ICE CORE RECORDS OF RECENT CLIMATIC VARIABILITY : GRIGORIEV AND IT-TISH ICE CAPS IN CENTRAL TIEN SHAN, CENTRAL ASIA

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ABSTRACT. Ice cores, 16.5 and 20-meters in length, were recovered under the auspices of a cooperative USSR — US glaciological research program on the Grigoriev and It-Tish ice caps in the Tien Shan, Central Asia. These have been analyzed for microparticle concentrations and size distributions, stable isotopic ratios ($\delta^{18}O$ and δD), selected chemical species, and Beta radioactivity. The $\delta^{18}O$ records reveal an enrichment of ~1‰ during the last 50 years, suggesting warmer temperatures. Concurrently, surface air temperatures at the meteorological station Tien Shan (elevation 3614 m) have increased ~0.5°C. Temperatures at 20-m depth in the Grigoriev ice cap have increased 2.2°C from -4.2°C in 1962, to -2°C in 1990. This regional warming is consistent with current global climate model projections for Central Asia under doubled atmospheric CO_2 concentration simulations. Finally, initial measurements of dust concentrations, $\delta^{18}O$, and δD from the nearby It-Tish ice cap margin strongly suggest the presence of glacial/interglacial stage ice near the bottom. Collectively, these data indicate that these high elevation, low latitude ice caps in Central Asia contain very long paleoenvironmental histories, which soon might be lost if the current warming trend continues in this region.

Introduction

The first cooperative glaciological research program between the former USSR and the US on ice caps in the Soviet Tien Shan and the Pamirs was conducted during July and August, 1990 under the auspices of the National Science Foundation's Program for US — USSR Cooperation in the Field of Basic Scientific Research. The Byrd Polar Research Center of the Ohio State University and the Institute of Geography in Moscow initiated an exploratory investigation of these ice caps to determine if meteorological and glaciological conditions in Central Asia are conducive for the preservation of a long, high-resolution (annual) paleoenvironmental history. The chemical and physical properties of the atmosphere preserved in such ice properties as microparticle (dust) concentrations, $\delta^{18}O$, δD, and various chemical species should provide a unique and otherwise unavailable paleoenvironmental history for Central Asia. To this end reconnaissance programs on the Grigoriev and It-Tish ice caps (42°N, 78°E; summit elevation 4660 m, Fig. 1) in the Tien Shan and the Pamir Firn Plateau (38°N, 73°E; summit elevation 6300 m) were conducted during the summer of 1990.

The central effort was to determine the basic glaciological and physiographic character of the Grigoriev ice cap in the Tien Shan. Using a short-pulse radar, ice thicknesses were measured at 24 sites (Fig. 1). The bedrock is relatively smooth with ice thicknesses ranging from 58 meters near the margin to 110 meters near the summit. Ice temperature at the summit was -2°C at a borehole depth of 20 meters. Figure 2 presents the density, visible stratigraphy, and temperature profiles measured in the upper 20 meters of the Grigoriev ice cap. The density is highly variable because the melting and refreezing which occurs on this ice cap produces high-density ice layers near the surface. The ice core stratigraphy is indicated in the center of the figure. On the right, temperature profiles are presented for pits and boreholes from the 1990 expedition and boreholes measured during the 1962 and 1987 Soviet expeditions.

Samples were collected from a number of snow pits and at the summit (elevation 4660 m) two ice cores (cores 1 and 2) were drilled to 20 and 16.5 meters, respectively (see Fig. 1). To test the feasibility of returning frozen cores from this remote region, 22-meters of ice core were transported successfully to the cold room facilities at the Ohio State University. Core 1 and pit samples were returned as bottled water samples.

Results

The analyses of microparticle concentrations (MPC), $\delta^{18}O$, liquid conductivity, and concentrations of Cl^-, SO_4^{2-}, and NO_3^- in cores 1 and 2 from the summit of Grigoriev ice cap are illustrated in Figures 3 and 4, respectively. The presence of original annual variations in both insoluble dust and $\delta^{18}O$ is difficult to discern due to partial alteration by melt water percolation and isotopic diffusion during the warm season. The presence of visible dust layers in the cores made preliminary dating possible as they were drilled. The final time scales were estimated

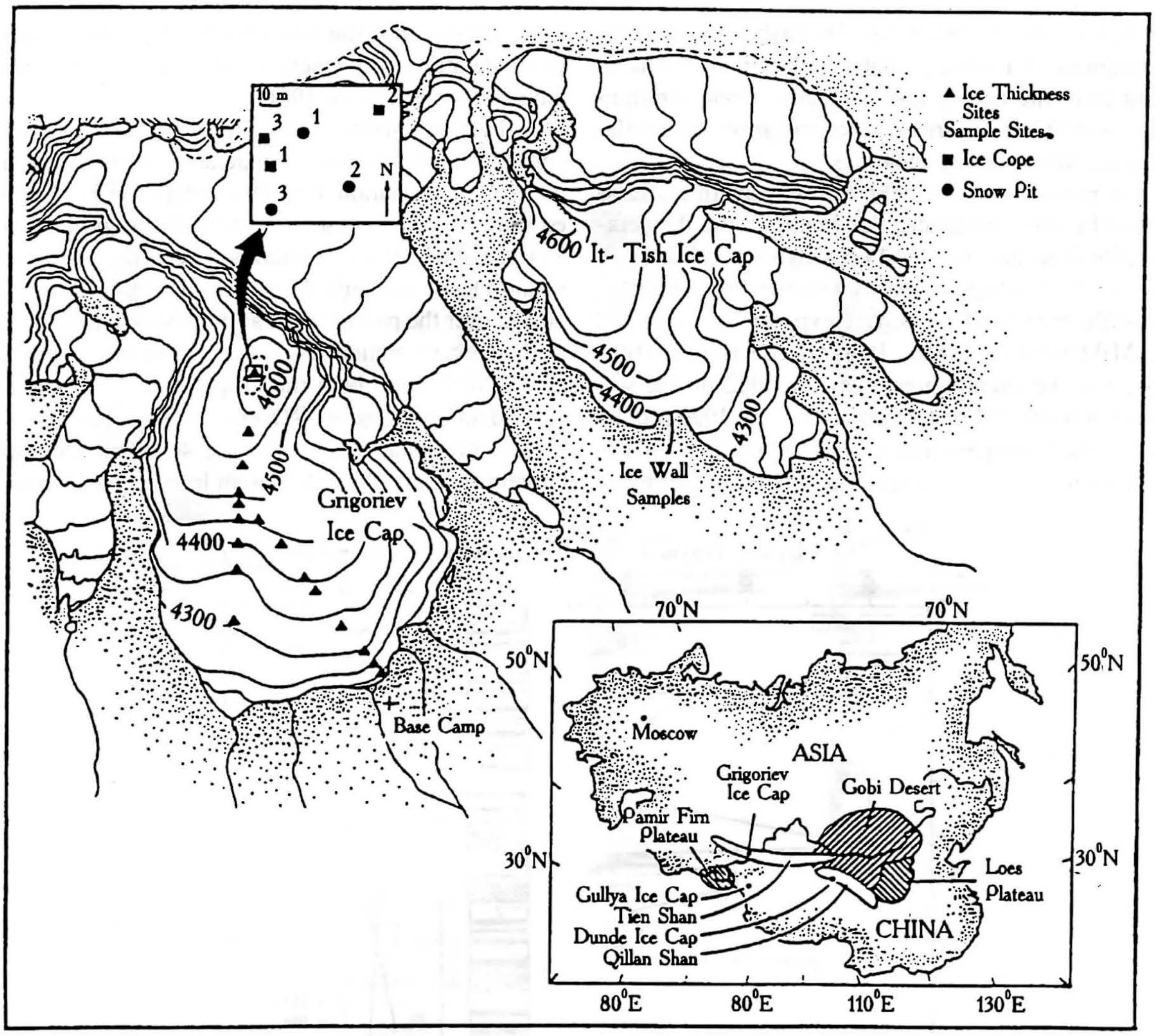

Fig. 1. The locations of the Grigoriev and It-Tish ice caps in Central Asia are shown along with ice cap topography and the locations where ice thicknesses were determined and samples were collected.

primarily from the visible dust layers with limited use of seasonal variations in both $\delta^{18}O$ and dust concentrations. The time scale was independently verified by the Beta (β) radioactivity peak at 11.9 meters in core 1, associated with the 1961 and 1962 Soviet thermonuclear tests. Calculations using this known time-stratigraphic horizon gives an average annual net accumulation of 330 mm (H_2O equivalent) for the last 28 years on Grigoriev ice cap. This net accumulation rate is comparable to that of 310 mm measured over the last 27 years at the meteorological station Tian Shan (elevation 3614 m) located 6 km west of the ice cap. Core 1 (Figure 3) contains a 50-year record, while core 2 (Figure 4) contains 40 years. Core 2 was analyzed in identical fashion to core 1, and the measured constituents are remarkably similar in both cores.

The $\delta^{18}O$ records from both cores (Figures 3 and 4) show a significant enrichment (less negative $\delta^{18}O$) in the upper 6.5 m, probably reflective of recent atmospheric warming. In addition the partial loss of seasonal $\delta^{18}O$ variation, especially in near-surface layers, is due to both isotopic diffusion and meltwater percolation, which further suggests recent warming in the vicinity of Grigoriev ice cap. A significant amount of melting and runoff were observed during the 1990 summer season, as well as a few large pools of standing water on flat areas of the ice cap below 4500-m elevation.

Background dust concentrations have increased since the mid-1970s (upper 6 m) which is consistent with the recently observed increase in aerosol measurements at four meteorological stations in the Pamir region of Tadjikistan (Finaev, 1988). The major inorganic chemical species present in the cores are NO_3^-, SO_4^{2-}, NH_4^+, and Ca^{2+}, while other species such as Na^+, Cl^- and Mg^{2+} occur in lower concentrations. Liquid conductivity (*LC*) variations appear most closely related with Cl^- concentration variations. Note in Figures 3 and 4 that Cl^-, and hence *LC*, have decreased since the late 1960s. Interesting differences and similarities are evident when the concentrations of chemical species on Grigoriev are compared with those measured in cores from the Dunde ice cap, China (Thompson et al., 1989; 1990) (38°06'N; 96°24'E; elevation: 5325 m) located on the northeastern margin of the Qinghai-Tibetan Plateau. While the same soluble chemical species are found in Grigoriev and Dunde ice caps, the overall concentrations of dissolved material are lower in Grigoriev than in Dunde. Especially significant are the lower average concentrations of Na^+ and Cl^- (≈17 of μequivalent e^{-1}) compared to ≈25 in μequivalent e^{-1} at Dunde ice cap. The higher Na^+ and Cl^- concentrations at Dunde probably reflect a large flux of salt dust from the nearby Qaidam Basin. Concentrations of NO_3^- and SO_4^{2-} in Grigoriev ice cap snow are similar to those in Dunde ice cap snow.

The presence of a recent warming in this area is supported by other evidence. For example, the temperature profile (Fig. 5a) measured on Grigoriev indicates an increase of 2.2°*C* when compared with the 1962 temperature profile measured by Soviet expeditions (Dikikh, 1965; Mikhalenko, 1989). In fact, the temperature increase may be slightly greater as the 1962 profile was measured at a site 200 meters lower than the 1990 profile. These borehole temperatures cannot be used as proxies for air temperatures. On glaciers where refreezing of meltwater occurs, as is the case on the Grigoriev ice cap, 20-m temperatures will generally exceed the mean annual air temperature (Paterson, 1981).

Further evidence of recent warming in this region comes from near-surface temperature observations at the meteorological station Tien Shan (elevation 3614 m; nearest station to the Grigoriev ice cap) and from the meteorological station Delingha (elevation 3200 m; nearest station to the Dunde ice cap). Figure 5b illustrates a warming of ~0.5°C over the past 60 years at the USSR station and ~1°*C* at the Chinese station. Figure 5c shows the decadal averages of $\delta^{18}O$ from both the Grigoriev and the Dunde ice caps, demonstrating an ^{18}O enrichment of approximately 1‰ in precipitation over the last 40 years. This isotopic enrichment generally indicates an increase in condensation

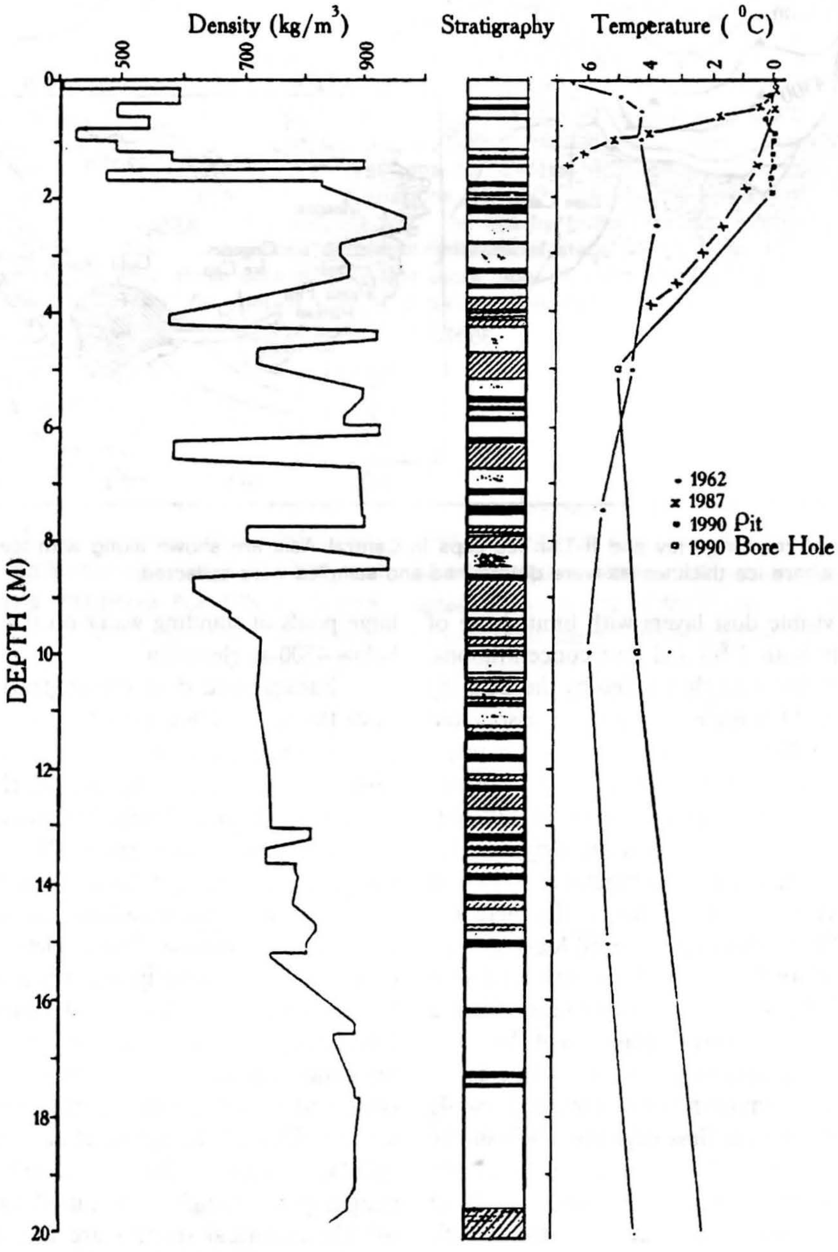

Fig. 2. Grigoriev ice cap. The 20-meter density profile in Core 1 (1990) is shown on the left and the corresponding ice core stratigraphy is illustrated in the middle. The symbols for stratigraphic features are as follows: black (bubble free ice layers); white (snow and/or firn); gray (ice with bubbles); diagonal lines (visible dust layers). On the right are borehole and pit temperatures measured in 1990 (this work) and during previous expeditions in 1962 and 1987

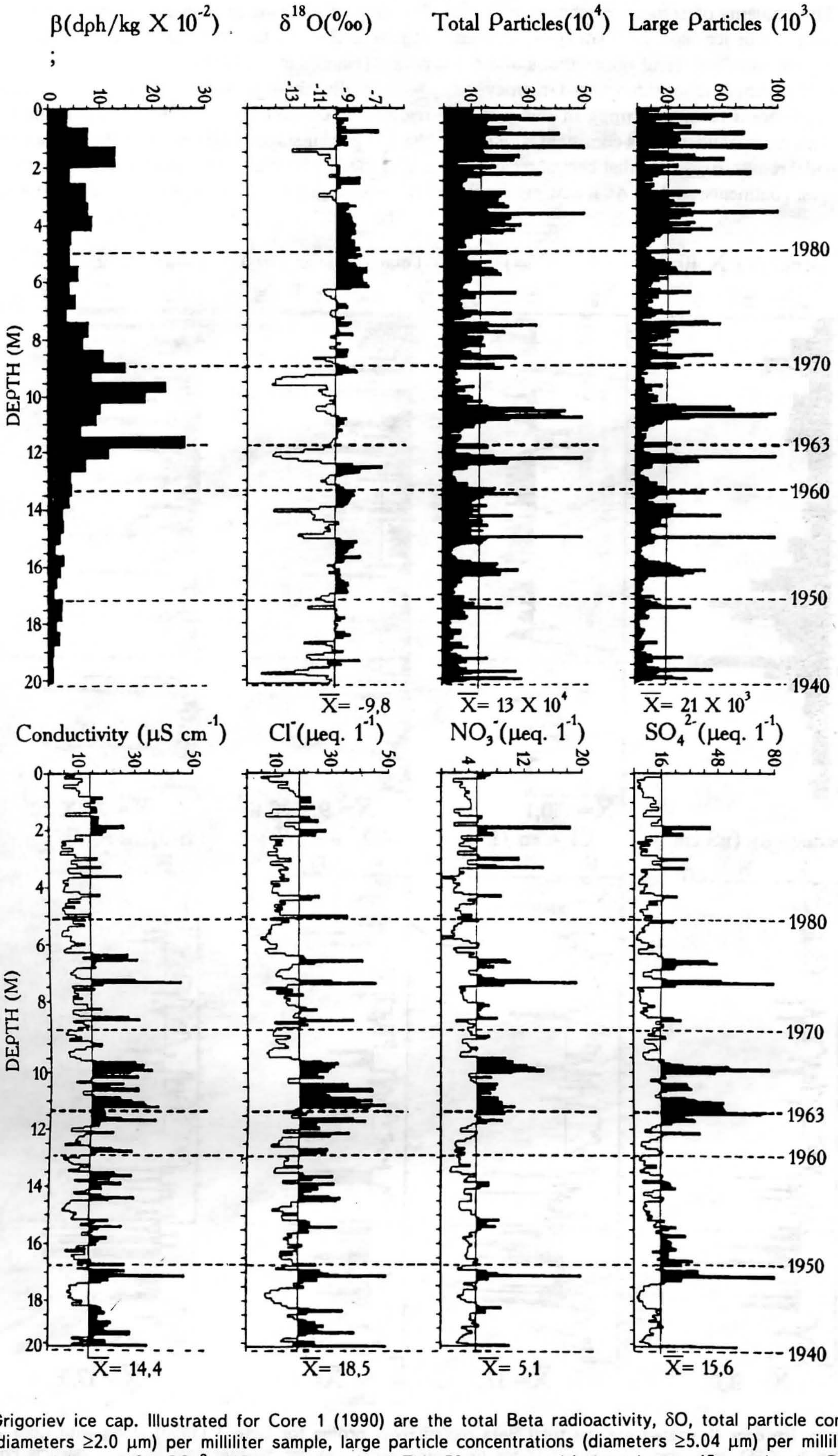

Fig. 3. Grigoriev ice cap. Illustrated for Core 1 (1990) are the total Beta radioactivity, δO, total particle concentrations (diameters ≥2.0 μm) per milliliter sample, large particle concentrations (diameters ≥5.04 μm) per milliliter sample, conductivity and Cl^-, SO_4^{2-}, NO_3^- concentrations. This 50 year record is based upon 45 samples for Beta and the analysis of 244 samples for each of the other constituents.

temperature. The similarity of isotopic enrichment on both the Grigoriev and Dunde ice caps, 1700 km apart, coupled with both the local meteorological observations and the 2.2°C increase in borehole temperatures on Grigoriev ice cap, strongly indicate a recent warming in this part of Central Asia. This regional warming is consistent with general climate model results, suggesting that central regions of the Earth's largest continents, such as Asia, may exhibit the first signs of warming in response to recent anthropogenic activity as they are far from the mitigating influence of the oceans (Hansen et al., 1988).

Finally, there is evidence that some ice caps in this region may contain very long records extending back into the last glacial stage (*LGS*) prior to the Holocene warming of the last 10,000 years. Photo 1 illustrates the marked visible stratigraphy along a vertical wall of the southern

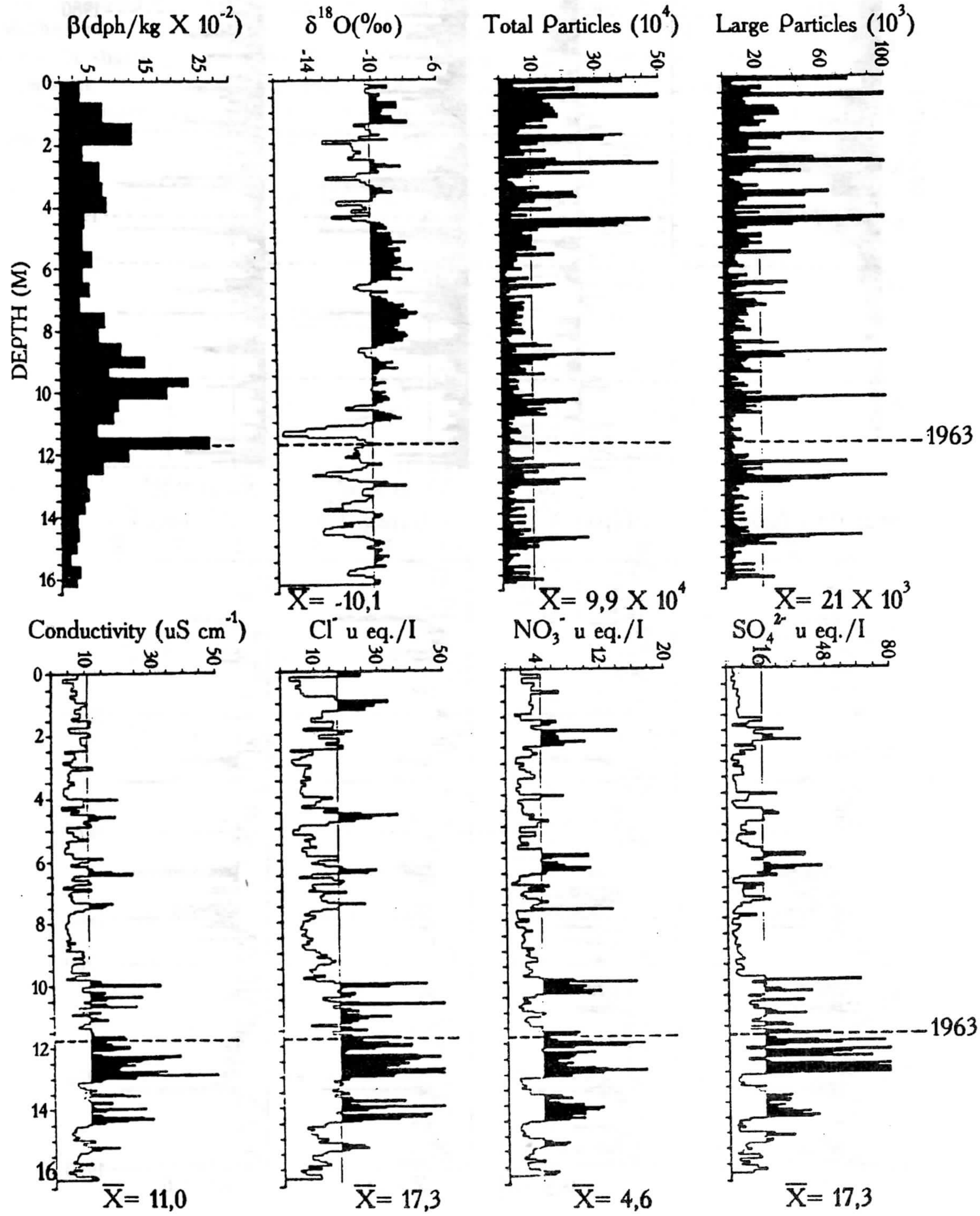

Fig. 4. Grigoriev ice cap. Illustrated are the total Beta radioactivity profile for Core 1 (1990) along with Core 2 (1990) profiles for $\delta^{18}O$, total particle concentrations (diameters ≥2.0 μm) per milliliter sample, large particle concentrations (diameters ≥5.04 μm) per milliliter sample, and Cl^-, SO_4^{2-}, NO_3^- concentrations. This 40 year record is based on the analysis of 205 samples for each core constituent

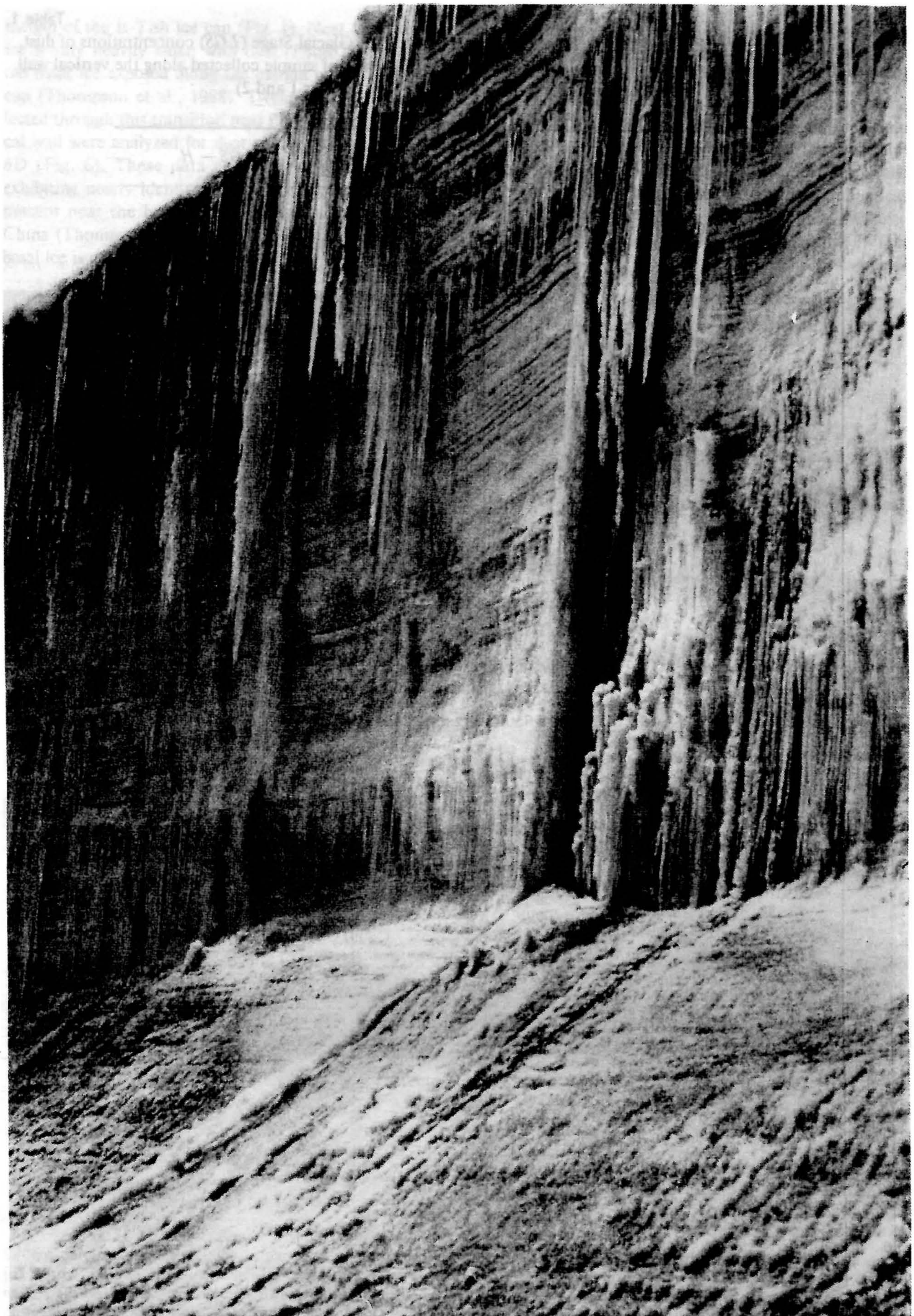

Photo 1. Evident here is marked visible stratigraphy along a vertical wall of the southern margin of the It-Tish ice cap

Table 1

The ratio (*LGS/H*) and difference (*LGS — H*) of Holocene (*H*) and Last Glacial Stage (*LGS*) concentrations of dust, soluble impurities and isotopic ratio as calculated for the 9-meter sequence of sample collected along the vertical wall of the margin of the It-Tish ice cap, USSR (Photos 1 and 2)

Parameter	*H*	*LGS*	*LGS/H*	Δ *LGS — H*
Dust(10^3) (dia≥2.01μm)	346.	7806.	22.6	7460.
Dust(10^3) (dia≥5.0μm)	63.	1803.	28.4	1740.
Conductivity (μS cm^{-1})	25.1	49.6	1.98	24.50
$\delta^{18}O$ (‰)	-11.25	-12.19	1.08	-0.94
δD (‰)	-71.30	-82.82	1.16	-11.52
δd (excess)	18.57	14.74	0.79	-3.83

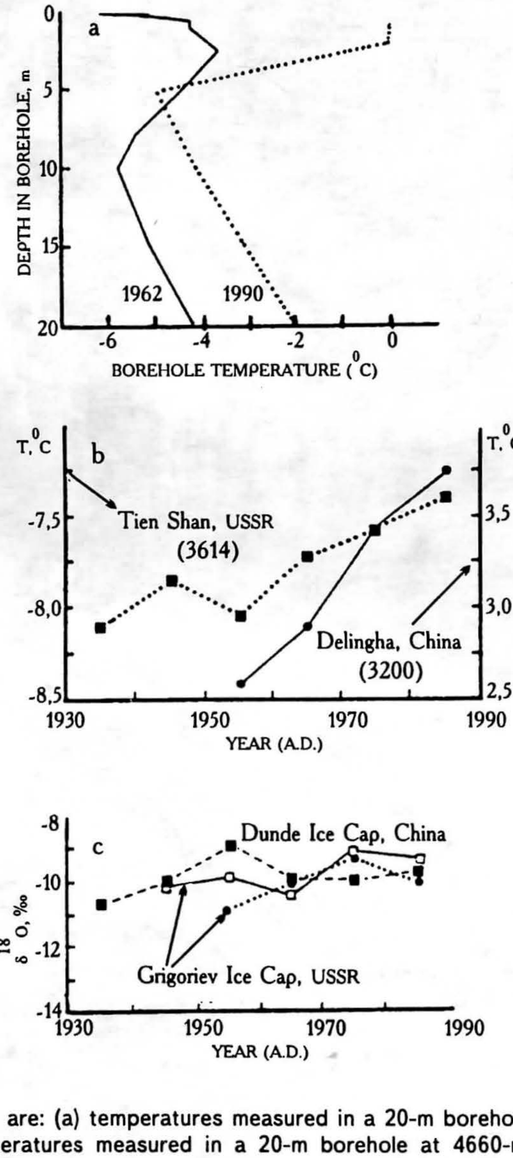

Fig. 5. Grigoriev ice cap. Illustrated are: (a) temperatures measured in a 20-m borehole at 4400 m elevation during a 1962 Soviet expedition and temperatures measured in a 20-m borehole at 4660-m elevation in 1990 (this work). (b) Decadal averages of mean annual surface temperatures measured at the USSR meteorological station Tien Shan (elevation 3614 m), 6 km from Grigoriev ice cap and at the Chinese meteorological station Delingha (elevation 3200 m), 100 km from Dunde ice cap. (c) Decadally averaged $\delta^{18}O$ values in two cores from the summit of the Grigoriev ice cap (USSR) and the Dunde ice cap (China)

margin of the It-Tish ice cap (Fig. 1). Near the base, the ice is very heavily laden with dust (Photo 2), similar to the basal ice exposed along the margin of the Dunde ice cap (Thompson et al., 1988). Twenty-four samples collected through this transition near the bottom of the vertical wall were analyzed for dust concentrations, $\delta^{18}O$ and δD (Fig. 6). These data confirm the presence of ice exhibiting nearly identical characteristics to the *LGS* ice present near the base of the Dunde ice cap in central China (Thompson et al., 1988; 1989; 1990). This It-Tish basal ice is characterized by increases in concentrations of dust with diameters ≥2.0 μm and diameters ≥5.0 μm by factors of ~23 and ~28, respectively (Table 1). In addition, the particulate-rich basal ice is depleted in ^{18}O by ~1‰, and in ^{2}H by ~11.5‰ (the reproducibility of the oxygen and hydrogen analysis is within ±0.07‰ and ±0.8‰ for $\delta^{18}O$ and δD, respectively) and the deuterium excess ($\delta d = \delta D - 8\ \delta^{18}O$) is roughly 75% that of the overlying ice. The concentrations of soluble chemical species are twice that in the overlying ice. The similarity of the physical and chemical characteristics of the It-Tish basal ice to the *LGS* basal ice in the Dunde ice cap leads

Photo 2. The ice illustrated in photo 1 at the base of the vertical wall is very heavily laden with visible dust

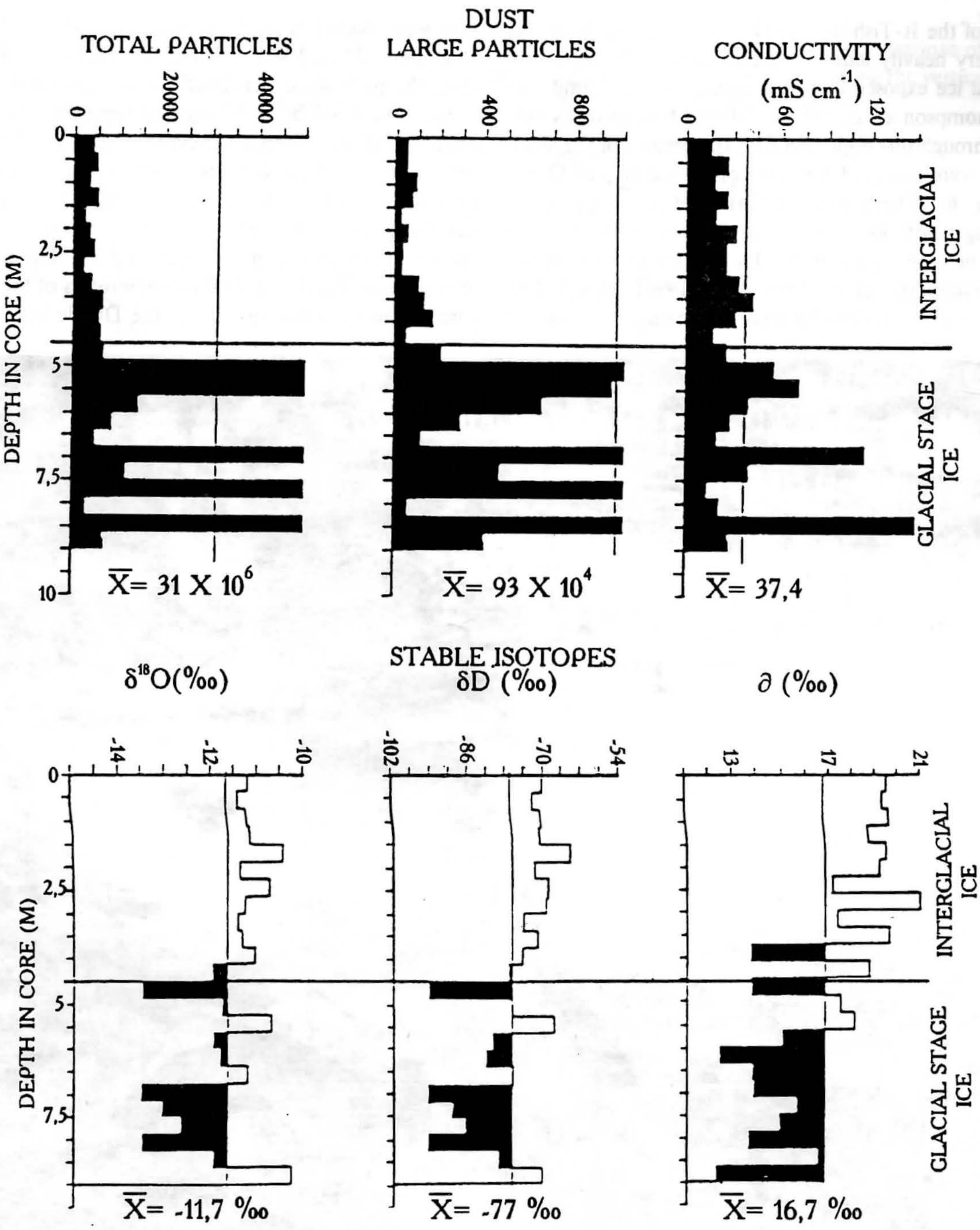

Fig. 6. It-Tish ice cap. Illustrated are the concentrations of total particles (diameters > 2.0 μm) per milliliter of sample, large particles (diameters > 5.04 μm) per milliliter of sample, liquid conductivity, $\delta^{18}O$, δD and deuterium excess (δd) from a 9-m vertical section near the bottom of the It-Tish ice cliff

us to conclude with reasonable confidence that the It-Tish basal ice was deposited during the last glacial stage.

The δd averages for the It-Tish interglacial and glacial stage ice are 18.6 and 14.7 ‰, respectively. Similarly, in the Dome C core (Antarctica), δd was lower in the glacial stage ice than in the Holocene ice and Jouzel et al. (1982) inferred that relative humidity over the ocean surface may have been higher under glacial stage conditions. A similar interpretation for deuterium excess, but for this temperate region, would imply increased moisture and hence a wetter climate during the glacial stage. Such a scenario of wetter conditions during the LGS is consistent with paleoenvironmental reconstructions from pollen and chemical sequences in the Dunde ice cap on the eastern Qinghai-Tibetan Plateau (Thompson et al., 1989; 1990). Alternatively, the lower δd in glacial stage ice could reflect cooler sea surface temperatures in the source area at that time. For example, Johnsen et al. (1989) report a decrease in mean δd of 3‰ in Greenland glacial stage ice from the 5.5‰ Holocene value. If the moisture source for the It-Tish ice cap has remained constant throughout the last glacial and current interglacial stage, then the lower δd for the *LGS* may reflect a cooler source area for the moisture source, which presumably is the ocean surface.

Conclusions

Oxygen isotopic ratios from the Grigoriev ice cap, coupled with the ~2.2°C increase in borehole temperatures over the last 27 years and an increase in regional surface temperatures of ~0.5°C over the last 60 years, indicate a recent warming in this region. When considered in light of similar results from the Dunde ice cap 1700-km away (Thompson et al., 1989; 1990), these high-elevation ice cap records suggest that this recent and continuing warming in Central Asia may be a large-scale feature of the current climate regime over the Plateau of Tibet. Additionally, dust and $\delta^{18}O$ analyses from the southern margin of the It-Tish ice cap indicate that long records, probably extending into the last glacial stage, are preserved in some Central Asian ice caps, similar to the long records available from several Chinese ice caps (Thompson et al., 1988). Finally, δd results from the It-Tish ice cap suggest that wetter conditions may have prevailed in this area during the last glacial stage, consistent with *LGS* conditions reconstructed from the Dunde ice cap records.

Currently, the ice caps of central Asia provide an important regional source of water for both irrigation and hydroelectric power. Additionally, they contain potentially long, high-resolution histories of climatic and environmental conditions. Should the recent warming in this region continue, it could endanger these ice caps and the valuable histories they contain. It may be prudent to extract these unique and potentially very long histories of paleoenvironmental changes expediently, before they are lost.

Acknowledgments

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ТРУДЫ МЕЖДУНАРОДНОГО СИМПОЗИУМА "СЕЗОННЫЕ И МНОГОЛЕТНИЕ КОЛЕБАНИЯ НИВАЛЬНЫХ И ГЛЯЦИАЛЬНЫХ ПРОЦЕССОВ В ГОРАХ"

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