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Effect of debris cover on species composition of living organisms in supraglacial lakes on a Himalayan glacier

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Abstract Supraglacial lakes on a Himalayan debris-covered glacier (Khumbu Glacier in east Nepal) were investigated to identify the organisms living in them. Two kinds of insects, a copepod, a branchiopod, and nine kinds of algae were observed in the lakes. The kinds of organisms identify three types of lakes. *Type A*: lakes with animals and algae; *Type B*: lakes with animals only; *Type C*: lakes without living organisms. Each type of lake had distinctly different water characteristics. Suspended sediment concentration of water in Type A lakes was significantly lower than that in Type B and Type C lakes. Electrical conductivity and surface temperature of lake water was highest in Type A lakes, followed by Type B and Type C lakes. Our results suggest that the species composition in supraglacial lakes is determined by water characteristics and the life span of the lake, which may be due to debris conditions around the lake.

INTRODUCTION

Glaciers are not anti-biotic environments. Recently, many kinds of cold-tolerant organisms have been found on glaciers of Himalayas, Tibet, Arctic, and Antarctic. For example, Kohshima (1984a,b, 1987a,b) found a specialized animal community consisting of cold-tolerant insects and copepods sustained on a Himalayan glacier by feeding on algae and bacteria growing in the near-surface snow and ice. He pointed out that the glacier is a unique freshwater ecosystem with a very simple and specialized biotic community based on the primary production of these algae.

Debris cover is extensive on mountain glaciers, especially those in the Himalaya. When the debris is thick, it is impossible for snow and ice algae to grow directly on the glacier surface. Some organisms inhabit the meltwater system of glaciers including ones with debris, for example in supraglacial lakes or meltwater channels on or beneath the surface (e.g. Clayton, 1964; Kohshima, 1985). However, few biological observations have been made, and the community in the meltwater systems of debris-covered glacier is still unexplored. Since community structure of living organisms is due to physical and chemical conditions of their habitat, the community in the meltwater systems, in particular in supraglacial lakes, may be largely affected by glacier surface conditions, such as debris thickness, debris characteristics, and/or glacial melting activity.

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This study aims to determine species composition of living organisms in supraglacial lakes on a Himalayan debris-covered glacier (Khumbu Glacier in east Nepal). Physical, chemical, and biological characteristics of the lakes are described. The relationship of the diversity and quantity of organisms to the physical process acting on the glacier surface, in particular the role of debris depending on its thickness, is discussed.

STUDY SITE

The research was carried out from 20 October to 10 November 1995, in Khumbu Glacier, east Nepal (Fig. 1). This glacier flows from the top of Mt Everest (Mt Sagarmarta, 8848 m a.s.l.) down to 4900 m a.s.l. over a distance of more than 15 km in the Khumbu Valley. The ablation area of the glacier is 10 km long from 4900 m a.s.l. to 5200 m a.s.l. and is covered with debris. The debris area has complex surface morphologies including debris-covered cones, large hollows, ice cliffs, lakes, and streams (Iwata *et al.*, 1980).

On the debris-covered area, more than 100 supraglacial lakes and ponds were observed in the study period. For simplicity, all will be referred to as lakes. They ranged from approximately 2 to 100 m in diameter. Figure 2 shows the distribution of the lakes on the ablation area. Forty lakes with practical access were chosen for investigation.

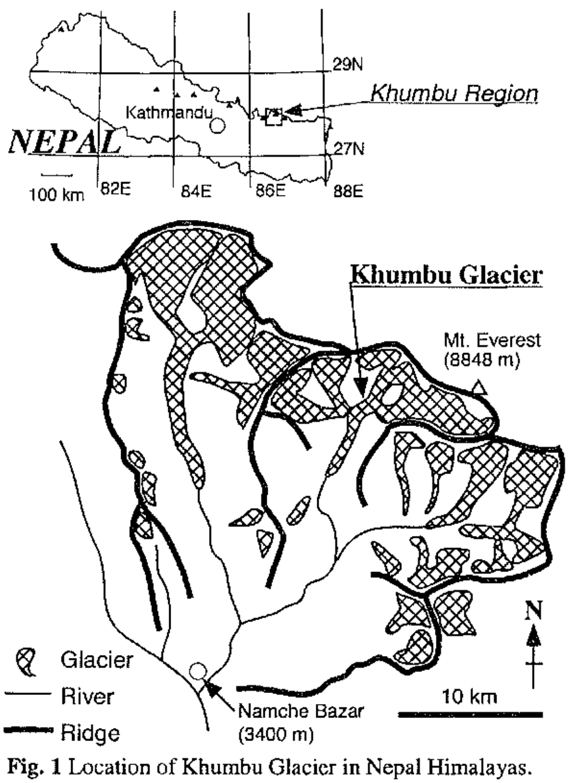

Fig. 1 Location of Khumbu Glacier in Nepal Himalayas.

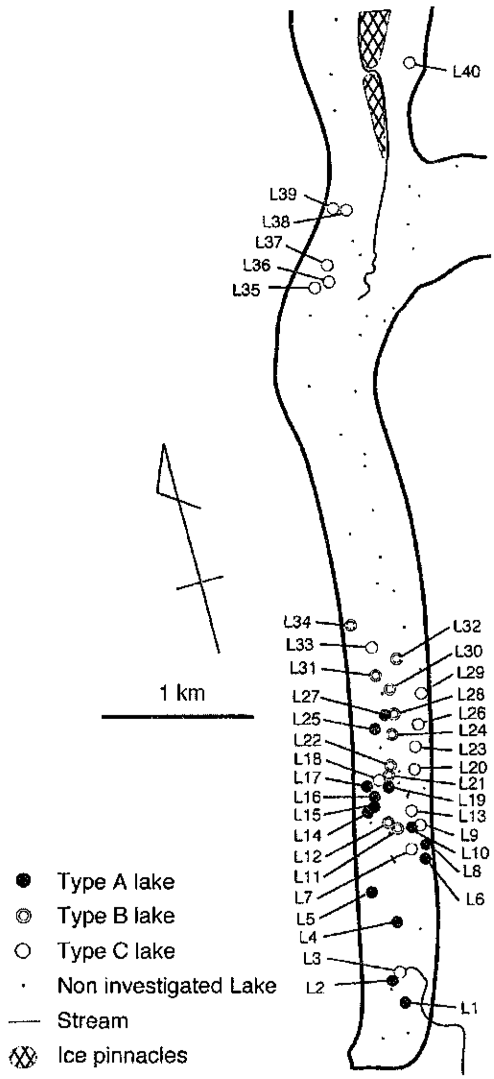

Fig. 2 Distribution of supraglacial lakes on Khumbu Glacier according to the species composition of each lake.

METHODS

Inhabitants of the 40 lakes were investigated in several ways. Insects and zooplanktons were sought in the lake bottom using a net of fine mesh. Lake water including benthos was collected by a pipette from the lakeside at each lake. The water was kept in 50 ml polyethylene bottles and was preserved as a 3% formalin solution. The samples were transported to Japan where organisms (microbes) in the water and benthos were analysed with a microscope. Bacteria were not analysed other than blue green bacteria (cyanobacteria), which are referred to here as algae for simplicity.

For each lake studied, the suspended sediment concentration (SSC, mg l^{-1}), water temperature (°C), and electrical conductivity (EC, μS cm^{-1}) were measured near the lake surface (5–10 cm in depth) at the lakeside. Measuring and sampling were done during the daytime (9:00–15:00) between 24 October and 7 November. Water temperature was measured with a thermistor thermometer (TAKARA D611). EC was measured with an EC meter (Model SC82, YOKOGAWA Co.). EC values were adjusted to 0°C. The water samples were transported to Japan and analysed at the Tokyo Institute of Technology. In order to measure SSC, 100 ml of sample water was first filtered through a pre-weighted membrane filter (Millipore HAWP047XX, pore size: 0.45 μm). Then, the filters were dried (65°C, 24 h), and the weight of the particles on the filter was measured with an electric balance (METTLER AE240, 0.01 mg resolution).

RESULTS

Living organisms in the supraglacial lakes

Two kinds of insect, a copepod, a branchiopod, and nine kinds of algae were observed. A list of the organisms is shown in Table 1. The insects, copepod, and branchiopod were at the bottom of the lakes. Algae were observed mainly in the benthos.

Table 1 List of living organisms found in supraglacial lakes of Khumbu Glacier.

	Family	Size (algae: cell size)	Remarks
Animal			
Stonefly	Capniidae	12–8 mm length, 1.8–2.0 mm width	Larva
Midge	Chironomidae	7–9 mm length, 0.7–0.9 mm width	Larva, black to yellow colour
Copepod	Diaptomidae	1.2–1.5 mm length, 0.4 mm width	red color
Branchiopod	Daphniadae	1.0–2.3 mm length, 0.8–1.0 mm width	*Daphnia* sp.
Plant			
Blue green alga 1	Oscillatoriaceae	1.5 µm length, 1.0 µm width	
Blue green alga 2	Oscillatoriaceae	1.5 µm length, 1.5 µm width	
Blue green alga 3	Chroococcaceae	3–10 µm in diameter	
Blue green alga 4	Nostocaceae	2–4 µm length, 2–4 µm width	*Anabaena* sp.
Green alga 1	Zygnemataceae	90–110 µm length, 16–18 µm width	
Green alga 2	Desmidiaceae	75–90 µm length, 70–80 µm width	*Cosmarium* sp.
Diatom 1	Fragilariaceae	15–20 µm length, 7–8 µm width	
Diatom 2	Naviculaceae	35–50 µm length, 8–10 µm width	
Diatom 3	Cymbellaceae	11–14 µm length, 3–4 µm width	

Species composition of the lakes

Table 2 shows the list of lakes and organisms observed in each lake. The species composition of the organisms was found to differ in the lakes. Fourteen of the 40 lakes were inhabited by algae and animals. Ten lakes were inhabited by only animals. Sixteen lakes were not inhabited by any organisms. Therefore, the lakes were divided

Table 2 List of investigated supraglacial lakes of Khumbu Glacier, showing water characteristics and living organism, and lake type.

Lake no.	Date	SSC (mg l^{-1})	EC (μS cm^{-2})	Water temperature (°C)	Ice cliff	Type of species composition	Stonefly	Midge	Copepod	Branchiopod	Blue green alga 1	Blue green alga 2	Blue green alga 3	Blue green alga 4	Green alga 1	Green alga 2	Diatom 1	Diatom 2	Diatom 3
1	2 Nov.	0.0	75.3	6.7		A		+	+		+	+		+	+	+	+	+	
2	27 Oct.	34.3	44.3	5.6		A	+	+	+	+	+								
3	27 Oct.	50.7	34.9	0.4		C													
4	28 Oct.	0.0	72.7	6.3		A	+	+	+		+	+		+					
5	28 Oct.	0.0	80.1	8.5		A		+			+	+	+	+	+	+	+	+	
6	28 Oct.	0.0	44.0	4.2		A		+	+		+						+	+	+
7	28 Oct.	15.2	22.4	1.6	+	C													
8	28 Oct.	0.0	25.9	5.3		A		+			+			+	+	+		+	+
9	29 Oct.	49.7	17.5	0.7	+	C													
10	29 Oct.	0.0	32.7	0.6		A	+	+			+			+					
11	24 Oct.	57.9	22.2	5.8	+	B	+	+											
12	27 Oct.	30.1	36.4	5.1	+	B	+	+											
13	29 Oct.	10.1	45.9	0.5	+	C													
14	24 Oct.	0.0	80.0	6.0		A		+			+	+	+	+	+		+		
15	24 Oct.	0.0	71.2	6.3		A	+	+	+		+			+	+	+	+		+
16	28 Oct.	21.3	79.7	5.7		A	+	+	+		+			+					
17	28 Oct.	0.0	90.0	8.3		A		+	+		+	+	+	+	+		+	+	
18	28 Oct.	64.2	41.4	4.7	+	C													
19	30 Oct.	3.0	38.3	3.3		A		+			+			+					+
20	29 Oct.	59.5	17.7	0.7		C													
21	30 Oct.	58.6	18.3	1.9	+	B		+											
22	30 Oct.	23.2	66.2	6.4	+	B	+	+											
23	29 Oct.	41.4	10.0	2.0	+	C													
24	20 Oct.	40.1	39.0	3.1	+	B		+											
25	29 Oct.	0.0	63.8	7.7		A	+	+	+		+	+	+		+		+	+	
26	31 Oct.	9.0	25.0	0.4	+	C													
27	29 Oct.	9.6	30.9	1.3		A		+											+
28	29 Oct.	55.6	28.1	1.4		B		+											
29	31 Oct.	3.0	38.0	0.9		C													
30	31 Oct.	12.1	25.7	1.5		B		+											
31	1 Nov.	40.1	23.6	3.0	+	B		+											
32	1 Nov.	43.2	33.1	0.8	+	B	+	+											
33	1 Nov.	86.5	19.1	2.2	+	C													
34	1 Nov.	7.0	15.9	0.6		B	+	+											
35	4 Nov.	5.0	10.0	0.6	+	C													
36	4 Nov.	18.0	14.9	0.7	+	C													
37	4 Nov.	3.0	17.6	1.0	+	C													
38	5 Nov.	0.0	2.4	0.6		C													
39	7 Nov.	20.1	20.3	0.4		C													
40	7 Nov.	0.0	16.6	0.5	+	C													

into three types:

Type A: lakes with animals and algae;
Type B: lakes with animals only;
Type C: lakes without living organisms.

Microscopy of the benthos of the lakes revealed that the benthos of Type A lakes contained much amorphous organic matter and much algae. On the other hand, the benthos of Type B and Type C lakes contained only fine mineral particles and a little amorphous organic matter. A food source for the animals in Type B lakes is likely to be this organic matter that is probably transported to the lakes from the surrounding terrain by wind.

Figure 2 shows the distribution of each lake type. Type A lakes tended to be distributed in the margin of the downstream area of the glacier. Type B lakes tended to be in the centre of the glacier. Type C lakes tended to be farther upstream.

Water characteristics of the lakes

SSC, EC, and surface temperature of lake water varied between the lakes (Table 2).

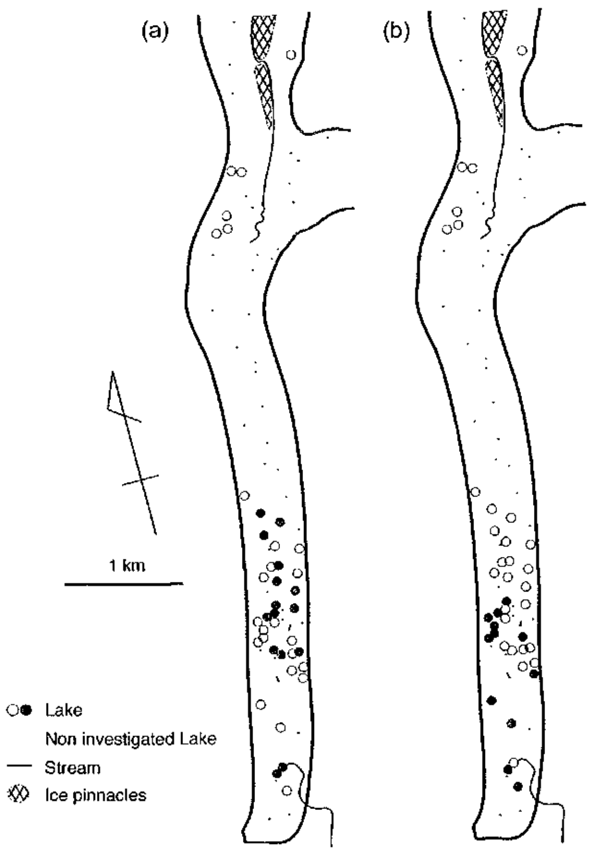

Fig. 3 Distribution of water characteristics of supraglacial lakes on Khumbu Glacier. (a) Suspended sediment concentration. ○: 0–30 mg l^{-1}; ●: > 30 mg l^{-1}. (b) Electrical conductivity. ○: 0–40 μS cm^{-2}; ●: > 40 μS cm^{-2}.

SSC of the lake water ranged from 0.0 to 86.5 mg l^{-1}. Mean SSC was 21.8 mg l^{-1}. The SSC of 12 lakes was 0.0 mg l^{-1}. EC of lake water ranged from 2.4 to 90.0 μS cm^{-2}. Mean EC was 37.3 μS cm^{-2}. Surface water temperature ranged from 0.4 to 8.5°C. Mean water temperature was 3.1°C.

Figure 3 shows the distribution of SSC and EC levels in the lakes. High SSC lakes (more than 30 mg l^{-1}) tended to lie toward the centre of the glacier. High EC lakes (more than 40 μS cm^{-2}) tended to be in the downstream area of the glacier.

Table 3 shows the characteristics of the water of each type of lake. SSC for Type B and Type C lakes was not significantly different (36.8 *vs* 27.2 mg l^{-1}, statistical *t*-test: $t = 2.06$, P (probability) = 0.30 > 0.05), but were significantly higher than Type A lakes (1.1 mg l^{-1}, Type A *vs* B: $t = 2.16$, $P = 0.00 < 0.05$; Type A *vs* C: $t = 2.09$, $P = 0.01 < 0.05$). Electrical conductivity and surface temperature of lake water were highest in Type A lakes, and lowest in Type C lakes.

Table 3 Water characteristics (mean values and standard error) for each lake type on Khumbu Glacier.

	Type A	Type B	Type C
SSC (mg l^{-1})	4.9 (±2.8)	36.8 (±5.8)	27.2 (±6.8)
EC (μS cm^{-2})	59.2 (±5.9)	30.9 (±4.6)	22.1 (±3.0)
Temperature (°C)	5.4 (±0.6)	3.0 (±0.7)	1.1 (±0.3)

DISCUSSION

The different characteristics of the water of the three lake types suggest that species composition is due to the characteristics of the lake water. Since suspended sediment particles in lake water decrease the transparency of the lake water, high SSC level of lake water inhibits the photosynthesis of algae and decreases algal growth. SSCs for most of Type A lakes were zero (10 of 14 lakes), and SSC for Type B and Type C lakes was significantly higher than that of Type A lakes. Therefore, lack of algae in communities of Type B and Type C lakes may be caused by the water turbidity. Nutrient conditions of the lake water must also affect species composition in the lakes, especially algal growth. High EC level of lake water indicates that the water is rich in solutes, which may include limiting nutrients. Since the EC level for lake water was the highest in Type A lakes, nutrient condition in Type A lakes may be relatively richer than in Type B lakes and in Type C lakes. Therefore, both SSC and EC play a role in the more abundant algae in Type A lakes.

Life span of lakes is also expected to affect species composition of the lakes. The lake distribution for 1995 on the glacier was different from the distribution in 1978 as reported by Iwata *et al.* (1980). This indicates that supraglacial lakes do not persist for a long time, but form and collapse repeatedly. This is probably due to changes of surface morphology caused by glacier flow and surface melting. Although the water characteristics of Type B and C lakes were similar, animals were observed only in Type B lakes. This is probably due to a difference in time since the formation of the lakes: Type B lakes may be older than Type C lakes and have been present long enough for colonization.

The lake water characteristics are probably affected by the debris condition around the lake. Meltwater from the glacier is the main water source for the lakes. Since the melting of debris-covered areas is concentrated at ice cliffs (Inoue & Yoshida, 1980), inflow to lakes with ice cliffs is relatively high. SSC of the lakes that had ice cliffs was significantly higher than the lakes without ice cliff (33.1 *vs* 12.6 mg l^{-1}; statistical *t*-test, $t = 2.945$, $P = 0.003 < 0.05$). This suggests that lake water with a high SSC level originates from an abundant meltwater supply. The meltwater may flow into the lakes carrying fine particles from the debris cover thus elevating the SSC. The distribution of lakes with low SSC also supports this idea. According to the debris thickness distribution on Khumbu Glacier compiled by Nakawo *et al.* (1986), the debris thickness in the downstream area of the glacier is more than 2 m on average. The lakes located in the downstream area had low SSC (less than 40 mg l^{-1}) except for L2 and L3 (Fig. 3(a)). Since the thick debris layer inhibits glacier melting (e.g. Nakawo & Young, 1981), the melting of glacier surface is likely to be slow in this area with consequent low inflow and generation of SSC. The high SSC lakes in this area (L2 and L3) were connected to a turbid meltwater stream that provided input of suspended sediment.

The distribution of high EC lakes suggests a solute source from organic soil debris around the lake. Lakes with high EC are distributed along the margin of downstream area of the glacier (Fig. 3(b)). According to Iwata *et al.* (1980), the debris of this area supports organic soil and vegetation patches. The lakes of this area are likely fed by water coming from or through organic soil. Since debris stability is required for the formation of organic soil, organic soil may develop only on areas of thick debris, where surface melting is strongly inhibited. Therefore, high EC lakes may form on thick and stable debris areas.

Thus, species composition of supraglacial lakes is likely to reflect the life span of the lakes and the debris condition around the lake. Type A lakes are formed in areas of stable and thick debris, Type B lakes are formed on thin debris area, Type C lakes are also formed on thin debris area, but have existed for a shorter time than Type B lakes.

According to Nakawo *et al.* (1986), supraglacial debris of this glacier has been forming for a period of the order of hundreds of years, since the last advance of the glacier. Numbers and distribution of each lake type might have changed with the debris formation. In the initial stage of debris formation, Type C lakes would have been dominant on the glacier surface when debris cover was thin, melting was intense, and surface morphology changed rapidly. As the debris became thicker, the number of Type B and Type A lakes might have increased. If the debris continues to thicken in the future, Type A lakes will eventually be dominant on the debris-covered area together with a more diverse ecology on the increasingly stable debris cover itself.

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