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Characteristics of cryoconite (surface dust on glaciers) and surface albedo of a Patagonian glacier, Tyndall Glacier, Southern Patagonia Icefield

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Abstract

Characteristics of cryoconite (surface dust on glaciers) and the surface albedo were investigated on a Patagonian glacier (Tyndall Glacier in Southern Patagonia Icefield, Chile). The amount of the cryoconite on the surface of the ablation area (14 - 71 g m^{-2}, mean: 47 g m^{-2} in dry weight) was much smaller as compared to those reported from other region such as Himalaya (50 - 900 g m^{-2}, mean: 300 g m^{-2}). The percentage of organic matter in the cryoconite (0.6% - 2.7%, mean: 1.8% in dry weight) was also smaller compared to those of glaciers in other parts of the world. Microscopic observation revealed that the cryoconite consisted of much mineral particles, amorphous organic matter, and small amount of snow algae. Cryoconite with granular structure, which is generally formed on the glaciers by algal activity in Himalayas, Tibet, and Arctic, was not observed. The surface albedo ranged from 0.34 to 0.66 (mean: 0.48), which is almost equivalent to albedo of clean bare ice surface. Our results indicate that the effect of cryoconite and biological activity on the surface albedo in this glacier is very small due to the small amount of the cryoconite and small algal production.

1. Introduction

Glacier variation is well focused now in relation to global climate change and water cycle. For example, Patagonian Icefield, one of the largest ice mass other than two polar ice sheets, has been revealed to retreat considerably and to account for 3.6% of global sea-level change during the last 50 years (e.g., Aniya, 1999). In order to assess the glacier variation, it is important to study mass balance and heat budget of the glaciers.

Surface albedo of the glaciers is one of the important factors to affect glacier heat budget and mass balance. The surface albedo is affected by amount and characteristics of surface dust, called cryoconite, which was named by the Arctic explorer, A. E. Nordenskjöld (1875). The cryoconite can reduce surface albedo on snow and ice by its dark coloration. For example, some glaciers in Himalayas are covered with a large amount of cryoconite, which substantially decreases their surface albedo and accelerates surface melting (Kohshima *et al.*, 1993). Thus, it is important to clarify characteristics of the cryoconite and its effect on the surface albedo.

Recent studies have revealed that cryoconite on glaciers contains a large amount of algae and bacteria (Gerdel and Drouet, 1960; Wharton *et al.*, 1981; 1985; Kohshima 1987; 1989; Takeuchi *et al.*, 2001a; 2001b). This suggests that these microbes play important roles in the formation process of the albedo-reducing material on the glaciers. Since living algae and some microbes have been reported on snow and ice in various parts of the world (Kol, 1942; Kol, 1968; Kol, 1969; Kol and Peterson, 1976; Ling and Seppelt, 1993; Yoshimura *et al.*, 1997), formation of cryoconite by biological activity may be a common phenomenon in glaciers globally. However, the information of biological aspect of the cryoconite is still few, in particular on Patagonian glaciers.

This study aims to clarify characteristics of cryoconite and its effect on surface albedo on a Patagonian glacier. The composition of cryoconite was biologically analyzed. Amount of the cryoconite and the surface albedo were measured in various parts of the glacier. Effect of the cryoconite on the surface albedo, and contribution of biological activities to the cryoconite formation on this glacier are discussed.

2. Study site and methods

The research was carried out on Tyndall Glacier, an outlet glacier of the Southern Patagonia Icefield, in November and December 1999 (Fig. 1). The glacier is located in Torrees del Paine National Park, Chile. This glacier flows southward from the ice field (Top: about 1700 m a.s.l.) up to the terminus in a proglacial lake at an elevation of about 50 m a.s.l. The length and area of the glacier are approximately 40 km and 355 km^2, respectively. The equlibrium line is approximately 13 km from the snout (i.e., approximately 1200 m a.s.l, Naruse *et al.*, 1987, see Fig. 1). Two small side -lobes on the left bank are slightly spilling into the eastern side valley at approximately 18 km from the terminus (Northern and Southern lobes, see Fig. 1). Sampling of cryoconite and measurements of surface albedo were carried out at six sites in the ablation area of the glacier. (S1-S6). Sites S4 and S6 were located near the lateral margin of the

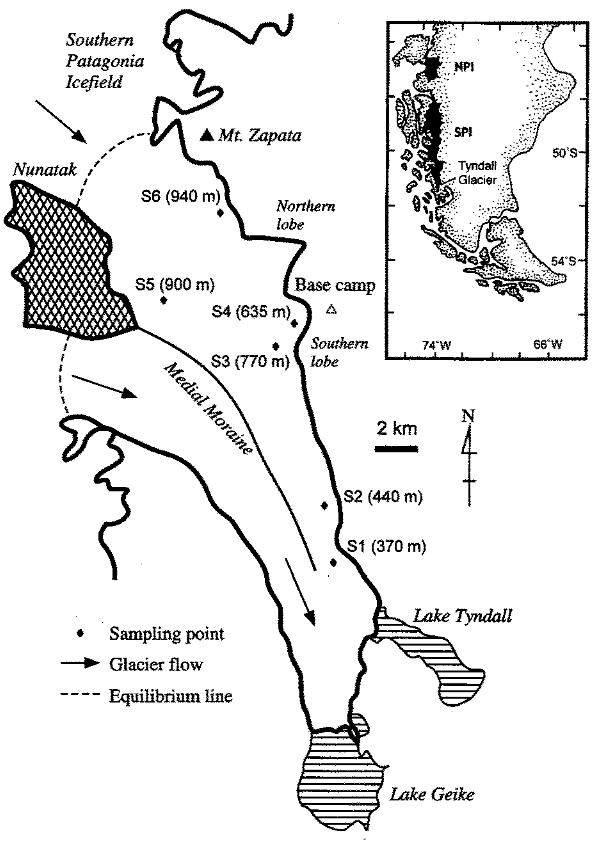

Fig. 1. Location of Tyndall Glacier in Patagonia Icefield and map of ablation area showing the sampling sites (S1-S6). The elevations at the each site are shown as above sea level.

glacier (less than 500 m from the lateral margin). The margin area including this two sites has lower elevation compared to the center part of the glacier (e.g., Nishida *et al.*, 1995).

Cryoconite was collected with a stainless steal scoop together with surface ice beneath it (1-2 cm in depth). The collected area on the surface was measured to calculate amount of the cryoconite per unit area. The collected samples were melted in plastic bags and preserved as 3 % formalin solution (in order to fix biological activity) in 100-ml clean polyethylene bottles. The cryoconite deposited on the bottoms of cryoconite holes (melt holes) was also collected with a pipette. The samples were transported to the biological laboratory of Tokyo Institute of Technology, Japan for analysis.

The organic matter in the cryoconite was measured by the following method. After the samples were dried (65℃, 24 hours) and weighed, they were combusted for 1 hour at 1000℃ in an electric furnace. The percentage of weight reduction by this procedure was measured.

The composition of the cryoconite was observed with an optical microscope (Nikon E600).

The surface albedo on each study site was measured by a portable photometer (model 2703, Abe Sekkei Co.). The measured wavelengths were 400, 450, 500, 550, 550, 600, 650, 700, 750, 850, 950, and 1050 nm. 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.

3. Results

3.1. Amount of the cryoconite on the glacier surface

Figure 2 shows the amount of the cryoconite (per unit area) on the ablation area of Tyndall Glacier. The amount of the cryoconite ranged from 13.6 to 71.4 g m^{-2} in dry weight (mean: 38 g m^{-2}). The amount slightly differed among the six sites, but was not related with altitude. The larger amount was observed at sites S4 and S6, which are located close to the lateral margin of the glacier.

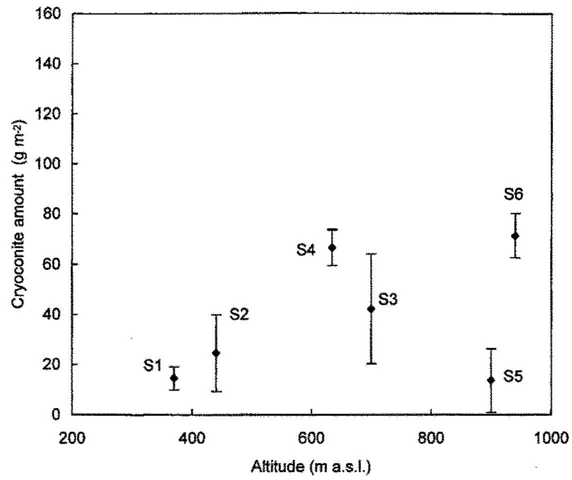

Fig. 2. Cryoconite amount on the surface of Tyndall Glacier. Error bar = standard error (sample number (n) = 5).

3.2. Composition of the cryoconite

Figure 3 shows the percentage of organic matter in the cryoconite. It ranged from 0.6% to 2.6% (mean: 1.8%). The percentage of organic matter in sites 3 and 4 (0.6%, 0.9%, respectively) was smaller compared to the other sites (2.1-2.1%). Fig. 4 shows the amount of organic matter per unit area. The amount of organic matter in the sites 3 and 4 is not significantly different from that of the other sites. This indicates that the cryoconite in the sites 3 and 4 contained a larger amount of mineral particles compared to the other sites. Since both sites 3 and 4 are located near the southern lobe, wind-blown mineral particles may be supplied in the sites from outside of the glacier through the southern lobe.

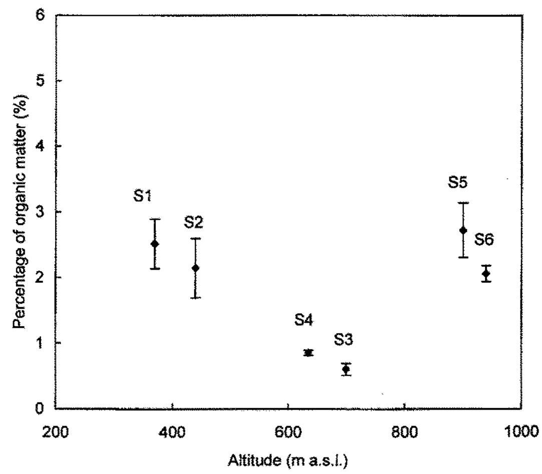

Fig. 3. Percentage of organic matter in the cryoconite on Tyndall Glacier. Error bar = standard error (n = 5).

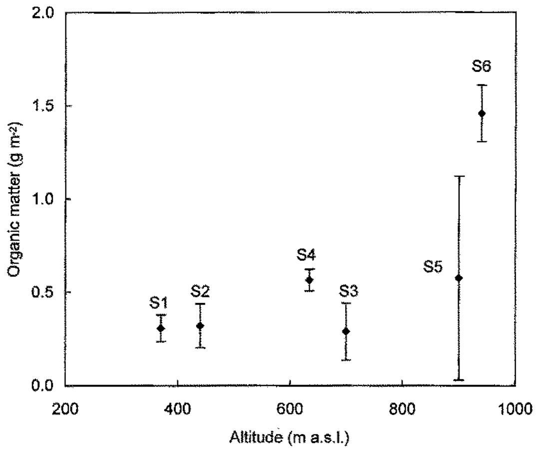

Fig. 4. Amount of organic matter on the surface of Tyndall Glacier. Error bar = standard error (n = 5).

Microscope observation revealed that the cryoconite consisted of mineral particles, amorphous organic matter, and small amount of snow algae (Fig. 5). These components appeared to be almost same among the study sites. The mineral particles were main component in the cryoconite. They were brown or transparent colored and approximately 5-50 μm in diameter. The amorphous organic matter was transparent or black, and 10-30 μm in size. The observed snow algae were *Mesotaenium* sp., *Cylindrocystis* sp., *Ancylonema* sp., *Chlamydomonas* sp., unknown green algae, and Oscillatoriacean alga. *Mesotaenium* sp. and *Cylindrocystis* sp. were commonly observed in the study sites (Fig. 5b, c). Detailed description of the snow algae will be published elsewhere.

3.3. *Albedo of the glacier surface*

Figure 6 shows the surface albedo on the ablation area of Tyndall Glacier. The surface albedo ranged from 0.34 to 0.66 (mean: 0.48). The albedo of site 5 (0.66) was particularly higher than the other sites. The albedos of sites 4 and 6 located close to the glacier lateral margin were lower than the other sites (0.34, 0.42, respectively).

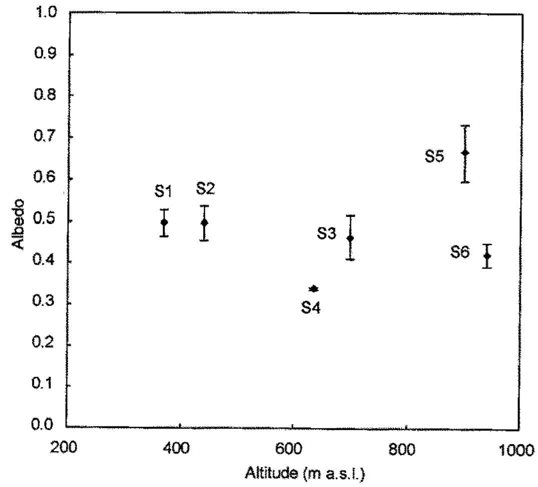

Fig. 6. Surface albedo on Tyndall Glacier. Error bar = Standard error (n = 5).

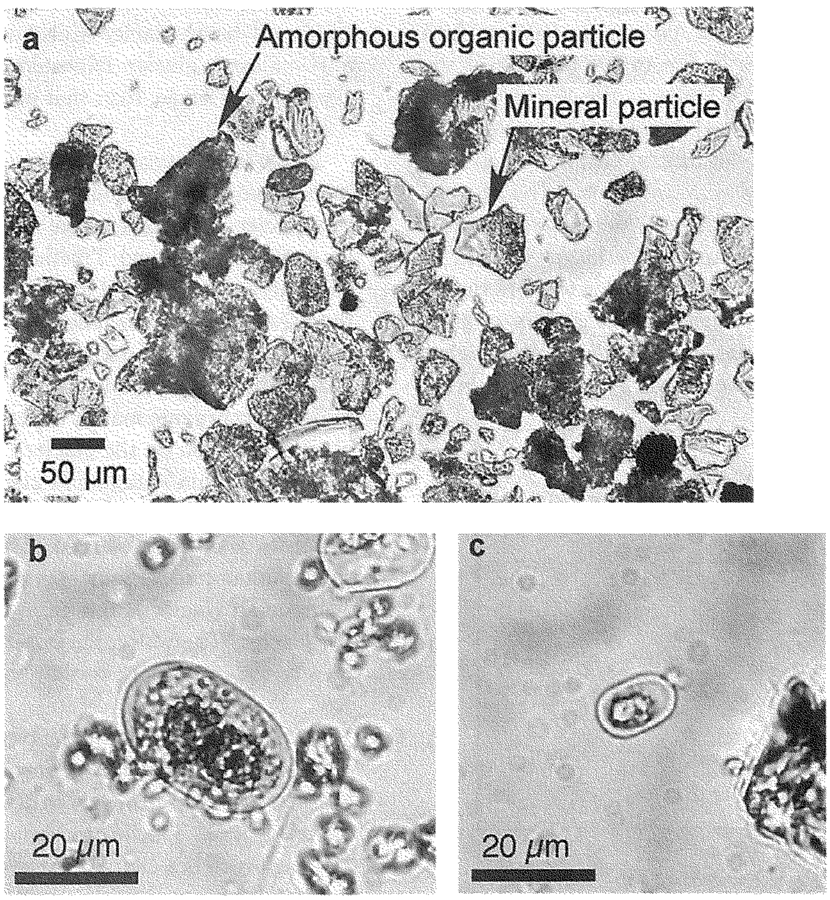

Fig. 5. Microscopy of the cryoconite on the surface of Tyndall Glacier (site 1, 300 m a.s.l.). *a.* Mineral particles and amorphous organic matter. *b.* Snow algae: *Cylindrocystis* sp., *c.* Snow algae: *Mesotaenium* sp.

Figure 7 shows the spectral albedo of the glacier surface of study sites. The spectral albedo generally decreased as the wavelength increased. Especially, in site 5 in which the highest albedo was observed, the albedo was particularly high in shorter wavelength (400-650 nm).

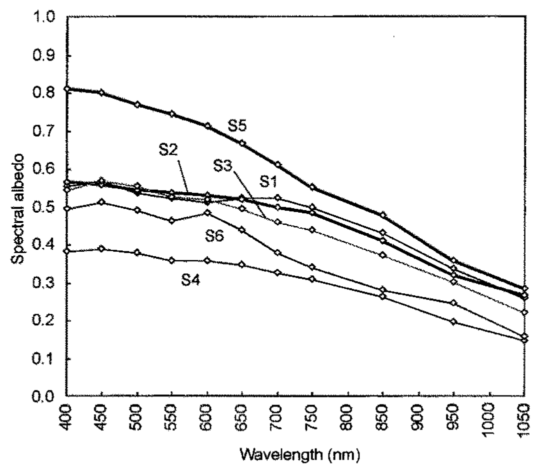

Fig. 7. Spectral albedo of the surface on Tyndall Glacier. The curves are mean surface albedo of 5 surfaces at each site.

4. Discussion

Figure 8 shows the relationship between surface albedo and cryoconite amount on the glacier surface. A statistical analysis revealed that the surface albedo negatively correlated with the cryoconite amount on the surface (Spearman's correlation coefficient (r_s) = -0.943, probability (P) < 0.01). This correlation suggests that the variation of the surface albedo among the study sites is due to the amount of the cryoconite on the surface. The sites near the glacier margin (sites 4 and 6) had lower albedo and larger amount of cryoconite relative to the sites of central parts of the glacier (sites 1, 2, 3 and 5). This trend was visibly observed in all of the ablation area: the glacier surface in margin area appeared to be dirtier than in central area. The larger amount of cryoconite in the margin area is probably due to more supply of wind-blown particles from outside of the glacier, relative to in the center area of the glacier. The remarkable higher albedo observed in site 5 may be caused by sunlight entering from crevasses into glacier ice. There were many deep crevasses in the site 5, while few crevasses in the other sites. The sunlight entering from crevasses may be scattered in the ice, come out from the glacier surface, and result in the measurement of the higher albedo. The higher albedo in shorter wavelength of site 5 (Fig. 7) supports this idea, since glacier ice has the greatest transmissivity of shorter wavelength light (0.40-0.65 nm, blue region).

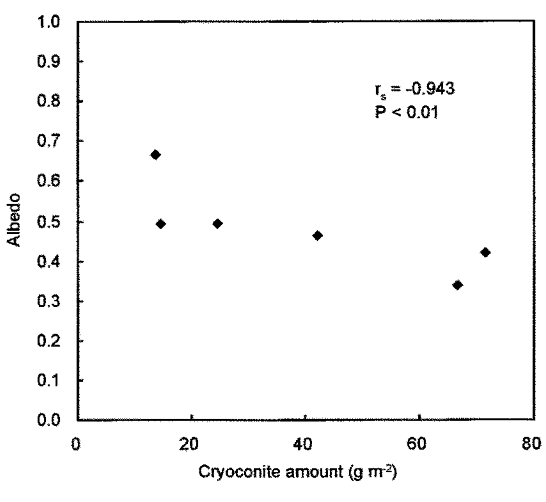

Fig. 8. Relationship between albedo and cryoconite amount on the surface of Tyndall Glacier. (rs = spearman's correlation coefficient, P = probability)

The amount of the cryoconite on the surface of this Patagonian glacier is much smaller compared to those that reported from Himalayan glaciers, where the surface albedo is remarkably reduced by the cryoconite (Kohshima *et al.*, 1993). For example, the amount of a Himalayan glacier (Yala Glacier) ranges from 50 to 900 g m^{-2} (mean: 300 g m^{-2}, Takeuchi *et al.*, 2000). The amount on the Patagonian glacier is approximately an eighth of that on the Himalayan glacier (38 versus 300 g m^{-2}). This suggests that the albedo reduction by the cryoconite on the Patagonian glacier is smaller compared to on the Himalayan glacier. The surface albedo on this Patagonian glacier (0.34 - 0.66, mean: 0.48) is almost equivalent to albedo of clean bare ice surface (0.34 - 0.51, Paterson, 1994). This indicates that the effect of cryoconite on the surface albedo is very small on the Patagonian glaciers, due to small amount of the cryoconite on the surface.

The percentage of organic matter in the cryoconite of this Patagonian glacier is also smaller compared to glaciers in other parts of the world. For example, percentages of organic matter of cryoconite were reported to range 15.7 - 20.1% in Greenland Ice Cap (Gerder and Drouet, 1960), 0.3 - 13.8% in Canadian Arctic (Takeuchi *et al.*, 2001a), 4.8 - 14.4% in a Tibetan glacier (Kohshima, 1989), and 6.3 - 22.0% in a Himalayan glacier (Kohshima, 1989). These values are significantly larger than that of this Patagonian glacier (0.6 - 2.7%).

The small percentage of organic matter suggests that the formation of cryoconite by biological activity is small on this glacier. According to the reports from the Arctic, Greenland, Himalayan, and Tibetan glaciers, a large amount of snow algae is contained in the cryoconite. On these glaciers, the algae (filamentous blue-green algae) and other particles often form granule structure (cryoconite granule), which enables high algal production (Takeuchi *et al.*, 2001b). The most of the organic matter contained in the cryoconite is the algal production on the glaciers (Takeuchi *et al.*, 2001b). In contrast, on this Patagonian glacier, the only small amount of snow algae is observed in the cryoconite, and the granule structure was not observed. These facts suggest that the small amount of organic matter in the cryoconite of the Patagonian glacier is due to the small algal production on the glacier. Therefore, the contribution of biological activities to the cryoconite formation may be small on this glacier.

The small amount of the cryoconite on this Patagonian glacier is likely due to small supply of wind-blown materials, low material concentration in glacial ice, and/or low biological production. The large annual snow accumulation on the glacier, which is a characteristic of Patagonian Icefield, may result in the low material concentration in the glacial ice. Since the annual snow accumulation in a Patagonian glacier is approximately 6 times as much as in Himalayan glaciers (3.4 m versus 0.58 m in water equivalent: Matsuoka and

Naruse, 1999 (Northern Patagonia Icefield), Fujita *et al.*, 1998 (Yala Glacier), respectively), the material concentration of the Patagonian glacier is possibly small compared to that of the Himalayan glacier. Furthermore, the large snow accumulation may cause low biological activity, because a large amount and frequent snow cover may hamper the algal photosynthesis on the glacier surface. In order to understand the variation of the surface albedo of the glaciers, it is important to know the factors that determine the amount of cryoconite and biological activity on the glacier. However most of them are still open questions.

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References

Aniya, M. (1999): Recent glacier variations of the Hielos Patagonicos, South America, and their contribution to sea-level change. Arctic, Antarctic, and Alpine Research, **31**, 165-173.

Fujita, K., Takeuchi, N., and Seko, K. (1998): Glaciological observations of Yala Glacier in Lantang Valley, Nepal Himalayas, 1994 and 1996. Bulletin of Glacier Research, **16**, 75-81.

Gerdel, R.W. and Drouet, F. (1960): The cryoconite of the Thule Area, Greenland. Trans. Am. Microsc. Soc., **79**, 256-272.

Kohshima, S. (1987): Formation of dirt layers and surface dust by micro -plant growth in Yala (Dakpatsen) Glacier, Nepal Himalayas. Bulletin of Glacier Research **5**, 63-68.

Kohshima, S. (1989): Glaciological importance of micro-organisms in the surface mud-like materials and dirt layer particles of the Chongce Ice Cap and Gozha glacier, West Kunlun Mountain, China. Bulletin of Glacier Research, **7**, 59-66.

Kohshima, S., Seko, K., and Yoshimura Y. (1993): Biotic acceleration of glacier melting in Yala Glacier, Langtang region, Nepal Himalaya. Snow and Glacier Hydrology (Proceeding of the Kathumandu Symposium, November 1992) IAHS Publ. **218**, 309-316.

Kol, E. (1942): The snow and ice algae of Alaska. Smithsonian Miscellaneous Collections, **101**, 1-36.

Kol, E. and Flint., E. A. (1968): Kryobiologie. Biologie und Limnologie des Schnees und Eises. I. Kryovegetation. Die Binnengewsser. Vol. 24 ed. by A. Thienemann, (founder), H.-J. Elster, W. Ohle, and E. Stuttgart. Schweizerbart'sche, Verlagsbunchhandlung, 216 p.

Kol, E. (1969): The red snow of Greenland. II. Acra Botanica Academiae Scientiarum Hungaricae, **15** (3-4), 281-289.

Kol, E. and Peterson, J. A. (1976): Cryociology. The Equatorial Glaciers of New Guinea, Results of the 1971-1973 Australian Universities' Expeditions to Irian Jaya: Survey, Glaciology, Meteorology, Biology and Paleoenvironments. ed. by G.S. Hope, , J.A. Peterson, , U. Radak, , and I. Allison, , Rotterdam, Balkema, 81-91.

Ling, H. U. and Seppelt., R. D. (1993): Snow algae of the Windmill Island, continental Antarctica. 2. Chloromonas rubroleosa sp. nov. (Volvocales, Chlrophyta), an alga of red snow. Journal of Phycology, **28**, 77-84.

Matsuoka, K. and Naruse, R. (1999): Mass blance features derived from a firn core at Hielo Patagonico Norte, South America. Arctic, Antarctic, and Alpine Research, **31**, 333-340.

Naruse, R., Pena, H., Aniya, M. and Inoue, J. (1987); Flow and surface structure of Tyndall Glacier, the Southern Patagonia Icefield. Bulletin of Glacier Research, **4**, 133-140.

Nishida, K., Satow, K., Aniya, M., Casassa, G. and Kadota, T. (1995); Thickness change and flow of Tyndall Glacier, Patagonia. Bulletin of Glacier Research, **13**, 29-34.

Nordenskjold, A.E. (1875): Cryoconite found 1870, July 19th-25th, on the inland ice, east of Auleitsivik Fjord, Disco Bay, Greenland; Geol. Mag., Decade 2, **2**, 157-162.

Paterson W. S. B. (1994): The physics of glaciers 3rd ed., Oxford, Elsevier, 480 p.

Takeuchi, N., Kohshima, S., Yoshimura, Y., Seko, K., and Fujita, K. (2000): Characteristics of cryoconite holes on a Himalayan glacier, Yala Glacier Central Nepal. Bulletin of Glaciological Research, **17**, 51-59.

Takeuchi, N., Kohshima, S., Goto-Azuma, K., and Korner, R. M. (2001a): Biological characteristics of dark colored material (cryoconite) on Canadian Arctic glaciers (Devon and Penny ice cap), Proceeding of the Memoirs of National Institute of Polar Research, Special Issue, **54**, in press.

Takeuchi, N., Kohshima, S., and Seko, K. (2001b): Structure, formation, darkening process of albedo reducing material (cryoconite) on a Himalayan glacier: a granular algal mat growing on the glacier. Arctic, Antarctic, and Alpine Research, **33**, in press.

Wharton, R. A., Vinyard, B. C., Parker, G. M., Simmons, Jr, G. M., and Seaburg, K. G. (1981): Algae in cryoconite holes on Canada Glacier in Southern Victorialand, Antarctica. Phycologia, **20**, 208-211.

Wharton, R. A., McKay, C. P., Simmons, G. M. and Parker, B. C. (1985): Cryoconite holes on glaciers. BioScience, **35**, 449-503.

Yoshimura,Y., Kohshima, S., and Ohtani, S. (1997): A Community of Snow Algae on A Himalayan Glacier: Change of Algal Biomass and Community Structure with Altitude. Arctic and Alpine Research, **29**, 128-139.