Climatic Changes for the last 2000 Years Inferred from Ice-Core Evidence in Tropical Ice Cores

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Abstract

Distinct annual dust layers are preserved both in the tropical Quelccaya ice cap located in the Southern Andes of Peru as well as in the Guliya ice cap in the far Western Kunlun mountains of Tibet. The Tibetan Plateau and Bolivian-Peruvian altiplano have similar mean elevations (~4000 metres) and their regional weather patterns are driven primarily by the sensible heat flux over these plateaus and latent heat release during precipitation. On average 70 to 80% of their annual snowfall arrives during their wet seasons, November to April on Quelccaya and April to August on Guliya.

This paper compares the 1500 year net accumulation (A_n) record from Quelccaya with the 2000 year net accumulation history from Guliya. This similarity between theses A_n histories is striking given that the sites are 20,000 km apart, lying on opposite sides of the Pacific Basin. During the overlapping 1500 years the major periods of drought and wetness appear contemporaneous, suggesting a teleconnection for higher-frequency climatic events such as the El Niño-Southern Oscillation (ENSO). Now, for the first time, a longer temporal perspective is available from ice core records and it suggests that lower-frequency teleconnections may exist as well.

Introduction

Ice sheets and ice caps serve as libraries of atmospheric history from which past climatic and environmental conditions may be extrapolated. Glaciers at high elevations on the Qinghai-Tibetan (Q-T) Plateau cover an area of $\approx$57,000 km^2 (Shi and Wang, 1981) and, if judiciously selected, may provide a spatially coherent climate history for this region. The Plateau, one of the most imposing topographic features on the Earth's surface, has a mean elevation of $\approx$5 km and comprises an area half that of the United States. The sensible heat flux and the latent heat release over the Q-T Plateau drive the regionally intense monsoon circulation and strongly influence global circulation patterns. Reliable meteorological observations are limited for much of this extensive region.

The primary ice core records currently available from this area are from the Dunde ice cap (38°06´N, 96°24´E; 5325 m.a.s.l.) on the northeastern margin of the Q-T

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Plateau and the Guliya ice cap (35°17′N, 81°29′E; 6710 m.a.s.l.) on the far western margin. The proxy climatic histories from both these sites are of high (annual) resolution. The Plateau experiences a marked annual cycle in which 70 to 80% of the precipitation falls during the Northern Hemispheric, summer producing a distinct visible stratigraphy in the glaciers which allows accurate dating of the ice cores and reconstruction of the net mass accumulation (Thompson, 1992; Thompson *et al,* 1989; 1993).

The Guliya ice cap is the highest, largest (> 200 km^2) and thickest (308.6 metres) subtropical ice cap yet investigated. It is part of an ice mass which extends over 8000 km^2 in the Western Kunlun Mountains. In a cooperative effort, investigators from the Byrd Polar Research Center (BPRC) at The Ohio State University (OSU) and the Lanzhou Institute of Glaciology and Geocryology (LIGG) undertook a three year field and laboratory program (1990 to 1992) to study this very high elevation ice cap. During the 1990 and 1991 field seasons, surface, snow pit and shallow core samples were recovered. In the summer of 1992, the cooperative BPRC-LIGG expedition successfully recovered three ice cores, 34.5 m, 93.2 m and 308.6 m in length. Annual accumulation is quite variable, ranging from 140 mm to 260 mm (H_2O equivalent) among the sites where it was measured. The combination of relatively high (though variable) accumulation, 10-metre borehole temperatures of -15.2°C to -17.7°C, and the distinct monsoonal climate produces the marked annual stratigraphy which is necessary to extract a high quality ice core record of climatic and environmental variability. This paper presents the most recent 2000 years of this ice core-derived history.

Field and Laboratory Methods

Table 1 presents the entire suite of cores drilled and pits sampled from 1990 to 1992. The 1990 expedition occurred from September to October (after the monsoon season) while the 1991 field program took place in May, (prior to the onset of the monsoons). In 1992 the field program occurred from July to August, during the primary accumulation season. Each year pits were excavated and sampled for dust, $\delta^{18}O$ and chemical analyses at the different drill sites. Each year ice thicknesses were measured with short pulse radar at various locations around the ice cap. Ice thicknesses range

Table 1. Spatial and temporal sampling on the Guliya ice cap. (P=pit, SC=shallow core, DC= deep core, b=bottled, i=ice). Refer to Figure 1 for site locations. Elevations were determined using GPS.

GULIYA ICE CAP SAMPLE SITES				
SITE	ELEVATION (m)	FALL, 1990	SPRING, 1991	SUMMER, 1992
1	6040 m	P(b) SC(b)	SC(i)	DC(b)
2	6200 m	SC(i)		P(i) DC(i)
3	6200 m		SC(b)	
Summit	6710 m	SC(i)	P(b) SC(b)	

from 103 metres at the summit to 200 metres at Site 1, to 310 metres at Site 2. Based upon the thicknesses and the results from the pit samples Sites 1 and 2 were chosen for drilling to bedrock.

At Site 1 (Fig. 1) an electromechanical drill was used in an air-filled hole to recover a core to 93.2 metres, where drilling was aborted because an unconformity in the ice layers was observed at 83 metres. This core was cut into 1783 samples in the field which were melted and put in bottles sealed with wax to prevent vapor transfer and preserve the isotopic record. At Site 2 the electromechanical drill was used in a dry hole to 200 metres and from 200 metres to bedrock (308.6 metres) a thermal drill was used with an alcohol/water mixture to insure better core quality. No hiatus was observed Core 2 and the visible layers remained horizontal throughout. The entire core was returned frozen to the cold rooms at BPRC-OSU.

The visible stratigraphy of the cores was recorded in the field and air bubble characteristics and crystal sizes were determined at various intervals along Core 2. All ice core, surface and pit samples were analyzed for microparticle concentrations (MPC), oxygen isotopic ratios ($\delta^{18}O$) and selected chemical species (Cl^-, NO^-_3 and SO_4^{-2}). All samples (except $\delta^{18}O$) were analyzed in a Class 100 Clean Room at BPRC. Samples for $\delta^{18}O$ were measured with a Finnegan Mat Delta-E mass spectrometer. The upper 20 metres of the 34.5 metre core drilled at Site 2 were analyzed with high temporal

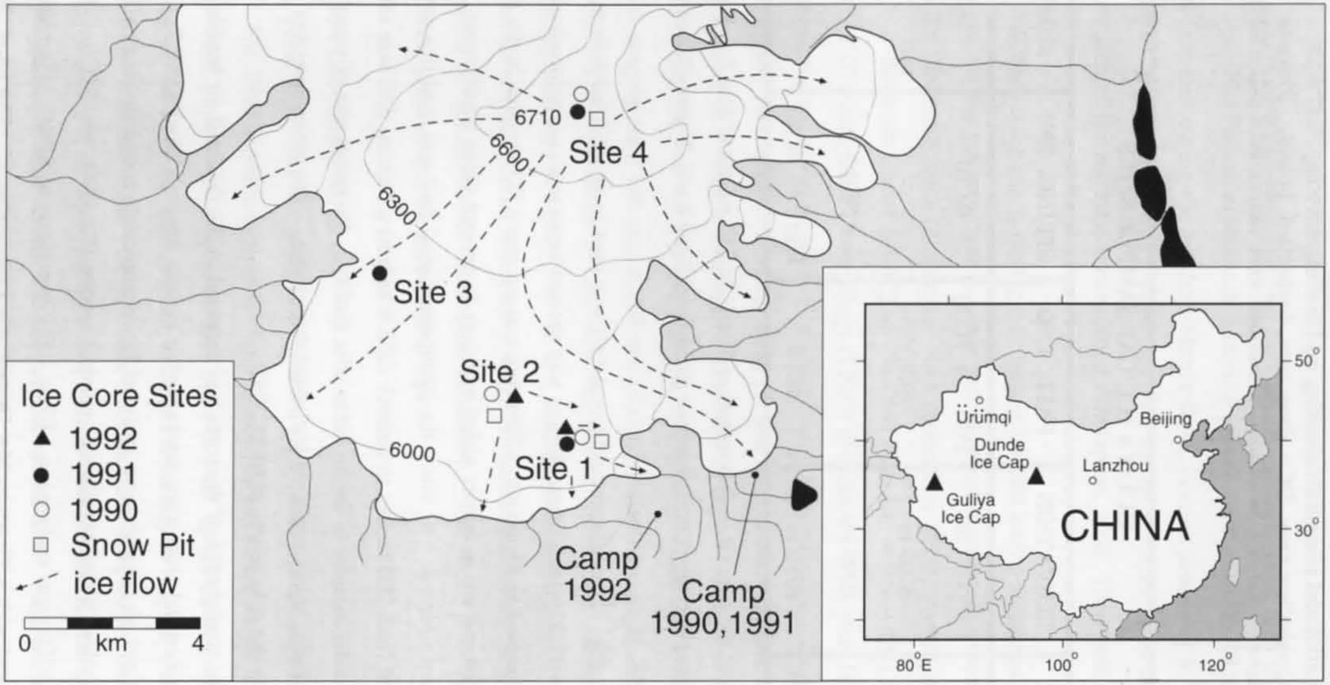

Figure 1: **Locations of the Guliya and Dunde ice caps are shown along with the snow pit and ice coring sites on Guliya.**

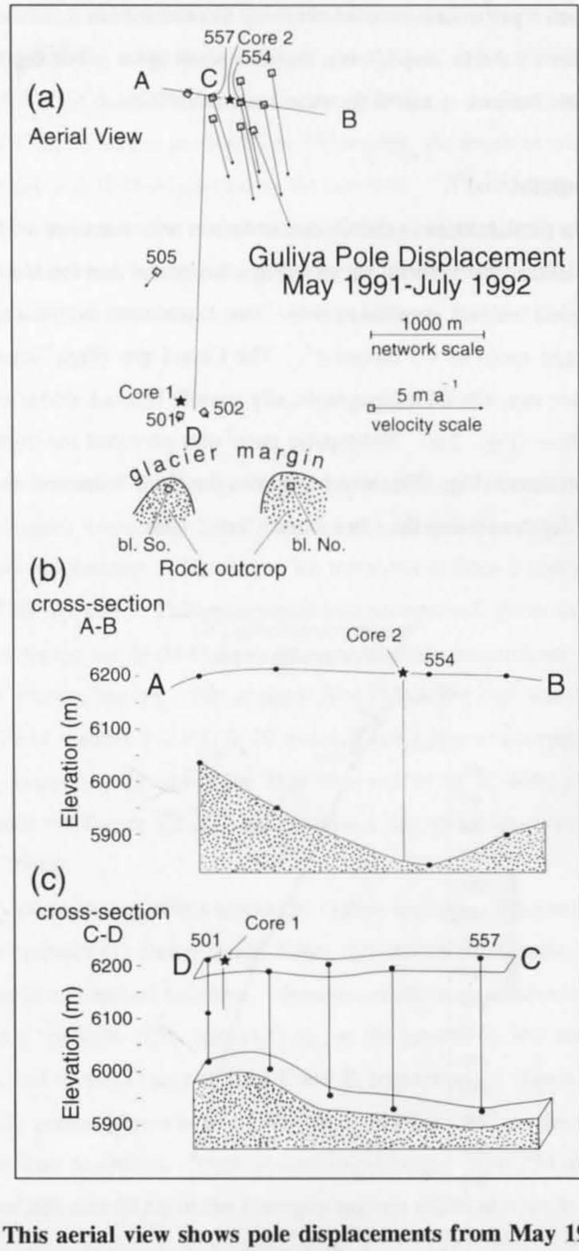

Figure 2: **(A) This aerial view shows pole displacements from May 1991 to July 1992 for the Core 1 and Core 2 drill sites. Displacements were determined relative to bedrock baselines: south point (bl. So.) and north point (bl. No.). The ice thickness profiles were measured during a short pulse radar survey along (B) transect A-B through the Core 2 drill site and along (B) transect C-D from the Core 2 drill site to the Core 1 drill site.**

resolution for solid particulate beta radioactivity (β) and tritium to locate in the core the massive 1962 Soviet Arctic atmospheric thermonuclear tests. The depth of this known time-stratigraphic horizon is useful for time scale calibration.

Geophysical Studies

The pole displacement in the Guliya strain-net was measured in June, 1991 and again in July, 1992. The velocity vectors (Fig. 2a) reveal that the Core 2 site, located over a topographic bedrock depression (Fig. 2b), experiences active ice flow toward the SSE at an average speed of 4.7 metres a^{-1}. The Core 1 site (Fig. 2c), located near the margin of the ice cap, sits on a topographically smooth bedrock dome and exhibits little horizontal ice flow (Fig. 2a). Short-pulse radar data provided the thicknesses shown along the A-B transect (Fig. 2b), which contains the Core 2 site and along the C-D transect (Fig. 2c) connecting the Core 2 and Core 1 sites.

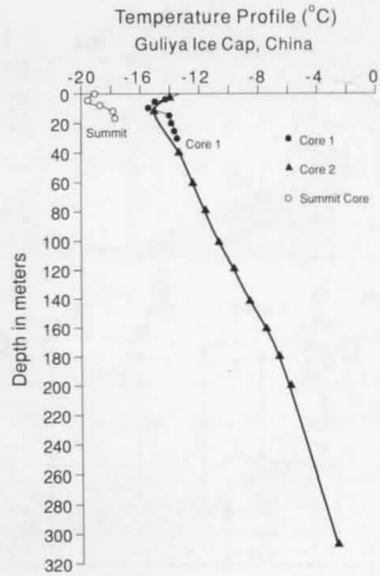

Figure 3: Vertical temperature profiles were measured in three boreholes using a 4 point calibration thermistor string. Temperatures in the 308.6 m hole range from -15.6°C at 10 metres to -2.1°C at the ice/bedrock contact. These data illustrate the Guliya is a "polar" ice cap.

Thermistors were used to measure borehole temperatures at each drill site (Fig. 3). Ten-metre temperatures range from -15.2°C and -15.6°C at Sites 1 and 2, respectively, to -17.4°C at the 1991 summit shallow drill site. At Site 2 temperatures ranged from -15.6°C at 10 metres to -5.6°C at 200 metres, the depth at which dry hole drilling was suspended and fluid was added to the borehole. A basal temperature of -2.1°C was recorded 4 days after the completion of drilling and thus, may not be representative of the equilibrium temperature due to the presence of the fluid. Nevertheless, the profile for the Core 2 borehole demonstrates that the Guliya ice cap thermally resembles a "polar" ice cap.

Discussion

The major drill sites on the Guliya ice cap are located near the 400 millibar level in the Earth's atmosphere where high level plateau and mountain processes are neither well documented nor understood. The firn to ice transition at Sites 1 and 2 lies within the upper metre of the ice cap. This observation was unexpected, given the higher elevation and lower temperatures on Guliya compared to those encountered on other glaciers in the Q-T Plateau region. For example, the Dunde ice cap, which is lower in elevation (5325 m) and warmer (-7.1°C at 10 metres), has a firn to ice transition at 30 metres. Even the Gregoriev ice cap in the Tien Shan (42°N 78°E; 4660 m.a.s.l.) to the north, is warmer than the Dunde ice cap, but contains a firn to ice transition at 22 metres (Thompson *et al.*, 1993).

The annual accumulation varies across the Guliya ice cap. Accumulation was measured by three methods (1) accumulation stakes, (2) visible stratigraphy in pits and (3) insoluble particulate β and tritium horizons. Measurements from accumulation poles vary from 650 mm a^{-1} of snow (256 mm H_2O eq.) at the summit to 380 and 320 mm a^{-1} of snow (169 and 143 mm H_2O eq.) at Sites 1 and 2, respectively. These values are consistent with stake results (Ageta *et al.*, 1989) from 1985 to 1987 on the Chongce Ice Cap, 30 kilometres west of Guliya. Here accumulation ranges from 150 mm (H_2O eq.) at 6000 m.a.s.l. to 300 mm (H_2O) at the Chongce summit (6200 m.a.s.l.).

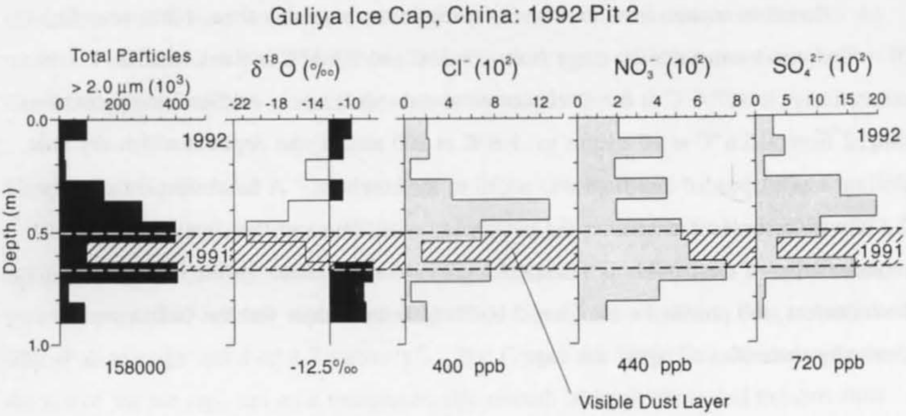

Figure 4: **The analyses of snow pit samples collected in 1992 at the Core 2 site, along with a major dust layer from 0.55 to 0.70 metres, indicate a 1991-92 layer thickness of ~500 mm of snow or 220 mm H_2O equivalent. Averages for each profile are shown.**

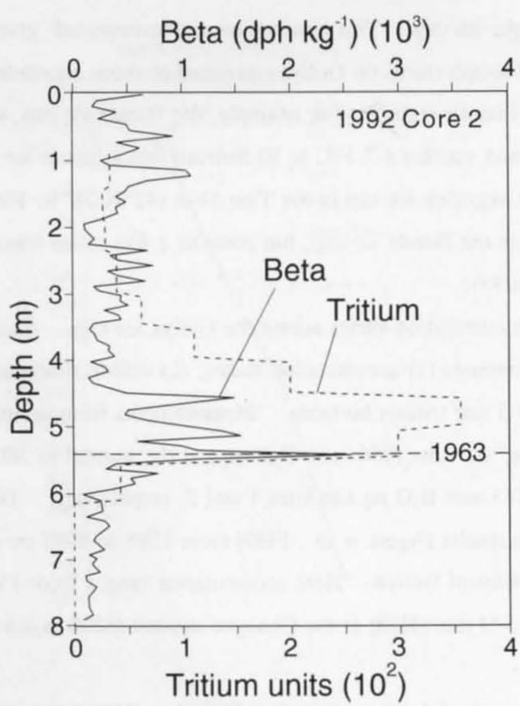

Figure 5: **Total Beta-radioactivity and tritium profiles from the Core 2 site clearly reveal the prominent 1963 marker location.**

A pit was excavated in 1992 adjacent to the accumulation pole at Site 2 where the 308.6 metre core was drilled. The visible dust layer between 0.55 and 0.70 m, coupled with the analyses of MPC, $\delta^{18}O$, and chemical species (Fig. 4), indicate a 1991-92 layer thickness of $\approx$500 mm of snow, or 220 mm H_2O eq. Figure 5 illustrates the insoluble particulate β and tritium profiles from a 34.5 metre core drilled at Site 2 in 1992. The highest activity occurs at 5.5 metres, and likely corresponds to the massive Soviet Arctic atmospheric thermonuclear testing of 1962-63. If correct, this indicates that A_n at Site 2 was 180 mm H_2O eq. from 1963 to 1992. The single year value (220 mm H_2O eq.) from the pit at Site 2 is consistent with the longer-term average determined from the Beta radioactivity profile from the last 29 years.

2000-Year Guliya Ice Core History

Based on the pit and surface studies discussed above the visible layers appear to be annual and may be used to date the core and extract annual layer thicknesses for perhaps the last 8000 years. This paper discusses only the most recent 2000 years.

The visible annual dust layers were used to reconstruct the net accumulation for the past 2000 years. Although layer thicknesses can be measured throughout both cores (Fig. 6), they do not directly represent the thickness of the originally deposited layer. The original layer is thinned and stretched as new snow accumulates and as the ice flows outward; therefore, the thinning of each layer must be estimated. This was done using a simple flow model discussed by Thompson *et al* (1985, 1989). The reconstructions presented here are particularly robust as the upper 132.1 metres of the core comprise less than one half of the total ice thickness. Thus, this portion of the core sits well above the bed and should be free of problems associated with basal topography and potentially contorted flow at depth.

The proxy reconstruction provides the first glimpse at the history of A_n at high elevations in far western China. The A_n records from Guliya and Dunde are compared (Fig. 7) with the historical wetness/dryness index for the eastern half of China (Zhang, 1981) since A.D. 1500. The low-frequency trends which are fairly consistent between the two ice core records are out of phase with those in the lower elevations of eastern China. Generally, wetter conditions on the Q-T Plateau from A.D. 1500 to 1700 and during the 20th century are contemporaneous with drier conditions in eastern China (Domrös and Gongbing, 1988; Wang and Zhang, 1992), suggesting an anti-phase

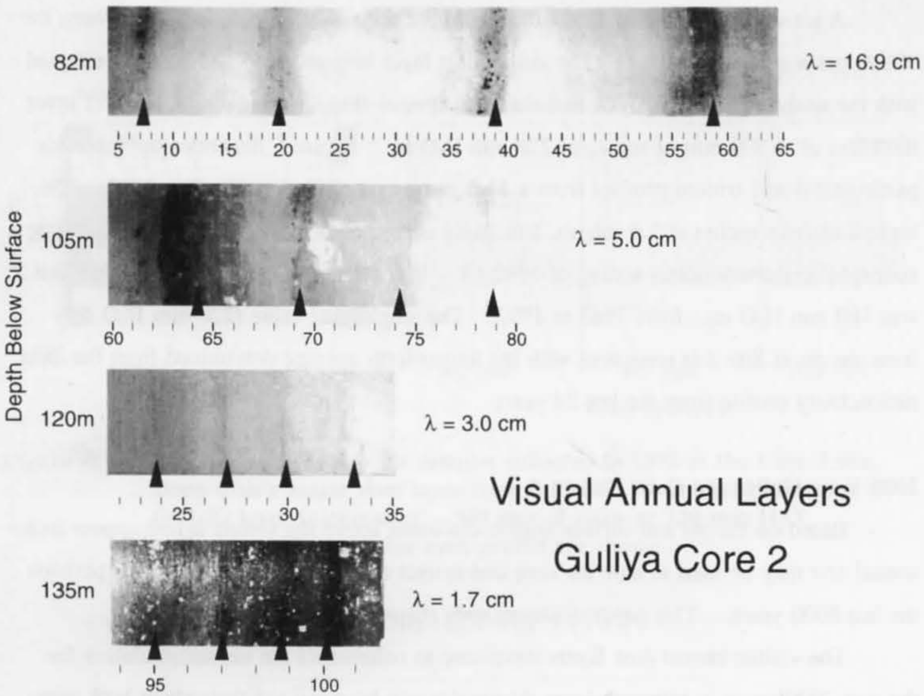

Figure 6. **Four representative core sections of the Guliya Core 2 show the distinct dry season dust layers (triangles) used for dating. Average thicknesses (λ) of these annual layers are shown, as is the layer thinning with depth.**

relationship in the lower frequencies of the precipitation histories between the high Q-T Plateau and the eastern lowlands of China. Analyses of rainfall pattern during the 17th century (Zhang and Crowley, 1989) indicate that dry conditions were prevalent primarily in northern and western China. They suggested that this pattern might reflect suppression of summer monsoon development, possibly as a result of expanded Eurasian snowcover (Dey *et al.*, 1985; Barnett *et al.*, 1988). The southeast and southwest monsoon systems are linked, but not in a simple way (Barry and Chorley, 1992: p. 247; Ramage, 1971: p. 186, 238).

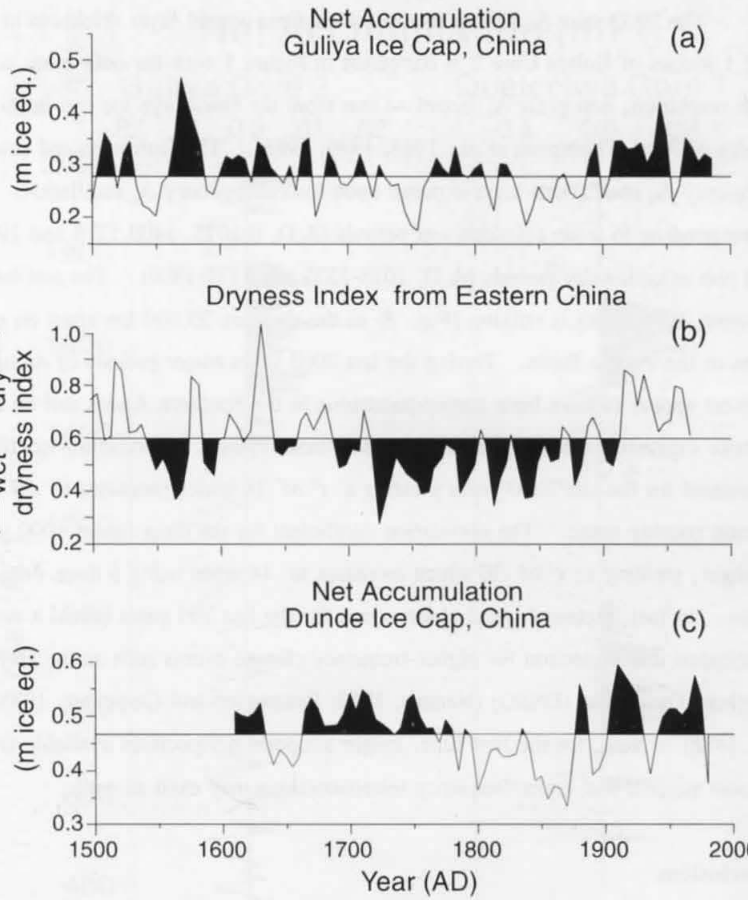

Figure 7: **Net accumulation since AD 1500 on Guliya (A) and Dunde (C) are shown with the historical dryness index from eastern China (B) from Zhang (1981). Drier conditions on Guliya tend to be associated with wetter conditions in eastern China. The ice core annual accumulation data were treated identically to Zhang's dust indices; that is, 10-year running means were calculated and every fifth point was plotted. The dryness index is depicted by (I_D) = 2D/N, where D is the number of stations with a wetness/dryness grade of 4 or 5 and N is the total number of stations considered. The "Yearly Charts" were used to compile the data set of 100 stations in eastern China (see Wang and Zhang, 1992: p. 303).**

The 2000-year A_n history reconstructed from annual layer thickness in the upper 132.1 metres of Guliya Core 2 is compared in Figure 8 with the only other comparable high resolution, non-polar A_n record — that from the Quelccaya ice cap in the southern Andes of Peru (Thompson *et al.*, 1985; 1986; 1988). The Guliya record reveals high-frequency A_n oscillations superimposed upon lower-frequency A_n oscillations corresponding to three extended wet periods (A.D. 0-1075, 1400-1775 and 1900-present) and two extended dry periods (A.D. 1075-1375 and 1775-1900). The similarity between A_n histories is striking (Fig. 8) as the sites are 20,000 km apart on opposite sides of the Pacific Basin. During the last 2000 years major periods of drought and wetness appear to have been contemporaneous in the Southern Andes and on the Tibetan Plateau suggesting a teleconnection between these regions. Correlation coefficient were calculated for the last 2000 years yielding a r^2 of .16 which increases to .27 using a three decade running mean. The correlation coefficient for the most recent 1000 years is stronger, yielding an r^2 of .30 which increases to .44 when using a three decade running mean. In fact, meteorological observations for the last 100 years reveal a well established teleconnection for higher-frequency climate events such as the El Niño-Southern Oscillation (ENSO) (Namais, 1963; Rasmusson and Carpenter, 1983; Barnett *et al.*, 1988). Now, for the first time, longer temporal perspectives available from ice core records suggest that lower-frequency teleconnections may exist as well.

Conclusions

Analyses of the ice cores from the Guliya ice cap provide the first high resolution, multi-proxy climate history from the far western Kunluns of China. This information should prove invaluable in the study of both regional and global climatic and environmental change on time scales of decades to millennia. A comparison with the only other comparable high resolution, non polar A_n record, that from the Quelccaya ice cap in the southern Andes of Peru, demonstrates a striking similarity between these A_n histories at sites which were 20,000 km apart. During the periods of overlap for the last 2000 years major periods of drought and wetness appear to have been contemporaneous in the Southern Andes and on the Tibetan Plateau, suggesting a low frequency teleconnection between these regions.

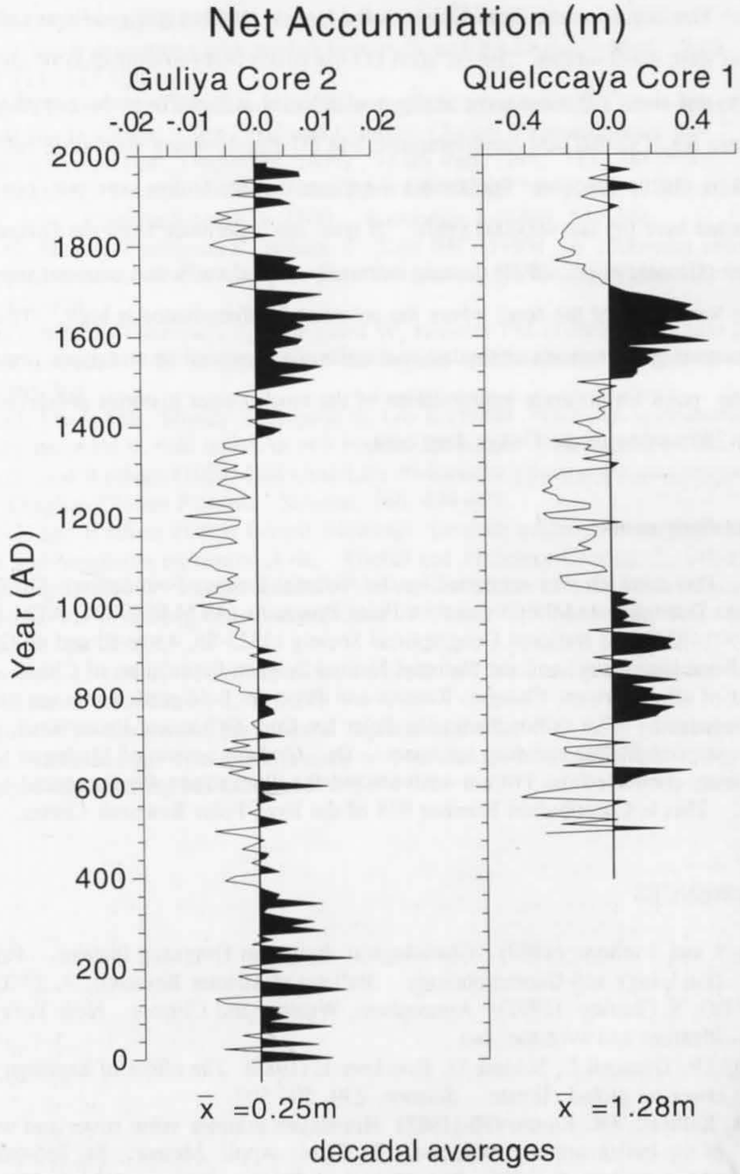

Figure 8: The 2000-year record of net accumulation (as decadal averages) on Guliya reveals contemporaneous trends with net accumulation on Quelccaya ice cap in Peru.

The 308.6 m core from Guliya is the longest ice core retrieved from an elevation greater than 4000 metres. Based upon (1) our preliminary examination of air bubbles and crystal sizes; (2) subsequent analyses of selected sections over the complete length of the core for $\delta^{18}O$ and dust concentrations; and (3) a preliminary time scale calculation based on visible dust layer thicknesses it appears that the Guliya core may contain ice deposited over the last 400,000 years. If true, the experience from the Greenland GISP II core (Grootes *et al.*, 1993) dictates extremely careful study and cautious interpretation of the lower part of the core, where the potential for disturbance is high. Thus, understanding the records of the last two millennia presented in this paper provides a starting point for accurate interpretation of the much longer histories preserved in the lower 200 metres of the Guliya deep core.

Acknowledgments

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