# 4.1 ICE CORE EVIDENCE FOR TROPICAL CLIMATE CHANGE: THE ROLE OF WATER VAPOR

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## 1. INTRODUCTION

Reliable meteorological observations for climate reconstruction are limited or absent prior to A.D. 1850 for much of the Earth and particularly in the Tibetan Plateau region of central Asia and in tropical South America. Over 50% of the Earth's surface lies between 30°N and 30°S and 75% of the world's inhabitants live and conduct their activities in these tropical regions. Thus, much of the climatic activity of significance to humanity, such as variations in the occurrence and intensity of the El Niño-Southern Oscillation and monsoons, are largely confined to lower latitudes. Moreover, the variability of these tropical systems and particularly that of the tropical hydrological system in response to regional and global climate forcing are not well understood.

Fortunately, ice core records are available from selected high altitude, low and mid-latitude ice caps. The ice core studies described here were undertaken as part of a long-term program to acquire the global-scale, high resolution climatic and environmental history essential for understanding more fully the linkages between the low and the high latitudes. Comparisons are made between two ice core records from the Tibetan Plateau: the Guliya ice cap, (35°N; 6200 m asl) and Dasuopu Glacier in the Chinese Himalaya (28°N, 7200 m asl). These Tibetan records are compared and contrasted with two recent tropical ice core records from Huascarán (Peru, 9°S, 6050 m asl) and Sajama (Bolivia, 18°S, 6550 m asl). Both contain ice deposited during the Last Glacial Stage (LGS) and the oxygen isotopic ratio ($\delta^{18}O$) of this ice suggests significant tropical cooling (~5°C) in the tropics. These 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, suggest that changes in water vapor inventories are a significant component of climate variability..

Water vapor is the most important greenhouse gas and keeps the Earth ~30°C warmer and allows life to exist. Water vapor creates a positive atmospheric feedback that amplifies changes in climate imposed by other factors. Hence, the greatest amplification of change in response to an increase in the global water vapor inventory would be expected in the tropics. The global temperature distribution generally ranges from high values in low latitudes to low values in higher latitudes. However, precipitation exhibits a somewhat different trend as it is enhanced between 0 and 5°N (rising arm of the Hadley Cell) and diminished around latitudes centered at ~ 28°N and ~28° S (the descending arm of the Hadley Cell). The paleoclimate record shows great variations in tropical hydrology which likely reflect changes in the intensity of the Halley Cell through time.

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## 2. THE ICE CORE RECORDS

The highly constrained time scale for the Sajama, Bolivia ice cores allows comparison of their $\delta^{18}O$ profiles with other tropical, subtropical and polar records. Such a comparison for this global array of cores reveals large-scale similarities as well as important regional differences. The $\delta^{18}O$ shift from Early Holocene to LGM is 5.4‰ on Sajama (Thompson et al. submitted), 6.3‰ on Huascarán (Thompson et al. 1995), 5.4‰ to 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). All these records show similar isotopic depletion, reflecting significant global cooling at the Late Glacial Maximum (LGM). These data contribute to a growing body of evidence that the LGM cooling was global. These other data originate from such diverse archives as corals (Guilderson et al. 1994; Beck et al. 1997), noble gases from groundwater (Stute et al. 1995); marine sediment pore fluids, (Schrag et al. 1996), snowline depression (Broecker and Denton 1990; Herd 1974; Klein et al. 1995; Osmaston 1965; Porter 1979; Rodbell 1992), and pollen studies (Colinvaux et al. 1996).

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 of very large impacts on atmospheric lapse rates, particularly in the tropics. As the Earth is a thermodynamically non-linear planet, tropical glaciers are very sensitive to climate change: Lapse rates will change more with height if the atmosphere is moister than if the atmosphere is drier. If sea surface temperatures (SST) warms uniformly across the globe, tropical lapse rates will decrease. Conversely with a global scale cooling they would increase and 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 and under colder conditions such as those of the LGS (5°-6° C cooling suggested by the ice cores and other records mentioned above) tropical glaciers would be expected to expand rapidly. Such changes between dry and moist adiabatic lapse rates should lead to tropical amplification of either a warming or a cooling.

## 3. 20TH CENTURY WARMING

Evidence is accumulating for a strong warming in the tropics during in the second half of the 20th Century. This warming is causing the rapid retreat and, in some cases, the disappearance, of ice caps and glaciers at high elevations in the tropics and subtropics. 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) is 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, 1991 and 1995. Comparison of the $\delta^{18}O$ records extracted at these four different times reveals that the seasonally resolved paleoclimatic record, formerly (1983) preserved as $\delta^{18}O$ variations, is no longer being retained within the currently accumulating snow (Thompson et al. 1993). 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 seven times between 1963 and 1998. These observations have documented a rapid retreat that has accelerated during this 35-year period. The rate of retreat from 1983 to 1991 was three times that from 1963 to 1983, and was five times faster in the most observational recent period (1993 to 1995). Associated with this increasing rate of retreat is a sevenfold increase in the rate of volume loss, determined by comparing the 1963 to 1978 volume-loss rate to that of 1993 to 1995. The latest observations made in 1995 confirm the continued acceleration of Qori Kalis' retreat, as well as further retreat of the other margins of the Quelccaya ice cap. Also between 1983 and 1991, three adjacent lakes have appeared.

Additional glaciological evidence for tropical warming exists. Hastenrath and Kruss (1992) 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 (Kaser and Noggler 1991). 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. It is important to note that this general retreat of high elevation tropical glaciers is concurrent with an increase in water-vapor content of the middle troposphere (Flohn et al. 1990) in the tropics. Water vapor feedback effects may be partially reponsible for the enhancement of atmospheric warming at this level (Diaz and Graham 1996).

The 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 provide further insight to the magnitude and frequency of these large-scale events. The ice cores 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 clearly demonstrate that some, if not all, of these unique archives are in imminent danger of being lost if the current warming persists. Clearly, the positive water vapor feedback leads to amplification of climatic changes in the tropics.

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