Article

A large amount of biogenic surface dust (cryoconite) on a glacier in the Qilian Mountains, China

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Abstract

Surface dust on glaciers can significantly affect surface albedo and subsequently the mass balance of the glaciers. The characteristics of surface dust (cryoconite) were investigated in September 2002 on the July 1st Glacier (Qiyi Glacier) in the Qilian Mountains, China. The bare ice surface of the glacier was mostly covered by fine brown dust. The amount of the surface dust (dry weight) ranged from 30.4 to 873 g m^{-2} (mean: 292 g m^{-2}, standard deviation: 196), which is significantly higher than that on glaciers in other parts of the world, and is equivalent to that on Himalayan glaciers on which the large amounts of dust have been reported. An analysis of organic matter and microscopy of the surface dust revealed that the dust contained high levels of organic matter, including living cyanobacteria. This suggests that the dust consists not only of deposit of wind-blown desert sand, but is also a product of microbial activity on the glacier. Measurements of surface albedo showed that the mean surface albedo in the ice area was smaller than that of the clean bare ice surface, suggesting that the albedo was significantly reduced by the surface dust. Large amounts of surface dust may be due to abundant windblown deposits of desert sand and high biological productivity on the glacial surface, probably a common characteristic of Asian glaciers.

1. Introduction

Surface dust is one of the major factors affecting the surface albedo of glaciers (*e.g.* Brock *et al.*, 2000; Cutler and Munro, 1996). The reduction of albedo by surface dust results in more melting of snow and ice. Thus, the quantity and characteristics of surface dust are important parameters for the mass balance of glaciers. Recent investigations have revealed a substantial thinning and terminus retreat of glaciers in many parts of the world (IPCC, 2001). Although climate change such as global warming usually accounts for the recent glacial shrinkage, the variations in surface dust are also a possible cause of shrinkage.

Surface dust usually consists of mineral particles and organic matter (*e.g.* Takeuchi *et al.*, 2001a). The mineral particles in the dust usually originate from basal till and/or wind-blown sands, while the organic portion of dust originates from wind-blown organic matter (*e.g.* pollen, plant fragments and soil particles) and from biological activity on the glacial surface. There are diverse organisms living on the glacial surface, such as snow algae, insects, ice worms, protozoa and bacteria. They are specialized species that have adapted to extremely cold environments and spend their whole lives on glaciers (*e.g.* Hoham and Duval, 2001; Kohshima, 1987). Surface dust contains products such as the organisms themselves, their dead remains and decomposed organic matter (humic substances). Since these organic particles in dust are usually darkly colored and large in volume, organic matter in dust is optically effective on the surface albedo (Takeuchi, 2002b; Takeuchi *et al.*, 2001b).

Both the quantity and characteristics of dust on the glacial surface vary from glacier to glacier. On glaciers in Patagonia and the Arctic, effect of dust on surface albedo is insignificant due to the small amounts accumulating there (Takeuchi *et al.*, 2001a; 2001c). In contrast, larger amounts of surface dust have been reported on some Asian glaciers. The wind-blown desert sand deposited on a Tibetan glacier (the Tanggula Mountains) has substantially reduced the surface albedo, thus affecting the mass balance of the glacier (Fujita, 2002). On some Himalayan glaciers, a dark biogenic dust (cryoconite) that covers the glacial surface significantly reduced the surface albedo (Takeuchi *et al.*, 2001a; Kohshima *et al.*, 1993). This biogenic dust is derived from snow algae and bacteria living on the glaciers. Thus, surface dust has a major influence on the glacial mass balance, particularly on Asian glaciers. However, our information about surface dust remains limited. In order to understand the variations in the recent change in glacial mass balance, it is important to study the characteristics of surface dust on glaciers.

This paper aims to describe the quantity and characteristics of surface dust on the July 1st Glacier (Qiyi Glacier) in the Qilian Mountains, China. After surface dust was collected from various parts of the glacier in September 2002, it was quantified and analyzed biologically in a laboratory. Its characteristics were compared with those on other glaciers across the world. The spatial variations in surface albedo were also measured on the July 1st glacier, and the effects of surface dust on the surface albedo are discussed.

2. Study site and methods

Our investigation was carried out on the July 1st Glacier (or Qiyi Glacier, 39°15′N, 97°45′E) in the Qilian Mountains of China from 10 June to 7 September, 2002. The Qilian Mountains, located along the northeast margin of the Tibetan Plateau, extend from east to west for a distance of approximately 500 km along the border between Gansu and Qinhai provinces (Fig. 1). Glaciers in the Qilian Mountains supply water to the Heife River Basin, which is one of the major oasis regions in western China. The study of glacial variations in this region is important for research into the long human history as well as the future water resources available to the present human population in this basin. The glacier flows south to north from a mountain peak (5159 m a.s.l.) down to its terminus at an elevation of 4305 m a.s.l. (Fig. 1). This glacier is one of the most easily accessible in China, and has been studied intermittently since 1958 by the Cold and Arid Regions Environmental and Engineering Research Institute of the Chinese Academy of Science. The glacier has reportedly retreated 1–2 meters per year on average in the 1970s and 80s (Xie *et al.*, 1985; Liu *et al.* 1992). Remote-sensing studies also showed that the area and volume of glaciers in the Qilian Mountains have generally decreased (Liu *et al.* 2003). Most of the surface of the glacier is bare ice or snow devoid of rock or stone debris. The length and area of the glacier are approximately 3 km and 3.04 km^2, respectively. The snow line in our study period (early September) was approximately 4900 m a.s.l., and was located between sites S10 and S11. Meteorological and glaciological data collected in the study period have been published by Matsuda *et al.* (2004).

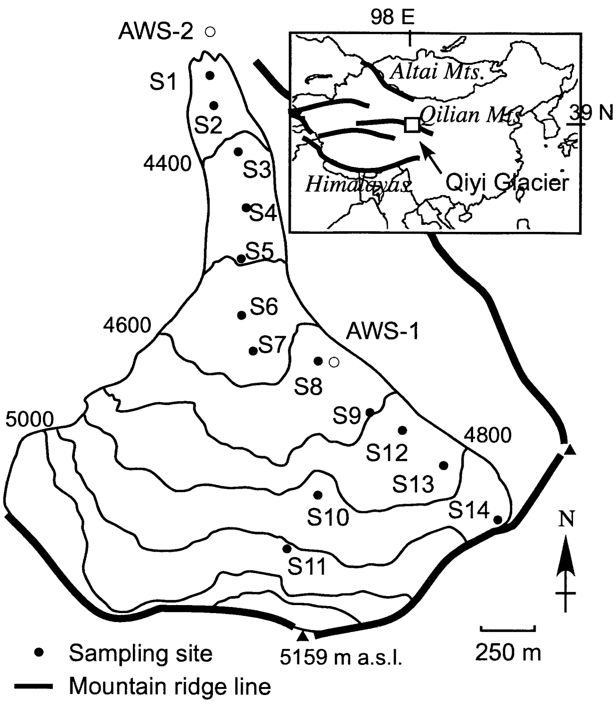

Fig. 1. Location and map of the July 1st Glacier in the Qilian Mountains, China. Study sites are shown on the map.

In order to quantify the amount of dust on the glacial surface and its organic-matter content, ice/snow on the surface layer was collected with a stainless-steel scoop (approximately 15×15 cm in area and 1–3 cm in depth) at 5 sites in the bare ice area (S2, S4, S 6, S8, and S10) and 1 site in the snow area (S11). Five samples were collected from randomly selected surfaces at each study site. The collection area on the surface was measured to calculate the amount of dust per unit area. To arrest the biological activity, the collected samples were melted and preserved as a 3% formalin solution in clean 100 ml polyethylene bottles. All samples were transported for analysis to the Research Institute for Humanity and Nature located in Kyoto, Japan. In the laboratory, the samples were dried (60℃, 24 hours) in pre-weighed crucibles. The amount of dust per unit area of the glacier was obtained from measurements of the dry weight and the sampling area. The dried samples were then combusted for 1 hour at 1000℃ 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. After combustion, only mineral particles remained. In order to investigate the composition of the surface dust, other samples of surface ice/snow were collected and examined in a laboratory with optical microscopes (Nikon SMZ800 and E 600).

The surface albedo was measured manually on August 18 with a portable albedo meter (Model: MR-40, Eiko Seiki, Japan) at thirteen sites between 4200 m and 5000 m a.s.l. along a longitudinal line (S1-S14 except S11, Fig. 1). These sites were selected because of their safe and easy accessibility. Moreover, the sites

Table 1. Surface slope angles for sites in this study.

Site	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S12	S13
Slope (degree)	10	12	5	14	8	16	14	14	11	12	14	10

were visibly representative of the surface conditions around each site in terms of surface roughness and amounts of dust. The measurements were made in a horizontal plane 1 m above the surface within 3 hours of local solar noon and under stable weather conditions, irrespective of cloudiness. The albedo was obtained from the mean of 3–8 measurements taken at each site, with each measurement requiring approximately three minutes. Since surface slopes varied among the study sites (Table 1), the observed horizontal albedo involved an error due to the slope (Jonsell *et al.*, 2003). The erroneously observed albedos were corrected to match albedos parallel to the sloping surface using the following equation introduced by Jonsell *et al.* (2003).

$$\alpha_t = \frac{R_h}{G_h(1-d)\dfrac{\cos\beta\cos Z + \sin\beta\sin Z\cos(\Omega-\Theta)}{\cos Z} + G_h d}, \quad (1)$$

where α_t is the albedo parallel to the sloping surface, R_h is the reflected shortwave radiation on a horizontal plane, G_h is the global radiation, d is the diffuse portion of G_h, Z is the solar zenith angle, Ω is the solar azimuth angle, and β is the slope angle of the surface with an azimuth angle Θ. In this study, the diffuse portion is equated with zero to simplify the calculations. In addition, 30 degrees, which is the zenith angle of local noon on the day of observation (August 18), is applied to Z. Ω and Θ are 180 and 0 degrees, respectively.

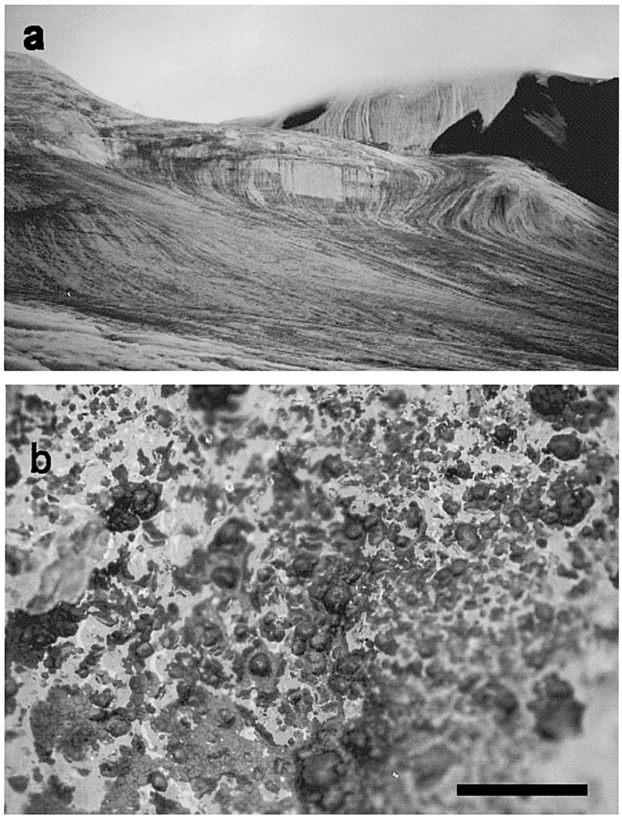

Fig. 2. Pictures of the surface of July 1st Glacier (toward top of the glacier from site S8). (a) Bare ice surface covered with fine brown dust (cryoconite) (5 September, 2002). (b) Fine brown colored dust on the bare ice surface. Scale bar is 1 cm.

3. Results

Most of the glacial surface of the ice area was covered with fine brown dust (Fig. 2, 3). The amounts of dust on the bare ice surface ranged from 30.4 to 873 g m^{-2} (mean: 292 g m^{-2}, standard deviation (SD) = 196) in dry weight. The altitudinal profile of those amounts of dust showed that the amount at the lowest elevation site (S2) was relatively smaller than those at the other sites (76.7 versus 236–536 g m^{-2}, Fig. 4). The largest amount of dust was at site S10 (4827 m a.s.l.), which was the highest elevation in the ice area. At each study site, dust was not uniformly distributed. In particular, dust on the ice surface tended to concentrate along longitudinal lines (Fig. 3a) that formed longitudinal stripes 50–100 cm wide on the bare ice surface. In some areas, dust had accumulated up to several centimeters in thickness. Dust also deposited at the bottom of cryoconite holes (Fig. 3b). Relatively higher numbers of cryoconite holes were observed at site S2, whereas only a few were observed from sites S 4 to S6. In the snow area, the dust amount was much smaller than that in the ice area, ranging from 21 to 31 g m^{-2} (mean: 24.4 g m^{-2}, SD = 4, site S11).

The surface dust contained levels of organic matter ranging from 4.1 to 12.6% (mean: 8.6%, SD = 1.9) in dry weight (Fig. 5). The percentage was highest at site S4 (11.1 ± 1.8%, mean ± SD), and gradually decreased down to site S10 (7.3 ± 0.37%) as the elevation increased. The organic-matter content in dust on the snow surface was smaller than that on the ice surface (site S11 in Fig. 1), ranging from 4.9 to 5.3% (mean: 5.0%, SD = 0.14).

The amount of organic matter per unit area on the glacial surface ranged from 2.1 to 64.0 g m^{-2} (mean: 25.4 g m^{-2}, SD = 16.5) on the ice surface, and from 1.1 to 1.6 (mean: 1.23 g m^{-2}, SD = 0.22) on the snow surface (Fig. 6). The amount was relatively lower at the lowest site (6.2 ± 3.7 g m^{-2}, S2) and higher at sites S4 and S10

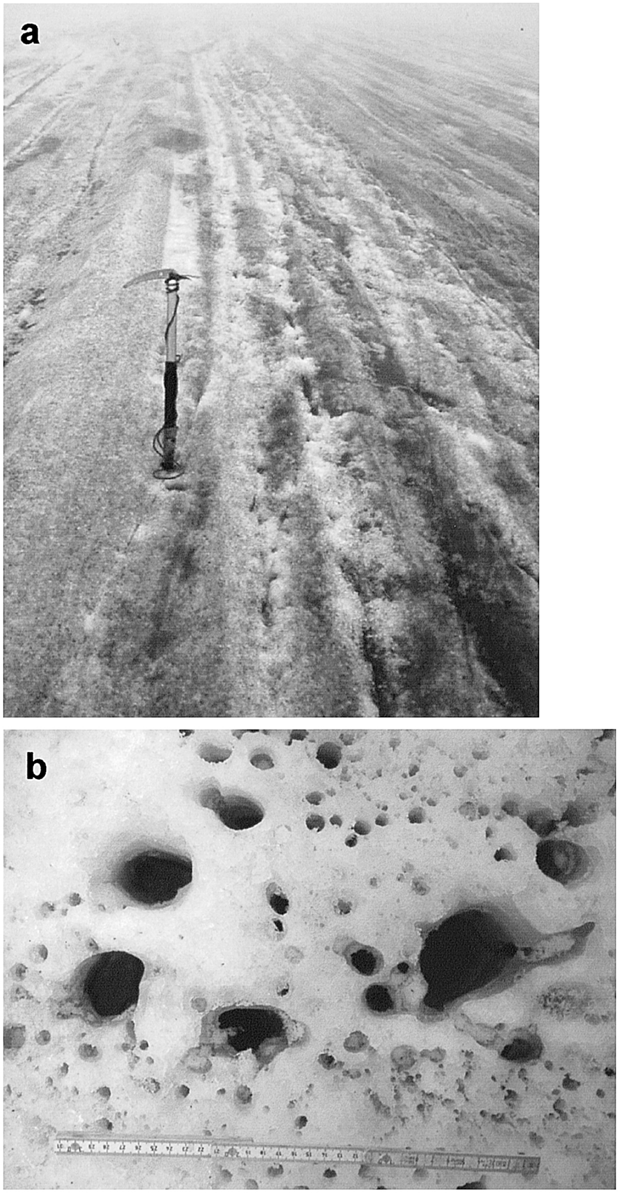

Fig. 3. Specific features of the bare ice surface on July 1st Glacier. (a) Dust was concentrated along a longitudinal line. (toward upper stream at site S6 on 4 September, 2002). (b) Cryoconite holes. Surface out of the holes is white weathered ice. (site S2 on 4 September, 2002).

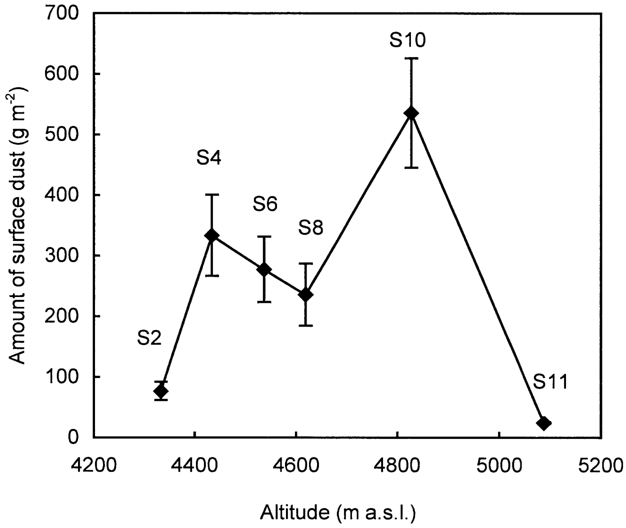

Fig. 4. Altitudinal distribution of amounts of surface dust on July 1st Glacier. Error bars indicate standard deviation.

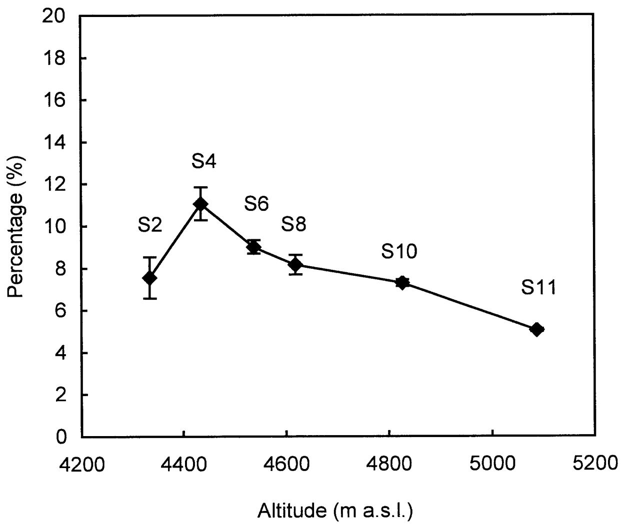

Fig. 5. Altitudinal distribution of organic matter contents in surface dust on July 1st Glacier. Error bars indicate standard deviation.

(37.9 ± 18.5 and $38.5 \pm 12.4\,g\,m^{-2}$, respectively).

The surface dust microscopically revealed mineral particles, amorphous organic matter, and living cyanobacteria (Fig. 7). Although the percentage of organic matter was not largely different between the dust in snow and ice areas (8.6% versus 5.0%), their components as observed by microscopy clearly differed (Fig. 7). Brown organic granules were the main component in dust from the ice area (S2-S10), whereas, mineral particles were the main component in the snow area dust (S11, Fig. 7). The brown organic granules in dust from the ice area were spherical in shape and contained abundant filamentous cyanobacteria and mineral particles. The size of the organic granules ranged from 0.13 to 2.7 mm (mean: 0.55 mm, SD = 0.27). Observation with a fluorescence microscope revealed at least two species of filamentous cyanobacteria with autofluorescence densely covering the surface of the granules. One was $3.9 \pm 1.0\,\mu m$ (mean $\pm$ SD) in cell diameter with a sheath (Fig. 7c), and the other was $2.3 \pm 0.37\,\mu m$ in cell diameter without a sheath (Fig. 7d). The mineral particles in the dust were brown, white, or transparent. The size of the particles observed with a microscope ranged from 25 to $165\,\mu m$ (mean: $69\,\mu m$, SD = 25) in diameter.

The observed horizontal albedos on the glacier ranged from 0.10 to 0.41 (mean: 0.21) in the ice area (Fig. 8). The albedos corrected for a sloping surface

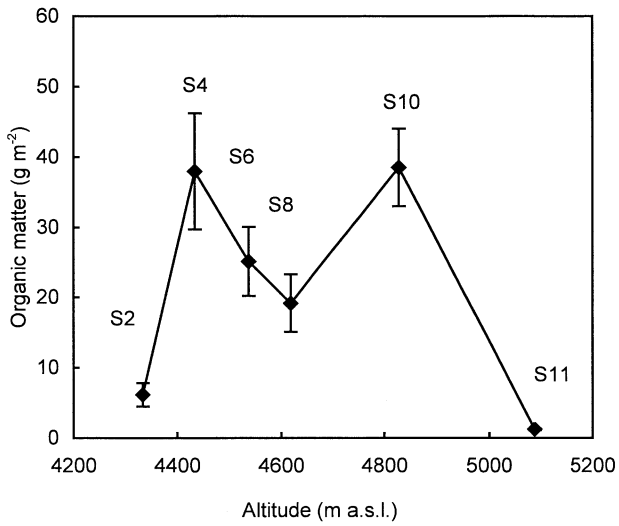

Fig. 6. Altitudinal distribution of amounts of organic matter on the surface of July 1st Glacier. Error bars indicate standard deviation.

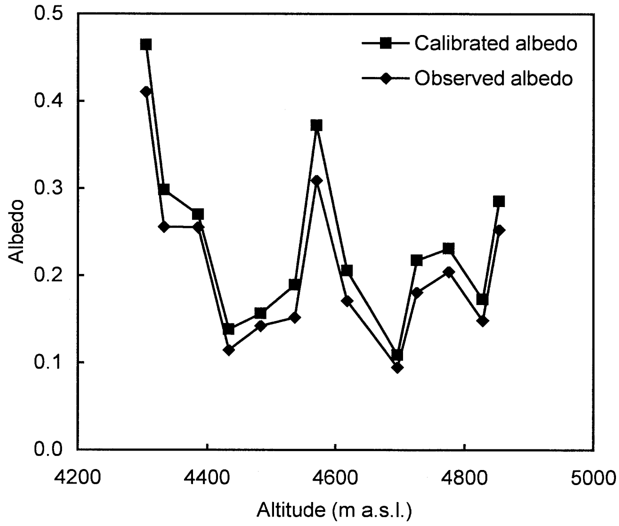

Fig. 8. Altitudinal profile of horizontal albedo observed on 18 August, 2002 and the corrected albedos for the sloping surface. The corrected albedo still has errors of diffusion, solar zenith and azimuth angle at observed time. True albedo should be somewhat between the two values. All studied sites were bare ice surface without snow on the day of measurement.

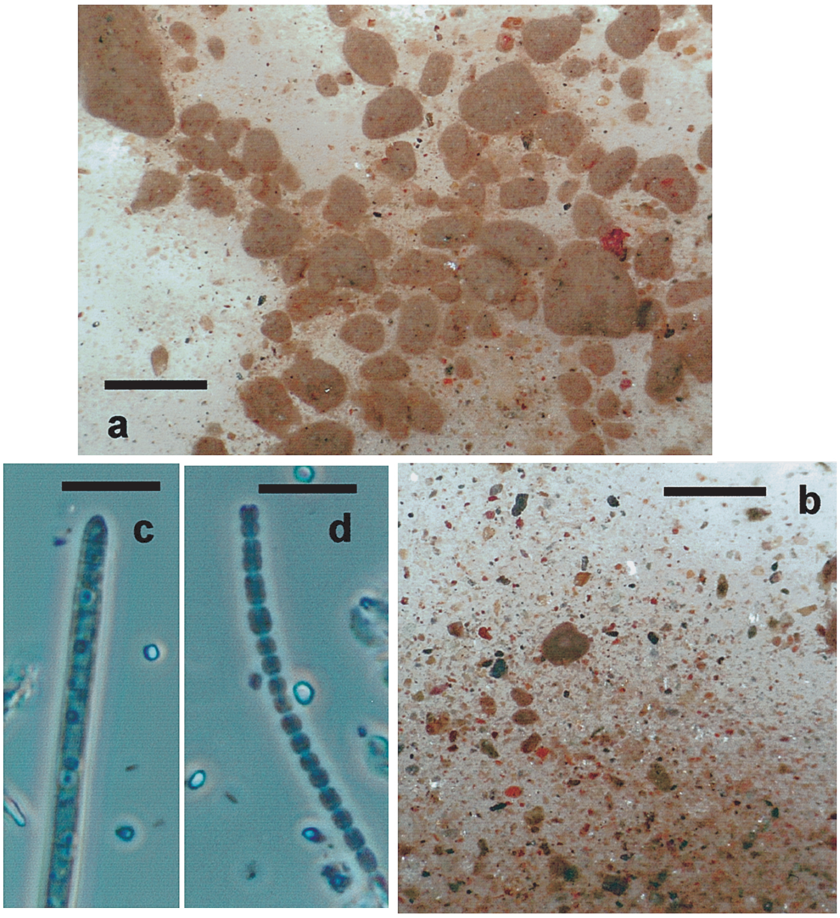

Fig. 7. Microscopic view of surface dust on the July 1st Glacier. (a) Dust (cryoconite) on the ice surface collected from site S2 on 4 September, 2002. Dust consisted mainly of small brown granules containing cyanobacteria and organic matter. (b) The dust collected on the snow surface from S11 on 5 September, 2002 consisted mainly of mineral particles. (c) (d) Two different species of cyanobacteria contained in the dust. Scale bars are 1 mm for (a) and (b), 10 μm for (c) and (d).

were higher than the measured horizontal albedos. The difference between before and after the correction of the albedos ranged from 0.01 to 0.06. The corrected albedos still contained errors due to the effects of diffuse radiation and the actual solar angle at each measurement. According to equation (1), the true albedos without these errors should be somewhere between the observed and corrected values. The corrected albedos without the slope effect varied from 0.11 to 0.46 (mean: 0.23, SD: 0.10). The longitudinal profile shows that the albedos were relatively higher (0.27–0.46) at the lower sites (sites S1-S3), at one middle site (S7) and at the highest site (S14). Albedos at the other sites was smaller than 0.25. The lowest albedo was 0.14 at site 9.

4. Discussion

The bare ice surface on the July 1st Glacier can be characterized as low albedo due to the large amounts of surface dust. Surface albedos of snow and ice are negatively correlated with amounts of impurities in the snow and ice (*e.g.* Aoki *et al.*, 2003). There was a consistently weak correlation between the amount of dust and surface albedo in the ice area of this glacier (Fig. 9). A surface with a smaller amount of dust (*e.g.* site S1) was higher albedo (0.30), whereas one with a larger amount (*e.g.* site S5) was lower albedo (0.17). This correlation suggests that variations in the surface albedo in the ice area were mainly due to the amount of the dust on the surface, indicating, therefore, that dust substantially affects the surface albedo in the ice area. The mean albedo in the ice area was 0.23, which is lower than that of a clean bare ice surface. For example, the mean bare ice albedo for a clean surface has been reported to be 0.38 on glaciers in western China (Bai and Yu, 1985). The difference between the bare ice albedo on the July 1st Glacier and the albedo on a clean surface is 0.15, which is likely due to the effect of surface dust on the surface albedo.

The higher albedo and smaller amounts of surface dust near the terminus of the glacier are the opposite of those on other mountain glaciers. Dust and debris usually accumulate in the tongue of a glacier since they are supplied from above by glacial flow or from the basal bed by marginal shearing. For example, the albedo on a glacier in the Austrian Alps was found to be lower at the terminus (0.10–0.16) compared with middle region (0.2–0.4) due to the accumulated dust and the presence of abundant meltwater (Van de Wal *et al.*, 1992). A lower albedo at the terminus has been also reported in the Switss Alps, Alaska, and western China (Brock *et al.*, 2000; Takeuchi, 2002a; Bai and Yu, 1985).

The smaller amount of dust in the area near the terminus of the glacier may be due to the development of weathered ice and cryoconite holes. White weathered ice (or weathering crust) is a porous ice with loosely interlocking crystals on the surface layer of a glacier (*e.g.* Müller and Keeler, 1969). Based on field observations, weathered ice was particularly abundant in the tongue of a glacier compared with the middle or upper part. The smaller dust amounts on weathered ice may result from dust sinking below the surface. The surface dust could sink through gaps in the porous ice, thus reducing the amount of dust on the surface layer (1–3 cm in depth as observed by the sampling procedure in this study). In addition, cryoconite holes, which were ubiquitous in this area (Fig. 3), may lower the dust concentration on the ice surface. Since the cryoconite holes trap the dust at their bottom, the ice surface around the holes was less dust concentration.

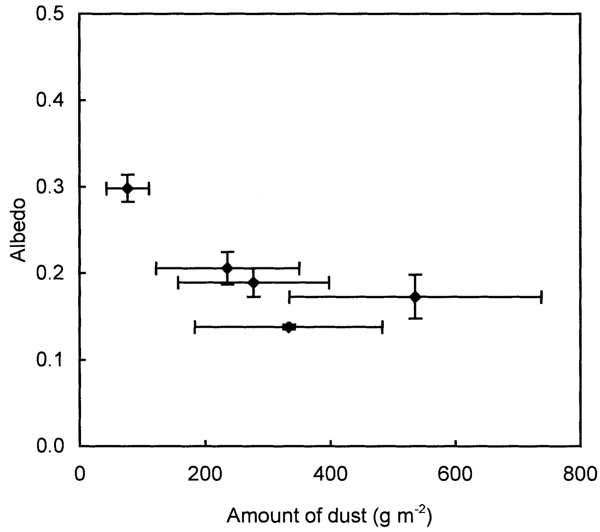

Fig. 9. Relationship between dust amounts and surface albedos in the ice area. Error bars indicate standard deviation.

The mechanism underlying the development of weathered ice and cryoconite holes at the area near the terminus is unclear. A possible explanation for the formation of these structure is that dryer, less humid air is blown from the desert extending downstream of the glacier. Such dry air could cause a sublimation of the glacial surface, particularly at the terminus area of the glacier, and could then cool the ice surface. That may prevent the disappearance of weathered ice and cryoconite hole structures, since these structures usually decay under conditions of positive latent or sensible heat dominance (*e.g.* Takeuchi *et al.,* 2000). Further study of the formation process of these surface structures is necessary for enhancing our understanding of the spatial variations of surface albedo on the glacier.

The amount of surface dust on the ice surface of the July 1st Glacier is markedly greater than on glaciers in other parts of the world. According to previous studies, the amounts of surface dust are less than

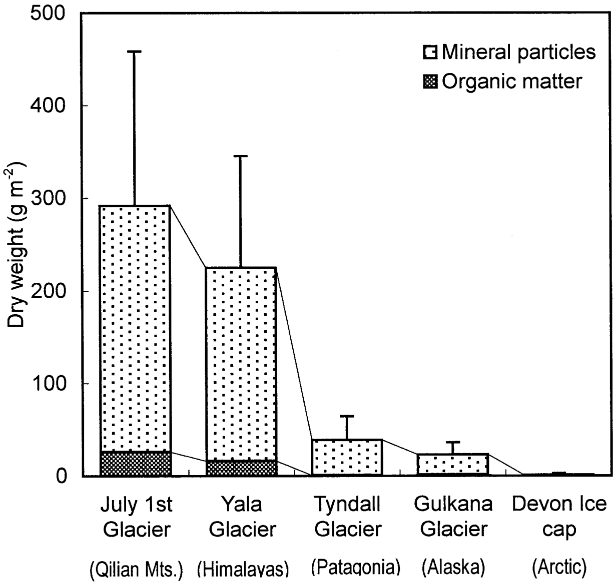

Fig. 10. Comparison of amounts of surface dust and their components among various glaciers around the world. Error bars indicate standard deviation.

100 g m^{-2} on glaciers in the Arctic, Alaska and Patagonia (Takeuchi, 2002a; Takeuchi *et al.*, 2001b; Takeuchi *et al.*, 2001c; Fig. 10), whereas the amount on the July 1 st Glacier was a significantly higher 292 g m^{-2} (mean). On the other hand, the amount of dust recorded on a Himalayan glacier was 225 g m^{-2} (Takeuchi *et al.*, 2000 and unpublished data), which is roughly equivalent to that on the July 1st Glacier (Fig. 10). Moreover, amounts of surface dust above 100 g m^{-2} were observed on two other Himalayan glaciers in Nepal and one Tibetan glacier in China (Takeuchi, unpublished data). Thus, greater amounts of surface dust may be a common characteristic of Asian glaciers.

The composition of surface dust suggests that dust in the ice area consists not only of deposits of wind-blown desert sand, but that it is also a product of microbial activity on the glacier. The desert surrounding the glacier is one of the major sources of airborne desert sand. This kind of sand has been reported to accumulate on the snow and ice of glaciers in western China (*e.g.* Wake and Mayewski, 1994). Since the microscopy of dust on the snow surface (site 11) showed that it consisted mainly of fine mineral particles (Fig. 7), it is likely to be mostly wind-blown desert sand. However, the composition of dust on the bare ice surface was different from that of dust on the snow surface. Dust in the ice area contained high levels of organic matter and cyanobacteria. The mass fraction of organic matter in dust on the ice surface (8.6%) was larger than that on the snow surface (5.0%). Microscopy showed that such dust consisted mainly of small brown granules, which were not observed on the snow surface (Fig. 7). In addition, their size, composition, and structure agree with those of cryoconite granules, already reported on a Himalayan glacier as an algal mat growing on the glacial surface (Takeuchi *et al.*, 2001a). Thus, these granules are likely to be the products of biological activity on the glacial surface. The mass fraction of organic matter in the dust is only 8.6% in dry weight, suggesting that mineral particles seem to be the main component (more than 90%). However, microscopy showed that organic matter was comparable to the mineral components in terms of particle volume. The smaller mass fraction of organic matter is likely due to the lower density of organic matter compared with that of mineral particles. Thus, organic components also appear to exert a major influence on the surface albedo. Although the quantitative contribution of each component to albedo reduction is uncertain, both organic and inorganic components are likely to be effective in reducing the surface albedo on this glacier.

Comparisons of dust components among a number of glaciers showed that both organic and inorganic components were higher on the July 1st glacier compared with those on the other glaciers (Fig. 10). The amount of mineral particles on the July 1st glacier was approximately 13-fold higher than the mean of those on the Patagonian, Alaskan and Arctic glaciers (266 versus 20.3 g m^{-2}), while the amount of organic matter was approximately 38-fold higher (25.4 versus 0.67 g m^{-2}). The higher amount of inorganic components on the July 1st glacier is probably due to its exposure to abundant wind-blown deposits of desert sand, while the higher amount of organic components may be the result of high biological productivity on the glacial surface.

Because of the notable difference in the albedo between a snow surface and a dust covered ice surface, the frequency of snowfall in summer may significantly affect the mass balance of this glacier. New snow covered the entire glacial surface several times during the summer of this study (Matsuda *et al.*, 2004). As Fujita and Ageta (2000) have suggested, snowfall in summer increases the surface albedo and reduces heat income to the glacial surface. Due to this albedo effect, Asian glaciers are more sensitive to climate change compared with winter-accumulation-type glaciers. Since the albedo on the July 1st Glacier is particularly low due to so much dust on the ice surface, the difference in the albedo between new snow and the dust-covered ice surface is greater than that clean ice surface without dust. Thus, the reduction in heat income to the glacial surface by snowfall is likely to be more significant on this glacier compared to that on glacier with a clean bare ice surface. This study showed that the factors affecting surface albedo on the July 1st Glacier are wind-blown deposits, biological activity and the development of weathered ice. Further research into each of these processes is important for a more accurate assessment of the mass balance of this glacier.

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