Late Glacial Stage and Holocene Tropical Ice Core Records from Huascarán, Peru

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Two ice cores from the col of Huascarán in the north-central Andes of Peru contain a paleoclimatic history extending well into the Wisconsinan (Würm) Glacial Stage and include evidence of the Younger Dryas cool phase. Glacial stage conditions at high elevations in the tropics appear to have been as much as 8° to 12°C cooler than today, the atmosphere contained about 200 times as much dust, and the Amazon Basin forest cover may have been much less extensive. Differences in both the oxygen isotope ratio $\delta^{18}O$ (8 per mil) and the deuterium excess (4.5 per mil) from the Late Glacial Stage to the Holocene are comparable with polar ice core records. These data imply that the tropical Atlantic was possibly 5° to 6°C cooler during the Late Glacial Stage, that the climate was warmest from 8400 to 5200 years before present, and that it cooled gradually, culminating with the Little Ice Age (200 to 500 years before present). A strong warming has dominated the last two centuries.

The significance of recent climatic and environmental variations must be evaluated from a perspective that can be provided by longer term proxy climate records. Such histories may be reconstructed from ice cores recovered from carefully selected high-elevation tropical ice caps, as well as from polar ice sheets. Records recovered from low-latitude ice caps are of particular interest because they are located in areas where climatic changes may directly and significantly affect human activities. In the past, several records have been obtained from tropical glaciers, including a 1500-year history (*1*) of climatic variation recovered in 1983 from the Quelccaya ice cap in southern Peru (Fig. 1). These ice core records have not revealed the nature of Late Glacial Stage (LGS)' conditions or the character of the LGS-Holocene transition in the tropics. Such a record of tropical temperatures and other environmental conditions would be a valuable addition to the limited data from this region and would help resolve recent questions about the sensitivity of the tropics during the last glaciation (*2*). Knowing the sensitivity of the tropics to global climate changes is essential for models attempting to simulate how Earth's climate system works during glacial stages and for models simulating future temperature scenarios under enhanced greenhouse gas concentrations (*2*). In this article, we present a tropical ice core record from Peru that extends into the LGS and provides the complete LGS-Holocene transition, including a Younger Dryas (YD) cooling event.

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The Huascarán cores. Between 1990 and 1992, a survey of five glaciers located north-south along the Cordillera Blanca (Fig. 1) was conducted to identify the best sites for acquiring long-term paleoclimatic and environmental records. In addition, satellite-linked automatic weather stations (AWS) were established on two of the sites, Hualcán and Pucahirca, to record current meteorological conditions at the top of the Andes. The col of Huascarán (9°06'41"S; 77°36'53"W), the highest (6048 m above sea level) and coldest of the sites, was selected for drilling to bedrock because shallow cores from all five sites confirmed that it contained the best preserved stratigraphic records (*3*).

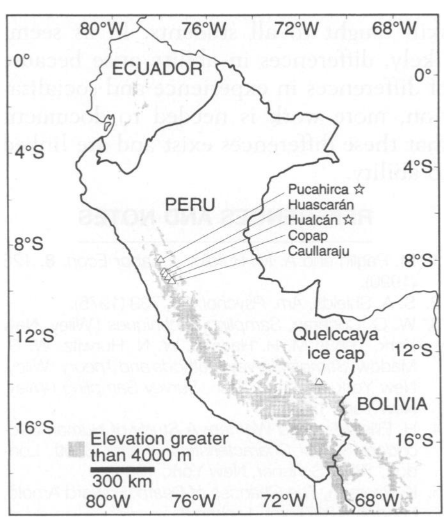

Fig. 1. Deep drilling sites (Huascarán and Quelccaya) along with the locations of the surveyed glaciers (△) and the automatic weather stations (AWS) installed in 1991 (stars).

In 1993, two ice cores were drilled to bedrock with a portable, lightweight, solar-powered thermal drilling system. Core 1 (C1), 160.4 m long [152.4 m ice equivalent (eq)], was cut while in the field into 2677 samples, which were melted and poured into bottles and sealed with wax. Core 2 (C2), 166.1 m long (158.4 m ice eq), was returned frozen to Ohio State University, where it was cut into 4675 samples (*4*). Samples from both cores were analyzed for microparticle (dust), chloride (Cl^-), nitrate (NO_3^-), and sulfate (SO_4^{2-}) concentrations, oxygen isotopic ratios ($\delta^{18}O$), and hydrogen isotopic ratios (δD).

At high elevations in the Peruvian Andes, 80 to 90 percent of the annual snowfall occurs in the austral summer and fall (November to May). A network of 15 stakes covering an area of 1.2 km by 2.3 km was established in September 1991 on the col of Huascarán to measure snow accumulation and the motion of the ice. In October 1992 and July 1993 the stake heights were remeasured and the stakes extended. The 1991 to 1992 average annual snow accumulation from the stakes (Fig. 2A) was 3.3 m, or 1.3 m H_2O eq (1.4 m ice eq), consistent with the 1 year of snow accumulation contained in the 3-m snow pits excavated in July of 1993 adjacent to each drill site.

Short-pulse radar measurements showed that ice thickness ranged from 127 m in the northeast to 218 m in the southwest corner of the col (Fig. 2B). Down-hole temperature measurements were difficult to obtain because an alcohol-water eutectic mixture was used to keep the hole open during drilling. The lowest borehole temperature (−5.2°C) was measured at a depth of 82.5 m just before the borehole closed by freezing. Mean annual air temperature on nearby Hualcán (August 1992 through July 1993) was −9.8°C. These data, along with observations made during drilling (*5*), indicate that the ice in the 6048-m-high col of Huascarán is frozen to the bed.

Late-glacial-stage conditions. The stratigraphic records of $\delta^{18}O$, NO_3^-, and dust for C2, along with $\delta^{18}O$ from C1, exhibit notable variations throughout both records, but the greatest variations are in the bottom 3 m of C2 and bottom 2.5 m of C1 (Fig. 3). Core 1 has been analyzed at a lower temporal resolution and is also 5.7 m shorter than C2, resulting in a different time-depth relation.

In the bottom 3 m of C2, $\delta^{18}O$ is depleted by 8 per mil, NO_3^- is reduced by a factor of 2 to 3, and dust concentrations increase ≈200 times. The same 8 per mil depletion is seen in the $\delta^{18}O$ record from C1 basal ice (Fig. 3D). During the deglaciation an abrupt return to cooler conditions is characterized by a depletion in ^{18}O of several per mil in both C1 and C2. These observations suggest the presence of LGS ice in the Huascarán cores; this conclusion is supported by several lines of evidence.

The contemporaneous increase in dust concentration and the depletion of ^{18}O have been documented in the LGS ice in every core retrieved to date (*6*). The dust and $\delta^{18}O$ records in the lower 5 m of Huascarán C2 (Fig. 4A) are quite similar to the dust and $\delta^{18}O$ records in the LGS sections of two polar ice cores. The change of 8 per mil between the end of the LGS and the Holocene on Huascarán is comparable to 6.0 per mil at Dome C (Fig. 4B) (*7*, *8*), 7 per mil at Dye 3 (Fig. 4C) (*9*), and 6.6 per mil at Summit (*10*) in central Greenland. The difference in deuterium excess from the Holocene (15.5 per mil) to the LGS (11 per mil) on Huascarán is 4.5 per mil, nearly identical to the difference of 4.3 per mil [Holocene (8.3 per mil) − LGS (4 per mil)] reported from the Dome C core (*11*). Although only two cores are shown here (Fig. 4, B and C), increased dust and ^{18}O depletion characterize LGS ice in cores from Byrd Station (*7*) and Vostok (*12*) in Antarctica, Camp Century (*7*) and Summit (*10*) in Greenland, Devon Island (*13*) in the Canadian Arctic, and Dunde ice cap (*14*) in China. Dust concentrations characteristically reach a maximum near the LGS termination, when $\delta^{18}O$ is most negative, and this same pattern is observed in the basal ice from Huascarán.

In all ice cores recovered to date, the end of the LGS is marked by increasing $\delta^{18}O$ (warming) and reduced dust deposition. In Greenland at Dye 3 (Fig. 4C) and Summit, the end of the LGS and beginning of the Bølling/Allerød are well-dated by layer counting at 15,000 ± 250 and 14,450 ± 200 years before present (B.P.) (*10*, *15*), respectively. The reduction of dust in Dome C was more gradual but also started about 15,000 years B.P. (*8*). These same patterns are found in the bottom parts of Huascarán C1 and C2 and strongly support our interpretation that Huascarán basal ice was deposited contemporaneously with the Dome C and Dye 3 ice containing the LGS and YD record.

Additional support is derived from the similarity of the $\delta^{18}O$ record in the lowest 3 m of Huascarán C2 with that from a deep-sea core (SU81-18) drilled off the coast of southern Portugal (Fig. 5) (*16*). The marine $\delta^{18}O$ record is from *Globigerina bulloides* tests (planktonic foraminifera) that were

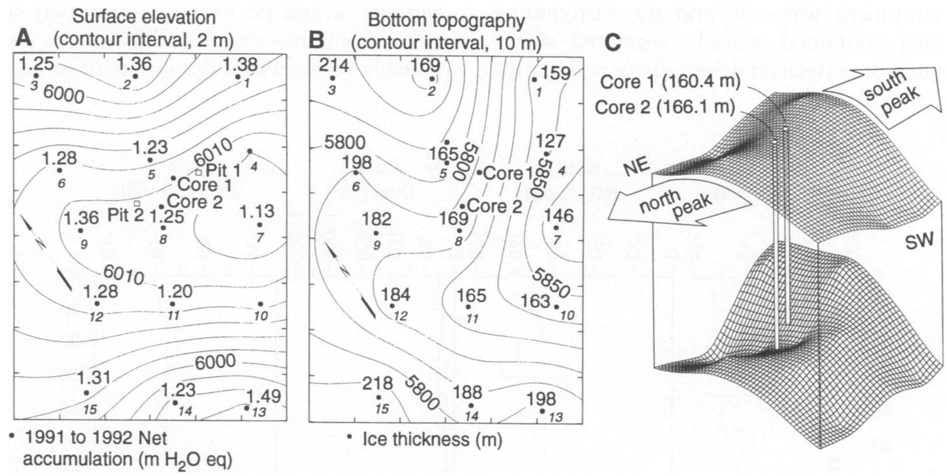

Fig. 2. (**A**) Surface elevation and (**B**) bottom topography provide (**C**) a schematic depicting the ice thicknesses on the col of Huascarán along with the locations of C1 and C2. Net accumulation measured from 1991 to 1992 at the accumulation stakes is shown in (A). The ice thickness at each stake is shown in (B).

^{14}C-dated by accelerator mass spectroscopy (AMS) and from which sea-surface temperatures were reconstructed by use of paleontological transfer functions. The *G. bulloides* $\delta^{18}O$ record is particularly appropriate for comparison with that from Huascarán because these foraminifera record February sea-surface temperatures (*16*), 80 percent of the precipitation on Huascarán arrives in the wet season (November to April), and the Atlantic Ocean is known to be the primary moisture source for the glaciers and ice caps along the crest of the Peruvian Andes (*17*). The major $\delta^{18}O$ variations in the marine core are reflected in the ice core (Fig. 5), including the prominent YD cooling during the deglaciation.

In the basal 1 m, the ice has thinned extensively so that a 20-mm sample may contain hundreds to thousands of years, making the record impossible to resolve further. The lowest few meters of ice contained very thin, horizontal, and undeformed layers, which extended right to the ice-bedrock contact. The ice at the base also contained air bubbles and showed no signs of melting, indicating that Huascarán ice has remained frozen to its bed and, on the basis of the evidence presented above, contains LGS ice.

The extreme dustiness of the LGS ice on Huascarán is consistent with reconstructions (*18*, *19*) for South America that indicate a reduction in atmospheric humidity, precipitation, and forest and grass cover during the LGS along with an enhancement of eolian transport and deposition. It is estimated that during the LGS, about 25 percent of South America was covered by eolian deposits such as dune fields and deflation basins (*18*), because winds were stronger and surface conditions were drier. The orientation of eolian features suggests that northeast trade winds were more persistent and penetrated farther south across western Amazonia (*18*) than at other times.

The NO_3^- concentrations (Fig. 3B) in the Huascarán LGS ice are much lower than in the Holocene ice. The significance of NO_3^- in ice cores is poorly understood at this time. Although few data are available for tropical ecosystems, recent evidence suggests that tropical rain forests and forest soils may be a major source of active atmospheric nitrogen species such as NO and NH_3, which are precursors for NO_3^- and NH_4^+, which occur as aerosols (*20*). These observations indicate that a major NO_3^- source lies close to Huascarán. The low NO_3^- concentrations in LGS ice (Fig. 3B) may imply that forest cover was significantly reduced in response to dry conditions and the expansion of grassland, as suggested by palynological studies in Brazil (*21*).

The Huascarán cores offer an opportunity to develop a high-resolution record of vegetation (and climate) changes for the Peruvian highlands. We examined pollen concentrations in five core sections (Fig. 3A). Two Late Holocene samples contain 600 to 1300 grains per liter, similar to concentrations found in the 1500-year record from the Quelccaya ice cap (*22*), and are dominated (46 to 70 percent) by *Alnus*, accompanied by minor taxa such as Gramineae, Chenopodiaceae, Compositae, and several others. Today, *Alnus* is a small tree growing in the subpuna shrubland and dry montane forest zones between 2800 and 3900 m on the eastern Andean slopes. The high abundance of *Alnus* implies that the pollen was transported long distances and upslope from the east (*23*). In contrast to the Late Holocene samples, abundances of *Alnus* in two Early Holocene samples are lower. The sample from LGS ice contains little pollen and thus suggests that the environment was cold and the surrounding area contained sparsely vegetated superpuna or periglacial desert where pollen productivity would be low. The transport of pollen from this source to Huascarán was probably reduced by a displacement of vegetation zones downward during the LGS.

The Holocene. To extract information about Holocene conditions in the Andes, we established a tentative time scale to facilitate comparison with other records. On Huascarán, as on Quelccaya, increased dust concentrations in the dry season result from reduced snow accumulation and more intense radiation receipt (*24*). We established the time-depth relation for the upper 119.3 m of C2 using the well-preserved seasonal fluctuations of dust, NO_3^-, and $\delta^{18}O$ (Fig. 6), which all show a maximum in the winter dry season (May to August). Four representative sections (Fig. 6, A through D), each containing 5 years, illustrate the seasonality of these constituents. The rapid reduction of annual layer thickness (λ) with depth (Fig. 6E) means that the lower third of the core contains most of the history. Annual variations in dust, NO_3^-, and $\delta^{18}O$ could not be resolved below 119.3 m because λ is too thin for detailed sampling.

We dated the lower 47 m by assuming that the prominent dip in $\delta^{18}O$ at 164.1 m in C2 (Fig. 4A) correlates with the YD time interval. The midpoint of this event was assigned an age of 12,250 years B.P. to be consistent with YD ages from layer counting in the GRIP and GISP 2 cores in Greenland (*10, 15*). In addition, two horizons (1915 A.D. at 84.67 m and 1817 A.D. at 119.26 m) dated by counting annual cycles in dust, NO_3^-, and $\delta^{18}O$ (Fig. 6) were selected for interpolation. Assuming steady-state conditions, the layer thinning with depth was estimated as a function of time with an empirical two-parameter function (*14*).

This Huascarán Holocene $\delta^{18}O$ history (Fig. 7) is remarkably consistent with a typical Holocene sequence (*25, 26*). Pollen histories (^{14}C years) in Colombia (*27*) and Peru (*23*) suggest that the Holocene began 10,000 years B.P. (Figs. 4 and 7). The dominance of Gramineae, Paramo herbs, and

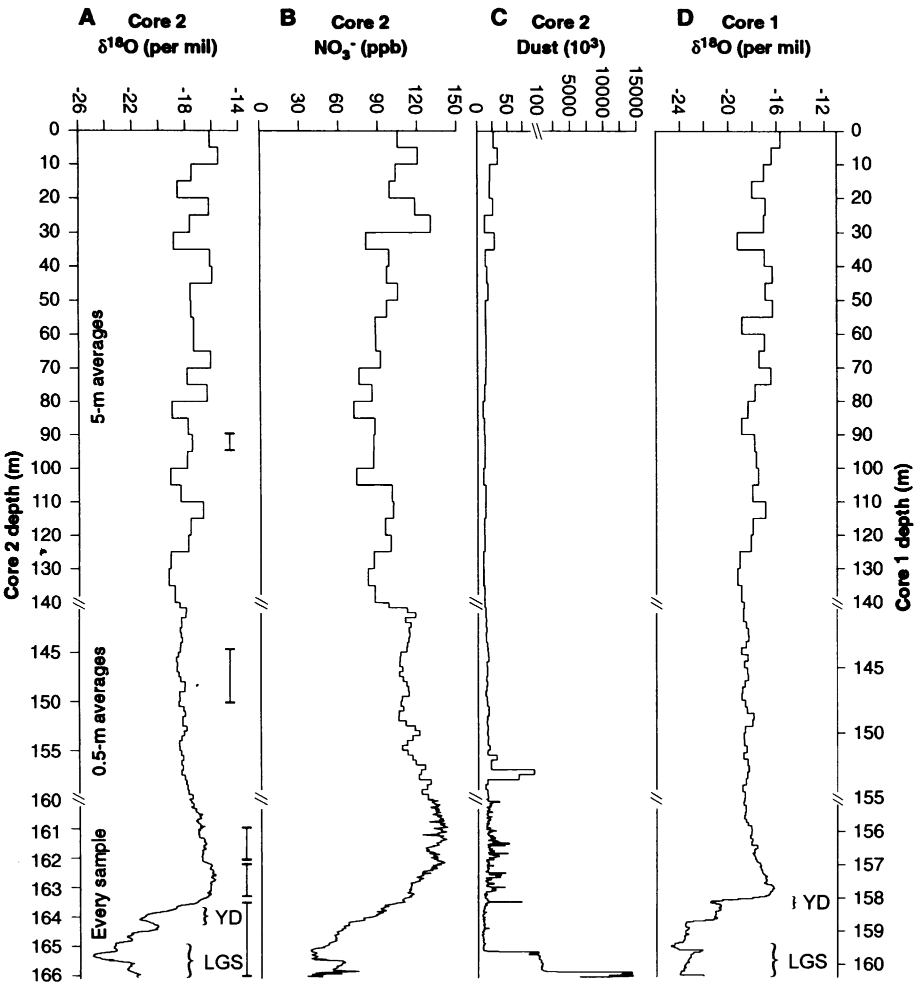

Fig. 3. Variation of (**A**) $\delta^{18}O$, (**B**) NO_3^- concentration, and (**C**) dust concentration with depth for C2 along with (**D**) $\delta^{18}O$ from C1, which illustrates reproducibility. The NO_3^- concentration is in parts per billion (ppb). Dust concentrations represent the number of particles with diameters ≥ 0.63 µm and ≤ 16.0 µm per milliliter sample. Vertical bars in (A) indicate core sections that were analyzed for pollen. Note the scale change for dust concentrations and that averaging intervals are reduced down the core to account for layer thinning.

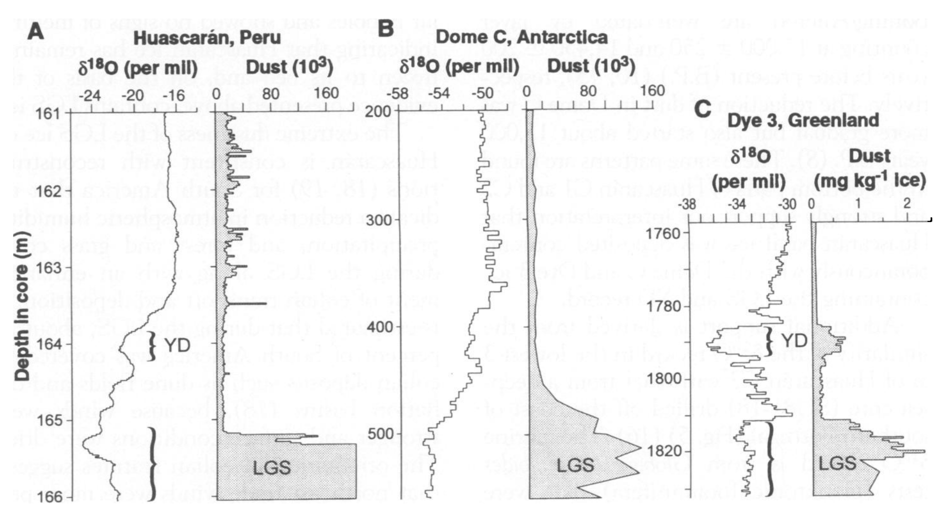

Fig. 4. The $\delta^{18}O$ and dust records from (**A**) Huascarán C2 compared with those from (**B**) Dome C, Antarctica, and (**C**) Dye 3, Greenland, for portions of those cores containing LGS ice, the glacial-interglacial transition, and the YD. Dust concentrations for Huascarán and Dome C represent the number of particles with diameters ≥ 0.63 µm and ≤ 16.0 µm per milliliter sample. For comparison of Huascarán dust with Dye 3 dust (in milligrams per kilogram of ice), the Huascarán Holocene average is 0.16 mg kg^{-1} and the LGS average is 32.2 mg kg^{-1}.

Andean forest taxa (*26*) from 10,000 to 7000 years B.P. indicates that the Andean forest zone in Colombia shifted upslope in response to warmer and moister conditions. This shift is consistent with the COHMAP (*28*) Holocene reconstructions, which show that lake levels were high and precipitation exceeded evaporation from 8.9° to 26.6°N. Farther upslope movement of Andean forests from 7000 to 5000 years B.P. is inferred from the reduction of Gramineae concomitant with an increase in Compositae and lower Andean forest taxa (*26*). The $\delta^{18}O$ record also shows that the warmest Holocene conditions prevailed between 8400 and 5200 years B.P., with the maximum warming from 6500 to 5200 years B.P.

After 5000 years B.P., pollen evidence indicates that mountain forest elements replaced lower Andean forest taxa as the tree line lowered in response to a cooler climate (*26*). This scenario and the temperature changes inferred from it are reflected in the Huascarán $\delta^{18}O$ history, which shows that the latter half of the Holocene experienced a gradual long-term cooling, reaching a minimum (−19.2 per mil) during the "Little Ice Age" (LIA) cool phase in the 17th and 18th centuries (Fig. 7). The LIA $\delta^{18}O$ decrease of 0.9 per mil on Huascarán is similar to that recorded in the Quelccaya ice cap 970 km to the south (*29*). The $\delta^{18}O$ has become dramatically enriched (1.5 per mil) in the past two centuries and in the past two decades has reached its highest value (−16.8 per mil) since 3000 years B.P.

Similar to $\delta^{18}O$, the NO_3^- history is dominated by a steady increase in the first half of the Holocene but lags $\delta^{18}O$ by about 2000 years throughout most of the period. Nitrate concentrations peaked around 3600 to 4200 years B.P., whereas the Holocene $\delta^{18}O$ peaks around 5200 to 6500 years B.P. Because successional vegetation changes occur slowly, we interpret this lag as evidence of the time required for maximum regrowth of the rain forests of Amazonia after their marked reduction during the LGS. Pollen evidence (*26*) suggests that modern vegetation patterns were established by about 3000 years B.P. In the most recent few thousand years, there appears to be no lag in the short-term changes in NO_3^- and $\delta^{18}O$. The lowest Holocene NO_3^- levels occurred during the LIA and have increased (as has $\delta^{18}O$) in the last two centuries.

Holocene dust concentrations on Huascarán do not exhibit major long-term trends as do NO_3^- and $\delta^{18}O$. Huascarán dust concentrations are only 3.5 percent of those measured on the Quelccaya ice cap 970 km south on the Altiplano. This relatively low abundance of dust reflects Huascarán's high elevation, which restricts dust flux. Likewise, the dry season dust layers so prominent on Quelccaya (*24*) are not visible on Huascarán. Six major Holocene dust events are seen (Fig. 7), but their origin is uncertain.

Climatic implications. The Huascarán ice core record extends well into the LGS, a time when conditions were much colder, the atmosphere was much dustier, and biological activity in the Amazon Basin to the east was substantially reduced. Simple $\delta^{18}O$-temperature relations used in polar regions (*30*), when applied to the $\delta^{18}O$ decrease of 8 per mil in LGS ice on Huascarán, suggest that air temperatures may have been lower by as much as 8° to 12°C at high elevation in the tropics. These temperatures are merely estimates because $\delta^{18}O$ depends on temperatures in the source area of evaporation, the transport history of the air masses, and air mass mixing. Regardless, cooler LGS temperatures in the tropics are at odds with the CLIMAP (*31*) LGS temperature reconstructions, which suggest that temperatures at low-elevation tropical sites changed only 1° to 2°C. The Huascarán records are consistent with a small but growing body of evidence, particularly from Barbados corals (*32*), snow line reconstruc-

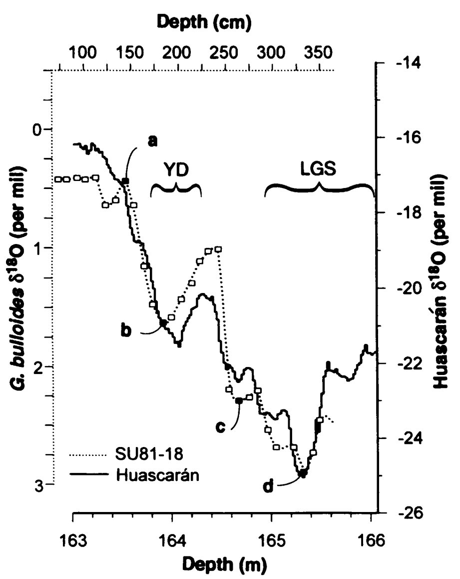

Fig. 5. The Huascarán $\delta^{18}O$ record (solid line, right axis) with the AMS ^{14}C-dated (□) $\delta^{18}O$ record (dotted line, left axis) of *G. bulloides* from a marine core drilled offshore of Portugal (*16*). Both records show the LGS and the glacial-interglacial transition with a distinct YD event. Four of the ^{14}C dates (■) from (*16*) were converted to calendar years (years B.P.) with a revised calibration procedure [(*38*) method A]. The dates shown are (a) 9890 years B.P.; (b) 12,160 years B.P.; (c) 14,990 years B.P., and (d) 17,510 years B.P.

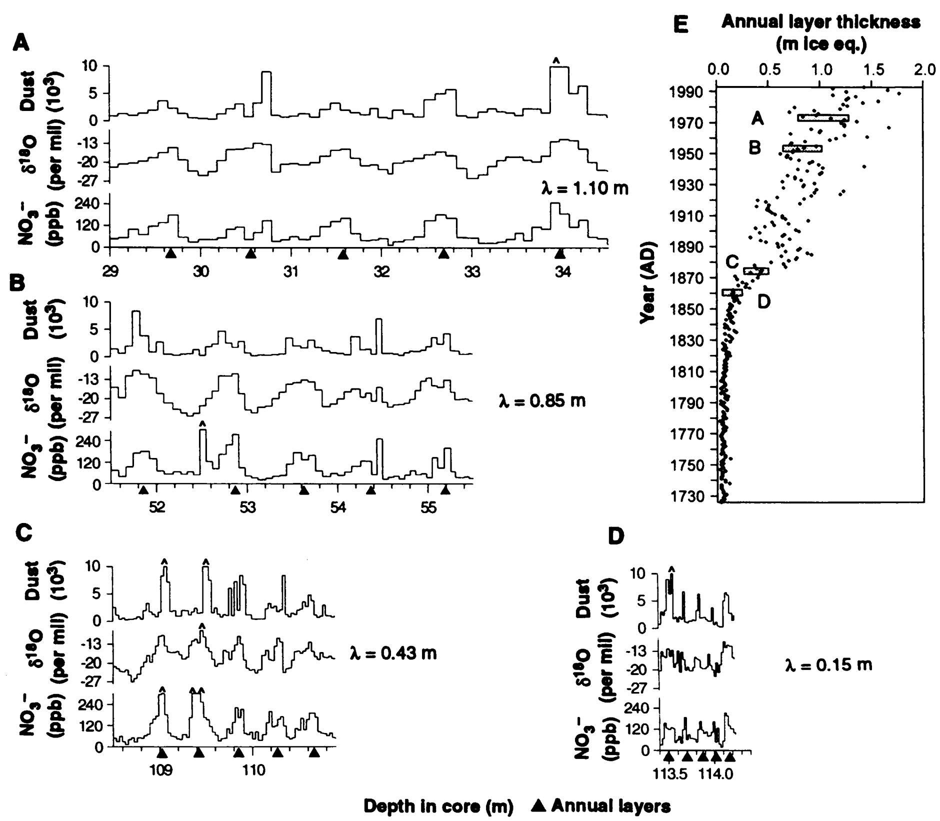

Fig. 6. Dust concentration, $\delta^{18}O$, and NO_3^- concentration in four core sections (**A** to **D**), each covering 5 years, from the upper 114 m of C2. The distinct seasonality of these parameters allowed layer counting in the upper 120 m of the core. The rapid thinning of the annual accumulation layers (▲) with depth is evident. The rectangles in (**E**) indicate the locations of the four core sections. Dust concentrations are the number of particles with diameters ≥2.0 μm and ≤40.3 μm per milliliter sample.

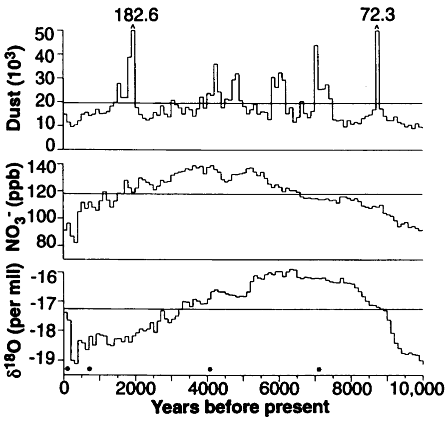

Fig. 7. The 100-year averages of $\delta^{18}O$, NO_3^-, and dust from C2 for the Holocene. Maximum Holocene warmth is evident from 8400 to 5200 years B.P., after which temperatures ($\delta^{18}O$ inferred) cooled through the Little Ice Age. The lag between $\delta^{18}O$ and NO_3^- concentrations may reflect regrowth of vegetation in response to warmer temperatures. Dust concentrations are the number of particles with diameters ≥ 0.63 μm and ≤ 16.0 μm per milliliter sample. Asterisks indicate the location of four Holocene pollen samples. The values of two peaks in dust concentration are labeled because they extend off the graph.

tions (*33*), vegetation changes (*26, 34*), and the noble gas concentrations in ground water (*35*), that indicate tropical continental temperatures were 5° to 8°C cooler during the LGS.

The tropical LGS dust record suggests that current estimates of tropical aerosol optical depths used in climate-model LGS reconstructions are underestimated. Atmospheric aerosol content, an important component of Earth's energy balance, today causes global mean temperatures to be 2° to 3°C cooler than they would be in the absence of aerosols (*36*). If the LGS dustiness can be linked to a marked cooling in the tropics, then an increase in dust may have contributed to the global synchroneity of glacial-stage conditions (*37*). The Huascarán records imply that the tropics were extremely sensitive to the colder LGS conditions and challenge the current view of tropical climate history and the role of the tropics during the LGS.

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