# Preliminary observations of sub-surface and shallow ice core at July 1st Glacier, China in 2002–2004

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## Abstract

The albedo reduction on glacier surfaces in past summers due to microbiological activities and mineral particles should be considered to reconstruct precise fluctuation of glacier mass balance. However, there is little knowledge on preservation of the microorganisms and the mineral particles in glacier ice. In particular, influence of superimposed ice formation on these preservations is unknown. As the first step to understand the albedo reduction process and to reconstruct surface albedo changes on glaciers in northwestern China, where superimposed ice formation has an impact on glacier mass balance, we report the glacier surface level changes, seasonal and annual changes of stratigraphy and analyzed results of short ice cores at upper parts of the July 1st Glacier from 2002 to 2004. Surface melting on the glacier was accelerated by dark-colored materials composed of cryoconite and mineral particles. The glacier surface level was lowered year by year and ELA (Equilibrium Line Altitude) was much higher than that in the 1970s and 1980s. An ice core of 1.82 m length included five cyanobacterial layers. As cyanobacteria grow during summer, these layers may be useful as markers for summer layers and allow to infer surface albedo changes in the past. Average annual snow mass balance estimated from the cyanobacterial peaks in the core is 313 mm, which corresponds to the annual precipitation observed near the terminus of the July 1st Glacier. These results would open up the possibilities that we could reconstruct past mass balance and albedo effects.

#### 1. Introduction

Glaciers in arid and semi-arid regions of central Asia are the most important sources of fresh water. However, glaciers in Qilian Mountains of China have been retreating and shrinking rapidly. Moreover, the shrinkage has been accelerated in the recent few decades (Liu, *et al.*, 1992, 2003; Sakai *et al.*, 2004). One of its reasons would be the temperature increasing, since Liu and Chen (2000) revealed that the recent air temperature increases were larger at higher altitudes in the Tibetan Plateau.

The Qilian Mountains are located in  $36-39^{\circ}$  N,  $94-104^{\circ}$  E, with length of about 850 km and width of 200-300 km, in the northwestern Qinghai-Tibetan Plateau of west China. There are 2815 glaciers, most of which are located on the north facing slopes, and the entire glaciated area was 1390.49 km<sup>2</sup> in 1980 (Wu, 1985).

July 1st Glacier is located on the western part of the Qilian Mountains. Many observations have been carried out since 1958 in glaciology, hydrology and meteorology (Lanzhou Institute of Glaciology and Geocryology, 1985, 1992; Shi *et al.*, 1988; Matsuda *et al.*, 2004; Sakai *et al.*, 2006). Some portion of the meltwater should refreeze in snow layer and form the superimposed ice. It is, therefore, necessary to take into account the refrozen amounts in order to estimate the mass balance of a glacier (Fujita *et al.*, 1996; Fujita and Ageta, 2000).

During winter, continental air makes this region dry and cold. On the other hand, in summer, southwesterly and southeasterly monsoons from Indian and Pacific Oceans provide the moisture to this region. Therefore, precipitation is concentrated in the summer season (from June to September), and snow accumulation and melting on the glaciers coincide during the summer season. There is relatively high precipitation (more than  $300 \text{ mm yr}^{-1}$ ) at high elevations (more than 3000 m a.s.l.) in these mountainous areas (Ding and Kang, 1985; Zhu and Wang, 1996), while there is little precipitation (less than 50 mm yr<sup>-1</sup>) downstream (Ding and Kang, 1985; Wang and Cheng, 1999).

The Japan-China joint research team has carried out many observations on the July 1st Glacier from June 2002 to September 2005. The observations on the glacier surfaces suggested that mud-like materials composed by microbiological activities during summer reduced the albedo, would accelerate the surface melting, and would affect the mass balance (Takeuchi et al., 2005). And recent shrinkage estimated from the altitudinal profiles of the mass balance (Matsuda et al., 2004) would be affected by the microbiological activities. However, determination of annual layers in ice cores obtained from superimposed ice zone has still been difficult. Moreover, influence of superimposed ice formation on preservation of microorganisms and mineral particles is unknown. As the first step to understand the albedo reduction process and to reconstruct the past surface albedo on glaciers from ice cores composed by superimposed ice in northwestern China, we present preliminary results regarding glacier surface level changes, seasonal and annual changes of stratigraphy near the surface, and analyses of short ice cores at the upper parts of July 1st Glacier from 2002 to 2004.

#### 2. Physical setting of July 1st Glacier

The July 1st Glacier is located at  $39^{\circ}15'N$ ,  $97^{\circ}45'E$ , in the Qilian Mountains, northwestern Qinghai-Tibetan Plateau of west China. The altitude of this glacier is 4295–5088 m a.s.l. and its length is 3.8 km (Liu *et al.*, 1992). Dyurgerov (2002) showed that the ELA was 4550–4710 m a.s.l. in the mid-1970s and 1980s.

The glacier is polar type (Huang, 1990), and the instant ice temperature data at 6 m depth in August showed  $-6^{\circ}$ C during the 1970s (Xie *et al.*, 1985). Some portion of the melt-water should refreeze in snow layer. It is, therefore, necessary to take into account the refrozen amount in order to estimate the mass balance of the glacier (Fujita *et al.*, 1996; Fujita and Ageta, 2000).

# 3. Observations and analysis methods

Meteorological observation, pit work and ice core drilling were carried out in 2002–2004 at ST8-2 (4613 m a.s.l.) and ST10 (4824 m a.s.l.) in the upper part of this glacier (Fig. 1). In the situations during the 1970s and 1980s, the locations of ST8-2 and ST10 were around the equilibrium line altitude and in the accumulation area, respectively.



Fig. 1. Location map of July 1st Glacier (upper) and contour map of the July 1st Glacier (lower) produced by Shi *et al.* (1988). Solid circles in the lower map show locations of the observation sites of ST8-2 and ST10.

Automatic weather stations (AWS) were installed at ST8-2 and ST10 to measure air temperature and surface level. Ice temperature was measured at ST8-2 from Jun 2002 to Jul 2004.

Pit works were carried out at ST10 from 16 Jun to 30 Aug in 2002 with intervals of 1-2 weeks to observe stratigraphy and surface level changes. On 17 Sep. 2003, an ice core of 1.82 m length was taken by hand drilling at ST10, and stratigraphy, ice crystal size and the major axis of bubble were observed on site. In 2004, we carried out surface snow pit surveys and ice core sampling on 30 May and 2 June at ST8-2 and ST 10. There was a snow layer on the ice with depth of 0.26 m on 30 May at ST8-2. A shallow ice core of 3.06 m length was obtained by using an ice auger after removing the entire surface snow cover. On the other hand, at ST10, an ice core was obtained by removing surface snow of 0.36 m thickness and its length was a 2.07 m. Stratigraphies of both the ice cores and the pits were observed on site. Snow densities were also measured at the pits.

The core samples were cut by pre-cleaned ceramic

knifes into each 0.05-0.10 m length. The core surface was scraped off by thickness of 10mm with precleaned ceramic knifes on site in order to eliminate contamination. These samples were packed into sterilized plastic bags. After melting, all samples were dispensed into clean plastic bottles for biological and isotopic analysis. Oxygen isotopes in the ice core samples were measured with a dual-inlet isotope mass spectrometer Finnigan Delta Plus at the Hydrospheric Atmospheric Research Center, Nagoya University. The biological samples were added with formalin of 3% in the sample volume for preservation. For analysis of microorganisms, sample of 0.03-0.10 ml volume was filtered on hydrophilic polytetrafluoroethylene (PTFE) membrane filters (JHWP01300: pore size 0.2  $\mu$ m, 13 mm diameter; Millipore, USA), and cells of microorganisms on the filters were counted by using a fluorescent microscope (NIKON: E-600). Microbiological density was determined by the counted cell numbers in samples and expressed in the unit of "cells mL<sup>-1</sup>". Mean cell volume ( $\mu$ m<sup>3</sup> cell<sup>-1</sup>) was estimated by measuring their dimensions with the microscope. Total biomass of microorganisms in the sample was represented by total cell volume ( $\mu m^3 m L^{-1}$ ), which was the product of the microbiological density and the mean cell volume.

# 4. Results and discussion

#### 4.1. Surface level changes in 2002-2004

Figure 2a shows surface level variations at ST8-2 measured with the stake during three periods (Jun 15 -Sep 4, 2002; Aug 14-Sep 21, 2003; and May 28-Sep 10, 2004) and with a snow depth meter from Sep. 22, 2003 to Sep. 9, 2004. The glacier surface level was lowered by about 3.5 m over the 3 summer seasons although our site was in the upper part of the glacier. Especially during the summers of 2002 and 2004, the surface lowering was severe. Moreover, snow accumulation is relatively small throughout the observation period. Figure 2b shows surface level variations at ST10 measured with a stake between Jun 13 and Sep 4, 2002, and with a snow depth meter from Sep 5, 2002 to Aug 3, 2004. In the 2003 summer, this instrument did not work temporarily. At this site, the glacier surface level was similarly lowered by about 2.5 m for the 3 summer seasons. Some amounts of snow accumulated in each spring, but the accumulated snow melted in the subsequent summer. In the mid-1970s, the altitudes of ST8-2 (4613 m a.s.l.) and ST10 (4824 m a.s.l.) were above ELA (Dvurgerov, 2002). However, our observations reveal that ELA was above ST10 in 2004, because the snow surface level continued lowering.

4.2. Seasonal change of sub-surface stratigraphy in 2002

Figure 3 shows the sub-surface stratigraphical



Fig. 2. Surface level changes at ST8-2 (a) and ST10 (b) from 2002 to 2004. Solid line indicates the data measured by snow depth meter. Triangles and squares show manual observations of surface level and ice level, respectively. Dotted lines (b) show the date of ice core sampling in 2003 and 2004.

changes in pits excavated during the 2002 summer at ST10. The surface level on the ordinate has the origin at that on 16 June. The surface level was lowered by 1.18 m from 16 Jun to 30 Aug. In June and July, the glacier was covered with compacted snow with a thin dirt layer. The snow cover was gradually thinning from 29 Jun, while internal ice layer was thickening. Moreover, mean ice temperature in June 2004 was - $6.6\,^\circ\!\mathrm{C}$  at  $0.62\text{--}1.00\,m\,depth$  and  $-3.2\,^\circ\!\mathrm{C}$  at  $0.43\text{--}0.62\,m$ depth. These suggest that superimposed ice would accumulate because internal layer was cold enough to refreeze melt water. By 6 August, the surface snow layer has completely melted and the surface level has been significantly lowered. Moreover, bare ice surface was covered with dark-colored dirt that contained cryoconite and mineral particles, and the glacier surface was changed to black color (Fig. 4). During 12-15 Aug, new snow covered the dirty ice surface due to snow accumulation. The AWS near the glacier terminus recorded precipitation at the same time (Sakai et al., 2006). On 23 August, dirty ice was exposed at surface because of the snow melting, and then the surface level started lowering again.



Fig. 3. Changes of surface snow stratigraphy (column) and albedo changes (solid line) at ST10 from 16 Jun to 30 Aug, 2002. Diamonds on the solid line mean that the albedo was measured on the same day as the stratigraphical observation, and the triangles mean that the dates were different. The marks of 'd' show dirt layers which could be observed visually.



Fig. 4. Photograph of glacier surface at ST10 on 6 Aug, 2002 when the dirt layer and ice layer appeared on the surface.

#### 4.3. Albedo change at ST10 in 2002

Solid line in Fig. 3 shows surface albedo change from 29 June to 25 August 2002 at ST10. The surface albedo was measured when a sub-surface pit survey was carried out (Fig. 3). The albedo was relatively high (0.42–0.88) from Jun to mid-Jul, and then changed relatively low (0.10–0.21) except on 12 August. Albedo of clean ice surface and dry snow is generally 0.40 and 0.84, respectively according to Paterson (1994). The observed albedo is lower than those general values after mid-Jul. The differences would arise from the surface conditions. Once dark-colored bare ice ap-

peared on the surface and coloration turned to black at the beginning of August, the albedo decreased quickly. However, on 12 August, the glacier was covered with snow (Sakai et al., 2006), and the albedo was relatively high. Therefore, the dark-colored bare ice would reduce the albedo. Cryoconite in dark-colored bare ice is known to reduce surface albedo on glaciers because the cryoconite has dark color and contains many kinds of microorganisms (Kohshima 1989; Takeuchi et al. 2001a, 2001b, 2005; Takeuchi, 2002). These studies suggest that not only mineral particles but also microbiological activities in glaciers play important roles in albedo reduction. To reconstruct the past fluctuation of the July 1st Glacier, we need to know albedo value, which is determined by these two factors, exactly. Therefore, dirt layers containing mineral particles and/or microorganisms in ice cores may enable to reconstruct past albedo fluctuation.

# 4.4. Snow pit and ice core in 2003 and 2004 4.4.1. Cyanobacteria in July 1st Glacier

Three species of cyanobacteria were observed in pit and ice core samples in 2003. Similar kinds of cyanobacteria were reported from glaciers in Alaska, Patagonia and China (Takeuchi, 2001; Takeuchi and Kohshima, 2004; Takeuchi *et al.*, 2005). These cyanobacteria are contained in the cryoconite and are one of its main components. A description of the three species is as follows.

Oscillatriaceae cyanobacteria. 1 (Fig. 5a): Trichomes are

 $2\text{-}5\mu\text{m}$  in width, and  $5\mu\text{m}$  in length. Total length is  $12.5\text{-}500\,\mu\text{m}.$ 

Oscillatriaceae cyanobacteria. 2 (Fig. 5b): Trichomes are  $1.5 \mu m$  in width, and  $2.5 \mu m$  in length. Total length is  $75-300 \mu m$ .

Oscillatriaceae cyanobacteria. 3 (Fig. 5c): Trichomes are  $2.5 \mu$ m in width,  $2.5 \mu$ m in length, and all cells are round. Total length is  $25\text{--}100 \mu$ m.

#### 4.4.2. Analyses of the Ice core at ST10 in 2003

Figure 6 shows the vertical profile of stratigraphy, cyanobacterial biomass, oxygen isotope ratio ( $\delta^{18}$  O), major axis length of bubble and ice crystal size of



Fig. 5. a) Oscillatriaceae cyanobacteria 1, b) Oscillatriaceae cyanobacteria 2, c) Oscillatriaceae cyanobacteria 3. All bars show  $10\,\mu$ m.

a 1.82 m depth ice core from ST10 in 2003. Glacier surface is covered with snow of 0.1 m thickness, which accumulated during the 2003 summer. The ice below surface snow must have formed before 2002 because the surface level continued to be lowered from June 2002 (Fig. 2b). This ice core contains one dense dirty layer at 0.57-0.72 m depth and three cryoconite grain rich layers at 0.19-0.26, 0.47-0.48 and 0.72-1.3 m depth. In the profile of cyanobacterial biomass, five peaks are found at 0.15-0.26, 0.52-0.57, 0.66-0.82, 1.02-1.2 and 1.4-1.5 m depth in Fig. 6b and the peaks at 0.15-0.26 and 0.66-0.82 m depth correspond to the cryoconite grain rich layer and the dirt layer, respectively. In Himalayan and Patagonian glaciers, snow microorganisms are reported to be useful for an annual marker in the glacier strata (Yoshimura et al., 2000; Shiraiwa et al., 2001), because microbiological activities increase during summer due to high temperature and existence of melt water. Also in the July 1st Glacier, microbiological activities increased during summer, because we observed an enormous amount of cyanobacteria growing on the summer surface by confirming the darkcolored surface. Furthermore, a large-sized particle (ex. pollen) is more difficult to move by melt water than chemical ions and isotopes, due to its size (Nakazawa et al., 2004), and the length of cyanobacteria cells  $(12.5-500\,\mu\text{m})$  is greater than the diameter of pollen (10–150 $\mu$ m). Cyanobacteria rich layers in this ice core, therefore, would be markers of summer layers. However, the glacier surface level continued to be lowered during recent years, which indicates that re-



Fig. 6. Profiles of ice core at ST10 taken in 2003. a) Stratigraphy, b) Biomass of cyanobacteria, c)δ<sup>18</sup>O, d) major axis of bubbles, e) ice crystal size. Solid line and dashed line show the maximum and minimum sizes, respectively.

cent year's accumulation would have melted completely and not be preserved. For this reason, we cannot decide the date of each layer in the ice core. However, this ice core appears to contain five summer layers from biological analysis. These layers were formed in past years when the drilling site was in accumulation area and colder than present, because the estimated summer layers were not disturbed. Then, as melting water should have been accumulated on superimposed ice and hardly run off, mass balance would be similar to precipitation. Therefore, average annual mass balance estimated from the cyanobacterial peak is 313mm over four years dated by the peak of the biomass, the value of which agrees with the annual precipitation (340-370 mm) observed in the July 1st Glacier in 2003 and in 2004 (Sakai et al., 2006). This result implies that summer layers and past mass balance fluctuations could be detected by the marker of cyanobacteria.

Dust layers, which contains much dusts and corresponds here to the dirt layer, may be also formed in the ice core from spring to summer, because a dust storm was mainly observed from March to June 1991 -1992 in Zhangye, located at the foot of the Qilian Mountains (Kai et al., 1997). Sakai et al. (2006) also reported a dust storm at July 1st Glacier in July 2004. A dust layer would be normally observed at least once every year, but we observed only one dirt layer in the ice core containing 5 annual layers, the dating of which was determined by the biomass peak. Accumulation of aerosol would change year by year because the frequency and intensity of dust storms will change depending on climate. In this study, we used only visual observations and can identify only a layer caused by a relatively large dust storm. As further studies, we will analyze the particle size of samples, then we may detect other dust layers.

The vertical profile of  $\delta^{18}$ O is relatively high at 0-0.1 and 0.52-0.72 m depth. Tian, et al. (2003) showed that  $\delta^{18}$ O in precipitation depends on temperature in the northern Tibetan Plateau, and summer precipitation has high  $\delta^{18}$ O. Actually, the summer surface snow in 2003 had high  $\delta^{18}$ O at ST10. Therefore, if there is no melting, a high value of  $\delta^{18}O$  will be a marker of a summer layer. Below 0.1 m depth,  $\delta^{18}$ O is high around the summer layers estimated from biological analysis. However, the peaks of high  $\delta^{18}$ O were not remarkable. In temperate regions, the profiles of isotope ratios are affected by melt water and often disturbed (Iizuka et al., 2000). Therefore, it is difficult to identify the summer layer only by isotope signals, but combination of peaks of  $\delta^{18}$ O and cyanobacteria may support more reliable dating.

At 0.57–0.66 m depth, a peak in the profile of the major axis of bubbles corresponds to the dirt layer (Fig. 6d). However, we cannot understand process of the bubble formation at present, because we do not have sufficient information.

At 0.27–0.66 and 1.72–1.82 m depths, ice crystal size is relatively large (Fig. 6e). The ice crystal size in superimposed ice should be small because the melt water comes down into contact with a cold ice layer and refreezes rapidly, and while the size should become larger when the meltwater refreezes slowly according to Wakahama and Hasemi (1974). However, we do not have sufficient information on ice temperature of this glacier and cannot understand the process. Further study will reveal the formation processes of bubbles and crystal size.

# 4.4.3. Analyses of the Ice cores and snow pits in 2004 Figures 7a and 7b show the stratigraphy of the

Table 1. Densities in snow pits at ST8-2 and ST10 in Jun 2004. Each sample is numbered by portion in the stratigraphy in Fig. 8b.

Sampling No.	Depth from snow surface (m)	Density (kg m <sup>-3</sup> )
st8-2-1	0.016	3.22
st8-2-2	0.076	3.56
st8-2-3	0.116	2.23
st8-2-4	0.176	2.16
st8-2-5	0.231	3.51
st10-1	0.014	3.27
st10-2	0.059	2.61
st10-3	0.106	2.92
st10-4	0.151	2.65
st10-5	0.191	3.04
st10-6	0.236	2.71
st10-7	0.268	2.47

# a) st8-2, 2004

	— 0.3 m		
			New snow
	1		Fine snow
			Granular snow
		·····	<u>3</u> Granular snow
[	0 m	5	Dirty granular snow

### b) st10, 2004



Fig. 7. Stratigraphy of snow pits at ST8-2 (a) and ST 10 (b) in June 2004. Squares (size:  $0.047 \times 0.059$  m) show sampling portions for density measurement, and their numbers correspond to those in Table 1.



Fig. 8. Stratigraphy of ice core taken at ST8-2 (a) and ST10 (b) in June 2004 and ST10 in September 2003 (c). Ice cores in 2004 are excavated below the bottom of snow pits. Dashed lines between b) and c) show the same layers in our estimation.

snow pits at ST8-2 and ST10 on 30 May and 2 Jun 2004, respectively, and sampling positions for density measurements. The surface was covered with firn snow by 0.26 m at ST8-2 and by 0.36 m at ST10. All density data are summarized in Table 1, which range from 2.16 to  $3.56 \text{ kg m}^{-3}$ . Ice core samples were excavated below the bottom of the firn at both sites of ST8-2 and ST10. Figures 8a and 8b show the stratigraphy of the cores from ST8-2 and ST10, respectively. The stratigraphy of the core from ST10 in 2003 is also shown in Figure 8c. The ice core of 3.06 m depth from ST8-2 site contains five dense dirty layers (0.6-0.75, 0.79-0.88, 1.05-1.08, 2.17-2.19 and 2.95-3.01 m depth) and two layers with red colored grains (0.75–0.79 and 0.9–0.99 m depth). Red materials were also found in the ice core at ST10 in 2003, and they were cryoconites which were composed of snow microorganisms and mineral particles. On the other hand, the ice core from ST10 site in 2004 contained 2 dense dirty layers (0.41-0.48 and 1.76-1.79 m depth). The surface level of the ST10 ice core in 2004 corresponded to the 0.12 m depth of the 2003 ice core from the snow depth meter record (Figures 2b, 8b and 8c). Therefore, the dirt layer at 0.41-0.48 m depth would correspond with the dirt layer at 0.61-0.7 m depth of in the 2003 ice core (Fig. 8c), and the lower dirt layer in the core taken in 2004 was not observed in the 2003 ice core, since the ice core in 2003 was not deep enough. These results suggest that the 2003 ice core corresponds well with the 2004 ice core. In that ice core, as the glacier surface was melted and lowered drastically, annual dating of recent years is impossible. However, we confirmed by visual observations that the glacier strata in further upstream part than ST10 had been kept clearly. Therefore, an ice core from this site may provide the past climatic information such as surface albedo.

# 5. Conclusion

The surface levels of July 1st Glacier was lowered by about 3.5 and 2.5 m at ST8 and ST10, respectively, from Jun 2002 to September/August 2004. These surface lowering would be accelerated by albedo reduction due to exposure of bare ice with dark-colored materials during summer. The dark-colored bare ice contained mineral particles and cryoconites. In the ice core, we observed cyanobacterial layers. As cyanobacteria grow during the summer, these layers should be formed during summer and seem to be markers for summer layers. Relatively high values of  $\delta^{18}$ O, which indicates summer layer, also corresponded with the peaks of cyanobacteria, although the seasonal cycles in  $\delta^{18}$ O value were ambiguous at the lower parts. Average annual mass balance in the ice core estimated from the cyanobacterial peak was 313 mm, which corresponded to the annual precipitation observed near the terminus of the July 1st Glacier. Detecting summer layers in the ice core by using the cyanobacteria peaks would open up the possibilities of reconstructing the past albedo.

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#### References

- Ding, L. and Kang, X. (1985): Climatic conditions for the development of glacier and their effect on the characteristics of glaciers in Qilian Mountains (in Chinese). Memoirs of Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, No. 5, 9–15.
- Dyurgerov, M. (2002): Glacier mass balance and regime. In Meier, M. and Armstrong, R. (eds.), Data of Measurement and Analysis, University of Colorado, Institute of Arctic and Alpine Research, Occasional Paper No. 55, 88 pp.
- Fujita, K. and Ageta, Y. (2000): Effect of summer accumulation on glacier mass balance on the Tibetan Plateau revealed by mass-balance model. J. Glaciol., 46 (153), 244– 252.
- Fujita, K., Seko, K., Ageta, Y., Pu, J. and Yao, T. (1996): Superimposed ice in glacier mass balance on the Tibetan Plateau. J. Glaciol., 42 (142) 454-460.
- Huang, M. (1990): On the temperature distribution of glaciers on China. J. Glaciol., **36** (123), 210–215.
- Iizuka, Y., Igarashi, M., Watanabe, K., Kamiyama, K. and Watanabe, O. (2000): Re-distribution of chemical compositions in the snowpack at the dome of Austfonna ice cap, Svalbard (in Japanese with English abstract). Seppyo, 62, 245-254.
- Kai, K., Huang, Z.C., Shiobara, M., Shen, Z. and Mitsuta, Y. (1997): Seasonal variation of aerosol optical thickness over the Zhangye oasis in the Hexi Corridor, China. J. Meteor. Soc. Japan, 75 (6), 1155–1163.
- Kohshima, S. (1989): Glaciological importance of microorganisms in the surface mud-like materials and dirt layer particles of Chongce Ice Cap and Gozha Glacier, West Kunlun Mountains, China. Bull. Glacier Res., **7**, 59–65.
- Lanzhou Institute of Glaciology and Geocryology (ed.) (1985): Glacier variations and utilizations in Qilian Mountains (in Chinese). Memoirs of Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, No. 5,

Science Press, Beijing, 185 pp.

- Lanzhou Institute of Glaciology and Geocryology (ed.) (1992): The monitoring of glacier, climate, runoff changes and research of cold region hydrology in Qilian Mountains (in Chinese with English abstract). Memoirs of Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, No. 7, Science Press, Beijing, 147 pp.
- Liu, C., Song, G. and Jin, M. (1992): Recent change and trend prediction of glacier in Qilian Mountain (in Chinese with English abstract). Memoirs of Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences. No. 7, 1–9.
- Liu, S., Sun, W., Shen, Y. and Li, G. (2003): Glacier changes since the Little Ice Age maximum in the western Qilian Shan, northwest China, and consequences of glacier discharge for water supply. J. Glaciol., **49** (164), 117–124.
- Liu, X. and Chen, B. (2000): Climatic warming in the Tibetan Plateau during recent decades. International Journal of Climatology, 20, 1729–1742.
- Matsuda, Y., Sakai, A., Fujita, K., Nakawo, M., Duan, K., Pu, J. and Yao, T. (2004): Glaciological observations on July 1st Glacier in Qilian Mountains of west China during summer 2002. Bull. Glaciological Res., **21**, 31–36.
- Nakazawa, F., Fujita, K., Uetake, J., Kohno, M., Fujiki, T., Arkhipov, S.M., Kameda, T., Suzuki, K. and Fujii, Y. (2004): Application of pollen analysis to dating of ice cores from lower-latitude glaciers. J. Geophy. Res., 109 (F 4), F04001, doi: 10.1029/2004 JF000125.
- Paterson, W. S. B. (1994): The Physics of Glaciers, 3rd edition. Pergamon, Oxford, 480 pp.
- Sakai, A., Fujita, K. Matsuda, Y., Kubota, J., Duan, K., Pu, J., Nakawo, M. and Yao, T. (2004): Five decades of shrinkage of the July 1st Glacier in the Qilian Mountains of China. The 4th international symposium on the Tibetan Plateau, Lhasa, China.
- Sakai, A., Matsuda, Y., Fujita, K., Matoba, S., Uetake, J., Satow, K., Duan, K., Pu, J., Nakawo, M. and Yao, T. (2006): Meteorological observation at July 1st Glacier in northwest China from 2002 to 2005. Bull. Glaciological Res., 23, (in this issue).
- Shi, Y., Huang, M., Ren, B., Bai, C., Deng, Y., Wang, P., Xie, Z., Yang, Z. and Zhang, J. (1988): An introduction to the glaciers in China (in Chinese). Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Science, Science Press, Beijing, 243 pp.
- Shiraiwa. T., Kohshima, S., Uemura, R., Yoshida, N., Matoba, S., Uetake, J. and Godoi, A. M. (2001): High net accumulation rates at the Southern Patagonia Icefield revealed by analysis of a 45.97-m-long ice core. Ann. Glaciol., 35, 84–90.
- Takeuchi, N. (2001): The altitudinal distribution of snow algae on an Alaska glacier (Gulkana Glacier in the Alaska range). Hydrol. Proc., **15**, 3447–3459.
- Takeuchi, N. (2002): Surface albedo and characteristics of cryoconite (biogenic surface dust) on an Alaska glacier, Gulkana Glacier in Alaska Ranage. Bull. Glaciological Res., 19, 63–70.
- Takeuchi, N. and Kohshima, S. (2004): A snow algal community on a Patagonian glacier, Tyndall Glacier in the Southern Patagonia Icefield. Arctic, Antarctic and Alpine Res., 36, 92–99.
- Takeuchi, N., Kohshima, S. and Seko, K. (2001a): Structure, formation, and darkening process of albedo-reduction material (cryoconite) on Himalayan glacier: granular algal mat growing on the glacier. Arctic, Antarctic and Alpine Res., 33, 115–122.
- Takeuchi, N., Kohshima, S., Shiraiwa, T. and Kubota, K. (2001 b): Characteristics of cryoconite (surface dust on glaciers) and surface albedo of Patagonian glacier, Tyndall Glacier, Southern Patagonia Icefield. Bull. Glaciological Res., 18, 65–69.
- Takeuchi, N., Matsuda, Y., Sakai, A. and Fujita, K. (2005): A large amount of biogenic surface dust (cryoconite) on a

glacier in the Qilian Mountains, China. Bull. Glaciological Res., **22**, 1–8.

- Tian, L., Yao, T., Schuster, P. F., White, J. W. C., Ichiyanagi, K., Pendall, E., Pu, J. and Yu, W. (2003): Oxygen-18 concentrations in recent precipitation and ice cores on the Tibetan Plateau. J. Geophys. Res., 108 (D9), 4293, doi: 10.1029/2002JD002173.
- Wakahama, G. and Hasemi, T. (1974): Formation of superimposed ice in sub-polar glaciers. Laboratory experiments and numerical simulations. Low Temperature Science, Ser. A, 32, 161–174.
- Wang, G. and Cheng, G. (1999): Water resource development and its influence on the environment in arid areas of China-the case of the Hei River basin. Journal of Arid Environments, **43**, 121-131.
- Wu, G. (1985): Glacier water resources and effect of glacier water in stream runoff in Qilian Mountains (in Chinese). Memoirs of Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, No. 5, 1–8.
- Xie, Z., Wu, G., Wang, L. and Wang, Z. (1985): Ice formation of glaciers in Qilian mountains (in Chinese). Memoirs of Lanzhou Institute of Glaciology and Cryopedology, Chinese Academy of Sciences, No. 5, 27–40.
- Yoshimura, Y., Kohshima, S., Takeuchi, N., Seko, K. and Fujita, K. (2000): Himalayan ice core dating with snow algae. J. Glaciol., **46**, 335-340.
- Zhu, S. and Wang, Q. (1996): Temporal-spatial distributions and recent changes of precipitation in the northern slopes of the Qilian Mountains. Journal of Glaciology and Geocryology, **18**, Special Issue, 296–304.