# TROPICAL GLACIER AND ICE CORE EVIDENCE OF CLIMATE CHANGE ON ANNUAL TO MILLENNIAL TIME SCALES

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**Abstract.** This paper examines the potential of the stable isotopic ratios, $^{18}O/^{16}O$ ($\delta^{18}O_{ice}$) and $^{2}H/^{1}H$ ($\delta D_{ice}$), preserved in mid to low latitude glaciers as a tool for paleoclimate reconstruction. Ice cores are particularly valuable as they contain additional data, such as dust concentrations, aerosol chemistry, and accumulation rates, that can be combined with the isotopic information to assist with inferences about the regional climate conditions prevailing at the time of deposition. We use a collection of multi-proxy ice core histories to explore the $\delta^{18}O$-climate relationship over the last 25,000 years that includes both Late Glacial Stage (LGS) and Holocene climate conditions. These results suggest that on centennial to millennial time scales atmospheric temperature is the principal control on the $\delta^{18}O_{ice}$ of the snowfall that sustains these high mountain ice fields.

Decadally averaged $\delta^{18}O_{ice}$ records from three Andean and three Tibetan ice cores are composited to produce a low latitude $\delta^{18}O_{ice}$ history for the last millennium. Comparison of this ice core composite with the Northern Hemisphere proxy record (1000–2000 A.D.) reconstructed by Mann et al. (1999) and measured temperatures (1856–2000) reported by Jones et al. (1999) suggests the ice cores have captured the decadal scale variability in the global temperature trends. These ice cores show a 20th century isotopic enrichment that suggests a large scale warming is underway at low latitudes. The rate of this isotopically inferred warming is amplified at higher elevations over the Tibetan Plateau while amplification in the Andes is latitude dependent with enrichment (warming) increasing equatorward. In concert with this apparent warming, *in situ* observations reveal that tropical glaciers are currently disappearing. A brief overview of the loss of these tropical data archives over the last 30 years is presented along with evaluation of recent changes in mean $\delta^{18}O_{ice}$ composition. The isotopic composition of precipitation should be viewed not only as a powerful proxy indicator of climate change, but also as an additional parameter to aid our understanding of the linkages between changes in the hydrologic cycle and global climate.

## 1. Introduction

Quantitative use of $\delta^{18}O_{ice}$ or $\delta D_{ice}$ as a proxy for the air temperature at the time of condensation (precipitation formation) requires establishing relevant transfer functions. In remote areas where most ice cores are recovered the requisite *in situ* meteorological observations and contemporaneous precipitation collections

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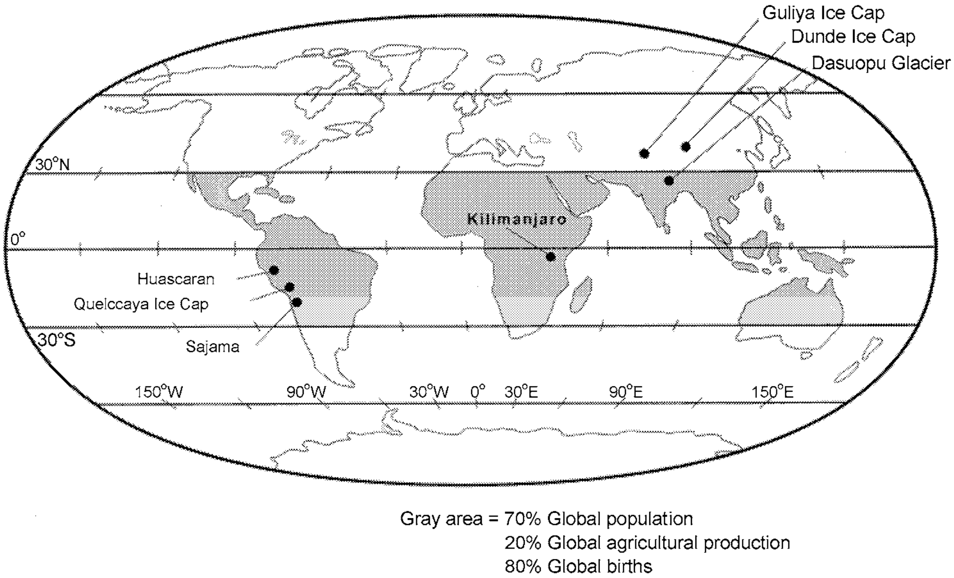


*Figure 1.* The seven ice coring sites discussed in this paper are illustrated. The gray area highlights the tropical region between 30° N and 30° S that contains 50% of the Earth's surface area and is home to ~70% of the population. The region accounts for ~80% of the new births and produces only ~20% of the global agricultural products.

are sparse or absent. The factors that govern the values of stable isotopic ratios in snowfall are enigmatic and at present, no satisfactory model has been developed to link them directly with any single meteorological or oceanographic factor. This is particularly problematic for the high elevation tropical glaciers, where complications arise not only from continental effects, but also from altitude effects associated with convection which is the primary precipitation mechanism over tropical South America and the monsoon dominated regions of Asia.

The oxygen isotopic ($\delta^{18}O_{ice}$) records from six low-latitude, high-altitude glaciers form the basis for this review which addresses the question of how faithfully these records document air temperature through time. The discussion is limited to the last 25,000 years, for which the richest data set exists, to provide a sufficient temporal perspective for both glacial and Holocene climate conditions. The ice core records (Figure 1) include three from the Tibetan Plateau (Dunde ice cap, (38° N, 5325 m asl), Guliya ice cap, (35° N; 6200 m asl) and Dasuopu Glacier in the Chinese Himalaya (28° N, 7200 m asl)] and three from the Andes of South America (Huascarán (Peru, 9° S, 6048 m asl), Quelccaya ice cap (Peru, 14° S, 5670 m asl) and Sajama (Bolivia, 18° S, 6542 m asl)).

Three of these sites (Guliya, Huascarán and Sajama) contain isotopically depleted (up to 5 to 6‰) ice deposited during the Last Glacial Stage (LGS) from which significant tropical cooling (up to ~5 °C) is inferred. These ice core records contribute to a growing body of evidence that the tropical climate was cooler and more variable during the LGS and have renewed interest in the tropical water vapor cycle. Ice core evidence for past changes in the tropical hydrological cycle, as well as evidence for recent warming at high elevations in the tropics, suggests that changes in water vapor inventories contribute significantly to the variability of tropical climate, and thereby to global climate as well.

## 2. LGS and Holocene $\delta^{18}O$ Histories Reflect Temperature

The 19 ka (thousands of years) proxy record recovered from Huascarán provided the first ice core evidence for cooler and drier LGS conditions in the Peruvian cordillera (Thompson et al., 1995). The average $\delta^{18}O_{ice}$ value for LGS ice is 6‰ lower (more depleted) than the average Holocene value, consistent with the LGS-Holocene depletions in cores from both Antarctica and Greenland (Table I). The 200 fold increase in mineral dust and 50% decrease in nitrate ($NO_3^-$) argues for much drier LGS conditions in the Cordillera Blanca as well as in the Amazon Basin (Thompson et al., 1995). The Huascarán record raised the question as to whether the $\delta^{18}O_{ice}$ values in tropical precipitation are controlled more by temperature or more by precipitation. Broecker (1995) argued that an 8‰ difference between maximum Holocene and LGM $\delta^{18}O_{ice}$ values in Huascarán called for an 11 °C cooling while Pierrehumbert (1999), using a simple Rayleigh distillation model, argued that the Huascarán isotopic shift could be explained by tropical LGM temperatures only 3 °C cooler than at present. Thompson et al. (2000a) examined the mechanisms responsible for the $\delta^{18}O_{ice}$ signature in Andean precipitation and concluded that century- to millennial-scale changes in $\delta^{18}O_{ice}$ are primarily temperature-dependent as is the case in the polar regions (Dansgaard, 1964; Dansgaard and Oeschger, 1989). Nevertheless, the issue remains open for discussion and interpretation (Baker et al., 2001).

New insight to this problem was attained in 1997 when ice cores were recovered to bedrock from the ice field atop Sajama in Bolivia (Figure 1). The ice contained sufficient organic material for AMS $^{14}C$ dating that allowed the construction of a tightly constrained time scale extending back ∼25 ka (Thompson et al., 1998). Figure 2 illustrates the continuous $\delta^{18}O_{ice}$ record for the entire ∼25 ka, along with the continuous $Cl^-$ and dust concentrations, and accumulation (in sigma units) reconstructed by interpolating between 25 independently dated time horizons (Thompson et al., 1998). In general, the LGS climate on the Bolivian Altiplano appears to have been much wetter, colder and less dusty than that in the Holocene when the concentrations of soluble anions, particularly $Cl^-$, and insoluble dust increased as the Altiplano lakes became desiccated in the early to mid-Holocene. Essentially, when the lakes are dry, the salts and dust are entrained by winds passing over the salt flats and once airborne they can be deposited in the snow that sustains the ice cap on Sajama. In a recent paper, Baker et al. (2001) concluded that the similar structure between Sajama's $\delta^{18}O_{ice}$ record and their $\gamma$-radiation record from

Table I

The average $\delta^{18}O_{ice}$ values for the last millennium are compared with those for the Early Holocene and Last Glacial Maximum for Sajama (Bolivia), Huascarán (Peru), GISP2 (Greenland), Guliya (China), and Byrd Station and Vostok (both in Antarctica)

| 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) | –16.7 | –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) | –14.2 | –13.1 | –18.5 | 4.3 | 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 |

the drill hole in the Salar de Uyuni (Bolivian Altiplano) bolstered their argument that $\delta^{18}O_{ice}$ is inversely correlated with precipitation amount (or runoff fraction). In fact, as we show more clearly here, the ice record argues just the opposite.

Figure 3 shows the continuous $\delta^{18}O_{ice}$ values and concentrations of $Cl^-$ and insoluble dust, and the reconstructed accumulation rates for two sections of the Sajama core: (a) the termination of the deglacial cold event and (b) the transition into Late Glacial Maximum. As noted earlier, accumulation is reconstructed using independently dated horizons and therefore is dependent on the availability of datable material and the accuracy of the dates. Figure 3b shows the details of the transition into the glacial maximum between 22 and 21.7 ka BP. The 5-fold increase in $Cl^-$, as well as the measured decrease in accumulation around 21.7 ka, are fully consistent with a transition to drier conditions. Over this transition there is no associated change in the $\delta^{18}O_{ice}$ mean value. Likewise Figure 3a demonstrates that during the termination of the deglaciation cold reversal, between 11.8 and 11.5 ka BP, a $\delta^{18}O_{ice}$ increase (enrichment) of 5.2‰ occurred while the $Cl^-$ and dust concentrations changes very little. At the same time there are no large changes in either regional precipitation amount or lake levels and the major change in accumulation $\sim$11.9 ka (Figure 3a) is associated with no major change in mean $\delta^{18}O_{ice}$ values.

The argument that temperature is the dominant control on $\delta^{18}O_{ice}$ is further supported by comparing the Sajama and Huascarán records. On Huascarán (9° S) LGS conditions were cold and dry while Holocene conditions were comparatively warm and wet (Thompson et al., 1995). In contrast, the ice core proxy records from Sajama (18° S) indicate cold and wet LGS conditions on the Bolivian Altiplano

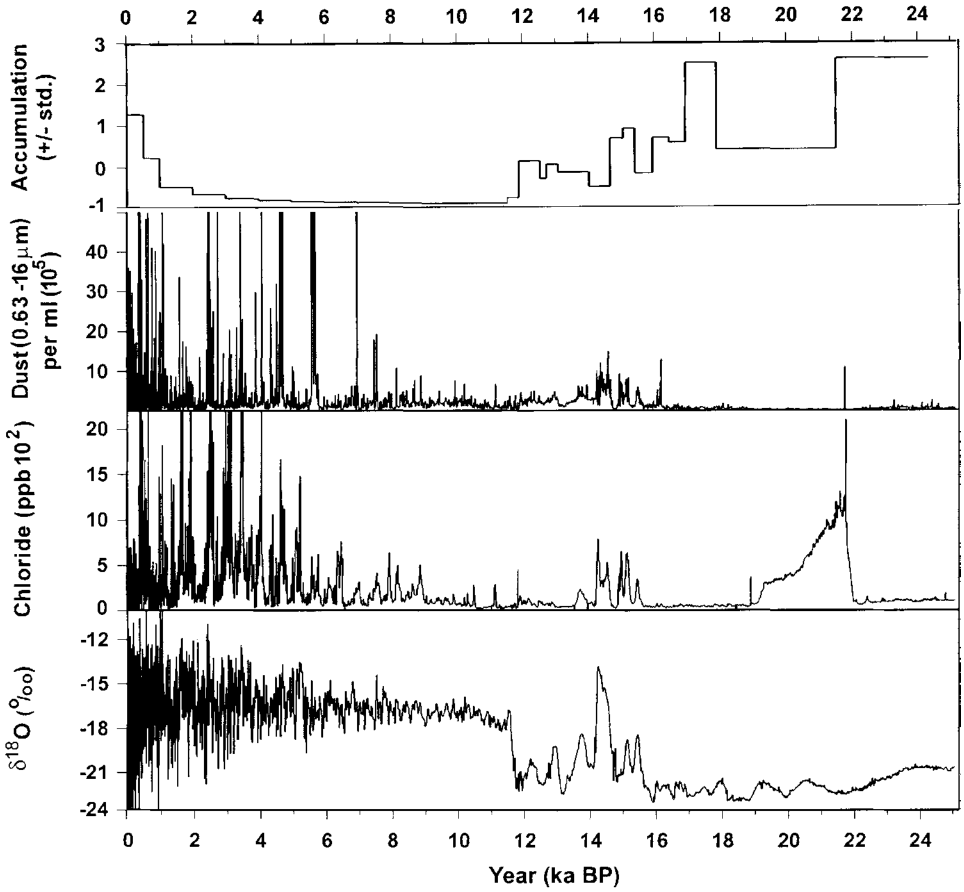


*Figure 2.* The reconstructed accumulation rates (in sigma units), the $\delta^{18}O_{ice}$, total dust (diameters $\geq$0.63 $\mu$m per ml sample) and chloride ($Cl^-$) concentrations and are shown for the entire Sajama Core 1 record extending back 25,000 years.

followed by a relatively warm and dry Holocene climate (Thompson et al., 1998). Table I illustrates the difference between the average $\delta^{18}O_{ice}$ for Holocene and LGS ice at six sites from pole to pole. The Holocene-LGS differences for Huascarán and Sajama are 6.3 and 5.4‰, respectively. Their mean LGS values are nearly identical (–22.9‰ versus –22.1‰) as are their mean early Holocene values (–16.6‰ versus –16.7‰). Clearly, precipitation amount is not the key factor determining $\delta^{18}O_{ice}$ in LGS snowfall on the Altiplano as argued by Baker et al. (2001). As in polar ice cores, the dominant factor controlling mean $\delta^{18}O_{ice}$ values in Andean snowfall on century to millennial time scales must be temperature, while on shorter (annual to decadal) scales both temperature and precipitation influence the local $\delta^{18}O_{ice}$ signal (Vuille et al., in press).

Figure 4 and Table I compare the $\delta^{18}O_{ice}$ histories from the three low latitude ice fields that extend back to the LGS with similar histories from three polar

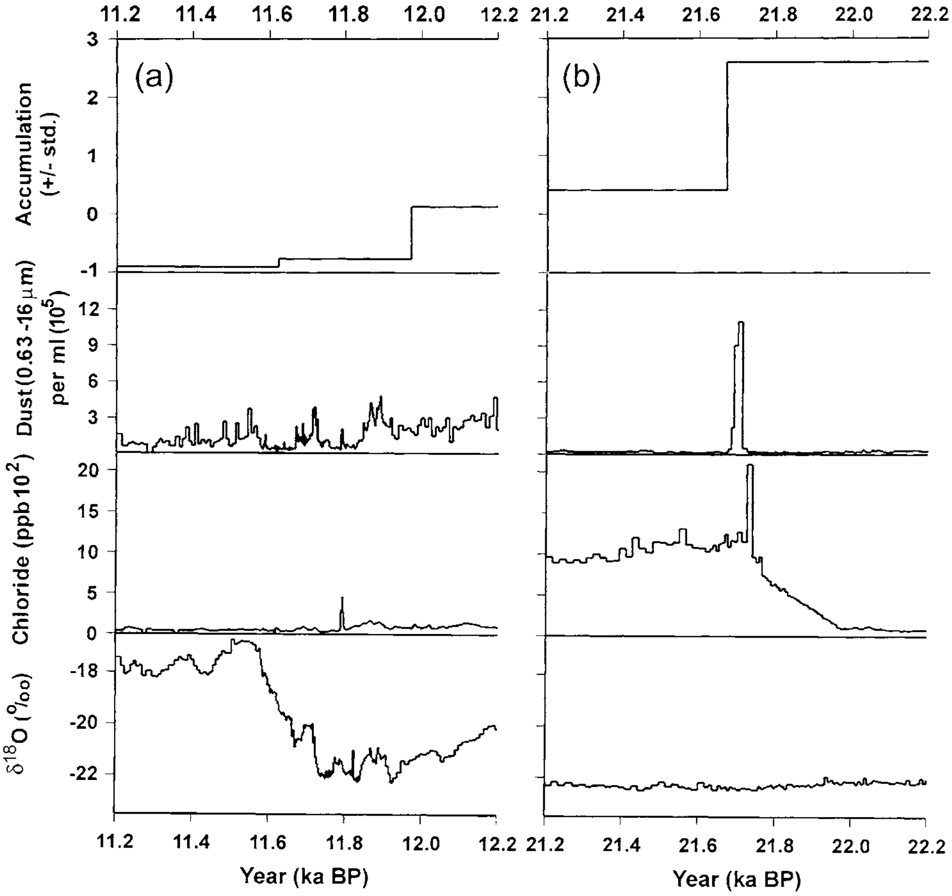


*Figure 3.* The reconstructed accumulation rate (in sigma units), the individual sample values of $\delta^{18}O_{ice}$ and the dust and chloride ($Cl^-$) concentrations are shown for (a) the transition from the deglacial cold reversal into the Holocene and (b) the transition into the Last Glacial Maximum for Sajama Core 1.

cores. These records show large-scale similarities as well as important regional differences, but strongly suggest that on millennial time scales $\delta^{18}O_{ice}$ changes in the tropics also represent large-scale climate processes, including temperature variations, just as they do in the polar regions. The $\delta^{18}O_{ice}$ difference between the Late Glacial Maximum (LGM) and Early Holocene (Figure 4, Table I) is 5.4‰ on Sajama (Thompson et al., 1998), 6.3‰ on Huascarán (Thompson et al., 1995), 5.4‰ on Guliya, (Thompson et al., 1997), 5.1‰ in central Greenland (Grootes et al., 1993), 6.6‰ at Byrd Station, Antarctica (Johnsen et al., 1972), and 5.4‰ at Vostok, Antarctica (Jouzel et al., 1987). These ice core records contribute to a growing body of evidence that LGM cooling was global and are supported by other tropical climate records. These other proxy histories originate from such diverse archives as corals (Guilderson et al., 1994; Beck et al., 1997), noble gases from

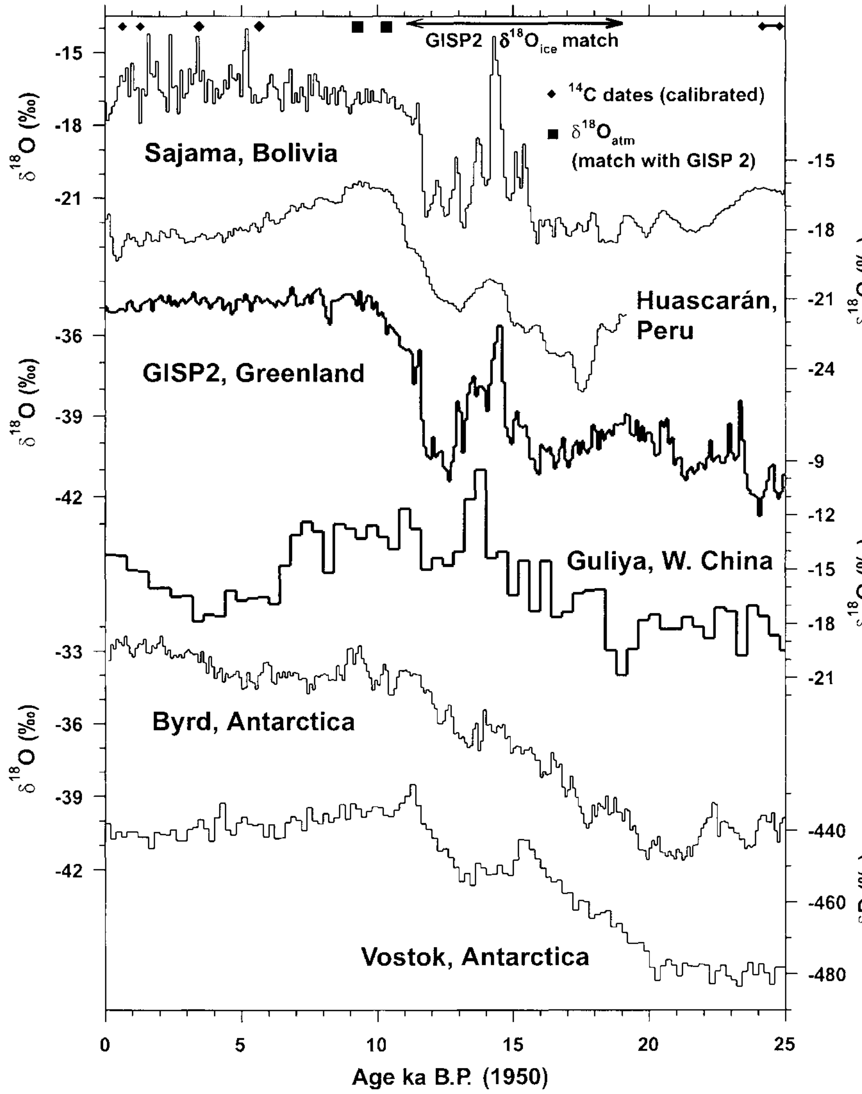


*Figure 4.* The $\delta^{18}O_{ice}$ histories for the last 25,000 years for six cores from the tropics to the poles show similar isotopic depletion (~5 to 7‰) in the Late Glacial Stage ice relative to Holocene ice.

groundwater (Stute et al., 1995), marine sediment pore fluids (Schrag et al., 1996), snowline depression (Broecker and Denton, 1990; Herd and Naeser, 1974; Klein et al., 1995; Osmaston, 1965; Porter, 1979; Rodbell, 1992), and pollen studies (Colinvaux et al., 1996).

Cooler tropical temperatures during the LGM would be expected to weaken the Hadley circulation (Rind, 1998) and to reduce the water vapor content of the atmosphere, thereby affecting environmental lapse rates, particularly in the tropics. Moreover, the large-scale tropical atmospheric circulation, dominated by the deep overturning in the Hadley (meridional) and the Walker (zonal) circulations, connects the climate regimes on the Tibetan Plateau to those in the Tropical Andes of South America and hence provides a link among these six ice core climate records. These two circulations interact and cannot always be decomposed into distinct components (Pierrehumbert, 2000). The environmental lapse rate is not linear, but depends upon the atmospheric water vapor content and degree of vertical mixing. With a moister, well-mixed atmosphere, lapse rates would be more variable with height than if the atmosphere were drier. If sea surface temperatures (SSTs) were to warm uniformly across the globe, tropical lapse rates should decrease and conversely with a global scale cooling they should increase. In both cases the changes would be enhanced at higher elevations in the tropics. Thus, under a warming Earth scenario tropical glaciers would be expected to retreat and under colder conditions, such as existed in the LGS, tropical glaciers should expand. Given the apparent stability of global tropical temperatures, it is reasonable to expect that signals of global temperature changes would be more uniform throughout the low latitudes.

## 3. $\delta^{18}$O Histories 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 (5325 m asl) on the northeast side, the Guliya ice cap (6200 m asl) on the northwest side and Dasuopu Glacier (7200 m asl) on the southern margin form a regional triangular pattern with elevations decreasing from south to north (Figure 1). Their millennial records of $\delta^{18}O_{ice}$ (Figure 5) show that Dasuopu, the highest site, has the 'coldest' isotopic average $\delta^{18}O_{ice}$ (–20.32‰), the lowest site, Dunde, has the 'warmest' isotopic average (–10.81‰) and Guliya, with an intermediate elevation, has a millennial average $\delta^{18}O_{ice}$ value of –14.23‰. The precipitation on Dasuopu is dominated by the advection of moisture from the Indian Ocean with possible contributions from the Arabian Sea during the summer monsoon. Dunde and Guliya also receive monsoonal precipitation traversing the plateau from the south, but snowfall is also likely to arrive with westerly flow at times during winter. These data provide qualitative evidence that temperature, and not the precipitation amount (or amount effect), is the dominant process controlling $\delta^{18}O_{ice}$ over at least this part of the Tibetan Plateau. This is further supported by the much stronger statistical relationship between the 5-year averages of $\delta^{18}O_{ice}$ on Dasuopu and Northern Hemisphere temperature anomalies ($R^2 = 0.37$) than between the 5-year averages of $\delta^{18}O_{ice}$ and accumulation on Dasuopu ($R^2 = 0.19$) for the period since 1860 A.D. (Thompson et al., 2000b, their Figure 6).

One of the most important questions concerning ice core $\delta^{18}O_{ice}$ records is whether they are a realistic proxy indicator of lower tropospheric temperatures. Our Chinese colleagues at the Laboratory of Ice Core and Cold Regions Environment

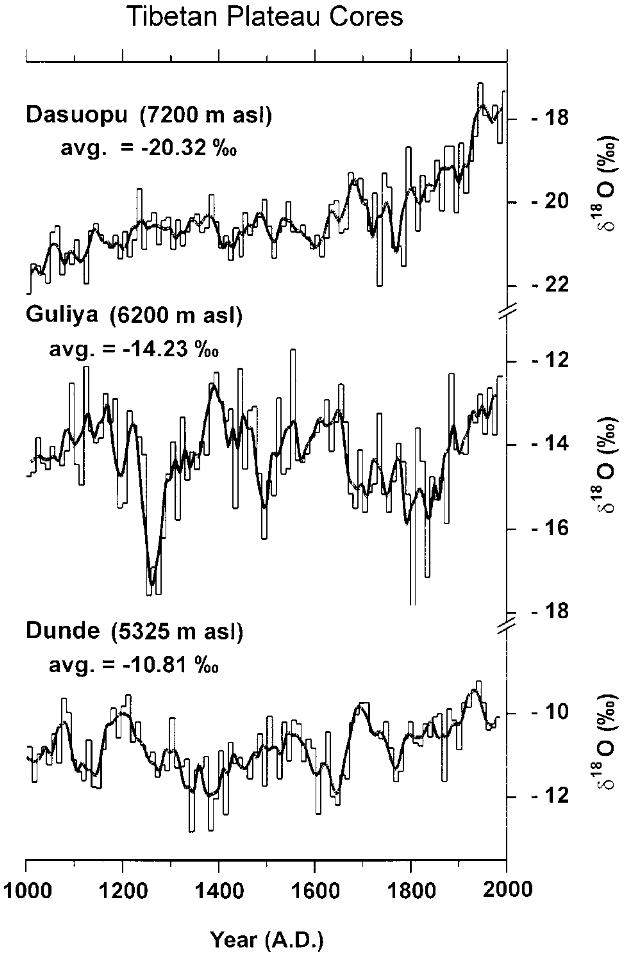


*Figure 5.* Decadal averages of $\delta^{18}O_{ice}$ (histogram) for the last millennium from three Tibetan ice cores (Dunde, Guliya and Dasuopu) are shown along with their respective elevations and millennial averages. The darker, smooth curve is a 3 decade running mean.

(LICCRE) of the Chinese Academy of Sciences in Lanzhou have collected precipitation samples and measured contemporaneous temperatures at six meteorological stations across the Tibetan Plateau. At the Delingha station, the closest observing site to the Dunde ice cap (150 km to southeast), a strong statistical relationship ($R^2 = 0.86$) exists between the monthly averages of temperature and $\delta^{18}O$ (Yao et al., 1996) for the two years of observation. Similarly, a strong relationship exists ($R^2 = 0.69$) between the temperature and $\delta^{18}O_{ice}$ averages for the ~90 individual precipitation events sampled over that same period. These observations suggest that on short time scales $\delta^{18}O_{ice}$ trends in precipitation provide a record of temperature trends on the northern part of the Tibetan Plateau. Further to the south, where monsoonal precipitation is more dominant, the $\delta^{18}O$-temperature relationship reverses, such that the most isotopically depleted snow arrives during the summer monsoon. However, as discussed later, intensified atmospheric convection leads to colder condensation temperatures that may be interpreted erroneously as an 'amount effect' (Thompson et al., 2000a). On annual time scales this $\delta^{18}O$-temperature relationship (e.g., depleted $\delta^{18}O_{ice}$ in the warm, wet season) reflects atmospheric dynamical processes, but over many decades to centuries, atmospheric temperature becomes the dominant process controlling average $\delta^{18}O_{ice}$.

The decadal averages of $\delta^{18}O_{ice}$ from the three Tibetan ice cores (Figure 5) display some major differences on both decadal and century scales. This is not surprising given the diverse regional settings that contribute to differences in precipitation source and post-depositional processes. The millennial $\delta^{18}O_{ice}$ histories from Dasuopu and Dunde contain broadly similar trends, while those on Guliya appear largely disconnected with those on Dunde (Thompson et al., 2000b). However, since 1800 all three $\delta^{18}O_{ice}$ histories show a consistent trend of enrichment, suggesting that a large spatial-scale warming has affected the region. The average $\delta^{18}O_{ice}$ in Dunde ice deposited since 1950 is enriched by 0.99‰ relative to the millennial mean and similar enrichments on Guliya and Dasuopu are 1.05‰ and 1.84‰, respectively. These data suggest that temperatures in the second-half of the 20th century on both Dunde and Dasuopu are the warmest of the millennium.

It is noteworthy that this recent warming is most pronounced at the highest elevation site, Dasuopu, along the southern edge of the Tibetan Plateau. This suggests an amplification of warming at higher elevations in the tropics as might be expected from atmospheric thermodynamic considerations discussed above. Although meteorological observations on the Plateau are relatively few and of short duration, some observational evidence does exist that supports the enhancement of warming at higher elevations. A recent study (Liu and Chen, 2000) utilizes monthly surface air temperature data from most meteorological stations on the Plateau since they were installed in the 1950s. They report a linearly increasing temperature trend of ~0.16 °C per decade from 1955 to 1996 and an increasing winter trend of ~0.32 °C per decade. Moreover, the rate of warming has increased with elevation. Their records from 178 stations across the Plateau reveal that the greatest rate of warming (~0.35 °C per decade) from 1960 to 1990 has occurred at the highest elevation sites. The $\delta^{18}O_{ice}$ records from the three Tibetan ice cores (Figure 5) show this same relationship, an enhancement of the rate of $\delta^{18}O_{ice}$ enrichment with increasing elevation.

### 3.2. THE ANDES OF SOUTH AMERICA

Ice cores have been recovered from three sites in the South American Andes (Figure 1). The moisture source for the three Andean ice fields is the tropical Atlantic Ocean by way of the Amazon Basin. The Atlantic appears to have remained the major moisture source for the Andean sites throughout the Holocene and the LGM as snowline gradients were inclined toward the Amazon Basin, as they are now

(Klein et al., 1995). As discussed above, on century to millennial time scales $\delta^{18}O_{ice}$ values are interpreted primarily as a proxy for atmospheric temperature at the time of condensation.

At present two models have been developed to explain the mechanisms responsible for the $\delta^{18}O_{ice}$ composition found in the Andean ice cores under modern (Holocene) conditions. Grootes et al. (1989) developed a hydrological model of moisture transport in which isotopic values are initially determined by the composition of ocean water and the subsequent modification as the vapor moves across the Amazon Basin and is recycled within thunderstorms. Each time condensation occurs in the air mass the heavier isotopes are preferentially removed. This condensate falls as precipitation on the land surface and during the wet season most of the isotopically enriched surface water is transported out of the Amazon Basin by the river system. In the dry season most of the precipitation that falls in the Amazon is re-evaporated, and thus little isotopic fractionation takes place within the air masses as they traverse the basin. In the wet season, the moisture reaching the base of the Andes has a mean $\delta^{18}O_{ice}$ value of approximately –20‰. When the air masses are forced to rise over the Andes (above 5000 meters) an additional $\sim$10‰ depletion occurs. This model explains the large seasonal difference in $\delta^{18}O_{ice}$ for a region that experiences an annual temperature range of only a few degrees Centigrade.

A more recent examination of the processes controlling $\delta^{18}O_{ice}$ in Andean precipitation includes another important consideration that is more relevant in mountainous, tropical environments than in the polar regions (Thompson et al., 2000a). In the Andes, snowfall generally originates from thunderstorms with convective cells that extend to great heights such that the mean level of condensation in these storms would be much higher than the condensation level for polar precipitation. More importantly, in the tropics both the geographic location and elevation of the zone of maximum condensation changes from the wet to the dry season. For example, during the wet season Huascarán (9° S) is situated squarely in the region of maximum deep convection, but in the dry season this zone moves to the north. During the height of the wet season, the condensation level is about 2 km higher where temperatures are cooler and conversely in the dry season condensation takes place at a lower, warmer level in the atmosphere. Thus, the more depleted $\delta^{18}O_{ice}$ values arrive in the wet season snow and could be interpreted as either an 'amount effect' or a temperature signal reflecting changes in the height of the zone of maximum condensation, or some combination of the two. In light of the climatological differences between Huascarán (warm, wet Holocene, Thompson et al., 1995, 2000a; Thompson, 2000) and Sajama (warm and dry Holocene, Thompson et al., 1998, 2000a; Thompson, 2000) and their similar Holocene $\delta^{18}O_{ice}$ averages, we argue that decadal to century variations in $\delta^{18}O_{ice}$ principally reflect temperature and not precipitation.

In 1983 a solar-powered drill system was used to retrieve two cores to bedrock on the Quelccaya ice cap (14° S) in the southern Andes of Peru. Although the Quelccaya ice core record only extends to 470 A.D., it is annually resolved (Thompson et al., 1985, 1986). Figure 6 illustrates the decadal averages of $\delta^{18}O_{ice}$ for the last millennium from the three Andean ice cores. Unlike, the Tibetan cores, there is no clear relationship between the elevation of the ice field and its millennial mean $\delta^{18}O_{ice}$ value. In fact, the highest site, Sajama, has the most enriched average $\delta^{18}O_{ice}$ (–16.73‰) and does not record the $\delta^{18}O_{ice}$ enrichment of the last 200 years that is quite clear in both Huascarán and Quelccaya as well as the three Tibetan cores. Just as interestingly, the Sajama $\delta^{18}O_{ice}$ record shows no convincing evidence of the 'Little Ice Age' cooling that is prominent in both Peruvian cores. This may be explained in part by Sajama's very dry environmental setting. The Sajama $\delta^{18}O_{ice}$ record likely contains an additional local signal that varies with fluctuations of the water in the nearby lakes. Under drier conditions, evaporation from the local lakes would isotopically enrich the remaining water, thus creating an enriched 'local' $\delta^{18}O$ signal in the water vapor from which the snow is condensed. Also the extreme dryness of the region may enhance post-depositional sublimation that would further modify the mean $\delta^{18}O_{ice}$ value preserved on Sajama. A more rigorous explanation of this obvious difference requires more *in situ* observations than are currently available.

Meteorological observations in the tropical Andes are relatively few and of short duration, similar to the dearth of data for Tibet. Recently, Vuille and Bradley (2000) have determined the mean annual temperature trends in the tropical Andes over the last six decades (A.D. 1939–1998). They found that temperature in the tropical Andes has increased by 0.10 °C to 0.11 °C per decade since 1939. Further, their data indicate 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 their data series, associated with the 1997/98 El Niño, were the warmest of the last six decades. Here the temperature trends also vary with elevation, but unlike those measured in Tibet (Liu and Chen, 2000), the rate of warming tends to diminish with increasing elevation. Since 1950 the average $\delta^{18}O_{ice}$ values on Huascarán and Quelccaya have enriched by +1.31‰ and +0.51‰, respectively, when compared to their millennial means. Note that the enrichment is greater at the most equatorial site, Huascarán. On Sajama, the highest and most southerly site (18° S), the average $\delta^{18}O_{ice}$ in the last 50 years is depleted by –0.20‰ relative to its millennial mean. Clearly, understanding the controls on $\delta^{18}O_{ice}$ in Sajama snowfall warrants additional investigation. A more detailed discussion of some of these controls for recent (since 1980) snowfall on Sajama, Quelccaya and Huascarán can be found in Henderson et al. (1999) and Vuille et al., in press.

## 4. 20th Century Warming

Evidence is accumulating for a strong warming in the tropics in the second half of the 20th century. Although cause and effect is difficult to confirm, it is likely that this warming is the principal driver of the rapid retreat and, in some cases, the dis-

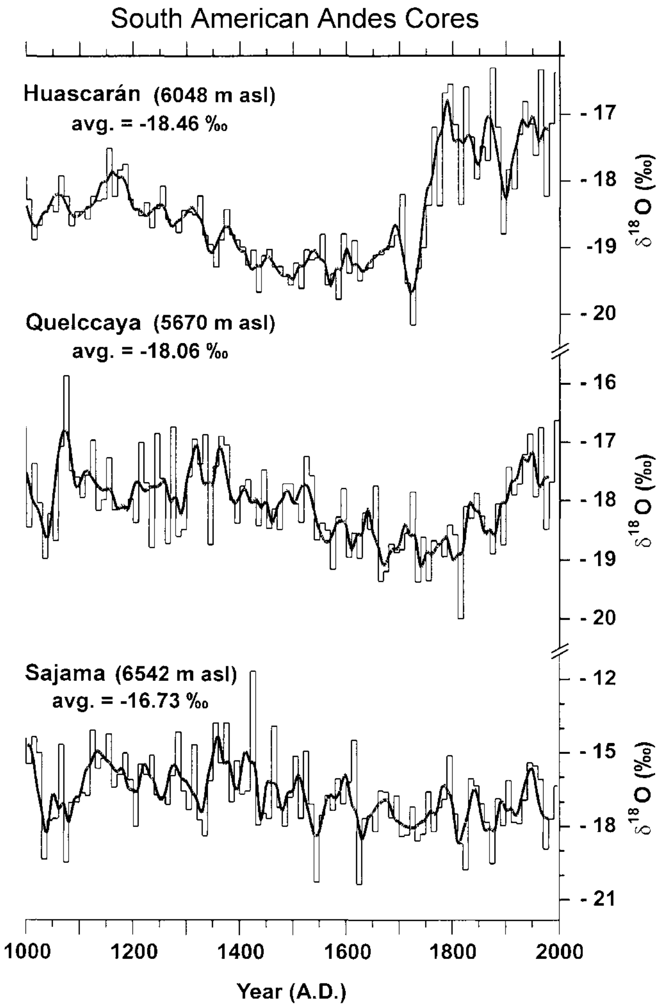


*Figure 6.* Decadal averages of $\delta^{18}O_{ice}$ (histogram) for the last millennium from three Andean ice cores (Huascarán, Quelccaya and Sajama) are shown along with their respective elevations and millennial averages. The darker, smooth curve is a 3 decade running mean.

appearance, of ice caps and glaciers at high elevations in the tropics and subtropics. The six cores discussed above provide an opportunity to examine the changes over the last millennium in $\delta^{18}O_{ice}$ at low latitudes in both hemispheres. By their nature ice cores record fluctuations in the local, regional and larger-scale environment. Thus, ice cores contain local signals that are superimposed upon more regional to global forcings. Unraveling these signals is challenging given there are only six low latitude ice cores that extend over the last millennium. Integrating the ice core histories with other local proxy records is certainly helpful in deciphering the local to regional events. To capture changes at larger spatial scales, we created regional composites of the decadal averages of $\delta^{18}O_{ice}$ for the Tibetan Plateau (Figure 7a) and the tropical South American Andes (Figure 7b). Moreover, since 70 to 80% of the snow in the tropical Andes of South America falls during the wet season (November to April) and on the Tibetan Plateau 70 to 80% of the snow falls in the monsoon season (May to August), combining all six of these records should give a more representative annual, and thus decadal, average $\delta^{18}O_{ice}$ for high elevations in the low latitudes. In Figure 7c all six cores, three from each hemisphere, were composited to construct a low latitude ice core $\delta^{18}O_{ice}$ history for the last millennium. This composite $\delta^{18}O_{ice}$ record shows enriched $\delta^{18}O_{ice}$ from 1140 to 1250 AD, possibly reflecting the 'Medieval Warm Period', and more depleted $\delta^{18}O_{ice}$ from $\sim$1300 to 1850 AD, correlative with the so called 'little ice age' (Bradley, 2000). However, the most dominant signal in the $\delta^{18}O_{ice}$ composite is the isotopic enrichment in the 20th century. Figure 7d presents the millennial record of decadal temperature variations reconstructed for the last millennium from different types of proxy data primarily from N.H. locations (Mann et al., 1999). The annual average N.H. instrumental temperature history from 1864 to 2000 (Jones et al., 1999 and updated from their web site) is also plotted in Figure 7d. Both records are presented as deviations from their respective 1961 to 1990 mean values. The similarities between the ice core $\delta^{18}O_{ice}$ composite and the best Northern Hemisphere temperature record over the last millennium provide strong evidence that over large distances and decadal and longer time scales, the dominant control on the ice core $\delta^{18}O_{ice}$ record is temperature. The composites illustrate that the 20th century $\delta^{18}O_{ice}$ enrichment is the dominant longer-term (e.g., century-scale) feature common to these regions that are geographically quite separated. The ice core results support meteorological evidence (Jones et al., 1999; Hansen et al., 2001) of a significant 20th century warming, but they have the added value of placing the observations within a longer-term perspective that seems to be signaling a large and unusual warming that is underway at high elevations in the tropics. This is significant as seasonal and annual temperature variations are rather small in the tropics.

Other evidence of this high elevation warming is provided by the alpine ice masses that are particularly sensitive to small changes in ambient temperatures as they exist very close to the melting point. The retreat of the Quelccaya ice cap (Peru) is now well documented (Brecher and Thompson, 1993; Thompson et al., 2000a) and since 1976 it has been visited repeatedly for extensive monitoring and sampling. In addition to the cores drilled to bedrock in 1983, shallow cores have been recovered from the summit of the ice cap in 1976, 1979, 1991, 1995 and 2000. Comparison of the $\delta^{18}O_{ice}$ records extracted at these six different times reveals that the mean $\delta^{18}O_{ice}$ values have continued to become more enriched and the seasonally resolved paleoclimatic ($\delta^{18}O_{ice}$) record that was excellently preserved in 1983 is no longer retained within the newly accumulating snow (Thompson et al., 1993; Thompson, 2000a). The percolation of meltwater throughout the accumulating snowpack is now homogenizing the stratigraphic record of $\delta^{18}O_{ice}$.

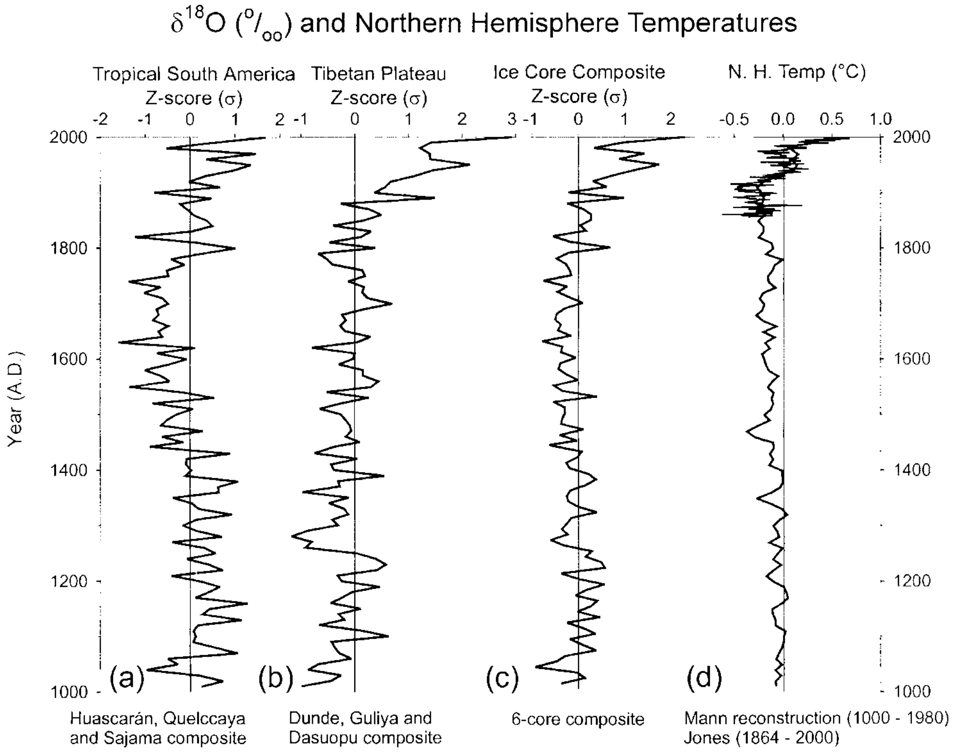


*Figure 7.* Regional composites, shown as z-scores, for the last millennium were constructed from the decadal averages of $\delta^{18}O_{ice}$ from three Andean ice cores (a) and three Tibetan ice cores (b). The composite of all six low latitude cores is shown in (c). The measured (Jones et al., 1999) and reconstructed (Mann et al., 1999) Northern Hemisphere temperatures are shown in (d) and are plotted as deviations (°C) from their respective 1961–1990 means. Note that the decadal average of $\delta^{18}O_{ice}$ for 1991 to 2000 is based on the 1991 to 1997 annual values for the Dasuopu core drilled in 1997 and on the 1991–1997 annual values for the Sajama drilled in 1997. The Quelccaya $\delta^{18}O_{ice}$ history has been updated to 2000 by drilling new shallow cores.

The retreat of the margins of Quelccaya has also been monitored. The extent and volume of its largest outlet glacier, Qori Kalis, has been measured eight times between 1963 and 2000. These observations document a rapid retreat that has accelerated over the 37-year observation period. The rate of retreat from 1983 to 1991 was three times that measured from 1963 to 1983. Using the 1963 to 1983 rate of retreat as a benchmark, Qori Kalis retreated five times faster from 1993 to 1995, eight times faster from 1995 to 1998, and thirty-two times faster from 1998 to 2000. The Qori Kalis retreat observations highlight the sensitivity of these ice fields to ambient air temperatures. In 1991 the eruption of Mount Pinatubo produced a globally distributed stratospheric sulfate layer that reduced globally averaged temperatures for several years. The two-year period from 1991 to 1993 is the only observation period since 1963 for which no retreat of Qori Kalis was measured. The retreating outlet glacier essentially 'stopped dead in its tracks', but by 1995 it had resumed its rapid retreat.

Additional glaciological evidence exists for tropical warming and concomitant ice loss. Hastenrath and Kruss (1992) reported that the total ice cover on Mount Kenya 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 (Kaser and Noggler, 1991). The ice fields on Kilimanjaro lost 73% of their area between 1912 and 1989 (Hastenrath and Greischar, 1997). In January and February of 2000, six ice cores measuring up to 50 meters in length were recovered from the three remaining ice fields of Kilimanjaro (Africa, 3° S, 5895 m asl). During the drilling OSU commissioned a new aerial photograph of the summit area that confirmed the continued loss of ice on all three ice fields. The updated calculation reveals that Kilimanjaro has now lost ∼80% of its ice coverage compared to 1912 (Thompson et al., 2002).

Tropical and subtropical ice core records have the potential to provide annual to millennial-scale records of El Niño-Southern Oscillation events and monsoon variability and will continue to provide additional insight to the magnitude and frequency of change in these and other large-scale climate phenomena. The composite low latitude record clearly shows unique changes underway in the 20th century in the low latitudes when viewed from the perspective of the last one-thousand years. The ice cores also contain archives of decadal- to millennial-scale climatic and environmental variability and provide unique insight to both regional and global scale events ranging from the so-called 'Little Ice Age', the Younger Dryas cold phase, to the Late Glacial Stage. The data presented here clearly demonstrate that some, if not all, of these unique archives are in imminent danger of being lost if the current warming persists. The societal relevance driving the urgent need to understand the nature of climate variability in the tropics is illustrated in Figure 1. The tropics (±30° from equator) account for 50% of the Earth's surface area, is home to ∼70% of the current population of 6.2 billion, produces only ∼20% of the world's agricultural goods and accounts for ∼80% of the world's births.

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