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Surface flow on the ablation area of the Lirung Glacier in Langtang Valley, Nepal Himalayas

Nozomu NAITO[1], **Masayoshi NAKAWO**[1], **Tatsuto AOKI**[2], **Katsuhiko ASAHI**[3]*, **Koji FUJITA**[1], **Akiko SAKAI**[1], **Tsutomu KADOTA**[4], **Takayuki SHIRAIWA**[5] **and Katsumoto SEKO**[1]
1 Institute for Hydrospheric-Atmospheric Sciences, Nagoya University, Nagoya, 464-8601 Japan
2 Department of Geography, University of Tokyo, Tokyo, 113-0033 Japan
3 Department of Geography, Tokyo Metropolitan University, Hachioji, Tokyo, 192-0397 Japan
4 MTS Institute Inc., Sudachokosaten Bldg., 1-5 Kanda Sudacho, Chiyoda-ku, Tokyo, 101-0041 Japan
5 Institute of Low Temperature Science, Hokkaido University, Sapporo, 060-0819 Japan

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Abstract

Surface flow velocities on the ablation area of the Lirung Glacier were calculated from the results of six surveys since 1989 to 1996. The annual flow speeds were about 6 m a^{-1} on the upper part of the ablation area near the icefall and the summer speeds were about one and half times faster than that. Around 2 km downstream from the upper part, the annual speeds decreased to about 2 m a^{-1} and the summer speeds were a little faster than that.

Ice thickness was estimated, using the laminar flow theory, to be about 100 m or more than that in the upper part and about 50 m in the lower part of the ablation area. The rate of surface lowering was also preliminarily estimated, using the continuity equation, to be a little less than 20 cm a^{-1} on the average in the ablation area.

1. Introduction

Variations of mountain glaciers in the world are important for assessing the change in global sea level (Meier, 1984). Glaciers in the Himalayas, especially are considered much sensitive to the recent global warming due to their characteristics of much summer accumulation (Ageta and Kadota, 1992). Quantitative studies on the glacier variations in the Himalayas are thus important and required for examining the effect to global sea level change, the interaction between glacier variation and climate change, and the change in local water resources. Because most of large glaciers are covered with debris on their ablation area and the debris-covered glaciers account for most of glacier area in the Himalayas, it is necessary to know particularly about the debris-covered glaciers for discussing the whole glacier variation in the Himalayas.

Studies of glacier flow and glacier dynamics are essential to quantitative studies on the glacier variations, because the variations in surface profiles and terminal positions of glaciers are controlled by not only the changes in glacier mass balance but also processes of glacier flow. Direct measurements of glacier flow, however, are so difficult in the Himalayas due to the circumstances such as remoteness and high altitude that there have been only several measurements so far. Measurements of flow on debris-covered glaciers in Nepal Himalayas, particularly have been made only on the Khumbu and the Nuptse Glaciers (Kodama and Mae, 1976).

This study presents results of flow measurement made on the Lirung Glacier, which was the third example for debris-covered glaciers in Nepal Himalayas. The Lirung Glacier is located in Langtang Valley, about 60 km north from Kathmandu, the capital city of Nepal, as shown in Fig. 1. The flow

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*Present address : Laboratory of Geoecology, Hokkaido University, Sapporo, 060-0810 Japan

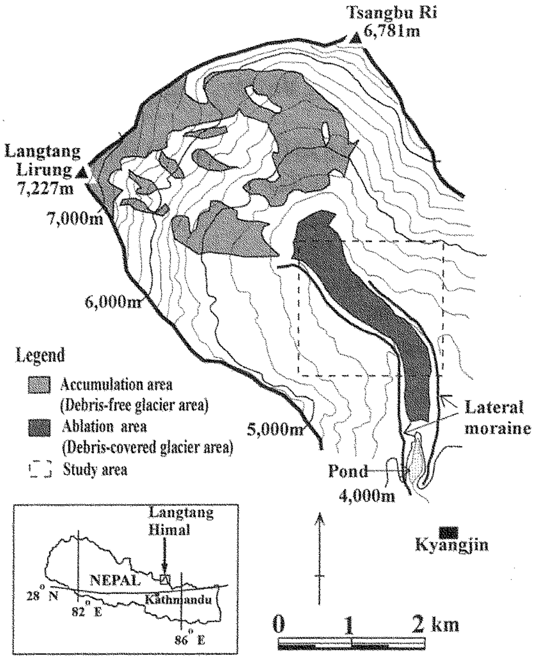

Fig. 1. Topographical map and location of the Lirung Glacier.

velocities were deduced from six surveys on the ablation area of the Lirung Glacier since 1989 to 1996.

In addition in this study, ice thickness in the Lirung Glacier, which is indispensable for model studies of glacier variation, is estimated from the obtained flow velocities, using the laminar flow theory. The rate of surface lowering, which is the result of ablation compensated by the emergence velocity due to compressing flow and exact direct measurement of which is very difficult because of the effect of flow and the very rugged surface topography, is also preliminarily estimated on the average in the ablation area from the flow velocities and the ice thickness, using the continuity equation.

2. Surveys

A topographical map of the Lirung Glacier is shown in Fig. 1. The ablation area of the Lirung Glacier is separated from the steep accumulation area and glacier ice is supplied from the accumulation area to the ablation area not by the continuous glacier flow but by avalanches over the icefall. Six surveys carried out on the Lirung Glacier since 1989 to 1996 were limited only on the ablation area because of the danger of avalanches as well as the steepness in the accumulation area. Table 1 shows the time of the surveys as well as the surveyed sites. The "upper", "middle" and "lower" parts are described as the relative location only in the ablation area. Surface markers, such as stakes and bolts, were fixed on the supraglacial debris, and they were surveyed twice or more times with a certain time interval. Total number of the markers was thirteen. Each survey was not carried out on all the markers. The number of the effective surveyed points, N in Table 1, means the number of the markers surveyed at each time.

Every survey was carried out with a theodolite and a laser distance meter at a bench mark fixed on the ridge of lateral moraine and with a mirror at markers on the glacier surface. At the bench mark, the horizontal angle between the directions to another bench mark and to a marker was measured. The instruments used at the surveys are also described in Table 1. The minimum reading units in angle of the theodolites were one second or less than that, and those in distance of the distance meters were all 1 mm, which lead to the reading errors in the surveys as less than 4 mm. But, with an uncertainty in setting the instruments at bench marks or markers, the total accuracy of a marker position is considered as less than 10 cm.

Table 1. Surveys for flow measurements on the ablation area of the Lirung Glacier. The site indicates the relative location only in the ablation area, N means the number of the effective surveyed points, and the instrument is that used at each survey.

Time		Site	N	Instrument
I	7 Dec. 1989	the lower part	6	Wild T2
II	21 Jul. 1994	the upper part	5	Wild T1600
III	4 Sep. 1994	the upper part	5	Wild T1600
IV	18 Jun. 1995	the lower part	1	Wild T2
V	31 May–19 Jun. 1996	the middle to the lower parts	7	SOKKIA SET2000
VI	16–20 Oct. 1996	the upper to the lower parts	10	SOKKIA SET2000

3. Results and discussions

3.1. *Spatial distribution of flow velocities*

Horizontal flow speeds at the thirteen surface markers are summarized in Table 2 by compiling the results of the six surveys. The distributions of the horizontal flow velocities are shown in Fig. 2. According to the periods between the surveys, both of the flow speeds and the velocities are classified to the annual ones or the summer ones. All the speeds were converted simply to meter per year for comparison, though the summer flow speeds were evaluated for only several months.

As all the markers were fixed to supraglacial debris, vertical displacements of the markers consisted of three components, the melting of ice under the debris, the emergence velocity due to compressing flow, and the downward displacement by the glacier movement according to the surface slope. In this subsection, only horizontal flow velocities are presented mainly because accurate estimation of the melting under the debris at each of the markers is very difficult. The vertical displacement of glacier surface is discussed in the later subsection in terms of the average rate of surface rising or lowering.

The flow speeds on the upper part were about 6 m a^{-1} on annual average and about 9 m a^{-1} in summer, that is, about one and half times of the annual average. On the other hand, around the center (L2 ~ L5) on the lower part, about 2 km downstream from the upper part, the flow speeds were only about 2 m a^{-1} on annual average and a little faster than that in summer. The lower part in the ablation area has been supposed to be a stagnant ice area (Shiraiwa and Yamada, 1991), but the result indicates that the ice flows even there. It is reasonable, in the ablation area, that flow speed decreases as going downstream, *i.e.*, compressing flow.

It is often observed that flow speed decreases from the center toward the lateral margin because of the drag of the lateral wall (Nye, 1965 ; Raymond, 1971). This feature is seen on the lower part (Fig. 2a), but not found on the upper part (Fig. 2b) probably because no marker was installed at sites sufficiently near the lateral margin on the upper part.

The annual velocities at L1, L6 and the summer ones at M1, M2, L6, which are located near the lateral margins, have transversal components toward the

Table 2. Horizontal flow speed (m a^{-1}) on the ablation area of the Lirung Glacier. Periods in brackets indicate the measured period. The initial character of a marker's name indicates the relative location in the ablation area (U : the upper, M : the middle, L : the lower part). The latter of the name is numbered laterally from the right bank to the left in the upper and the lower parts, or longitudinally downstream in the middle part. Markers are stakes on supraglacial debris in the upper and the middle parts, and bolts on the debris rocks in the lower part.

a. The upper part

Marker	Annual speed [4 Sep. 1994-16 Oct. 1996]	Summer speed [21 Jul. 1994-4 Sep. 1994]
U1	6.0	9.7
U2		9.0
U3		8.8
U4	5.7	9.2

b. The middle part

Marker	Summer speed
M1	2.8 [21 Jul. 1994-4 Sep. 1994]
M2	6.3 [19 Jun. 1996-17 Oct. 1996]
M3	7.5 [31 May. 1996-20 Oct. 1996]

c. The lower part

	Annual speed		Summer speed
Marker	[7 Dec. 1989-20 Oct. 1996]	[18 Jun. 1995-11 Jun. 1996]	[11 Jun. 1996-20 Oct. 1996]
L1	0.8		
L2	2.0		2.1
L3	1.8		1.9
L4	1.7		2.0
L5	2.1	2.2	2.5
L6	1.0		2.0

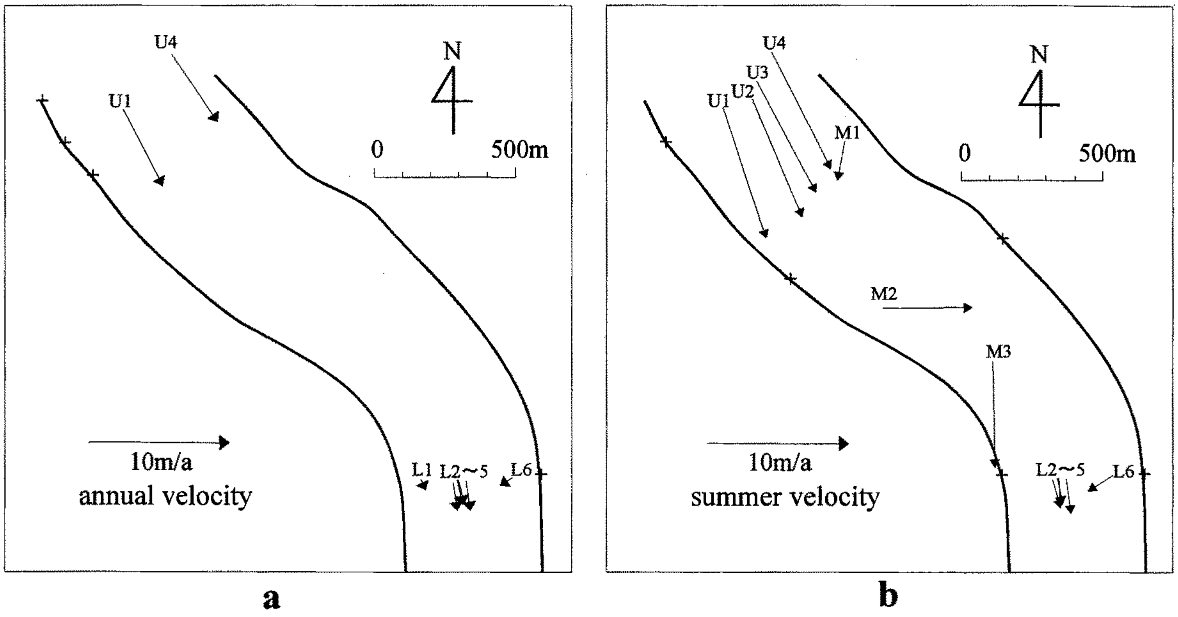

Fig. 2. Distribution of the annual (**a**) and the summer (**b**) horizontal surface flow velocities on the ablation area of the Lirung Glacier. Area of the figures are shown in Fig. 1 by a dashed frame. Two thick lines show the ridges of lateral moraines. Plus symbols on the moraines indicate the bench marks used in the surveys related to each flow measurement.

center (Fig. 2). Normal valley glaciers flow transversally toward the lateral margin in the ablation area (e.g. Raymond, 1971), as transversal profiles of the surfaces are convex upward (Hooke, 1998). The observed transversal direction of flow is possibly affected by the local topography as the debris-covered surface on the ablation area of the Lirung Glacier is not smooth but very rugged and complicated. Figure 3 shows a transversal surface profile on the lower part. The slope is transversally toward the center at the two markers, L1 and L6, flowing transversally toward the center.

3.2. Temporal variations of flow speeds

The summer flow speed was faster than the annual average at any marker as shown in Table 2 and Fig. 2. It suggests the seasonal variation in flow speed, which is high in summer and low in winter. It is considered as the effect of melt water to enhance the basal sliding in summer (Iken and Bindschadler, 1986).

Two annual flow speeds were obtained at L5 for different periods as shown in Table 2c, but no significant change was found. It would be difficult, however,

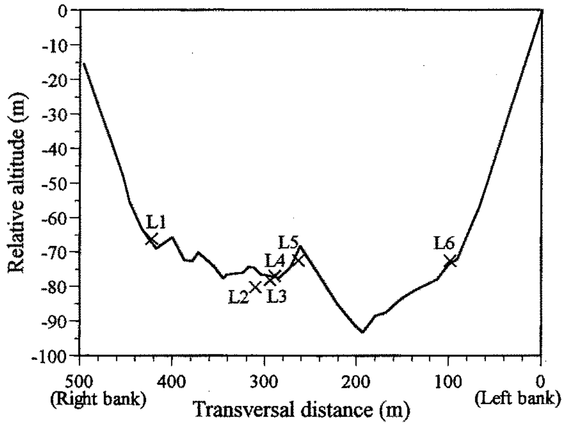

Fig. 3. Transversal surface profile on the lower part in the ablation area of the Lirung Glacier, surveyed on 11 June, 1996. Transversal distance and relative altitude on the coordinates are from the bench mark on the ridge of the left bank lateral moraine. Cross symbols indicate the markers (L1~6) used in this study for flow measurement. Steep slopes outside L1 and L6 are side walls of the lateral moraines.

to have a firm conclusion about the inter-annual variation of flow speed, as no data are available at the other sites.

3.3. *Estimation of ice thickness*

Horizontal surface flow speed consists of two components, the plastic deformation of glacier ice and the basal sliding. Assuming a laminar flow, the plastic deformation of glacier ice, U_d, is given by

$$U_d = \frac{2A}{n+1}(\rho g \sin \alpha)^n H^{n+1} \tag{1}$$

(Paterson, 1994), where H is ice thickness, α is slope of glacier surface, ρ is density of glacier ice and g is the gravitational acceleration. Then A and n are the factors in the flow law of ice, of which the former is mainly dependent on ice temperature and the latter is taken as a constant, 3. Because ice temperature in a glacier has hardly seasonal variation except in relatively thin surface layer, U_d can be regarded approximately as constant during a whole year.

If dividing a year for convenience into two seasons, summer and winter, and neglecting basal sliding in the winter,

$$U_d = U_w = \frac{U_a \Delta t_a - U_s \Delta t_s}{\Delta t_a - \Delta t_s}, \tag{2}$$

where U_w, U_s and U_a are the surface flow speeds in the winter seasonal, the summer seasonal and the annual averages, respectively. Δt_a and Δt_s are the periods of one year (365 days) and of the summer (122 days), respectively. In this calculation, the summer was defined as four months from June to September, when discharge from the Lirung Glacier was significantly greater than that in the winter (Fukushima *et al.*, 1987 ; Sakai *et al.*, 1997). The summer flow speeds, U_s, were assumed as equal to those shown in Table 2, though the periods for the evaluations are different from the summer defined in this calculation.

Using equations (1) and (2), ice thickness, H, could be calculated at the markers where both of the summer and the annual flow speeds were obtained. The value of ρ was taken as 900 kgm^{-3}. Surface slopes, α, were measured from a map of the ablation area of the Lirung Glacier compiled by Aoki and Asahi (1998). The values of A were adopted from Paterson (1994). The results are shown in Table 3 for different ice temperatures between 0 to −5°C. Ice temperature in the ablation area of the Lirung Glacier is considered to be roughly in this range from the previous studies concerning ice temperatures of other glaciers in Nepal Himalayas (*e.g.* Mae *et al.*, 1975 ; Tanaka *et al.*, 1980 ; Ozawa and Yamada, 1989). The calculation of the ice thickness resulted in about 100 m or more than that in the upper part and about 50 m in the lower part for the Lirung Glacier.

Table 3. Estimation of ice thickness, H, in the ablation area of the Lirung Glacier. Ice temperature, T_i, was assumed as a constant value throughout the whole parts in the ablation area. The factor in the flow law of ice, A, was taken from Paterson (1994) for respective ice temperature, and surface slope, α, was measured from the map (Aoki and Asahi, 1998).

Marker	H(m)					α (°)
	Estimated range	Calculated value				
		T_i (°C)	0	−2	−5	
		A (s^{-1}kPa^{-3})	6.8×10^{-15}	2.4×10^{-15}	1.6×10^{-15}	
U1	70-110		75	97	108	7.0
U4	110-170		114	148	163	3.9
L2	40-70		45	58	65	10.7
L3	30-50		33	43	48	15.4
L4	50-80		54	70	78	7.8
L5	30-50		31	41	45	17.5
L6	20-30		22	28	31	18.3

This estimation, however, is very rough, since other effects related with glacier flow as follows were not considered. The shape factor, which takes the effect of the drag from the lateral walls in a valley glaciers into account, should be in the parentheses on the right term of equation (1) (Paterson, 1994). Introducing the shape factor, which is a positive value less than one, ice thickness would be calculated as greater than the values in Table 3. The longitudinal stress gradient was also neglected in the calculation. If taking it into account, ice thickness would be obtained as less than those in Table 3 particularly in the upper part near the icefall, because strong compression should occur there. These effects, however, were not taken into consideration in the present estimation because of limited information.

3.4. *Estimation of surface lowering*

The continuity equation in a glacier is

$$\frac{\partial Q}{\partial x} + \frac{\partial S}{\partial t} = bW, \tag{3}$$

where Q is flux, S is cross-sectional area, W is width of glacier surface and b is mass balance. t is time and x is longitudinal distance positive downstream. Assuming parabolic cross-sectional shapes,

$$W = kH^{1/2}, \tag{4}$$

$$S = \frac{2}{3}WH, \tag{5}$$

$$Q = \overline{U_C}S = \frac{2}{3}r\overline{U_T}WH, \tag{6}$$

where H is the ice thickness at transversal center, k is a factor dependent only on location not on time, and r is a ratio of the flow speed averaged in cross-section, $\overline{U_C}$, to that averaged on the transversal surface line, $\overline{U_T}$. Assuming a uniform width of glacier surface ($\partial W/\partial x = 0$), which seems to be adequate for the ablation area of the Lirung Glacier, the continuity equation (3) turns out to be

$$\frac{2}{3}\frac{\partial}{\partial x}(r\overline{U_T}H) + \frac{1}{kH^{1/2}}\frac{2}{3}k\frac{\partial}{\partial t}(H^{3/2}) = b$$

$$\therefore \quad \frac{\partial H}{\partial t} = b - \frac{2}{3}\frac{\partial}{\partial x}(r\overline{U_T}H). \tag{7}$$

By the way, the value of r is considered to be nearly equal to the ratio of the flow speed averaged in the depth, $\overline{U_H}$, to the surface velocity, U, at the transversal center. Thus, using the laminar flow theory and equation (2), the ratio is given by

$$r = \frac{\overline{U_C}}{\overline{U_T}} \approx \frac{\overline{U_H}}{U} = \frac{\frac{n+1}{n+2}U_d + U_b}{U_d + U_b} = 1 - \frac{U_w}{(n+2)U_a}, \tag{8}$$

where U_b is the basal sliding.

By applying equation (7) with equation (8) to the area between the upper and the lower parts, which covers almost the whole ablation area, the rate of ice thickening, $\partial H/\partial t$, which means the rate of surface rising, can be estimated on the average in the area. In this calculation, mass balance, b, was adopted for the average on the ablation area, 35 cm a^{-1}, from an estimation with a hydrogical model of the Lirung Glacier by Rana (1997). Then the ice thickness at the transversal center, H, was taken as 110 m and 50 m on the upper and the lower parts, respectively, though the values are roughly estimated by the laminar flow approximation which, strictly speaking, contradicts the definition in this calculation. The last term in equation (7) means the effect of compressing flow to the surface rising, that is, the emergence velocity. Those components for calculation of equation (7) are shown in Table 4, where the three terms in equation (7) are each described as one value for the area, because they are treated just as the averages on the area. The result shows that about half of the ablation is compensated by the emergence velocity, and consequently, the surface is lowered with a rate of a little less than 20 cm a^{-1} on average in the ablation area of the Lirung Glacier.

For the lower part which is shown in Fig. 3, Yamada *et al.* (1992) described from comparison of the two transversal surface profiles surveyed in 1987 and 1989 that the surface did not show remarkable change ; some parts were slightly lowered and the others rose. On the other hand, Asahi (1998) indicated for the same part from comparison of the two profiles in 1989 and 1996 that the surface lowering of about 1 m a^{-1} was recognized. The result in this study cannot be simply compared with the previous ones, because the previous studies were limited only on the lower transversal line and did not handle the effects of the flow and the very rugged topography. The present result, however, must be noted to show nothing more than a rough estimation based on several assumptions. For more detailed studies on the variations of surface profile, a numerical simulation would be required in future.

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Table 4. The rate of surface rising, $\partial H/\partial t$, and the other components for the calculation for the ablation area of the Lirung Glacier. The ratio of the flow speed averaged in cross-section to the transversally average surface flow speed, $\overline{U_T}$, is represented by r. Ice thickness, H, is treated as that at the transversal center. The effect of compressing flow to the surface rising, $-\frac{2}{3}\frac{\partial}{\partial x}(r\overline{U_T}H)$, means the emergence velocity. Mass balance, b, was taken from Rana (1997).

Site	r	$\overline{U_T}$ (m a^{-1})	H (m)	$-\frac{2}{3}\frac{\partial}{\partial x}(r\overline{U_T}H)$ (m a^{-1})	b (m a^{-1})	$\frac{\partial H}{\partial t}$ (m a^{-1})
the upper part	0.86	5.9	110	0.18	−0.35	−0.17
the lower part	0.83	1.6	50			

Culture, Japanese Government.

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