HIGH ALTITUDE, MID- AND LOW-LATITUDE ICE CORE RECORDS: IMPLICATIONS FOR OUR FUTURE

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1. INTRODUCTION

The 20th Century has seen the acceleration of unprecedented global and regional-scale climatic and environmental changes to which humans are vulnerable, and by which we will become increasingly more affected in the coming centuries. One-half of the Earth's surface area lies in the tropics between 30° N and 30° S, and this area supports about 70 percent of the global population. Thus, temporal and spatial variations in the occurrence and intensity of coupled ocean-atmosphere phenomena such as El Niño and the Monsoons, which are most strongly expressed in the tropics and subtropics, are of world-wide significance. Unfortunately, meteorological observations in these regions are scarce and of short duration, particularly from high elevation sites. However, ice core records are available from low-latitude, high-altitude glaciers, and when they are combined with high-resolution proxy histories such as those from tree rings, lacustrine and marine cores, corals, etc., they provide an unprecedented view of the Earth's climatic history over several millennia. This paper provides an overview of these unique glacier archives of past climate and environmental changes on millennial to decadal time scales. Unfortunately, these glacier archives of our past climate and environmental history are at risk. This is illustrated by the recent history of one tropical glacier in particular, the Quelccaya ice cap,

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as shown by a photo of its margin in 1977 (Figure 1a) compared with one taken in 2002 (Figure 1b).

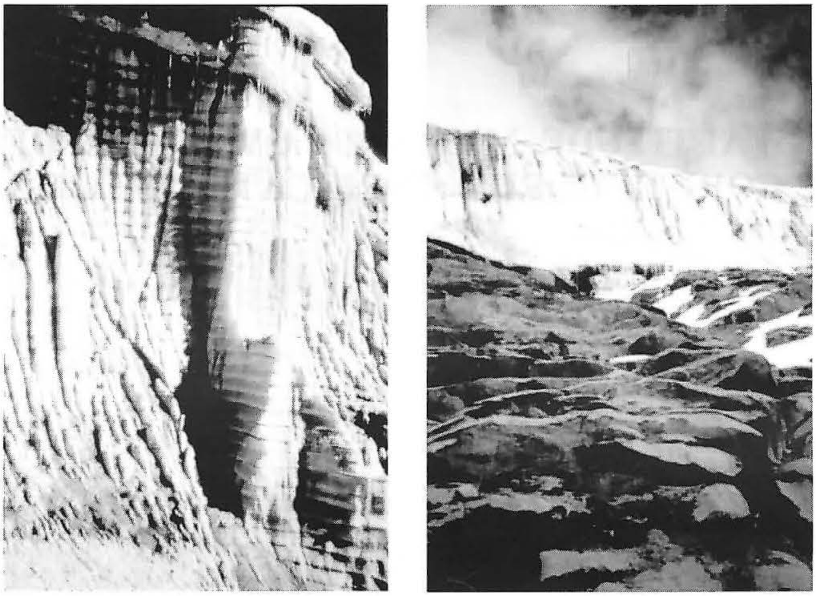

Figure -1. The The margin of the Quelccaya ice cap in (1) 1977 and in (b) 2002

Over the last 25 years the principle objective of the Ice Core Paleoclimatology Research Group (ICPRG) at the Byrd Polar Research Center (BPRC) at the Ohio State University has been the acquisition and analysis of a global array of ice cores that can provide high-resolution climatic and environmental histories which contribute to our understanding of the complex interactions within the Earth's coupled climate system. With the help of new light-weight drilling equipment, we have achieved one of our main scientific objectives by expanding our research from the polar regions to remote ice fields on some of the highest tropical and subtropical mountains. Ice core records from mountains in Africa, South America, and China make it possible to study processes in the subtropical and tropical latitudes where human activities are concentrated. The 15 sites from where the ICPRG has retrieved high-altitude ice cores are shown in Figure 2. We utilize an ever-expanding ice core database of multiple proxy information (i.e. stable isotopes of oxygen, or (δ^{18} O) and hydrogen, insoluble dust, major and minor ion chemistry, precipitation reconstruction) that spans the globe in spatial coverage and is of the highest possible temporal resolution.

Some of the accomplishments and challenges of our ice core research, as well as those of our colleagues in the USGS and other American institutes, along with those of Chinese, Russian, French and Swiss scientists, are highlighted in this volume.

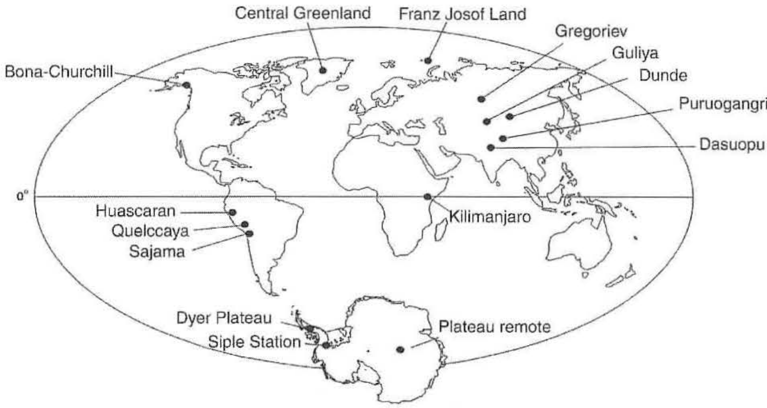

Figure -2. Locations of sites from where ice cores have been taken by the Ice Core Paleoclimate Research Group.

The records contained within the Earth's alpine ice caps and glaciers provide a wealth of data that contribute to a broad spectrum of critical scientific questions. These range from the reconstruction of high-resolution climate histories to help explore the oscillatory nature of the climate system, to the timing, duration, and severity of abrupt climate events, to the relative magnitude of 20th Century global climate change and its impact on the cryosphere. The information from these ice core studies complements other proxy records that compose the Earth's climate history, which is the ultimate yardstick by which the significance of present and projected anthropogenic effects will be assessed.

2. WHAT WE'VE LEARNED FROM MID-AND LOW-LATITUDE ALPINE ICE CORES

The first program to drill a low-latitude mountain core to bedrock was carried out on the Quelccaya ice cap in Southern Peru (14°S, 71°W) in 1983. In 2002, a subarctic alpine site, Bona-Churchill in the Wrangell Mountains in southeast Alaska, was drilled and 623 meters of ice core were recovered, with one core from surface to bedrock measuring 460 meters in length. In between these two programs, we have recovered cores from the Tibetan Plateau (Dunde, Guliya, Dasuopu, Puruogangri), from the Andes (Huascarán and Sajama) and from Kilimanjaro in East Africa. With the exception of Puruogangri and Bona-Churchill, all the cores have been analyzed and their overall climate records have been published.

Under the Puruogangri project, two ice cores that were obtained during the collaborative expedition conducted by the Laboratory of Ice Core and Cold Regions Environment, Cold and Arid Regions Environmental and Engineering Research Institute (LICCRE, formally the Lanzhou Institute of Glaciology and Geocryology) and BPRC are being analyzed for physical and chemical parameters.

Figure -3. (a) The margin of the Puruogangri ice cap, central Tibetan Plateau demonstrating the distinct seasonal dust layering. (b) An ice core from the puruogangri ice cap.

Figure 3a illustrates the distinct annual dust layers recorded in this ice cap located in the center of Tibet, where each spring aeolian sand leaves an identifiable seasonal horizon that can be seen at the margin. At the margin of this ice cap, over 2000 years can be discerned by counting these layers which average about 50 centimeters in thickness. Figure 3b illustrates one of the cores recovered from the summit of the ice cap in which these annual layers can be seen. The marked enrichment in ^{18}O in the ice over the most recent half century at this location (Figure 4), is consistent with findings from glaciers on the northeastern and southern sides of the Plateau (*Thompson et al.*, 1989; *Thompson et al.*, 2000b).

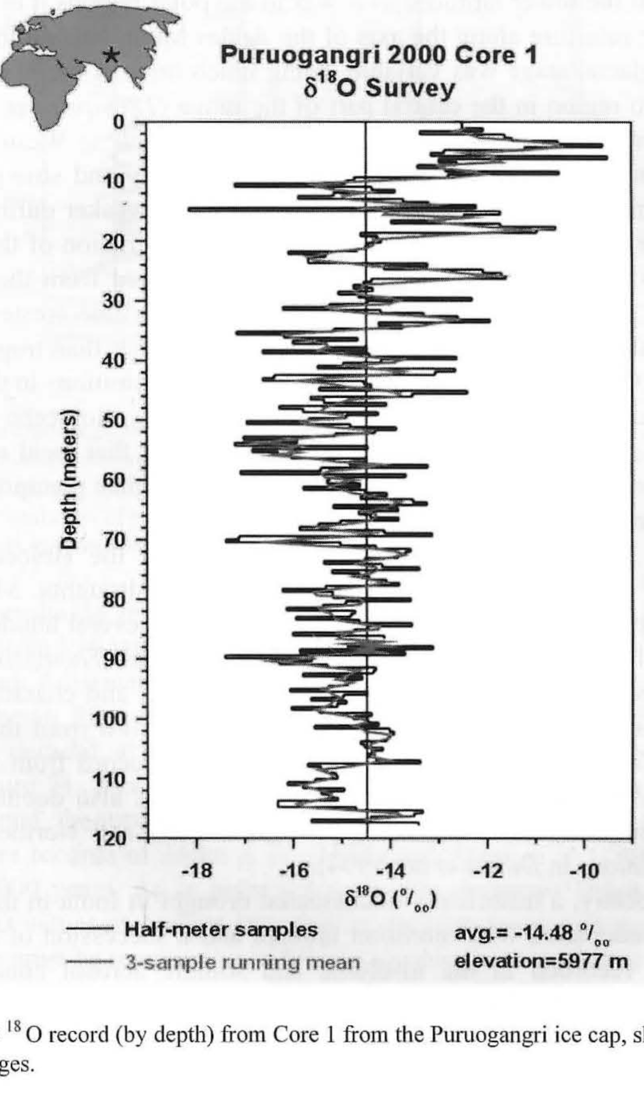

Figure -4. $\delta^{18}O$ record (by depth) from Core 1 from the Puruogangri ice cap, shown as half-meter averages.

Low-latitude, high-altitude ice core records have revealed the nature of climate variability over both glacial and interglacial time scales, specifically over the last 25 thousand years since the Last Glacial Maximum (LGM). Two records from the South American Andes (Huascarán in Northern Peru at 9°S, 78°W and Sajama in Bolivia at 18°S, 69°W) and one fom the Tibetan Plateau (Guliya at 35°N, 81°E) extend to or past the LGM and confirm, along with other climate proxy records (eg. *Stute et al.*, 1995; *Guilderson et al.,* 1994), that the LGM was much colder in the tropics and subtropics than previously believed (*Thompson et al.*, 1995; *Thompson et al.*, 1998). The Guliya record covers over 700,000 years and is the oldest low- latitude, high-altitude record recovered as of this writing (*Thompson et al.*, 1997). Although the LGM period was consistently colder, it was not consistently drier through the lower latitudes as it was in the polar regions. For example, the effective moisture along the axis of the Andes Mountains during the end of the last glacial stage was variable, being much drier in the north than in the Altiplano region in the central part of the range (*Thompson et al.*, 1995; *Thompson et al.,* 1998; *Davis*, 2002). In another example in Western China, the Guliya ice cap is partly affected by the variability and strength of the Southwest Indian Monsoon system, which was much weaker during the last glacial stage than during the Holocene. However, this region of the Tibetan Plateau also receives (and received) moisture generated from the cyclonic activity carried over Eurasia by the prevailing wintertime westerlies. Not only were lake levels in the Western Kunlun Shan higher than tropical lakes during the LGM (*Li and Shi*, 1992), but the dust concentrations in the Guliya ice core record were consistent with those of the Early Holocene when the summer Asian Monsoons became stronger suggesting that local sources of aerosols were inhibited during this cold period by higher precipitation and soil moisture levels (*Davis*, 2002).

Tropical and subtropical ice core records during the Holocene show evidence of major climatic disruptions, specifically droughts. Major dust events, beginning between 4.2 and 4.5 ka and lasting several hundred years, are observed in the Huascarán and Kilimanjaro ice cores (*Thompson*, 2000b; *Thompson et al.*, 2002a, respectively), and the timing and character of the dust spike is similar to one seen in a marine core record from the Gulf of Oman (*Cullen et al.*, 2000) and a speleothem δ^{13}C record from a cave in Israel (*Bar-Matthews et al.*, 1997). This dry period is also documented in several other proxy climate records throughout Asia and Northern Africa (see contributions in *Dalfes et al.*, 1994).

More recently, a historically documented drought in India in the 1790's, which was associated with monsoon failures and a succession of severe El Niños, was recorded in the insoluble and soluble aerosol concentration records in the Dasuopu ice core (*Thompson et al.*, 2000b). Another recorded

Asian Monsoon failure in the late 1870's (*Lamb*, 1982) is noticeable in the Dasuopu dust flux record, which is a parameter that incorporates both the dust concentration and the annual accumulation rate of ice on the glacier surface.

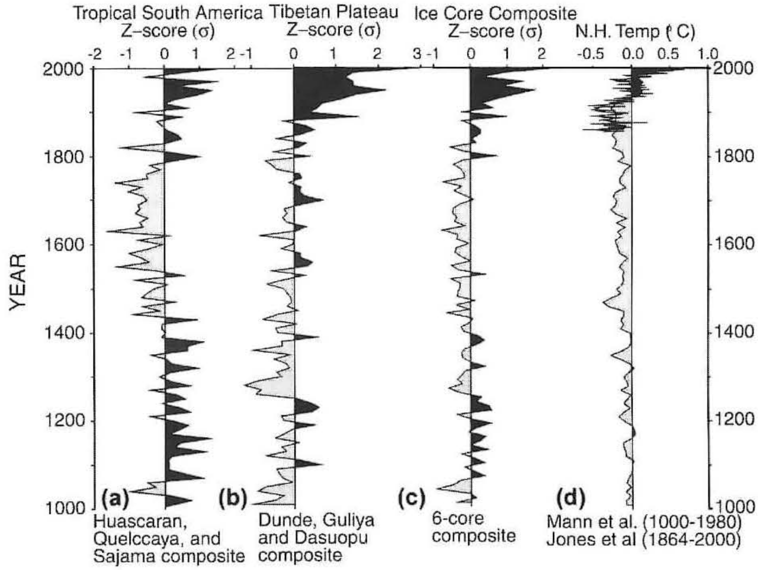

Figure -5. Composite records of decadal averages of δ^{18} O from ice cores from (a) the South American Andes (Huascaran, Quelccaya, Sajama) and (b) the Tibetan Platteau (Dunde, Guliya and Dasuopu) from 1000 A.D. to the present. All six ice-core records are combined (c) to give a total view of variations in δ^{18} O over the last millennium in the tropics, which is compared with the Northern Hemisphere reconstructed temperature record (d).

High-resolution records of Late Holocene variations in temperature are available from low latitude alpine ice cores. Composites of the δ^{18} O profiles of the South American cores (Huascarán, Quelccaya, and Sajama) and three of the Tibetan Plateau cores (Dunde, Guliya and Dasuopu) show similar trends in decadal averages over the last millennium (*Thompson et al.*, 2003)(Figure 5). When all six of the records from these mountain glaciers are combined, the resulting composite is similar to the Northern Hemisphere temperature records of *Mann et al.* (1998) and *Jones et al.* (1998) covering the last 1000 years. As in polar ice cores, the dominant factor controlling mean δ^{18} O values in Andean snowfall on decadal, centennial and millennial timescales must be temperature, while on seasonal to annual time scales both temperature and precipitation influence the local δ^{18} O signal (*Vuille et al.*, 2003). Not only do these comparisons argue for the important role of temperature in the composition of oxygen isotopic ratios in glacier ice, but they also demonstrate abrupt warming from the late 19^{th} Century through the 20^{th} Century. Indeed, the 20th Century was the warmest period in the last 1000 years, which also encompasses the time of the "Medieval Warming".

The recent warming is recorded in tropical alpine glaciers in other ways, both within the ice core records and by the rapid retreat of many of the ice fields. In the Andes, on the Tibetan Plateau and in the East Africa Rift Valley region this climate change has left its mark. For example, the many ice fields on Kilimanjaro covered an area of 12.1 km^2 in 1912, but today only 2.6 km^2 remains. If the current rate of retreat continues, the perennial ice on this mountain will likely disappear within the next 20 years (*Thompson et al.*, 2002a). The lower elevation ice caps in the Andes are experiencing damage to their seasonal δ^{18} O signals from the lifting of the 0^o C isotherm (*Davis et al.*, 1995). For example, not only is the seasonal isotope signal on the Quelccaya ice cap at 14^o S in Southern Peru being smoothed out as meltwater percolates through the upper layers of the snow (*Thompson et al.*, 1993), but the ice margins are undergoing rapid and accelerating retreat.

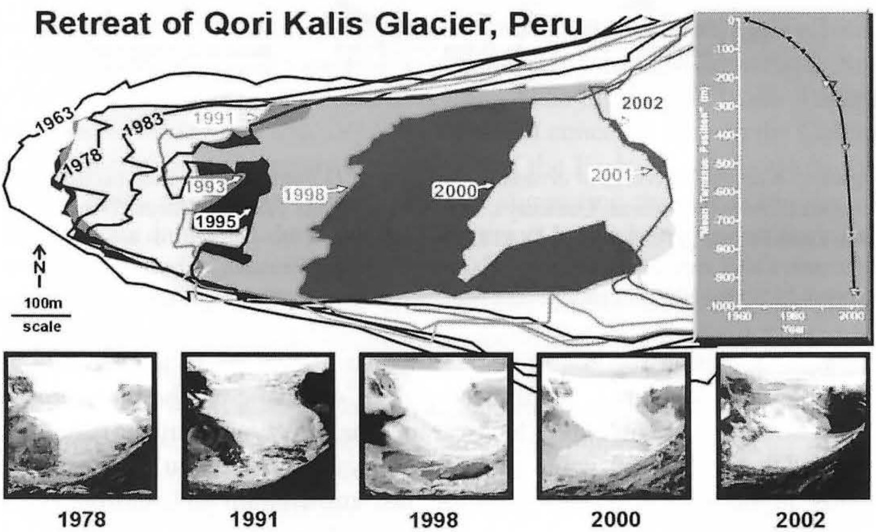

Figure -6. The history of the retreat of the Quelccaya outlet glaciewr, Qori Kalis, from 1963 to 2002.

Figure 6 documents the retreat of Quelccaya's largest outlet glacier, Qori Kalis, which has been studied by terrestrial photogrammetry since 1978 (*Thompson et. al.* 2000a). The rate of this retreat from 1983 to 1991 (14 m/yr) was almost three times that between 1963 and 1983 (5 m/yr), and in the 2000/2001 year reached 205 m/yr. The sequence of ten maps documents the rapid and accelerating retreat whereby the glacier front is now retreating about 40 times faster than it did in the initial measurement period from 1963 to 1978.

3. IMPORTANT QUESTIONS STILL TO BE ANSWERED

Seasonal and annual resolution of chemical and physical parameters in ice core records from the Andes Mountains have allowed reconstruction of the variability of the ENSO phenomenon over several hundred years (*Thompson et al.*, 1984; 1992; *Henderson*, 1996; *Henderson et al.,* 1999). Because the effects of El Niño and La Niña events are spatially variable, ice core records from the northernmost (Columbia) and southernmost (Patagonia) reaches of the Andes Mountains will help further resolve the frequency and intensity of ENSO, along with temperature variations long before human documentation. This will aid in placing the modern climate changes and the modern ENSO into a more comprehensive perspective. The opportunity to study ENSO teleconnections in the most recent centuries between the tropics and the northern subarctic latitudes will be provided by the completed high-resolution record from the Bona- Churchill col in the St. Elias Range of southeast Alaska.

Variability of the South Asian Monsoon is also of vital importance for a large percentage of the world's population that lives in the affected areas. The ICPRG has drilled four cores across the Tibetan Plateau that have yielded millennial-scale histories of monsoon variability across this large region and information on the interaction between the Monsoon system and the prevailing westerlies that are traced back to the Atlantic Ocean. Although marine cores from the Arabian Sea show that the intensity of the South Asian Monsoon has increased over the last four centuries (*Anderson et al.*, 2002), the Dasuopu record from the Himalayas demonstrates that since the early 19^{th} Century the amount of precipitation falling on this region has decreased (*Thompson et al.*, 2000b). However, the Dunde record from the north side of the Plateau shows an accumulation history that is opposite to that in the Himalayas (*Davis and Thompson*, this volume). Like ENSO, therefore, the South Asian Monsoon systems have varying geographical effects. Retrieval of ice core records from the west side of the Himalayas, which is more directly affected by the SW Indian Monsoon than is the east side where Dasuopu is located, will provide a more comprehensive overview of the precipitation and temperature histories of the Himalayas as a whole. The glaciers on these mountains are vital sources of stream water for the populations of Nepal and India during the dry seasons, and their recent disappearance should be a source of great concern for these countries. Meteorological data from around the world suggest that the Earth's globally averaged temperature has increased 0.6°C since 1950. The El Niño year of 1998 saw the highest globally averaged temperatures on record, while 2001 (a La Niña year) was the second warmest, and 2002 (a non-El Niño year) exceeded the 2001 average temperature. The marked warmth of the last two decades has contributed to the widespread melting of low-latitude, high-altitude glaciers. During this time, the ICPRG has been monitoring the accelerating retreat of this tropical ice in conjunction with its global ice core drilling and climate reconstruction program. Some of the clearest evidence for major climate warming underway today comes from the tropical glaciers, recorded in both the ice core $\delta^{18}O$ records and in the drastic retreats of both total area and total volume.

The rapid retreat causes concern for two reasons. First, these glaciers are the world's "water towers", and their loss threatens water resources necessary for hydroelectric production, crop irrigation and municipal water supplies for many nations. The ice fields constitute a "bank account" that is drawn upon during dry periods to supply populations downstream. The current melting is cashing in on that account, which was built over thousands of years but is not currently being replenished. As Figure 7 illustrates, all the mountain glaciers in the tropical latitudes are currently retreating, as are most glaciers in middle and subpolar latitudes. The land between 30°N and 30°S, which constitutes 50 percent of the global surface area, is home to 70 percent of the world's population and 80 percent of the world's births. However, only 20 percent of the global agricultural production takes place in these climatically sensitive regions.

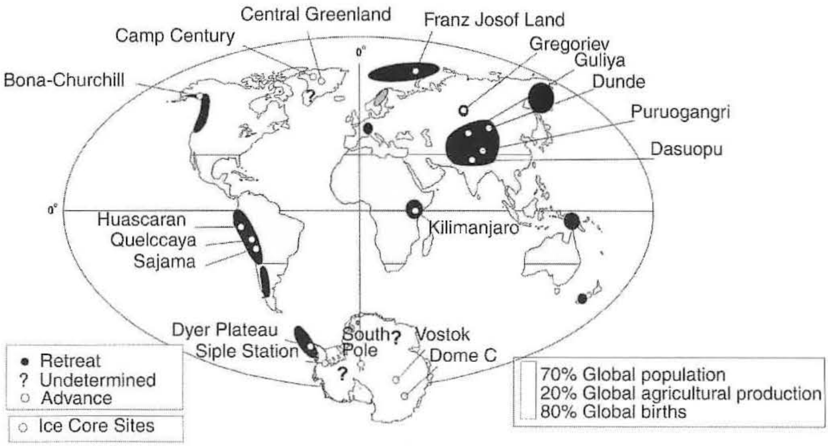

Figure -7. Map demonstrating the current condition of the Earth's cryosphere. Dark shading depicts regions where glacier retreat is underway, while lighter shading depicts where glacier advance is occurring. Shading over land between 30°N and 30°S indicates the tropical regions where most human activity is currently concentrated

The second concern that is brought about by the disappearance of these ice fields is that they contain paleoclimatic histories that are unattainable elsewhere and, as they melt, the records preserved therein are forever lost. These records are needed to discern how climate has changed in the past in these regions and to assist in predicting future changes. For example, climate records from low-latitude ice cores give us a view of widespread abrupt climate events in the tropics that occurred about 4,200 years (discussed above) and about 5,200 and B.P. (*Thompson et al.*, 2002). These climatic "excursions" may have been catastrophic for early civilizations in Europe, Northern Africa, around the Mediterranean and in the Middle East. However, the geographic scale of these changes, their causes, the thresholds that triggered them, and the role of the tropical hydrological system are still mysteries. The multi-proxy analyses of ice cores is proving to be invaluable in the determination of long-term changes in the magnitude and the frequency of ENSO and monsoon variability over the past approximately 20,000 years, and how these systems may be related. However, high priority needs to be given to more precise dating of paleoclimate records, those from ice cores as well as other sources. In addition, paleoclimate data and climate models must be integrated to better understand past processes in climate change.

The mechanisms responsible for the current global warming remain a topic of much debate, but the scientific evidence verifies that the Earth's globally averaged surface temperature is indeed increasing, although at varying rates. For example, over the extensive, elevated area of the Tibetan Plateau, the warming trend is amplified and is accelerating with increasing altitude (*Thompson et al.*, 2000a). Although it is important to place this current warming and tropical glacier retreat into a long-term perspective, it is nevertheless undeniable that global water resources are at risk, and mountain glaciers and their unique climate histories are disappearing at an ever increasing rate. In order to preserve these records that are essential for examining how climate changes, we must accelerate the rate at which ice cores are being recovered and focus on those ice fields that are at the greatest risk. Thus, the loss of tropical mountain glaciers and the climate histories they contain presents an urgency to recover these archives.

4. REFERENCES

Anderson, D.M., Overpeck, J.T., and Gupta, A.K., 2002, Increase in the Asian Southwest Monsoon during the past four centuries. *Science* 297, 596-599.

Bar-Matthews, M., Ayalon, A. Kaufman, A., Wasserburg, G.J., 1999, The Eastern Mediterranean paleoclimate as a reflection of regional events: Soreq Cave, Israel. *Earth and Planetary Letters* 166, 85-95.

Cullen, H.M., deMenocal, P.B., Hemming, S., Hemming, G., Brown, G.H., Guilderson, T., Sirocko, F., 2000, Climate change and the collapse of the Akkadian empire: Evidence from the deep sea. *Geology* 28, 379-382.

Dalfes, H.N., Kukla, G., and Weiss, H., Eds., 1994, *Third Millennium BC Climate Change and Old World Collapse*. Springer, Berlin, 723 pp.

Davis, M.E., Thompson, L.G., Mosley-Thompson, E., Lin, P.N., Mikhalenko, V.N., and Dai, J., 1995, Recent ice-core climate records from the Cordillera Blanca, Peru. *Annals of Glaciology* 21, 225-230.

Davis, M.E., 2002, Climatic interpretations of eolian dust records from low-latitude, high-altitude ice cores. PhD Thesis, The Ohio State University.

Davis, M.E. and Thompson, L.G., 2003, Four centuries of climatic variation across the Tibetan Plateau from ice-core accumulation and $\delta^{18}O$ records. In: *Earth Paleoenvironments: Records Preserved in Mid and Low Latitude Glaciers* (L.D. Cecil, J.R. Green, L.G. Thompson, eds.) Kluwer, New York.

Guilderson, T.P., Fairbanks, R.G., and Rubenstone, J.L., 1994, Tropical temperature variations since 22,000 years ago: modulating inter-hemispheric climate change. *Science* 263, 663-665

Henderson, K.A., 1996, The El Niño-Southern Oscillation and other modes of interannual tropical climate variability as recorded in ice cores from the Nevado Huascarán col, Peru. M.S. Thesis, The Ohio State University.

Henderson, K.A., Thompson, L.G., and Lin, P.N., 1999, Recording of El Niño in ice core δ O $_{18}$ records from Nevado Huascarán, Peru. *Journal of Geophysical Research, D* 104, 31,053-31,065.

Jones, P.D., Briffa, K.R., Barnett, T.P., and Tett, S.F.B., 1998, High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with general circulation model control-run temperatures. *Holocene* 8, 455-471.

Lamb. H.H., 1982, *Climate History and the Modern World*. Methuen, London, 387 pp.

Li, S. and Y. Shi. (1992) Glacial and lake fluctuations in the area of the west Kunlun Mountains during the last 45,000 years. *Annals of Glaciology* 16, 79-84.

Mann, M.E., Bradley, R.S., and Hughes, M.K., 1998, Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* 392, 779-787.

Stute, M., Forster, M., Frischkorn, H., Serejo, A., Clark, J.F., Schlosser, P., Broecker, W.S., and Bonani, G., 1995, Cooling of tropical Brazil (5°C) during the last glacial maximum. *Science* 269, 379-383.

Thompson, L.G., Mosley-Thompson, E., and Arnao, B.M., 1984, El Niño-Southern Oscillation events recorded in the stratigraphy of the tropical Quelccaya ice cap, Peru. *Science*, 226, 50-52.

Thompson, L.G. and 9 others, 1989, Holocene-Late Pleistocene climatic ice core records from Qinghai-Tibetan Plateau. *Science* 246, 474-477.

Thompson, L.G., Mosley-Thompson, E., and Thompson, P.A., 1992, Reconstructing interannual climate variability from tropical and subtropical ice-core records In: *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation* (H.F. Diaz and V. Markgraf, eds.) Cambridge University Press, Cambridge, pp. 295-322.

Thompson, L.G. and 6 others. 1993, "Recent warming": ice core evidence from tropical ice cores with emphasis upon Central Asia. *Global and Planetary Change* 7, 145-146.

Thompson, L.G. and 7 others, 1995, Late Glacial Stage and Holocene tropical ice core records from Huascarán, Peru. *Science* 269, 47-50.

Thompson, L.G. and 9 others, 1997, Tropical climate instability: the last glacial cycle from a Qinghai-Tibetan ice core. *Science* 276, 1821-1825.

Thompson, L.G. and 10 others, 1998, A 25,000 year tropical climate history from Bolivian ice cores. *Science* 282, 1858-1864.

Thompson, L.G., 2000a, Ice-core evidence for climate change in the Tropics: implications for our future. *Quaternary Science Reviews* 19, 19-36.

Thompson, L.G., Yao, T., Mosley-Thompson, E., Davis. M.E., Henderson, K.A., and Lin, P.N., 2000b, A high-resolution millennial record of the South Asian Monsoon from Himalayan ice cores. *Science* 289, 1916-1919.

Thompson, L.G. and 10 others, 2002, Kilimanjaro ice core records: Evidence of Holocene climate change in tropical Africa. *Science* 298, 589-593.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Lin, P.N., Henderson, K., and Mashiotta, T.A., 2003, Tropical glacier and ice core evidence of climate change on annual to millennial time scales. *Climatic Change* 59, 137-155.

Vuille, M, Bradley, R.S., Healy, R., Werner, M., Hardy, D.R., Thompson, L.G., and Keiming, F., 2003, Modeling $\delta^{18}O$ in precipitation over the tropical Americas, Part II: Simulation of the stable isotope signal in Andean ice cores. *Journal of Geophysical Research*, 108, 10.1029/2001JD002039.