Shrinkage of the Khumbu Glacier, east Nepal from 1978 to 1995

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Abstract Surface lowering of the Khumbu Glacier, a large debris-covered glacier in the Nepal Himalayas, was detected by means of ground surveying in 1978 and in 1995. Over this interval the surface of the glacier lowered about 10 m throughout the debris-covered ablation area. Lowering in the lowermost part of the glacier, where surface ablation may be negligible, might result from subglacial meltwater interaction. Indication that ice flow is slowing suggests that shrinkage may accelerate even if ablation conditions remain unchanged.

INTRODUCTION

Glaciers are retreating worldwide. In the Nepal Himalayas small glaciers have been shrinking since at least the late 1970s (e.g. Kadota, 1997). Small glaciers in the Himalayas are debris-free and changes in the positions of their termini are easily detected. On the other hand, ablation areas of large glaciers are covered with thick debris and the lowest parts of these glaciers are stagnant ice. Positions of their active termini are hard to define or detect. To evaluate the status of such glaciers, it is necessary to study changes in ice thickness.

The Khumbu Glacier is one of the large debris-covered glaciers in the Nepal Himalayas. In 1978 the "Debris Cover Project" (part of Glaciological Expedition of Nepal called GEN) conducted extensive studies and prepared large-scale topographic maps for four areas in the ablation area (Higuchi, 1980; Watanabe *et al.*, 1980). In 1995, a topographic survey was carried out in the same four areas as 1978, resulting in the production of new topographic maps.

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This paper describes changes in surface level in the ablation area of the Khumbu Glacier from the 1978 and the 1995 maps, and discusses its spatial pattern relevant to supraglacial debris distributions.

KHUMBU GLACIER

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 (8501 m) and Nuptse (7861 m). The equilibrium line lies around 5600 m a.s.l. 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.

Mapped areas are shown by four rectangles in Fig. 1, named sequentially from lowest to highest as I, II, III and IV. Descriptions of the areas (after Watanabe *et al.*, 1980) are as follows:

(a) *Area I*: fossil or stagnant ice area with rough surface topography; surface features with large boulder concentration and fluvial topography with partial covering of vegetation.

(b) *Area II*: the boundary zone between active and stagnant ice area; rough surface with steep ridges and troughs without water pools or glacier ponds. The most intensive subsidence of the glacier surface is in Area II, where the height difference from the crest of the lateral moraine to the glacier surface reaches a maximum of about 100 m.

(c) *Area III*: typical area of compound glacier, where one tributary glacier meets the trunk glacier, with varying roughness on different surfaces.

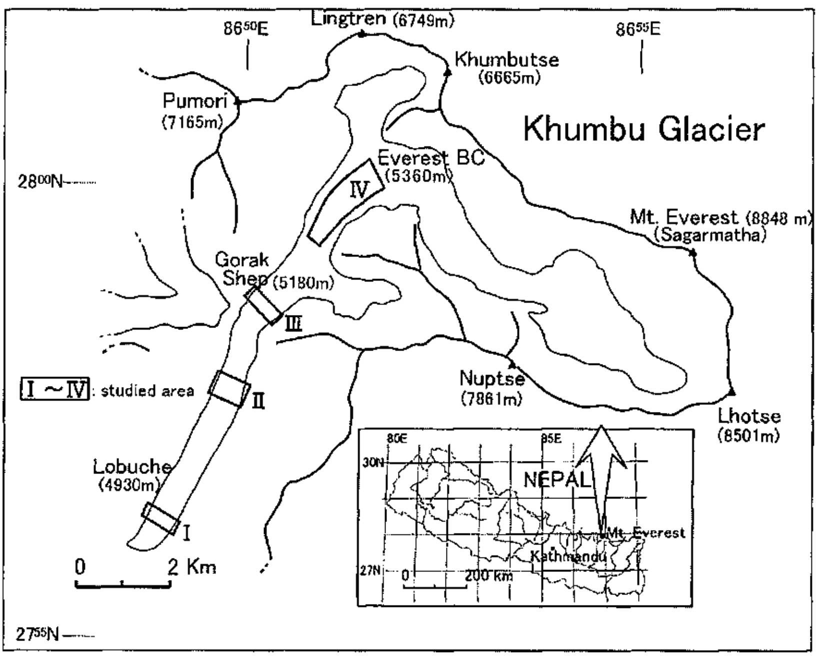

Fig. 1 Map of the Khumbu Glacier. The studied areas (I–IV) are shown by the rectangles.

(d) *Area IV*: surface topography characterized by transitional change from ogive form to ice pinnacle row. Significant debris first appears in Area IV.

SURVEYS

Data from 1978 were measured in the monsoon season (Iwata *et al.*, 1980). In Area I, Area II and Area III, contour maps were made at 1:1000 by surveying a grid with a Wild T2 theodolite and plane table. Area IV was mapped on a 1:2500 scale by tacheometry (using stadia readings). The 1995 survey used mostly the same benchmarks as in 1978. Angles and distances were measured with a theodolite (Wild T2) and an electronic distance meter (Sokkisya RED1A) as the main instruments. A transverse line set out in 1978 (*X–X'* in Fig. 2(a)) was resurveyed in Area I. In Area II ground photogrammetry was carried out. A pair of stereoscopic photographs of the area was taken from the crest of the each lateral moraine (total two pairs) using a camera (Pentax PAMS645) horizontally set on a tripod. Several ground control points together with camera positions were measured from a benchmark on the crest of the left lateral moraine. A topographic map (Fig. 3) was prepared using a plotter (Wild BC2) with contour interval 5 m (original scale 1:2000). Many locations were hidden behind high topography, especially the foot areas of the inside slopes of the lateral moraines. These areas could not be plotted. Broken lines in Fig. 3 represent hand-drawn elevations, which were approximately drawn with

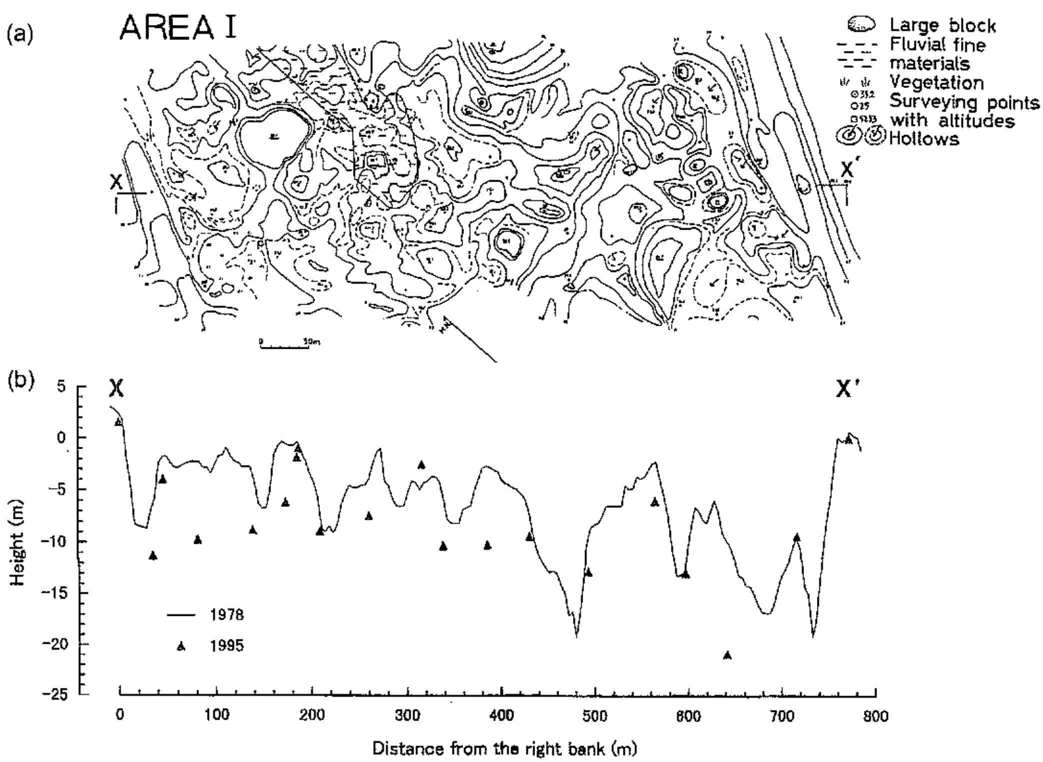

Fig. 2 (a) Topographic map of Area I in 1978 (after Watanabe *et al.*, 1980). A transverse line measured in 1978 and in 1995 is shown by *X–X'*. (b) Surface profiles along the line *X–X'* in 1978 (solid line) and in 1995 (solid triangles).

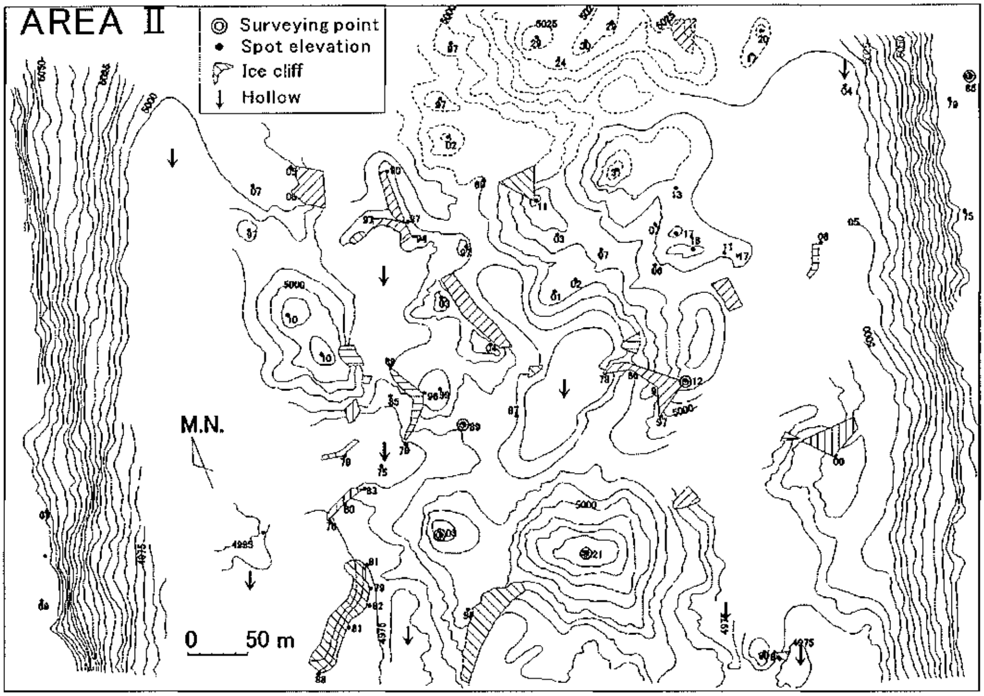

Fig. 3 Topographic map of Area II in 1995. The contour interval is 5 m. Broken lines represent hand-drawn elevations, which were not surveyed due to being hidden behind high convex topography. Solid circles show locations of spot elevations. The adjacent numbers (XX) give elevations with the following code: XX between 01 and 50 indicates 50XX m; XX between 51 and 99 indicates 49XX m. The surveying point on the crest of the left-hand lateral moraine is one of the benchmarks. Ground control points on the glacier are also shown as surveying points.

the aid of pictures taken during the survey. A survey of control points and plane table surveying were conducted in Area III. A topographic map (Fig. 4) was prepared with contour intervals of 5 m (original scale 1:2500). In Area IV traverse surveying was carried out. A topographic map (Fig. 5) was prepared with contour intervals of 10 m (original scale 1:5000). The surveyed area was limited to the lower part of the 1978 survey.

CHANGES IN SURFACE LEVEL FROM 1978 TO 1995

The surface topography of the glacier is extremely rough and evolves by both differential ablation and flow in Areas II, III and IV. Therefore, changes in surface elevations within these areas were investigated using several different statistical methods. In Area I, however, elevations along a transverse line were simply compared, because the 1995 survey showed no glacial flow in this area.

Area I

Elevations along a transverse line (*X–X′* in Fig. 2(a)) were compared. Figure 2(b) shows the surface profiles in 1978 and in 1995 along the line *X–X*. The surface level had lowered by 5–8 m on the right-hand bank.

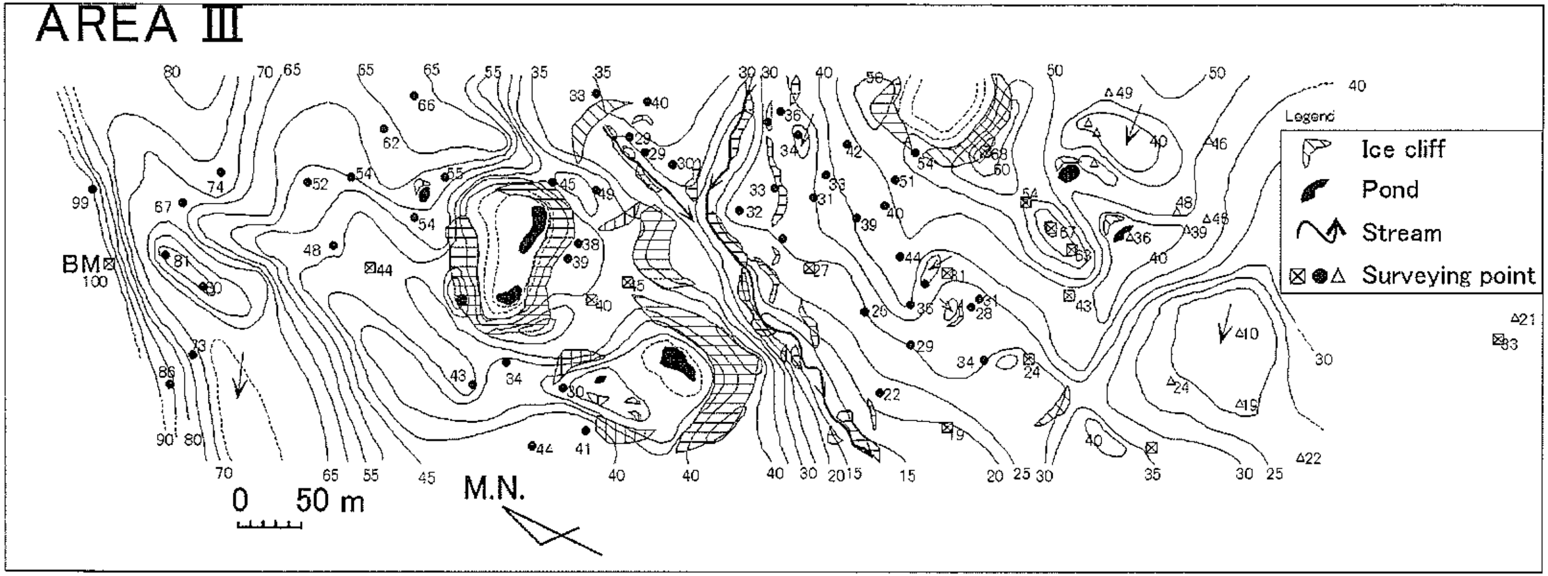

Fig. 4 Topographic map of Area III in 1995. The contour interval is 5 m. Elevations are shown according to the datum height set as 100 m at BM on the crest of the right-hand lateral moraine.

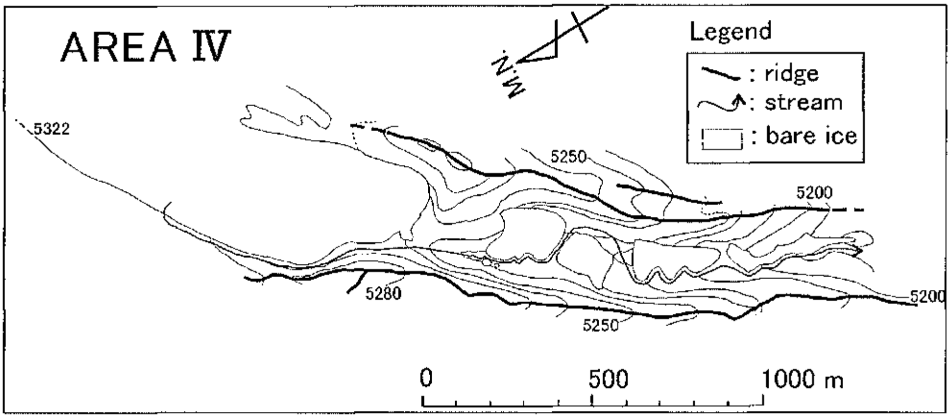

Fig. 5 Topographic map of Area IV in 1995. The contour interval is 10 m. The bare ice shown in this figure comprises ice pinnacles. The area of ice pinnacles was not surveyed.

Area II

Maximum and minimum elevations in each 50 m × 50 m mesh area obtained from the maps were used for comparison in Area II. Figure 6 shows frequency distributions of maximum and minimum elevations, and relative relief (maximum minus minimum) in 1978 and in 1995. The mean elevations of the maximum/minimum heights in 1978 and 1995 are 5019/4999 m and 5005/4989 m respectively. The surface level was 10–14 m

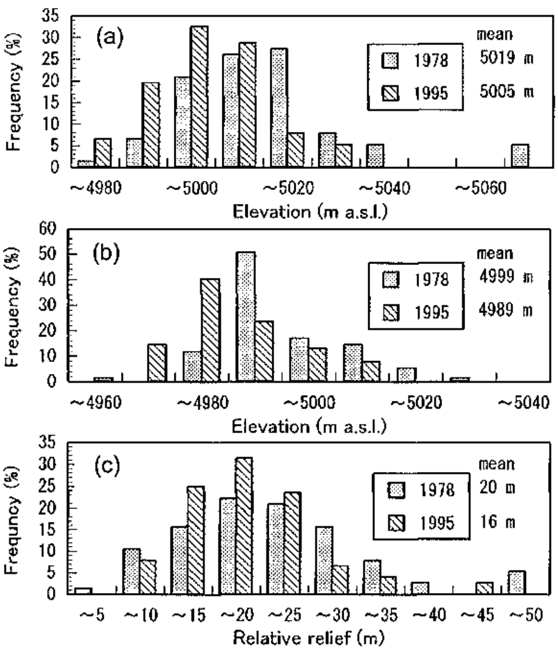

Fig. 6 Frequency distributions in Area II: (a) maximum elevations, (b) minimum elevations and (c) relative relief in 1978 and in 1995. A total number of samples (meshes: 50 m × 50 m each) is 77.

lower on average. The mean heights of the relative relief in 1978 and in 1995 are 20 m and 16 m respectively, indicating a slight decrease in surface roughness. Collapse of debris cones may account for the decrease the relative relief.

Area III

Maximum and minimum elevations in each 50 m × 50 m mesh area obtained from the maps were used for comparison in Area III. Figure 7 shows frequency distributions of maximum and minimum elevations, and relative relief in 1978 and 1995. The mean elevations of the maximum/minimum heights in 1978 and in 1995 are 5129/5116 m and 5123/5108 m respectively. The surface level lowered by 6–8 m on average. The mean heights of the relative relief in 1978 and in 1995 are 13 m and 15 m respectively, indicating a slight increase in surface roughness.

Area IV

Average elevations in each 50 m × 50 m mesh area obtained from the maps were used for comparison. The areas occupied by ice pinnacles (bare ice in Fig. 5) were excluded from the comparison because the 1995 survey did not obtain topographic data for the ice pinnacles. Figure 8 shows frequency distributions of average elevations in 1978 and 1995. The average elevations on the left/right-hand bank of the row of ice

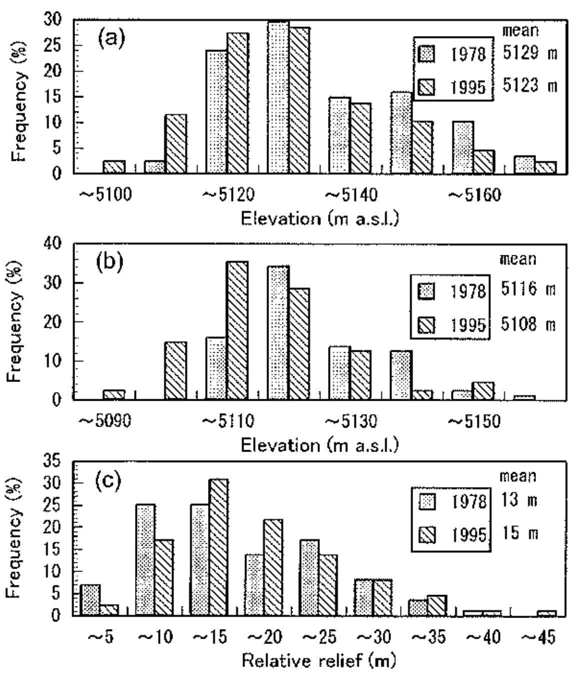

Fig. 7 Frequency distributions in Area III: (a) maximum elevations, (b) minimum elevations and (c) relative relief in 1978 and in 1995. The total number of samples (meshes: 50 m × 50 m each) is 88.

pinnacles in 1978 and in 1995 are 5260/5262 m and 5254/5244 m, respectively. The surface level lowered by 6 m on the left-hand side and 18 m on the right-hand side on average.

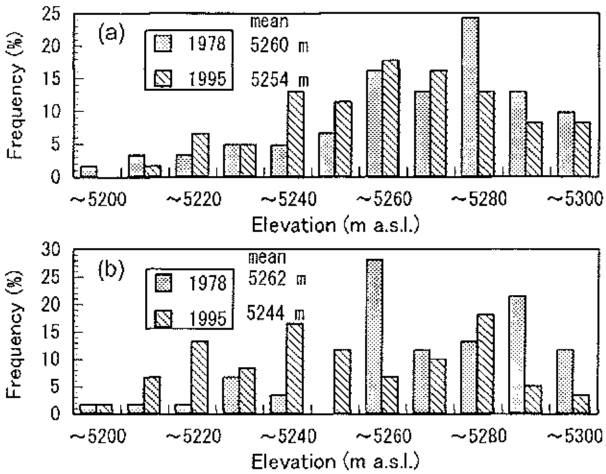

Fig. 8 Frequency distributions of average elevations in Area IV for 1978 and 1995: (a) left-hand bank, (b) right-hand side of the ice pinnacle row. The total number of samples (meshes: 50 m × 50 m each) is 62 on the left and 61 on the right.

DISCUSSION

Although supraglacial debris rapidly increases in thickness with downstream distance below Area IV (Nakawo *et al.*, 1986), there was a more or less uniform lowering of the surface along this stretch of the ablation area from 1978 to 1995. In fact, Inoue (1977) detected surface ablation over the full ablation area except near the apparent terminus where Area I lies. Although ablation under debris cover decreases as debris cover thickens, ablation on/around ice cliffs and ponds is so extensive that the aerial mean ablation rates in Areas II and III may be more or less comparable to that in Area IV where bare ice and thin debris cover are dominant (Inoue & Yoshida, 1980). In Area I, however, surface ablation may be negligibly small (Inoue & Yoshida, 1980). Surface lowering in this area could result from subsurface melting in meltwater passages.

Surface lowering along the ablation area was derived by Nakawo *et al.* (1999) using a simple continuity equation that accounts for ablation and flow divergence. Annual ablation rates were estimated using thermal data derived from satellite data and meteorological data obtained in the 1970s. This analysis suggests that the glacier would shrink under the same climatic conditions as in the 1970s.

Although no further information has been obtained on ablation conditions since the 1970s, there are some observations on recent ice flow conditions based on displacements of some identifiable topographic features in the time series of topographic maps and satellite images. Seko *et al.* (1998) found a trend of decreasing flow speed after the 1950s in the uppermost part of the ablation area where Area IV lies. Iwata *et al.* (2000) reported that on the right-hand side in the upper part of this area, at the confluence of the tributaries from Lingtren and Khumbtse (see Fig. 1), two large hollows emerged and that the relative relief became small between 1978 and 1995. This suggests that a decline of ice flow from the tributary may be responsible for the greater lowering on the right-hand bank (18 m on average) compared with that in the left -hand bank (6 m on average) in Area IV.

Surface lowering in the ablation area occurs when ablation exceeds inflow from upstream. Slowing of ice flow might accelerate shrinkage of the glacier even if ablation conditions remain unchanged.

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REFERENCES

Higuchi, K. (1980) Outline of the Glaciological Expedition of Nepal (4). *J. Japan. Soc. Snow Ice (Seppyo)* **41**, special issue, 1–4.

Inoue, J. (1977) Mass budget of Khumbu Glacier. *J. Japan. Soc. Snow Ice (Seppyo)* **39**, special issue, 15–19.

Inoue, J. & Yoshida, M. (1980) Ablation and heat exchange over Khumbu Glacier. *J. Japan. Soc. Snow Ice (Seppyo)* **41**, special issue, 26–33.

Iwata, S., Watanabe, O. & Fushimi, H. (1980) Surface morphology in the ablation area of the Khumbu Glacier. *J. Japan. Soc. Snow Ice (Seppyo)* **41**, special issue, 9–17.

Iwata, S., Aoki, T., Kadota, T., Seko, K. & Yamaguchi, S. (2000) Morphological evolution of the debris-cover on Khumbu Glacier, Nepal, between 1978 and 1995. In: *Debris-Covered Glaciers* (ed. by M. Nakawo, C. F. Raymond & A. Fountain) (Proc. Seattle Workshop, September 2000). IAHS Publ. no. 264 (this volume).

Kadota, T. (1997) On the recent shrinkage of small glaciers in the Nepal Himalayas. Doctoral Thesis, Nagoya University, Japan.

Nakawo, M., Iwata, S., Watanabe, O. & Yoshida, M. (1986) Processes which distribute supraglacial debris on the Khumbu Glacier, Nepal Himalaya. *Ann. Glaciol.* **8**, 129–131.

Nakawo, M., Yabuki, H. & Sakai, A. (1999) Characteristics of Khumbu Glacier, Nepal Himalaya: recent change in the debris-covered area. *Ann. Glaciol.* **28**, 118–122.

Seko, K., Yabuki, H., Nakawo, M., Sakai, A., Kadota, T. & Yamada, Y. (1998) Changing surface features of Khumbu Glacier, Nepal Himalayas revealed by SPOT images. *Bull. Glacier Res.* **16**, 33–41.

Watanabe, O., Fushimi, H., Ikegami, K., Tanaka, Y., Yoshida, M., Iwata, S., Inoue, J. & Upaday, B. P. (1980) Outline of studies on supraglacial debris of the Khumbu Glacier, Khumbu region. *J. Japan. Soc. Snow Ice (Seppyo)* **41**, special issue, 5–8.