.92	−17.69	.183
1795-1794	1,074	1,077	335,900.	511,515.	6,735.	2.47	−17.19	−.468
1794-1793	1,078	1,081	103,205.	321,340.	42,210.	2.89	−16.02	−.990
1793-1792	1,082	1,085	152,465.	218,840.	7,090.	2.70	−16.97	−.427
1792-1791	1,086	1,089	114,735.	206,060.	4,740.	2.67	−18.24	−.681
1791-1790	1,090	1,094	205,772.	352,536.	10,740.	2.72	−19.71	−.111
1790-1789	1,095	1,096	119,800.	194,940.	2,500.	2.44	−19.81	−.367
1789-1788	1,097	1,099	260,407.	497,107.	11,680.	2.34	−18.19	−1.182
1788-1787	1,100	1,104	183,664.	328,880.	6,452.	2.60	−19.40	−.327
1787-1786	1,105	1,107	133,980.	308,853.	9,973.	3.08	−19.90	−1.151
1786-1785	1,108	1,112	314,632.	691,264.	15,588.	3.31	−19.57	.278
1785-1784	1,113	1,116	125,555.	247,960.	11,810.	3.26	−15.40	−.608
1784-1783	1,117	1,120	508,740.	878,750.	7,195.	3.18	−18.30	−.048
1783-1782	1,121	1,124	455,090.	1,000,520.	36,915.	3.38	−19.29	−.946
1782-1781	1,125	1,127	155,727.	276,067.	2,393.	4.18	−17.74	−.786
1781-1780	1,128	1,131	233,770.	493,680.	26,675.	3.53	−19.38	−.943
1780-1779	1,132	1,134	81,033.	311,347.	24,127.	3.16	−22.18	−.927
1779-1778	1,135	1,137	609,707.	1,261,293.	36,727.	2.59	−19.14	−1.321
1778-1777	1,138	1,141	241,290.	565,080.	7,690.	2.63	−18.50	−.720
1777-1776	1,142	1,145	204,100.	530,655.	17,120.	2.50	−20.74	−.113
1776-1775	1,146	1,148	84,520.	165,780.	2,540.	2.59	−20.49	−.391
1775-1774	1,149	1,152	436,380.	658,715.	4,800.	2.55	−17.82	−.075
1774-1773	1,153	1,155	232,633.	382,007.	4,300.	2.80	−18.03	−.954
1773-1772	1,156	1,158	429,107.	741,613.	10,987.	3.48	−19.12	−.488
1772-1771	1,159	1,161	295,633.	447,720.	8,493.	4.58	−15.94	−.321
1771-1770	1,162	1,166	193,780.	488,904.	18,188.	2.97	−18.85	−2.729
1770-1769	1,167	1,168	76,480.	273,410.	6,980.	1.25	−18.52	0.931
1769-1768	1,169	1,171	292,533.	457,987.	5,247.	2.47	−21.15	−1.493
1768-1767	1,172	1,173	87,200.	116,400.	3,170.	2.67	−18.01	−.867
1767-1766	1,174	1,175	398,170.	601,180.	15,160.	2.80	−15.47	−1.161
1766-1765	1,176	1,179	196,105.	357,695.	4,920.	3.03	−19.23	.400
1765-1764	1,180	1,182	222,920.	573,880.	17,587.	2.46	−19.36	−.824
1764-1763	1,183	1,185	506,267.	1,057,386.	13,860.	3.04	−18.37	−.810
1763-1762	1,186	1,189	237,935.	531,025.	17,335.	3.23	−18.39	−.169
1762-1761	1,190	1,192	107,800.	178,227.	5,613.	3.54	−19.62	−.153

TABLE 1. Annual Averages of Dust Concentrations, Conductivity, Oxygen Isotopes, and Ice Accumulation as Deviations From the Mean, Quelccaya Summit Ice Core, 1475-1984—Continued

Year	Samples		Particle Concentrations per Milliliter Samples			Electrical Conductivity ($\mu S\ cm^{B6}$)	$\delta^{18}O$	Accumulation (ice equivalent) Percent of Standard Deviation
			.63-.80 μm*	>.63 μm*	>1.59 μm*			
1761-1760	1,193	1,196	450,690.	800,825.	15,820.	3.37	−18.11	−.452
1760-1759	1,197	1,199	501,600.	932,140.	18,700.	2.60	−18.95	−1.072
1759-1758	1,200	1,203	197,660.	374,205.	13,200.	2.79	−19.87	.215
1758-1757	1,204	1,206	228,640.	392,107.	9,927.	2.48	−21.81	−.407
1757-1756	1,207	1,209	150,087.	311,593.	10,027.	2.63	−20.28	−.874
1756-1755	1,210	1,212	348,347.	719,320.	19,260.	2.61	−18.99	−.217
1755-1754	1,213	1,216	334,890.	577,285.	6,860.	2.69	−18.96	.608
1754-1753	1,217	1,219	234,193.	392,167.	8,740.	2.89	−19.32	−.998
1753-1752	1,220	1,223	206,650.	362,025.	10,275.	2.46	−19.11	.318
1752-1751	1,224	1,227	708,330.	1,290,810.	27,315.	2.80	−18.79	−.319
1751-1750	1,228	1,232	231,228.	462,876.	16,128.	2.50	−17.85	.680
1750-1749	1,233	1,235	260,647.	508,913.	10,160.	2.63	−18.49	−.620
1749-1748	1,236	1,238	287,747.	452,440.	5,320.	2.64	−17.56	−1.930
1748-1747	1,239	1,241	362,700.	485,680.	3,067.	2.60	−14.91	.401
1747-1746	1,242	1,244	157,047.	331,867.	6,187.	2.25	−19.46	.418
1746-1745	1,245	1,247	162,753.	266,627.	4,560.	2.57	−21.07	−.234
1745-1744	1,248	1,251	281,320.	421,825.	1,915.	2.56	−18.94	.450
1744-1743	1,252	1,256	206,904.	424,916.	8,448.	3.05	−19.62	.130
1743-1742	1,257	1,260	198,565.	336,505.	12,345.	2.55	−21.44	.145
1742-1741	1,261	1,264	478,275.	701,500.	7,325.	2.68	−19.30	−.518
1741-1740	1,265	1,267	615,960.	787,933.	7,007.	2.68	−16.57	−.165
1740-1739	1,268	1,272	370,148.	743,720.	19,944.	2.79	−17.22	.530
1739-1738	1,273	1,278	831,343.	1,544,013.	43,477.	4.36	−17.94	.546
1738-1737	1,279	1,281	268,947.	453,327.	8,013.	2.92	−17.28	−.812
1737-1736	1,282	1,285	557,615.	846,560.	13,125.	3.73	−19.05	−.800
1736-1735	1,286	1,289	341,205.	530,610.	8,465.	3.90	−19.33	−.098
1735-1734	1,290	1,293	417,970.	589,195.	3,370.	2.67	−18.72	.955
1734-1733	1,294	1,297	286,590.	530,345.	3,825.	2.47	−20.52	2.362
1733-1732	1,298	1,302	355,632.	525,272.	5,436.	2.59	−19.08	−1.803
1732-1731	1,303	1,307	436,292.	648,264.	5,140.	2.44	−22.90	1.354
1731-1730	1,308	1,312	529,200.	954,524.	33,140.	2.53	−19.53	.669
1730-1729	1,313	1,315	440,367.	628,673.	6,347.	2.31	−19.49	−2.133
1729-1728	1,316	1,319	341,170.	551,020.	5,925.	2.39	−15.61	−.007
1728-1727	1,320	1,323	786,795.	1,215,690.	30,175.	3.38	−17.93	−.349
1727-1726	1,324	1,327	198,105.	598,135.	34,420.	1.87	−19.86	−.337
1726-1725	1,328	1,333	171,353.	352,103.	9,863.	2.68	−19.81	1.455
1725-1724	1,334	1,337	485,170.	836,875.	11,145.	2.90	−21.65	−.672
1724-1723	1,338	1,339	193,840.	585,660.	7,120.	2.78	−14.70	−1.378
1723-1722	1,340	1,343	322,430.	553,540.	8,935.	2.88	−15.35	−.291
1722-1721	1,344	1,347	872,260.	1,504,780.	49,070.	3.44	−17.22	.080
1721-1720	1,348	1,351	150,895.	352,125.	10,660.	3.05	−19.11	.454
1720-1719	1,352	1,355	292,580.	531,740.	11,760.	3.22	−17.24	−.620
1719-1718	1,356	1,358	416,627.	818,313.	6,993.	3.62	−18.48	−.610
1718-1717	1,359	1,362	550,007.	937,967.	20,860.	2.51	−19.42	.493
1717-1716	1,363	1,365	173,933.	408,220.	9,993.	2.10	−19.88	−.590
1716-1715	1,366	1,370	160,696.	361,488.	16,472.	2.25	−21.23	.153
1715-1714	1,371	1,375	401,320.	867,036.	31,024.	2.88	−18.82	.899
1714-1713	1,376	1,379	161,310.	303,165.	3,285.	2.43	−19.29	0.508
1713-1712	1,380	1,383	278,430.	648,090.	21,265.	2.77	−15.89	−.920
1712-1711	1,384	1,387	151,610.	291,580.	6,120.	2.73	−17.04	.570
1711-1710	1,388	1,391	353,490.	746,255.	12,770.	3.85	−17.62	.211
1710-1709	1,392	1,394	269,900.	438,167.	3,673.	2.41	−17.72	−.894
1709-1708	1,395	1,398	370,380.	696,775.	8,365.	2.31	−15.69	.234
1708-1707	1,399	1,402	155,610.	325,885.	7,260.	2.36	−20.35	.246
1707-1706	1,403	1,406	212,530.	405,545.	9,540.	2.81	−18.04	−.118
1706-1705	1,407	1,410	82,307.	214,547.	12,273.	3.05	−17.46	.645
1705-1704	1,411	1,414	434,450.	992,980.	31,255.	3.38	−20.30	.280

TABLE 1. Annual Averages of Dust Concentrations, Conductivity, Oxygen Isotopes, and Ice Accumulation as Deviations From the Mean, Quelccaya Summit Ice Core, 1475–1984

Year	Samples		Particle Concentrations per Milliliter Sample .63–.80 μm*	>.63 μm*	>1.59 μm*	Electrical Conductivity (μS cm⁻¹)	$\delta^{18}O$	Accumulation (ice equivalent) Percent of Standard Deviation
1704-1703	1,415	1,418	244,475.	464,890.	14,225.	2.94	−19.81	.291
1703-1702	1,419	1,422	267,525.	394,515.	3,780.	2.55	−19.47	.681
1702-1701	1,423	1,426	550,125.	986,100.	10,380.	2.76	−18.63	1.073
1701-1700	1,427	1,430	236,970.	450,250.	10,595.	2.55	−20.46	−.818
1700-1699	1,431	1,436	192,170.	451,650.	16,580.	2.63	−17.95	4.153
1699-1698	1,437	1,440	411,725.	780,195.	10,090.	2.83	−19.53	.347
1698-1697	1,441	1,443	141,487.	442,733.	13,267.	3.06	−21.57	−1.177
1697-1696	1,444	1,446	245,507.	474,867.	10,927.	2.73	−19.43	−.400
1696-1695	1,447	1,450	312,990.	762,450.	29,705.	2.60	−18.82	.764
1695-1694	1,451	1,454	377,215.	639,280.	9,790.	2.66	−17.66	.390
1694-1693	1,455	1,457	208,367.	597,240.	28,200.	2.68	−16.72	−1.341
1693-1692	1,458	1,461	294,880.	591,920.	7,520.	2.51	−17.80	−.559
1692-1691	1,462	1,466	312,800.	496,452.	5,860.	2.60	−20.26	1.589
1691-1690	1,467	1,470	254,020.	413,845.	14,800.	2.94	−16.42	1.018
1690-1689	1,471	1,475	176,120.	253,880.	5,160.	3.10	−20.44	1.029
1689-1688	1,476	1,478	156,747.	395,967.	23,667.	2.41	−21.67	−.721
1688-1687	1,479	1,483	210,616.	391,312.	9,408.	2.63	−16.84	.857
1687-1686	1,484	1,487	129,875.	287,600.	16,025.	2.62	−16.51	2.441
1686-1685	1,488	1,490	390,453.	761,240.	27,220.	2.75	−20.09	.091
1685-1684	1,491	1,493	471,980.	712,400.	8,240.	2.58	−19.54	−.295
1684-1683	1,494	1,497	599,600.	987,775.	20,750.	2.88	−17.81	.110
1683-1682	1,498	1,500	403,153.	730,540.	14,260.	2.69	−19.24	.516
1682-1681	1,501	1,503	280,693.	401,613.	3,027.	2.40	−16.88	−.269
1681-1680	1,504	1,506	129,327.	327,900.	33,613.	2.88	−19.20	−1.057
1680-1679	1,507	1,513	201,394.	455,777.	15,803.	2.77	−19.55	1.745
1679-1678	1,514	1,518	266,784.	408,984.	10,648.	2.68	−19.33	3.358
1678-1677	1,519	1,521	73,393.	153,560.	2,700.	2.45	−20.66	.166
1677-1676	1,522	1,524	186,833.	521,320.	41,500.	3.24	−18.58	.979
1676-1675	1,525	1,529	472,920.	914,008.	25,392.	3.02	−18.84	1.392
1675-1674	1,530	1,533	360,575.	630,920.	6,400.	2.38	−18.80	1.404
1674-1673	1,534	1,536	766,233.	1,152,426.	14,413.	2.86	−20.05	.607
1673-1672	1,537	1,541	352,780.	638,392.	22,572.	2.71	−19.56	1.022
1672-1671	1,542	1,545	46,175.	188,080.	13,325.	2.63	−19.16	1.439
1671-1670	1,546	1,549	237,275.	532,185.	25,785.	2.67	−17.33	1.044
1670-1669	1,550	1,552	569,260.	912,693.	15,347.	2.76	−19.59	−.576
1669-1668	1,553	1,556	307,190.	523,690.	16,190.	2.56	−19.09	1.474
1668-1667	1,557	1,559	342,460.	600,593.	15,733.	2.47	−19.12	−.561
1667-1666	1,560	1,564	327,752.	755,072.	21,880.	2.62	−19.62	2.317
1666-1665	1,565	1,568	320,490.	624,780.	27,395.	2.77	−18.41	1.097
1665-1664	1,569	1,571	475,960.	878,953.	25,547.	2.10	−22.73	.079
1664-1663	1,572	1,577	416,183.	923,067.	40,340.	3.26	−19.95	2.562
1663-1662	1,578	1,581	361,530.	661,215.	24,900.	3.41	−20.36	.716
1662-1661	1,582	1,584	326,453.	490,380.	7,540.	2.60	−15.94	−.517
1661-1660	1,585	1,589	218,844.	353,020.	13,392.	2.56	−18.41	3.017
1660-1659	1,590	1,594	246,256.	525,384.	30,348.	3.11	−19.94	1.784
1659-1658	1,595	1,597	174,460.	338,493.	23,327.	2.82	−17.75	.754
1658-1657	1,598	1,602	196,324.	309,928.	5,752.	3.05	−17.37	1.182
1657-1656	1,603	1,605	543,260.	876,300.	14,487.	2.61	−14.17	.774
1656-1655	1,606	1,609	469,175.	729,555.	12,510.	3.06	−16.79	.155
1655-1654	1,610	1,612	360,740.	614,833.	14,133.	2.89	−18.64	.793
1654-1653	1,613	1,616	249,220.	526,360.	8,890.	3.22	−19.46	.382
1653-1652	1,617	1,620	281,550.	560,975.	13,615.	3.45	−18.59	1.234
1652-1651	1,621	1,623	154,673.	345,020.	5,120.	3.09	−16.24	−.023
1651-1650	1,624	1,627	426,750.	923,810.	21,500.	3.04	−20.13	2.058
1650-1649	1,628	1,631	216,365.	629,320.	25,920.	2.91	−18.32	1.265
1649-1648	1,632	1,636	348,356.	589,324.	8,412.	3.18	−18.16	1.445
1648-1647	1,637	1,639	179,827.	266,573.	4,660.	3.15	−16.09	.009

TABLE 1. Annual Averages of Dust Concentrations, Conductivity, Oxygen Isotopes, and Ice Accumulation as Deviations From the Mean, Quelccaya Summit Ice Core, 1475-1984—Continued

Year	Samples		Particle Concentrations per Milliliter Sample .63-.80 μm*	>.63 μm*	>1.59 μm*	Electrical Conductivity (μS cm⁻¹)	$\delta^{18}O$	Accumulation (ice equivalent) Percent of Standard Deviation
1647-1646	1,640	1,643	512,785.	819,055.	18,835.	3.22	−16.63	2.148
1646-1645	1,644	1,648	266,032.	477,712.	7,944.	3.40	−17.55	.452
1645-1644	1,649	1,651	246,813.	432,740.	10,113.	3.40	−17.61	.033
1644-1643	1,652	1,656	341,556.	525,156.	9,388.	3.30	−20.23	2.184
1643-1642	1,657	1,659	166,060.	326,740.	9,120.	3.39	−19.05	1.337
1642-1641	1,660	1,664	441,168.	744,424.	10,760.	2.60	−22.39	.918
1641-1640	1,665	1,668	411,380.	702,090.	19,345.	2.80	−19.77	1.358
1640-1639	1,669	1,672	539,900.	868,110.	8,745.	3.01	−17.29	1.369
1639-1638	1,673	1,678	413,087.	770,823.	22,410.	2.58	−19.52	3.109
1638-1637	1,679	1,682	471,450.	810,970.	15,155.	2.82	−19.72	.522
1637-1636	1,683	1,685	365,240.	792,033.	27,033.	2.48	−17.61	.965
1636-1635	1,686	1,689	519,580.	845,690.	13,590.	2.59	−13.81	.540
1635-1634	1,690	1,693	443,130.	675,855.	12,230.	2.17	−16.35	1.420
1634-1633	1,694	1,697	453,060.	624,725.	5,235.	2.50	−17.89	.994
1633-1632	1,698	1,700	309,280.	562,000.	15,780.	2.58	−17.94	.129
1632-1631	1,701	1,704	444,345.	774,650.	19,550.	2.28	−19.15	1.013
1631-1630	1,705	1,709	231,696.	561,236.	17,388.	2.10	−20.65	2.340
1630-1629	1,710	1,714	411,432.	569,684.	8,188.	2.24	−19.42	2.792
1629-1628	1,715	1,718	142,205.	274,545.	28,010.	2.06	−20.01	1.042
1628-1627	1,719	1,721	290,173.	525,133.	13,520.	1.97	−20.89	.169
1627-1626	1,722	1,726	168,888.	373,000.	11,640.	2.06	−19.65	2.388
1626-1625	1,727	1,730	131,565.	225,555.	5,945.	2.30	−20.24	1.514
1625-1624	1,731	1,734	222,665.	419,180.	6,575.	2.21	−18.22	1.081
1624-1623	1,735	1,738	349,660.	523,220.	13,960.	2.20	−17.04	.646
1623-1622	1,739	1,741	253,300.	465,627.	11,767.	2.37	−19.61	1.101
1622-1621	1,742	1,746	595,044.	959,180.	15,604.	2.48	−18.91	.887
1621-1620	1,747	1,750	331,740.	488,405.	7,280.	2.41	−17.79	1.120
1620-1619	1,751	1,754	396,355.	649,055.	13,390.	2.53	−17.36	2.026
1619-1618	1,755	1,757	419,553.	689,307.	19,260.	2.80	−17.26	−.206
1618-1617	1,758	1,761	370,085.	892,395.	33,445.	2.44	−18.58	−.199
1617-1616	1,762	1,764	323,573.	617,753.	22,113.	2.44	−18.95	−.642
1616-1615	1,765	1,766	340,130.	555,420.	12,120.	2.38	−18.49	−1.086
1615-1614	1,767	1,768	112,690.	187,620.	9,700.	2.20	−18.49	−.177
1614-1613	1,769	1,771	190,027.	315,207.	16,907.	3.16	−19.05	.963
1613-1612	1,772	1,773	250,550.	381,910.	7,600.	2.17	−18.35	−.888
1612-1611	1,774	1,775	265,990.	420,760.	9,090.	2.18	−18.15	−.109
1611-1610	1,776	1,778	188,820.	530,753.	21,900.	2.30	−19.75	−.147
1610-1609	1,779	1,781	316,627.	532,660.	13,500.	2.38	−18.30	−.139
1609-1608	1,782	1,784	534,367.	906,373.	38,640.	2.45	−17.21	.326
1608-1607	1,785	1,786	161,470.	354,090.	11,510.	1.84	−17.17	.334
1607-1606	1,787	1,789	261,680.	556,933.	32,660.	2.17	−16.81	.801
1606-1605	1,790	1,792	274,767.	472,707.	18,887.	2.02	−18.57	.351
1605-1604	1,793	1,796	177,080.	402,065.	27,580.	2.48	−19.46	1.741
1604-1603	1,797	1,800	276,985.	576,320.	33,100.	2.48	−19.32	1.752
1603-1602	1,801	1,804	136,655.	490,985.	72,555.	2.55	−20.47	1.070
1599-1598	1,815	1,819	197,568.	451,472.	9,224.	2.63	−18.97	1.808
1598-1597	1,820	1,822	27,847.	185,907.	26,260.	2.31	−18.31	−.046
1597-1596	1,823	1,826	435,135.	938,065.	38,710.	2.80	−18.18	.429
1596-1595	1,827	1,828	67,200.	174,780.	4,980.	2.26	−17.02	−.030
1595-1594	1,829	1,831	359,653.	787,367.	8,687.	2.30	−16.65	−.023
1594-1593	1,832	1,835	174,705.	562,040.	18,680.	2.64	−17.00	1.395
1593-1592	1,836	1,838	450,107.	720,300.	4,960.	3.25	−17.36	−.949
1592-1591	1,839	1,841	82,260.	227,260.	12,013.	2.35	−17.92	.001
1591-1590	1,842	1,844	597,907.	1,217,046.	33,333.	2.73	−18.16	.010
1590-1589	1,845	1,847	242,220.	521,987.	8,567.	3.03	−18.36	.018
1589-1588	1,848	1,851	283,695.	749,670.	10,970.	2.43	−18.88	1.449
1588-1587	1,852	1,855	596,275.	893,050.	11,160.	2.80	−19.35	.985

TABLE 1. Annual Averages of Dust Concentrations, Conductivity, Oxygen Isotopes, and Ice Accumulation as Deviations From the Mean. Quelccaya Summit Ice Core, 1475–1984

Year	Samples		Particle Concentrations per Milliliter Sample .63–.80 μm*	>.63 μm*	>1.59 μm*	Electrical Conductivity (μS cm⁻¹)	$\delta^{18}O$	Accumulation (ice equivalent) Percent of Standard Deviation
1587-1586	1,856	1,858	101,333.	439,940.	41,213.	2.43	−19.24	1.948
1586-1585	1,859	1,861	191,180.	315,067.	11,680.	2.78	−19.79	−.427
1585-1584	1,862	1,864	175,980.	605,400.	15,667.	2.52	−17.38	.059
1584-1583	1,865	1,867	224,287.	439,700.	11,873.	2.74	−15.36	.546
1583-1582	1,868	1,870	377,747.	604,960.	15,120.	3.67	−17.82	.028
1582-1581	1,871	1,873	200,920.	377,280.	21,220.	2.68	−18.16	.565
1581-1580	1,874	1,876	252,887.	548,453.	22,680.	2.94	−19.19	1.056
1580-1579	1,877	1,879	67,887.	177,067.	16,800.	3.46	−17.64	.101
1579-1578	1,880	1,882	207,593.	688,287.	15,087.	2.62	−18.35	.110
1578-1577	1,883	1,885	368,060.	714,953.	10,547.	2.96	−22.17	.603
1577-1576	1,886	1,888	286,240.	684,653.	52,827.	3.12	−18.29	1.098
1576-1575	1,889	1,891	102,447.	310,800.	11,540.	3.17	−20.05	1.109
1575-1574	1,892	1,894	457,900.	791,387.	9,227.	2.56	−18.94	.632
1574-1573	1,895	1,898	152,725.	351,160.	11,500.	3.21	−17.30	−.336
1573-1572	1,899	1,901	129,153.	226,093.	3,940.	3.63	−20.58	1.141
1572-1571	1,902	1,904	63,167.	131,373.	4,547.	3.17	−21.13	−.810
1571-1570	1,905	1,907	102,567.	167,480.	5,147.	3.00	−16.43	−.312
1570-1569	1,908	1,910	253,847.	409,847.	6,840.	2.93	−18.32	.188
1569-1568	1,911	1,913	71,413.	276,033.	21,147.	2.66	−20.85	.444
1568-1567	1,914	1,916	122,587.	210,767.	11,500.	2.74	−19.17	−.041
1567-1566	1,917	1,918	406,940.	707,220.	39,970.	3.00	−19.48	−.776
1566-1565	1,919	1,921	249,340.	439,540.	16,867.	3.00	−13.88	.721
1565-1564	1,922	1,923	88,230.	138,160.	8,230.	3.19	−17.93	−1.259
1564-1563	1,924	1,925	86,230.	252,880.	10,560.	2.80	−16.98	.243
1563-1562	1,926	1,928	237,727.	516,720.	17,727.	3.15	−18.15	.253
1562-1561	1,929	1,931	228,573.	468,180.	15,187.	3.11	−20.27	1.764
1561-1560	1,932	1,935	222,375.	493,155.	8,580.	3.05	−18.06	.271
1560-1559	1,936	1,938	65,407.	173,067.	11,667.	3.27	−20.23	.281
1559-1558	1,939	1,941	135,693.	361,053.	6,347.	2.39	−18.15	.794
1558-1557	1,942	1,944	419,560.	649,107.	6,880.	2.75	−19.45	−.710
1557-1556	1,945	1,947	313,947.	582,333.	17,907.	2.85	−17.42	.309
1556-1555	1,948	1,950	284,640.	599,547.	21,993.	2.44	−18.41	−.188
1555-1554	1,951	1,953	333,047.	635,107.	14,833.	2.94	−17.41	−.180
1554-1553	1,954	1,956	171,073.	469,913.	13,687.	2.94	−17.87	−.171
1553-1552	1,957	1,958	132,540.	384,810.	9,910.	2.74	−21.06	−.162
1552-1551	1,959	1,963	186,120.	334,540.	7,024.	2.51	−17.31	1.892
1551-1550	1,964	1,965	92,750.	222,700.	12,240.	2.49	−17.99	.368
1550-1549	1,966	1,967	60,260.	124,180.	4,980.	2.77	−18.63	−.649
1549-1548	1,968	1,970	183,613.	329,453.	8,147.	2.36	−19.57	.903
1548-1547	1,971	1,973	362,573.	670,127.	19,680.	2.41	−19.25	−.118
1547-1546	1,974	1,976	126,160.	311,040.	11,560.	2.17	−18.08	.408
1546-1545	1,977	1,978	37,490.	72,920.	6,690.	2.71	−17.15	−1.136
1545-1544	1,979	1,982	171,935.	291,585.	9,910.	2.44	−19.63	2.506
1544-1543	1,983	1,985	263,967.	441,327.	9,047.	3.10	−18.21	.959
1543-1542	1,986	1,988	134,367.	295,280.	11,607.	2.50	−18.56	.450
1542-1541	1,989	1,990	334,600.	637,870.	27,530.	2.51	−18.02	−.585
1541-1540	1,991	1,992	175,400.	374,460.	26,060.	2.30	−19.46	−.053
1540-1539	1,993	1,994	156,110.	352,030.	20,520.	1.75	−18.65	−1.094
1539-1538	1,995	1,997	126,753.	257,513.	10,727.	2.18	−17.02	.492
1538-1537	1,998	1,999	213,320.	467,290.	4,990.	2.45	−18.31	−.025
1537-1536	2,000	2,002	243,627.	391,360.	3,433.	3.12	−17.25	1.042
1536-1535	2,003	2,005	73,027.	160,253.	9,853.	2.44	−18.33	−.006
1535-1534	2,006	2,007	248,460.	1,009,140.	17,960.	2.73	−18.79	−.527
1534-1533	2,008	2,009	166,120.	411,640.	28,960.	2.84	−16.72	.546
1533-1532	2,010	2,012	302,960.	616,320.	33,487.	2.39	−19.15	.557
1532-1531	2,013	2,014	219,290.	366,290.	6,610.	2.76	−18.58	−.020
1531-1530	2,015	2,017	297,173.	461,740.	11,907.	2.94	−14.27	−1.029

TABLE 1. Annual Averages of Dust Concentrations, Conductivity, Oxygen Isotopes, and Ice Accumulation as Deviations From the Mean, Quelccaya Summit Ice Core, 1475-1984—Continued

Year	Samples		Particle Concentrations per Milliliter Sample			Electrical Conductivity ($\mu S\ cm^{-1}$)	$\delta^{18}O$	Accumulation (ice equivalent) Percent of Standard Deviation
			.63-.80 μm*	>.63 μm*	>1.59 μm*			
1530-1529	2,018	2,019	685,400.	1,184,060.	34,560.	2.76	−17.30	.590
1529-1528	2,020	2,022	350,007.	743,033.	16,087.	2.47	−19.81	1.679
1528-1527	2,023	2,024	285,850.	530,220.	5,070.	2.15	−17.41	−.466
1527-1526	2,025	2,026	131,220.	189,500.	6,460.	2.27	−16.08	−.999
1526-1525	2,027	2,028	172,440.	774,130.	35,050.	2.43	−16.75	.094
1525-1524	2,029	2,030	342,270.	591,810.	16,390.	2.36	−18.30	−.983
1524-1523	2,031	2,032	171,860.	386,380.	13,920.	2.45	−17.33	−.976
1523-1522	2,033	2,035	259,893.	467,660.	8,220.	2.34	−17.44	.125
1522-1521	2,036	2,036	68,960.	184,400.	3,240.	2.29	−18.24	−.960
1521-1520	2,037	2,039	410,460.	713,487.	20,093.	2.53	−15.05	1.243
1520-1519	2,040	2,041	351,760.	517,130.	4,330.	2.39	−15.94	−1.494
1519-1518	2,042	2,042	42,340.	206,700.	49,380.	2.95	−19.61	−.385
1518-1517	2,043	2,044	207,040.	388,410.	5,860.	2.30	−19.12	−.375
1517-1516	2,045	2,047	32,153.	95,460.	8,533.	2.77	−18.01	1.795
1516-1515	2,048	2,048	36,740.	247,920.	18,600.	2.30	−18.24	−1.467
1515-1514	2,049	2,051	178,833.	369,507.	7,573.	2.24	−18.42	.767
1514-1513	2,052	2,053	148,080.	347,580.	6,190.	1.99	−19.39	.221
1513-1512	2,054	2,056	547,760.	936,900.	8,920.	2.34	−19.05	−.328
1512-1511	2,057	2,058	156,710.	375,110.	19,230.	2.31	−17.68	−1.440
1511-1510	2,059	2,062	126,615.	239,340.	11,370.	2.72	−16.32	1.379
1510-1509	2,063	2,064	169,530.	340,290.	5,580.	2.38	−17.77	1.393
1509-1508	2,065	2,066	148,910.	457,920.	23,190.	2.18	−17.37	−.854
1508-1507	2,067	2,068	115,730.	285,920.	24,690.	2.45	−17.29	−1.412
1507-1506	2,069	2,071	166,433.	340,433.	8,333.	2.85	−18.13	1.436
1506-1505	2,072	2,073	473,350.	848,850.	17,790.	2.13	−16.80	.311
1505-1504	2,074	2,076	165,993.	374,867.	19,520.	2.52	−16.94	.894
1504-1503	2,077	2,077	11,460.	25,220.	2,740.	2.52	−20.43	−.810
1503-1502	2,078	2,079	439,550.	681,270.	11,100.	3.56	−20.26	−.228
1502-1501	2,080	2,081	529,460.	911,250.	20,660.	2.42	−19.20	−.793
1501-1500	2,082	2,083	223,140.	544,600.	32,650.	2.20	−16.30	.947
1500-1499	2,084	2,085	175,660.	412,910.	11,730.	2.19	−17.82	−1.353
1499-1498	2,086	2,087	197,360.	402,730.	10,670.	2.33	−19.04	.394
1498-1497	2,088	2,089	98,290.	390,210.	28,870.	2.10	−18.22	−.176
1497-1496	2,090	2,092	347,213.	804,040.	25,187.	2.14	−18.66	−.165
1496-1495	2,093	2,094	39,960.	156,050.	32,100.	2.56	−18.77	−.739
1495-1494	2,095	2,095	345,980.	523,780.	13,840.	2.10	−17.49	−.730
1494-1493	2,096	2,097	344,940.	670,350.	9,340.	2.24	−17.35	−.720
1493-1492	2,098	2,098	109,560.	198,760.	13,480.	2.46	−16.33	−1.889
1492-1491	2,099	2,100	105,270.	150,950.	4,580.	2.70	−17.49	−.111
1491-1490	2,101	2,101	805,140.	1,278,620.	7,500.	2.50	−16.05	−1.876
1490-1489	2,102	2,102	68,380.	113,120.	2,980.	2.18	−17.66	−1.276
1489-1488	2,103	2,104	350,600.	726,740.	28,320.	2.11	−17.48	−1.268
1488-1487	2,105	2,105	431,080.	757,580.	8,980.	1.86	−16.92	−.664
1487-1486	2,106	2,107	187,680.	302,230.	4,020.	2.05	−17.21	−.654
1486-1485	2,108	2,109	553,440.	774,750.	8,680.	1.85	−16.99	−.644
1485-1484	2,110	2,112	308,053.	519,220.	7,887.	1.69	−17.86	1.170
1484-1483	2,113	2,113	325,320.	461,420.	3,920.	1.89	−18.42	−1.228
1483-1482	2,114	2,115	243,550.	381,690.	5,220.	1.88	−18.57	−.615
1482-1481	2,116	2,117	117,100.	268,710.	11,480.	2.02	−17.71	−.605
1481-1480	2,118	2,119	156,380.	271,160.	5,200.	1.70	−18.57	−.595
1480-1479	2,120	2,121	66,660.	107,700.	1,780.	2.05	−17.36	−1.805
1479-1478	2,122	2,122	68,040.	171,520.	18,140.	1.79	−17.40	−1.798
1478-1477	2,123	2,123	41,620.	99,280.	3,460.	1.94	−18.53	−.565
1477-1476	2,124	2,125	223,310.	323,290.	8,860.	2.06	−18.67	−.555
1476-1475	2,126	2,127	254,040.	427,000.	9,200.	2.03	−19.21	−1.778

*Range of particle diameter.

and again from the 1700's to the latter half of the 1800's; after that the snow cover became marginal. By the early 1900's it had disappeared for good. Since the turn of the century glacier retreat has been reported for many regions of the South American Andes [Broggi, 1943; Oppenheim and Spann, 1946; Petersen, 1967; Wood, 1970 and Schubert, 1972].

These historical observations are consistent with the climate record inferred from the Quelccaya ice cores. As figure 4 illustrates the climate turned colder (i.e., more negative $\delta^{18}O$ values) and became wetter in the 1500's. The 1700's were the coldest century of the LIA period. A marked warming began in the 1880's and has continued to the present. This is consistent with the disappearance of snow cover by the beginning of the 1900's in the Ecuadorian Andes and the retreat of glaciers throughout the Andes since the turn of the century.

A.D. 1600 Eruption of Huaynaputina

The largest dust event in both the insoluble and soluble particle records is an ash layer from the eruption of Huaynaputina in A.D. 1600. This eruption was the most violent on record in the central Andes. The summit of the preexistent volcanic cone was completely removed by the explosion. The eruption left a very pronounced stratigraphic marker in the Quelccaya ice cores, which can be seen clearly in Figures 3, 4, and 5. During the eruptive phase, February 19 to March 6, 1600 [Simkin et al., 1981], there was total darkness for 7 days in Arequipa (16°25′ S., 71°32′ W.), 80 km to the northwest, and houses collapsed under the weight of ash accumulating on the roofs [Bullard, 1962; Francis, 1981]. In the surrounding country the eruption of Huaynaputina left a thick bed of ashes, often mistaken for

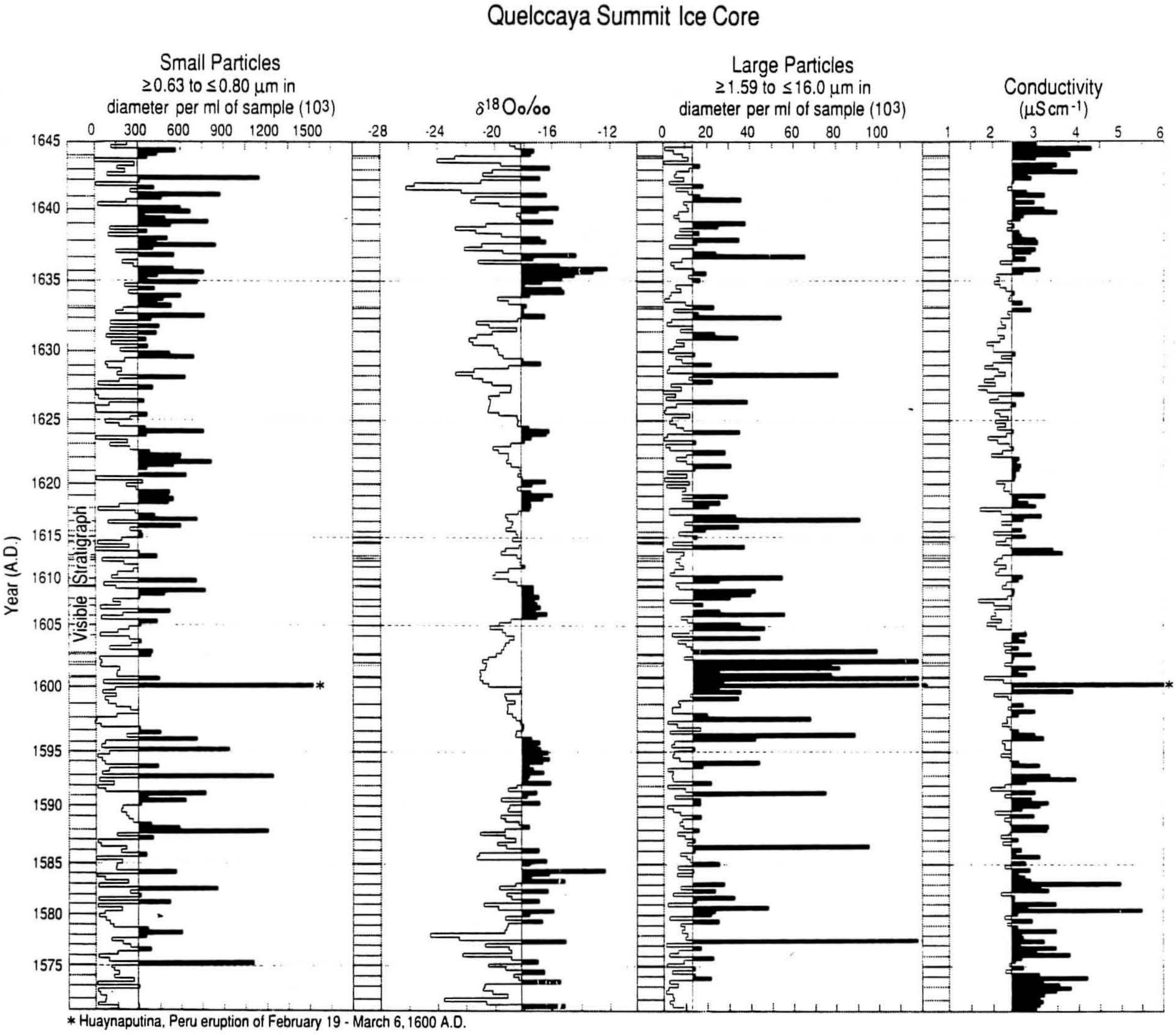

Fig. 5. Illustrates the individual sample variations in small particles greater than or equal to 0.63 to less than or equal to 0.80 µm and large particles greater than or equal to 1.59 to less than or equal to 16.0 µm in diameter per mL of sample, $\delta^{18}O$, conductivity and visible stratigraphy for the period 1570 to 1645. This represents the most unusual period during the Little Ice Age in which the 1600 eruption of Huaynaputina occurred and the 1590–1630 period when particle concentrations and mean conductivity levels, with the exception of the Huaynaputina eruption, were generally lower and the annual range in $\delta^{18}O$ was much less than the Little Ice Age average.

snow, that tops the summits of mountains of southern Peru. Identification (in both cores) of the Huaynaputina ash (16°35′ S., 71°32′ W.) provides an independent verification of the time scale [Thompson et al., 1986]. Thus the annual variation in microparticles and oxygen isotopes, along with the A.D. 1600 Huaynaputina eruption, were used to refine the visual stratigraphic time scale. Consequently, the Quelccaya cores have been dated absolutely to A.D. 1600 and back to 1500 with an estimated uncertainty of plus or minus 2 years.

Figure 5 presents the individual sample variations of small particles, oxygen isotopes, large particles, conductivity, and visible stratigraphy over the period from A.D. 1570 to 1645. The eruptive phase lasted only 2 weeks and left a very sharp peak in small particles and conductivity. However, a very broad peak occurs in the large size particle profile. The likely explanation is the fact that the eruption occurred during the wet season in the Andes of southern Peru. A large portion of the finer grained ash (less than 1.65 μm) was washed away, while the larger ash fraction remained as an exposed layer covering much of the terrain of southern Peru. As a result this ash layer served as a source of wind-blown material for almost 10 years after the eruption; hence the large particle peak is much broader in the ice core record.

During A.D. 1570 to 1645, the period 1590 to 1630 was characterized by lower concentrations of small particles and lower values of conductivity (Figures 4 and 5). Of particular interest here is the sharp decrease in the annual range of oxygen isotope variations during this period. This sharp decrease in range (Figures 5 and 6) may be due in part to the influence of Huaynaputina eruption on both the atmospheric circulation and on the net radiation balance of the ice cap. The increase in absorption of radiation on the surface of the ice cap must have been tremendous shortly after the eruption [Warren, 1984]. If melting occurred then the decrease in the seasonal range in oxygen isotope values in the A.D. 1600 layer, and perhaps in a few preceeding years, may have resulted from percolation of melt water. However, it is likely that the ash layer was quickly buried by the more than 2 m of snowfall, which accumulate each wet season on the ice cap. Thus it is more probable that the decrease in seasonal ranges of oxygen isotopes

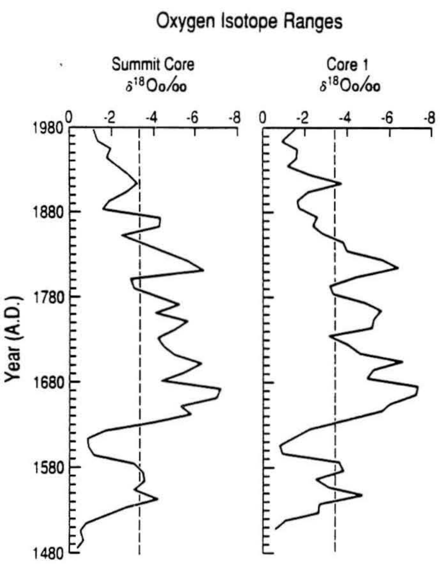

Fig. 6. Illustrates the annual range in oxygen isotope values in the Summit Core and Core 1 from Quelccaya. The annual range in oxygen isotopes actually increases by 100 percent during the Little Ice Age peaking between 1650-1710. Low ranges occur in both pre- and post-Little Ice Age periods as well as in the unusual period from 1590 to 1630 during the Little Ice Age.

for the period from A.D. 1600 to 1630, as well as the decrease in particles and conductivities, reflect a change in the larger scale atmospheric circulation of the region.

Figure 6 illustrates the very unusual phenomenon where the annual oxygen isotope ranges actually increase with depth in the Quelccaya ice cores. Between A.D. 1530 and 1880 the average oxygen isotope ratios are 0.9 ‰ lower than in preceeding or subsequent periods (Figure 3). Interestingly, the seasonal range in $\delta^{18}O$, which averages 2 ‰ for the period A.D. 1880 to 1980, doubles to an average of 4 ‰ during the LIA from A.D. 1520 to 1880 (fig. 6). The large annual $\delta^{18}O$ signal may reflect the increased seasonality during this period, a feature noted in the historical records of Europe [Gribben and Lamb, 1978; Lamb, 1984a, b]. Alternatively, the annual signal may have been better preserved under the climatic conditions prevailing on the Quelccaya ice cap during the LIA. The largest seasonal ranges in oxygen isotopes occur during the LIA period from A.D. 1500 to 1880 with maximum ranges from A.D. 1630 to 1700.

Evidence of Abrupt Climatic Change at Onset and Termination of LIA

The Quelccaya ice core records suggest that the onset and termination of the LIA in southern Peru occurred abruptly. The onset of this period, inferred from the increase in microparticles and the sharp increase in conductivities (Figure 3 and 4), occurred over a three year period 1486-1489. The high seasonal oscillations and typically more negative $\delta^{18}O$, which characterize the $\delta^{18}O$ signal throughout the LIA, did not begin until the 1520's: 30 years after the initial increase in both soluble and large-diameter (greater 1.59 μm) insoluble particulates. These ice core records suggest that the onset of the LIA occurred within a few decades. The initial increase in the number of microparticles and conductivity, which characterize the entire LIA, were very abrupt (A.D. 1490). The dry season dust layers are very distinct in the visual stratigraphy before A.D. 1490. The general increase in soluble and insoluble particles at the onset of the LIA may have reduced the overall clarity of the ice core making the dry season dust layers appear less apparent after A.D. 1490.

One of the most abrupt events recorded in the Quelccaya ice cores is the termination of the LIA (Figure 4). Near A.D. 1880 there is a sharp reduction in both the insoluble and soluble particulate concentrations, which occur within 1 to 2 years [Thompson and Mosley-Thompson, 1987]. These reduced levels are more characteristic of the last 100 years. In addition the large annual amplitudes in the seasonal $\delta^{18}O$ variations, which characterized the LIA period, rapidly decrease in less than 5 years around A.D. 1880. Evidence for a rather abrupt change in the annual precipitation index for the northern hemisphere continental region is evident around A.D. 1880 [Bradley et al., 1987].

Many geological records of climatic variability covering the last 1000 years lack good temporal resolution. This reinforces the conventional expectation of gradual climatic change. The relatively large annual accumulation on some ice sheets and ice caps, and especially on Quelccaya (1.15 meters ice equivalent a^{-1}), allows reconstruction of both high frequency (annual) and long-term climatic variations. Some evidence of abrupt changes within the climate system have been reported from polar ice cores; e.g., Camp Century [Thompson, 1977] and Dye 3 [Dansgaard et al., 1982; Herron and Langway, 1985] in Greenland. These results, and those from the tropical Quelccaya ice cap, strongly support our conclusion that atmospheric conditions can change substantially in only a few years. Because ice cores offer the most direct evidence of the past variations in atmospheric aerosols, precipitation, and temperatures it is imperative to seize the opportunity to acquire this information, which is essential for better understanding the causes of past fluctuations in climate.

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