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# Surface lowering over the ablation area of Lirung Glacier, Nepal Himalayas

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## Abstract

Repeated surveys for six transverse surface profiles on the debris-covered ablation area of Lirung Glacier, Nepal Himalayas, reveal that the glacier surface has lowered from 1996 to 1999. The average annual rate of the surface lowering is evaluated to be in a range from 1 to 2 m $a^{-1}$. The emergence velocity is also estimated to be about 0.2 m $a^{-1}$ on average for the ablation area, using surface flow and ice thickness data. A relation with mass balance in the continuity equation roughly supports these results. The surface lowering is suggested to have accelerated possibly since late 1980s. In addition, the lowering rate is discussed in comparison with those on other glaciers in the Nepal Himalayas.

## 1. Introduction

Sea level rise according to global warming has recently been worried as global issues. For assessing changes in the global sea level, variations of mountain glaciers are important. Glaciers in the Asian highland regions including the Himalayas, as well as in Alaska and Patagonia, are especially considered to make critical contributions to the sea level rise (Meier, 1984; Warrick *et al.*, 1996). The Himalayan glaciers are characterized by being summer-accumulation type, variations of which are much sensitive to changes in air temperature (e.g. Ageta, 1983; Naito *et al.*, 2001). Recent observations have actually clarified many glaciers in the Himalayas to be shrinking (Ageta *et al.*, 2001). Moreover, the recent shrinkages of small debris-free glaciers in the Nepal Himalayas are considered to be relatively large in the world, in relation to their mass balance amplitudes (Fujita *et al.*, 1997).

The ablation areas of most large glaciers in the Himalayas are covered with thick supraglacial debris. Shrinkages of such debris-covered glaciers have caused generation of many glacial lakes, outburst floods of which have often damaged local villages in the Himalayan countries (e.g. Yamada, 1998). It is difficult to detect the shrinkage of debris-covered glaciers, however, because the glaciers have much rugged and non-uniform surfaces and so surveys are required on wider areas than a line or points on the surface at least two times. Such detailed observations have ever been scarce in the Himalayas due to practical reasons. The only debris-covered glacier that has previously been observed for its detailed shrinkage is Khumbu Glacier, Nepal Himalayas (Kadota *et al.*, 2000). More studies have been strongly desired on the shrinkages of debris-covered glaciers in the Himalayas, because of their importance for the social problems such as the global sea level rise, the glacier lake outbursts and local water resources. The present study, thus, examines shrinkage of Lirung Glacier, another debris-covered glacier in the Nepal Himalayas, and provides the related discussions.

## 2. Surveys

The Lirung Glacier is located in Langtang Valley, about 60 km north of Kathmandu, the capital of Nepal, as shown in Fig. 1. Its accumulation area spreads on the steep slope eastward of Mt. Langtang Lirung (7227 m a.s.l.), and its debris-covered ablation area lies beneath an icefall. The accumulation area is almost impossible to access due to its steepness and frequent avalanches so that topographical surveys for evaluation of the glacier fluctuation have been limited on the ablation area.

Aoki and Asahi (1998) previously surveyed thirteen transverse profiles on the ablation area in the spring of 1996. Six profiles among them, the location of which are shown in Fig. 1, were resurveyed in the period from April 27 to May 4, 1999. In the survey, a digital theodolite and a laser distance meter (SOKKIA SET2000) were used at benchmarks, which had been fixed on steady rocks on the lateral moraine ridges, and a mirror was at surveyed points on the glacier

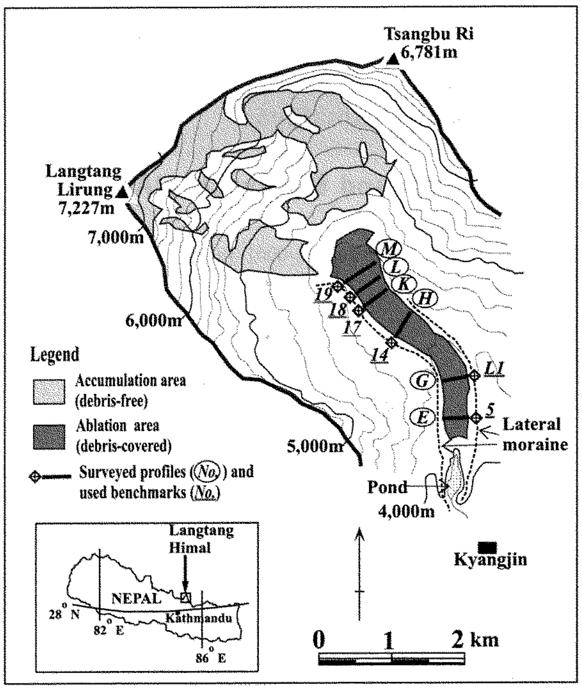


Fig. 1. Topographic map and location of the Lirung Glacier. Names of the surveyed transverse profiles and the used benchmarks correspond to Aoki and Asahi (1998).

surface. The surveyed points in 1999 amounted to 165 in total, which resulted in 27.5 points along each transverse profile on average, and the average spacing of the points was 14.2 m. The resurvey in 1999 was carried out on each transverse profile along a specific horizontal direction from the same benchmark for the 1996 survey as described in Aoki and Asahi (1998, Table 2). Using the survey data in the spring of 1996 and 1999, we examined the changes in the six transverse profiles during the three years.

## 3. Results

The surveyed profiles of the six transverse lines in 1996 and 1999 are shown in Fig. 2, and the annual rate of vertical change in the profiles during the period are calculated as shown in Fig. 3. Here, the shaded parts of the profiles in Fig. 2 have been omitted in the calculation for the annual rate in Fig. 3. The shaded lateral parts except a middle part of the Profile K are not glacier surface but side slopes of the lateral moraines. The middle part of the Profile K could not be surveyed due to topographical invisibility

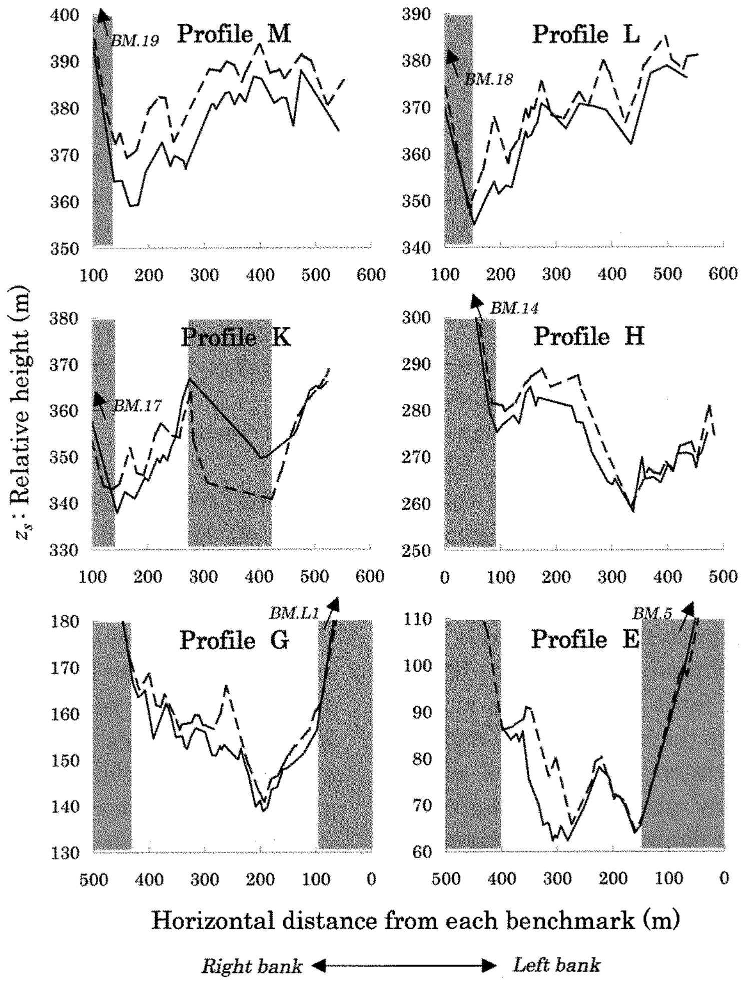


Fig. 2. Changes of the six transverse profiles on the ablation area of the Lirung Glacier. Locations of the profiles are drawn in Fig. 1. The ordinate indicates relative height from the base point installed by Aoki and Asahi (1998), the altitude of which was estimated to be about 3974.5 m a.s.l. Solid and dashed lines represent the profiles in the spring of 1999 and 1996, respectively. Shaded steep parts near lateral ends show side walls of the lateral moraines, which are not glacier surface. The other shaded part in middle of Profile K was topographically invisible from the benchmark. These shaded parts are ignored in calculation for Fig. 3 and Table 1.

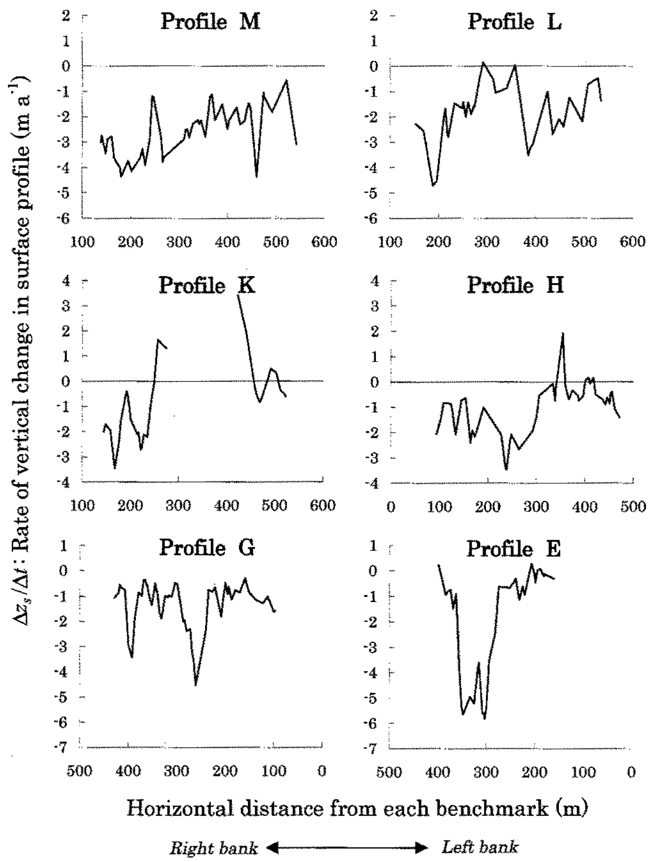


Fig. 3. Distributions of annual rate of vertical change in the six surface profiles during 1996 to 1999. The rate was calculated from the surveyed profiles shown in Fig. 2, and a negative value means surface lowering.

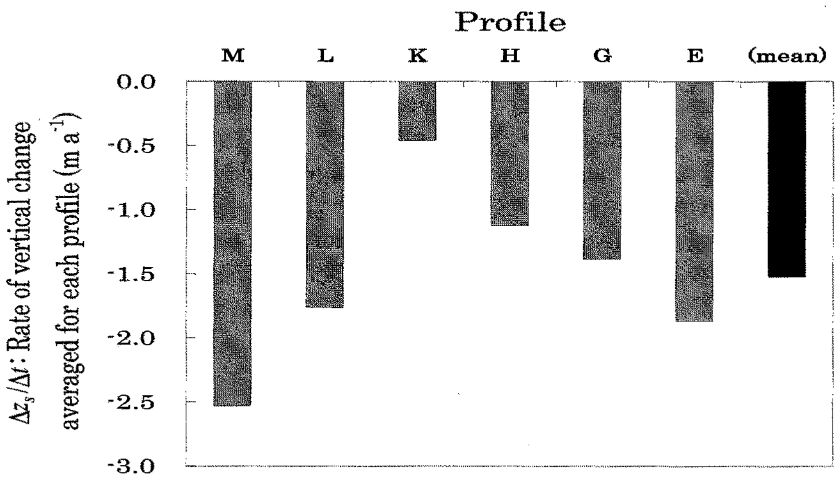


Fig.4. The annual rate of vertical change averaged for each transverse profile, same as compiled in Table 1.

Table 1. Vertical change averaged for each transverse profile on the ablation area of the Lirung Glacier. The symbol of $\Delta t$ indicates the period between the surveys in 1996 and 1999. The $\Delta z_s$ and $\Delta z_s/\Delta t$ represent the amount and the rate of the vertical change, respectively, negative sign of which means surface lowering.

| Profile | $\Delta t$ (day) | $\Delta z_s$ (m) | $\Delta z_s/\Delta t$ (m a$^{-1}$) |
|---|---|---|---|
| M | 1070 | −7.42 | −2.53 |
| L | 1069 | −5.16 | −1.76 |
| K | 1070 | −1.36 | −0.46 |
| H | 1071 | −3.30 | −1.12 |
| G | 1056 | −4.00 | −1.38 |
| E | 1048 | −5.36 | −1.87 |
| mean | | −4.43 | −1.52 |

from the benchmark. Surface lowering during 1996 to 1999 is seen on average for each profile, although some points appear to have moved upward. As the debris-covered surface is much rugged, the points moving apparently upward should be caused by convex surfaces flowing from upstream parts. Because such a rugged surface flows, it is difficult to discuss the precise changes of each surface profile in this study.

The vertical change on each profile was averaged, as shown in Fig. 4 and compiled in Table 1. In the averaging, taking inconstant spacing of the surveyed points into consideration, the vertical change was integrated along transversal direction and then divided by the horizontal distance. Figure 4 and Table 1 reveal that the average rate of surface lowering on each transverse profile ranges roughly from 1 to 2 m a$^{-1}$, the mean value of which is 1.5 m a$^{-1}$.

## 4. Discussions

Considering glacier ice to be incompressible, changes in surface level of a glacier can be expressed by the following continuity equation;

$$\frac{\partial H}{\partial t}=b-\frac{1}{W}\frac{\partial Q}{\partial x}, \tag{1}$$

where $H$ is glacier thickness, $b$ is mass balance in ice equivalent, $W$ is glacier width, $Q$ is ice flux through a transverse cross-section, and $x$ indicates longitudinal distance positive downstream. The last term in Eq. (1) represents that compressive/extensive flow causes to increase/decrease glacier thickness. This effect is so called emergence/submergence velocity. Glacier flow on an ablation area is normally compressive. Naito *et al.* (1998) have previously estimated the emergence velocity, $w_e$, on the ablation area of the Lirung Glacier from surface flow measurements, using by the following equation.

$$w_e=-\frac{1}{W}\frac{\partial Q}{\partial x}=-\frac{2}{3}\frac{\partial}{\partial x}\left[H\left(U_a-\frac{1}{n+2}U_w\right)\right] \tag{2}$$

where $U_a$ and $U_w$ indicate transversally averaged flow speeds on glacier surface in a whole year and winter season, respectively, and $n$ is a parameter in the flow law of ice, which is generally considered to be 3. The required assumptions to obtain Eq. (2) are; a parabolic shape of a transverse cross-section, a uniform surface width, a laminar flow and a negligible basal sliding in winter season (Naito *et al.*, 1998). For glacier thickness, $H$, in Eq. (2), using its measurement with radio echo-soundings by Gades *et al.* (2000) instead of its estimate from laminar flow theories, we revised the previous estimate of the emergence velocity by Naito *et al.* (1998) as seen in Table 2. The revision leads to about 0.2 m a$^{-1}$ of the emergence velocity on average for the ablation area of the Lirung Glacier, which does not much differ from the previous estimate.

Table 2. Estimation of emergence velocity, $w_e$, on the ablation area of the Lirung Glacier, based on Eq. (2). Glacier thickness, $H$, is given after radio echo-soundings by Gades *et al.* (2000). Transversally averaged surface flow speeds, $U_a$ in a whole year and $U_w$ in winter, are referred from the measurements and estimates, respectively, by Naito *et al.* (1998), who defined the winter to be non-monsoon season from October to May. The symbol of $\Delta x$ denotes longitudinal distance along the central flow line.

| Profile | $H$(m) | $U_a$(m a$^{-1}$) | $U_w$(m a$^{-1}$) | $\Delta x$ (m) | $w_e$(m a$^{-1}$) |
|---|---|---|---|---|---|
| M | 160 | 5.9 | 4.0 | 1810 | 0.24 |
| G | 90 | 1.7 | 1.5 | | |

In the continuity equation, the present result of the mean $-1.5$ m a$^{-1}$ for the change in surface level and the revised estimate of about 0.2 m a$^{-1}$ for the emergence velocity should lead to about $-1.7$ m a$^{-1}$ for the mean mass balance on the ablation area of the Lirung Glacier. On the other hand, Rana (1997) calculated the melting averaged on the ablation area to be about 1.2 m in a monsoon season with a hydrological model of the Lirung Glacier. Naito *et al.* (1998) previously cited this value to be $-0.35$ m, but the citation has been found to be incorrect, and here, we correct the value. As accumulation should be negligible on the debris-covered area and additional ablation could be occurred in non-monsoon season, the annual mass balance rate would be considered to be less than $-1.2$ m a$^{-1}$ on the ablation area. The discrepant mass balance of $-0.5$ m a$^{-1}$ between this value ($-1.2$ m a$^{-1}$) and the present result ($-1.7$ m a$^{-1}$) might be attributed to the additional ablation in non-monsoon season that was excluded in Rana (1997)'s calculation. As the discrepancy is small compared with the resulted range of surface lowering in the present study, however, the present result could not conflict with Rana (1997)'s calculation. After all, a relation in the continuity equation would suggest the present evaluation of the surface lowering and the emergence velocity to be roughly adequate.

Yamada *et al.* (1992) previously tried to detect changes in surface level on the Profile G from surveys in 1987 and 1989, but could not obtain remarkable ones. Asahi (1998), on the other hand, recognized a surface lowering rate of about 1 m a$^{-1}$, for the same profile from surveys in 1989 and 1996. These previous results should be noted that the survey interval by Yamada *et al.* (1992) might be not sufficiently long and that both the previous studies were limited on only one transverse profile. These previous results and the present one, nevertheless, would suggest a possibility that the glacier would have turned from a stationary state in the late 1980s to a shrinking one in the 1990s and the shrinkage would have been accelerated during the 1990s. If this acceleration tendency of the glacier shrinkage is actual, it would correspond to those observed for other glaciers in the Nepal Himalayas during the 1990s; that on the debris-covered ablation area of Khumbu Glacier (Kadota *et al.*, 2002) and those on three small debris-free glaciers (Fujita *et al.*, 1998, 2001a, 2001b). As the previous studies for the Lirung Glacier include the above-mentioned problems, however, the tendency of glacier shrinkage for the Lirung Glacier needs to be carefully reconfirmed.

Table 3 summarizes the surface lowering rates observed on glaciers in the Nepal Himalayas. The present result for the Lirung Glacier seems similar to the rate obtained for the Khumbu Glacier. Then, simple comparison with the rates measured for the other three debris-free glaciers would imply that those for both the debris-covered Lirung and Khumbu Glaciers might be rather rapid in the 1990s. An attention should be paid, however, to that the rates for the debris-covered glaciers are evaluated only on their

Table 3. Comparison of annual rates of surface lowering observed on glaciers in the Nepal Himalayas. The lowering rates are shown in ice equivalent. Code letters for the glacier type of D and C mean debris-covered and debris-free (clean type) glaciers, respectively. Numbered remarks indicate kinds of the targeted areas where the surface lowering was detected as;
*1 : only a part of ablation area,
*2 : ablation area,
*3 : whole glacier area including accumulation area.

| Glacier name | Period | Annual rate of surface lowering (m $a^{-1}$) | Glacier type and remarks | Data source |
|---|---|---|---|---|
| Lirung | 1987-1989 | (not remarkable) | D, *1 | Yamada *et al.* (1992) |
| | 1989-1996 | about 1 | D, *1 | Asahi (1998) |
| | 1996-1999 | 1-2 | D, *2 | this study |
| Khumbu | 1978-1995 | 0.3-1.1 | D, *2 | Kadota *et al.* (2000) |
| | 1995-1999 | about 2 | D, *1 | Kadota *et al.* (2002) |
| AX010 | 1978-1991 | 0.75 | C, *3 | Kadota (1997) |
| | 1991-1996 | 1.21 | C, *3 | Kadota (1997) |
| | 1996-1999 | 0.86 | C, *3 | Fujita *et al.* (2001a) |
| Yala | 1982-1994 | 0.31 | C, *3 | Fujita *et al.* (1998) |
| | 1994-1996 | 1.05 | C, *3 | Fujita *et al.* (1998) |
| Rikha Samba | 1974-1994 | 0.63 | C, *3 | Fujita *et al.* (1997) |

ablation areas. For more exact comparison and general discussion on the glacier shrinkage in the Himalayas, the states on accumulation areas of large debris-covered glaciers should be taken into consideration.

## 5. Concluding remarks

A surface lowering was detected on the debris-covered ablation area of the Lirung Glacier, Nepal Himalayas from 1996 to 1999. Its annual rate was evaluated to be in a range from 1 to 2 m $a^{-1}$. Using the previous measurements of surface flow speeds and ice thickness, an estimate of emergence velocity on the ablation area was revised to be about 0.2 m $a^{-1}$. These results of the surface lowering and the emergence velocity could be roughly supported through a relation with mass balance in the continuity equation. Then the surface lowering might be accelerated since the late 1980s, though the acceleration tendency should be carefully verified. The rate of surface lowering on the ablation area of the Lirung Glacier seemed to be similar to that for Khumbu Glacier, another debris-covered glacier in the Nepal Himalayas. Moreover, a simple comparison with the rates for small debris-free glaciers in the Nepal Himalayas could classify those for the two debris-covered glaciers as relatively rapid.

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