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The Altitudinal Distribution of Snow Algae on an Alaska Glacier (Gulkana Glacier in the Alaska Range)

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ABSTRACT

The altitudinal distribution of a snow algal community was investigated on an Alaska glacier (Gulkana Glacier in the Alaska Range) from 1270 m to 1770 m a.s.l.. Seven species of snow algae (chlorophyta and cyanobacteria) were observed on the glacier surface. The species were *Chlamydomonas nivalis*, *Mesotaenium bregrenii*, *Ancylonema Nordenskioldii*, *Cylindrocystis brébissonii*, *Koliella* sp, and two Oscilllatriaceae cyanobacteria. The altitudinal distribution of snow algae was different between the species: *C. nivalis* was distributed on the middle to upper area, *M. bregrenii*, *A. Nordenskioldii*, and one Oscilllatriaceae cyanobacterium on the middle to lower area, *Koliella* sp on the middle area, and *C. brébissoni* and one Oscilllatriaceae cyanobacterium on the lower area. The total cell concentration and cell volume biomass of the snow algae ranged from 4.4×10^3 to 9.9×10^5 cells ml^{-1} and from 33 to 2211 µl m^{-2}, respectively. The cell volume biomass changed with altitude; the biomass increased with altitude below 1600 m a.s.l., and decreased above 1600 m a.s.l. The community structure showed that *A. Nordenskioldii* dominated on the lower part of the glacier (below 1600 m), and that *C. nivalis* dominated on the upper part (above 1600 m). The species diversity was relatively high at the lowest (1270 m) and middle site (1590 m). The results are compared with the algal community on Himalayan glaciers. The altitudinal distribution of snow algae are discussed in terms of the physical and chemical condition of the glacier surface.

Keywords: snow algae, Alaska, glacier, community structure, algal biomass.

INTRODUCTION

Snow algae are cold-tolerant algae growing on snow and ice and have been reported on snow fields and glaciers in many parts of the world. Visible snow algal blooms are well known as red snow. The color is caused by red-pigmented chlorophyta (green algae, usually *Chamydomonas nivalis*) and has been well studied taxonomically and physiologically on snow fields (e.g. Müller *et al*., 1998; Hoham and Blinn, 1979; Kol and Eurola, 1974; Thomas, 1972; Kol, 1969). The snow algae sustain cold-tolerant animal and bacterial communities on snow fields and glaciers. For example, algae sustain midges and copepods on Himalayan glaciers, and ice worms and collembolas on North American glaciers (e.g. Aitchison, 2001; Kikuchi, 1994; Kohshima, 1984; Goodman, 1971). These organisms form very simple and closed ecosystems on snow fields or glaciers (e.g. Kohshima, 1987). The ecology of snow algae is important for understanding the glacial ecosystem. However, ecological information of snow algae is still limited in particular on glaciers.

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Recently, investigators have discovered that snow algae have geophysically interesting aspects. Blooms of snow algae can reduce the surface albedo of snow and ice, and largely affect their melting. For example, some glaciers in Himalayas are covered with a large amount of dark-colored biogenic material (cryoconite) derived from snow algae and bacteria (Takeuchi *et al*., 2001; Kohshima *et al*., 1993). The material substantially decreases the surface albedo and accelerates surface melting of the glacier. Thus, snow algal activity possibly affects heat budget and mass balance of glaciers. Furthermore, Yoshimura *et al*. (2000) have reported that snow algae can be used as an indicator to date ice cores drilled from glaciers. The biomass and community structure of algae in ice cores may also have information on the paleo-environment. Thus, it is important to understand the ecology of snow algae for studies of glacier variations and ice-cores.

In this paper, the author aims to describe a community structure of snow algae on an Alaska glacier (Gulkana Glacier in the Alaska Range). There have been two reports about snow algae in Alaska (Kol, 1942; Kobayashi,1967), but this is the first report on quantity of algal biomass on a glacier in Alaska. The altitudinal distribution of a snow algal community was qualitatively analyzed. The results are compared with that on a Himalayan glacier, which is the only glacier upon which the algal community has ever quantified. The altitudinal distribution of the algal community on the Alaska glacier is discussed in terms of the physical and chemical condition of the glacier surface.

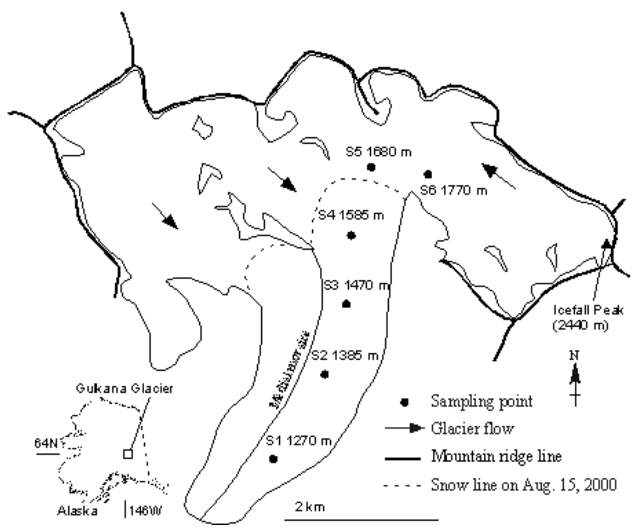

Figure 1 A map of Gulkana Glacier in the Alaska Range, showing sampling sites on the glacier surface.

STUDY SITE AND METHODS

The research was carried out on Gulkana Glacier, from 15 to19 August 2000. The glacier is located in the central Alaska Range (Fig. 1), and 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 U.S. Geological Survey (e.g. Marsh, 2000). Most of the surface is debris-free bare ice or snow. The length and area of the glacier are approximately 4 km and 21.8 km^2, respectively. The equilibrium line of the glacial mass balance in this year was approximately 1720 m (USGS, personal communication). Collections of surface ice/snow were carried out at six sites, from 1270 m to 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 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 significant at this time in the snow area around 1700 m a.s.l., including S5. The bare ice at the lower area was slightly covered with brown or black fine dust consisting mineral particles and organic matter (cryoconite).

Surface ice/snow 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 collected samples were melted and preserved as a 3 % formalin solution in 125-mL clean polyethylene bottles. For identification of algal species, some samples were kept frozen in plastic bags. All samples were transported by car to the International Arctic Research Center, University of Alaska Fairbanks, for analysis.

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 strained 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 with a hydrophilized PTFE membrane filter (pore size 0.5 µm, Millipore FHLC01300) 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 per mL) 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 to sum up each algal volume, which was calculated to multiply the mean cell volume (mL) by the mean algal density (cells m^{-2}). Community structure was represented by the mean proportion of each species in five samples to the total algal volume at each sampling point.

Species diversity was calculated using Simpson's diversity index *D* (Begon *et al*., 1990):

$$D = \frac{1}{\sum_{i=1}^{s} Pi^2}$$

where *S* is the total number of species in the community, and *Pi* is the proportion of the *i*th species to the total algal biomass.

RESULTS

Seven species of snow algae (chlorophyta and cyanobacteria) were observed on the glacier surface (Fig.2). Four of them (*C. nivalis, M. bregrenii*, *A. Nordenskioldii*, and *C. brébissoni*) have been reported throughout Alaska by Kol (1942). Besides the seven species, small amount of *Cholomonas nivalis*, *Trochiscia* sp., and *Smithsonimonas Abbottii* were observed, but these species were not quantified in this paper. The descriptions of the seven species are as follows:

Chlorophyta (Green algae)

Chlamydomonas nivalis Wille (Figs. 2a, b, c)

Cells round or oval, red orange pigmented. A choloroplast with one pyrenoid. Round cells 24.4 ± 2.8 µm (mean ± SD) in diameter with stellated outer envelop (Hypnozygotes). Oval cells 28.9 ± 4.2 in length, 24.2 ± 2.4 in width. Small round cells 12.9 ± 5.1 in diameter (resting cells). Biflagellate vegetative cells with thick mucilaginous wall were also observed (Fig.2a).

Mesotaenium bregrenii (Wittrock) Lagerheim (Fig. 2f)

Cells single or paired, cylindric with rounded apices. Chloroplast one to two, with one pyrenoid. 12.4 ± 2.3 µm in length, 7.7 ± 0.81 µm in width. Cell sap dark brownish.

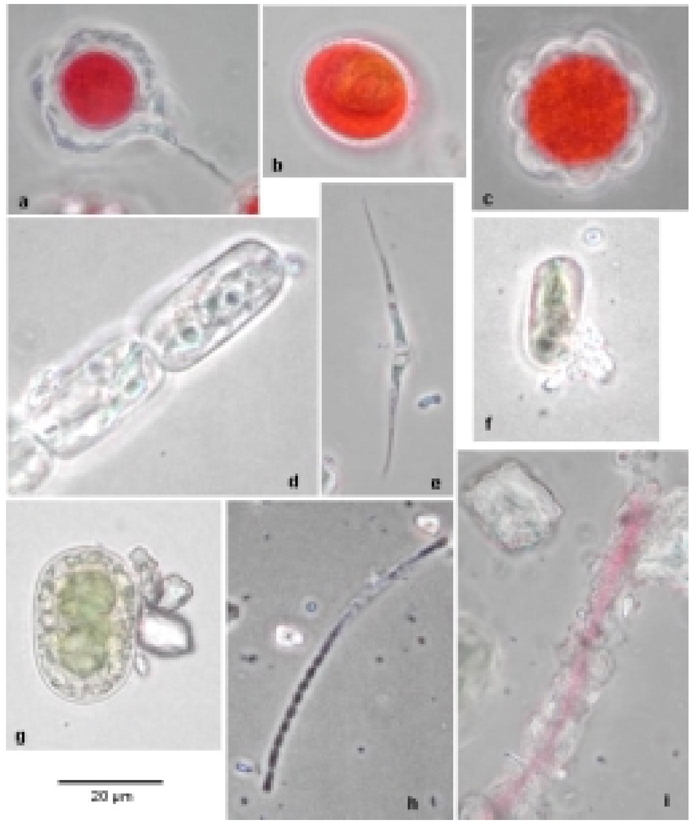

Figure 2 Pictures of the snow algae observed on Gulkana Glacier. a, b, c. *Chlamydomonas nivalis*, d. *Ancylonema Nordenskioldii*, e. *Koliella* sp., f. *Mesotaenium bregrenii*, g. *Cylindrocystis brébissonii*, h. Oscilllatriaceae cyanobacteria 1, i. Oscilllatriaceae cyanobacteria 2

Ancylonema Nordenskioldii Berggren (Fig. 2d)

Filaments straight or slightly curved, consisting of 2–20 cells. Cells 24.4 ± 5.4 μm in length, 11.3 ± 1.0 μm in width. Chloroplast with one or two pyrenoids. Cell sap usually dark brownish.

Cylindrocystis brébissonii (Ralfs) De Bary f. cryophila Kol (Fig. 2g)

Cells cylindric with rounded apices. Choloroplast axial usually two, with one pyrenoid. Cells 32.2 ± 6.0 μm in length, 21.6 ± 1.3 in width.

Koliella sp. (Fig. 2e)

Cells usually solitary, two after cell division, straight spindle shape. 3.2 ± 0.63 μm in width, 40.4 ± 7.9 μm in length.

Cyanobacteria (blue-green algae)

Oscilllatriaceae cyanobacteria 1 (Fig. 2h)

Trichomes 1.2 ± 0.18 μm in width, 1.8 ± 0.45 μm in length. Cells about 1.5 times longer than the width.

Oscilllatriaceae cyanobacteria 2 (Fig. 2i)

Trichomes 1.5 ± 0.29 µm in width, 2.1 ± 0.54 µm in length with thick mucilaginous sheath (4.9 ± 1.4 µm in thickness). Cells about 1.5 times longer than the width. Large amounts of dust (mineral particles and organic matter) are attached to the sheath.

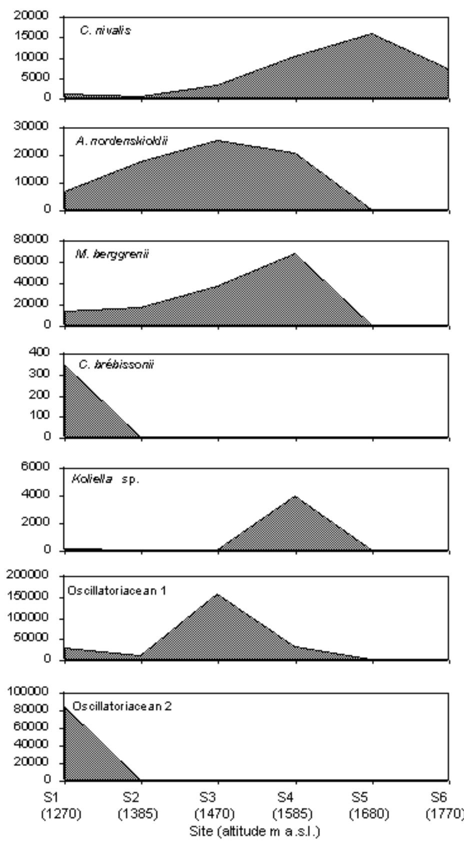

Figure 3 Altitudinal distribution of the cell number concentration (cells mL^{-1}) of each snow alga on Gulkana Glacier.

The total cell concentration of the snow algae ranged from 4.4 x 10^3 to 2.0 x 10^5 cells ml^{-1}. The altitudinal distribution of the concentration was different between the species. Figure 3 shows the altitudinal distribution of each snow alga. *C. nivalis* was distributed on the middle to upper area, *M. bregrenii*, *A. Nordenskioldii* , and one Oscilllatriaceae cyanobacterium on the middle to lower area, *Koliella* sp. on the middle area, and *C. brébissoni* and one Oscilllatriaceae cyanobacterium on the lower area.

The total volume biomass ranged from 33 to 2207 µl m^{-2}. Fig. 4 shows the altitudinal distribution of the total cell volume biomass together with that of Yala Glacier in the Himalayas (Yoshimura *et al*., 1997). The cell volume biomass in the ice area on Gulkana Glacier is comparable to that on the Himalayan glacier (0.03–2.2 versus 0.12–1.08 mL m^{-2}, respectively), while the biomass in the snow area on Gulkana Glacier is significantly larger than that on the Himalayan glacier (0.060–0.41 versus 0.0018–0.078 mL m^{-2}, respectively). The biomass on Gulkana Glacier changed with altitude: the biomass increased with altitude below 1600 m a.s.l., and decreased above 1600 m a.s.l. A statistical analysis (one way ANOVA) revealed that the altitudinal variation of the biomass is significant ($F = 3.09$, $P = 0.0271 < 0.05$). This altitudinal distribution is different from the distribution on the Himalayan glacier, upon which the biomass decreased continuously with altitude in both the ice and snow areas.

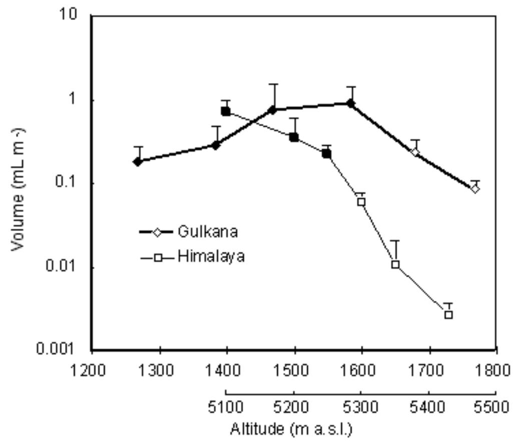

Figure 4 Altitudinal change of the total cell volume biomass on Gulkana Glacier (1200-1800 m) and Yala Glacier in Himalayas (5100-5500 m, Yoshimura et al. 1997) . Solid and open marks indicate ice and snow area, respectively. Error bar = standard deviation.

Figure 5 shows the altitudinal change of the proportion of each species to the total algal biomass. The community structure showed that *A. Nordenskioldii* dominated on the lower part of the glacier (below 1600 m), and that *C. nivalis* dominated on the upper part (above 1600 m). These upper and lower areas correspond to the ice and snow area, respectively. On the upper snow sites (S5 and S6), *C. nivalis* was the only observed species (100% dominance).

Figure 6 shows the altitudinal change of the species diversity of the algal communities. The species diversity was lowest at the higher two sites (S5 and S6), where only *C. nivalis* was observed. The diversity was relatively high at the lowest (S1) and middle site (S4).

DISCUSSION

The altitudinal distribution of each species (Fig.3) may suggest the preferred condition of each species on the glacier surface. Both physical and chemical conditions on the glacial surface change with altitude (Yoshimura *et al*., 1997). The most significant change of the glacier surface is the change from bare ice in the lower area to snow in the higher area. According to Yoshimura *et al*. (1997), the snow algae on glaciers can be classified into four types: snow-environment specialists

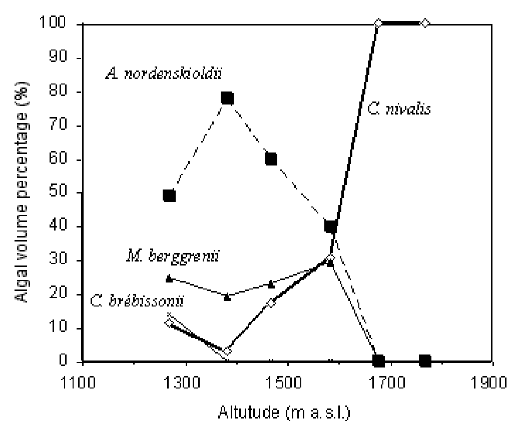

Figure 5 Altitudinal change of the community structure of snow algae on Gulkana Glacier (proportion of cell volume biomass). Error bar = standard deviation.

(observed on the snow surface), ice-environment specialists (observed on bare ice), generalists (observed on both snow and ice), and opportunists (observed on special part of the ice or snow surface). On the basis of this classification, the snow algae on this glacier can be categorized as follows: *C. nivalis* as a generalist, *A. nordenskioldii* and *M. bregrenii* as ice-environment specialists, and *C. brébissonii, Koliella* sp., and two Oscilllatriaceae cyanobacteria as opportunists. Kol (1942) has classified the snow algae of Alaska into the types of preferred environments. According to her report, *C. nivalis* is classified as snow-preferring algae, *A. nordenskioldii* and *M. bregreni* are ice-preferring algae, and *C. brébissonii* is algae both snow and ice. Our results are consistent with her classification for *A. nordenskioldii* and *M. bregrenii*, but not consistent for *C. nivalis* and *C. brébissonii*. However, *C. nivalis* is likely regarded as snow algae on Gulkana Glacier, because the maximum cell concentration of the alga occurred at snow area S5, and the alga was completely dominated at snow areas S5 and S6. The alga observed on the ice area was probably come upper the snow area, washed down by meltwater and/or from snow that had covered the ice surface before it melted.

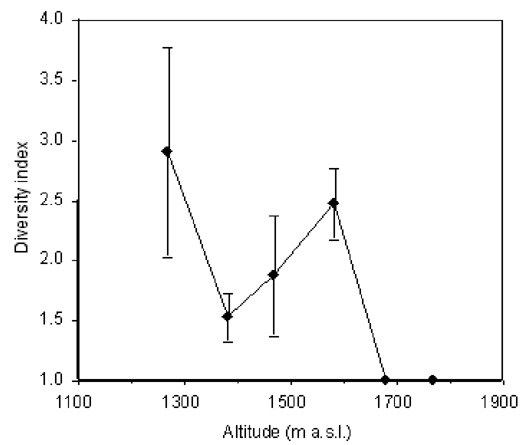

Figure 6 Altitudinal change of the simpson's diversity index of the snow algal community on Gulkana Glaicer. Error bar = standard deviation.

The condition of the distribution of the four opportunists may be associated with physical or biological conditions on the glacier surface. The *Koliella* sp. may prefer an area with high species diversity. The distribution of this alga (mainly at S4 and a little at S1) corresponded to the area where significantly higher species diversity occurred relative to the other sites. The alga may be able to survive in areas with keen species competition. The distribution of Oscillaoriacean 1 may be associated with the distribution of cryoconite holes. A cryoconite hole is a water-filled depression on the glacial ice surface; it occurred mainly at sites S2–S3 on this glacier. A larger amount of Oscillatoriacean 1 was observed at the bottom of cryoconite holes relative to the bare-ice surface (not quantified), suggesting that the cryoconite hole is suitable habitat for this alga. The alga on the ice surface in the area may be derived from cryoconite holes. The condition for *C. brébissonii* and Oscilllatriaceae 2, observed at only S1, were uncertain. They may be associated with the amount of mineral particles present, since a larger amount of mineral particles was observed on the ice surface of S1 relative to the other site. The mineral particles may affect the nutrient condition and then affect the community structure of the snow algae at this site.

The larger biomass in the snow area of Gulkana Glacier compared with that of the Himalayan glacier is probably due to the small frequency of snow cover in summer on Gulkana Glacier. According to Yoshimura *et al*. (1997), the light condition of algal habitat is the most important factor for the biomass on the glacier surface. Since Himalayan glaciers are affected by summer monsoon precipitation, snow often covers the glacier surface, and reduces the light intensity of algal habitat in summer. The frequency and thickness of the snow cover on the algal habitat increases with altitude due to a decrease in air temperature; consequently the biomass decreases with altitude and the biomass in the upper snow area is particularly small (Yoshimura *et al*. 1997, Takeuchi *et al*. 1998). In contrast, on Gulkana Glacier, snow accumulation on the glacier mainly occurs in winter (March 2000), and does not often cover the algal habitat of the surface in summer. Therefore, the light condition of algal habitat is likely better on Gulkana Glacier relative to the Himalayan glaciers, particularly in the upper snow area. Nutrient condition and pH are also possible factors as suggested by Jones (1991). However, they do not differ between Alaska and Himalayan snow. For example, nitrate is 2.0 μeq L^{-1} for snow in the Alaska Range (1999–2000 mean, National Atmospheric Deposition Program) and 2.1 μeq L^{-1} (Wake *et al*. 1990). The pH was 4.7 to 5.3 for snow and 4.9 to 5.7 for ice on Gulkana Glacier (measured in this research), while 5.2 to 5.9 for snow and 4.9 to 5.4 for ice on the Himalayan Glacier (Yoshimura *et al*. 1997).

The altitudinal distribution of the algal biomass on Gulkana Glacier may be due to other factors than the light condition. On the Himalayan glacier, the biomass decreased continuously with altitude and has been explained by an increase of snow cover frequency with altitude, which reduces the light intensity of algal habitat (Yoshimura *et al*. 1997). On Gulkana Glacier, the biomass increased with altitude in ice areas S1–S4 and decreased with altitude in snow areas S5–S6. This cannot be explained by the snow cover frequency as it can in the case of the Himalayan glacier. In the snow area of the glacier, melt water availability may be one of the reasons for the altitudinal distribution. Liquid melt water is required for algal growth on the snow surface. Snow melting occurs more in the lower area relative to the higher area due to a difference in air temperature. Thus, the algal biomass is larger in the lower area on snow surface. On the bare-ice area of the glacier, the biomass distribution may be affected by the amount of running meltwater on the glacier surface. The meltwater on the ice surface can wash the snow algae out of the glacier. Since the amount of meltwater is larger at lower altitudes, the algal biomass would decrease as altitude decreases. In particular, the algae on this glacier seems to be easily washed out by running water, because they mainly consisted of unicellular green algae and did not aggregate nor attach to anything like mineral particles. In contrast, on the Himalayan glaciers the algal aggregation is formed with mineral particles and organic matter by filamentous cyanobacteria (Takeuchi *et al*. 2001). This aggregation seems be an effective means to avoid being flushed from a glacier by running melt water and to play a role of maintaining a high biomass in the lower area of the glacier.

The species diversity of the snow algae is likely due to the instability of the glacier surface (snow cover condition) as suggested by Yoshimura *et al.* (1997). The high diversity in the middle area of the glacier (S4) may result from a change of the snow cover condition, which allows for the presence of both snow and ice environment specialists. In fact, the community of this area mainly consisted of *C. nivalis* (a snow specialist), and *A. nordenskioldii*, and *M. bregrenii* (ice specialists). The reason for the high diversity at the lowest site (S1) is uncertain. The high diversity at the lowest site was not observed on the Himalayan glaciers. This may be due to larger amounts of mineral particles in this area, which provide nutrients and therefore probably change the growth condition of the algae.

Although species composition on Gulkana Glacier is similar to that reported on Himalayan glaciers, the proportion of each species to total biomass is different. *A. nordenskioldii*, *M. bregrenii*, and *C. brébissonii* were observed on both Alaska and Himalayan glaciers. However, *A. nordenskioldii* dominated the bare-ice area of the Alaska glacier, while *C. brébissonii* dominates the ice area of the Himalayan glaciers (Yoshimura *et al*. 1997, Takeuchi *et al*. 1998). Additionally, the proportion of cyanobacteria to total algal biomass is less significant on the Alaska glacier compared to the Himalayan glacier (0–1% versus12–24%, respectively). This difference probably results from environmental factors affecting the species competition. However, this factor is uncertain. It is possible that the difference of solar light intensity and/or the amount of mineral particles between Alaska and Himalayan glaciers affect the algal community.

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