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A shallow ice core re-drilled on the Dunde Ice Cap, western China: recent changes in the Asian high mountains

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Abstract
A 51 m deep ice core was re-drilled on the Dunde Ice Cap of western China in 2002, 15 years after the previous ice core drilling in 1987. Dating by seasonal variations in $\delta^{18}O$ and particle concentration showed that this 51 m deep ice core covered approximately the last 150 years. The stratigraphy and density showed that more than 90% of the ice core was refrozen ice layers, which comprised less than 5% of the annual accumulation in the older core. This indicates that the ice cap had experienced a more intense melting since 1987, possibly due to climate warming in this region. Mean net accumulation since the last drilling (2002–1987) was 176 mm a^{-1}, which was considerably smaller than that obtained from the 1987 core (390 mm a^{-1}, 1987–1963), indicating a significant decrease of net accumulation on the ice cap in the more recent period. The $\delta^{18}O$ record showed an increasing trend in the late 19th century and the highest in the 1950s, which is consistent with the previous core findings. However, there has been no significant increase in $\delta^{18}O$ during the last two decades, in contrast to the warming trends suggested by the melt features and other climate records. This discrepancy may be due to the modification of $\delta^{18}O$ records by melt water runoff, percolation, and refreezing on the ice cap. Results strongly suggest recent significant mass loss of glaciers in the Asian high mountains and serious shortage of water supply for local people in this arid region in the near future.

Keywords: ice core, climate warming, Tibetan plateau, glacier, water resource

1. Introduction

The Dunde Ice Cap is the first place where deep ice cores have been drilled in the Asian high mountains (Thompson *et al* 1989). The ice cores were recovered at the top of the ice cap (5325 m asl) in 1987 and were approximately 140 m deep from the surface to the bedrock. The climate changes over the past 10 000 years have been reconstructed from various analyses of the ice cores, and these records have been used in

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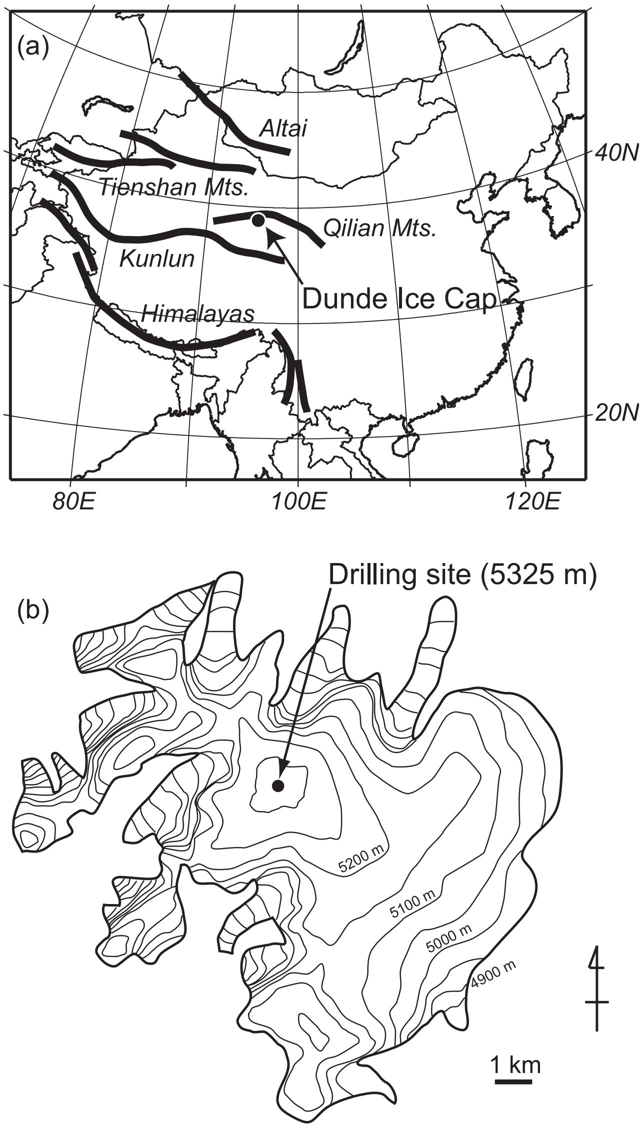

Figure 1. Location of the Dunde Ice Cap in the Qilian Mountains, China (a), and a topographic map of the ice cap showing the location of the drilling site (b).

many climate studies in the Asian region (e.g. Sheppard *et al* 2004, Thompson *et al* 2006). The ice core records have shown that the last 60 years were the warmest periods of the record (Thompson *et al* 1989). However, subsequent studies have reported that the global climate has warmed further since the 1990s (e.g. Mann and Jones 2003, IPCC 2007). An extension of the ice core records to the present day is of great interest in terms of glaciology and hydrology as well as climatology in this region.

Simultaneous with enhanced warming in the 1990s, environmental changes have raised concern in western China, where the ice cap is located. Although western China is arid and less populated than eastern China, it has been populated and developed significantly since the 1990s due to government policy (e.g. Wang *et al* 2007). However, lack of water and degradation of vegetation have become apparent recently in many places in this region (e.g. Wang and Cheng 1999). The water shortages may be due to climate change and also to the impact of human activities such as overuse of agricultural water and degradation of vegetation by overgrazing of livestock. For example, the Hei River, which is the largest inland river originating from the Qilian Mountains in western China, showed a significant decrease of discharge from the 1980s to the 1990s (44.1% at the lower reaches Wang and Cheng 1999). Studies suggest that the decrease was mainly due to cultivated land expansion in the midstream region (e.g. Wang *et al* 2007). It is also important to evaluate recent climate and glacial changes in mountain regions since the river and ground water mainly originates from glaciers or precipitation in the high mountains.

In this letter, we present the stratigraphy, oxygen stable isotopes, and particle concentration of a shallow ice core drilled on the top of the Dunde Ice Cap in 2002. The records were compared with those of the previous ice cores drilled in 1987, and we discuss recent changes of the ice cap and the environment in this region.

2. Study site and methods

The Dunde Ice Cap (38°06′N, 96°24.5′E) is located in the Qilian Mountains, which are in the northeast margin of the Tibetan Plateau (figure 1). The Qilian Mountains extend from east to west approximately 500 km to form the border of the Gansu and Qinhai Provinces. Several rivers originate from glaciers in this mountain range and flow into the Gobi Desert north of the mountains. The water supplied by rivers or groundwater has sustained local people living in this arid area for thousands of years.

A 51 m deep ice core was recovered in October 2002 at the top of the ice cap. The drilling site was determined with a handheld GPS receiver to identify the last drilling site in 1987, and was probably within 100 m from the last site. The ice core was transported in the frozen state by truck to a cold room of the Cold and Arid Regions Environmental and Engineering Research Institute in Lanzhou, China, and then by air cargo to a cold laboratory in the Snow and Ice Research Center in Nagaoka, Japan. In the laboratory, all core sections were weighed to obtain the density. The density was calculated from the weight divided by the columnar volume of each core section (9.0 cm in diameter). The density possibly has an error of 5% or less due to the irregularity of the cross sections. The visual stratigraphy of all core sections was recorded. The stratigraphy recorded in this study was firn (layers consisting of snow grains) and ice layers (transparent layers without snow grains; figure 2(a)). The core was then cut every 5 cm and used for analyses of oxygen and hydrogen stable isotopes, tritium, and particle concentration. The total number of samples was 870. Oxygen and hydrogen stable isotope ratios (δ^{18}O and δD) were analyzed with a mass spectrometer (Finnigan Delta Plus) in the Hydrospheric Atmospheric Research Center, Nagoya University. The calibration procedure has been shown in Fujita and Abe (2006). The analytical precisions of δ^{18}O and δD measurements were 0.05 and 0.5‰, respectively. The deuterium excess (D excess) was obtained from a definition by Craig (1961) as $d = \delta\mathrm{D} - 8.0\delta^{18}\mathrm{O}$. Particle concentrations were analyzed with a laser particle counter (Met One Model-211) at the National Institute for Polar Research, Tokyo. The

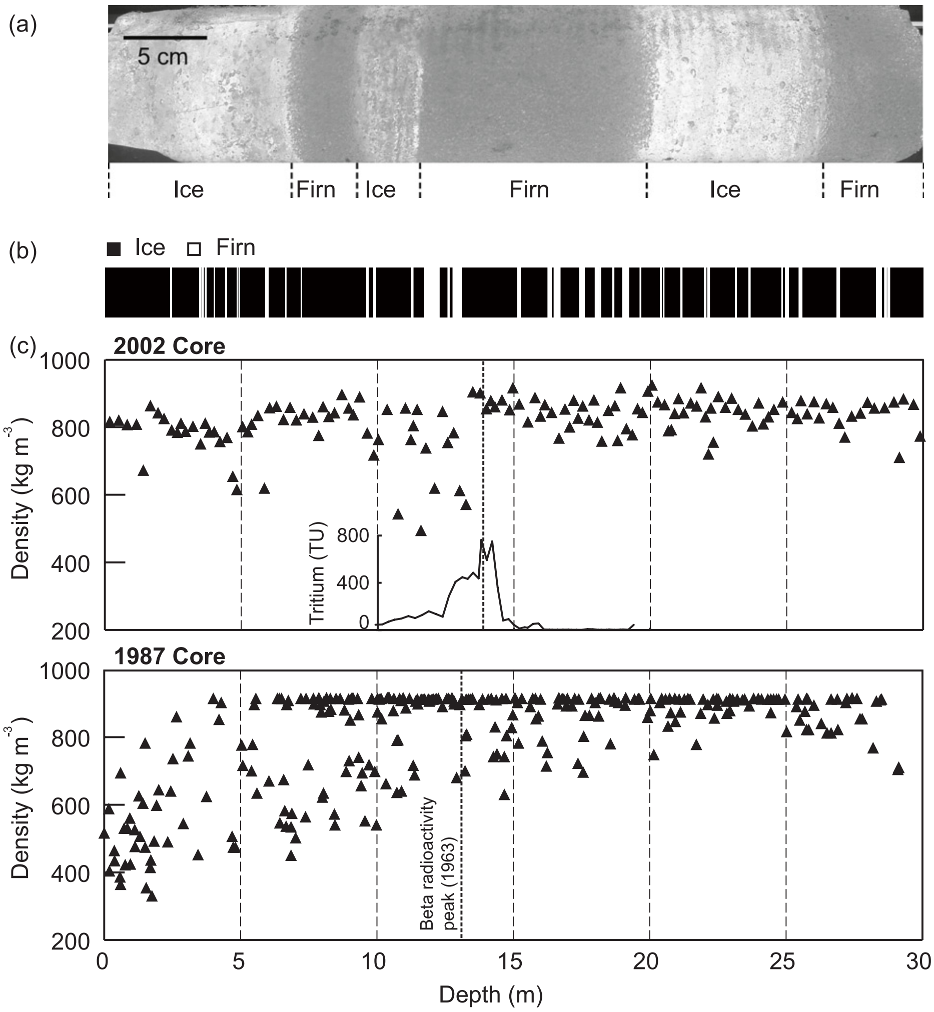

Figure 2. Photograph of an ice core section between depths of 28.35 and 28.82 m (a), and the upper 30 m profiles of the visual stratigraphy (b), and the density of the 2002 ice core and density of the 1987 ice core (c) for the Dunde Ice Cap. The tritium profile between 10 and 20 m of the 2002 core is also shown. The density of the 1987 core is according to Thompson *et al* (1990).

ranges of particle size for the measurements were 0.52–0.71, 0.71–1.00, 1.00–1.42, 1.42–2.00, 2.00–2.82, 2.82–4.00, 4.00–5.70, 5.70–8.00, 8.00–11.15, and 11.15–16.00 μm.

3. Results and discussion

3.1. Density, visual stratigraphy, and dating of the ice core

The stratigraphy and density profile showed abundant melting features from the surface to the end of the ice core (figure 2). The visible stratigraphy showed that the firn layers accounted for only 7.1% of the total length of the core, while refrozen ice accounted for the remaining 92.9%. The mean density of the entire ice core was 833 kg m^{-3}. As compared with the core drilled in 1987 (Thompson *et al* 1990), our core has a density that is generally higher and melting features are much more abundant, particularly in the upper 10 m (figure 2). According to a report on the previous core (Thompson *et al* 1989), the melt feature (i.e. ice layers) made up less than 5% of the annual accumulation. This suggests that the ice cap melted more intensely after the last drilling, probably due to climate warming.

The tritium record shows a maximum at a depth of 13.8 m (figure 2), which corresponded to the maximum fallout from nuclear weapons testing in 1963. Annual layers were dated with the variations in particle concentrations and δ^{18}O as those of the 1987 core had been dated. In spite of abundant melt features, the spring maximum of particle concentration remained in the core (figure 3). The seasonal variations in δ^{18}O also partly remained (up to 6.2‰). The dating was consistent with the tritium maximum in 1963, and showed that this 51 m deep ice core covered the last 156 years from 2002 to 1846 AD. However, the dating uncertainty at the end of the core is possibly 10 years or less, on the basis of the number of unclear peaks of particle concentration and δ^{18}O that may cause ambiguous identification of annual layers. For the 1987 ice core, Henderson *et al* (2006) suggested that the dating had an error of three years at 1817 AD.

3.2. Stable isotopes and net accumulation

The 11-year running mean of the δ^{18}O record in the 2002 core showed an increasing trend in the late 19th century, least negative in the 1950s, and no significant change in the last 30

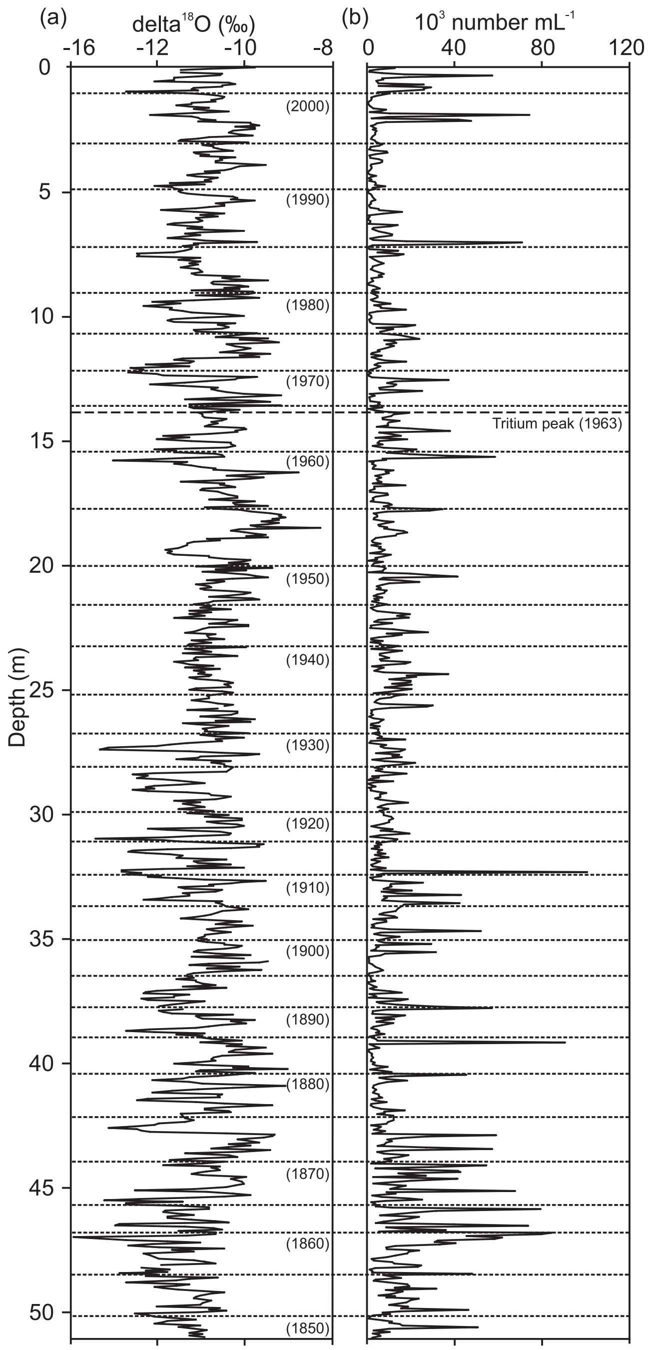

Figure 3. Records of (a) the oxygen stable isotope ratio (δ^{18}O) and (b) the particle concentration (size range: 2.0–2.8 μm) from the surface down to 51 m of the 2002 ice core of the Dunde Ice Cap.

years (figure 4(a)). The period of the running mean was chosen because the dating of the ice core has an uncertainty of 10 years or less. As suggested by many previous studies (e.g. Tian *et al* 2002, Yao *et al* 1996, 2006), the δ^{18}O is related to long-term trends of air temperature in this region. The decadal trends generally agreed with those for the 1987 core (figure 4(b)), and the coefficient of correlation between 2002 and 1987 cores (11-year running mean) is statistically significant (Pearson's correlation coefficient $(r) = 0.788$, sample number $(n) = 133$, probability $(P) = 0.0000 < 0.01$). However, the annual mean values did not agree for the two cores (figures 4(a) and (b)). Also, the decadal δ^{18}O values differed slightly between the cores in some parts, for example, between 1865 and 1945 (mean of the difference between the two cores: 0.62‰). The disagreement is probably due to a different cutting interval, disagreement of annual boundaries, and spatial variation in the δ^{18}O values caused by the melting and refreezing process. It is also possibly due to summer surface melting and dislocation of the melt water to deeper depths which would lead to a positive isotope shift at deeper depths. The annual mean of D excess in the 2002 core varied from −14.5‰ to 28.1‰ with a mean of 15.9‰ for the 156 years in this core. The 11-year running mean showed relatively high levels in the 1890s, 1940–50s, and 1970s–2000s, and lower levels in the 1870s, 1910s, 1930s, and 1960s (figure 4(d)). This variation possibly indicates a variation of moisture sources as suggested by Tian *et al* (2007).

Comparison between the two cores demonstrated a significant decrease in annual net accumulation in the 15 years. For the 1987 core, the beta radioactivity peak was found at a depth of 13.0 m (figure 2 Thompson *et al* 1990) and corresponds to the tritium peak in the 2002 core. The net accumulation from the depth to the surface of the 1987 core was 9360 mm water equivalent (w.e.) and the mean annual net accumulation was 390 mm a^{-1} during the period (Thompson *et al* 1990). On the basis of the net accumulation, the tritium peak in the 2002 core would be expected at a depth of approximately 18 m, but the actual result was 13.8 m. This suggests a considerable decrease of net accumulation over the last 15 years. On the basis of the density profile of the 2002 core, the net accumulation from 1963 (the year of tritium peak) to 2002 (the surface) was 11 121 mm w.e. Therefore, the net accumulation since the last drilling (1987) to 2002 was 1761 mm, and the mean annual net accumulation was 117 mm a^{-1}, which is a 70% reduction from that between 1963 and 1987 (390 mm a^{-1}).

3.3. Recent changes in the ice cap and environment in this region

Most of the melt features in this core strongly suggest significant warming in the last 15 years in this region. Other climate records from this region also show a warming trend after the 1990s. For example, surface air temperature records at the closest meteorological station (Delingha, 150 km east of the ice cap, elevation: 2982 m asl, station No 52737) showed an increase from the late 1970s to the 2000s (figure 4(c), data from the Global Historical Climatology Network (GHCN-Monthly), http://www.ncdc.noaa.gov/oa/climate/ghcn-monthly/, and Yao *et al* 2006). Other stations located in the northern Tibetan plateau also showed a gradual increase from the late 1980s to the 2000s (Yao *et al* 2006). The more significant melt features in this ice core compared to the last core are consistent with these observations, which further suggest that the warming is significant in the high areas over 5000 m asl.

Despite this direct evidence of warming in the ice core, there was no significant increase of the δ^{18}O in the last 15 years. Previous work has revealed that approximately 80% of precipitation occurs in summer on this ice cap, and that the δ^{18}O of precipitation in this region is well correlated with

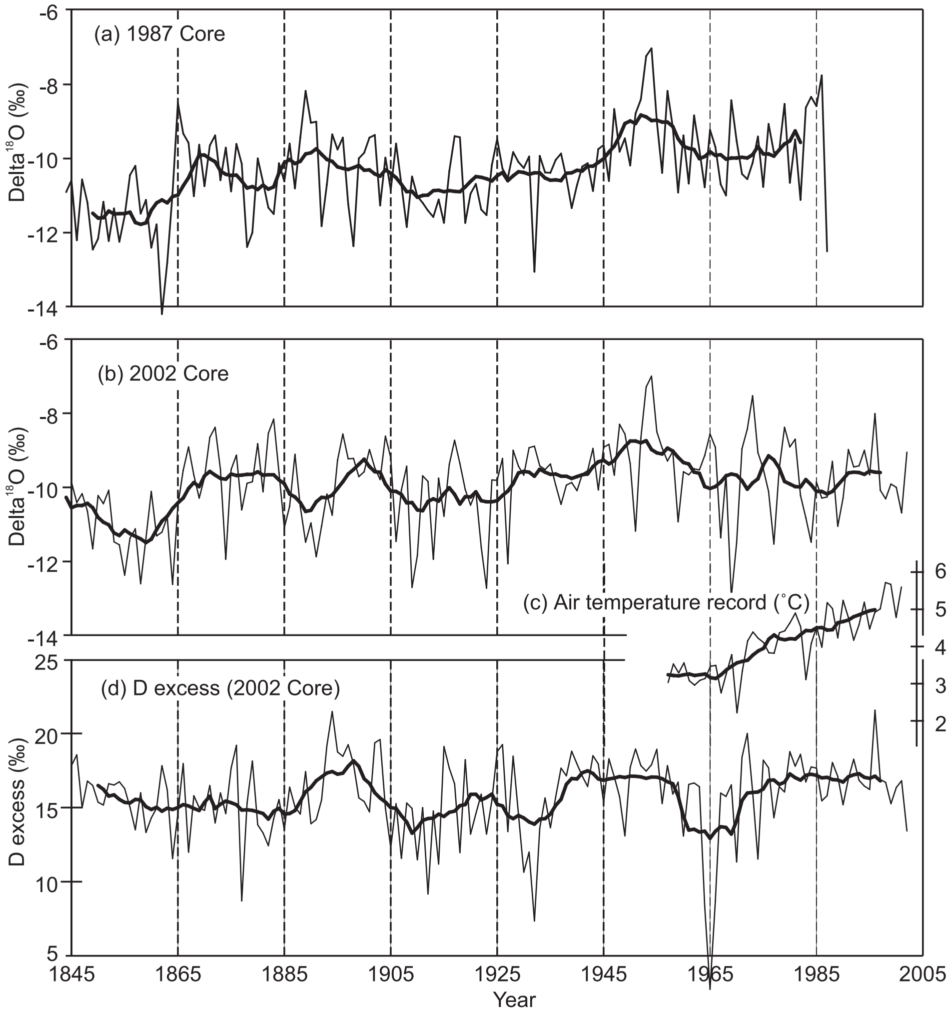

Figure 4. Comparison of annual values of the Dunde ice core and instrumental meteorological station observations. Oxygen stable isotope ratios (δ^{18}O) of (a) the 1987 ice core and (b) 2002 ice cores; (c) the instrumental record of the air temperature at Delingha station, and (d) the D excess of the 2002 ice core.

summer air temperature (Tian *et al* 2002, Yao *et al* 1996, 2006). However, although the δ^{18}O was highest in the 1950s and gradually decreased to the 1990s, surface air temperature records continuously increased from the 1950s to the 1990s (figure 4). One of the possible causes of this discrepancy is a change of moisture sources (e.g. Tian *et al* 2007). However, such a change is unlikely because there was no significant change in the decadal variation of the D excess in the last 15 years (figure 4(d)). Post-depositional modification of stable isotopic signals in the ice core could also account for the discrepancies (e.g. Koerner *et al* 1973). In a warm summer, melt water percolates down and refreezes within the cold snow layer. If the melt water saturates the snow layer, the melt water drains to the melt stream network of the ice cap. This runoff of melt water could cause a decrease in the fraction of summer accumulation against bulk annual precipitation; consequently, the fractional contribution of winter negative δ^{18}O could increase when averaging the very negative winter snowpack and the remaining summer snow. The layers in the upper 5 m of this core were almost continuously refrozen ice without any firn layer. This stratigraphy strongly suggests that there was complete saturation of the snow cover during the summer, so some of the summer accumulation must have been drained. Although the borehole temperatures were not measured in 2002, those in 1987 were $-3.7\,^{\circ}$C at 5 m and $-7.3\,^{\circ}$C at 10 m depth (Thompson *et al* 1990) and could be close to $0\,^{\circ}$C near the surface layers in 2002 on the assumption of climate warming. These ice temperatures could allow some of the percolating melt water to refreeze on the ice surface beneath and remaining water to run off. If more melt occurs, winter snow is further removed to give a less negative δ^{18}O value (Koerner *et al* 1973). However, since the annual signals in particle concentration remained in this part, the hiatus of annual layers was unlikely. Therefore, runoff of summer accumulation may cause the inconsistency between the δ^{18}O record and air temperature, which suggests that the use of δ^{18}O as a proxy for air temperature has become problematic for this mountain ice core in the present conditions.

Although the net accumulation in the ice core significantly decreased in the last 15 years, the precipitation records at the nearby meteorological stations showed a stable or slight increase in the last two decades. For example, rain-gauge measurements (GHCN-Monthly) at the Delingha and the Jyuquan (150 km northeast of the ice cap, station No 52737, 1477 m asl) stations show a slight increase from 1961 to 2001. Yatagai (2007) indicated that precipitation records around the Qilian Mountains show a consistently increasing trend from 1961 to 2001. Therefore, the recent decrease in net accumulation was not likely to be due to precipitation, and was more likely to be due to significant runoff from the intense summer melt over the last 15 years. The net accumulation decrease caused by melt water runoff should result in considerable mass loss of the ice cap. A glacial mass balance survey on the July 1st Glacier in the Qilian Mountains, located 70 km northeast of the ice cap, revealed that the glacier (both length and surface level) has decreased continuously since the 1950s, and its shrinkage was particularly significant after the late 1980s (Sakai *et al* 2006). The study concluded that increasing air temperature caused the recent accelerated shrinkage of the glacier. The records of the 1987 and the 2002 Dunde ice cores are consistent with these observational facts and also support the idea that the mass balance has been more negative since the late 1980s in glaciers of this region.

Although the ice core showed that significant changes of climate occurred in the mountain area at over 5000 m after the 1980s, these changes are unlikely to account for the recent water shortage in the lower downstream basin. Since the mass loss of glaciers in the mountains causes more runoff into rivers, the changes are rather likely to result in an increased discharge to the oasis areas. Therefore, the water shortage is more likely to be due to human impacts such as overuse of agricultural water and degradation by overgrazing of livestock as suggested by Wang *et al* (2007). However, if the negative trends of mass balance of glaciers and ice caps continue, these natural water reservoirs will run dry in the future and will have an impact on the water supply in this basin.

4. Concluding remarks

Comparison between the ice cores drilled in 1987 and 2002 on the Dunde Ice Cap revealed significant changes in glacial conditions as well as climate in this region since the late 1980s. The changes in stratigraphy and density profile of the ice cores suggest significant warming in this area. The decrease of net accumulation suggests a significant mass loss on the ice cap in the last 15 years. These changes are consistent with other meteorological records at the surface stations in this region, and also with the negative mass balance of a glacier observed in this mountain range. Despite direct evidence of recent warming, no significant change in the δ^{18}O was found, suggesting the use of the oxygen stable isotope as a proxy for air temperature to be problematic for the present ice cap conditions.

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