

Part II

Methods of Estimating Ancient Temperature

To understand climate changes of the past, proxies for actual temperature measurements are required. Geologists routinely interpret conditions of the past, including climate. Several techniques for evaluating ancient temperatures have been developed recently. Some of these newer proxies bring to the forefront valuable information on past climate changes.

5 | Stable Isotopes and their Relationship to Temperature as Recorded in Low-Latitude Ice Cores

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ABSTRACT

The potential of stable isotopic ratios ($^{18}\text{O}/^{16}\text{O}$ and $^2\text{H}/^1\text{H}$) in mid- to low-latitude glaciers as a modern tool for paleoclimate reconstruction is reviewed. To interpret quantitatively the ice-core isotopic records, the response of the isotopic composition of precipitation to long-term fluctuations of key climatic parameters (temperature, precipitation amount, relative humidity) over the given area should be known. Furthermore, it is important to establish the transfer functions that relate the climate-induced changes of the isotopic composition of precipitation to the isotope record preserved in the glacier. This paper will present long-term perspectives of isotopic composition variations in ice cores spanning the last 25,000 years from the mid- to low-latitude glaciers. The $\delta^{18}\text{O}$ records from the far western Tibetan Plateau suggest temperatures as warm as today occurred approximately 3000 years ago. However, $\delta^{18}\text{O}$ records from the Himalayas and the eastern side of the Tibetan Plateau confirm that the twentieth century is the warmest period in the last 12,000 years. In the South American Andes on Huascarán, $\delta^{18}\text{O}$ records suggest temperatures as warm as those of today occurred 5000 years ago.

All the tropical glaciers for which data exist are disappearing. The evidence for recent and rapid warming in the low latitudes is presented and possible reasons for this warming are examined. The

isotopic composition of precipitation should be viewed not only as a powerful proxy indicator of climate, but also as an additional parameter for understanding climate-induced changes in the water cycle, on both regional and global scales.

INTRODUCTION

An overview is presented of some of the oxygen isotopic ($\delta^{18}\text{O}$) records from low-latitude, high-altitude glaciers of the world. This paper addresses the question of how faithfully these archives record temperature and then examines 25,000 years of documented climatic history. Finally, an overview of the disappearance of these tropical archives in the last 30 years is presented.

The work presented here reflects the combined efforts of a team of scientists and engineers at the Byrd Polar Research Center of the Ohio State University (OSU), and our colleagues in China, Peru, and Bolivia. These records have been recovered over the previous two decades as part of an ongoing program to reconstruct earth's past climate and environment from a global array of ice cores, as shown in **Figure 1**. The latest addition to this array is the cores drilled on Kilimanjaro in Tanzania. Here, six cores were drilled to bedrock in 2000 from the wasting ice fields on the top of the mountain. Drilling the glaciers was accomplished by using two systems, electrical/mechanical and

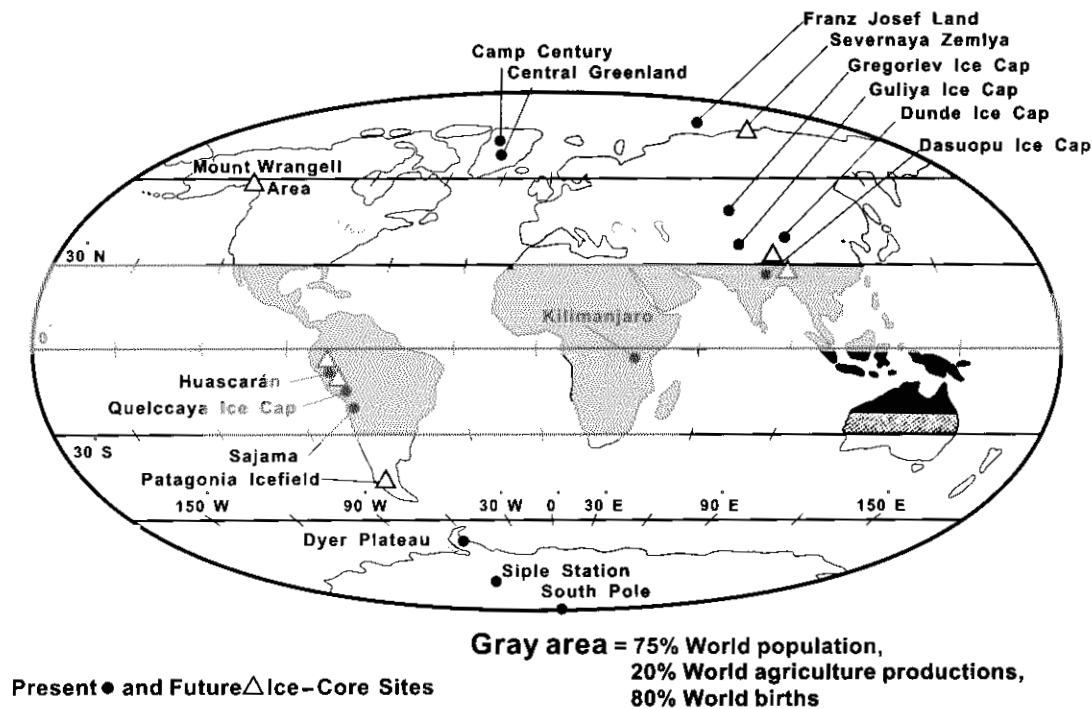


Figure 1 This map shows the ice-core sites where ice cores have already been recovered, as well as planned future sites. The gray area between 30°N and 30°S represents the tropical regions of the world that contain 50% of the surface area, 75% of the population, and 80% of the new births, yet produce only 20% of the agricultural products.

thermal-alcohol. In all our drilling programs, at least two and usually three ice cores are recovered so that the records in the archive can be verified by duplication. The cores are always transported to the Byrd Polar Research Center frozen and are analyzed for stable isotopes, dust, chemistry, and radioactivity produced by atmospheric thermonuclear testing.

A glacier is formed when fresh snow accumulates and survives the ablation season. The snow is buried and becomes firn; eventually, as the density continues to increase, it becomes ice. When we investigate ice-core parameters such as oxygen isotopic ratios ($\delta^{18}\text{O}$), we try to reconstruct the atmospheric input signal of temperatures, although there are postdepositional processes that can potentially alter that signal as densification takes place. Stable isotopes can be altered by vapor transfer through the snowpack as temperatures change both diurnally and seasonally. The relative importance of this process can be evaluated by drilling multiple cores at each site.

Whether a glacier is polar or tropical, three key factors determine the length of the record preserved within it. The first consideration is the annual accumulation rate, i.e., the amount of snow that falls each year on the ice cap; the second factor is the thickness of the glacier (most tropical glaciers are less than 300 meters thick); and the third and most important factor is the temperature at the ice-bedrock contact. If a glacier is frozen to bedrock and has remained frozen through its life, then time cannot be lost from the base. Thus, very old archives of climate and environmental variability can be preserved in quite thin ice caps.

The annual climate of the tropics is often dominated by a distinct wet (summer) and dry (winter) season. The glaciers are nourished during the wet season, and during the dry season a prominent dust layer is deposited on the ice surface. It often forms distinct visible layers such as those exposed along the vertical margin of the Quelccaya ice cap, pictured in **Figure 2**, which illustrates the strong seasonal nature of the tropical climatic and environmental record archived in these glaciers. All the records discussed in this paper were recovered from areas characterized by distinct wet and dry seasons. Ice cores provide unique archives of the past, not only because they can provide well-dated histories of climatic and environmental change as recorded in the layers of ice, but also because one can examine possible climatic forcings such as greenhouse gases, changes in solar activity, and volcanic eruptions. The emphasis here is on the stable isotope archive as a proxy for temperature in six ice cores (low-latitude, high-altitude: 400 to 500 millibar atmospheric pressure), three from the Tibetan Plateau and three from the tropical Andes of South America.

THE TIBETAN PLATEAU

One of the most important questions concerning a stable isotopic record is whether it represents a proxy indicator of temperature for the lower troposphere. We have collaborated with our Chinese colleagues at the Lanzhou Institute of Glaciology and Geocryology (LIGG), who have collected precipitation samples and measured temperatures at six meteorological stations across the Tibetan Plateau. At the Delingha station, which is the closest to the Dunde ice cap (150 km to southeast), the correlation coefficient (R^2) is 0.86 (see **Table 1**), showing a very strong relationship between temperature and $\delta^{18}\text{O}$ (Yao et al., 1996). These data suggest that for the period of measurement, as well as for longer time periods (Thompson, 2000; Thompson et al., 2000a), the $\delta^{18}\text{O}$ faithfully records temperature in this section of the Plateau.

Since 1987, ice core records have been recovered from three sites along the perimeter of the Tibetan Plateau (**Figure 3**). The Dunde ice cap, drilled in 1987, lies in the north-central part of the plateau and covers about 60 km². The scale of this ice cap is illustrated in **Figure 4**, showing (in center) the Mongolian ponies used to transport the drilling equipment to the drill site. **Figure 5**

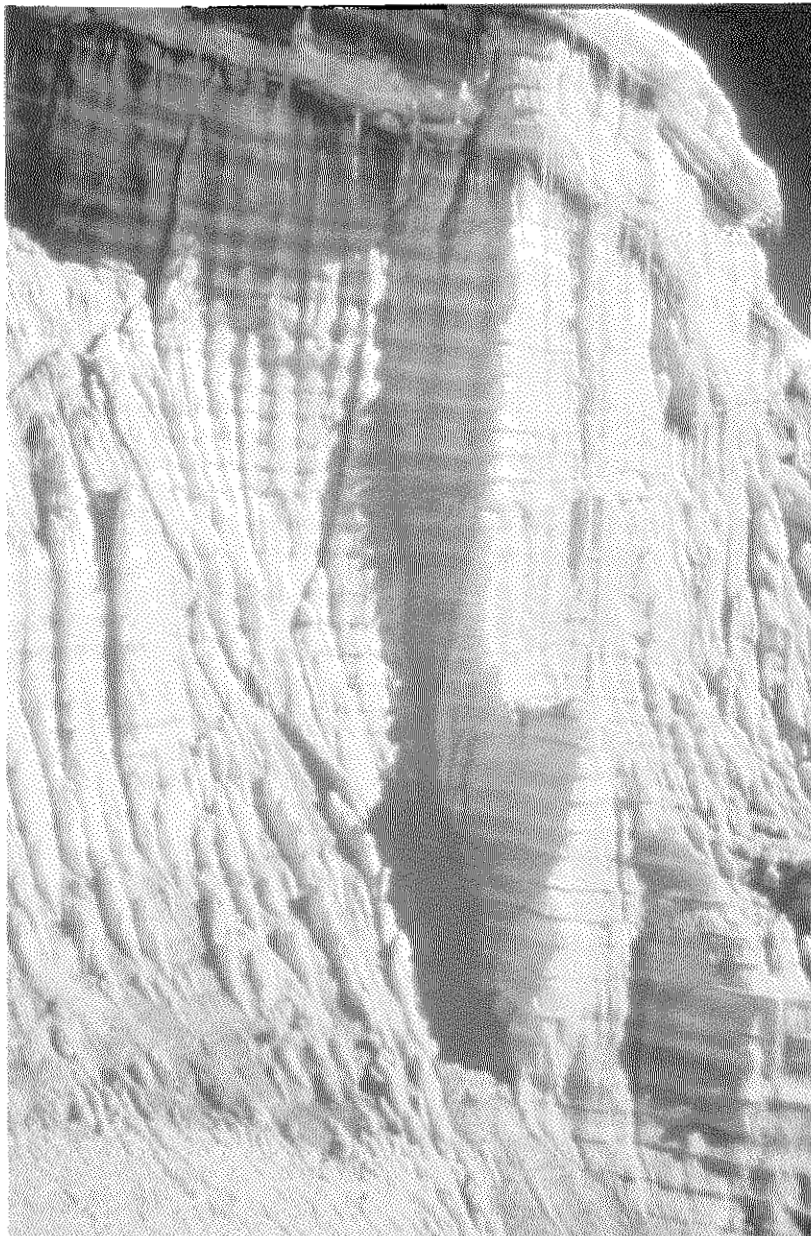


Figure 2 A 50-m ice cliff near the margin of the Quelccaya ice cap in the southeastern Peruvian Andes about 5650 m above sea level. The individual layers represent annual increments of accumulation.

illustrates the $\delta^{18}\text{O}$ record from Dunde, plotted as 50-year averages, that extends back approximately 12,000 years. The histograms illustrate periods that are warmer and colder than the mean. The projection (shaded) of the most recent 50-year period (1938–1987) back 12,000 years indicates that the most recent 50-year period is the most isotopically enriched 50-year period.

Table 1 Linear regression coefficients between $\delta^{18}\text{O}$ and air temperature for both individual precipitation events and monthly averages of precipitation collected at three meteorological stations on the north-central Tibetan Plateau. Delingha is the meteorological station closest to the Dunde ice cap.

Station	Long.	Lat.	Alt. (m)	Averages for Individual Events		Regression			
				$\delta^{18}\text{O}$ %	Air Temp. °C	Individual Events		Monthly Average	
						Regression	Coeff.	Regression	Coeff.
Delingha	97°22'E	37°22'N	2981.5	-8.66	7.40	$\delta^{18}\text{O}(\%) = 0.67T - 13.59$	$R^2 = 0.69$	$\delta^{18}\text{O}(\%) = 0.76T - 14.29$	$R^2 = 0.86$
Tuotuohe	97°22'E	37°22'N	2981.5	-8.66	7.40	$\delta^{18}\text{O}(\%) = 0.36T - 11.2$	$R^2 = 0.13$	$\delta^{18}\text{O}(\%) = 0.48T - 11.09$	$R^2 = 0.45$
Xining	97°22'E	37°22'N	2981.5	-8.66	7.40	$\delta^{18}\text{O}(\%) = 0.29T - 8.51$	$R^2 = 0.14$	$\delta^{18}\text{O}(\%) = 0.49T - 10.51$	$R^2 = 0.60$

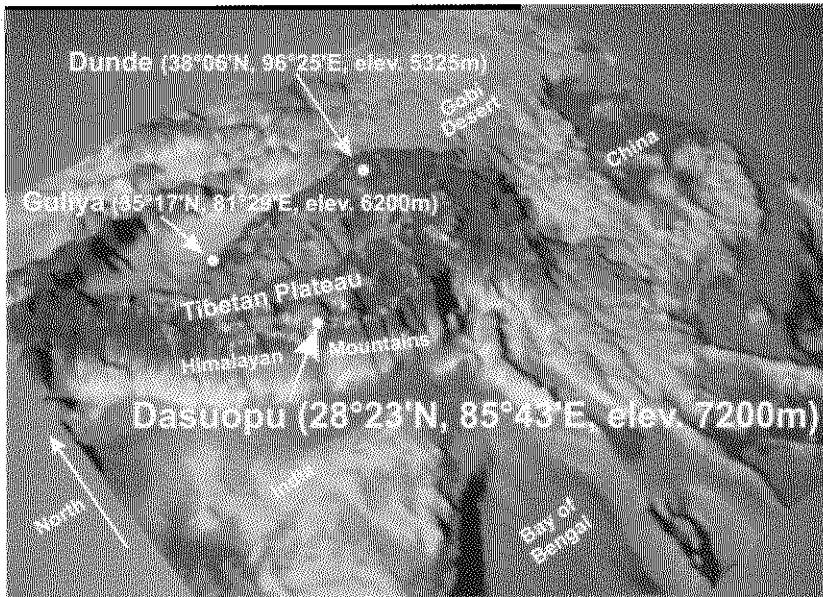


Figure 3 Locations and elevations of the Dunde, Guliya, and Dasuopu ice core sites on the Tibetan Plateau.



Figure 4 The eastern margin of the Dundee ice cap in the Qilian Mountains on the northeastern margin of the Qinghai-Tibetan Plateau. The ice cap covers 60 km² and attains a summit elevation of 5325 m.

Figure 6 illustrates 1000 years of decadal averaged $\delta^{18}\text{O}$ for Dundee, along with similar results from two more recent sites: the Guliya ice cap in the far western Kunlun Mountains and the Dasuopu Glacier at 7200 meters in the Himalayas on the southern margin of the Tibetan Plateau (Thompson et al., 2000a). The overall characteristics of the profiles reveal major differences throughout the last millennium, possibly due to different precipitation sources and postdepositional processes. However, over the last 200 years, all three cores clearly show strong isotopic enrichment, suggesting a recent warming across the entire Tibetan Plateau.

THE ANDES OF SOUTH AMERICA

Figure 7 illustrates the three sites in the tropical Andes from which ice cores have been recovered. For all sites, the moisture source is the tropical Atlantic Ocean by way of the Amazon Basin. This source has remained constant since the Last Glacial Maximum (LGM) (about 20,000 years ago), as revealed by the fact that the mountain snowlines at that time were tilted toward the Amazon Basin, as they are at present (Klein et al., 1995).

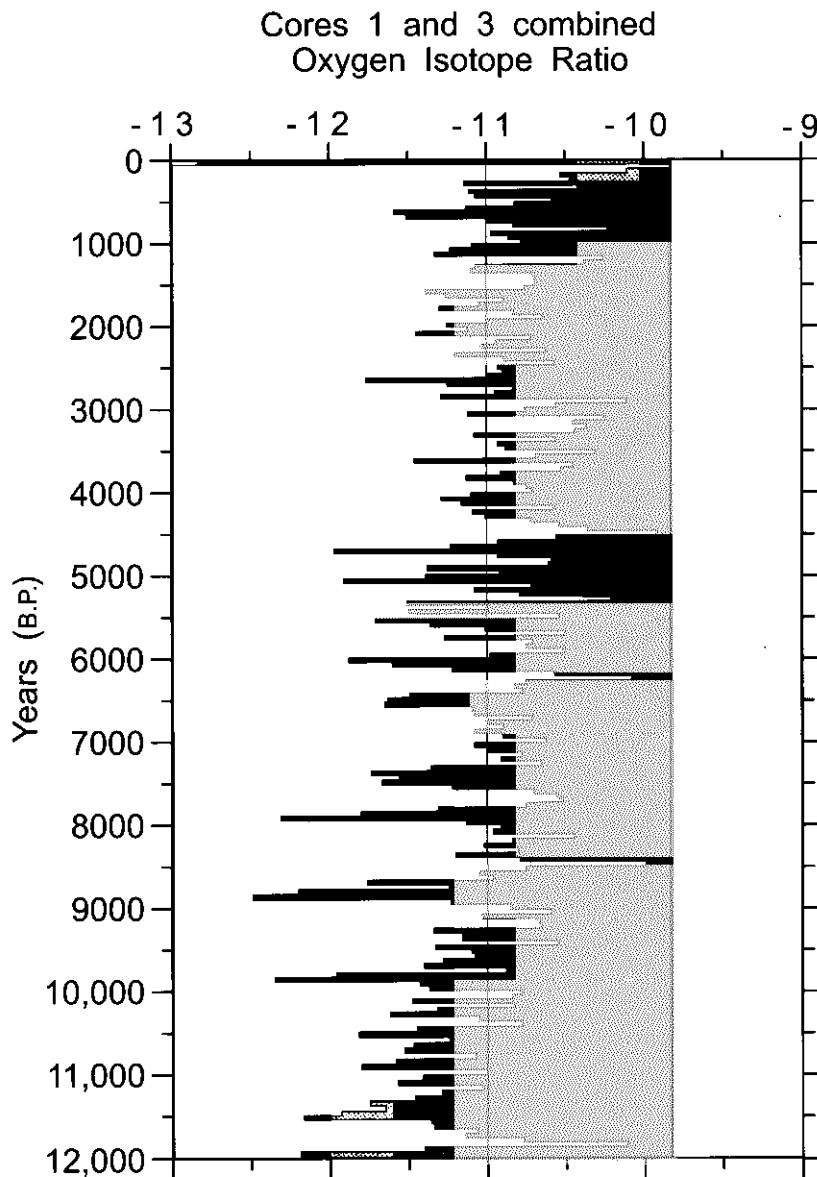


Figure 5 Fifty-year averages of $\delta^{18}\text{O}$ from the combination of cores 1 and 3 for the last 12,000 years from the Dundee ice cap, China. The reference line at -11% represents the long-term average of the records, and projections into the gray area indicate 50-year periods with warmer than average $\delta^{18}\text{O}$. Note that the most recent 50-year period (1937–1987) is the warmest since the end of the last glacial stage.

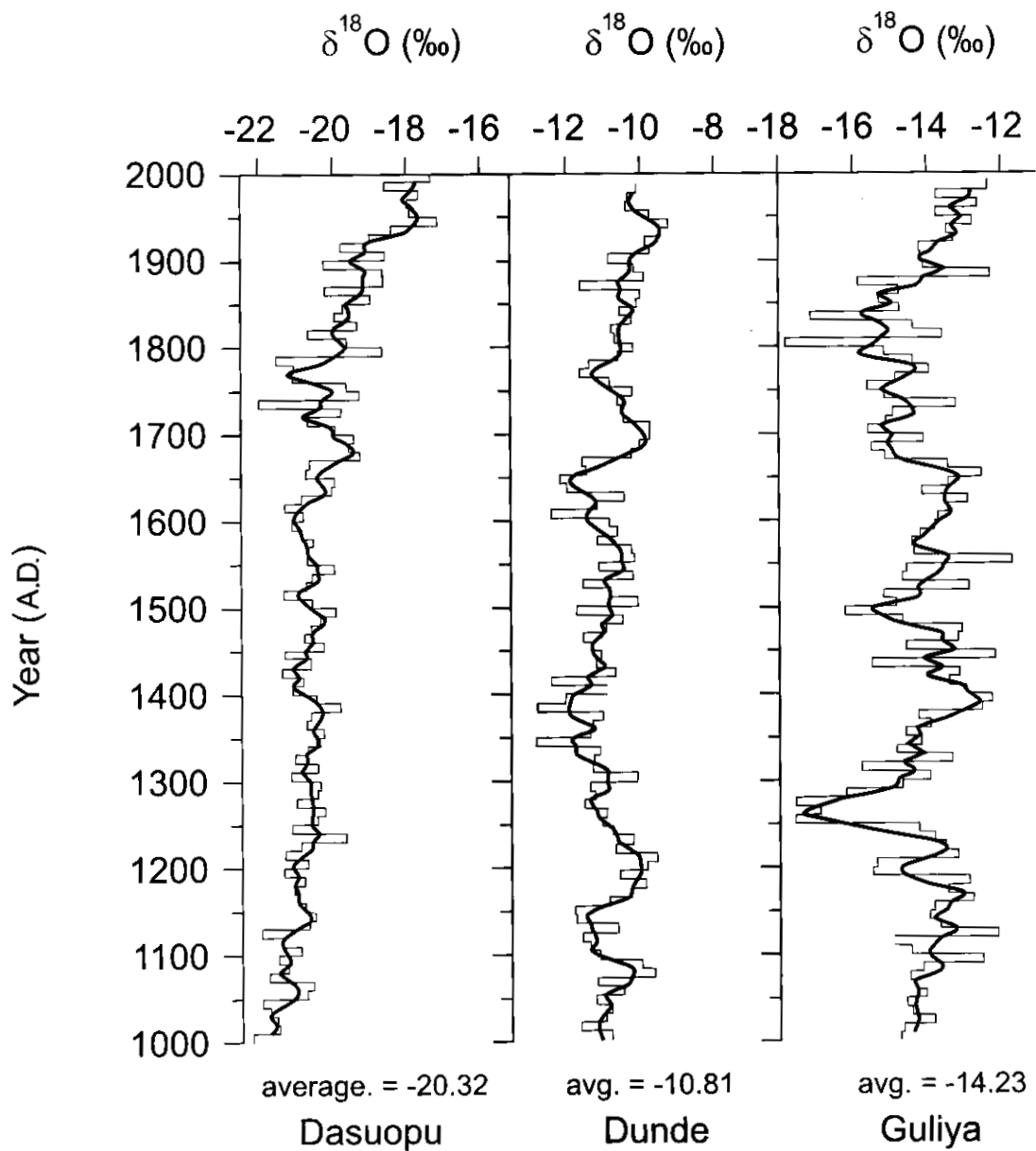


Figure 6 Decadal averages of $\delta^{18}\text{O}$ for Dasuopu, Dunde, and Guliya are shown for the last 1000 years. The dark lines represent three-decade running means.

Huascarán (9°S , 77°W , 6048 m asl [meters above sea level]), the highest tropical mountain on earth, is located between the Amazon Basin to the east and the center of the El Niño-Pacific warm pool to the west. The ice cores were drilled with the use of solar power (**Figure 8**) in the col between the north and south peaks at an elevation of 6050 m. Two $\delta^{18}\text{O}$ profiles from cores drilled 100 m

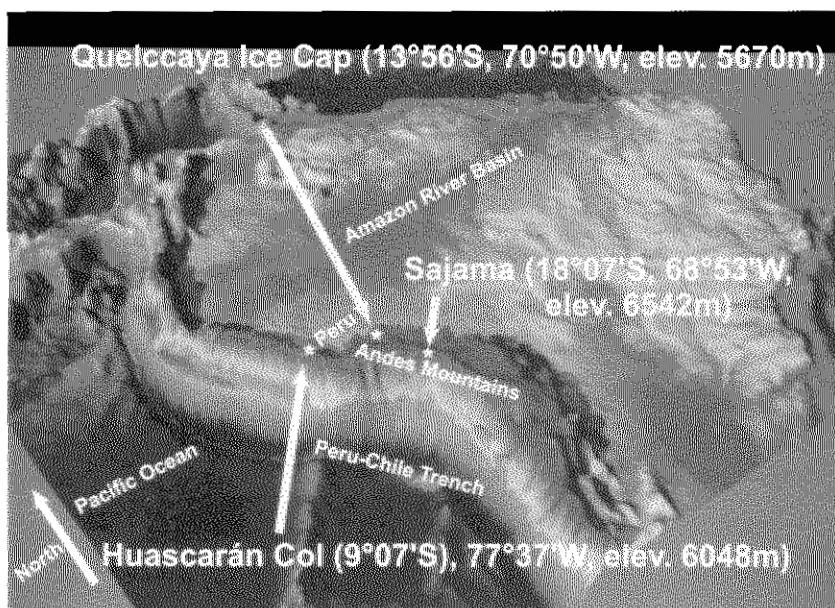


Figure 7 This map shows the locations and elevations of the three tropical ice-core sites in the Andes of South America.

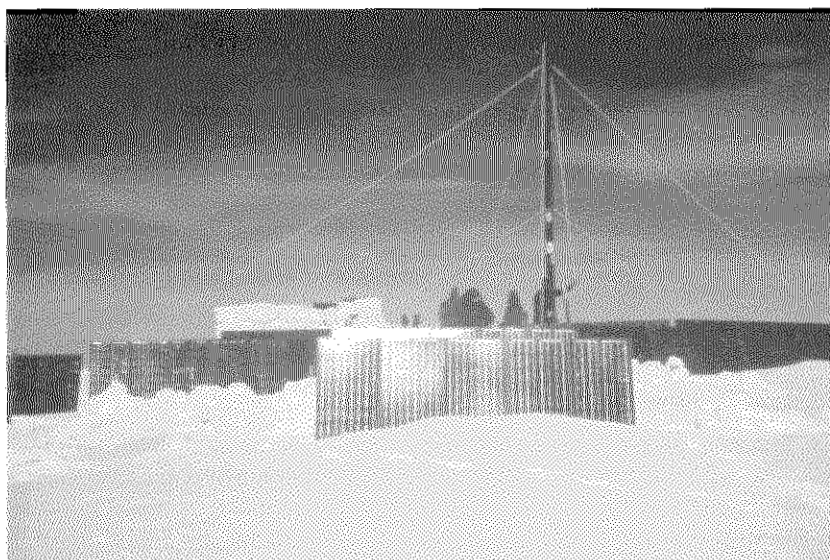


Figure 8 An array of 60 photovoltaic cells was used on the col of Huascarán in 1993 to produce four kilowatts of power which allowed recovery of two ice cores to bedrock (over 166 m in depth). This reflects an environmentally correct way to recover ice cores from pristine tropical environments.

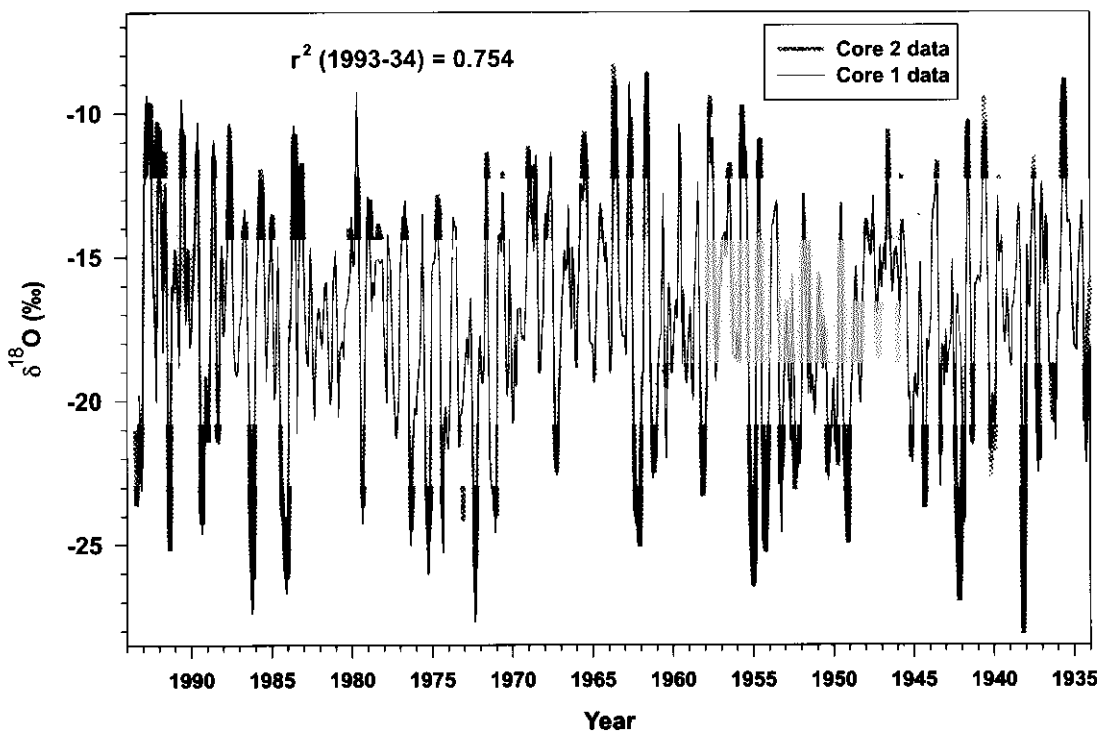


Figure 9 Individual $\delta^{18}\text{O}$ samples are plotted for the two cores drilled on the col of Huascarán. The sites are separated by a 100-m horizontal distance. The similarity of these profiles demonstrates that drifting snow and other surface disturbances have little effect on the reproducibility of the record from site to site.

apart are shown in **Figure 9**. Core 1 was brought back from the field as bottled water samples and core 2 was transported to OSU frozen. This diagram illustrates that stable isotope records are spatially reproducible across the glacier. Of concern, however, is the issue of temporal reproducibility, or how much the input signal changes with time as it becomes buried in the ice cap. **Figure 10** illustrates the $\delta^{18}\text{O}$ signal in a firn core drilled in 1980 with a mean value of -17.56‰ and compares the same period of time covered in the deep ice cores drilled in 1993 to bedrock. Even after 13 years, the mean isotopic value is -17.33‰ , which is nearly identical. This clearly illustrates that at least under present-day climate conditions, these ice cores faithfully archive and preserve the isotopic signature at this tropical site.

Currently, two models have been used to explain the $\delta^{18}\text{O}$ composition of ice cores in the tropical Andes. The model developed by Grootes et al. (1989) is a hydrological model of moisture transport (**Figure 11**). The isotopic values are initially determined by the composition of ocean water, and as the vapor moves across the Amazon Basin, it is recycled in thunderstorms. Every time condensation takes place, the heavier isotopes are preferentially removed. This moisture falls from clouds and is transported out of the Amazon Basin by the river system in the wet season. In the dry season most of the water that falls in the Amazon is reevaporated, and thus very little isotopic fractionation takes place (**Figure 11**). However, by the time the moisture

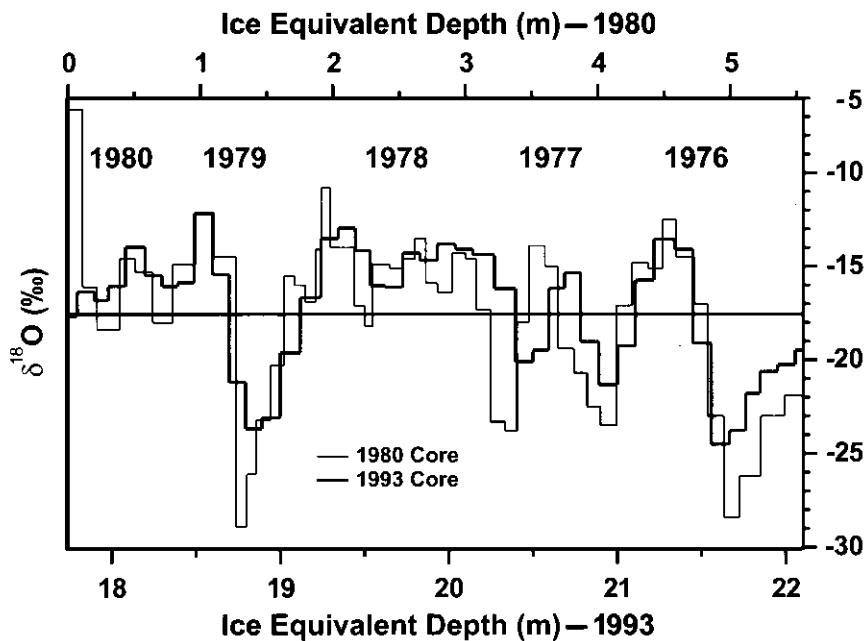


Figure 10 The $\delta^{18}\text{O}$ record from a 10-m core drilled in 1980 on the Huascarán col is compared with that representing the same time period but drilled 13 years later (1993) as Huascarán core 2. Comparison of these records demonstrates that very little alteration of the input signal has occurred with time and depth.

reaches the base of the Andes in the wet season, it has a mean isotopic value of -20‰ . When the air masses are forced to rise over the Andes (above 5000 m) an additional 10‰ depletion takes place.

The second model brings into consideration another important factor by which interpretation of stable isotopes in the tropics differs from interpretations in the higher latitudes. In the Andes, the snowfall comes from thunderstorms, i.e., convective cells with great vertical extent. Therefore, the mean level of condensation in the tropics is higher than that in the polar regions. More importantly, the location and height of the mean condensation level changes from the wet to the dry season. In the wet season, Huascarán is in the center of the region affected by maximum deep convection, but in the dry season this activity moves to the north. The condensation level during the height of the wet season is roughly 2 km higher where the temperatures are cooler, while in the dry season condensation occurs at a lower, warmer level in the atmosphere. The isotopic composition of precipitation may well reflect these changes (Thompson et al., 2000b).

Figure 12 illustrates a record of $\delta^{18}\text{O}$ and the concentrations of dust and nitrate (NO_3^-) from Huascarán over the most recent 100 years of the record. Because of the preservation of the very distinct annual signal in the upper sections of these ice cores, they can be used to provide records of El Niño–Southern Oscillation (ENSO) variations (Henderson et al., 1999).

A profile of centennial averages of $\delta^{18}\text{O}$ over the last 20,000 years (**Figure 13**) illustrates that the isotopic depletion of 6.3‰ during the LGM is very similar to that in polar regions (Thompson

Isotope Fractionation Model involving Amazon Basin hydrology

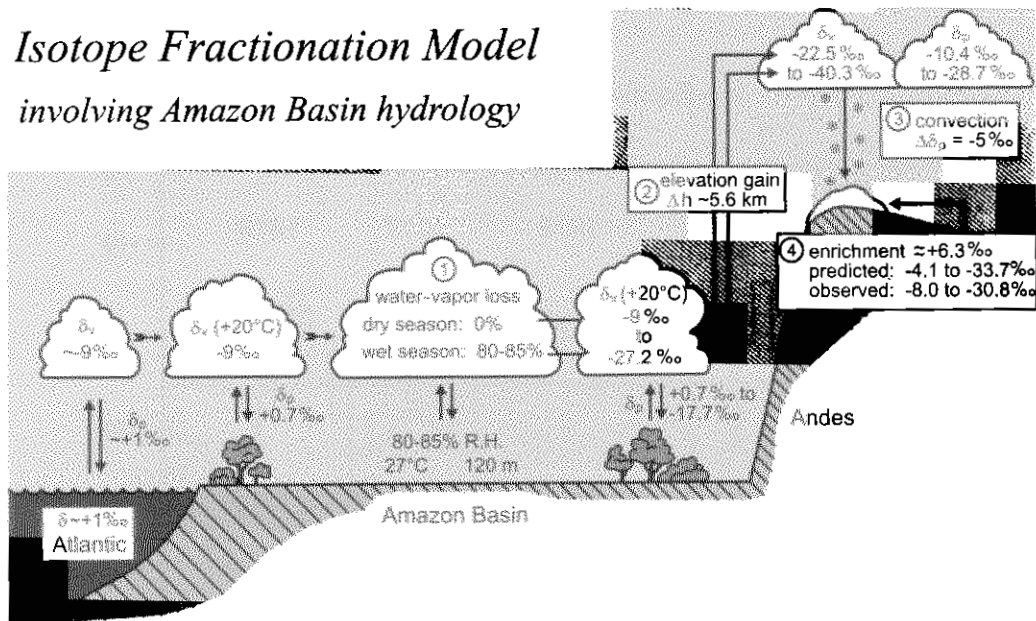


Figure 11 This schematic traces the $\delta^{18}\text{O}$ composition of water vapor and precipitation along a transect from the Atlantic Ocean to the top of the Andes (Quelccaya ice cap). This figure was modified from Grootes et al. (1989).

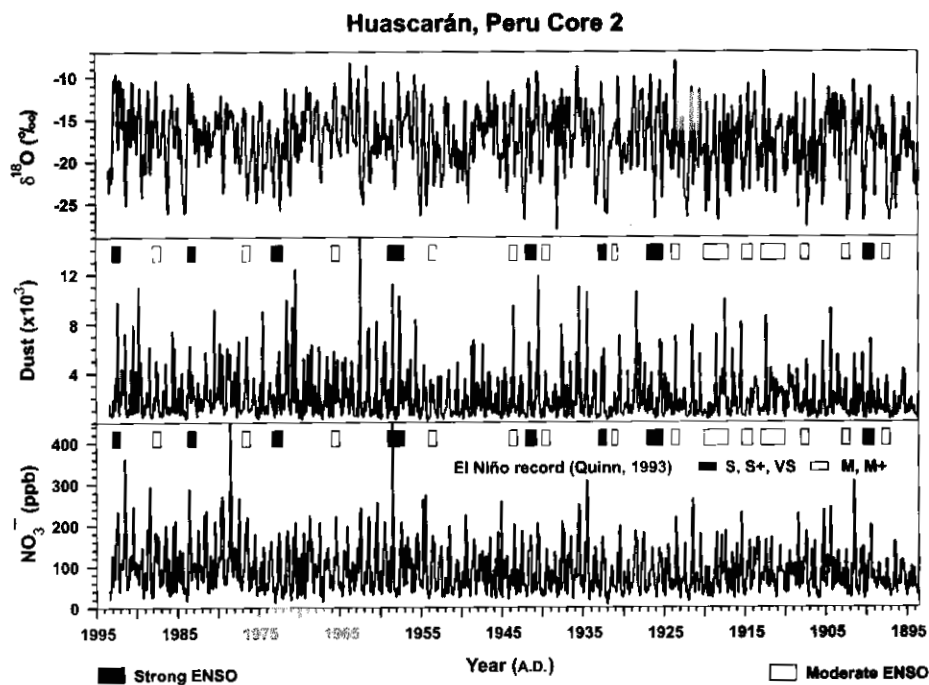


Figure 12 Seasonal variations in $\delta^{18}\text{O}$ and concentrations of (NO_3^-) and insoluble dust measured in Huascarán core 2 for the last 100 years. Also shown are the El Niño events identified by Quinn (1993). Dust concentrations are for particles with diameters $> 2.0 \mu\text{m}$ per milliliter sample.

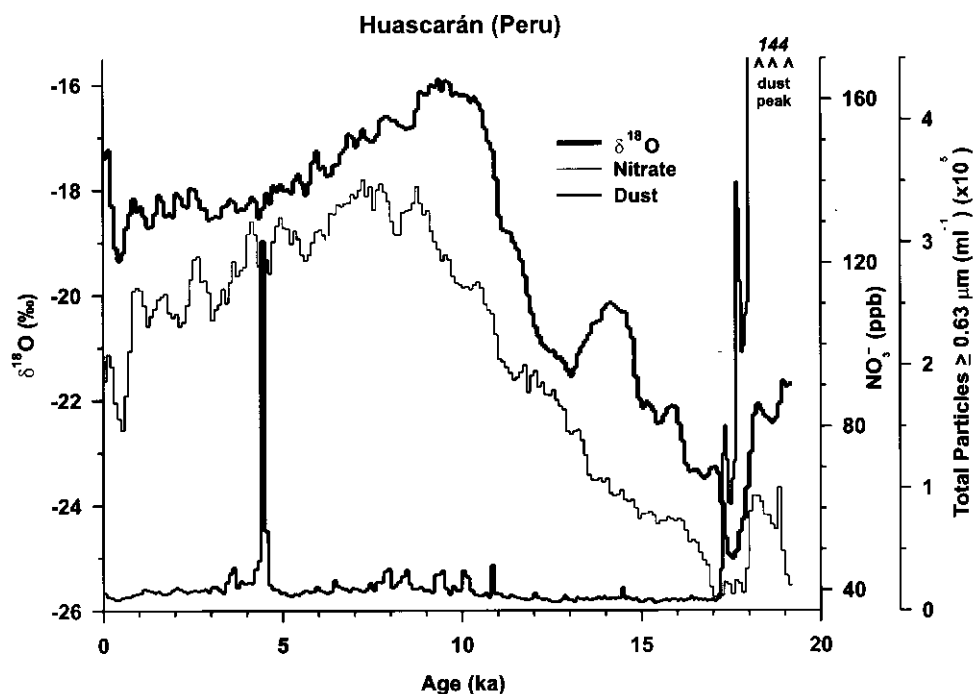


Figure 13 Comparison of the 100-year averages of $\delta^{18}\text{O}$ and concentrations NO_3^- and dust particles with diameters $> 2.0 \mu\text{m}$ from Huascarán over the last 20,000 years.

et al., 1995). The enrichment of the last 200 years is unprecedented in the most recent 5000 years of this record. Between 11,000 and 6000 years B.P. (before the present), however, $\delta^{18}\text{O}$ values are the highest of the entire climatic history presented by this ice-core record. This observation suggests that this part of the world was even warmer in the early Holocene than it is today.

The Quelccaya ice cap (14°S) was drilled in 1983 and has provided an annually resolved record of climatic variation extending back to A.D. 470 (Thompson et al., 1985; 1986; 1989). The reproducibility of the $\delta^{18}\text{O}$ records between two cores over the last 500 years is demonstrated in **Figure 14**. Also demonstrated is how well the $\delta^{18}\text{O}$ records reflect the Northern Hemisphere temperature record as reconstructed by Mann et al. (1998). In fact, the Quelccaya ice cap has provided the clearest $\delta^{18}\text{O}$ record of the "Little Ice Age" of any ice core recovered to date.

Further to the south is Sajama, Bolivia (18°S). It is a 6550-m asl extinct volcano on which two cores were drilled to bedrock in 1997 (Thompson et al., 1998). The ice cores from this site are very unusual in that they contain both insect and plant remains in sufficient supply to allow accelerated mass spectrometer (AMS) carbon-14 (^{14}C) dating by two separate laboratories. Thus, unusually good absolute time control is possible for the Sajama records. **Figure 15** illustrates the 25,000 calendar years of reconstructed climate history. Not only does the $\delta^{18}\text{O}$ show a 5.4‰ decrease in glacial conditions, similar to Huascarán and the polar ice cores, but it also demonstrates that this area which is very dry today was very wet during the LGM. Moreover, the good time control for the Sajama record allows a detailed comparison with the GISP II (Greenland Ice Sheet Project 2) core (Grootes et al., 1993) from central Greenland (**Figure 16**). The Younger Dryas (in Greenland) or deglaciation cold reversal (in Bolivia) are very clear in both these cores, each showing a depletion

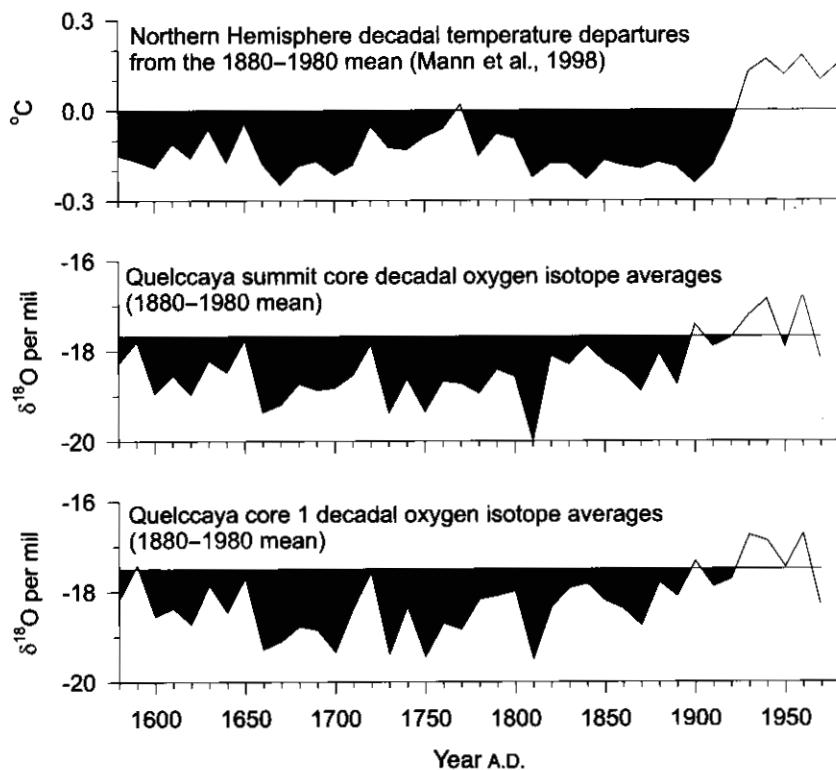


Figure 14 Decadal temperature departures (from the 1881–1980 mean) in the Northern Hemisphere (Mann et al., 1998) from 1580 to 1980, compared with decadal averaged $\delta^{18}\text{O}$ for both Quelccaya ice cores. The solid line is the 1881–1980 mean.

of 5.2‰. Additionally, the abruptness of the termination of the event, as far as it can be constrained by the timescales, appears to be the same in the tropics as in the high latitudes. These data indicate that the natural climate system may actually operate in modes and be capable of very rapid abrupt changes at magnitudes which have not been documented by human observations.

These new ice-core records challenge existing paradigms of the earth's climate system because whether we look at ice core records from Antarctica, Greenland, or the low- to mid-latitudes, the Holocene period (last 10,000 years) shows quite different trends. On the other hand, the isotopic shift from the glacial maximum to early Holocene is very similar around the world, suggesting a global cooling during glacial maximum of 5° to 6°C. We believe that the recent noble gas work on groundwater (Stute et al., 1995; Weyhenmeyer et al., 2000), pollen (Colinvaux et al., 1996), tropical corals (Guilderson et al., 1994; Beck et al., 1997), and marine sediment pore fluids (Shrag et al., 1996) all supports the temperature interpretation placed on these tropical ice-core stable isotopic results.

THE MELTING OF THE TROPICAL GLACIER CLIMATE ARCHIVES

There is mounting evidence for a recent, strong warming in the tropics, which is signaled by the rapid retreat and even disappearance of ice caps and glaciers at high elevations. Indeed, we have

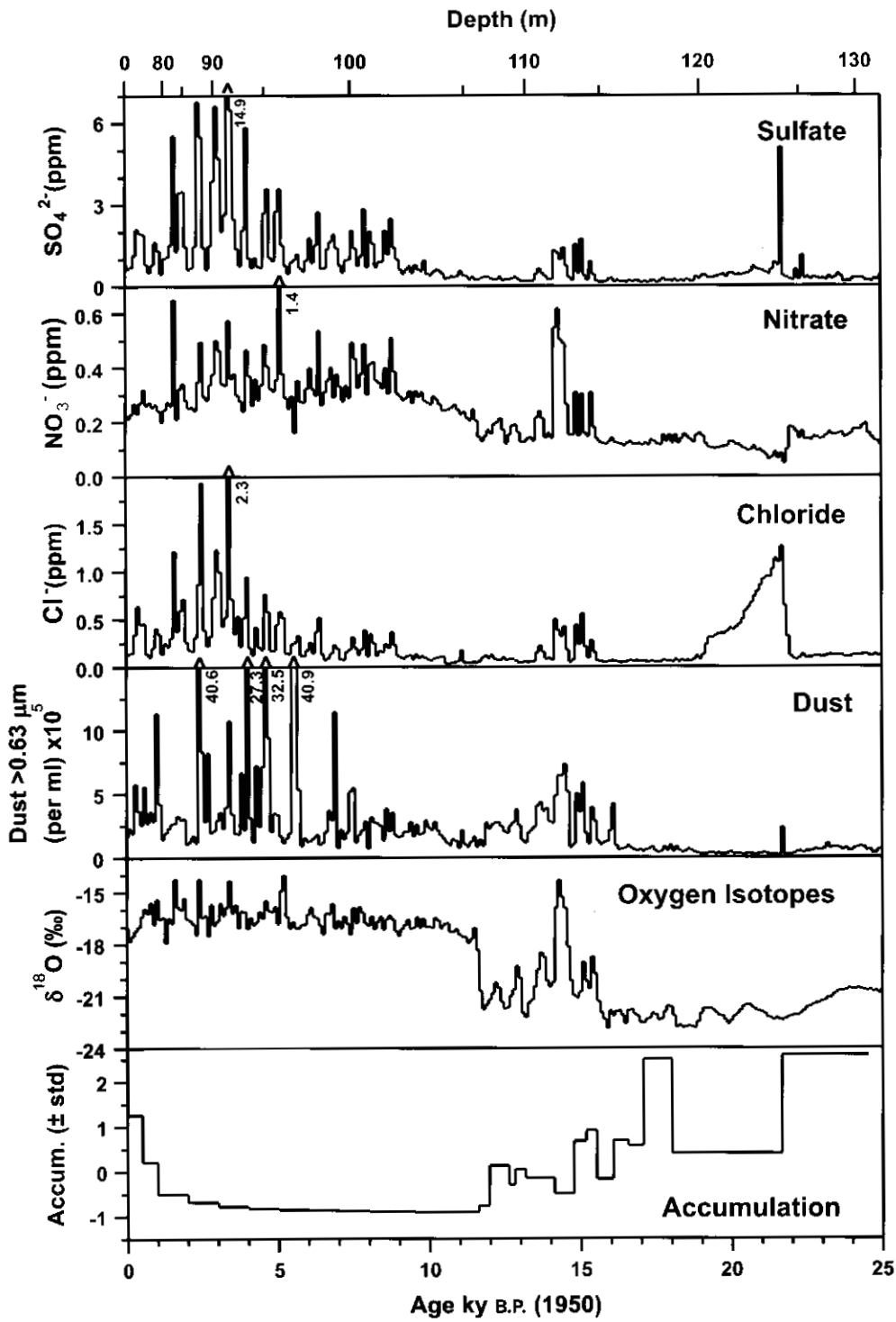


Figure 15 The 100-year averages of $\delta^{18}\text{O}$ and concentrations of dust, chloride (Cl^-), nitrate (NO_3^-), and sulfate (SO_4^{2-}) from Sajama core 1 are shown for the past 25,000 years. The accumulation record is the average of cores 1 and 2 (Thompson et al., 1998). ky B.P. = thousand years before the present.

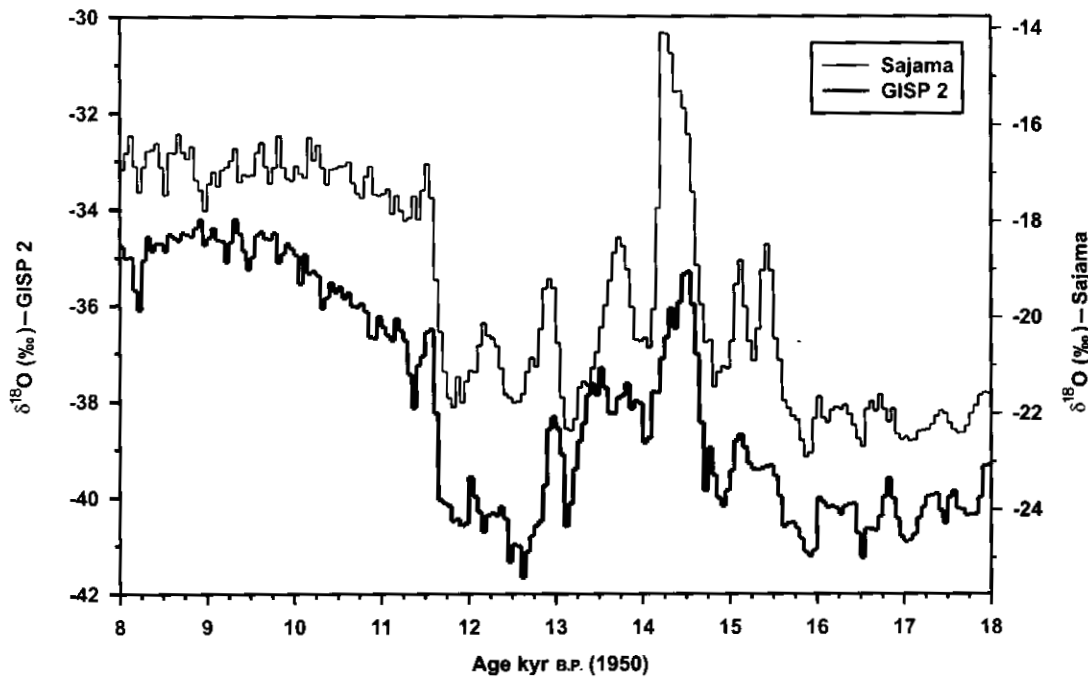


Figure 16 The 50-year averages of $\delta^{18}\text{O}$ since the deglaciation as recorded in the tropical Sajama, Bolivia, and polar GISP 2 Greenland ice cores.

extensively documented these changes on Quelccaya, one of the best-studied tropical ice caps. $\delta^{18}\text{O}$ profiles from shallow cores drilled on Quelccaya in 1976 from different elevations along the summit of the ice cap are illustrated in **Figure 17**. At the highest elevation site an annual cycle in $\delta^{18}\text{O}$ existed and this isotopic signal allowed dating of the most recent 600 years of the ice cores drilled to bedrock in 1983. Cores also recovered in 1976 from lower elevation sites on Quelccaya show a loss of annual $\delta^{18}\text{O}$ cyclicity with depth due to melting and movement of water through the firn column. Since 1976, Quelccaya has been visited repeatedly for monitoring. In 1991, another shallow core was drilled at the summit. It revealed that the seasonally resolved paleoclimatic record, formerly preserved as $\delta^{18}\text{O}$ variations, was no longer being retained within the accumulating snowfall. The percolation of meltwater throughout the snowpack was vertically homogenizing the $\delta^{18}\text{O}$, enriching the mean isotopic value by 2‰ between 1976 and 1991, indicating a strong recent warming.

The general warming of the twentieth century is now well documented. Although not all regions of the earth have warmed, the globally averaged temperature has increased 0.7°C since the end of the nineteenth century (Hansen et al., 1999). Annual global land-temperature anomalies, as measured by meteorological stations, indicate that 1998 was the warmest year on record, and the 1990s have been the warmest decade on record. The best interpretation of proxy records from borehole temperatures, stable isotopes from ice cores, tree-ring data, and other proxy data suggests that the decade of the 1990s was the warmest in the last 1000 years (Mann et al., 1999).

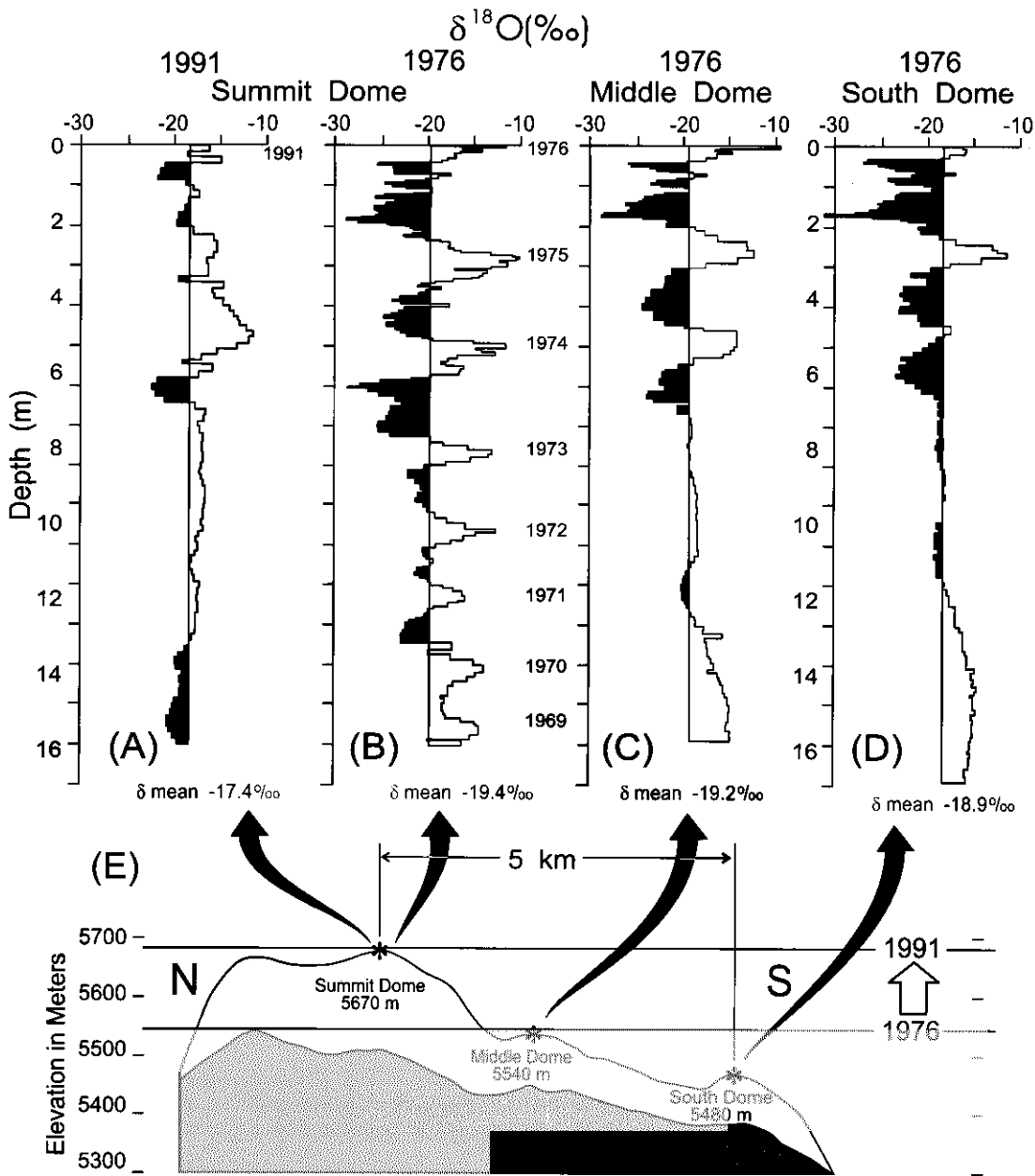


Figure 17 The $\delta^{18}\text{O}$ profiles drilled in 1976 along a north-south transect (summit, middle, and south domes) on the Quelccaya ice cap, Peru, are compared with a 1991 record from the summit dome. Also shown is the rise in the 0°C melting line between 1976 and 1991.

Tropical ice masses are particularly sensitive to small changes in ambient temperatures because they already exist very close to the melting point. The retreat of Quelccaya has been monitored since 1978 by terrestrial photogrammetry of a valley glacier called Qori Kalis on the western side of the ice cap (Brecher and Thompson, 1993; Thompson et al., 1993). The movement of the ice front and the volume loss have been determined for six time intervals, and these observations document a drastic retreat of the glacier that has accelerated with time. The latest photographic evidence from 1998 indicates that this retreat continues to accelerate. It was twice as great in the latest three-year period, between 1995 and 1998, as it was in the previous two-year period, between 1993 and 1995 (48.7 vs. 28.7 m a⁻¹ (meters per year)). Currently, the retreat rate is an order of magnitude greater than it was from 1963 to 1978, when comparison between the position from the first terrestrial photograph and that from the aerial photographs gave a value of 4.9 m a⁻¹. The volume loss has accelerated at an even greater rate. The graph in the lower right of **Figure 18** illustrates the retreat of the terminus. The sketch map shows the position of the glacier terminus for each of the seven determinations since 1963. Note that the small proglacial lake that first appeared in the 1991 photograph has continued to grow with the retreat of the ice front, and in 1998 it was twice as large as in 1991 (**Figure 18**). The retreat of Qori Kalis is consistent with the records from two ice cores drilled on the col of Huascarán whose $\delta^{18}\text{O}$ records (discussed earlier) indicate that the nineteenth and twentieth centuries were the warmest in the last 5000 years.

Additional glaciological evidence for tropical warming exists. Hastenrath and Kruss (1992) report that the total ice cover on Mount Kenya decreased by 40% between 1963 and 1987 and continues to diminish today. The Speke Glacier in the Ruwenzori Range of Uganda has retreated substantially since it was first observed in 1958 (Kaser and Noggler, 1991). Today the total ice mass on Kilimanjaro is roughly 25% of that which existed in 1912 (Hastenrath and Greischar, 1997). Schubert (1992) noted that in the Sierra Nevada de Merida of Venezuela, at least three glaciers have disappeared since 1972. The shrinking of these ice masses in the high mountains of Africa and South America is consistent with similar observations throughout most of the world.

We believe that warming is being enhanced through the tropical hydrological system at the higher-elevation sites in the tropics. At these latitudes, water evaporates from the oceans and heat energy is released from the latent heat of condensation at the higher elevations. A change in the tropical lapse rate may have occurred in the late 1970s (Gaffen et al., 2000). The authors found, if anything, a cooling since 1979 relative to the surface in the records from both satellite and the radiosonde data. Over the longer record from about 1960 to present, they found evidence of differential temperature changes, with the lower troposphere warming somewhat more. This is in opposition to the glacier records. However, a small temperature rise at the surface evidently is being enhanced through latent heat release at these higher elevations associated with enhanced deep convection in the tropics, to account for not only the retreat but also the acceleration in the rate of retreat of tropical glaciers. Water vapor, pumped into the atmosphere at low latitudes, is the most important greenhouse gas on earth. Thus, the increases in CO₂ leading to surface warming may be enhanced through positive feedbacks and generate an increasing global inventory of water vapor. Two of the factors we must try to understand are how the tropical hydrological system has varied through time and how the water-vapor content in the atmosphere has changed in response. Because the forcing is driven from the tropics, changes in the global water-vapor content can have dramatic impacts on the climates of both the Northern and Southern Hemispheres. Clearly, much more research is needed in this area. We must realize that the tropical glaciers may be the “canary in the cage” for the earth’s climate system.

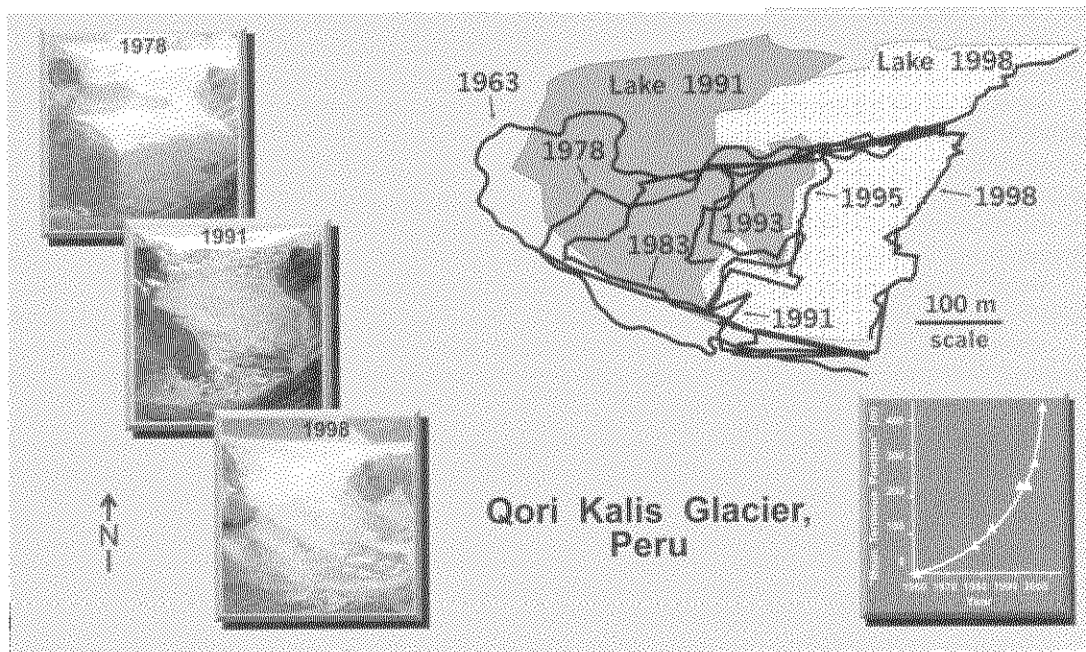


Figure 18 Recent warming in the Peruvian Andes is illustrated by the mapped and photographed changes in the extent of the tropical outlet glacier, Qori Kalis, from 1963 to 1998. The right-hand graph illustrates the exponential increase in the rate of retreat of the Qori Kalis margin since 1963

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