A 1000 year climate ice-core record from the Guliya ice cap, China: its relationship to global climate variability

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ABSTRACT. In 1992, an American–Chinese expedition successfully recovered three ice cores (308.6, 93.2 and 34.5 m) from the Guliya ice cap (summit 6710 m a.s.l.) in the far western Kunlun on the Qinghai–Tibetan Plateau, China. Guliya resembles a "polar" ice cap with 10 m, 200 m and basal temperatures of −15.6°, −5.9° and −2.1°C, respectively. The 308.6 m core to bedrock is the longest ice core retrieved from an elevation greater than 4000 m a.s.l. and provides the first ice-core history from the western side of the Qinghai Plateau. The Plateau experiences a pronounced annual precipitation cycle during which 70–80% of annual total precipitation falls in the summer monsoon season. This leads to a marked visible stratigraphy in the glaciers which allows accurate dating of the ice cores and reconstruction of the net mass accumulation.

This paper presents (1) the results of the geophysical program to determine ice thickness, ice flow and surface topography, (2) an assessment of net accumulation from stake measurements, snow pits and shallow core samples, and (3) the analyses of the upper 100 m of the 308.6 m core which provide a 1000 year history, including the "Little Ice Age", which is compared with Chinese historical records. Extended periods of positive accumulation on Guliya are closely contemporaneous with dry periods in eastern China. A trans-Pacific teleconnection is suggested by the strong temporal coherence between extended wet and dry phases on Guliya and on the Quelccaya ice cap, Peru.

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 ≈57 000 km² (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 ≈4.5 km and comprises an area half that of the U.S.A. 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 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 70–80% 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 and others, 1989, 1993; Thompson, 1992).

The Guliya ice cap is the highest, largest (> 200 km²) and thickest (308.6 m) subtropical ice cap yet investigated. It is part of an ice mass which extends over 8000 km² in the western Kunlun Mountains. In a cooperative effort, investigators from the Byrd Polar, Research Center (BPRC) of The Ohio State University (OSU), U.S.A., and the Lanzhou Institute of Glaciology and Geocryology (LIGG), China, undertook a 3 year field and laboratory program (1990–92) 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, 93.2 and 308.6 m in length. Annual accumulation is quite variable ranging from 140 to 260 mm w.e. among sites. The combination of relatively high (though variable) accumulation, 10 m borehole temperatures of −15.2° 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 1000 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 took place from September to October, after the monsoon season; the 1991 field program in May, prior to the onset of the monsoons; and the 1992 field program 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 from 103 m at the summit, to 200 m at site 1, to 310 m 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 m where drilling was aborted because an unconformity in the ice layers was observed at 83m. 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 m, and from 200 m to bedrock (308.6 m) a thermal drill was used with an alcohol/water mixture to ensure better core quality. No hiatus was observed in 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 micro-particle concentrations (MPC), oxygen-isotopic ratios ($\delta^{18}O$) and selected chemical species (Cl^-, NO_3^- and SO_4^{2-}). Core 2 was cut into 4300 samples for MPC and $\delta^{18}O$ and 3200 samples for chemical analyses. MPC was measured using two Coulter counters (Model TAII) equipped with 30 and 100 μm aperture tubes which provide particle concentrations in sizes ranging in diameter from 0.63 to 40 μm. The concentrations of specific chemical species were determined using a Dionex Model 2010i ion chromatograph (see Dai and others (1995) for methodological discussion). All samples (except $\delta^{18}O$) were analyzed in a class-100 clean room at BPRC, and $\delta^{18}O$ was measured with a Finnegan Mat

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*

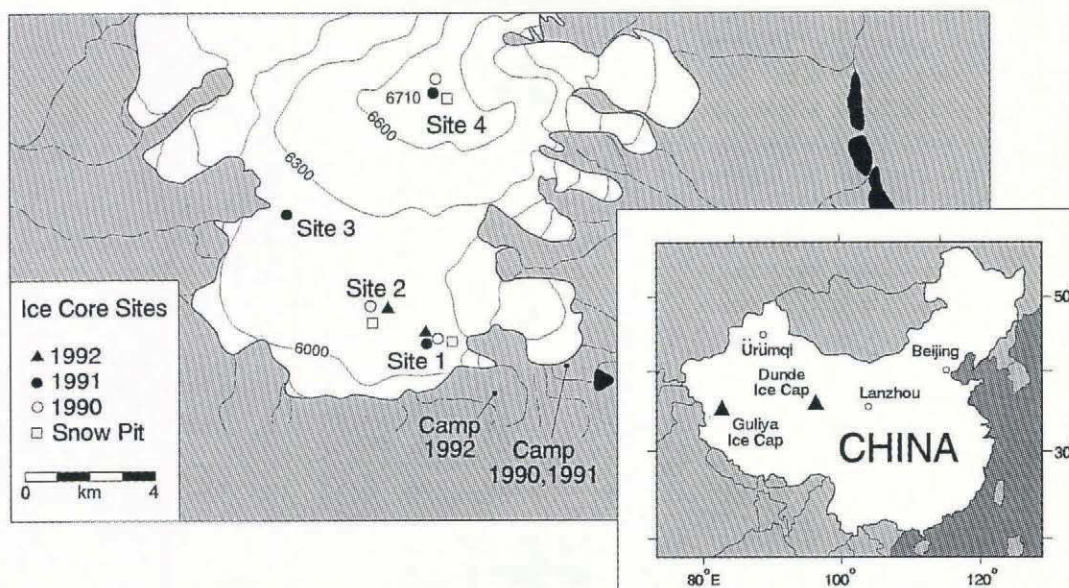| Site	Elevation	Nature of samples		
		Fall	Spring	Summer
	m	1990	1991	1992
1	6040	P(b) SC(b)	SC(i)	DC(b)
2	6200	SC(i)		P(i) DC(i)
3	6200		SC(b)	
Summit	6710	SC(i)	P(b) SC(b)	

Fig. 1. *Locations of the Guliya and Dunde ice caps, and of snow-pit and ice-coring sites on Guliya.*

Delta-E mass spectrometer. Finally, the upper 20 m of the 34.5 m core drilled at site 2 were analyzed with high temporal resolution for solid particulate beta radio-activity (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 south-southeast at an average speed of 4.8 m 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) containing the core 2 site, and along the C–D transect (Fig. 2c) connecting the core 2 and core 1 sites.

Thermistors were used to measure borehole tempera-tures at each drill site (Fig. 3). 10 m temperatures range from –15.2° 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 m to –5.6°C at 200 m, the depth where dry-hole drilling was suspended and fluid was added to the borehole. A basal temperature of –2.1°C was recorded four 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 mbar 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 meter 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 m), has a firn-to-ice transition at 30 m. 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 it contains a firn-to-ice transition at 22 m (Thompson and others, 1993).

The annual accumulation (A_n) 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 w.e.) at the summit to 380 and 320 mm a^{-1} (169 and 143 mm w.e.) at sites 1 and 2, respectively. These values are consistent with stake results (Ageta and others, 1989) from 1985 to 1987 on the
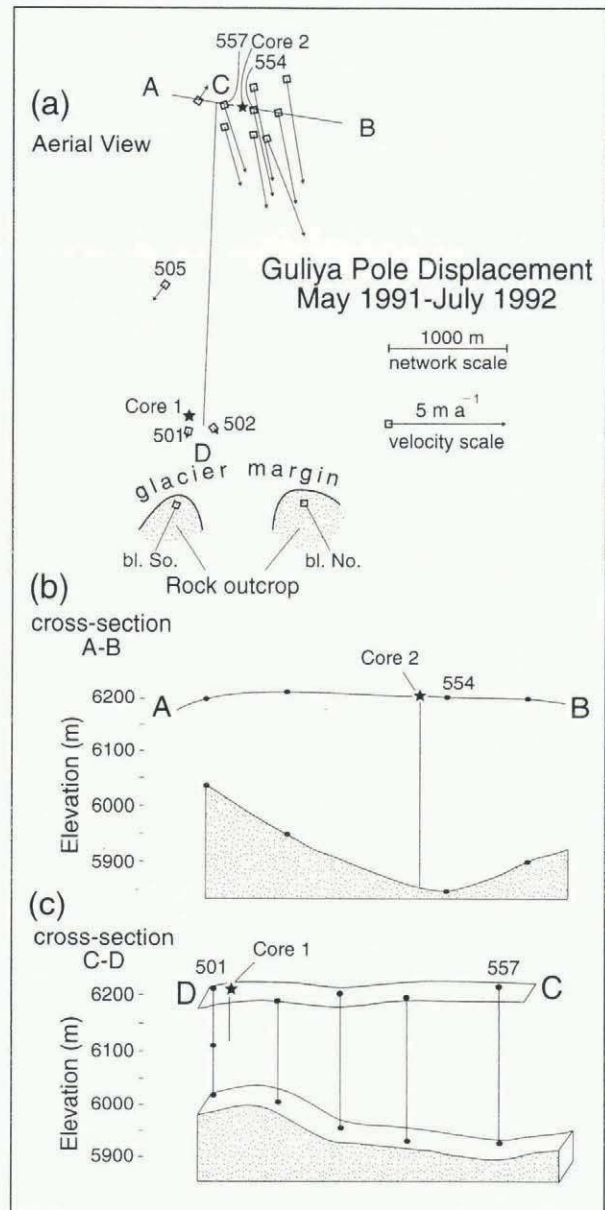

Fig. 2. (a) Aerial view of pole displacements from May 1991 to July 1992 for the core 1 and core 2 drill sites. Displacements were determined relative to bedrock base lines: south point (bl. So.) and north point (bl. No.). The ice-thickness profiles were measured during a short-pulse radar survey along (b) transect A–B through the core 2 drill site and along (c) transect C–D from the core 2 drill site to the core 1 drill site.

Chongce ice cap, 30 km west of Guliya. Here accumula-tion ranges from 150 mm w.e. at 6000 m to 300 mm w.e. at the Chongce summit (6200 m).

A pit was excavated in 1992 adjacent to the accumulation pole at site 2 where the 308.6 m 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 ≈500 mm of snow or 220 mm w.e. Figure 5 illustrates the insoluble particulate β and tritium profiles from a 34.5 m core drilled at site 2 in 1992. The highest activity occurs at 5.5 m, 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 w.e.

Temperature Profile (°C)
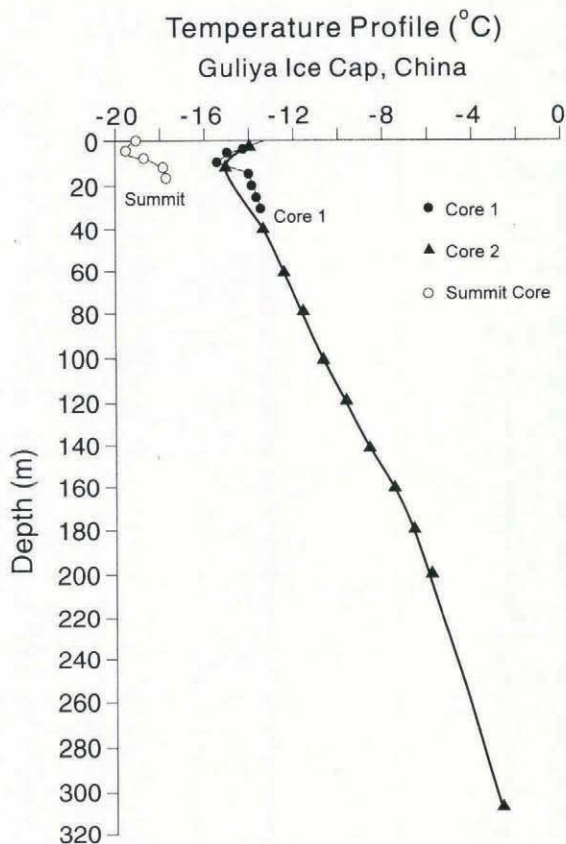### Guliya Ice Cap, China

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

Fig. 5. The total beta-radioactivity and tritium profiles from the core 2 site clearly reveal the prominent 1963 marker horizon.

last 8000 years. This paper discusses only the most recent 1000 years.

The visible annual dust layers were used to reconstruct the net accumulation for the past 1000 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 and others (1985, 1989). The reconstructions presented here are particularly robust as the upper 100 m of the core comprise only one-third of the total ice thickness. Thus, this part of the core sits well above the bed and should be free of problems associated with basal topography and potentially contorted flow at depth.

This proxy reconstruction provides the first glimpse of 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 1500 AD. The low-frequency trends which are fairly consistent between

from 1963 to 1992. The single-year value (220 mm w.e.) from the pit at site 2 is consistent with the longer-term average determined from the beta radioactivity profile for the last 29 years.

1000 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 the
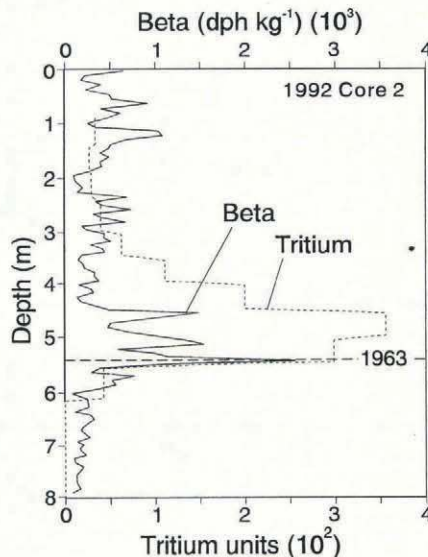
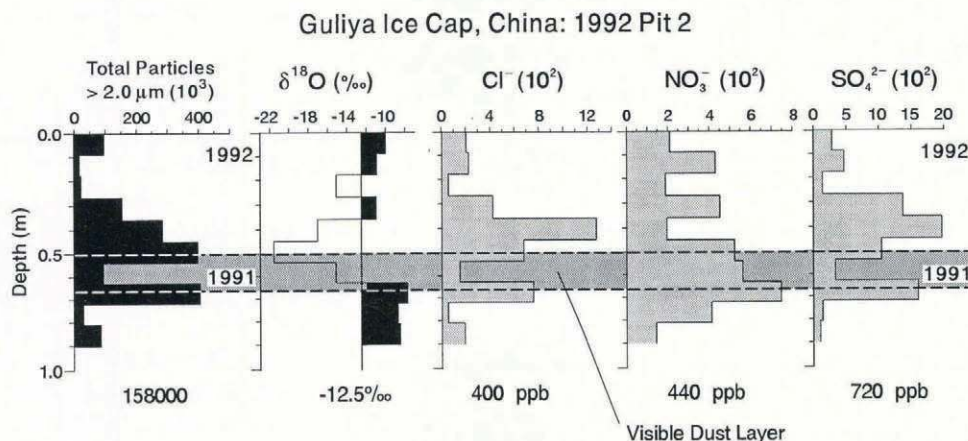### Guliya Ice Cap, China: 1992 Pit 2

Fig. 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 m, indicating a 1991/92 layer thickness of ≈500 mm of snow, or 220 mm w.e. Averages for each profile are shown.
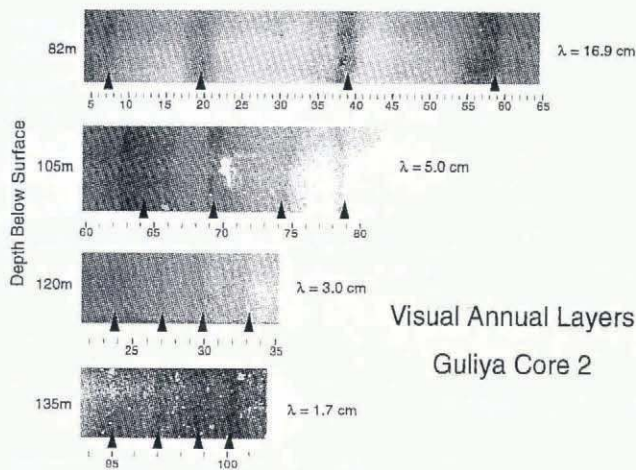
Fig. 6. *Four representative core sections of Guliya core 2 show the distinct dry-season dust layers (triangles) used for dating. Average thicknesses (λ) of these annual layers are shown as is the layer thinning with depth.*

Fig. 7. *Net accumulation since 1500 AD on (a) Guliya and (c) Dunde, with (b) the historical dryness index from eastern China 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 (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 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 1500 to 1700 AD 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 relationship in the lower frequencies of the precipitation histories between the high Q–T Plateau and the eastern lowlands of China. Analyses of rainfall patterns during the 17th century (Zhang and Crowley, 1989) indicate that dry conditions were prevalent primarily in northern and western China. They suggest that this pattern might reflect suppression of summer monsoon development, possibly as a result of expanded Eurasian snow cover (Dey and others, 1985; Barnett and others, 1988). The southeast and southwest monsoon systems are linked, but not in a simple way (Ramage, 1971, p. 186, 238; Barry and Chorley, 1992, p. 247).

The 1000 year A_n history reconstructed from annual layer thicknesses in the upper 100 m of Guliya core 2 is compared in Figure 8 with the only other comparable high-resolution, non-polar A_n record, that from Quelccaya ice cap in the southern Andes of Peru (Thompson and others, 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 (1000–1075 AD, 1400–1775 AD and 1900–present) and two extended dry periods (1075–1375 and 1775–1900 AD). The similarity between these 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 1000 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. 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 and others, 1988). Now, for the first time, longer temporal perspectives available from ice-core records suggest that lower-frequency teleconnections may exist as well.
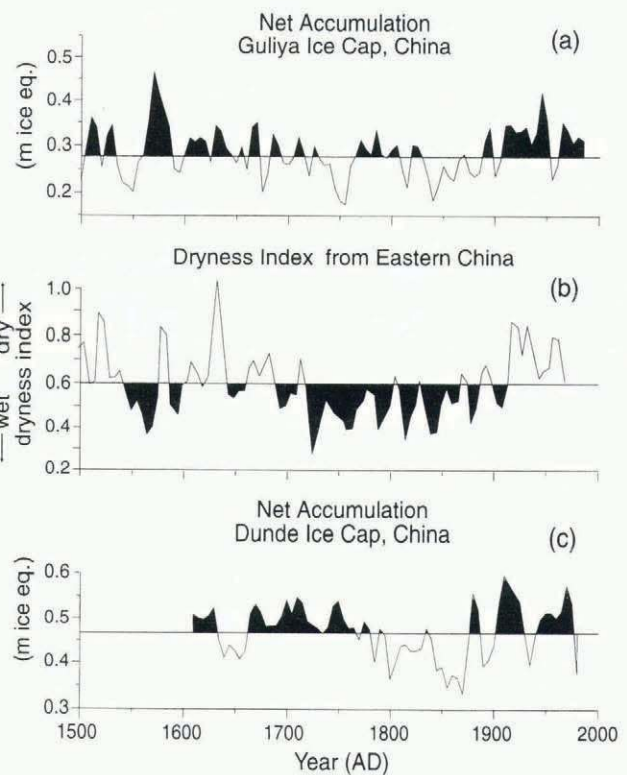
Additional environmental information for the last 1000 years is available from the Guliya ice cap. Figure 9 presents the decadal averages of MPC, $\delta^{18}O$, NO_3^-, SO_4^{2-} and Cl^-. The most negative $\delta^{18}O$ values (generally indicating lower temperatures) occur at the beginning of the current millennium. Thus, this record does not indicate the presence of the "Medieval Warm Epoch" (MWE) and supports the suggestion by Hughes and Diaz (1994) that the MWE was not global in extent. From 1300 to 1800 AD, contemporaneous with much of the "Little Ice Age" (LIA), $\delta^{18}O$ appears more enriched (suggesting warmer conditions) similar to the ice-core $\delta^{18}O$ histories from sites in the Antarctic Peninsula (Aristarain and others, 1986; Peel, 1992; Thompson and others, 1995) and at Siple Station at the base of the Peninsula (Mosley-Thompson, 1992). The major isotopically warmer and cooler periods are not synchronous for Dunde and Guliya although both records show a persistence of warmer conditions since the 1940s (see Yao and Thompson, 1992; Lin and others, 1995).

There are two major periods of enhanced atmospheric dust concentrations, 1430–1550 and 1680–1900 AD, with shorter events (a few decades or less) centered on 1150, 1300 and 1600 AD as well as from 1950 to the present.
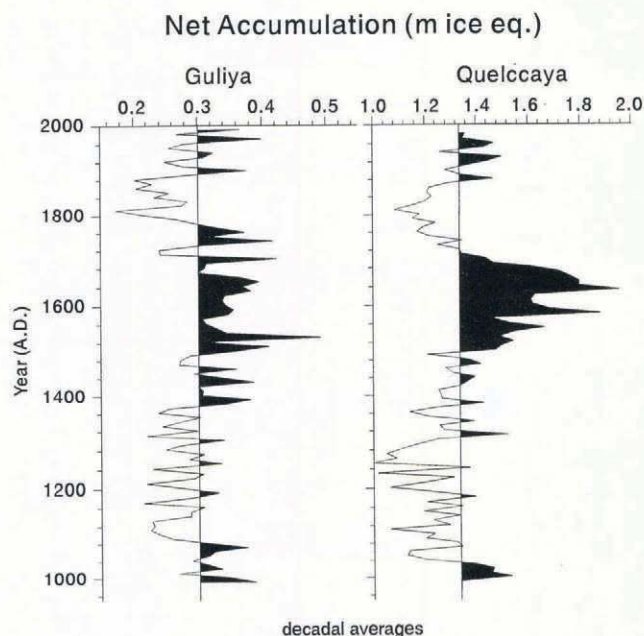
Net Accumulation (m ice eq.)

Fig. 8. The 1000 year record of net accumulation (as decadal averages) on Guliya reveals contemporaneous trends with net accumulation on the Quelccaya ice cap, Peru.

decades long), contemporaneous concentration peaks around 1590 and 1710 AD. A second peak around 1620 occurs in NO_3^- and Cl^-, but not in SO_4^{2-}. The major peaks in soluble anions occur when insoluble dust levels are low, suggesting that the soluble fraction of the aerosols has a different source from the insoluble fraction. In general, the more negative $\delta^{18}O$ values from 1000 to 1300 AD are associated with higher concentrations of NO_3^-, SO_4^{2-} and Cl^- and lower concentrations of insoluble dust.

CONCLUSIONS

Analyses of the ice cores from Guliya ice cap provide the first high-resolution, multi-proxy climate history from the far western Kunlun, 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. The $\delta^{18}O$ records from the Dunde and Guliya ice caps in China and the Gregoriev ice cap reveal a significant enrichment in ^{18}O (indicating warming) over the past few decades (Thompson and others, 1993; Lin and others, 1995). Unlike the results from Dunde, the Guliya $\delta^{18}O$ values for recent decades are not unprecedented (unique) in the last 1000 years. However, the recent warming over the Q–T Plateau is consistent with model results (e.g. Hansen and others, 1988) suggesting that the central region of the Asian continent may be one of the first places to exhibit an unambiguous signal of the anticipated "greenhouse warming" as it is far from the mitigating influences of oceans. More confident projections about future climate changes require better description and understanding of the sources of past natural climatic variance on the same time-scales (Bradley and Jones, 1993). Certainly, the
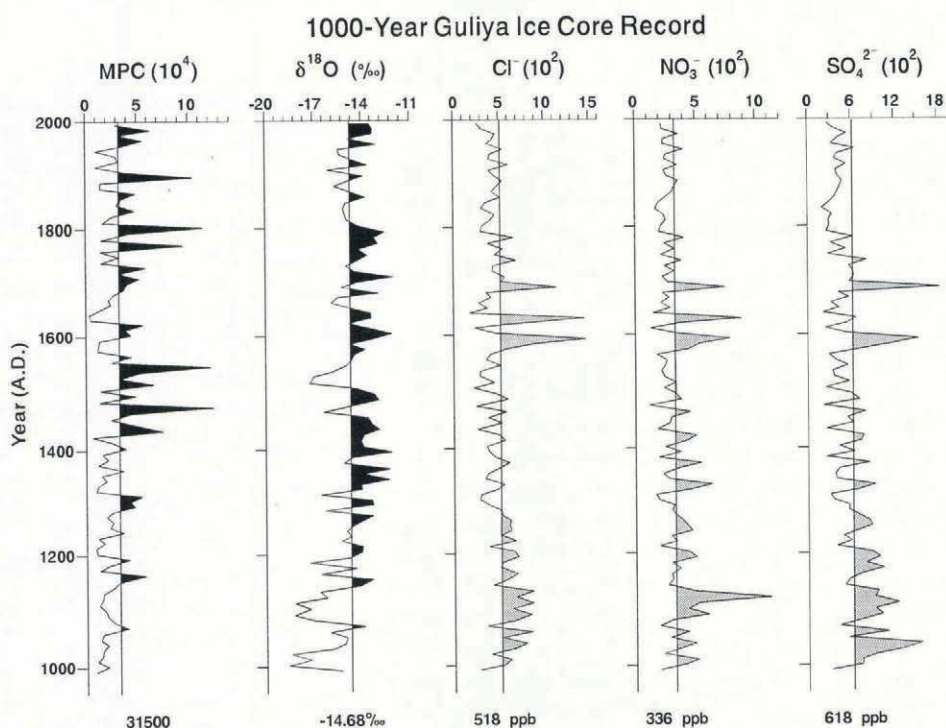
Most of the LIA period is characterized by elevated dust concentrations, consistent with the historical dust-fall records of Zhang (1984) and with ice-core dust records from the South Pole (Mosley-Thompson and others, 1993) and Quelccaya ice cap (Thompson, 1992). The NO_3^-, SO_4^{2-} and Cl^- records show no long-term trends over the millennium, suggesting no anthropogenic contribution in the snow at this high-elevation site. The fluxes of NO_3^-, SO_4^{2-} and Cl^- are consistently high from 1000 to 1300 AD and remain consistently low thereafter to the present. All three anions exhibit brief (one or two

1000-Year Guliya Ice Core Record

Fig. 9. Decadal averages of MPC (microparticle concentrations (diameters $\geq 2.0\,\mu m$)) per milliliter sample, $\delta^{18}O$, and concentrations of Cl^-, NO_3^- and SO_4^{2-} in ppb, along with their respective averages for the last 1000 years on the Guliya ice cap. Averages for each profile are shown.

potential impact of global warming on the strength of the monsoon system could be significant and warrants investigation (Meehl and Washington, 1993).

The 308.6 m core from Guliya is the longest ice core retrieved from an elevation greater than 4000 m. 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 concentration, 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 so, the experience from the Greenland GISP2 core (Grootes and others, 1993) dictates extremely careful study and cautious interpretation of the lower part of the core, as the potential for disturbance is high in the lower part of the core. Thus, understanding the records of the last millennium presented in this paper provides a starting-point for accurate interpretation of the much longer histories preserved in the lower 200 m of the Guliya deep core.

ACKNOWLEDGEMENTS

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