Variation in Suspended Sediment Concentration of Supraglacial Lakes on Debris-covered Area of the Lirung Glacier in the Nepal Himalayas

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Abstract

Spatial and temporal variations in the suspended sediment concentration (SSC) of supraglacial lakes in debris-covered areas were investigated on the Lirung Glacier in the Langtang region of central Nepal from May to Octorber 1996. Twenty-eight lakes of various sizes were observed on the glacier. SSC varied widely among the lakes from 0 to 364 mg l^{-1}. Monthly observations showed that SSC of lakes also varied temporally, but there was no common trend in seasonality among the lakes. Measurement of the settling rate of suspended sediment in lake water indicated that SSC rapidly decreased from 37 mg l^{-1} to 4 mg l^{-1} within a day. Our results suggest that in lakes where SSC is high it is maintained mainly by a supply of high SSC meltwater to the lakes and that the low SSC of other lakes is due to little meltwater inflow to the lakes. Variations in SSC among lakes probably result from heterogeneous distribution of debris thickness and ice cliffs that affect the melting of glacial ice around the lakes. Seasonal changes in SSC are probably due to changing meteorological conditions and/or debris cover and ice cliffs around the lakes. The availability of lake turbidity would enable quicker and safer determination of the meltwater supply of lakes via remote-sensing techniques, and may be useful for elucidating the status of supraglacial lakes and glacier melting on debris-covered glaciers.

Key words: debris-covered glacier, Himalayas, supraglacial lake, suspended sediment concentration, turbidity

1. Introduction

Debris-covered glaciers with rock debris covering the ablation area are common in the Himalayan region (Fujii & Higuchi, 1977). Debris areas usually have complex surface morphologies including supraglacial lakes, debris-covered cones, large hollows, ice cliffs and streams (Iwata *et al*., 1980). Since the thick debris cover suppresses surface melting of glaciers, supraglacial lakes and ice cliffs play an important role in the complicated melting processes of debris-covered areas on this type of glacier (*e.g*., Inoue & Yoshida, 1980; Sakai *et al*., 2000). Recently, some supraglacial lakes on debris-covered glaciers have expanded rapidly and outbursted in the Himalayan region. Big floods caused by these outbursts (glacier lake outburst floods, GLOFs) have killed inhabitants and destroyed the natural environment downstream (Yamada & Sharma, 1993). In order to understand the process of lake expansion in small supraglacial lakes, it is important to quantify their physical characteristics.

Water sources and meltwater supply processes are especially important to consider because lake expansion results from much glacial meltwater input, and/or from melting of the glacier ice at the sides and bottom of the lakes (Chikita *et al*., 1997). Furthermore, the characteristics of supraglacial lakes are important to know as they provide an understanding of the chemical composition of discharge meltwater and the biological community living there. Recent studies have revealed that supraglacial lakes on debris-covered glaciers play a role in the hydrolysis of fresh reactive minerals (Bhatt *et al*., 2007). The lakes are also inhabited by diverse organisms, such as insects, copepods and algae (Takeuchi & Kohshima, 2000). Their community structure varies widely among the lakes, probably due to physical and/or chemical conditions of the lakes' water. However, few studies of supraglacial lakes have been done, since unstable debris on such glaciers makes them a dangerous environment for field investigations.

Variation in water turbidity of supraglacial lakes is visibly significant on debris covered glaciers. Iwata *et al.* (1980) reported variation in water turbidity of supraglacial lakes on the Khumbu Glacier in Eastern Nepal. They found that glacial lakes on upper parts with relatively thin debris-cover tended to have turbid water, whereas terminal lakes on glaciers with thick debris cover tended to have clear water. In areas with thin debris cover, surface melting and the meltwater supply are higher than in areas with thick debris cover (Nakawo & Young, 1981). Therefore lake water turbidity may be positively related to meltwater supply. However, causes of such variation in lake water turbidity are still unknown. Since turbidity levels can be quickly estimated visually as brightness or coloration of water (*e.g.*, Ritchie & Cooper, 1988; Roberts *et al.*, 1995), the discovery and characterization/quantification of a relationship between turbidity and meltwater supply would enable quicker and safer determination of lake status via remote-sensing techniques. In fact, variations in turbidity of supraglacial lakes on a debris-covered area of a Himalayan glacier were successfully detected using ASTER satellite images (Wessels *et al.*, 2002).

This study aims to describe spatial and temporal variations in the suspended sediment concentration (SSC) of surface water of supraglacial lakes and to determine factors in the variations on the Lirung Glacier of the Langtang region of Nepal, which is a typical Himalayan debris-covered glacier. SSC, electrical conductivity (EC) and water temperature in all the lakes on the debris-covered area of the glacier were measured during the melting season (May - October) of 1996. The settling rate of suspended sediment of the lake water and diurnal variations of lake water levels were also measured at selected lakes to understand the relationship between lake water SSC and meltwater supply to the lakes.

2. Study Site and General Morphology of the Lakes

All investigations were carried out on the Lirung Glacier in the Langtang region of central Nepal (Fig. 1) from May 5, 1996 to October 18, 1996. The study included the monsoon season, which occurs between July and September. The 4 km long glacier flows south (from 7,200 m down to 3,900 m a.s.l., Fig. 2a) and is located on the southeastern side of Mt. Langtang Lirung. The equilibrium line was located at approximately 5,500 m in the study period. The glacier is separated into two parts at 4,200 m a.s.l.: the upper part and lower part (Fig. 3). Between the two parts, basal rock is exposed for approximately 100 m. The debris free upper part flows from the top of Mt. Langtang Lirung down to 4,800 m on a steep

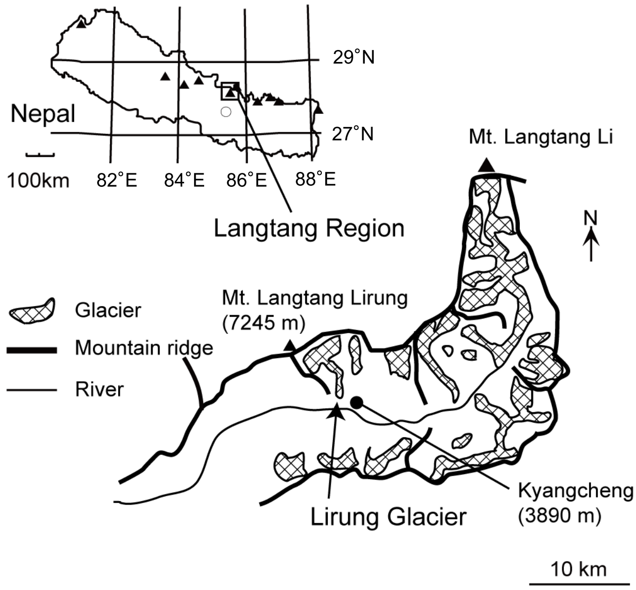

Fig. 1 Location of the Lirung Glacier in the Nepal Himalayas.

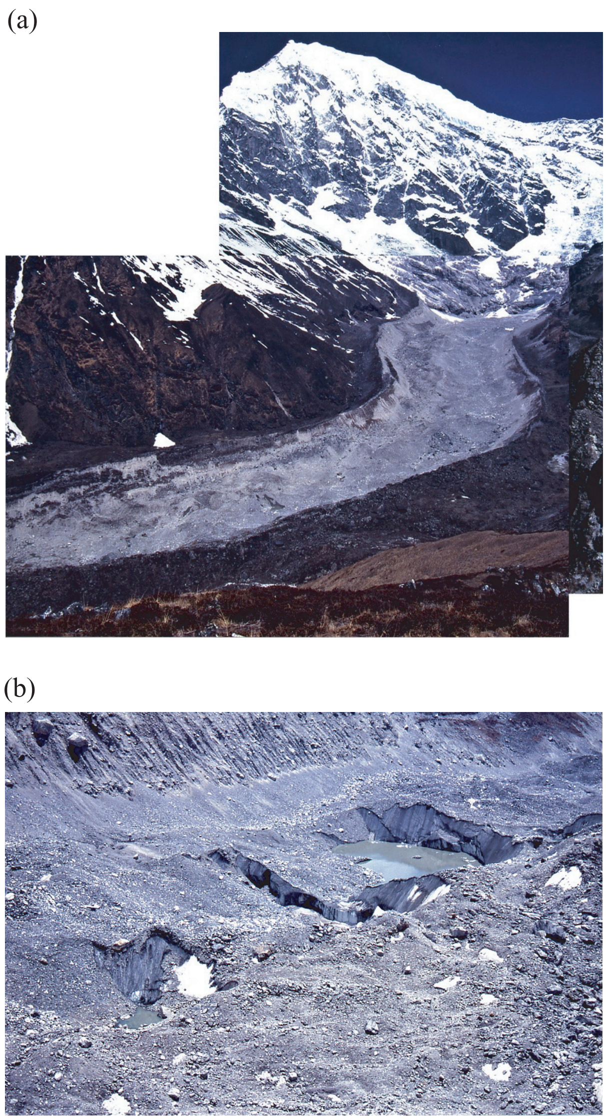

Fig. 2 (a) The Lirung Glacier in May, 1996. (b) Supraglacial lakes on the debris covered surface. A large (L24) and small (L25) lake on the upperpart of the glacier.

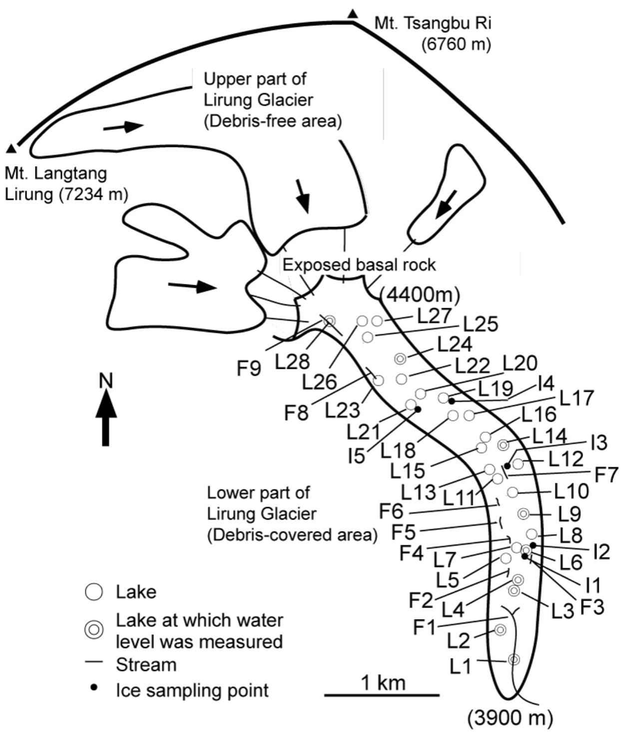

Fig. 3 Distribution of supraglacial lakes on the Lirung Glacier in May 1996.

slope. The lower part flows along the valley bottom and is mostly covered with thick debris. Snow and ice are supplied from the upper part to the lower part mostly by avalanches. Meltwater flowing into the lower part from the upper part was observed on the exposed basal rock.

The debris surface of the lower part of the glacier is marked by morphologies such as cones, hollows and ice cliffs; these are similar to those observed on the Khumbu Glacier (Iwata *et al*., 1980). The surface level is lower than the lateral and terminal moraines. The debris surface from the terminus up to about 1 km upstream is relatively flat with some vegetation.

Twenty-eight supraglacial lakes or ponds were found on the lower part of the Lirung Glacier in the pre-monsoon season (Table 1). For simplicity, all will be referred to as lakes. Figure 3 shows the supraglacial lake distribution. All the lakes were located at the bottom of surface depressions on the debris-covered area. Lake sizes ranged from approximately 2 to 100 m in diameter. The largest and probably deepest lake (L24) was more than 100 m in diameter and 8 m in depth. The smallest lake (L10) was 2 m in diameter and 1 m in depth. Though the depth was not measured in any other of the lakes, they appeared to be less than eight meters deep (the depth of the largest lake, L24).

More than half of the lakes (17 out of 28) had ice cliffs

Table 1 SSC and characteristics of supraglacial lakes on the Lirung Glacier. The times shown are Nepali standard time (GMT+5:45). The size of each lake is represented by L: ≥10,000 m^2, M: 10,000 - 100 m^2, S: <100 m^2. The size change is represented by +: enlarged, 0: no change, –: reduced.

Lake No.	Size of lake	Water Flow	Ice Cliff	Pre-monsoon Date	Time	SSC (mg l^{-1})	EC (μS cm)	Water Temp. (°C)	Post-monsoon Date	Time	SSC (mg l^{-1})	EC (μS cm)	Water temp. (°C)	Size change	Midge	Algae
L1	L	+		5/8	7:43	81	21.0	1.3	10/12	13:14	137	30.1	5.9	0		
L2	M			5/9	16:00	0	42.4	11.5	10/12	12:59	1	26.0	9.0	0	+	+
L3	M			5/8	8:29	4	13.9	6.4	10/12	12:27	21	8.7	4.5	+	+	+
L4	M		+	5/8	8:49	66	11.4	3.9	10/12	12:08	35	7.7	4.2	+	+	
L5	M			5/10	13:29	9	12.8	8.2	10/12	10:10	0	3.2	2.1	−		
L6	M		+	5/8	9:45	37	11.0	3.0	10/12	11:38	30	4.4	2.4	−	+	
L7	S		+	5/9	10:55	39	15.5	6.9	10/12		disappeared					
L8	S			5/8	10:11	2	19.3	6.6	10/12		disappeared					
L9	M		+	5/9	12:38	36	9.5	2.7	10/12	8:44	36	7.9	0.2	−	+	
L10	S			5/13	9:29	0	8.3	3.9	10/12	9:26	5	4.9	1.2	+		
L11	M		+	5/13	10:28	29	15.6	0.8	10/12		disappeared					
L12	M		+	5/13	12:47	89	8.1	2.0	10/13		disappeared					
L13	M		+	5/13	11:00	28	17.9	2.7	10/13		disappeared					
L14	M		+	5/13	12:01	25	15.9	4.8	10/13	11:51	10	8.8	4.5	0	+	
L15	M		+	5/13	12:22	58	11.3	4.6	10/13	12:05	52	6.2	3.2	0	+	
L16	S		+	5/13	13:13	40	10.6	4.7	10/13		disappeared				+	
L17	M			6/15	11:28	0	6.3	5.7	10/13	11:29	31	4.8	1.5	+		
L18	M		+	6/15	11:11	44	8.6	3.3	10/13		disappeared					
L19	M		+	6/15	9:44	15	3.9	2.5	10/13	9:34	0	4.2	1.8	−		
L20	M		+	6/15	10:16	27	5.7	2.1	10/13		disappeared					
L21	M		+	6/15	10:40	364	10.6	1.8	10/13	10:17	40	5.9	0.6	−		
L22	M		+	5/11	12:43	11	10.1	2.4	10/14		disappeared				+	
L23	M	+		5/11	13:43	182	13.8	0.4	10/16	12:14	60	18.6	0.6	−		
L24	L		+	5/11	13:12	37	8.8	4.0	10/14	10:00	25	9.0	5.3	−	+	
L25	M		+	5/11	12:05	14	14.2	5.0	10/14		disappeared					
L26	M			5/11	11:26	9	9.3	4.5	10/14		disappeared					
L27	M			5/11	11:47	5	7.5	4.4	10/14		disappeared					
L28	M	+		5/11	10:50	31	12.0	1.4	10/16		disappeared					
Mean						46	12.7	4.0			32	10.0	3.1			

larger than 2 m × 2 m around them. In the daytime, a large amount of meltwater was observed flowing into the lakes from these ice cliffs. Nine supraglacial streams were present in the debris-covered area (F1-F9, Fig. 3). Since all of these streams flowed out from openings in the ice and into other openings in the ice or debris, the streams were likely to be connected with englacial drainage channels. Three long-shaped lakes located near the terminus or margin of the glacier (L1, L23, L28) were associated with supraglacial streams. In these three lakes, the surface water moved downstream slowly. In the other 25 lakes, no inlet or outlet channels and no obvious surface water flow were observed.

3. Measurements

3.1 Water characteristics

For each lake studied, suspended sediment concentration (SSC, mg l^{-1}), electrical conductivity (EC, µS cm^{-1}) and water temperature (˚C) were measured near the lake surface (5 - 10 cm in depth) at the lakeside. The measuring/sampling at all of the lakes was carried out during the daytime (9:00-13:00) in the pre-monsoon season (May and June) and post-monsoon season (October). EC and water temperature was measured with an EC meter (Model SC82, YOKOGAWA Co.). EC values were compensated to 25˚C. The water samples were transported to Japan and analyzed 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, 24h), and the weight of the particles on the filter was measured with an electric balance (METTLER AE240, 0.01 mg resolution). Although these measured values are all point measurements and do not indicate the average water characteristics of the lakes, daytime variation of each measurement appears to be smaller than the ranges of measured values. For example, the daytime variation of measured characters in L1 on May 30, 1996 (7:00-16:00) ranged from 111 mg l^{-1} to 158 mg l^{-1} (± 17%) for SSC, and 34-37 µS cm^{-1} for EC (± 4%). Thus, we assumed that these data were approximate to the characteristics of each lake.

Organisms living at lake bottoms were sought using a net of fine mesh at each lake. Lake water including benthos was collected by a pipette at each lake from the lakeside. The water was kept in 50 ml polyethylene bottles and preserved as a 3% formalin solution. The samples were transported to Japan where organisms (microbes) in the water and benthos were analyzed with a microscope.

Water characteristics of stream water (seven sites) and glacial ice (five sites) were also measured in the same way (Table 2, Fig. 3). EC and water temperature of stream water were measured directly from the streamside. One hundred ml of the water was collected in plastic bottles for SSC measurement. Ice samples were collected in plastic bags with an ice axe from ice cliffs after surface debris on the ice was washed off. Air was excluded as the ice melted in the plastic bags. The EC of the melted water was measured. One hundred ml of each meltwater sample was collected in plastic bottles for SSC measurements.

To measure seasonal changes in lake water SSC, 100 ml of surface lake water was collected from the lakeside of six lakes (L1, L2, L3, L4, L6, and L24), which were selected based on safe accessibility. The sampling was done monthly during the study period (May 8, June 13, July 14, August 15, September 14 and October 13). The lake water was measured at a consistent time (noon) for all the monthly samples.

Table 2 Water characteristics of streams and ice on the Lirung Glacier.

No.	Date	Time	SSC (mg l^{-1})	EC (µS cm^{-1})	Water Temp.(˚C)
F1	5/9	8:18	65	13.9	0.3
F2	5/9	9:20	261	13.7	0.2
F3	5/8	9:36	185	14.1	0.3
F4	5/9	11:30	182	14.8	0.3
F5	5/9	11:55	221	15.0	0.2
F6	5/8	12:22	219	14.3	0.2
F7	5/13	9:35	114	14.8	0.4
I1	6/17		110	11.5	-
I2	5/29		557	2.6	-
I3	6/17		91	2.4	-
I4	6/15		549	3.5	-
I5	6/15		127	1.3	-

3.2 Settling rate of suspended sediment in lake water

To measure the settling rate of suspended sediment of turbid lake water, SSC in a lake water sample was measured over time in a container without disturbance. Surface lake-water (about 65 l) was collected from the lakeside of L6, which is a representative turbid lake and safely accessible (May 30, 1996). The water was kept undisturbed in a plastic container (54 cm × 34 cm × 38 cm, length, width, and height, respectively). Then, 100 ml was sampled from surface of the water at noon every day until June 17 (19 days) to measure SSC.

3.3 Water levels of lakes

At nine lakes that were safely accessible (L1, L2, L3, L4, L6, L9, L15, L24, L28 in Fig. 3), the water level was automatically recorded every 30 minutes (single point measurements). The water level was measured with a water pressure sensor (VPRNP Hirose-Rika Co., output: 5 mV = 1 cm deep). The data were recorded in dataloggers (DATAMARK, Hakusankogyo Co., recording resolution = 1 mV). The sensors were placed about 10 cm beneath the minimum water level, and were shaded from sunlight. The measurements were carried out during a 3-7 day period for each lake (Table 3) in the pre-monsoon

Table 3 Water level changes and water characteristics of nine lakes on the Lirung Glacier.

Lake No.	Measured period	Time of max. water level	Time of min. water level	Amplitude of the change (cm) Min-Max (Mean)	Surface water flow	SSC (mg l^{-1})	EC (μS cm^{-1})
L1	5/7-6/30	18:00-23:00 (6:00-8:00)	9:00-13:00	5.0-39 (18.7)	+	81	21.0
L2	6/19-6/22	No Diurnal change	−			0	42.4
L3	5/10-5/16	No Diurnal change	−			4	13.9
L4	5/10-5/17	13:00-14:00	6:00-7:00	1.7-4.0 (2.3)	−	66	11.4
L6	5/28-6/4	13:00-14:30	6:00-8:00	2.8-7.5 (4.7)	−	37	11.0
L9	5/28-6/3	13:00-16:30	6:30-9:30	3.0-7.3 (5.1)	−	36	9.5
L15	7/1-7/5	10:30-13:30	6:00-8:00	1.4-1.5 (1.4)	−	58	11.3
L24	6/16-6/18	13:00-16:00	11:00	1.0-1.8 (1.4)	−	37	8.8
L28	6/9-6/11	16:30-17:00	8:00-9:30	2.5-8.2 (5.4)	+	31	12.0

season (from May 5 to July 10, 1996). For L1 (Fig. 3), the water level and water temperature were recorded every hour (single point measurements) with a water level meter (MD-8C, CTI Science Co. at 1 cm increments, 0.1˚C increments, respectively) from May 5 to October 30.

4. Results

4.1 SSC, EC and temperature of the surface lake-water, stream and ice

SSC of the lake water in the pre-monsoon season ranged widely among the lakes from 0 to 364 mg l^{-1} (mean = 45.8 mg l^{-1}, Table 1). A histogram of SSC distribution shows that there were two frequent ranges of lake-water SSC, which were 0 - 10 mg l^{-1} and 30 - 40 mg l^{-1} (Fig. 4a). The variation in SSC appeared to be consistent with the visible water turbidity of each lake. The water of the higher SSC lakes was visibly turbid from a distance. The water color of these lakes was creamy yellow or creamy green (Fig. 5a). In contrast, the lower SSC lakes (*e.g.*, L2, L10, L17) were clear blue (Fig. 5b). Although the turbidity of some lakes appeared to vary spatially within the lake, the spatial variation seemed to be obviously smaller than the turbidity variation among the lakes. The spatial distribution of lake water SSC on the debris-covered area showed no clear trend along the glacier (Fig. 6a). Both higher and lower SSC lakes were distributed from the lower to upper parts of the debris- covered area.

Lake water EC was generally found to be low (3.9 - 21.0 μS cm^{-1}, mean = 12.7 μS cm^{-1}, SE = 1.3, n = 28) except for L2 (42.4 μS cm^{-1}) in lakes near the terminus. EC values tended to be higher (> 15 μS cm^{-1}) in lakes located in the lower half of the debris-covered area, and lower (< 10 μS cm^{-1}) in lakes located in the upper half of it (Fig. 3). Temperatures of the surface lake-water also varied among the lakes (0.4˚C - 11.5˚C, mean = 4.0˚C, SE = 0.46, n = 28, Table 1).

In the post-monsoon season (October), 15 of the 28 lakes were observed at the same position wheareas the other 13 lakes had disappeared (Fig. 6, Table 1). There were no newly appearing lakes. Some of the lakes changed in size (area). Four of the 15 lakes had expanded whereas seven lakes had shrunk and the remaining four lakes showed no significant change (Table 1). Lake water SSC varied from 0 to 137 mg l^{-1} in this season (mean = 32.0 mg l^{-1}, Table 1). A histogram of lake water SSC shows a similar distribution to that of the pre-monsoon season (Fig. 4b). There were the same two frequent ranges of lake water SSC, which were 0 - 10 mg l^{-1} and 30 - 40 mg l^{-1}. EC and water temperature varied from 3.2 to 30.1 μS cm^{-1} (mean: 10.0 μS cm^{-1}) and 0.2˚C to 9.0˚C (mean: 3.1˚C), respectively. There were no significant differences in the mean of SSC, EC, or water temperature between pre- and post-monsoon seasons.

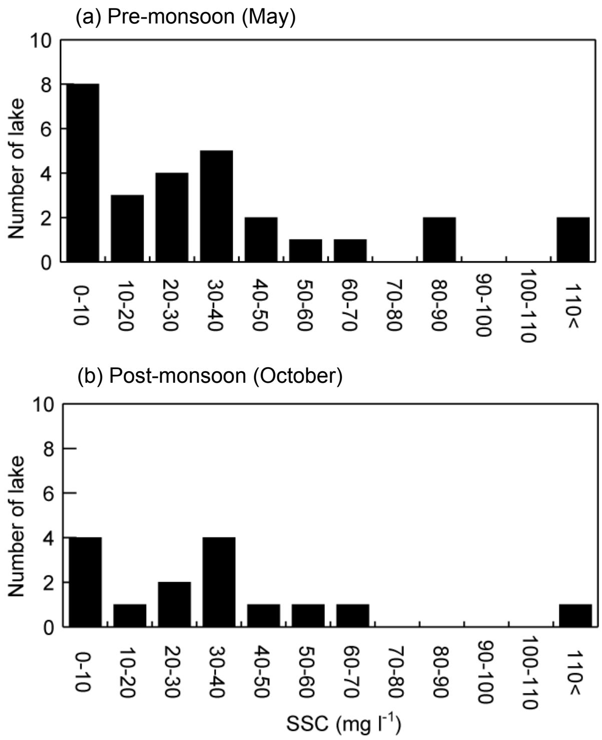

Fig. 4 Histograms of lake water SSC on the Lirung Glacier in the pre- and post-monsoon seasons of 1996.

Living organisms were found in the lake water and at the bottom of lakes in both pre- and post-monsoon seasons. A midge and algae were observed in two lakes (L2 and L3) and the midge only was observed in eight lakes (L4, L6, L9, L14, L15, L16, L22, L24, Table 1). No organism was found in the other 18 lakes. The algae observed included several taxa of green algae, diatoms, and cyanobacteria.

(a)

(b)

Fig. 5 Photographs of two supraglacial lakes of different turbidity. The SSC level can be recognized by water turbidity: (a) high-SSC water appears creamy yellow (L20, SSC = 364 mg l^{-1}, width = 2 m). (b) almost-zero-SSC water appears clear blue (L10, SSC = 0 mg l^{-1}, width = 2 m).

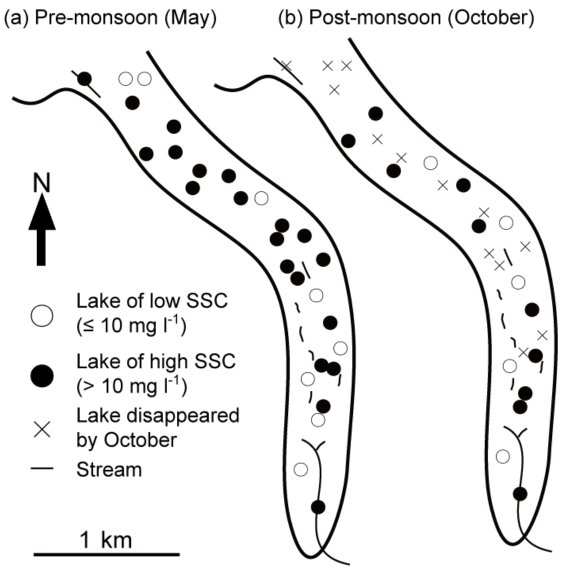

Fig. 6 Spatial distribution of lake water SSC on the Lirung Glacier in the pre- and post-monsoon seasons of 1996.

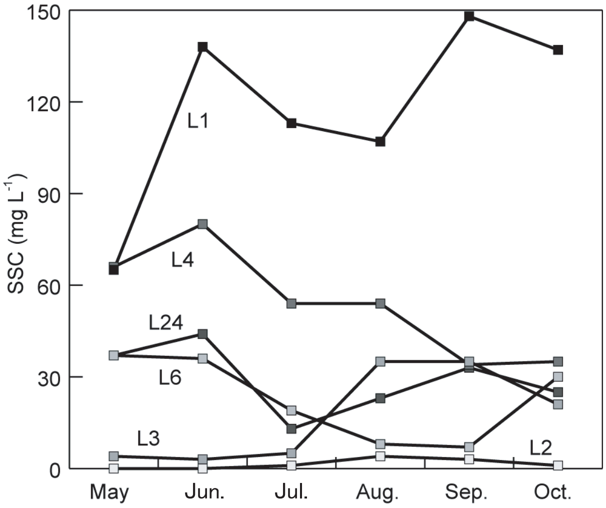

Fig. 7 Seasonal changes of SSC at six lakes on the Lirung Glacier. The values of each month are SSC on May 8, June 13, July 14, August 15, September 14 and October 13, respectively.

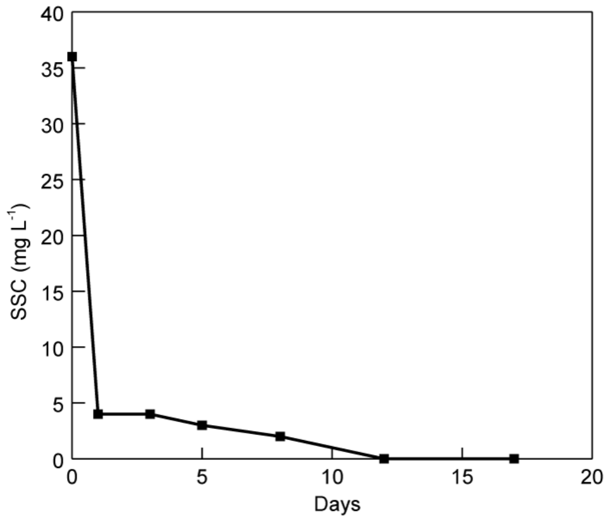

Fig. 8 Changes in the SSC of turbid water from Lake L6 in a container.

The water characteristics of streams and ice meltwater on this glacier are shown in Table 2. Compared to lake water characteristics, the water of seven streams (F1-F7) had higher mean SSCs (178 mg l^{-1} versus 45.8 mg l^{-1}, statistical t-test: t value (t) = –4.363, probability (P) = 0.000 < 0.05), but the EC means did not differ significantly (14.4 μS cm^{-1} versus 12.7 μS cm^{-1}, t = –1.25, P = 0.222 > 0.05). The mean water temperature of the streams was low (0.27°C, range = 0.2°C - 0.4°C, SE = 0.029, n = 7). Ice samples collected from five ice cliffs on the glacier had higher mean SSCs (287 mg l^{-1} versus 45.8 mg l^{-1}, t = –4.48, P = 0.000 < 0.05), but lower mean EC (4.3 μS cm^{-1} versus 12.7 μS cm^{-1}, t = 2.54, P = 0.016 < 0.05) relative to the lake water means.

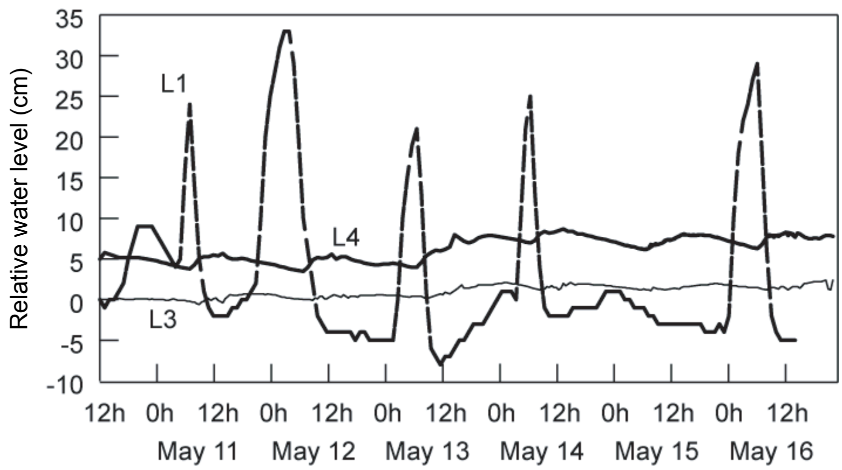

Fig. 9 Diurnal changes in relative water level of three supraglacial lakes (L3, L4, and L1) on the Lirung Glacier from May 10 to 16, 1996.

4.2 Seasonal changes in lake water SSC

The monthly observations revealed that lake water SSC changed temporally in the selected lakes from the pre-monsoon to post-monsoon season, but there was no common trend among the lakes (Fig. 7). The SSCs of L1 and L3 increased during that period whereas that of L4 decreased. The SSCs of L6 and L24 decreased once in summer and increased again by October. The SSC of L2, of which was a lower SSC, kept its low value and showed no significant change during the study period.

4.3 Settling rate of suspended sediment in lake water

Figure 8 shows the change in SSC of water in a container collected from the turbid lake water of L6. In undisturbed water, SSC rapidly decreased from 37 mg l^{-1} to 4 mg l^{-1} within a day. From there, SSC gradually decreased and finally become zero after eleven days. Sediments were observed at the bottom of the container after the second day and were likely to be deposits of the suspended particles in the turbid lake water.

4.4 Water level changes

Measurements of the water levels of nine lakes showed various patterns of temporal change. Seven of the nine lakes studied (L1, L4, L6, L9, L15, L24, L28) showed clear diurnal patterns, and two lakes (L2, L3) showed no diurnal patterns (Table 3). Figure 9 contrasts water-level changes measured simultaneously at three lakes (L1, L3 and L4). The L1 and L4 water levels showed clear diurnal changes, whereas the L3 water levels did not. The trend of the water level of L4 appeared to be to increase from early morning, becoming maximal in the afternoon, and decreasing to a minimum in the morning. This pattern was observed at five other lakes (L6, L9, L15, L24, L28). The diurnal pattern of L1 differed from that of the other five lakes. It showed an irregular pattern, which had a maximal level late at night or in the morning, and a minimum in the afternoon. L1 is only the lake that showed an irregular diurnal pattern.

The pattern of water level changes was found to be associated with lake water SSC. Table 3 shows SSC and EC for the lakes at which the water level was measured. The mean SSC was significantly higher for the seven lakes with diurnal changes than that of the two lakes without diurnal changes in water level (49.4 mg l^{-1} versus 2.0 mg l^{-1}, $t = 3.35$, $P = 0.012 < 0.05$). No significant difference was found in EC between the two lake types (12.1 µS cm^{-1} versus 28.2 µS cm^{-1}, $t = 2.36$, $P = 0.051 > 0.05$).

5. Discussion

5.1 Lake water SSC and meltwater supply

The two peaks in the distribution of lake water SSC (Fig. 4) indicate that there are two distincitive lake types, which are the low-SSC type (0 - 10 mg l^{-1}) and high-SSC Type (> 10 mg l^{-1}). Lake water SSC was not correlated with EC or water temperature of the lakes. EC and water temperature of all the lakes were generally low, suggesting that the main source of lake water of both types was glacial meltwater. The SSC type may be due to local conditions of each lake regarding meltwater supply.

The measurement of the settling rate of suspended particles (Fig. 8) suggests that a high SSC of lake water cannot be maintained without water disturbance, and/or quick turnover of the lake water, being replaced by an appreciable supply of high SSC water. The supposed appreciable and constant supply of high SSC water is meltwater from ice cliffs and drainage water systems. The stream water and glacial ice of the ice cliffs on this glacier were found to have higher SSCs (Table 2). Since the streams were thought to be part of the glacial drainage systems, and the ice cliffs were thought to represent meltwater, these potential lake water sources may have higher SSC compared to the lake water.

The higher SSC of the lakes with diurnal water level change (*i.e.,* a suspected large supply of meltwater) relative to the lake without diurnal change (*i.e.,* a suspected scant supply of meltwater, Table 3) supports the idea that the high water SSC of lakes could be maintained by the meltwater supply. Since net radiation accounts for more than 90% of the incoming heat in Himalayan glaciers (*e.g.*, Takeuchi *et al.*, 2000) and it reaches a maximum at around noon time, the diurnal cycle of water level with a maximum in the afternoon suggests that the lakes are mainly fed by surface meltwater from their local watersheds; including the ice cliffs around the lake. The irregular diurnal pattern of the L1 water level suggests that the lake was mainly fed through drainage water systems with meltwater that originated from an area far upside the glacier. The traveling time of water through drainage water systems has been reported to vary depending on the water amount (Collins, 1995), and the water flow in drainage water systems is likely to increase suddenly due to the eventual collapse of lakes located above.

Disturbance of the lake water could be caused by wind, debris falls or inflow of water. It is unlikely that wind is responsible for maintaining SSC, since high and low-SSC lakes were located side by side (for example L3 and L4). Disturbance caused by falling debris or water inflowing from ice cliffs seemed to be more important in maintaining high SSC of the lake water. The higher turbidity of lake water near ice cliffs (*e.g.*, L18), suggests that the high SSC had been kept by disturbance from meltwater inflow and debris falling from ice cliffs into the lakes. The *in situ* measurement of ice cliff melt rates on this glacier was 7.2 cm day^{-1} (Sakai *et al.*, 1998). Debris falls from ice cliffs were often observed as ice cliff melting proceeded. The lakes that had ice cliffs or surface water flow, had significantly higher SSC than the lakes which had neither ice cliffs nor surface-water flow (62.7 mg l^{-1} versus 3.63 mg l^{-1}, $t = 3.27$, $P = 0.004 < 0.05$). This fact supports the idea that the disturbances caused by water flow and debris falls from ice cliffs could maintain high SSC levels.

These observations of water supplies and disturbances of lake water suggest that high SSC in supraglacial lakes is likely to be maintained by the following factors: (1) a large supply of high SSC water from the glacial ice surface and/or glacial drainage water system, and (2) disturbance of lake water by these water flows and/or by debris falling into the lakes from the ice cliffs. In contrast, the low-SSC type is likely to be receiving little meltwater.

5.2 Factors of spatial and temporal variations in lake water SSC

The major factor affecting variations in lake water SSC is likely to be the amount of meltwater supplied to the lakes. As suggested by Takeuchi and Kohshima (2000), the amount of meltwater supplied probably depends on the melting activity of the glacier surface around the lake. Since the thick debris inhibits glacier melting (*e.g.*, Nakawo & Young, 1981), the melting activity is likely to be related to debris thickness on the ice surface. Lakes with a large meltwater supply would be located in areas with thin debris, whereas lakes with little meltwater would be in an area with thick debris. Furthermore, lakes that have ice cliffs at their side would have an abundant meltwater supply. Thus, differing meltwater supplies among the lakes is probably due to spatial variation in debris thickness and ice cliffs on the glacier surface.

The lack of spatial trends in lake water SSC on the Lirung Glacier is probably due to distribution of debris thickness. A previous study on the Khumbu Glacier in eastern Nepal showed that low-SSC type lakes were generally distributed in the downstream area of the glacier, since the debris thickness in the area was more than 2 m on average (Takeuchi & Kohshima, 2000). On the Lirung Glacier, the distribution of low-SSC type lakes showed no such trend. They were located from the upper to the lower parts of the debris-covered area (Fig. 6). This is probably due to little area with thick debris cover of more than 2 m in the downstream area and heterogeneous distribution of debris thickness on this glacier.

The seasonal change in lake water SSC is probably explained by changes in meteorological conditions and/or debris cover and ice cliffs around the lakes. Since observations have revealed that the melting activity of this glacier is highest in the period from May to June (Rana, 1997), the meltwater supply is likely to reach a maximum in that season. Thus, surface water SSC of lakes would increase in the pre-monsoon season and then decrease after the season. The changes in lake-water SSC of L4 roughly agreed with the seasonal changes in melting activity of the glacier (Fig. 7). However, the SSC of the other lakes showed no such seasonality. In these lakes, changes in debris cover and ice cliffs are likely to be more significant compared with the meteorological conditions during the period. The average melt rate of ice cliffs was 7.2 cm day^{-1} during the monsoon season on this glacier (Sakai *et al.*, 1998). Melting of ice cliffs may significantly alter the area of ice cliffs and the morphology and distribution of debris cover, affecting the amount of meltwater supplied to the lake. Glacial flow would also change the morphology of the glacial surface. In fact, changes in debris cover and ice cliffs were ubiquitously observed during the study period. L2 was only the lake that kept a low SSC value without significant seasonal change. This lake is probably located on thick, stable debris cover. Thus, an increase of lake water SSC may be caused by the expansion of ice cliffs and/or thinning of the debris cover, whereas a decrease may be caused by a reduction of ice cliffs and/or thickening of the debris cover around lakes.

The number of lakes on the debris-covered area decreased during the study period, indicating that lakes drastically form and collapse in the melting season. Since low-SSC type lakes should be located on relatively thick debris cover, they could be expected to have a longer life span. However, the SSCs of the disappearing lakes varied widely from 2 to 89 mg l^{-1}, thus the life span of lakes appears not to be related with lake water SSC on this glacier. The distribution of the disappearing lakes and the spatial distribution of lake water SSC on this glacier indicate that most of the debris-covered area on the glacier is actively deforming during the melting season.

The living organisms found in the lakes mostly match those in supraglacial lakes on the Khumbu Glacier of eastern Nepal (Takeuchi & Kohshima, 2000). Based on the biological categories in Takeuchi and Kohshima (2000), two lakes, L2 and L3, correspond to Type A lakes (lakes with animals (the midge) and algae), eight lakes to Type B lakes (with animals (the midge) only), and the others to Type C lakes (without living organisms). The lake water SSCs of each lake type are consistent with the previous finding on the Khumbu Glacier: a lower SSC supports Type A and a higher SSC, Types B and C (Table 1). Only two Type A lakes existed on the Lirung Glacier (14 lakes on the Khumbu Glacier in contrast), suggesting that a thick, stable debris cover, which allows inhabitation by diverse organisms, is limited on the Lirung Glacier.

6. Conclusions

Measurements of the settling rate of suspended particles and water level changes of supraglacial lakes in the debris-covered area of the Lirung Glacier revealed that a high SSC level in supraglacial lakes is likely to be maintained by an abundant supply of high-SSC meltwater from the glacial ice surface and/or glacial drainage water system, and/or disturbance of lake-water by these water flows and/or by debris stones falling into the lakes from the ice cliffs. In contrast, the low-SSC type is likely to receive little meltwater. No clear trend in spatial variation in lake water SSC was found, suggesting a heterogeneous distribution of debris thickness and ice cliffs on this glacier. Lake water SSC also varied seasonally and it is probably explained by changes in meteorological conditions and/or debris cover and ice cliffs around the lakes.

A positive relationship between SSC and meltwater supply implies that supraglacial lakes can be distinguished by lake water turbidity between lakes with and without meltwater supply. Turbid lakes and non-turbid lakes can be regarded as those supplied with meltwater and those supplied with little meltwater, respectively. The availability of lake turbidity would enable quicker and safer determinations of meltwater supply of lakes via remote-sensing techniques, and may be useful for elucidating the status of supraglacial lakes and glacier melting. For example, the turbidity of lakes can be used as an indicator of probability of lake expansion. The expansion of supraglacial lakes may occur more in highly turbid cases (meltwater-supplied lakes) relative to non-turbid lakes (no meltwater supply), because lake expansion results from a large water supply to the lakes, and/or from melting of glacier ice at the side and bottom of the lakes (Chikita *et al*., 1997). Furthermore, lake-water turbidity may be used as a rough indicator of melting activity on debris-covered glaciers. Distribution of turbid lakes may indicate a melting area on a debris-covered surface, because the meltwater supply to the lakes may be the result of melting activity around the lake, except for lakes fed with englacial water systems. Thus, turbidity of supraglacial lakes may be a useful indicator of rough melting conditions of debris-covered areas.

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