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Effect of cryoconite and snow algal communities on surface albedo on maritime glaciers in south Alaska

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Abstract

In order to evaluate the effect of cryoconite on surface albedo on glaciers, surface albedo, characteristics of cryoconite, and snow algal communities were investigated on two maritime glaciers; Worthington and Matanuska Glaciers in south Alaska, U.S.A. The surface albedo in the ice area ranged from 0.37 to 0.74 and the mean was 0.53. The amount of cryoconite on the glacier surface ranged from 0.2 to 14 g m^{-2} and the mean was 3.8 g m^{-2}. Organic matter content in the cryoconite ranged from 1.0 to 9.8% and the mean was 4.7%. Snow algal communities on the glaciers were dominated by three green algae, which were *Mesotaenium breggrenii, Ancylonema nordenskioldii* and *Chlamydomonas nivalis*. The cell volume biomass of the snow algae ranged from 0.015 to 0.056 mL m^{-2} and the mean was 0.039 m^{-2}. As compared with an inland glacier of Alaska, Gulkana Glacier, the effect of cryoconite on glacial surface albedo seemed to be smaller in the two maritime glaciers in this study. The surface albedo is higher and amount of cryoconite is smaller in the maritime glaciers than the inland glacier. The organic matter content and algal biomass are smaller in the maritime glaciers than the inland glacier. The smaller amount of cryoconite and algal biomass on the maritime glaciers may be caused by washing of cryoconite and algae out of the glaciers by large amounts of running meltwater on the bare ice surface. The meltwater can be produced more on the maritime glaciers, since the ablation rate is higher than on the inland glacier surface.

1. Introduction

Cryoconite is biogenic surface dust on the glacial surface and is common on many glaciers in the world (*e.g.* Gajda, 1958; Wharton *et al.*, 1985). Cryoconite usually consists of mineral particles and organic matter. The organic part of cryoconite is derived from biological activity on the glacier and consists of the organisms themselves, their dead bodies, and decomposed organic matter (humic substances). The organisms include snow algae, insects, ice worms, protozoa, and bacteria (*e.g.* Hoham and Duval, 2001). They are special species adapted to the extremely cold environment and spend their whole lives on glaciers. Cryoconite is formed as a result of their biological activity on the glaciers.

Surface albedo of snow and ice can be reduced by impurities such as cryoconite (*e.g.* Warren and Wiscombe, 1980). Cryoconite can thereby contribute to acceleration of melting of the glacier surface. Especially, organic matter in cryoconite is optically effective on the albedo reduction, since the organic matter is usually dark-colored and large volume particles (Takeuchi, 2002b; Takeuchi *et al.*, 2001b). The reduction of surface albedo increases the solar radiation absorbed by the glacier surface and result in more melting of the glacier. Since the organic matter in the cryoconite is produced by the organisms living on glaciers, the biological activity on the glacier would affect the surface albedo and ablation of the glacier and then may affect shrinkage of glaciers. Recent investigations revealed substantial thinning and terminus retreat of glaciers in many parts of the world (*e.g.* Arendt *et al.*, 2002). The cryoconite may take part of the shrinkage of glaciers. Thus, it is important to study the formation processes of cryoconite on the glacier.

Recent studies have revealed that characteristics of cryoconite differ among glaciers. For example, as cryoconite on Himalayan glaciers is dark-colored and densely covers the glacier surface in the ablation area (Kohshima *et al.*, 1993; Takeuchi *et al.*, 2001b), the cryoconite significantly reduces 8–15% of the surface albedo on the Himalayan glaciers. The melting rate was reported to be 3 times larger than that of the surface without the cryoconite (Kohshima *et al.*, 1993).

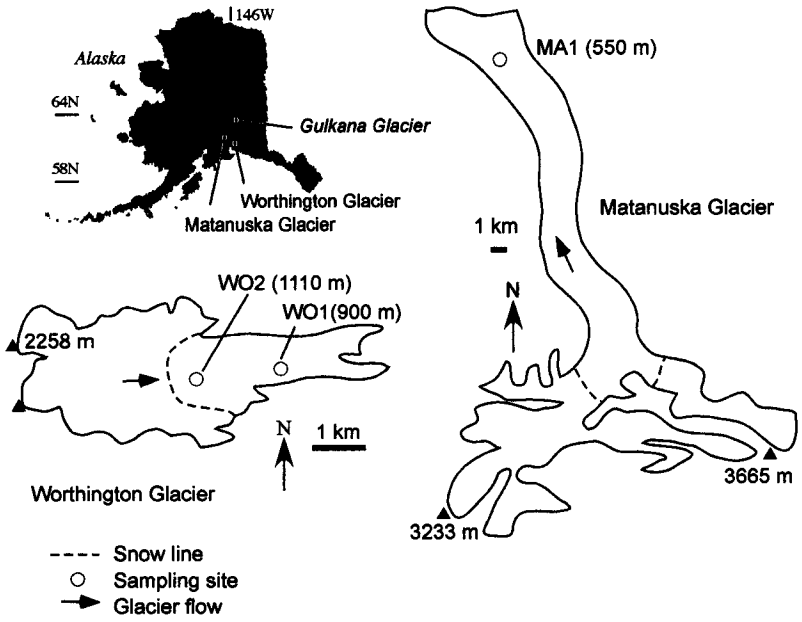

Fig. 1 Maps of Worthington and Matanuska Glaciers in the Chugach Mountains, Alaska, showing sampling sites (WO1, WO2, and MA1) on the glacier surface.

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 is small in these glaciers probably due to low biological activity. Furthermore, the cryoconite on Tibetan glaciers has pale brown coloration due to less amounts of dark-colored humic substances (Takeuchi *et al.*, 2002b). This type of cryoconite is less effective on the surface albedo due to its high reflectivity of light. Thus, the effect of cryoconite on the surface albedo differs among glaciers. The variation of cryoconite is important to study the glacial mass balance and heat budget. 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 and understand the relation of the surface albedo, characteristics of cryoconite, and snow algal community on two maritime glaciers in south Alaska. In this study, the spectral albedo and amount of cryoconite were measured on the ice surface of the glaciers. The characteristics of the cryoconite and snow algal community on the glacier surface were analyzed in a laboratory. The results are compared with those of an inland glacier of Alaska, which is in different geographical and climate condition.

2. Study sites and methods

The investigation was carried out on the Worthington and Matanuska Glaciers located in the Chugach Mountains in south Alaska (Figs. 1 and 2) on September 7-9, 2000. Worthington Glacier is a small temperate glacier and flows west to east from a mountain peak (2550 m a.s.l.) toward east down to the terminus at an elevation of approximately 820 m a.s.l. The size of the glacier is approximately 8 km long with 1 km

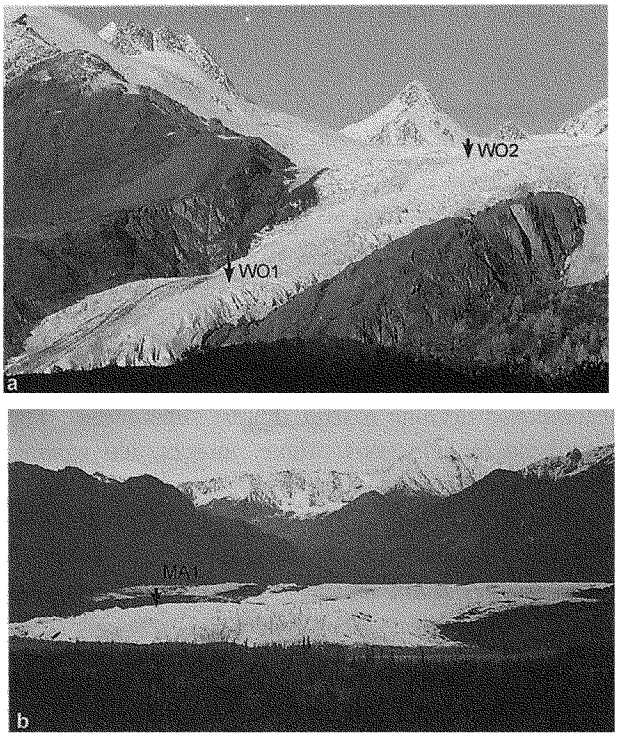

Fig. 2 View of Worthington (a, September, 2000) and Matanuska Glaciers (b, August 2001). The picture of Matanuska was taken a year after this field work. The sampling sites are shown in each picture.

wide. The snow line at the studied time was approximately 1150 m a.s.l. Matanuska Glacier is a long valley glacier and flows from some mountain peaks (around 3200-3700 m a.s.l.) towards north. The terminus is at an elevation of approximately 500 m a.s.l. The size of the glacier is approximately 130 km in length with 3 km wide. The snow line at this time was approximately 1650 m a.s.l. Both the glaciers are easily accessible from highway. Most of the surface of both glaciers is bare ice or snow (Fig. 3) without debris cover (rock and stone). Surface albedo measurement and ice sampling were carried out at two sites on Worthington Glacier (WO1 and WO2) and one site on Matanuska Glacier (MA1), locating between 550 m and 1110 m a.s.l. (Fig. 1). The surface condition of the sampling sites was bare ice on both glaciers. These sites were representative bare ice surfaces and safely accessible. Red snow was visually significant during the study period in the snow area above snow line on Worthington Glacier.

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. The weather condition was cloudy on Worthington Glacier and clear on Matanuska Glacier. The measured wavelengths were 12 points in visible and near inferred region (400, 450, 500, 550, 550, 600, 650, 700, 750, 850, 950, and 1050 nm). The measurements were made at 30 cm above the surface. The measured area was approximately 80 cm^2. 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, which were randomly selected in an area approximately 100×100 m^2 at each site.

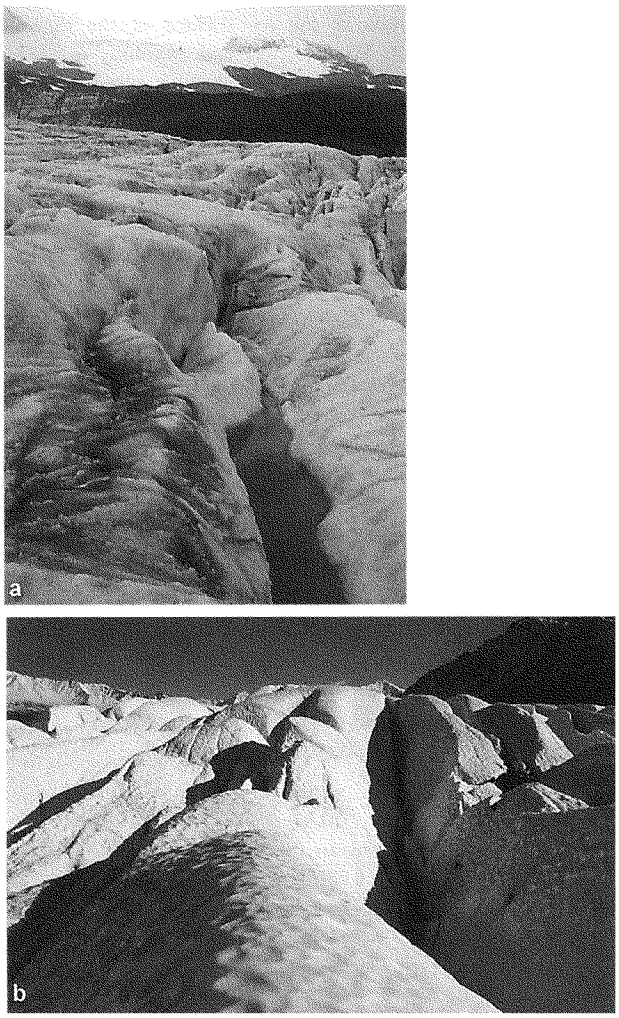

Fig. 3 The bare ice surface of each glacier (a, site WO2 on Worthington Glacier; b, site MA1 on Matanuska Glacier). Cryoconite (dark-colored dust) can be seen to cover the surface partly.

In order to measure the amount of cryoconite on the glacier surface and organic matter content of cryoconite, ice in surface layer was collected with a stainless-steel scoop (approximately 15×15 cm in area and 1-3 cm in depth) at the area where the spectral albedo was measured. The five samples were collected at each studied site. The collected area on the surface was measured to calculate the amount of cryoconite per unit area. Cryoconite also existed at the bottom of cryoconite holes, which are water-filled cylindrical depressions on the glacier surface of both glaciers. The size ranged from 7 to 13 in depth, from 3 to 8 in diameter. The cryoconite in cryoconite holes also was collected with a pipet in five holes at each studied site. 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).

In order to measure algal biomass on the glacier surface, another set of surface ice was collected with a stainless-steel scoop (1-2 cm in depth). The collected area on the surface was measured to calculate the amount of the algal volume biomass per unit area. The five samples were collected at randomly selected surface at each studied site. The collected samples were melted and preserved as a 3% formalin solution in clean 125 mL polyethylene bottles. These formalin samples were used for cell concentration counting. For identification of algal species, other samples were collected and kept frozen in a cooler. All samples were transported by car to the International Arctic

Research Center, University of Alaska Fairbanks, for analysis. The frozen samples were kept at −5 °C in a freezer.

The algal biomass of each site was represented by the cell number per unit water volume and algal volume per unit area. Cell counts and estimations of cell volume were conducted with an optical microscope (Nikon E600). The samples were stained with 0.5% erythrosine (0.1 mL was added to 3 mL of the sample) and ultrasonicated for 5 min to loosen sedimented particles. 50-1000 μL of the sample water was filtered through a hydrophilized PTFE membrane filter (pore size 0.5 μm, Millipore FHLC01300), which became transparent with water, and the number of algae on the filter was counted (1-3 lines on the filter). The counting was conducted 3-6 times on each sample. From the mean results and filtered sample water, the cell concentration (cells mL^{-1}) of the sample was obtained. Mean cell volume was estimated by measuring the size of 50-100 cells for each species. The total algal biomass was estimated by summing values obtained by multiplying algal concentrations by the mean cell volume. This calculation was done for each species at each site. To obtain spatial biomass at each site, the total biomass was represent as cell volume per unit area of glacier surface (μL m^{-2}). Community structure was represented by the mean proportion of each species to the total algal volume at each sampling point.

3. Results

3.1 Albedo of the glacier surface

The surface albedo measured on both glaciers was shown in Table 1. The albedo ranged from 0.37 to 0.58 and the mean was 0.46 for Worthington Glacier, and from 0.55 to 0.74 and the mean was 0.66 for Matanuska Glacier. There is statistically no significant difference between two sites on Worthington Glacier (t-test: statistic t value (t)=0.719, probability (P)=0.49>0.05). However, a statistical analysis shows that albedos for two sites on Worthington Glacier were significantly smaller than that of the site on Matanuska Glacier (t-test: WO1 vs. MA1, t=4.56, t=0.006<0.05; WO2 vs. MA1, t=4.15, P = 0.003<0.05).

Figure 4 shows the spectral albedo of the glacier surface of study sites. The spectral albedo decreased as the wavelength increased. Especially, at the site of Matanuska Glacier in which the highest albedo was observed, the albedo was particularly high in shorter wavelength (400-650 nm).

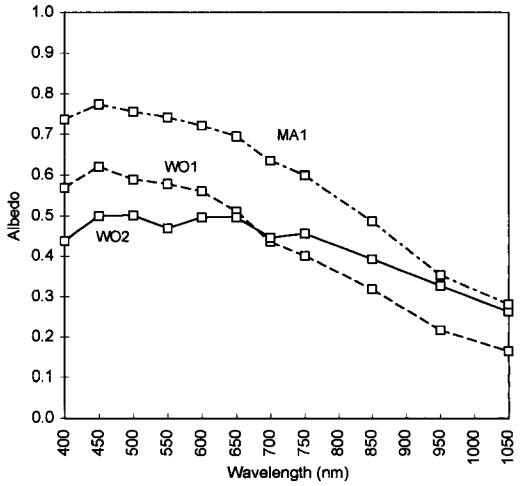

Fig. 4 Spectral albedo of the ice surface of the three sampling sites on Worthington and Matanuska Glaciers. The curves are the mean surface albedo of 5 surfaces at each site.

3.2 Characteristics of cryoconite on the glaciers

The dry weight amount of cryoconite on the bare ice surface ranged from 0.2 to 9.5 g m^{-2} (mean: 4.0 g m^{-2}) for Worthington Glacier and from 0.2 to 13.9 g m^{-2} (mean: 3.3 g m^{-2}) for Matanuska Glacier (Table 1). There was statistically no significant difference between the studied sites (t-test: WO1 vs. WO2, t=1.96, P=0.085>0.05; WO1 vs. MA1, t=0.429, P=0.679>0.05; WO2 vs. MA1, t=0.809, P=0.442>0.05). The mineral particles contained in the cryoconite ranged from 0.16 to 9.1 g m^{-2} (mean: 3.7 g m^{-2}) for Worthington Glacier and from 0.15 to 13.2 g m^{-2} (mean: 3.2 g m^{-2}) for Matanuska Glacier (Table 1).

Organic matter content of the cryoconite on the bare ice surface ranged from 4.4 to 9.8% (mean: 6.2%)

Table 1. Surface albedo and characteristics of cryoconite on Worthington and Matanuska Glaciers. SD=standard deviation.

Site		WO1 mean (SD)	WO2 mean (SD)	MA1 mean (SD)
Surface albedo		0.48 (0.04)	0.46 (0.07)	0.66 (0.08)
Amount of cryoconite	(g m^{-2})	2.10 (2.61)	5.80 (3.31)	3.35 (5.92)
Mineral	(g m^{-2})	1.97 (2.47)	5.51 (3.16)	3.19 (5.66)
Organic matter	(g m^{-2})	0.14 (0.14)	0.29 (0.15)	0.15 (0.26)
Organic matter content (bare ice surface)	(%)	6.6 (2.2)	5.8 (2.1)	2.8 (1.8)
Organic matter content (cryoconite hole)	(%)	3.8 (0.3)	5.1 (0.7)	4.1 (1.0)

for Worthington Glacier and 1.0 to 4.5% (mean: 2.8%) for Matanuska Glacier (Table 1). The content was larger on Worthington Glacier than Matanuska Glacier.

Organic matter content of the cryoconite collected from the bottom of cryoconite holes ranged from 3.3 to 5.9 (mean: 4.4%) on Worthington Glacier, from 2.8 to 5.2% (mean: 4.1%) on Matanuska Glacier (Table 1). The organic matter content in the cryoconite holes was slightly smaller than that of the bare ice surface on Worthington Glacier, while the organic matter content in cryoconite holes was larger than on the bare ice surface on Matanuska Glacier. However, the differences of organic matter content between the cryoconite hole and bare ice surface were not statistically significant at any studied site.

3.3 Snow algal community on the glaciers

Three species of Chlorophyta (green algae) and two of cyanobacteria were observed in the cryoconite on both of the glaciers. The species were *Mesotaenium (M.) breggrenii, Ancylonema (A.) nordenskioldii Chlamydomonas (C.) nivalis* as green algae, and two Oscillatoriaceae cyanobacteria. The three species of green algae have been reported as common algae on glaciers in Northern Hemisphere as well as in Alaska (*e.g.* Yoshimura *et al.*, 1997; Kol, 1942).

The total cell volume biomass of the snow algae was generally small on both glaciers (Fig. 5). It ranged from 0.0004 to 0.24 mL m^{-2} (mean: 0.051 mL m^{-2}) for Worthington Glacier, from 0.0 to 0.048 mL m^{-2} (mean: 0.015 mL m^{-2}) for Matanuska Glacier. There was statistically no significant difference between the studied sites (t-test: WO1 vs. WO2, $t=0.194$, $P=0.801>0.05$; WO1 vs. MA1, $t=0.854$, $P=0.441>0.05$; WO2 vs. MA1, $t=1.45$, $P=0.186>0.05$).

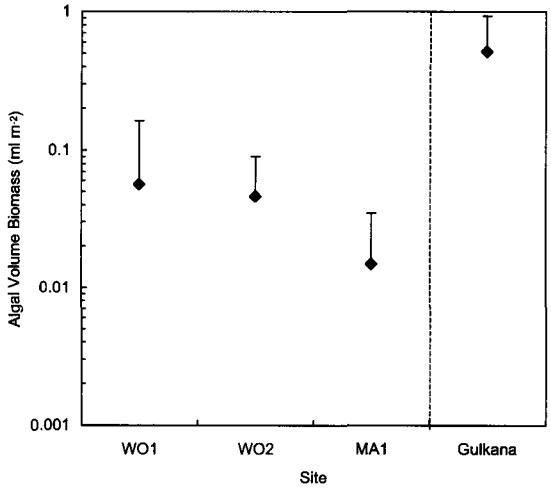

Fig. 5 Total cell volume biomass of the three studied sites on Worthington and Matanuska Glaciers, showing with that of an inland glacier (Gulkana Glacier) in Alaska (Takeuchi, 2001d). Error bar=standard deviation.

The community structure showed that algal communities on the glaciers were dominated by three green algae (Fig. 6). The species were *M. breggrenii, A. nordenskioldii,* and *C. nivalis*. Two Oscillatoriaceae cyanobacteria were minor species on both glaciers (less than 2%). The most dominant species was different between the two glaciers. *M. breggrenii* was dominant at both two sites on Worthington Glacier, while *A. nordenskioldii* was dominant on Matanuska Glacier. Percentage of *M. breggrenii* in the total cell volume biomass was 70-81% on Worthington Glacier and 26% on Matanuska Glacier. Percentage of *A. nordenskioldii* was 11-14% on Worthington Glacier and 66% on Matanuska Glacier. *C. nivalis* was the third dominance on both glaciers (7-17%).

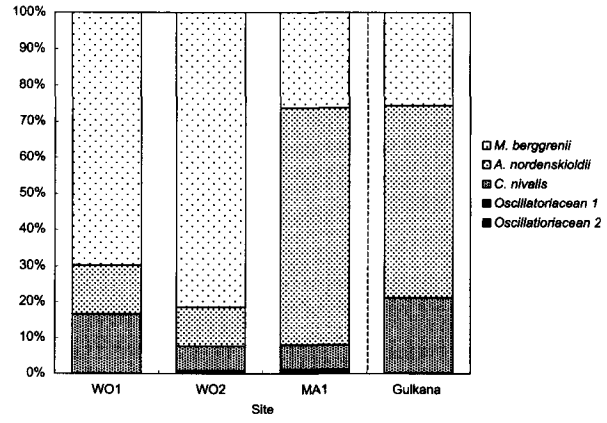

Fig. 6 Community structure of snow algae of each studied site on Worthington and Matanuska Glaciers (proportion of cell volume biomass), showing with that of an inland glacier (Gulkana Glacier) in Alaska (Takeuchi, 2002a).

4. Discussion

The surface albedo on the studied two glaciers is almost equivalent to the albedo of clean bare ice surface of 0.34-0.51 by Paterson (1994). The spectral albedo of the studied sites also indicates clean ice surface; namely, the decrease of spectral albedo with wavelength observed on the two glacier is a characteristic feature of the clear glacial ice (Zeng *et al.*, 1984). Thus, it is suggested from this study that the effect of cryoconite on the surface albedo is small on the two glaciers due to small amount of the cryoconite on the surface.

As compared with an inland glacier of Alaska, Gulkana glacier, the surface albedo is significantly higher in those studied maritime glaciers (Fig. 7). According to the report on the inland glacier (Takeuchi, 2002a), the mean surface albedo is 0.32 in the ice area, which is significantly lower than that of the maritime glaciers in this study (0.53: mean of the 3 sampling sites). A statistical analysis (one-way ANOVA) shows significant difference of the surface

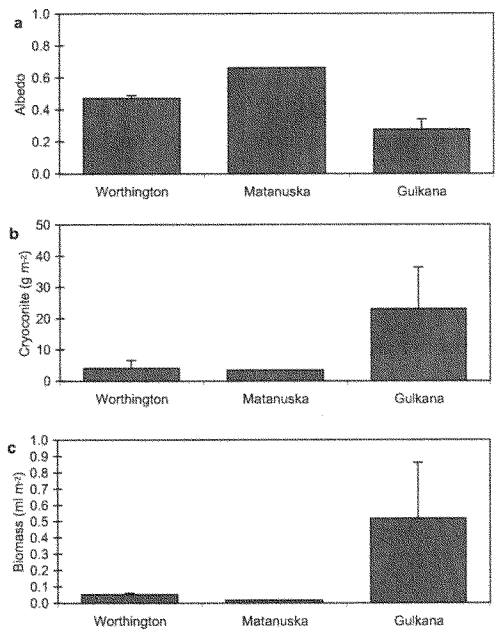

Fig. 7 Comparison of surface albedo (a), cryoconite amount (b), and algal biomass (c) between the maritime glaciers (in this study) and an inland glacier in Alaska (Takeuchi, 2001d; 2002a). Error bar=standard deviation.

albedo among the glaciers (variance ratio (F)=31.37, probability (P)=0.000<0.05). Furthermore, the amount of cryoconite is smaller in the maritime glaciers (Fig. 7) than the inland glacier. The amount of cryoconite in the ice area is 23 g m^{-2} on the inland glacier, which is approximately 6 times larger than that on the maritime glaciers (3.8 g m^{-2}). Thus, the surface albedo and amount of cryoconite on the ice surface differed between inland and maritime glaciers. The smaller amount of cryoconite is likely to cause higher albedo on the maritime glaciers.

The biological activity is also likely to differ between the maritime and inland glaciers. The organic matter content in the cryoconite is smaller in the maritime glaciers than that of the inland glacier. The organic matter content on the inland glacier is 7.1% (Takeuchi, 2002a), which is larger than that on the both of maritime glaciers (6.1% for Worthington, 2.8% for Matanuska Glaciers). The total cell volume biomass of the inland glaciers is also smaller in the maritime glaciers (Figs. 4 and 6). The biomass on the inland glacier is 0.52 mL m^{-2} as a mean (Takeuchi, 2001d), which is 13 fold larger than that of the maritime glaciers (0.039 mL m^{-2}). On the other hand, the community structure is similar between the inland and maritime glaciers. The algal communities of both maritime and inland glaciers were dominated by same three species of green algae (Fig. 6). This suggests that the community consisting of the three green algae is common structure on both maritime and inland glaciers in Alaska. The smaller algal biomass on the maritime glaciers suggests that the snow algae on the glaciers are less active compared to the inland glacier. The smaller organic matter content of cryoconite on the maritime glaciers may be due to the smaller algal production on the glaciers.

As the cryoconite is formed by biological activity as suggested by previous studies (*e.g.* Takeuchi *et al.*, 2001b), the relation of albedo, cryoconite, and algal biomass in Fig. 7 seems to indicate that the smaller algal production causes the smaller amount of cryoconite, and then the surface albedo became higher on the maritime glaciers. The snow algal activity on the glacial surface usually depends on nutrient, solar radiation intensity, and melt water disturbance (Yoshimura *et al.*, 1997, Takeuchi, 2001d). The nutrients data are not available in this study. Although the radiation data are also not available, the radiation condition of the maritime glacier can be considered to cause the smaller algal activity. Generally, the climate condition of the maritime mountain region tends to be cloudy as compared to the inland region because clouds can frequently form in this region due to a large amount of water vapor came from the ocean (the Gulf of Alaska). For example, the mean annual precipitation in Valdez City, which is located 25 km west from Worthington Glacier, is 1584 mm of water equivalent (Streten and Wendler, 1968). This is larger than that on Gulkana Glacier (1013 mm, 1968-98 mean, U.S. Geological Survey), suggesting cloudy condition on maritime glaciers. The cloudy condition would reduce the solar radiation on the glacier surface, consequently photosynthesis of snow algae would become less active. Thus, the radiation might cause the smaller algal biomass on the maritime glaciers.

The physical condition of the glaciers, especially ablation of the glacial surface, is more likely to cause the differences of biological activity and also amount of cryoconite between the maritime and inland glaciers. The maritime glacier is characterized by a large amount of annual precipitation due to water vapor coming from the ocean. The large amount of snow accumulation enables the maritime glaciers to flow down lower elevation. For example, terminus elevations of Worthington and Matanuska Glaciers (maritime) are 820 and 500 m a.s.l., respectively, while that of Gulkana Glacier (inland) is 1220 m a.s.l.. Hence, the altitude of the studied surface differed between the glaciers. The elevation of the studied sites on the inland glacier is 1270-1585 m a.s.l., which is much higher than the studied sites on the maritime glaciers (500-1110 m a.s.l.). Since air temperature is higher in lower elevation, the ablation of glacier surface would be greater in the maritime glaciers. According to summer ablation measurement on the maritime and inland glaciers, the ice ablation on Worthington Glacier, 70 mm day^{-1} is two fold larger than 29 mm day^{-1} on Gulkana Glacier (Mayo and Péwé, 1963; Streten and Wendler, 1968). As the result of large ablation on the maritime glaciers, a large amount of meltwater is

likely to flow on the bare-ice surface of the glaciers. Since the running meltwater can wash the material on the ice surface out of the glaciers, the small amount of algal biomass and cryoconite would possibly remain on the ice surface of the maritime glacier. Thus, larger ablation on the maritime glaciers may be responsible for the smaller amount of algae and cryoconite, consequently the surface albedo on the maritime glaciers can be as high as the clean glacial surface.

Since the data discussed in this paper cover only three glaciers in Alaska, the comparison between the maritime and inland glaciers might be less convinced. For further detailed discussion, it is necessary to use more extensive data of the glaciers in Alaska. Remote sensing technique would be useful to study surface albedo and cryoconite contaminant in extensive area. The geographical distribution of the cryoconite would help to understand formation process of the cryoconite and its relation to biological activity.

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