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Some shrinking features in the uppermost ablation area of the Khumbu Glacier, east Nepal, 1995-1999

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Abstract

An accelerated surface lowering of the Khumbu Glacier, one of debris-covered glaciers in the Nepal Himalayas, was detected by repeated mappings in the uppermost ablation area of the glacier. The surface lowered at a rate of about 2 m a^{-1} in 1995-1999 whereas about 1 m a^{-1} in 1978-1995. Mean ice flow velocity decreased to about 18 m a^{-1} in 1995-1999 from about 26 m a^{-1} in 1987-1995. Using ice thickness data and flow velocity in 1999, annual ablation over the respected area was roughly evaluated to be about 3.5 m a^{-1}. This value was almost compatible to the value obtained by *in-situ* observation in the late 1970s. Decrease of influx of ice from the upglacier was suggested as a possible cause of recent accelerated surface lowering.

1. Introduction

Shrinkage of the Khumbu Glacier from 1978 to 1995 was reported by Kadota *et al.* (2000). They found that the surface lowered overall of the ablation area. Glaciological Expedition in Nepal (GEN) in 1999 conducted radio-echo soundings and additional topographic mapping in the ablation area. This paper describes changes in uppermost ablation area of the Khumbu Glacier that were observed by the most recent mapping.

2. Physical setting

Khumbu Glacier is situated in the Khumbu region, east Nepal (Fig. 1). The glacier starts from the basin surrounded by Mt. Sagarmatha (Mt. Everest, 8848 m), Lhotse (8511 m) and Nuptse (7861 m). The equilibrium line lies around 5600 m within the icefall and supraglacial debris appears at the foot of the icefall with increasing thickness towards the terminus. The distance from the foot of the icefall to the terminus is about 10 km. The area studied is the uppermost part of the ablation area (named as Area IV by Watanabe *et al.* 1980). This area is characterized by a transitional change from ogive form to ice pinnacle row (Fig. 1).

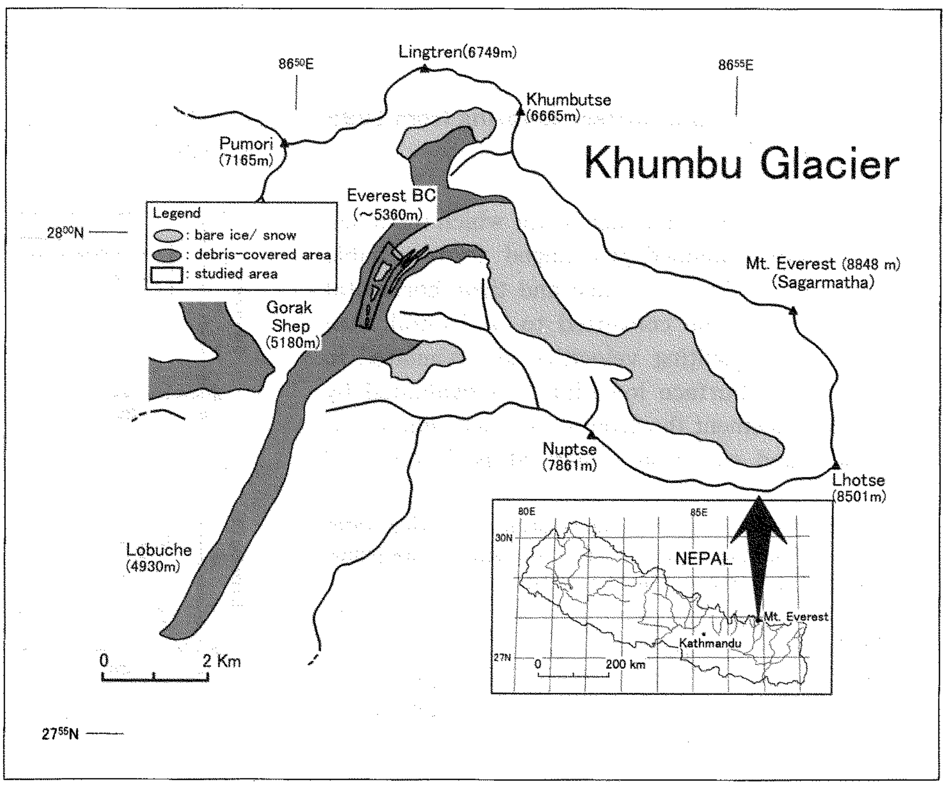

Fig. 1. A map of the Khumbu Glacier. The location of the studied area is shown.

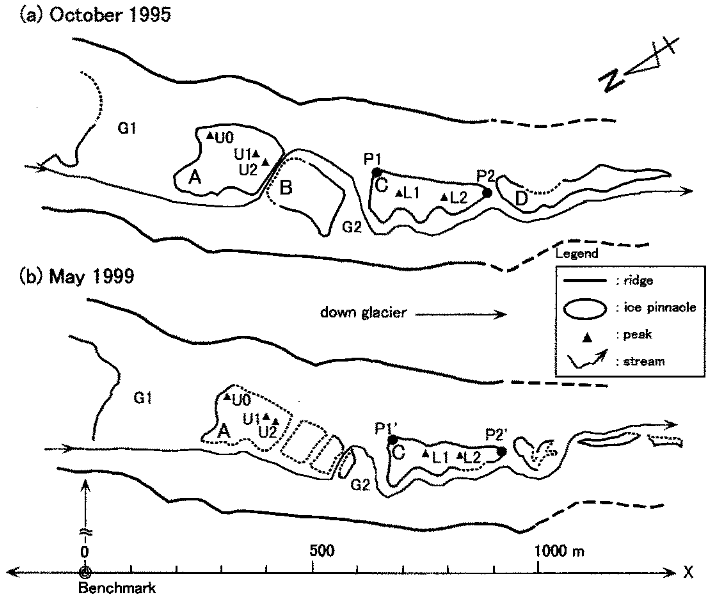

Fig. 2. Maps of the ice pinnacle zone in the Khumbu Glacier, (a) in 1995, (b) in 1999. A to D and U0 to L2 denote the ice pinnacles and peaks surveyed respectively. G1 and G2 are gaps in the ice pinnacle row. The scale bar also represents an abscissa of the coordinates positive downglacier. The origin of the coordinates is the benchmark on the crest of the right lateral moraine.

3. Survey

Surveys were made using various theodolites and electronic distance meters. Margins of ice pinnacles and longitudinal ridges were surveyed by traverses in 1995 and in 1999. Results of mapping are shown in Fig. 2. Horizontal displacements of ice pinnacles are clearly seen. A total of five peaks of ice pinnacles were located relative to the benchmarks on the crest of the right lateral moraine by triangulation in 1996 and 1999 (Fig. 2).

4. Results for flow and surface lowering from 1995 to 1999

The peaks and ice pinnacle C for which the longitudinal length remained unchanged form reliable markers on the glacier surface and their horizontal displacements can be converted to horizontal flow velocities. The resulting velocities are tabulated in Table 1 and 2. Surface lowering was evaluated by vertical displacement (horizontal displacement x surface slope) and elevation change at each surveyed point. Surface slope was read from a topographical map at a scale 1/50000 (National Geographic Magazine, 1988) to be 60/1000. The surface lowered at an average rate of about 2 m a^{-1} between 1995 and 1999 (Table 1 and 2). Figure 3 shows surface lowering distributions along the margins of the ice pinnacles (a)

Table 1. Horizontal velocities and surface lowering rates obtained from the displacements of the peaks of ice pinnacles. (period: October 1996-May 1999)

Peak	Horizontal velocity (m a^{-1})	Lowering rate (m a^{-1})
U0	17.5	1.8
U1	17.5	1.9
U2	17.4	1.4
L1	15.2	2.1
L2	16.8	1.9

Table 2. Horizontal velocities and surface lowering rates obtained from the displacements of the ice pinnacle C. (period: October 1995-May 1999)

Position	Horizontal velocity (m a^{-1})	Lowering rate (m a^{-1})
P1	17.8	2.1
P2	17.9	1.9

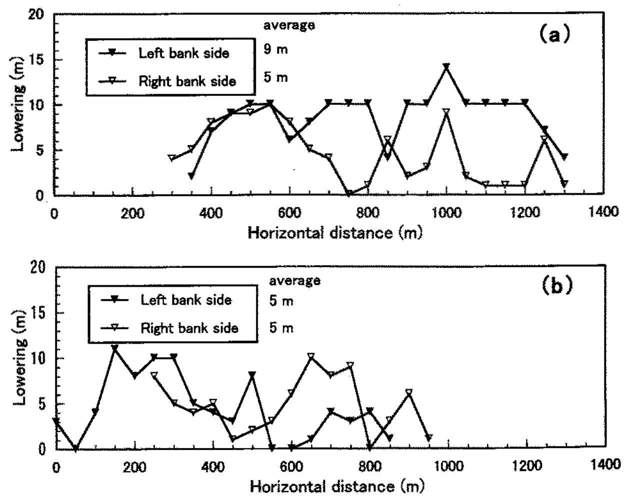

Fig. 3. Surface lowering distributions during 1995-1999, (a) along the edges of the ice pinnacles, (b) along the ridges beside the ice pinnacle row.

and along the ridges beside the ice pinnacle row (b). The surface lowered by about 5 to 9 m on average from 1995 to 1999, which resulted in lowering at a rate of 1.4 to 2.5 m a^{-1} on average.

5. Discussion and concluding remarks

5.1. Ice flow

Seko *et al.* (1998) obtained ice velocities in the ice pinnacle zone using satellite images in 1987 and 1995. Figure 4 shows the longitudinal distribution of average flow speeds in the ice pinnacle zone for the period 1987-1995 (after Seko *et al.*, 1998. Fig. 8. modified), 1995-1999 and 1996-1999. It is obvious that flow speed has decreased over the last decade.

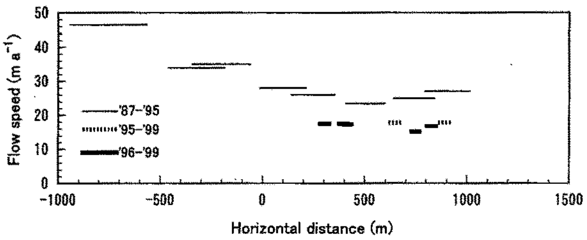

Fig. 4. The longitudinal distributions of the mean ice flow speeds in the ice pinnacle zone of the Khumbu Glacier for the period 1987-1995 (thin solid lines, after Seko *et al.*, 1998, modified), 1996-1999 (thick solid line) and for 1995-1999 (dotted lines). The abscissa is same as that in Fig. 2.

5.2. Thinning rate of ice

Kadota *et al.* (2000) obtained the surface lowering over the ice pinnacle zone by comparing the average elevations in 50 m x 50 m mesh area in the maps prepared by the surveys in 1978 and in 1995. Resulting average lowering rates in 1978-1995 and those in 1995-1999 are tabulated in Table 3. It can be concluded that thinning of ice has accelerated.

Table 3. Mean surface lowering rates along the ice pinnacle row during the periods 1978-1995 and 1995-1999.

Period	Left bank side (m a^{-1})	Right bank side (m a^{-1})
'78-'95	0.35	1.1
'95-'99	1.4-2.5	1.4

5.3. Ablation over the ice pinnacle zone

Annual ablation rate in the area between G1 and G2 was roughly estimated to be about 3.5 m a^{-1} from the following continuity equation.

$$\Delta h/\Delta t = b + (Q_1 - Q_2)/S,$$

where $\Delta h/\Delta t$; thickness changing rate (-2 m a^{-1}), b; mass balance (m a^{-1}), Q_1; ice flux through cross-section at G1 (m^3 a^{-1}), Q_2; ice flux through cross-section at G2 (m^3 a^{-1}), S; surface area (m^2). Ice fluxes were calculated using the ice thickness data (Gades *et al.*, 2000) and surface velocity obtained in 1999, namely 358 m deep at G1, 324 m deep at G2 and 18 m a^{-1} respectively. Surface width was obtained from the map (National Geographic Magazine, 1988). In the calculation, parabolic shapes of the cross-section and 80 % of surface velocity for mean velocity were assumed. Note that mass balance in the equation can be considered to be ablation rate because accumulation there is negligible.

The average ablation rate in the ice pinnacle zone obtained by Inoue and Yoshida (1980) was 0.025 m d^{-1}, which was based on their field observation (by stake method) in whole of August 1978. If ablation takes place with this ablation rate over ablation period, from mid-May to end of September (about 140 days), resulting annual ablation rate comes 3.5 m a^{-1}. Consequently it can be considered that ablation condition in the ice pinnacle zone has not changed so much since the late 1970s.

5.4. Cause of accelerated surface lowering

Surface lowering results from either decreased influx of ice or increased ablation (or from both). The foregoing discussion may suggest that the accelerated surface lowering in the ice pinnacle zone of the Khumbu Glacier was caused by decreased influx of ice. This may also suggest decrease of mass balance (decrease in accumulation and/or increase in ablation) in the accumulation area.

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