Bulletin of Glaciological Research 26 (2008) *33–40*

Miaoergou Glaciers in the Kalik Mountains, western China: Report of a reconnaissance for future ice core drilling and biological study

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(Received July 22, 2008; Revised manuscript accepted September 1, 2008)

Abstract

Glaciological field studies on Miaoergou Glaciers in the Kalik Mountains, western China were carried out in 2003 and 2004 to investigate the possibility of future ice core drilling and biological observation. Two glaciers, which have dome-shaped accumulation areas at an elevation of approximately 4500 m a.s.l., were investigated. Radio-eco soundings showed that the ice thickness at the top of the two glaciers was 43.7 and 29.6 m, respectively. Snow-pit observations revealed that superimposed ice appeared at 20–50 cm below the surfaces at the top of both glaciers, indicating that significant melting had occurred during summer. Analyses of a 2-m-depth ice core drilled on one of the glaciers showed that it consisted mostly of continuously refrozen ice and that the $\delta^{18}O$ varied from $-15.7‰$ to $-7.2‰$ with a mean of $-10.2‰$. In the ice core were three visible dust layers, one of which contained various microbes including cyanobacteria. Whereas the $\delta^{18}O$ record had proved rather unsatisfactory as an air temperature proxy due to melt water runoff, a reconstruction of dust deposition and biological activity on the glacier might be possible using an ice-core study.

1. Introduction

Several ice cores have been drilled on glaciers in high Asian mountains since the late 1980s. These cores have revealed environmental conditions dating back hundreds to thousands of years in this region and have significantly contributed to our understanding of the climate system in that region (*e.g.* Thompson *et al.,* 2006). These cores have also revealed geographical variations in the climate history of the Asian high plateau. For example, there have been antisynchroneities in stable isotopes between the eastern and western Tibetan Plateau (Lin *et al.,* 1995), as well as in accumulations between the eastern and western Himalayas (Kaspari *et al.,* 2008) for the last thousand years. In order to understand the spatial variations in former environments and climates in the Asian high plateau, more ice cores need to be recovered from new locations.

Geographical variations can also be made apparent by studying microbial communities living on those glaciers. Recent studies have revealed diverse biological communities on many glaciers across the world (*e.g.* Kohshima, 1987). Such communities usually consist of snow algae, bacteria, micro animals, and insects. These are specialized species that have adapted to live on snow and ice environments. Community structure and biomass vary among glaciers in different geographical locations. For example, snow algal communities differ on glaciers from northern Asia (Altai), middle (Tibet), and southern Asia (Himalayas; Takeuchi *et al.,* 2006). The characteristics of organic matter derived from such biological activities also vary on different Asian glaciers (Takeuchi, 2002 b). The biogenic material is usually composed of a dark sediment called cryoconite (*e.g.* Takeuchi *et al.,* 2001a). These geographical variations in biological communities and biogenic materials may be due to differences in the physical and/or chemical conditions on glaciers, but they need to be better understood for future studies of glacial eco-systems and the usefulness of biogenic materials for ice core analysis.

The Kalik Mountains are located at the eastern boundary of the Tien Shan Mountains of western China at elevations up to approximately 4800 m a.s.l. There are more than 30 small glaciers in this mountain range, some of which appear promising sites for ice core drilling. The geographical location of this mountain range is very important in terms of its atmospheric circulation. This area is on a boundary between two major sources of water vapor: east (monsoon vapor from the Pacific or Indian Oceans) and west (westerly vapor from the Arctic or Atlantic Oceans; *e.g.* Tian *et al.,* 2007). Therefore, ice cores drilled in this mountain range could provide valuable information on the Asian climate system.

We carried out two reconnaissance field trips in the in summers of 2003 and 2004. This paper describes the physical, chemical, and biological conditions on the two Miaoergou Glaciers as a promising ice core drilling sites based on our investigations.

2. Study site and methods

These investigations were carried out on two Miaoergou Glaciers (43°03′N, 94°18′E) in the Kalik Mountains, which are located north of Hami City in the Xinjyang Uygur autonomous region of China (Fig. 1 (a)). The Miaoergou Glacier is named after a small village in that area. There are more than 30 small glaciers in this mountain range (Fig. 1 (b)). The term "Miaoergou Glacier" does not denote one specific glacier, but rather refers to all the glaciers in the mountain range covered in this paper. There is a serious dearth of glaciological information on these glaciers. There have been only a few reports on the glaciers in this mountain region, all of which were published in Chinese (*e.g.* Li *et al.,* 2007).

Two of the glaciers (A and B in Fig. 1 (b)) were investigated in this study, and were selected because they have a dome-shaped accumulation area and are relatively accessible (Fig. 2). Elevations of the top of the glaciers are 4510 m a.s.l. for Glacier A and 4530 m a.s.l. for Glacier B. Both glaciers flow mainly westward down to their terminus at 4200 m a.s.l. for Glacier A and 4230 m a.s.l. for Glacier B. Field studies were carried out from 5 to 10 September 2003 on Glacier A, and from 27 August to 4 September 2004 on Glaciers A and B. The local people (Uyghurs) of a village in this area refer to Glaciers A and B as Ailixibixi and Kazaidabutai, respectively. Glacier A is accessible from the village of Badashi, and Glacier B from Shuiting Village.

Ice thickness was sounded using two ice-penetrating radar systems. One system designed by Matsuoka *et al.* (2004) was used on Glacier A in 2003; its pulse amplitude and the center frequency of its transmitted signal were about 990 V and 5 MHz, respectively. The system included a controller, which sets the measurement parameters, and displays and stores data. Further specifications of the system are described in Matsuoka *et al.* (2004). The measurements were continuously conducted from SA3 to the top of the glacier (SA7) via SA4, SA5, SA6 in Fig. 3.

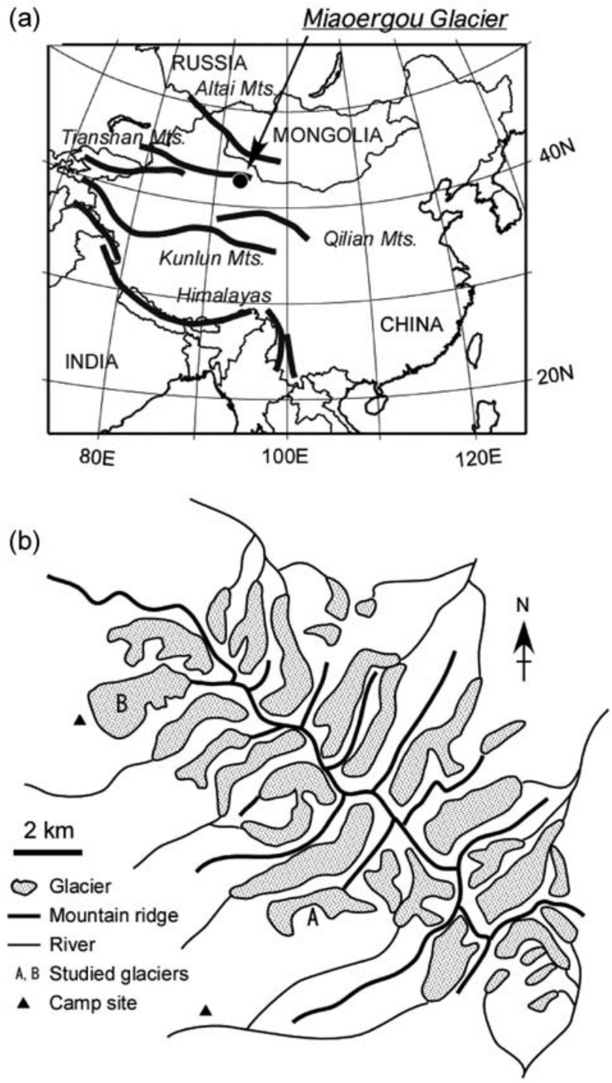

Fig. 1. Location (a) and map (b) of the Miaoergou Glaciers in the Kalik Mountains, China. Two studied glaciers (Glaciers A and B), and campsites are shown on the map.

The second system using radar was manufactured by Ohio State University, and employed on Glacier B in 2004. It was powered by a 12 V battery, and produced a short pulse signal of a few hundred volts in amplitude which was radiated using a resistively loaded dipole antenna. The center frequency of the transmitted signal was about 5 MHz. A dipole antenna identical to that of the transmitter was used for a receiver. The transmitted and returned signals were recorded by an oscilloscope (Tektronic Digital Storage Oscilloscope) and photographed; travel time was then measured. The measurements were conducted at 6 sites on the glacier (SB1-SB6 in Fig. 4). The ice thickness (d) was calculated by the following equation:

$$d=\sqrt{\left(\frac{\nu T}{2}\right)^2-L^2} \tag{1}$$

where v (m μs^{-1}) is the velocity of the radio wave, T

Fig. 2. Pictures of the surface of Miaoergou Glaciers (a) View of top of the Glacier A from site SA3. (b) View of Glacier B on the way to camp site.

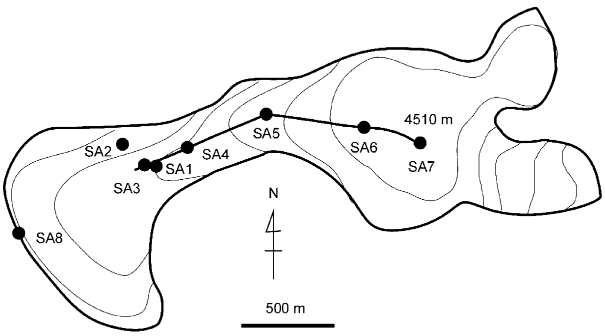

Fig. 3. Map of Glacier A showing study sites for radio-eco sounding and surface ice sampling.

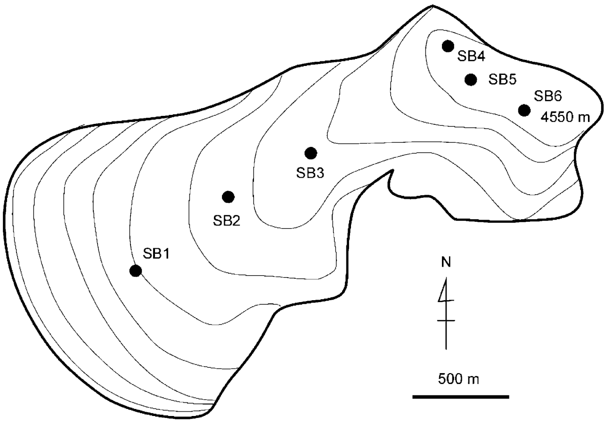

Fig. 4. Map of Glacier B showing study sites for radio-eco sounding and surface ice sampling.

(μs) is delay time, and $2L$ (m) is antenna-separation distance.

To measure annual net accumulation (mass balance) on the glacial surface, 5 bamboo stakes each 2-m in length were installed at sites SA3, SA4, SA5, SA6, and SA7 on Glacier A in 2003. These stakes were buried about 50 cm below the snow surface. Two old stakes at SA1 and SA2, which were found during our fieldwork in 2003 and may have been installed before by other researchers, were also measured in 2003 and 2004. The change of stake height above the glacial surface between 2003 and 2004 was measured.

Snow pits were dug at SA3 on Glacier A in 2003 and at the top (SB6) of Glacier B in 2004. Stratigraphy was recorded and density measured every 10 cm. Snow samples were collected at every 10 cm of the snow pits and put in plastic bags (Warlpak). In addition to the snow-pit study, a 2-m-deep ice core was drilled at the top (SB6) of Glacier B. Stratigraphy was recorded, and weight was measured for density immediately after drilling. The ice core was then cut into 5-cm sections, and each one was stored in a plastic bag (Warlpak). When the snow-pit and ice-core samples were melted in the bags, pH and electrical conductivity were then measured (D-54, Horiba, Japan). Then, the samples were poured into glass vials for isotope analysis, and into plastic bottles for particle and microbial analyses. Formalin was added to the plastic bottles to arrest biological activity. All samples were then transported to the Research Institute for Humanity and Nature in Kyoto, Japan.

The samples were analyzed at Nagoya University for oxygen and hydrogen stable isotopes with a mass spectrometer (Finnigan Delta XP). The analytical precision of δ^{18}O and δD measurements were 0.05 and 0.5‰, respectively. Deuterium excess (D excess) was obtained from a definition by Craig (1961) as $d = \delta D - 8.0\,\delta^{18}O$. Particle concentration was measured by visual counting under an optical microscope (E600, Nikon, Japan). 200 μL of the samples was filtered with a hydrophilized membrane filter (pore size 0.5 μm, 13 mm diameter, Advantec, H020A013A). The particles on the filter were observed with an optical microscope. Particles more than 2 μm in diameter were counted, and particle concentration was obtained. Microbes on the filter were also examined using a florescent microscope.

Surface ice on the ablation area of both glaciers was collected in order to quantify dust and to describe microbes on the glaciers. Ice on the surface layers was collected with a stainless-steel scoop (approximately 10 cm × 10 cm in area and 1–3 cm in depth) in the bare ice areas from one site on Glacier A and two sites on Glacier B (SA8, SB1, SB2, Figs.3 and 4). Five samples were collected from randomly selected surfaces at each study site. Collection areas on the surface were measured to calculate the amount of dust per unit area. To arrest biological activity, the collected samples were melted and preserved as a 3% formalin solution in clean 30-ml polyethylene bottles. All samples were transported for analysis to a laboratory of the Research Institute for Humanity and Nature, in Kyoto, Japan. The samples were dried (60℃, 24 hours) in pre-weighed crucibles. The amount of dust per unit area of the glacier was obtained based on measurements of the dry weight and the sampling area. The dried samples were then combusted for 3 hours at 500℃ in an electric furnace, and weighed again. The amount of organic matter was calculated from the difference in weight between the dried and combusted samples, this method is slightly modified from Dean (1974). After combustion, only mineral particles remained. To investigate the composition of the surface dust, other samples of surface ice/snow were collected and examined with optical microscopes (Leica MZ125, and Nikon E600).

3. Results

3.1 Radio-echo soundings

Radio-echo soundings showed the ice-thickness variations of Glaciers A and B. Figure 5 depicts an example of a time series of received voltage (SA3 on Glacier A); reflection signals were clearly observed in the wave. The result of continuous measurements along a glacial longitudinal line from SA3 to SA7 on Glacier A was shown in Fig. 6. The ice thickness ranged from 21.2 to 53.6 m, while that at the top of the glacier, which was a potential drilling site, was 41.7 m; the thickest ice was found near site SA6 (53.6 m).

The results of radio-echo soundings on Glacier B were shown in Table 1. The thickness ranged from 29.6 to 76.5 m, while that at the top of the glacier was 29.6 m. The thickest ice was found at site SB2 (76.5 m).

3.2 Stake measurement

All five stakes installed on Glacier A in 2003 could not be found the following year, 2004. They most likely fell on the glacial surface due to significant ablation (more than 50 cm) in summer of 2004, and were buried in new snow. Thus, the stakes could not be used for net accumulation measurements. However, the two old stakes (SA1 and SA2) found at the middle of Glacier A in 2003 were still intact and could be re-measured in 2004. The mass balance between 2003 and 2004 at both stakes was negative. The height changes were 62 cm for SA1 and 69 cm for SA2.

3.3 Snow pit and ice core

A 0.56-m deep snow pit at site SA3 on Glacier A showed a stratigraphy with a mix of snow and ice layers (Fig. 7). Beneath the bottom of the snow pit was a thick ice layer. Snow density ranged from 299 to 517 kg m^{-3}, and three visible dust layers were found

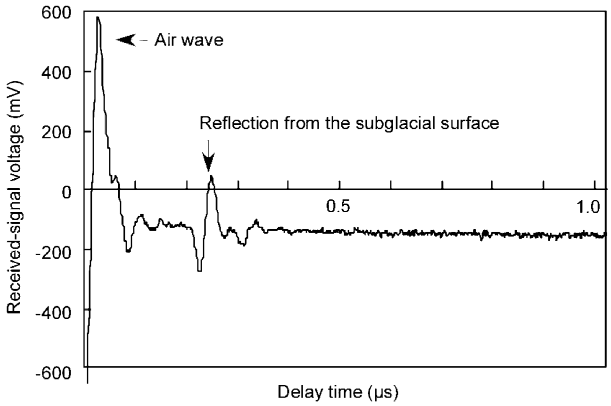

Fig. 5. Time series of received voltage at the site SA3 on Glacier A.

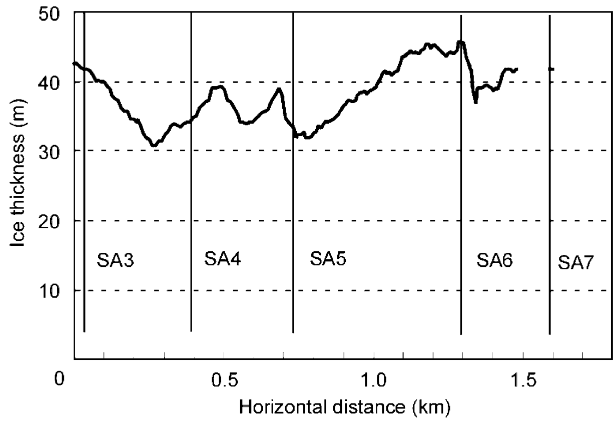

Fig. 6. Ice thickness profile along the study sites showing in Fig. 3. The thickness was calculated based on a radio propagation speed of 169 m μ sec^{-1}.

Table 1. Results of radio radar sounding on the Glacier B

Site	Coordinate	Elevation m a.s.l.	Travel time μ sec	Depth m
SB1	N43 06.344 E94 14.294	4230	0.7448	69.8
SB2	N43 06.561 E94 14.747	4306	0.8220	76.5
SB3	N43 06.716 E94 14.984	4347	0.5828	55.7
SB4	N43 06.939 E94 15.699	4493	0.3656	36.4
SB5	N43 07.001 E94 15.537	4466	0.3360	35.9
SB6	N43 06.908 E94 16.015	4528	0.2932	29.6

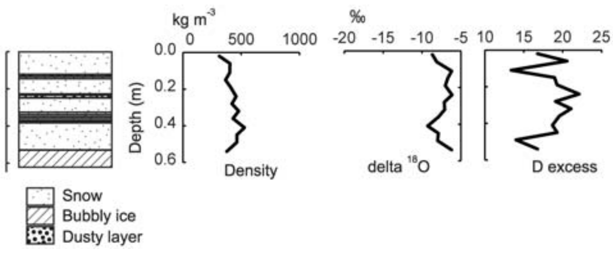

Fig. 7. Stratigraphy, $\delta^{18}O$, D excess of a 0.6-m-snow pit at site SA3 on Glacier A.

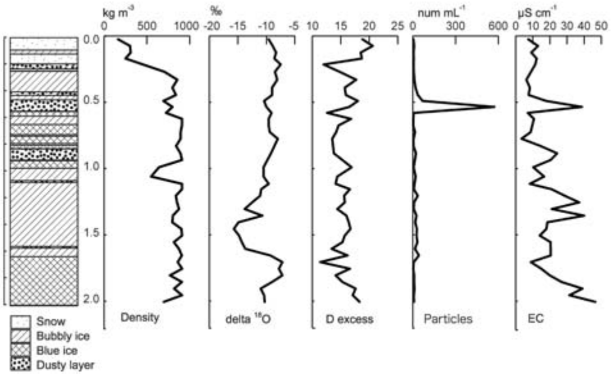

Fig. 8. Stratigraphy, δ^{18}O, D excess, electrical conductivity of a 2-m-ice core drilled at site SB6 on Glacier B.

in the pit. The δ^{18}O ranged from -9.28 to -6.15‰ (mean: -7.42‰), and D excess ranged from 13.4 to 22.1‰ (mean: 18.4‰).

The stratigraphy and density profile of a 2-m deep ice core drilled at SB6 (4550 m, the top of Glacier B) showed that there was a snow layer only above 0.24 m, while the remainder below that depth was refrozen ice (Fig. 8). Three visible dust layers were apparent in the stratigraphy. The δ^{18}O profile showed a range of variations with a maximum (-7.21‰) at 1.71 m and minimum (-15.74‰) at 1.46 m. The mean δ^{18}O was -10.21‰, with D-excess ranging from 11.4 to 20.6‰ (mean: 15.8‰). Electrical conductivity varied from 3.44 to 46.50 μS cm^{-1} (mean: 17.98 μS cm^{-1}), and particle concentrations in the core from 2.7×10^3 to 5.7×10^5 numbers mL^{-1} (mean: 2.8×10^4 numbers mL^{-1}). There was a distinctive peak of particle concentrations at 0.54 m. Observation with fluorescent microscopy revealed that abundant microbes including filamentous and unicellular cyanobacteria were contained in this dust layer (Fig. 9).

3.4 Dust on the ablation surface

Table 2 shows the characteristics of surface dust collected from the bare ice areas on Glaciers A and B. The amounts of dust in dry weight ranged from 73.6 to 205 g m^{-2} (mean: 142 g m^{-2}, standard deviation (SD)= 51) on Glacier A, and from 27.1 to 295.6 g m^{-2} (mean: 98.2 g m^{-2}, SD=89) on Glacier B. The surface dust contained levels of organic matter ranging from 7.6 to 11.2% (mean: 9.6%, SD=1.1) in dry weight. The amounts of organic matter per unit area on the ice surface ranged from 2.7 to 31.1 g m^{-2} (mean: 10.9 g m^{-2}, SD= 8.1).

A microscopic study of the surface dust revealed mineral particles, amorphous organic matter, and living cyanobacteria. Brown organic granules, which were the main component of the dust, were spherical in shape and contained an abundance of filamentous cyanobacteria and mineral particles (Fig. 10). The size of the organic granules ranged from 0.22 to 1.8 mm

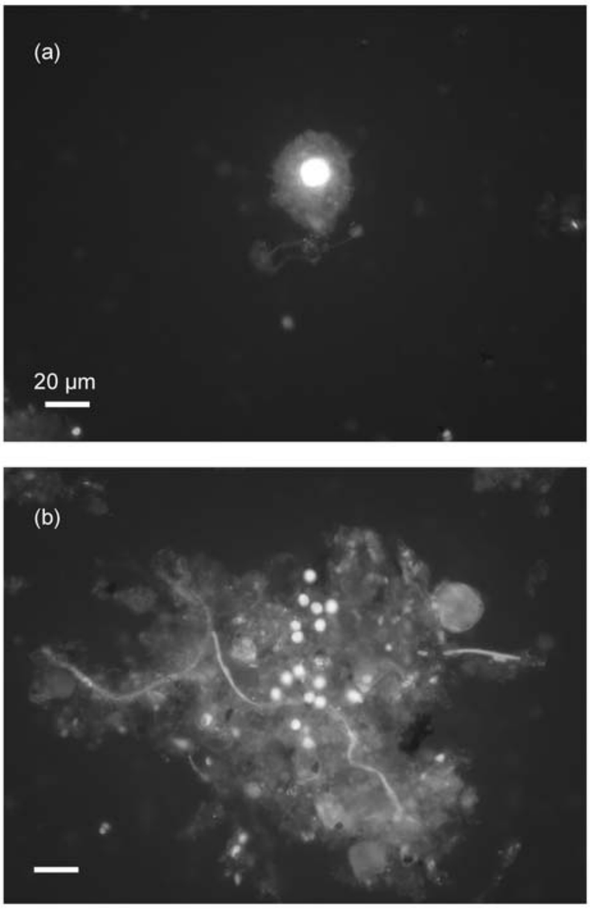

Fig. 9. Microbes in an ice core sample on Glacier B (0.54 m from the surface) observed with a fluorescent microscope. (a) a green alga, (b) filamentous and unicellular cyanobacteria.

Table 2. Amount of cryoconite, mineral particles, and organic matter on the ablation surfaces on the Miaoergou Glaciers.

Glacier and sampling site (altitude)	Date	Surface condition	Total surface dust (cryoconite) g m^{-2}	Mineral particles g m^{-2}	Organic matter g m^{-2} (%)
Glacier A SA8 (4200)	2003/9/8	Ice	142 ± 51	128 ± 46	13.9 ± 5.6 (9.6 ± 0.53)
Glacier B SB1 (4230)	2004/8/29	Ice	104 ± 112	93 ± 100	10.9 ± 12 (10.5 ± 0.46)
Glacier B SB2 (4306)	2004/8/29	Ice	92 ± 72	84 ± 66	7.8 ± 5.9 (8.6 ± 0.30)

(mean: 0.75 mm, SD=0.22) for SA8 on Glacier A, and from 0.20 to 2.9 mm (mean: 1.0 mm, SD=0.44) for SB1 on Glacier B. Observation with a fluorescence microscope revealed at least three taxa of filamentous cyanobacteria with autofluorescence densely covering the surface of the granules. The cell size (diameter) and characteristics of the three taxa were: (1) 4.7 ± 0.79 μm (mean±SD) with a sheath, (2) 2.2 ± 0.26 μm with a sheath, and (3) 1.4 ± 0.14 μm without a sheath (Fig. 11). The mineral particles in the dust were brown, white, or transparent, and were microscopically observed to

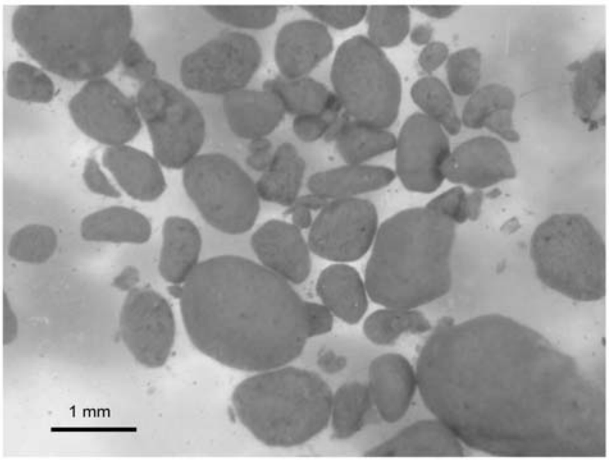

Fig. 10. Surface dust (cryoconite granules) at SA1 on Glacier A.

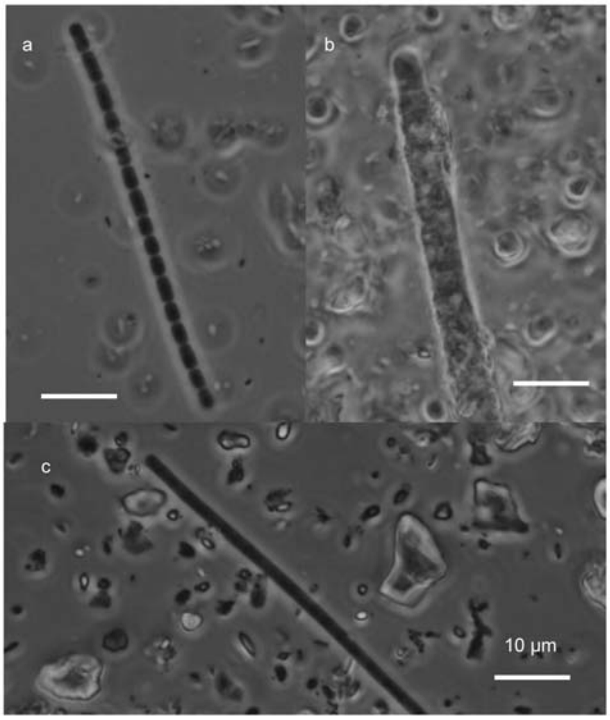

Fig. 11. Photos of three taxa of filamentous cyanobacteria observed on Glaciers A and B.

range from 3.1 to 63 μm (mean: 10.7 μm, SD = 7.1 for those larger than 3.0 μm) in diameter. The minerals appeared to be quartz, feldspar, mica, calcite, and clay minerals, although more detailed analysis will be required.

4. Discussion

4.1 Suitability of glaciers as ice core drilling sites

Both of Glaciers A and B were dome-shaped with a flat surface at the top, which seemed to be suitable for ice core drilling since flat annual layers with little glacial flow can be expected at such sites. However, results of our field investigation showed some potential difficulties for ice core drilling. The ice thicknesses measured by radio-echo sounding at the top of Glaciers A and B were 43.7 and 29.6 m, respectively, which are generally shallower compared with ice cores drilled on other Asian glaciers. For example, ice cores of 140 m were recovered from the Dunde Ice Cap in the Qilian Mountains (Thompson 1989), while a 320-m core was recovered from the Guliya Ice Cap in the Kunlun Mountains (Thompson *et al.,* 1997). Shallower ice depths on glaciers suggest that they contain only the ice from relatively shorter time periods or the ice of thin annual layers (less amounts of annual net accumulation). Moreover, significant melting features observed in the snow pits and ice cores on glaciers also imply analytical difficulties for ice core study. Significant melting at the top of the glaciers is revealed by stake measurements and the stratigraphy of a 2-m ice-core sample. The stake installed at top of Glacier A (4510 m a.s.l.) in 2003, was found to have fallen by the following summer. This indicates that the surface level has dropped by at least 50 cm due to summer melting. Percolating melt water can alter both the chemical and isotopic records in ice cores (*e.g.* Li *et al.,* 2006; Hou *et al.,* 2006; Koerner *et al.,* 1973). Although some variations in a stable isotope in a 2-m ice-core sample were observed (Fig. 8), the record seems to imply difficulties in their usefulness as an air temperature proxy, since continuous refrozen ice in an ice core suggests that some accumulation has been lost due to melt water runoff (Koerner *et al.,* 1973). Thus, the suitability of chemical and isotope information for ice core study on these glaciers appears questionable.

In contrast to chemical and isotopic records, however, insoluble particles are more likely to prove useful for such ice core studies. Microscopy of our ice core samples revealed a clear dust peak at a depth of 0.51–0.56 m. The dust peak layer was probably formed by a spring maximum of airborne dust in this region. A variation in dust concentrations can be used for the dating of an ice core (*e.g.* Han *et al.,* 2006). In addition, annual dust flux derived from such concentrations would provide valuable data on environmental changes in a region. Moreover, microscopy has revealed significant numbers of microbes contained in dust layers. A layer 0.51–0.56 cm in depth was found to contain unicellular and filamentous cyanobacteria. Cyanobacteria are among the most common microbes on glaciers in this region (Takeuchi *et al.,* 2005). Their biomass and community structure can reflect environmental conditions such as radiation and nutrients, thus making their analysis a potential source of valuable data for the reconstruction of past environments from an ice core.

Ice cores were drilled in 1993 at an elevation of 4100 m on the Ürümqi No. 1 Glacier, which is located approximately 300 km west of the Miaoergou Glaciers. The cores have been analyzed and revealed the history of soluble ions and dust concentrations in the region (*e.g.* Lee *et al.,* 2003). However, the $\delta^{18}O$ records of the ice cores were found to be significantly altered by melt water, which rendered them unsuitable as an air temperature proxy (Hou *et al.,* 2006). The conditions of intense melting on the Miaoergou Glaciers seemed similar to that at the drilling site of the Ürümqi No. 1 Glacier. Although the use of chemical and isotopic records would be problematic on both the Miaoergou and Ürümqi glaciers, a geographical comparison of the records of dust flux and/or microbes might provide valuable information to improve our knowledge of dust transportation and the variations of the biological community in this region.

4.2 Dust and microbes on the ablation surface

Surface dust in the ice areas of the both glaciers contained high levels of organic matter and cyanobacteria. The percentage of organic matter on the glaciers (8.6–10.5%, Table 2) is comparable to those on glaciers in the Tien Shan Mountains (mean 11.2%, Takeuchi and Li, 2008), and in the Qilian Mountains (mean: 8.7%, Takeuchi *et al.,* 2005), and in the Himalayas (mean: 7.13%, Takeuchi *et al.,* 2001a), on which an abundance of microbes has been reported. Microscopy showed that the dust consisted mainly of minute brown granules (Fig. 7). Their size, composition, and structure resemble those of the cryoconite granules, which grow as algal mats on the glacial surface (*e.g.* Takeuchi *et al.,* 2001a). Such granules are therefore likely to be the products of biological activity on the glacial surface.

The amount of total (organic plus inorganic) surface dust on the ice surface of the Miaoergou Glaciers is less than on other Asian glaciers in China and the Himalayas, but is markedly greater than on glaciers in other parts of the world. According to previous studies, the average amount on the Ürümqi Glacier No. 1 in the Tien Shan Mountains was 334 $g\,m^{-2}$ (Takeuchi and Li, 2008), while that on the July 1st Glacier in the Qilian Mountains was 292 $g\,m^{-2}$ (Takeuchi *et al.,* 2005), and that on the Yala Glacier in the Himalayas was 225 $g\,m^{-2}$ (Takeuchi *et al.,* 2001a). These amounts are roughly two- to three-fold greater than those on the Miaoergou Glaciers (92–142 $g\,m^{-2}$, Table 2); the lesser dust amounts on the latter may be due to low levels of airborne dust deposition on the glaciers. In contrast, the amounts of surface dust are reported to be less than 50 $g\,m^{-2}$ on glaciers in the Canadian Arctic, Alaska, and Patagonia (Takeuchi, 2002a; Takeuchi *et al.,* 2001b; Takeuchi *et al.,* 2001c), suggesting that the dust deposition on the Miaoergou Glaciers is larger than those glaciers.

The surface dust on the glaciers is likely to significantly reduce the surface albedo, as reported on other Asian glaciers. The surface dust on Chinese and Himalayan glaciers has been reported to substantially reduce surface albedo and to accelerate ablation of the glaciers (*e.g.* Kohshima *et al.,* 1993; Takeuchi *et al.,* 2001b). Since the dust was visibly apparent on the ice surfaces of our studied glaciers, its effect on surface albedo is likely to be substantial, even although the amounts of dust were smaller than those on other Asian glaciers. Both the organic and inorganic components of dust seem to contribute to surface albedo reduction, though the quantitative contribution of each component to the total reduction is uncertain.

Cyanobacterial dominance in algal communities on the glacial surface in our study is similar to those reported on glaciers in the Tien Shan and Qilian Mountains, but different from those in the Altai and Himalayas. Filamentous cyanobacteria were dominant on the glacial ablation surface of Ürümqi Glacier No. 1 and the July 1st Glacier, and no green algae (Chlorophyta) were observed on those glaciers (Takeuchi and Li, 2008, Takeuchi *et al.,* 2005). In contrast, algal communities consisting of cyanobacteria and green algae were observed on the Akkem Glacier in the Altai and Yala Glacier in the Himalayas (Takeuchi *et al.,* 2006; Yoshimura *et al.,* 1997). Our results showed that the cyanobacterial dominance in snow algal communities is common on the glaciers in the northern part of the Tibetan Plateau from eastern Tienshan (Ürümqi Glacier No. 1 and the Miaoergou Glaciers) to the Qilian Mountains (July 1st Glacier), and that it differs from the one in Altaic and Himalayan glaciers. This geographical difference in algal communities may result from physical and/or chemical conditions on the glaciers, and could prove valuable in understanding the characteristics of Asian glaciers. Further investigations of other glaciers in this region will be required to reveal the underlying factors responsible for such geographical variation in glacial microbial communities.

Acknowledgments

We wish to thank the staff and students (Xingping Zhang, Chongyi E, Yong Wang, and Chao Lu) of Qinghai Normal University, Akiyo Yatagai of the Research Institute for Humanity and Nature for their generous field assistance. We are also indebted to the staff of the Hydrospheric Atmospheric Research Center of Nagoya University for their help in stable isotope analysis. We also thank S. Kohshima for review of this manuscript. This study was a part of the Oasis and the Ili Projects funded by the Research Institute for Humanity and Nature, and was also supported by the Japanese Government's Special Coordination Fund for the Promotion of Science and Technology. Laboratory analyses were partly supported by a Grant-in-Aid for Young Scientists (A, No. 18681005) and by a Grant-in-Aid for Scientific Research (No. 19310020 and 19201005) from the Japan Society for the Promotion of Science (JSPS).

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