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STABLE ISOTOPES AND THEIR RELATIONSHIP TO TEMPERATURE AND PRECIPITATION AS RECORDED IN LOW LATITUDE ICE CORES

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Abstract. The potential of stable isotopic ratios ($^{18}O/^{16}O$ and $^{2}H/^{1}H$) in mid to low latitude glaciers as modern tools for paleoclimate reconstruction is reviewed. 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. 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 a 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. The factors that govern the values of stable isotopes in snowfall are enigmatic and as yet no satisfactory model has been developed to link them directly with any one meteorological or oceanographic factor. This is particularly problematic in the high altitude glaciers in the tropics, where complications are present due not only to continental effects, but also to altitude effects and convective air mass instability, particularly in the monsoon climates of the tropics. This paper presents long and short-term perspectives of isotopic composition variations in ice cores spanning the last 25,000 years from the mid- to low-latitude glaciers. The isotopic records will also be examined as a function of the altitude of the individual coring sites which ranges from 5325 meters to 7200 meters. On the short, term isotopic records from ice cores from the Andes of South America, the Tibetan Plateau and Kilimanjaro in Africa through the year 2000 will be presented. All the tropical glaciers for which data exist are disappearing, and these sites show isotopic enrichment in the 20th century that suggests that large scale low latitude warming is taking place. In general this warming appears to be amplified at higher elevation sites. The evidence for recent and rapid warming in the low latitudes is presented and possible reasons for this warming are examined.

1. INTRODUCTION

An overview is presented of the oxygen isotopic ($\delta^{18}O$) records from seven low latitude, high altitude glaciers around the world. This paper will address the question of how well these data record temperature through time and then will examine the perspective provided by over 25,000 years of documented climatic history. Finally an overview of the disappearance of these tropical archives over the last 30 years is presented along with evaluation of recent changes in mean stable isotopic composition.

Ice core records are available from selected high altitude, low and mid-latitude ice caps (Figure 1). Comparisons are made between three from the Tibetan Plateau: Dunde, (38°N, 5325 m asl), Guliya, (35°N; 6200 m asl) and Dasuopu in the Chinese Himalayas (28°N, 7200 m asl). These Tibetan records are compared with three tropical ice core records from the Andes of South America, Huascarán, Peru (9°S, 6050 m asl) Quelccaya, Peru (14°S, 5670 m asl) and Sajama (Bolivia, 18°S, 6550 m asl). Finally, we introduce our most recent site at Kilimanjaro, Tanzania (3°S, 5895 m asl). Some of these sites contain ice deposited during the Last Glacial Stage (LGS) and the δ^{18}O of this ice suggests significant cooling (~5°C) in the tropics. These records contribute to a growing body of evidence that tropical climate was cooler and more variable during the LGS [1,2] and to renewed interest in the low latitude water vapor cycle. Ice core evidence for past changes in this hydrological cycle, as well as evidence for recent warming at high elevations in the tropics, suggest that changes in water vapor inventories are a significant component of climate variability.

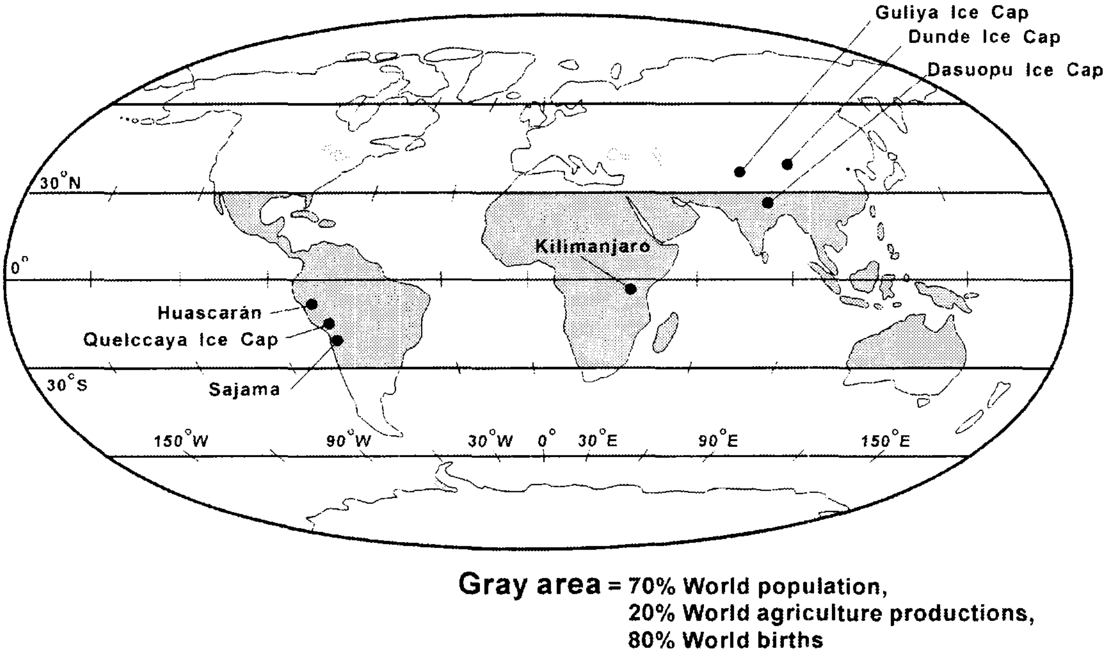

FIG. 1. Map illustrating the seven sites from which ice cores have been recovered. The shaded area between 30°N and 30°S represents the tropical regions that contain 50% of the world's surface area, 75% of the its population and 80% of the new births, but only produces 20% of the agricultural products.

2. δ^{18}O AS A TEMPERATURE RECORDER IN LGS/EARLY HOLOCENE ICE CORES FROM TROPICAL SOUTH AMERICA

The controversy over whether oxygen isotopic ratios are more influenced by temperature or by precipitation is addressed by the examination of the climatic and environmental history from Sajama, which is one of the best dated of the all the tropical ice core records. The profiles of δ^{18}O, dust and anion concentrations were transferred to a ^{14}C-constrained time scale (Figure 2) according to techniques discussed in [2]. The increases in dust and anions, particularly in chloride (Cl^-) are linked to the desiccation of the Altiplano lakes, and when the lakes are dry aerosols are entrained by winds over the salt flats and deposited on the ice cap. In general, the LGS is much wetter, colder and less dusty than the dryer Holocene climate on the Altiplano.

Recently, Baker *et al.* [3] asserted that since the Sajama δ^{18}O record shows a similar structure to the nearby Salar de Uyuni γ-radiation record, then the $\delta^{18}O_{ice}$ is inversely correlated with precipitation amount (or runoff fraction). However, this is disputed by the ice core record itself. A closer examination of the termination of the deglaciation cold reversal between 11.8 and 11.5 ka (Figure 3a) shows an isotopic enrichment of 5.2‰ at a time when the Cl^- and dust concentrations changed very little. This indicates that during a time of rapid and dramatic warming, the lake levels remained relatively stable, suggesting that regional precipitation rates did not vary. Another example of the disconnect between temperature and effective moisture is seen in Figure 3b, the transition into the Last Glacial Maximum (LGM) between 22 ka and 21.7 ka. Here, the lake levels were clearly decreasing, as reflected by a five-fold increase in Cl^-, but there was no change in the $\delta^{18}O$ of the precipitation on the ice cap. Thus, as in polar cores, temperature is the more dominant control on the mean oxygen isotopic values of tropical snow than precipitation amounts.

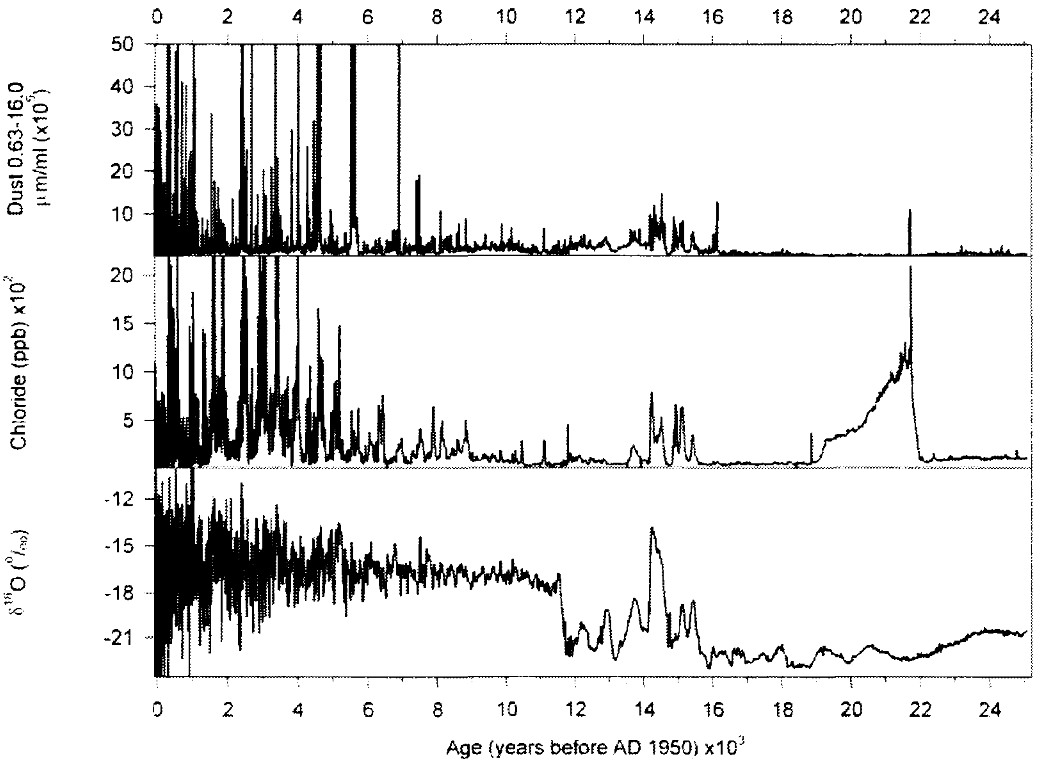

FIG. 2. High-resolution plots of $\delta^{18}O_{ice}$, and dust and chloride (Cl^-) concentrations from Sajama for the past 25 ka.

Additional arguments for this case are taken from the comparison of the climate reconstruction from Sajama with that from Huascarán at 9°S of the equator [4]. The record from the latter illustrates that the LGS in northern Peru was cold and dry, but that the Early Holocene was warm and wet. Conversely, the Sajama record [2] clearly shows that the climate history on the Altiplano was of a cold and wet LGS and a warm and dry Early Holocene. However, the LGS isotopic mean on Huascarán of -22.9‰ is very close to the Sajama mean of -22.1‰, and the Early Holocene Huascarán average of -16.6‰ is almost identical to -16.7‰ for Sajama. This strongly argues that the long-term $\delta^{18}O$ is not inversely correlated to precipitation amount as argued by Baker *et al.* [3], since almost equal isotopic values occur under quite different effective precipitation conditions.

In a global array of ice core records, the $\delta^{18}O$ shift from Early Holocene to LGM is similar (Figure 4, Table I), and includes 5.4‰ in Sajama [2], 6.3‰ in Huascarán [4], 5.4‰ to 5.1‰ in central Greenland [5], 6.6‰ in Byrd Station, Antarctica [6] and 5.4‰ in Vostok, Antarctica [7]. These ice core records join with other proxy data to provide a picture of significant global cooling during the LGM. These other data originate from such diverse archives as corals [8,9], noble gases from groundwater [10]; marine sediment pore fluids, [11], snowline depression [12-17], and pollen studies [18].

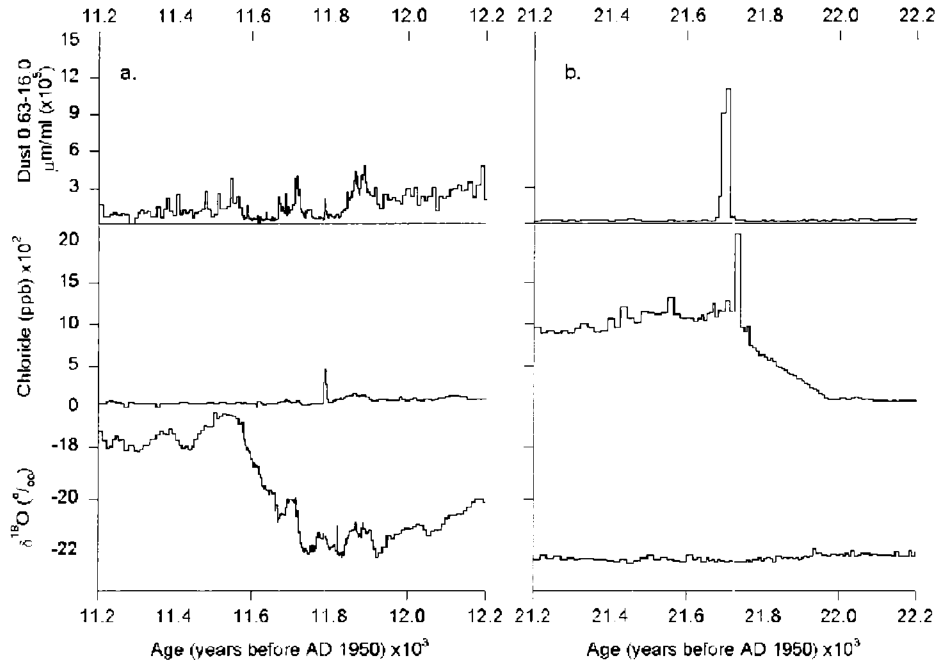

FIG. 3. (a) Detailed plots of $\delta^{18}O_{ice}$, and dust and Cl^- concentration variations during the transition from the deglaciation climatic reversal (DCR) into the Holocene in the Sajama record. (b) The same parameters from the Sajama record during the Last Glacial Maximum.

TABLE I. Comparison of averages of $\delta^{18}O_{ice}$ for the Modern period (0 to 1 ka), the early Holocene (EH, 6.8 to 10 ka) and the Last Glacial Maximum (LGM, 18.0-21.2 ka) and the differences between the LGM and the Modern and the LGM and the EH for the cores shown in Figure 4.

Core:	Modern (0-1 ka)	Early Holocene (EH) (6.8 - 10.0 ka)	Last Glacial Maximum (LGM) (18.0-21.2 ka)	LGM-Modern (‰)	LGM-EH (‰)
Sajama (Bolivia)	-16.8	-16.7	-22.1	5.4	5.4
Huascarán (Peru)	-18.5	-16.6	-22.9	4.4	6.3
GISP2 (Greenland)	-35.0	-34.6	-39.7	4.7	5.1
Guliya (W. China)	-14.4	-13.1	-18.5	4.1	5.4
Byrd (Antarctica)	-32.8	-33.9	-40.5	7.6	6.6
Vostok (Antarctica)	-441(-56.4)	-436(-55.7)	-472(-60.2)	3.9	4.5
Vostok (21.0 - 24.2 ka)	-441(-56.4)	-436(-55.7)	-479(-61.1)	4.8	5.4

These cooler tropical temperatures during the LGM would likely weaken the Hadley circulation and lower the water vapor budget of the Earth's atmosphere. Such changes have the potential for very large impacts on adiabatic lapse rates, particularly in the tropics. As the Earth is a thermodynamically non-linear planet, tropical glaciers are particularly sensitive to climate change. Lapse rates will undergo a greater change with height in a moister atmosphere than in a drier atmosphere. If sea surface temperatures (SST) warm uniformly around the globe, tropical lapse rates will decrease, conversely a global-scale cooling would lead to increased rates. In both cases the changes would be greater at high elevations in the tropics. Thus, according to the Clausius-Clapeyron relationship, under a warming Earth scenario tropical glaciers would be expected to retreat rapidly, but under colder conditions such as those of the LGS, with 5° to 6°C cooling suggested by the ice cores and other records mentioned above, tropical glaciers would be expected to expand rapidly. Therefore, such changes between dry and moist adiabatic lapse rates should lead to tropical amplification of either a warming or a cooling.

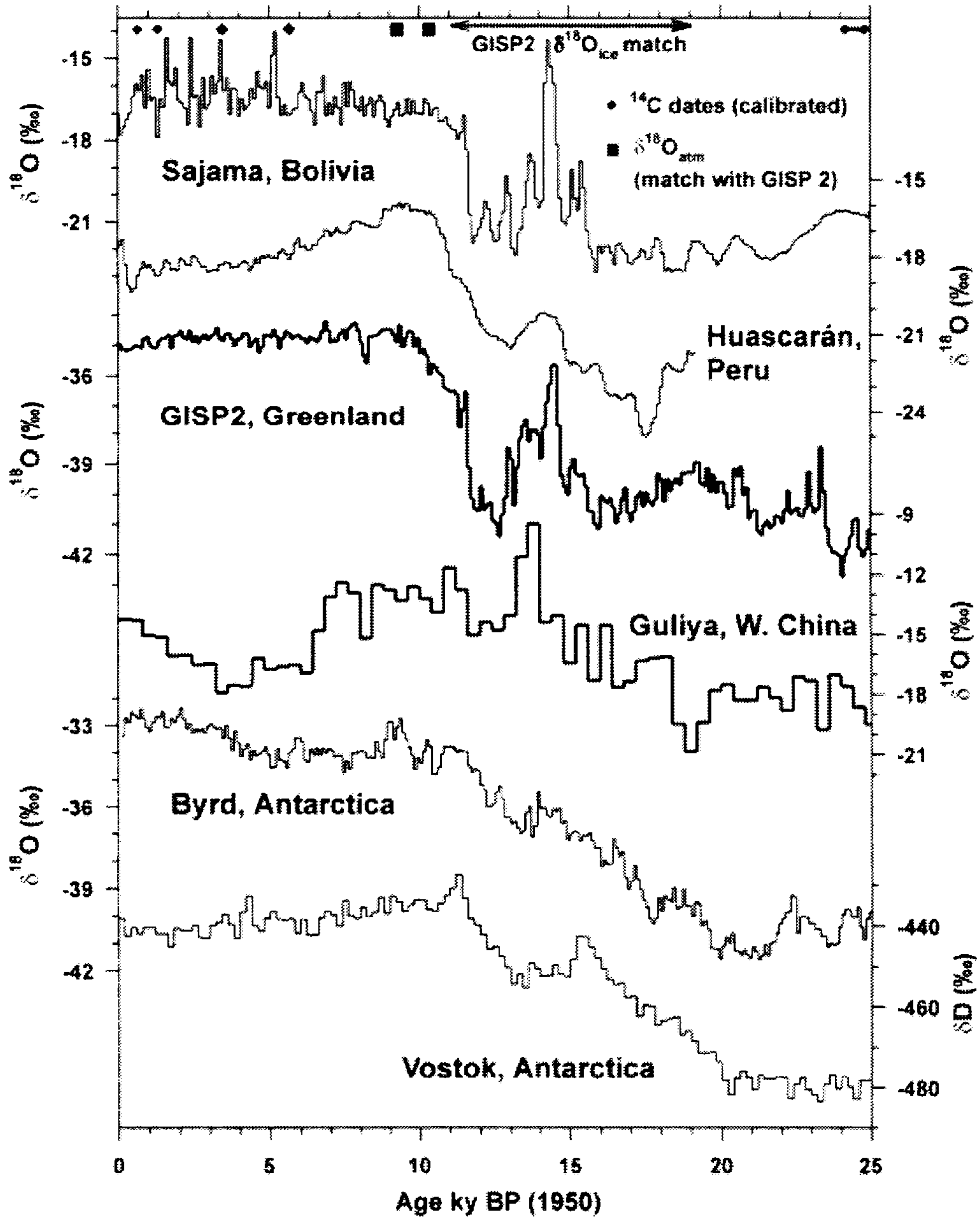

FIG. 4. Global extent of the Late Glacial Stage and a climatic reversal (cooling) during deglaciation is illustrated by the stable isotope records from two tropical sites (Sajama and Huascarán), two Northern Hemisphere sites (Guliya and GISP 2) and two Southern Hemisphere sites (Byrd Station and Vostok). All records shown are 100-year averages, except the records for Vostok (200-year averages) and Guliya (400-year averages).

3. STABLE ISOTOPES OVER THE LAST MILLENNIUM

3.1. The Tibetan Plateau

Long ice core records are available from three sites on the Tibetan Plateau. The Dunde ice cap, the Guliya ice cap, and the Dasuopu glacier form a regional triangular pattern with summit elevations decreasing from south to north (Fig.1). Dasuopu, the highest site, has the most depleted average $\delta^{18}O$ (-20.32‰ for the last millennium) while the lowest elevation site, Dunde has the least isotopically depleted millennial average (-10.81‰). The elevation of Guliya is between the other sites, and has a medium isotopic value of -14.23 ‰ for the last millennium (Figure 5). As the precipitation at all these sites is dominated by the advection of moisture from the Indian Ocean with possible contributions from the Arabian Sea during the summer monsoon, these data provide qualitative support for the hypothesis that temperature, not the amount effect, is the dominant process controlling $\delta^{18}O$ over the Tibetan Plateau. This is further supported by the much stronger statistical relationship between $\delta^{18}O$ and NH temperatures ($r^2 = 0.37$), and the much weaker relationship between $\delta^{18}O$ and accumulation ($r^2 = 0.19$) [19].

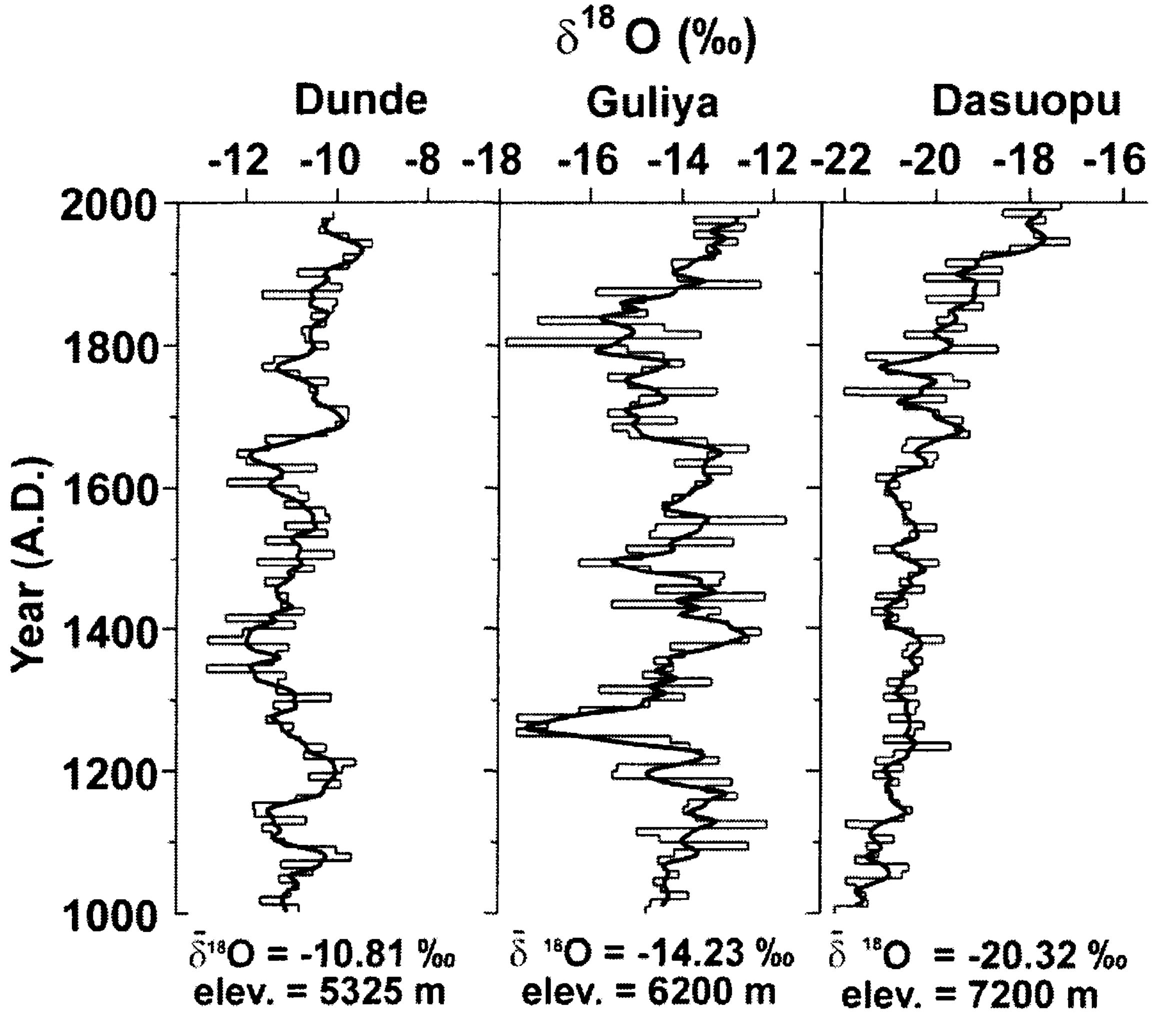

FIG. 5. Decadal averages of $\delta^{18}O_{ice}$ for the last millennium from Dunde, Guliya and Dasuopu, Tibetan Plateau.

The question of whether stable isotopes are proxy indicators of temperature for the lower troposphere was qualitatively addressed above in the discussion of long-term climate records from Andean cores. However, in order to quantify that relationship, real-time field observations and measurements are required. We have collaborated with our Chinese colleagues at the Lanzhou Institute of Glaciology and Geocryology (LIGG), who 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 the southeast), the r^2 between the $\delta^{18}O$ of the precipitation collected and the atmospheric temperature measured at the time of collection is 0.86 [20]. These data suggest, at least for the period of measurement, that $\delta^{18}O$ is a faithful recorder of temperature in this section of the Plateau.

Figure 5 compares the decadal averages of $\delta^{18}O$ over the last 1000 years for the three Tibetan Plateau ice cores. These profiles display major differences through the past millennium, possibly due to their different precipitation sources and post-depositional processes. Over most of the millennium, the $\delta^{18}O$-inferred temperature variations recorded on Guliya have been generally out of phase with those on Dunde [19]. Dasuopu and Dunde show broadly more similar trends, although the Dunde profile contains more higher amplitude variations before 1250 AD.. Over the last 200 years, however, all three clearly show strong isotopic enrichment taking place, suggesting a recent warming across the entire Tibetan Plateau. This warming is particularly notable in the 20th century (although the recent isotopic enrichment is more pronounced on Dasuopu) and is the most regionally consistent climate signal of the last 1000 years.

Meteorological observations on the Plateau are relatively few and of short duration. A recent study [21] utilizes monthly surface air temperature data from most meteorological stations on the Plateau since their installation in the 1950's. Not only do they report a linearly increasing annual temperature trend of ~0.16°C per decade from 1955 to 1996 and an increasing winter trend of ~0.32°C per decade, they also report evidence that the rate of warming has increased with elevation. The 1960 to 1990 records from 178 stations across the Plateau reveal that the greatest rate of warming (~0.35°C per decade) has occurred at the highest elevation sites. Consistent with these recent meteorological data, the $\delta^{18}O$ records from the three Plateau ice cores reveal the same trend of increasing isotopic enrichment with increasing elevation. Specifically, the average $\delta^{18}O$ in Dunde since 1950 is 0.99 $^{0}/_{00}$ higher than the millennial mean while on Guliya it is 1.05$^{0}/_{00}$ and on Dasuopu it is 1.84$^{0}/_{00}$ (Figure 6). The isotopically inferred 20th century temperatures on both Dunde and Dasuopu are the warmest of the millennium and the recent warming is most pronounced at the highest elevation site, Dasuopu, along the southern edge of the Tibetan Plateau (Figure 5).

3.2. The Andes of South America

The map in Figure 1 illustrates the three sites in the tropical Andes from which ice cores have been recovered. The sites lie in a southeast-northwest trend from 18°S to 9°S. Huascarán, the most equatorial of the three and the world's highest tropical mountain, provided in 1993 two records of climate variability that extend the LGS. Cores recovered from the Quelccaya ice cap (14°S) in 1983 yielded an annually resolved record back to A.D. 470 [22-24]. Further to the south, Sajama, Bolivia (18°S) is a 6550 m asl extinct volcano on which two cores were drilled to bedrock in 1997 [2]. The ice cores from this site are very unusual in that they contain both insects and plant remains in large enough supply to allow AMS ^{14}C dating to be made in two separate laboratories. Thus, unusually good absolute time control is possible for these records.

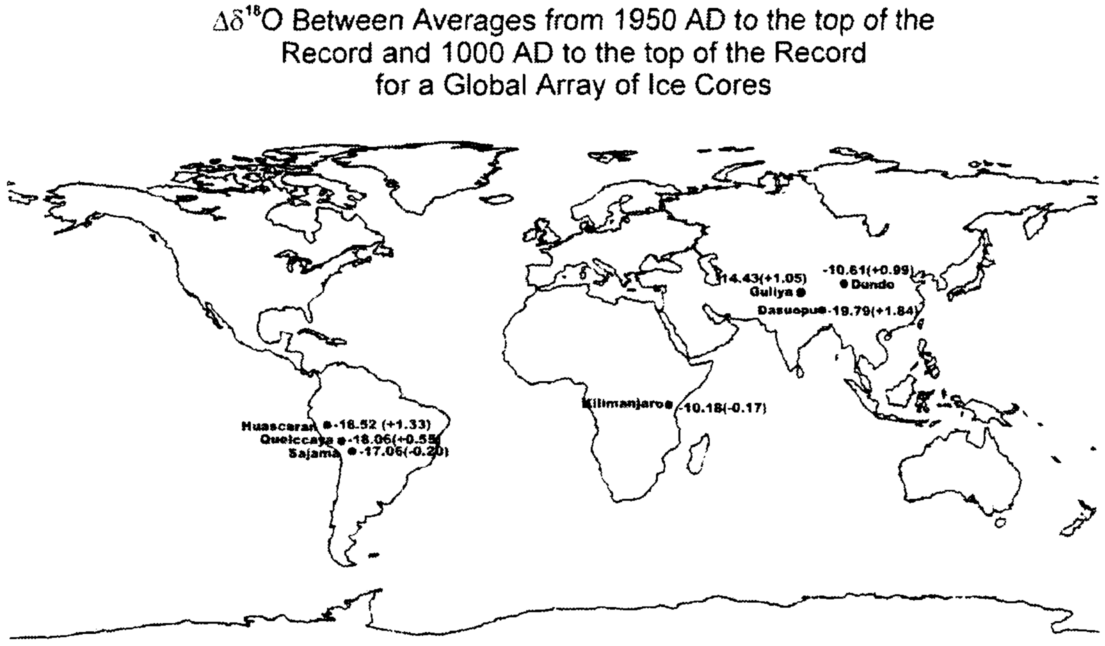

FIG. 6. *Global map showing mean* $\delta^{8}O_{ice}$ *from 1000 AD to the top of each record for the seven high-altitude ice core sites, with the differences between those means and the means from 1950 AD to the top of each record in parentheses.*

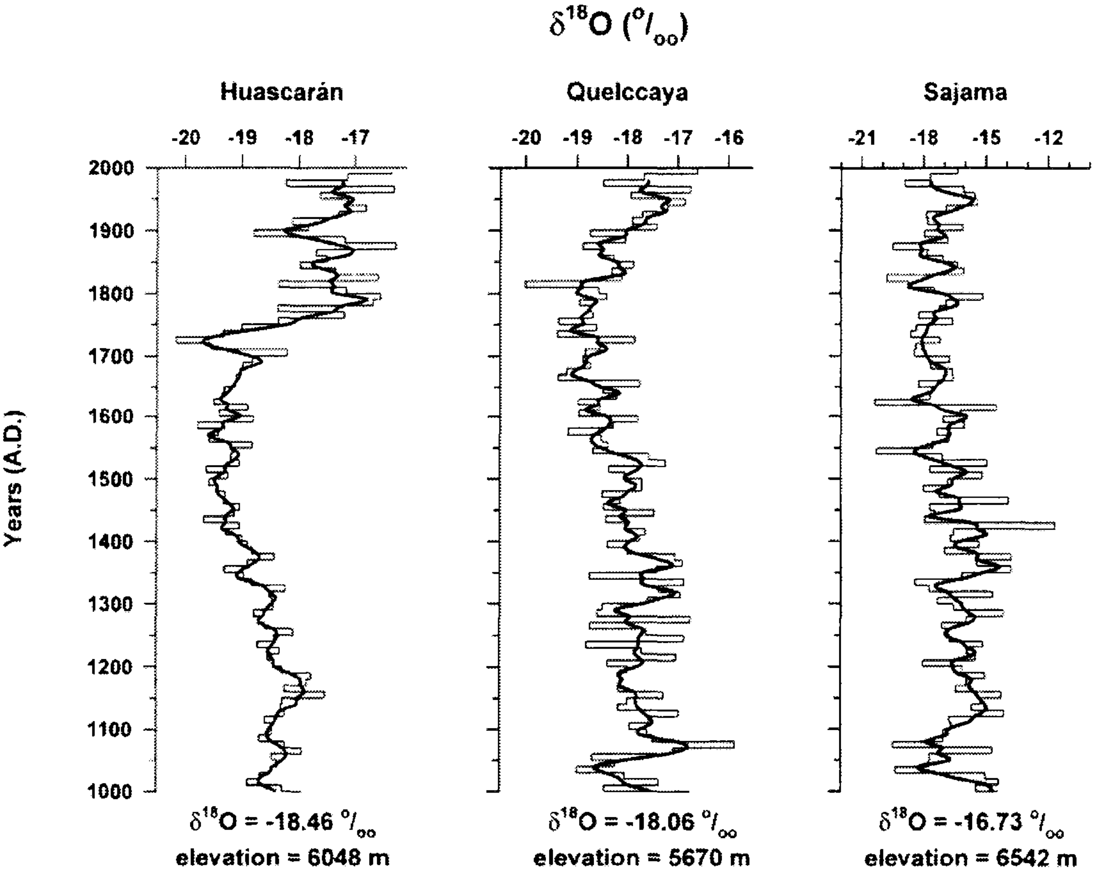

FIG. 7. *Decadal averages of* $\delta^{8}O_{ice}$ *for the last millennium from the three tropical Andes sites, Huascarán, Quelccaya and Sajama.*

Figure 7 compares the decadal oxygen isotopic values from these three tropical Andean sites for the last 1000 years. Earlier than 1700 AD the profiles show similar trends, but Sajama does not record the isotopic enrichment of the last 200 years that is quite obvious in Huascarán, Quelccaya and all three of the Tibetan Plateau sites. Moreover, unlike the Tibetan cores there is no clear relationship between elevation and mean isotopic value over the last millennium. Sajama at 6542 m asl is the highest of the three glaciers, but it contains the most enriched average $\delta^{18}O$ ($-16.73^{o}/_{oo}$). The inconsistencies presented by this ice core may be related to the extreme aridity of the Altiplano region and the potential role of post-deposition sublimation.

For all the Andean sites the moisture source is the tropical Atlantic Ocean by way of the Amazon Basin, and this source has remained consistent since the LGM as shown by the tilt of the mountain snowlines toward the Amazon Basin both at 20 ka and today [14]. The seasonality of the $\delta^{18}O$ in the South American records is opposite that of the polar regions, i.e. the most depleted values occur in wet season (summer) snowfall and the most enriched in the dry season (winter) layers. Currently there are at least two models which explain the $\delta^{18}O$ composition of ice cores in the tropical Andes. The first, developed by Grootes *et al.* [25], is a hydrological model of moisture transport. The isotopic values are initially determined by the composition of oceanic water, and as the vapor moves across the Amazon Basin it is recycled in thunderstorms. Each time condensation takes place the heavier isotopes are preferentially removed. The condensate 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 re-evaporated, and thus very little isotopic fractionation takes place. However, by the time the moisture reaches the base of the Andes in the wet season, it has a mean isotopic value of $-20^{o}/_{oo}$. When the air masses are forced to rise over the Andes (above 5000 meters) an additional $10^{o}/_{oo}$ depletion takes place.

There is a major factor to take into account when considering the interpretation of stable isotopes in the tropics, and how they differ from those in the higher latitudes. In the Andes, the snowfall comes from thunderstorms that contain convective cells with very high vertical extent, therefore the mean level of condensation is higher than in the polar regions. More importantly, this condensation level changes in location and height from wet to dry season. In the wet season, Huascarán is located 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 about two km higher, where the temperatures are cooler, and in the dry season condensation forms at a lower, warmer elevation in the atmosphere. The isotopic composition of precipitation may well reflect these changes [26].

Meteorological observations in the tropical Andes, as in Tibet, are scarce and cover relatively little time. In a recent study, Vuille and Bradley [27] determined that the mean annual temperature trends in the tropical Andes over the last six decades (1939-1998) have increased by 0.10°C-0.11°C/decade. Furthermore, they found that the rate of warming has more than tripled over the last 25 years (0.32°C - 0.34°C/decade) and that the last two years of the series, associated with the 1997/98 El Nino, were the warmest of the last six decades. However, the Andes temperature trends vary conversely with altitude and show a generally reduced warming with increasing elevation. This trend is generally consistent with the mean millennial isotopic values from the Andean ice cores. The mean $\delta^{18}O$ since 1950 AD compared to the 1000th year mean shows which is enrichment toward the equator (Figure 6). The greatest enrichment since 1950 AD of $1.33^{o}/_{oo}$ occurs in the most tropical site Huascarán, a lesser enrichment of $0.51^{o}/_{oo}$ occurs at Quelccaya, while Sajama actually shows a $-0.20^{o}/_{oo}$ depletion since 1950.

4. 20^{TH} CENTURY GLACIER RETREAT

Evidence is accumulating for a strong warming in the tropics during in the second half of the 20^{th} century that is causing the rapid retreat and, in some cases, the disappearance, of ice caps and glaciers at high elevations. These ice masses are particularly sensitive to small changes in ambient temperatures as they exist very close to the melting point. This warming and the concomitant retreat of the Quelccaya ice cap (Peru) are well documented. Since 1976 Quelccaya has been visited repeatedly for extensive monitoring and sampling. In addition to the deep drilling in 1983, shallow cores were taken from the summit of the ice cap in 1976, 1979, 1991, 1995 and 2000. Comparison of the $\delta^{18}O$ records extracted at these six different times reveals (1) the mean isotopic values have continued to become more enriched and (2) the seasonally resolved paleoclimatic record, preserved in the cores drilled in 1983 as $\delta^{18}O$ variations, is no longer being retained within the currently accumulating snow [1,26]. The percolation of meltwater throughout the accumulating snowpack is homogenizing the stratigraphic record of $\delta^{18}O$.

The retreat of the margins of Quelccaya has also been monitored. The extent and volume of the largest outlet glacier, Qori Kalis, was measured eight times between 1963 and 2000. These observations have documented a rapid retreat that has accelerated during this 37-year period. The rate of retreat from 1983 to 1991 was three times that from 1963 to 1983, and was five times faster in period from 1993 to 1995, eight times faster in the period 1995 to 1998 and thirty-two times faster in the most recent observational period (1998 to 2000). The latest observations made in 2000 confirm the continued acceleration of Qori Kalis' retreat, as well as further retreat of the other margins of the Quelccaya ice cap.

Additional glaciological evidence for tropical warming exists. Hastenrath and Kruss [28] report that the total ice cover on Mount Kenya has decreased by 40% between 1963 and 1987 and today it continues to diminish. The Speke glacier in the Ruwenzori Range of Uganda has retreated substantially since it was first observed in 1958 [29]. The ice fields on Kilimanjaro have lost 75% of their area between 1912 and 1989 [30]. The shrinking of these ice masses in the high mountains of Africa and South America is consistent with other tropical observations.

Tropical and subtropical ice core records have the potential to provide annual to millennial-scale records of climate, El Niño-Southern Oscillation events and monsoon variability and will provide further insight into the magnitude and frequency of these large-scale events. These data also provide unique perspectives for viewing both regional and global scale events ranging from the so-called "Little Ice Age" to the Younger Dryas cold phase to the Late Glacial Stage. There is unambiguous evidence that some, if not all of these archives are in imminent danger of being lost if the current warming persists.

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