

Surface albedo and characteristics of cryoconite (biogenic surface dust) on an Alaska glacier, Gulkana Glacier in the Alaska Range

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Abstract

Surface albedo and characteristics of cryoconite (surface dust on glaciers) were investigated on the Gulkana Glacier in the Alaska Range, U.S.A. The surface albedo ranged from 0.11 to 0.52 (mean: 0.32) in the ice area (below the snow line) and from 0.57 to 0.86 (mean: 0.71) in the snow area (above the snow line). The amount of cryoconite on the glacier surface ranged from 1.0 to 102 g m⁻² (mean: 23 g m⁻²) in the ice area and from 0.8 to 1.7 g m⁻² (mean: 1.2 g m⁻²) in the snow area. The proportion of organic matter in the cryoconite was higher in the snow area (10.2 to 22.1%, mean: 15.5%) than in the ice area (2.4 to 11.0%, mean: 7.1%). Microscopy of the cryoconite revealed that cryoconite on the ice area consisted of mineral particles, snow algae, and dark colored organic matter. The results show that the surface albedo in the ice area was reduced approximately 0.13 by cryoconite. The large amount of snow algae and organic matter in the cryoconite suggests that biological activity takes part in the albedo reduction. In the snow area, spectral albedo of the surface and microscopy of the cryoconite suggest that the surface albedo was significantly reduced by red snow algae (*Chlamydomonas nivalis*). The results were compared with those of a Himalayan glacier.

1. Introduction

Recent investigations revealed significant shrinkage of glaciers in many parts of the world. Glaciers in Alaska also generally showed substantial thinning and terminus retreat (e.g. Sapiano *et al.*, 1998). Since glacier shrinkage may cause global sea level rise and water source depletion (e.g. Meier, 1984), it is important to study the processes associated with glacier change.

Glacier shrinkage may result from climate change such as global warming. Factors causing glacier change are usually thought to be physical conditions around the glaciers, such as air temperature and precipitation (e.g. Oerlemans and Fortuin, 1992). However, recent studies showed that not only physical factors, but also a biological factor may affect glacier change (e.g. Kohshima *et al.*, 1993; Takeuchi *et al.*, 2001b). Glaciers are inhabited by unique living organisms, such as snow algae, insects, ice worms, and bacteria (e.g. Hoham and Duval, 2001). They are completely adapted to the extremely cold environment and spend their whole lives on glaciers. Organic matter derived from their biological activity, such as the organisms themselves, their dead bodies, and decomposed organic matter, can accumulate on the glacier surface, leading to changes in the surface

albedo of the glacier. The reduction of surface albedo increases the solar radiation absorbed by the glacier surface and results in more melting of the glacier. Although a large amount of debris on the glacier has an effect of heat insulation and inhibits the ablation of snow and ice (e.g. Mattson *et al.*, 1993), the amount of this biogenic debris is generally much smaller than that amount retarding the ablation. Thus, the biological activity on the glacier would affect the surface albedo and accelerate ablation of the glacier. For example, some glaciers in the Himalayas are covered with a dark-colored biogenic material (cryoconite) derived from snow algae and bacteria (Kohshima *et al.*, 1993; Takeuchi *et al.*, 2001b). The albedo of the intact surface bearing the cryoconite was substantially lower than that of the surface from which the cryoconite was artificially removed (5% versus 37%). The melting rate of the intact surface was reported to be 3 times larger than that of the surface without the cryoconite (Kohshima *et al.*, 1993). In contrast, on some glaciers in Patagonia and the Arctic, the amount of cryoconite is small and the glacier surface is rather clean (Takeuchi *et al.*, 2001a; 2001c). The effect of cryoconite on surface albedo in these glaciers is small probably due to low biological activity. These facts suggest that the biological activity and its effect on albedo vary among glaciers. However, information

about cryoconite on glaciers is still limited and factors affecting biological activity and the formation process of cryoconite are still unclear.

This paper aims to describe the surface albedo and characteristics of cryoconite on an Alaska glacier, the Gulkana Glacier in the Alaska Range. Although there are some reports of snow algae living in Alaska glaciers (Kol, 1942; Takeuchi, 2001d), their effect on the surface albedo is unknown. In this study, the spectral albedo and amount of cryoconite were measured at six sites of different elevation on the glacier. The biological characteristics of the cryoconite were analysed in a laboratory. The effect of the biological activity on the surface albedo is discussed in the ice and snow area respectively. The results are compared with those of a Himalayan glacier where significant albedo reduction by biological activity has been reported.

2. Study site and methods

The investigation was carried out on the Gulkana Glacier, located in the central Alaska Range (Figs. 1 and 2) from 15 to 19 August 2000. The glacier flows west to south from Icefall Peak (about 2440 m a.s.l.) down to the terminus at an elevation of about 1220 m a.s.l. This glacier is easily accessible from the Richardson Highway and has been monitored for a long time by the U.S. Geological Survey (e.g. March, 2000). The glacier has been generally receding during last 50 years and has lost 11 ± 5 m in ice equivalent thickness averaged over the whole glacier between 1954 and 1993 (Dowdeswell *et al.*, 1997). Most of the surface is bare ice or snow without debris cover (rock and stone). The length and area of the glacier are approxi-

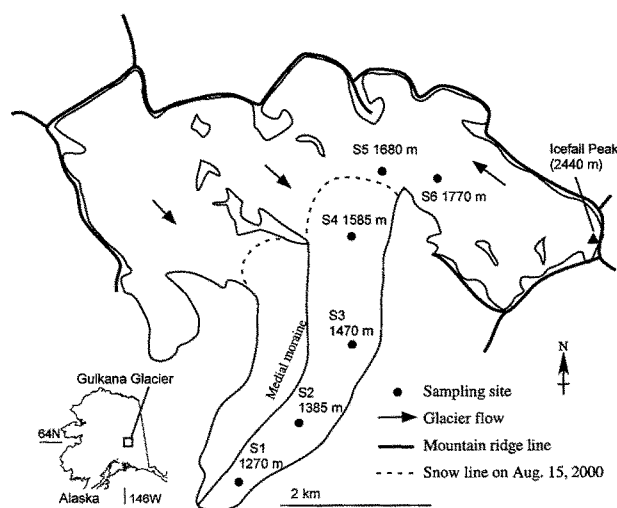


Fig. 1. A map of Gulkana Glacier in the Alaska Range, showing sampling sites on the glacier surface.

mately 4 km and 21.8 km², respectively. The equilibrium line of the glacial mass balance in the year (2000) was approximately 1720 m a.s.l. (USGS, personal communication). Surface albedo measurement and ice/snow sampling were carried out at six sites, located between 1270 m and 1770 m a.s.l. (S1 – S6, Fig. 1). The snow line at this time was approximately 1650 m a.s.l., which is located between collection site S4 and S5. Hence, the surface condition of the sampling sites was snow at the upper two sites (S5, S6), and bare ice at the lower four sites (S1 – S4). Red snow was visually significant during the study period in the snow area around 1700 m a.s.l., including S5.

The surface albedo on each study site was measured with a portable photometer (model 2703, Abe Sekkei Co. Japan) within 3 hours of local solar noon



a

Fig. 2. View of Gulkana Glacier from approximately 8 km away from the terminus (a) and the bare ice surface covered with cryoconite (b, near S3, 2001.8.7).



b

under cloud free condition. The measured wavelengths were 400, 450, 500, 550, 600, 650, 700, 750, 850, 950, and 1050 nm. The measurements were made at 30 cm above the surface. The albedo was calculated from the total of reflected irradiance of the surface and that of a standard white reference plate. The mean albedo was obtained from values of 5 different surfaces at each site.

In order to measure the amount of cryoconite on the glacier surface and organic matter content of cryoconite, ice/snow in surface layer was collected with a stainless-steel scoop (approximately 15×15 cm in area and 1–3 cm in depth). The collected area on the surface was measured to calculate the amount of cryoconite per unit area. The collected samples were melted and preserved as a 3% formalin solution in 125-ml clean polyethylene bottles to fix biological activity. All samples were transported by car to the International Arctic Research Center, University of Alaska Fairbanks, for analysis. In the laboratory, the samples were dried (65°C, 24 hours) in pre-weighed crucibles. The amount of cryoconite per unit area of the glacier was obtained from the dry weight and the sampling area. Then, the dried samples were combusted for 1 hour at 1000°C in an electric furnace, and weighed again. The amount of organic matter was obtained from the difference the weight of between the dried and combusted samples. After combustion, only mineral particles remained.

The composition of the cryoconite was examined with an optical microscope (Nikon SMZ800 and E600).

3. Results

3.1. Albedo of the glacier surface

Figure 3 shows the altitudinal change of mean surface albedo on Gulkana Glacier with error bars

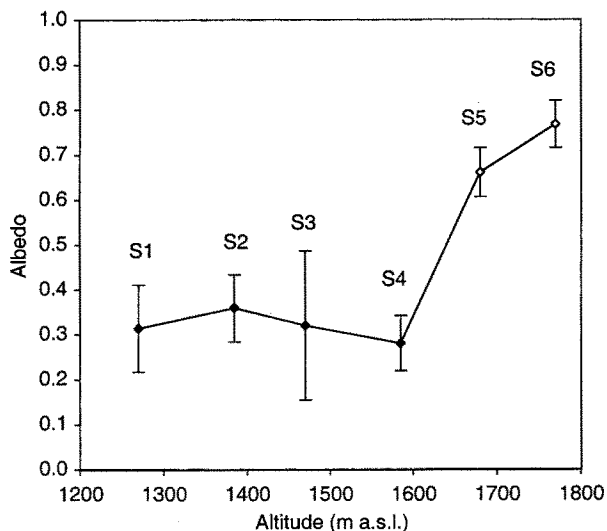


Fig. 3. Change of surface albedo with altitude on the Gulkana Glacier. Solid and open marks indicate ice and snow area, respectively.

based on standard deviation. The surface albedo ranged from 0.11 to 0.52 (mean: 0.32) in the ice area (S1–S4) and from 0.57 to 0.86 (mean: 0.71) in the snow area (S5–S6). In the ice area, the albedos at the lowest site (S1) and highest site (S4) appear to be lower than that at the other sites. However, there was no statistically significant difference in the surface albedo among the sites in the ice area (One-way ANOVA, statistical f value (f) = 0.38, Probability (P) = 0.77 > 0.05). In the snow area, the surface albedo was significantly lower at the lower elevation site (S5) compared to that of the higher elevation site (S6) (statistical t value (t) = -3.17, P = 0.013 < 0.05). The standard deviation of albedo was comparably larger in the ice area than in the snow area. The standard deviation ranged from 0.054 to 0.166 in the ice area and ranged from 0.053 to 0.054 in the snow area. The highest standard deviation in the ice area occurred at site S3 (0.166).

Figure 4 shows the spectral albedo of the glacier surface of each study site. In the ice area, the albedos of each site were almost the same at longer wavelengths (750–1050 nm), while they varied at shorter wavelengths (400–700 nm). In the snow area, the spectral albedos were generally higher than those in the ice area. Remarkable light absorptions were shown at 500–550 nm and 700 nm on the spectrum of site S5.

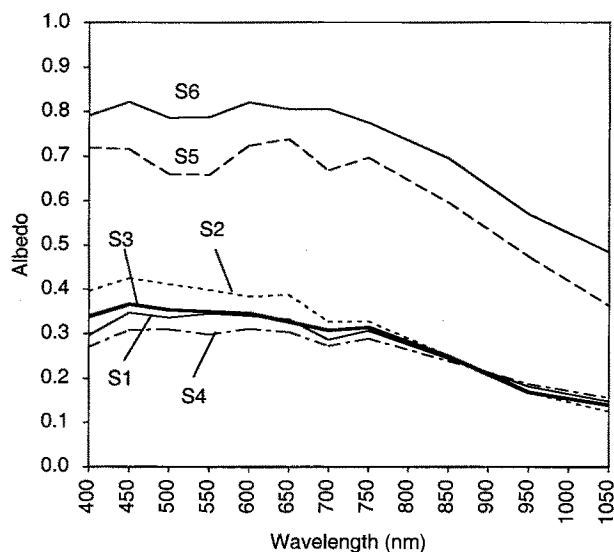


Fig. 4. Spectral albedo of the surface on Gulkana Glacier. The curves are mean surface albedo of 5 surfaces at each site.

3.2. Amount of the cryoconite on the glacier surface

The amount of cryoconite (per unit area) on the glacier surface was larger in the ice area than in the snow area (Fig. 5). The amount of cryoconite ranged from 1.0 to 102 g m⁻² (mean: 23 g m⁻²) in the ice area and from 0.8 to 1.7 g m⁻² (mean: 1.2 g m⁻²) in the snow area. There was no clear relationship between altitude and the amount of cryoconite on this glacier. The

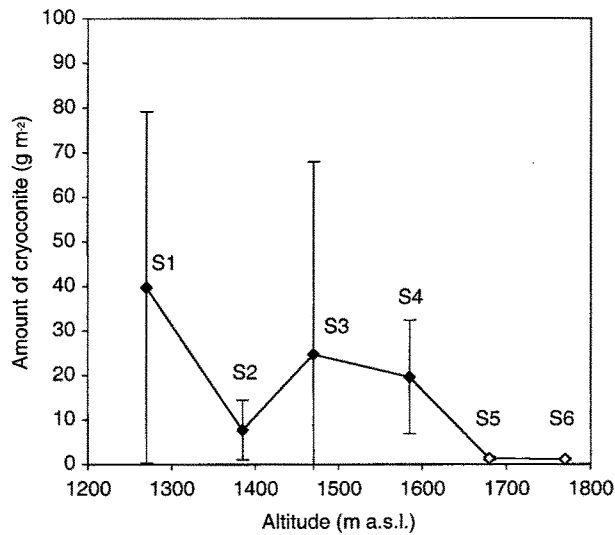


Fig. 5. Mean amount of cryoconite (dryweight g m^{-2}) on the surface of Gulkana Glacier. Solid and open marks indicate ice and snow area, respectively. Error bar = standard deviation.

largest cryoconite amount was observed at the lowest site (S1). The standard deviation of the amount ranged from 6.7 to 43.1 in the ice area and from 0.14 to 0.37 in the snow area. The largest standard deviation was at site S3 (43.1), where the largest standard deviation of albedo occurred.

3.3. Composition of the cryoconite

The altitudinal distribution of mineral amount was almost same as that of cryoconite (Fig. 6). The amount of mineral particles ranged from 0.84 to 97.8 g m^{-2} (mean: 21.6 g m^{-2}) in the ice area and from 0.67 to 1.44 g m^{-2} (mean: 1.02 g m^{-2}) in the snow area. The largest amount of mineral particles occurred at the lowest site (S1). The standard deviation of the mineral

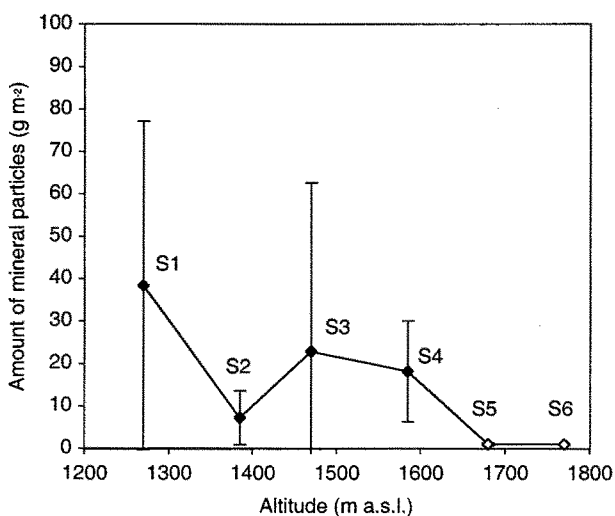


Fig. 6. Mean amount of mineral particles (dryweight g m^{-2}) on the surface of Gulkana Glacier. Solid and open marks indicate ice and snow area, respectively. Error bar = standard deviation.

amount ranged from 6.3 to 39.8 in the ice area and from 0.13 to 0.28 in the snow area. The largest standard deviation was observed at site S3 (39.8).

In contrast with mineral particles, the altitudinal distribution of organic matter was different from that of cryoconite (Fig. 7). The amount of organic matter ranged from 0.12 to 7.9 (mean: 1.34) in the ice area and from 0.09 to 0.31 (mean: 0.18) in the snow area. The amounts of organic matter were larger in the middle part of the glacier (S3, S4), and lower at the lower sites (S1, S2) and in the snow area. The largest amount of organic matter occurred at site S3. The percentage of organic matter in dry weight is larger in the snow area than in the ice area (Fig. 8). The organic matter content of the cryoconite ranged from 2.4 to 11.0%

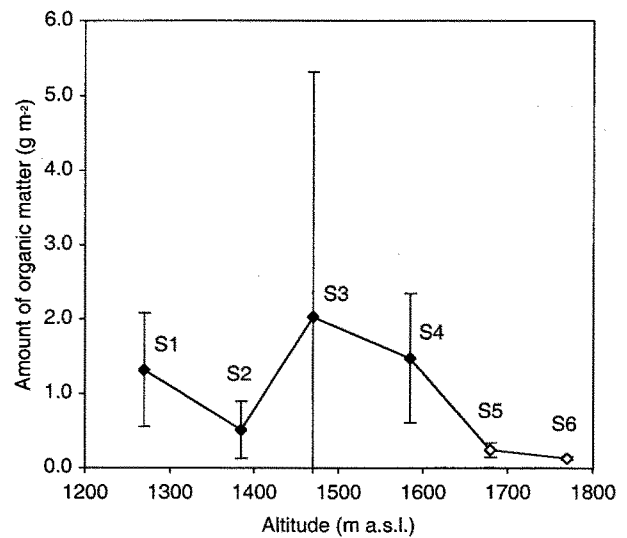


Fig. 7. Mean amount of organic matter (dry weight g m^{-2}) on the surface of Gulkana Glacier. Solid and open marks indicate ice and snow area, respectively. Error bar = standard deviation.

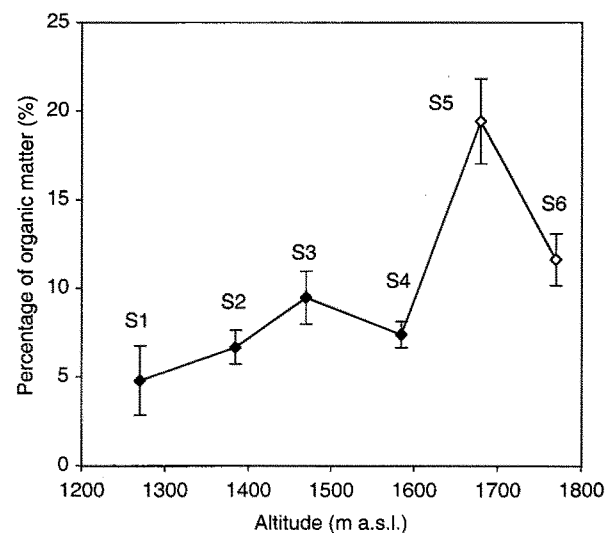


Fig. 8. Percentage of organic matter in cryoconite on Gulkana Glacier. Solid and open marks indicate ice and snow area, respectively. Error bar = standard deviation.

(mean: 7.1%) in the ice area and from 10.2 to 22.1% (mean: 15.5%) in the snow areas. The largest percentage occurred at site S5, where red snow was significantly visible (19.4%). The percentage is lower in the lower the ice area (S1 and S2, 4.8 – 8.0%) compared with the upper ice area (S3 and S4, 9.5 – 10.3%).

Microscopy of the cryoconite revealed that cryoconite in the ice area consisted of mineral particles, snow algae, and dark colored organic matter (Fig. 9a). These components appeared to be almost the same among the study sites in the ice area. The dark colored organic matter was the main component in the cryoconite. The organic matter was usually black, and 40 – 800 μm (mean: 200 μm) in diameter. It was the aggregation of living and dead unicellular green algae with mucus substances. The mineral particles were brown, white, or transparent in color and approximately 23 – 480 μm (mean: 92 μm) in diameter. Cryoconite on the snow area mainly consisted of cells

of red snow algae (*Chlamydomonas nivalis*, Fig. 9b). The red snow algae were observed both at S5 and S6, but were more abundant at S5. Mineral particles were also observed, but their amount is rather small compared with the algal cells.

4. Discussion

4.1. Effect of cryoconite on the surface albedo of the ice area

Figure 10a shows the relationship between the amount of cryoconite and surface albedo in the ice area. A statistical analysis revealed that the surface albedo negatively correlated with the cryoconite amount on the surface (Spearman's correlation coefficient (r_s) = -0.826 , probability (P) < 0.01). This correlation suggests that the variation of the surface albedo in the ice area is mainly due to the amount of the cryoconite on the surface. The cryoconite, there-

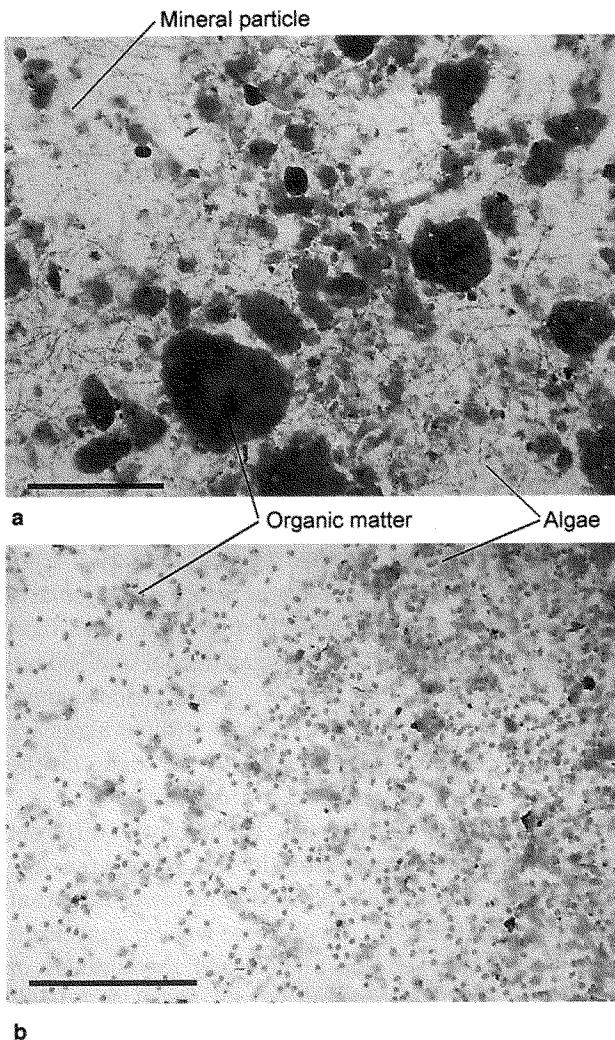


Fig. 9. Microscopy of the cryoconite on the surface of Gulkana Glacier. a: site S4 (the ice area), b: site S5 (the snow area). Scale bar = 0.5 mm. The cryoconite include snow algae, dark-colored organic granules, and mineral particles. In the snow area, the cells of red colored snow algae (*Chlamydomonas nivalis*) were main component.

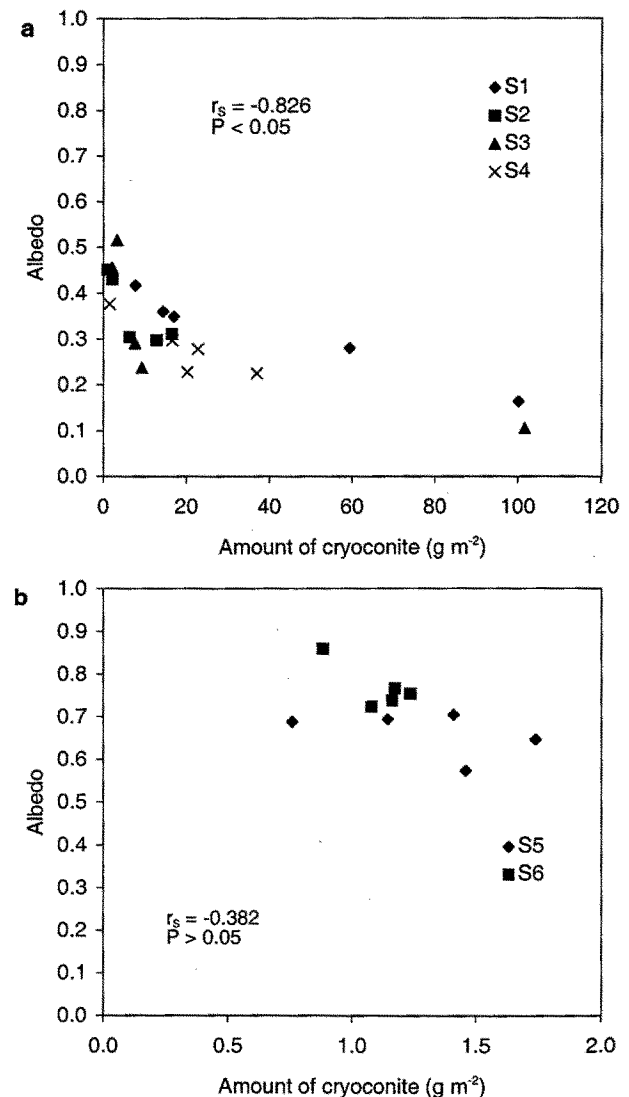


Fig. 10. Relationship between albedo and amount of cryoconite in the ice area (a) and snow area (b) of Gulkana Glacier. (r_s = spearman's correlation coefficient, P = probability)

fore, substantially affect the surface albedo in the ice area. The mean albedo in the ice area was 0.32, which is lower than that of clean bare ice. In general, surface albedo of clean bare ice has been reported to be 0.34 – 0.51 (Paterson, 1994). On this glacier, the albedo of clean bare ice surface, where the amounts of cryoconite were less than 5 g m^{-2} , ranged from 0.38 to 0.52 (mean: 0.45). The difference of albedo between the mean and clean bare ice is likely due to the mean effect of cryoconite on the ice surface. Therefore, the surface albedo in the ice area was reduced approximately 0.13 by cryoconite on this glacier. The main component of the cryoconite was a dark colored organic matter. Since the organic matter contained a large amount of living and dead snow algae, biological activity has a part in the albedo reduction on this glacier.

Although large amounts of debris can act as a heat-insulator and inhibit the ablation of snow and ice (e.g. Mattson *et al.*, 1993), the amount of cryoconite on this glacier is much smaller than that the amount retarding the ablation. According to Mattson *et al.*, (1993), debris cover more than approximately 30 mm in thickness decreases ablation of glacier surface under the debris. The largest amount of cryoconite on the glacier was 102 g m^{-2} at site S3. This amount is less than 2 mm thickness of debris cover and much less than the amount sufficient to retard the ablation. Therefore, the cryoconite could accelerate the ablation of this glacier.

Although there was no significant difference in cryoconite amount among the study sites in the ice area, characteristics of cryoconite varied with altitude. The rate of organic matter in cryoconite in the lower part of the ice area (S1 and S2) is comparatively lower than the higher part (S3 and S4). This is probably due to the larger mineral particle supply in the lower area and/or larger organic matter production in the upper ice area. One of the sources of mineral particles on the glacier is windblown dust. Soil particles and fine glacial deposits downstream of the glacier are likely carried by wind to the glacier surface. Since these windblown particles come from downstream, larger amounts of particles may accumulate in the lower area of the glacier. Also, mineral particles that come from side or medial moraine can accumulate on the surface at lower elevations, since the distance from the side and medial moraine becomes smaller at lower sampling sites (S1 and S2, Fig. 1). In fact, coarser mineral particles (1 – 5 mm in diameter), which are too large to be picked up by wind, were observed in the cryoconite samples from sites S1 and S2. The higher organic matter content in the upper ice area is likely due to the larger productivity of snow algae. The biomass of snow algae on this glacier increases with altitude in the ice area, and the highest biomass occurred at site S4 (Takeuchi, 2001d).

Snow algal production is probably the main source of organic matter on the glacier. Therefore, more organic matter may be produced at the upper part of the ice area than the lower part. The large mineral supply at site S1 and the large algal production at site S4 may cause the lower albedo of each site.

The large standard deviation of the albedo at site S3 indicates that the surface albedo is particularly irregular at this site. The amount of cryoconite also showed a large standard deviation, suggesting that the albedo variation results from irregular distribution of cryoconite at this site. The patchy distribution of cryoconite is probably due to the effect of supraglacial streams. There were many supraglacial streams of 20 – 100 cm wide in this area. The running water can wash out the cryoconite on the glacier surface and concentrate it in certain places along the streams. The irregular distribution of cryoconite may cause surface roughness in this area. The surface in this area was particularly rough compared to other areas. The level of the surface covered with cryoconite was 30 – 100 cm lower than the level of the surface covered with little cryoconite. This is probably caused by faster melting of the surface covered with cryoconite, relative to the surface covered with little cryoconite.

4.2. Effect of red snow algae on the surface albedo of the snow area

The results of spectral albedo suggest that the surface albedo in the snow area (above the snow line) is reduced by the red snow algae. Main factors affecting albedo of the snow surface are snow granule size and contaminant (Warren and Wiscombe, 1980). The data of granule size is not available in this study. However, the light absorptions at 500 – 550 nm and 700 nm in the spectral albedo (Fig. 4) suggest that the albedo was strongly affected by contamination from red snow algae (*Chlamydomonas nivalis*) particularly at site S5, because pigments of the algae have light absorption at 390 – 570 nm for carotenoid and 680 nm for chlorophyll (Bidigare *et al.*, 1993). Since comparable data of surface albedo of snow without algae are not available, quantitative effect of the algae on the albedo could not be obtained in this study.

The surface albedo was significantly different between the two study sites in the snow area: the albedo at the lower site (S5, 0.66) was lower than that of upper part (S6, 0.77). Since there was no significant correlation between the albedo and the amount of cryoconite in the snow area ($r_s = -0.382$, $P > 0.05$, Fig. 10b) and no significant difference in the amount of cryoconite between site S5 and S6 (statistical t value = 1.114, $P = 0.316 > 0.05$), the albedo difference between two sites is not due to the amount of cryoconite (dry weight) as is the case in the ice area. Algal biomass at site S5 was reported to be significantly larger than that of S6 (0.232 versus 0.084 cell ml

m^{-2} , Takeuchi, 2001d). Therefore, albedo difference is likely due to the larger amount of the red colored algae at site S5.

According to the report on the snow algae of this glacier (Takeuchi, 2001d), the algal biomass difference between these two sites is probably due to the availability of liquid melt-water, which is one of the essential factors for algal growth. During the study period, the red snow was visibly significant in the area just above the snow line (the lowest elevation in the snow area). This is probably the result of much melt-water availability at this area due to a higher air temperature. Therefore, the algal bloom appears to considerably affect the surface albedo in the snow area, particularly at the area near the snow line on this glacier.

4.3. Comparison with a Himalayan glacier

4.3.1. Albedo and cryoconite in the ice area

Although the results show significant surface albedo reduction by biogenic cryoconite on this Alaska glacier, the effect of cryoconite appears to be smaller when compared to a Himalayan glacier, especially in the ice area. On a Himalayan glacier (Yala glacier), the surface albedo of the ice area is 0.13 (Takeuchi *et al.*, 2001b), which is lower than that of the Gulkana Glacier (0.32). The amount of cryoconite in the ice area of the Himalayan glacier is 300 g m^{-2} (mean, Takeuchi *et al.*, 2000), which is approximately 13-fold larger than that of the Gulkana Glacier (23 g m^{-2}). This indicates that the higher surface albedo of the Gulkana Glacier compared with the Himalayan glacier is due to the larger amount of cryoconite on the surface. However, the total biomass of snow algae in the ice area of Gulkana Glacier is comparable to that of the Himalayan glacier. The total biomass is $0.17 - 0.88 \text{ cell ml m}^{-2}$ (mean: 0.52) on Gulkana Glacier (Takeuchi, 2001d) and $0.22 - 0.69$ (mean: 0.42) cell ml m^{-2} in the Himalayan glacier (Yoshimura *et al.*, 1997). Although snow alga was reported to be a primal source of organic matter on the glacier surface (Takeuchi *et al.*, 2001b; Kohshima, 1987), this fact shows that the total algal biomass is not the only factor affecting cryoconite formation.

Although the total algal biomass was almost same level in the Alaska and Himalayan glaciers, the community structure of snow algae was different (Takeuchi, 2001d). The algal community of the ice area on the Alaska glacier consists of mostly unicellular green algae, while that on the Himalayan glacier consists of unicellular green algae and filamentous cyanobacteria (Oscillatoriaceae cyanobacteria). The proportion of the cyanobacteria to total algal biomass is less significant on the Alaska glacier than the Himalayan glacier (0 - 1% versus 12 - 24%, respectively). The filamentous cyanobacteria were reported to play an important role in the formation of cryoconite on the Himalayan glacier (Takeuchi *et al.*,

2001b). They can entangle mineral and organic particles and form a granular algal mat (cryoconite granule), which is a main component of cryoconite of the glacier. These cryoconite granules seem to be an effective means of avoiding wash out from a glacier by running meltwater and maintaining a large cryoconite amount on the Himalayan glacier. In contrast, unicellular green algae can not form an algal mat like cryoconite granules. Some species of the green algae formed a small aggregation on the Alaska glacier, but the aggregation seems to be less effective to prevent wash out. Therefore, it is possible that the small amount of cryoconite on the Alaska glacier is due to the small biomass of filamentous cyanobacteria.

4.3.2. Albedo and cryoconite in the snow area

Since quantitative effect of the biogenic material on the surface albedo in the snow area is uncertain on both the Alaska and Himalayan glaciers, difference of the effect of biological activity between the glaciers is unknown. However, characteristics of the albedo reducing material in the snow area are different between the two glaciers. The red snow algal cells were the main component of the cryoconite on the Alaska glacier, whereas the red algae are not significant on the Himalayan glacier. Yoshimura *et al.* (1997) described the condition of the snow surface on the Himalayan glacier where the snow samples were collected to measure algal biomass. According to the description, red snow was evident at only one out of 11 sampled points in the snow area. The other 10 points were covered with blackish dirty cryoconite. The dirty cryoconite consisted of mainly dark-colored organic matter, and also algae, bacteria, and mineral particles (Takeuchi, 1999). The algal biomass in the snow area on the Himalayan glacier is significantly smaller than that on Gulkana Glacier ($0.0018 - 0.078$ versus $0.060 - 0.41 \text{ ml m}^{-2}$, respectively, Takeuchi, 2001d). Thus, the snow surface albedo on the Himalayan glacier is likely reduced by the dark organic matter rather than the algal cells.

According to the report of snow algae (Takeuchi, 2001d), a lowered frequency of snow cover in summer causes the larger biomass of snow algae in the snow area on the Alaska glacier. In contrast, snow often covers the surface of the Himalayan glacier in summer monsoon season, and reduces the light intensity of algal habitat, and then inhibits growth of snow algae (Yoshimura *et al.*, 2000). The algae on the Himalayan glacier grow mainly in spring to early summer, when precipitation is small (pre-monsoon season). After snow covers the glacier surface, the decomposition of organic matter by bacteria may become more significant than algal growth, and the dead algal cells and the other organic matter may change to dark colored organic matter (humic substances). On the Alaska glacier, the algal growth may continue until late

summer, because of less frequency of snow cover in summer. Thus, the different characteristics of the albedo-reducing material in the snow area between the Alaska and Himalayan glaciers may be due to difference of meteorological condition in summer of the glaciers.

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