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"Recent warming": ice core evidence from tropical ice cores with emphasis on Central Asia

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ABSTRACT

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Ice cores from the tropics and subtropics, in conjunction with those from the polar regions, provide a multifaceted record (dust, chemistry, stable isotopes, accumulation) of environmental changes which can be viewed both spatially and temporally This paper emphasizes the oxygen isotopic record ($\delta^{18}O$) preserved in cores from the poles to the tropics and assesses the evidence for global warming in the last 50-100 years From north to south these records include Camp Century, Greenland, Dunde and Guliya Ice Caps, China, Gregoriev Ice Cap, Kirghizia (formerly part of USSR), Quelccaya Ice Cap, Peru and Siple Station and South Pole, Antarctica The central Asian records along with that from Quelccaya provide strong evidence of recent and rapid warming in the tropics and subtropics For the Dunde Ice Cap, where a long paleoclimatic record is available, the warming in this century appears to be unprecedented in the Holocene These tropical and subtropical records contrast sharply with those from polar cores which show little evidence of a recent warming These data suggest that either the recent warming is a middle and lower latitude phenomenon or that these high altitude tropical and subtropical glaciers may be more sensitive to climate changes than the massive polar ice sheets Regardless, the current rapid disintegration of many tropical and subtropical glaciers may result in the permanent loss of numerous unique archives

Introduction

The patterns and sources of interannual, decadal and centennial climatic variability are least well known and constitute a gap in our understanding of the global climate system. Comparisons of climate model results with systematic regional, continental, hemispheric and global-scale compilations of high-resolution paleoclimatic data are needed to fill this gap and to develop more realistic climate models. The Earth's ice sheets and ice caps are recognized as "the best of only a few" libraries of atmospheric history from which past climatic and environmental conditions may be extrapolated. However, much of the climatic activity of significance to humanity may not be strongly expressed in (or may not reach) the polar ice caps. Fortunately, ice core records also can be recovered from a limited number of high-altitude, low- and mid-latitude "polar" type ice caps (Fig 1) In addition, the high accumulation on these ice caps and at some locations on the polar ice sheets makes it possible to recover high resolution records for the last 1000 years. Changes in the physical character and chemical composition of the atmosphere may be reconstructed using soluble and insoluble dust, stable isotopes, net accumulation changes and, in some cases, trapped gases. Additionally, non-polar ice core records provide a unique archive of biological changes as inferred from pollen, diatoms and plant fragments. Such environmental

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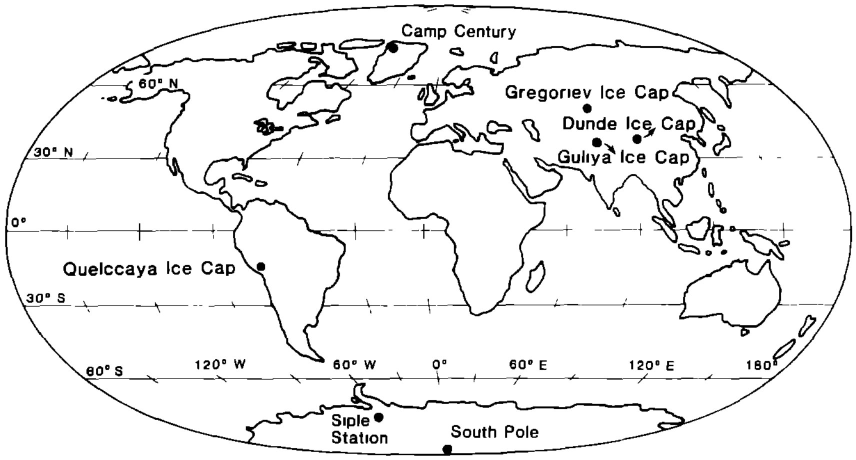


Fig 1 Location of the Camp Century, Greenland, Dunde, Guliya and Gregoriev Ice Caps in central Asia, the tropical Quelccaya Ice Cap in Peru, the Siple Station and South Pole core in Antarctica

information is not readily available from polar ice cores. Thus, the variety of chemical and physical data extracted from ice caps and ice sheets provide a multi-faceted record of both the climatic and environmental history of the Earth which is critical to the assessment of the relative impor-

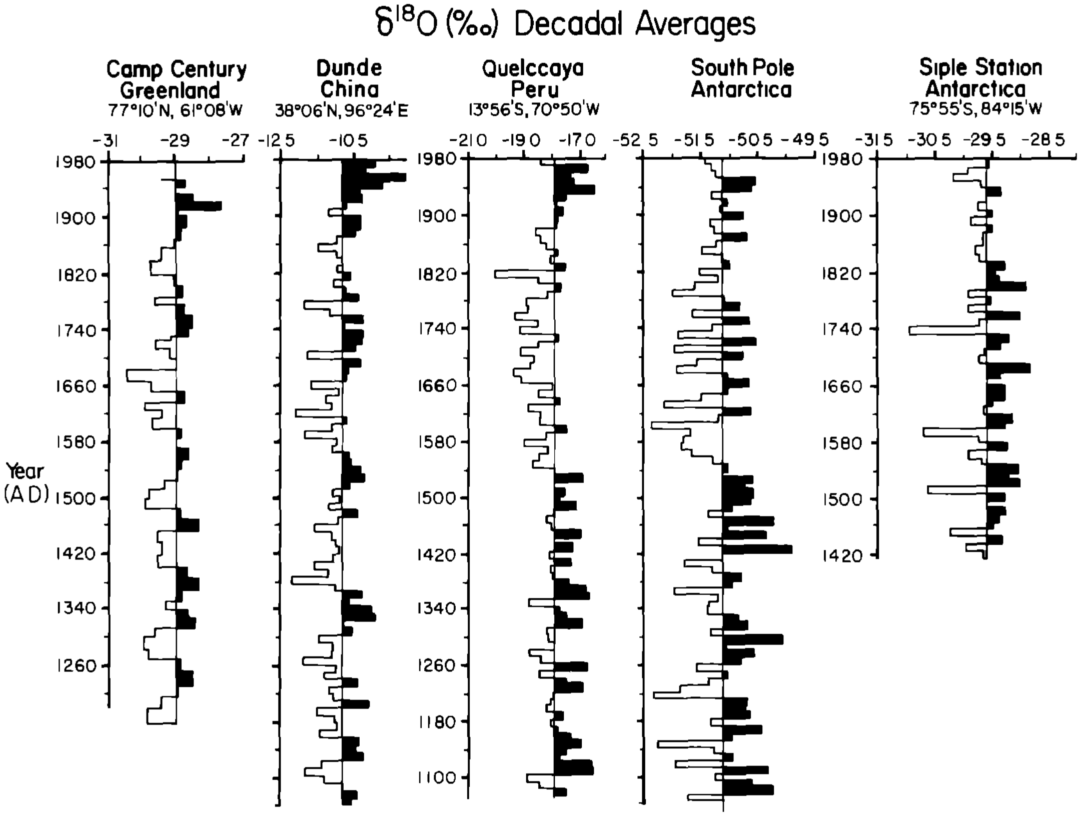


Fig. 2 Decadal averages of the $\delta^{18}O$ records in a N–S transect from Camp Century, Greenland (Johnsen et al., 1970) in the north to South Pole Station, Antarctica in the south The shaded areas represent isotopically less negative (warmer) periods and the unshaded areas represent isotopically more negative (colder) periods relative to the individual record means

tance of such climate system components as volcanic activity, greenhouse gas concentrations, atmospheric dust loading and solar variability. Understanding the climate system with the goal of prediction requires a global synthesis of its history over a period of time from which the most reliable, diverse and complete data sets exist. At the same time, the longer records encompassing glacial/interglacial fluctuations, while lacking in temporal resolution, are important as they provide a much longer perspective from which the recent (last 1000 years) variations must be viewed

High resolution reconstruction of the last 1000 years is critical for a variety of reasons. (1) it is most relevant to human activities, present and future, as recent climatic and environmental variability due to human activities are superimposed; (2) times of extremes existed within the Holocene such as the "Little Ice Age" period; (3) maximum data coverage exists, (4) multi-proxy reconstructions are feasible; (5) annual (or seasonal) resolution is possible; (6) leads, lags and rates of change within the climate system can be studied directly, (7) the causes of the observed changes are undetermined; and (8) potential forcing functions may be identified and tested.

Results

The global perspective

The assimilation of multi-faceted ice core data sets from polar and non-polar regions reveals both temporal and spatial variability of the particular ice core parameter under consideration (i.e., dust, chemistry, gases, isotopes, etc). Here we examine a global array of $\delta^{18}O$ records to assess whether the available ice core histories provide evidence of recent global warming. In varying degrees, $\delta^{18}O$ records reflect (1) condensation air temperatures, (2) nature of atmospheric processes between the water vapor source and the deposition site, (3) local conditions such as diffusion and densification which modify the preserved $\delta^{18}O$ signal, (4) the surface elevation of the depositional site and (5) the latitude of the site (see Dansgaard et al., 1973 and Bradley, 1985, for reviews). Although the quantitative relationship between atmospheric temperatures and $\delta^{18}O$ and their spatial representativeness are still under discussion, $\delta^{18}O$ continues to be widely applied as a proxy for climate and in particular, for temperature (Dansgaard et al , 1973, Jouzel et al., 1983; Thompson et al , 1986 and Peel et al , 1988)

Figure 2 provides a global perspective of the decadal and centennial variations for the last 500–1000 years from five diverse sites Here isotopically heavier, or warmer periods, are shaded while isotopically lighter, or colder periods, are unshaded There is a large diversity in detail not unlike that expected if five widely dispersed meteorological stations were used to reconstruct global temperatures However, several common features are evident: (1) the isotopic variability is similar in the two northern hemisphere sites including a rather pronounced ~ 180-yr oscillation in the Dunde record, (2) the $\delta^{18}O$ records from the tropical Quelccaya Ice Cap, Peru and South Pole, Antarctica show strong similarities including a "Little Ice Age" (~ A D 1530–1900) which is characterized by more negative $\delta^{18}O$ values; and (3) all non-Antarctic sites are isotopically less negative (warmer) during the twentieth century. Of these five records, the Siple Station record is unique, exhibiting less negative $\delta^{18}O$ and hence presumably warmer conditions during much of the "Little Ice Age" (Mosley-Thompson et al., 1990; Thompson, 1992). Both Antarctic records are isotopically lighter in the twentieth century, but with differing trends for the last 30 years. At South Pole $\delta^{18}O$ suggests a continued cooling, while at Siple Station $\delta^{18}O$ suggests a warming trend since the 1960's, consistent with the warming trend in the Antarctic Peninsula from 1960 to 1990 (Mosley-Thompson et al , 1991; Peel et al , 1988)

Central Asia

Two ice cores to bedrock from the Dunde Ice Cap (38°06′N, 96°24′E, 5325 masl), Qilian Mountains, on the northeastern margin of the Qinghai–Tibetan Plateau of China provide a detailed record of Holocene and Wisconsin–Würm late glacial stage (LGS) climate changes in the sub-

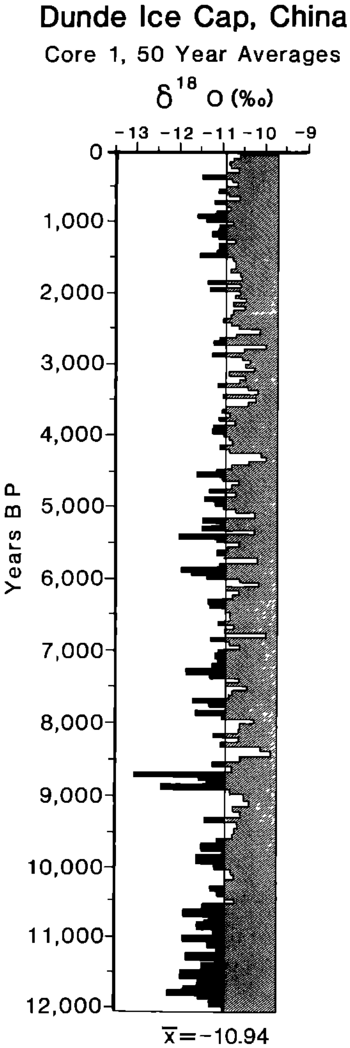


Fig 3 Fifty-year averages of $\delta^{18}O$ for the last 12,000 years from Core D-1 on the Dunde Ice Cap, China, are compared with the projection (shaded) of the most recent 50-yr average, 1937–1987 Viewed from the long-term perspective, 1937–1987 is the warmest 50-yr period since the end of the last glacial stage

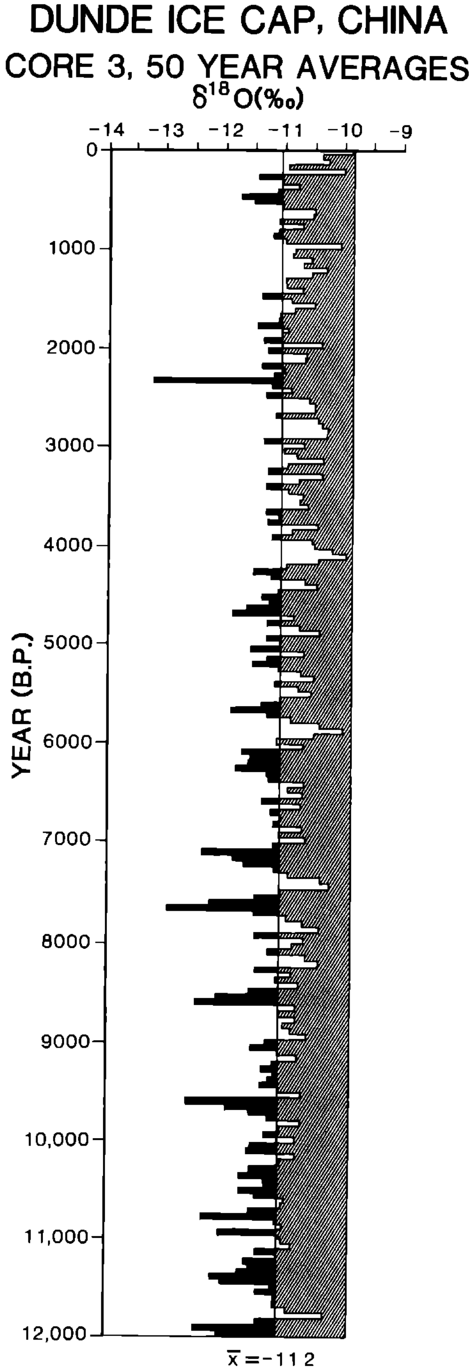


Fig 4 Fifty-year averages of $\delta^{18}O$ for the last 12,000 years from Core D-3 on the Dunde Ice Cap, China, are compared with the projection (shaded) of the most recent 50-yr average, 1937–1987 Viewed from the long-term perspective, 1937–1987 is the warmest 50-yr period since the end of the last glacial stage

tropics (Thompson et al., 1988b, 1989, 1990; Xie et al , 1989; Yao et al , 1990; Yao and Thompson, 1992) The ice core records provide a long-term perspective of climate change. In Fig. 3, 50-yr averages of $\delta^{18}O$ for the last 12,000 yr are presented for core 1 D-1 These data, based on the analysis of 3280 samples, show both colder and warmer periods since the termination of the last glacial stage. The shaded portion reflects the $\delta^{18}O$ average for the 50-yr period from 1937 to

1987 and demonstrates that it is isotopically, the warmest 50-yr period in the record. However, these 50-yr averages must be viewed cautiously as the most recent 50-yr average includes 320 samples, while the lower 50-yr averages, are based on 2–5 samples, a result of densification and thinning due to flow

Core D-3 was also drilled on the Dunde Ice Cap and unlike core D-1 which was returned entirely as bottled samples, the lower 80 m were returned to OSU as ice Thus, core D-3 was sectioned into much smaller samples which provided a higher time resolution. The resulting $\delta^{18}O$ profile (Fig 4) represents the 50-yr averages of 7045 samples, more than double that in core D-1. In core D-3 the most recent 50-yr average represents 384 samples while the lower 50-yr averages represent 4–10 samples. Comparison of the two $\delta^{18}O$ records demonstrates their reproducibility and provides strong evidence that the most recent 50-yr period, as well as the last century (1887–1984) are isotopically the warmest periods in the 12,000-yr record. When viewed from the long-term perspective provided by these cores, the most recent warming does indeed appear to be significant, exceeding the maximum warmth of the earlier Holocene periods in central Asia. Meteorological observations from Delingha station 100 km to the southeast, the closest station to Dunde, shows a 1.2°C warming since the mid-1950s, when the record began

Large-scale variations of $\delta^{18}O$ over the past 40–180 yr in central Asia appear to be directly related to similar large-scale trends in temperature. The 5-yr running means of $\delta^{18}O$ from the Dunde Ice Cap are compared in Fig 5 with 5-yr running means of Northern Hemisphere temperatures (Hansen and Lebedeff, 1987). For the period from 1895 to 1985 the correlation coefficient (r) is 0.5 (significant at the 99.9% level). This correlation suggests that the Dunde Ice Cap $\delta^{18}O$ should serve as a good proxy for larger-scale temperature variations.

The recent $\delta^{18}O$ enrichment, interpreted as a function of recent warming in this region, is not restricted to the Dunde Ice Cap In 1990 two cores, 16-m and 20-m, were drilled on the summit of the Gregoriev Ice Cap in the Tian Shan of Kirghizia (42°N, 78°E, 4660 masl). The preliminary time scale was calibrated using a distinct time horizon provided by the 1963 Beta peak in core 1 (Fig. 6). The $\delta^{18}O$ records from both cores

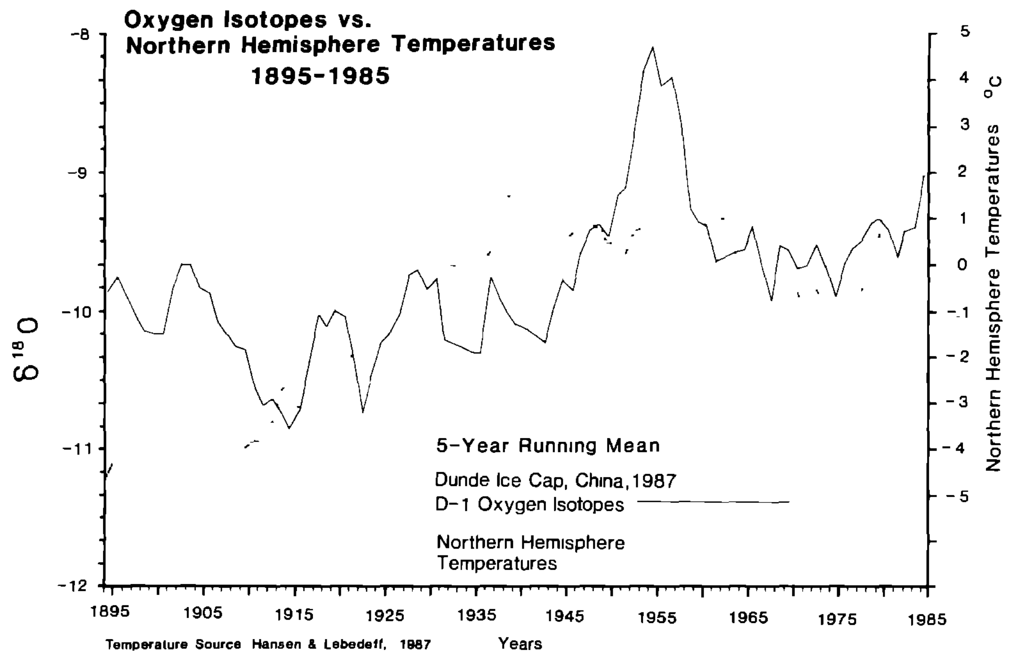


Fig 5 Five-year running means of $\delta^{18}O$ from Dunde core and Northern Hemisphere temperatures from 1895 to 1985

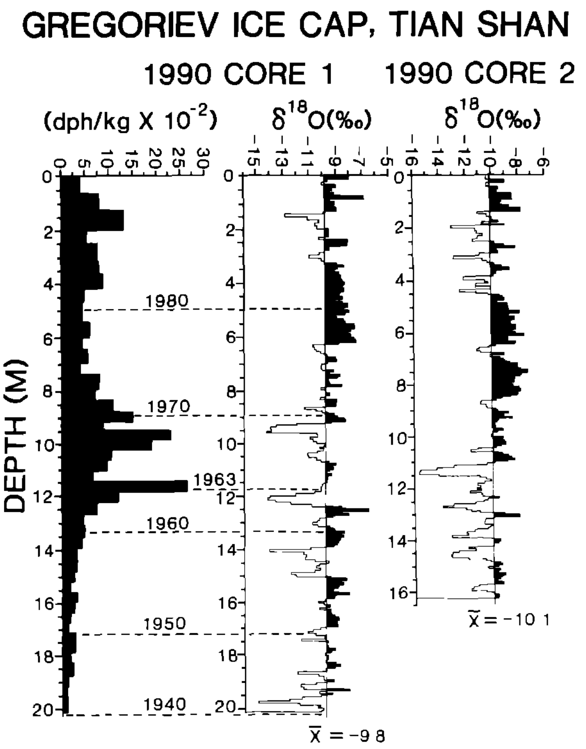


Fig 6 Total β-radioactivity and $\delta^{18}O$ from the 20-m Core 1 and $\delta^{18}O$ from the 16-m Core 2 drilled in 1990 from the summit of the Gregoriev Ice Cap, Kirghizia

(Fig. 6) exhibit a significant enrichment of ^{18}O (less negative $\delta^{18}O$) in the upper layers, possibly in response to recent atmospheric warming. In addition, the partial loss of the seasonal $\delta^{18}O$ variations, especially in the near-surface layers, arises from both isotopic diffusion and meltwater percolation which are consistent with a recent warming in the vicinity of Gregoriev. 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

A recent warming in this area is supported by other evidence. For example, the temperature profile (Fig. 7a) measured on Gregoriev indicates an increase of 2.2°C at 20 m when compared with the 20-m temperature measured in 1962 by Soviet expeditions (Dekikh, 1965; Mikhalenko, 1989). In fact, the temperature increase may be slightly greater as the 1962 measurement was at a site 200-m lower than the 1990 measurement. On glaciers where refreezing of meltwater occurs, as

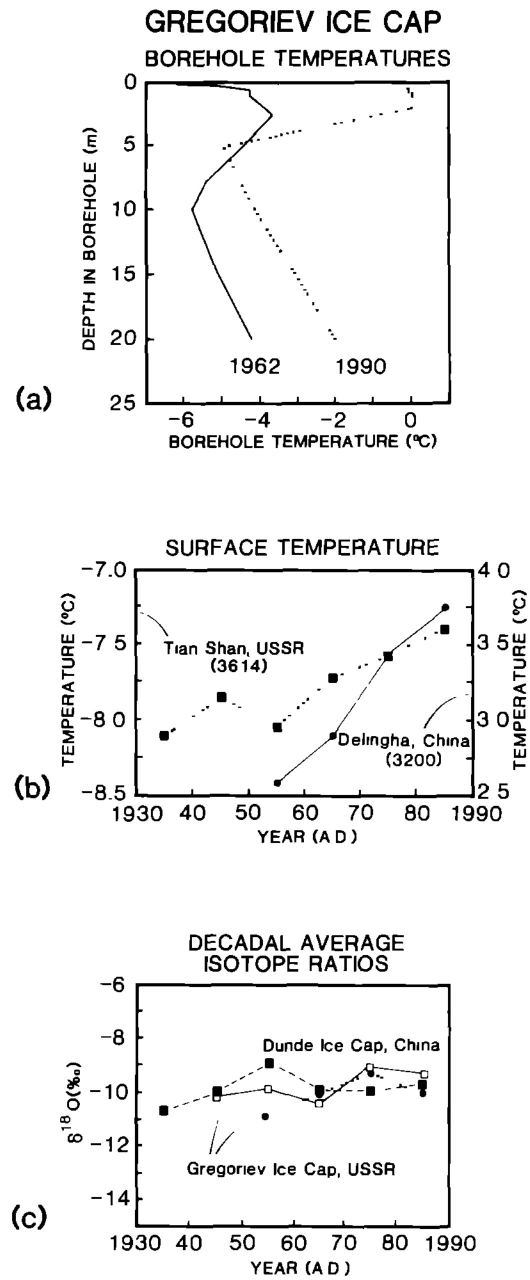
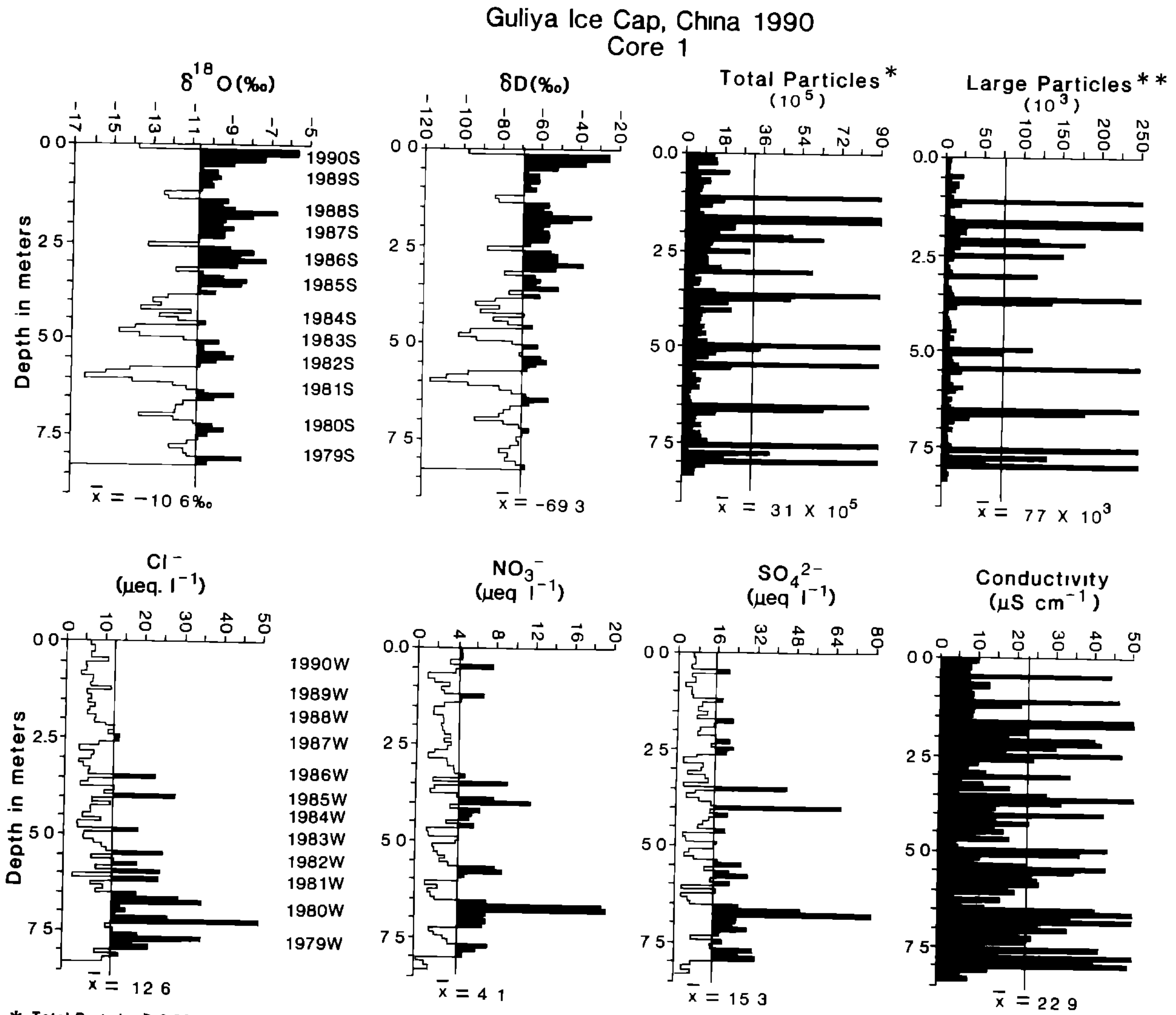


Fig 7 (A) Borehole temperatures measured in a 20-m borehole at 4400 m elevation during a 1962 Soviet expedition are compared with temperatures measured at 4660 m elevation in 1990 by a joint USA–USSR expedition (B) Decadal averages of surface temperatures measured at the USSR Tian Shan Meteorological Station (3614 m elevation), 6 km from Gregoriev Ice Cap and from the Chinese Delingha meteorological station (3200 m elevation), 100 km from the Dunde Ice Cap (C) Decadally averaged $\delta^{18}O$ values in two summit cores from the Gregoriev Ice Cap, former USSR, and from the Dunde Ice Cap, China.

in the case of the Gregoriev Ice Cap, 20-m temperatures will generally exceed the mean annual air temperature (Paterson, 1981). Therefore, the 2.2°C warming must be considered as an upper limit.

Further evidence of recent warming in this region comes from near-surface temperature observations at the Tian Shan Meteorological Station (3614 m elevation, nearest station to the Gregoriev Ice Cap) and from the Delingha meteorological station (3200 m, nearest station to the Dunde Ice Cap). Figure 7b illustrates a warming of 0.5°C over the past 60 yr at the former USSR station and of 1.2°C at the Chinese station. Figure 7c shows the decadal averages of $\delta^{18}O$ from both the Gregoriev and the Dunde Ice Caps, demonstrating an ^{18}O enrichment of approximately 1‰ in precipitation over the last 40 yr. Isotopic enrichment generally indicates an increase in condensation temperature. The similar-



* Total Particles ≥ 0.63 to ≤ 16.0μm in Diameter per ml of Sample (10^5)

** Large Particles ≥ 1.59 to ≤ 16.0μm in Diameter per ml of Sample (10^3)

Fig 8 Measurements of $\delta^{18}O$, δD, total particles (diameter ≥ 0.63 μm in diameter per ml sample), large particles (≥ 5.04 μm in diameter per ml of sample), Cl^-, NO_3^- and SO_4^{2-} and conductivity in an 8-m core from Site 1, Guliya Ice Cap, Western Kunlun, China

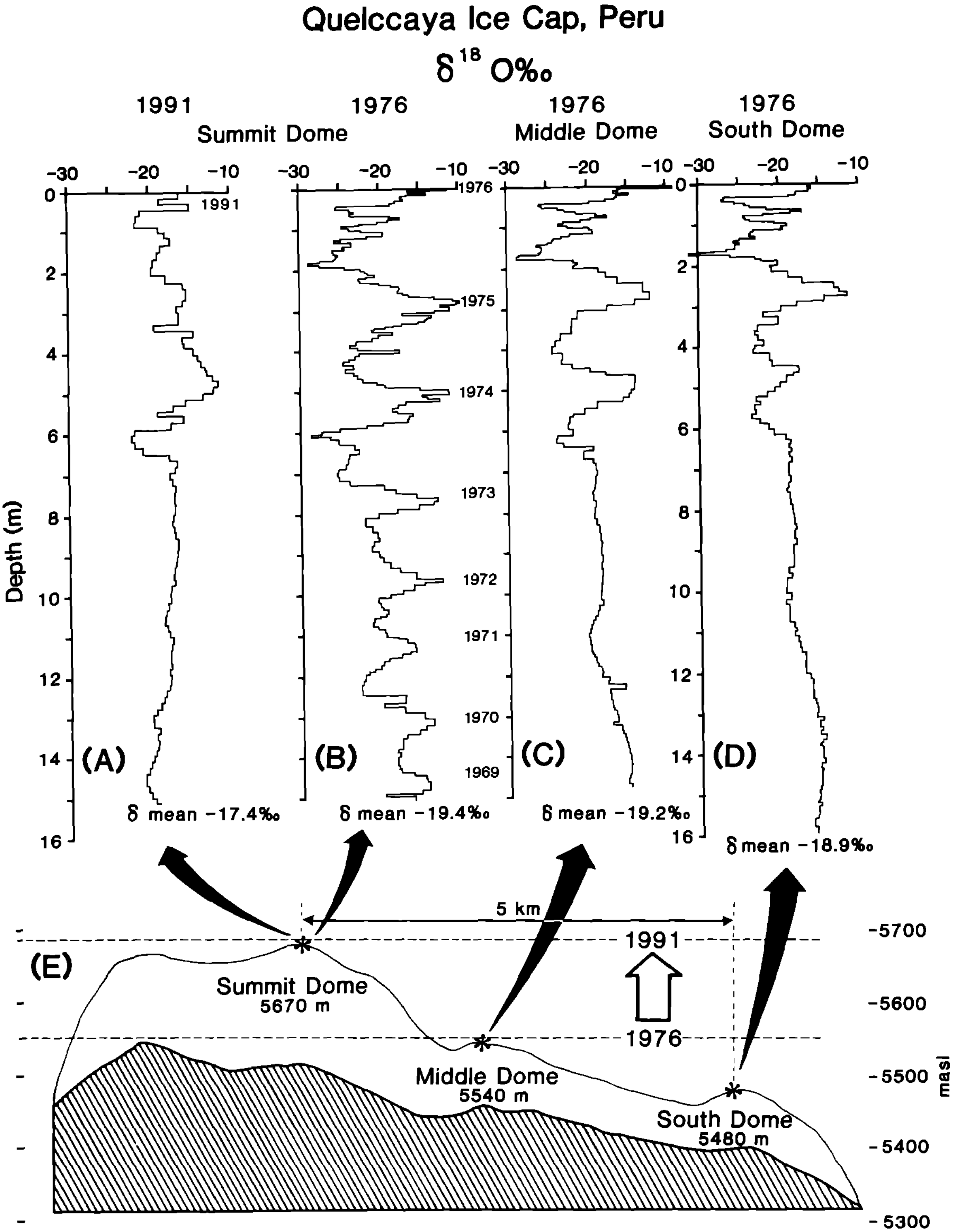


Fig 9 Tropical Quelccaya Ice Cap, Peru oxygen isotope profiles from a core drilled in 1991 on (A) the summit dome and cores drilled in 1976 on (B) the summit dome, (C) the middle dome and (D) the south dome (E) N–S cross-section of the Quelccaya Ice Cap illustrating the locations from which the $\delta^{18}O$ records in (A)–(D) were drilled and reveals the 130-m rise in the percolation zone from 1976 to 1991

ity of the isotopic enrichment on both the Gregoriev and Dunde Ice Caps, 1700 km apart, coupled with both the local meteorological observations and the 2.2°C increase in borehole temperatures on Gregoriev, strongly suggest a recent warming in this part of central Asia.

Recently, a new drilling program has been initiated on the Guliya Ice Cap (35°17′N, 81°29′E, 6707 masl), located in the western Kunlun Mountains (Fig 1), where conventional long-term climatic data are completely absent. An 8-m ice core was collected and analyzed for microparticle concentrations (MPC) and size distributions, stable isotopic ratios ($\delta^{18}O$ and δD) and selected chemical species (Fig. 8) Annual accumulation over the last ten years has averaged 650 mm H_2O equivalent. On Guliya, high MPC is associated with less negative $\delta^{18}O$ during the summer/fall seasons. Seasonal variations in $\delta^{18}O$ and δD, total and large-diameter insoluble particle concentrations and liquid conductivity (soluble dust) are reasonably well preserved and will allow accurate dating of the deep cores recovered in 1992. The annual peak concentrations of Cl^-, NO_3^- and SO_4^{2-} are generally associated with more negative $\delta^{18}O$ and δD which reflect winter precipitation This relationship is strongest for NO_3^- variations (The isotopic records reveal an interesting trend with values becoming progressively less negative toward 1990, presumably re-

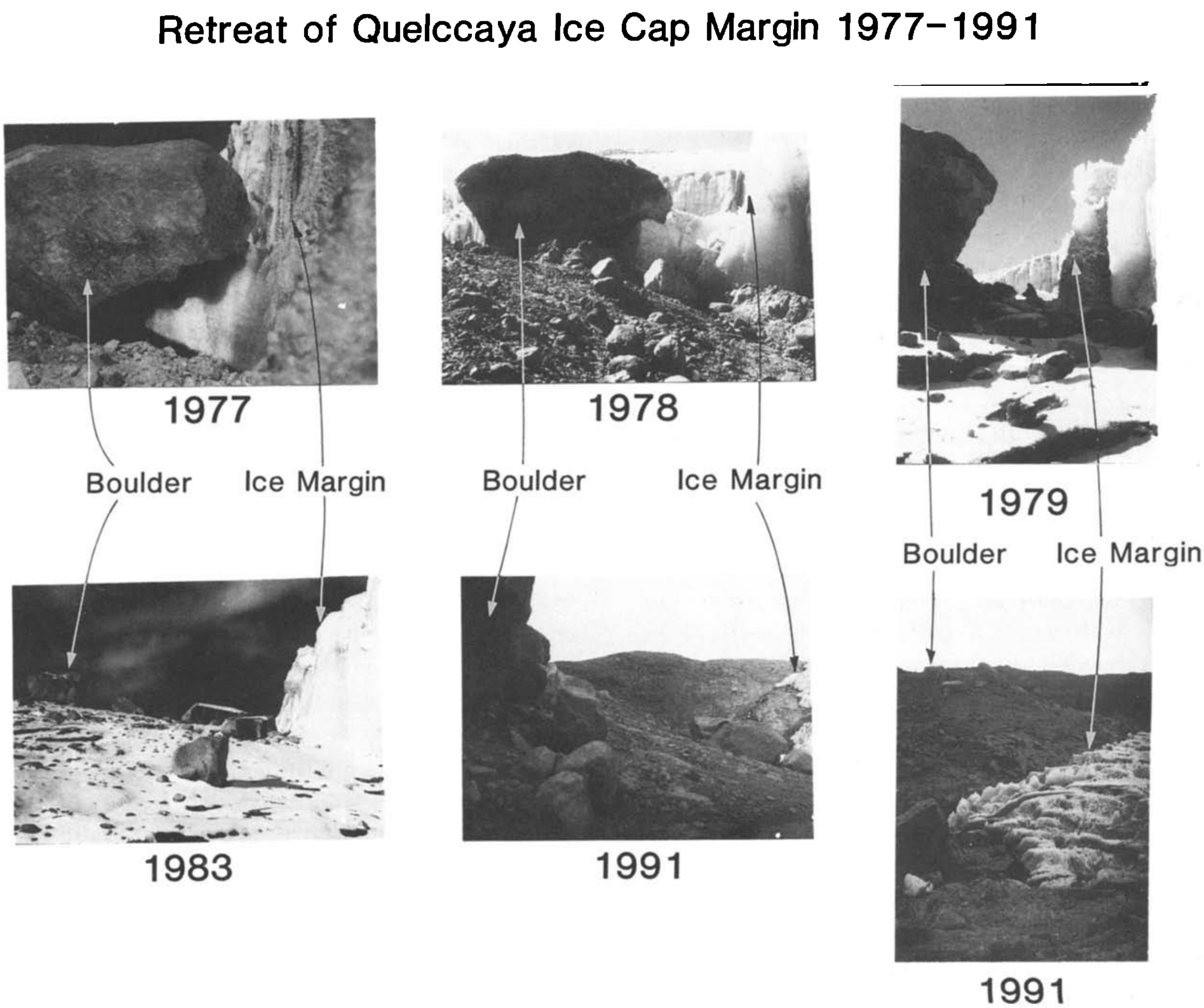


Fig 10 Boulder and Quelccaya Ice Cap western margin as seen in 1977, 1978, 1979, 1983 and 1991

flecting warmer condensation temperatures or a warmer moisture source region). The average $\delta^{18}O$ for 1980–1985 is $-11.46‰$, while the average for 1986–1990 is $-9.53‰$, a 1 9‰ increase. The δD values show a similar trend, with an increase of 20‰ since 1985. These isotopic results are very consistent with those from the Dunde Ice Cap on the eastern edge of the Plateau (Thompson et al., 1989, 1990) and the Gregoriev Ice Cap. A potentially important relationship exists between the trends over the last ten years in $\delta^{18}O$ and Cl^-, NO_3^- and SO_4^{2-}. Between 1980 and 1990 $\delta^{18}O$ has become progressively less negative while Cl^-, NO_3^- and SO_4^{2-} concentrations have decreased.

Quelccaya Ice Cap, Peru

A 1500-year record extracted in 1983 from the Quelccaya Ice Cap (Thompson et al., 1986, 1988a) in the tropical Andes of Peru (13°56′S, 70°50′W′, 5670 masl) was recently updated by the analysis of a new core drilled in October, 1991. Figure 9 illustrates the $\delta^{18}O$ records from ice cores drilled in 1976 on Quelccaya at three locations: the 5670 masl summit dome (Fig. 9B), the 5540 masl middle dome (Fig. 9C) and the 5480 masl south dome (Fig. 9D). The 1976 records are compared in Fig 9 with results from the upper 15 m of a 21.4-m core drilled on the summit dome in 1991 (Fig 9A). In the 1976 south and middle dome cores the annual $\delta^{18}O$ signal is lost below 6 m due to percolation of meltwater. However, the $\delta^{18}O$ record from the 1976 summit core shows well-preserved seasonal variations throughout its length with a mean $\delta^{18}O$ value of $-19.40‰$. When the 1976 $\delta^{18}O$ record is compared with the 1991 $\delta^{18}O$ record from the same site (Figs. 9A,B) it is evident that (1) the $\delta^{18}O$ values have been enriched by 2‰ and (2) annual variations in $\delta^{18}O$ are no longer preserved at this site. If the survey to assess the quality of the record preserved in this ice cap had been conducted in 1991, Quelccaya would have been eliminated as a possible site for acquisition of a long ice core paleoclimatic history.

The impact of the recent warming on the Quelccaya Ice Cap can be seen in the massive and accelerating retreat of the margin of the ice cap as illustrated for 1977, 1978, 1979, 1983 and 1991 in Fig. 10. If the current warming trend persists, then many of these unique tropical and subtropical archives of climate and environmental history are in imminent danger of being lost.

Conclusions

Model results of Hansen et al. (1988) suggest that the central part 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. Certainly the Dunde ice core results suggest that the recent warming on the Tibetan Plateau has been substantial in relation to the Holocene record. Recent radiosonde data from southern India (Flohn and Kapala, 1989) show that, in fact, the average tropospheric temperature has increased nearly 1°C since 1965. Wang et al (1991) in model simulations found that trace gases increased the temperature from the surface all the way up to 30 km, with peak warming of $> 6°C$ near 8 km. All the ice core records presented here come between 5 and 7 km. These results would support their findings, indicating large warming of the tropical tropopause. Eventually more robust temperature-isotope transfer functions must be developed for the Tibetan Plateau and indeed, for all regions of the Earth where ice core isotopic records provide a proxy indication of temperature.

Ice core climatic and environmental records from low, middle and high latitudes greatly increase our knowledge and understanding of the course of past climatic events, which is essential for prediction of future climatic oscillations, which may or may not be dominated by increasing greenhouse gas concentrations The forcing factors, internal and external, which have operated in the past will continue to operate and influence the course of events (Grove, 1988) The Dunde Ice Cap cores provide the first ice core record of the Holocene–late Pleistocene climate from the subtropics The stable isotope record indicates that the last 60 yr on the Tibetan Plateau have been the warmest period in the entire record.

Other climatically unique periods which are global in scale such as the "Little Ice Age" also must result from large-scale climatic forcing. The expression of the "Little Ice Age" in any record is quite variable and appears to be more distinct in higher elevation sites, such as Dunde, Quelccaya and South Pole than in the lower elevation polar sites of Camp Century and Siple Station We suggest two reasons for this. First, climatic change is probably a function of elevation. Recent results from Guliya, Dunde and Quelccaya Ice Caps suggest that the recent warming may be expressed more strongly and earlier at higher elevation low latitude sites. Secondly, it is likely that subtle changes in climate like the "Little Ice Age" are more clearly recorded farther from the mitigating influence of the oceans.

The tropical and subtropical ice core records may potentially provide long records of El Niño/Southern Oscillation events and monsoon variability and thus provide insight to the variations in the magnitude and frequency of these global-scale events. Moreover, a global array of cores can contribute to establishing a record of changes in global precipitation over the last 1000 yr and possibly provide records of geographical variations in the concentrations of selected greenhouse gases. These data also make it very clear that some of these unique archives of climate and environmental history are in imminent danger of being lost forever if the current warming trend persists.

Acknowledgements

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