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Changing surface features of Khumbu Glacier, Nepal Himalayas revealed by SPOT images

Katsumoto SEKO[1], Hironori YABUKI[1], Masayoshi NAKAWO[1], Akiko SAKAI[1], Tsutomu KADOTA[1], Yutaka YAMADA[2]

1 Institute for Hydrospheric-Atmospheric Sciences, Nagoya Univ. Nagoya, 464-8601 JAPAN

2 Nagaoka Inst. of Snow and Ice Studies, NIED, STA, Suyoshi-cho, Nagaoka, 940-0821 JAPAN

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Abstract

Changes in surface features on Khumbu Glacier, Nepal Himalayas were examined using high resolution satellite images (SPOT HRV). We detected clearly a bare ice zone with ice pinnacles, and supra-glacial ponds in the debris-covered ablation zone. Comparing satellite images as well as previous topographic maps, it was detected that the ice pinnacle zone has gradually shrunk in area since 1956. Ice flow velocities were found to have decreased recently, especially in upper stream part. The total area of supra-glacial ponds, on the other hand, showed no apparent trend, having a high variability.

1. Introduction

Several small Himalayan glaciers whose length is less than a few kilometers have retreated since 1970s (*e.g.* Kadota *et al.*, 1993). It is difficult, however, to detect the variation of large debris covered glaciers (from ten to several tens of kilometers in length) solely by ground-based observations. A satellite remote sensing using high resolution sensors is thought to be useful for such detection. Nakawo *et al.* (1993) tried to classify surface features with satellite data, and suggested the possible detection of ice flow velocities at a debris covered glacier.

Khumbu Glacier is a typical large glacier with supra-glacial debris in the Nepal Himalayas (Fig. 1). The ablation zone is almost covered with rock debris whose thickness is up to several meters (Nakawo *et al.*, 1986). Various types of micro-morphology, whose characteristic scale is several tens of meters (Iwata *et al.*, 1980), were detected, with which surface ice velocities were obtained. This study focuses on the temporal changes of the flow velocities and surface features such as bare ice zones with ice pinnacles and supra-glacial ponds.

2. Data

We investigated the surface micro-morphology of the glacier using SPOT HRV data obtained in January 1987 (panchromatic image) and November 1995 (panchromatic and multi-spectral image). The spatial resolution was 10m in panchromatic image and 20m in multi-spectral image. Table 1 shows wave length and resolution of SPOT HRV. Figure 2 shows a SPOT HRV multi-spectral image at Khumbu region taken in November 1995. Figure 3 shows a close up image of Khumbu Glacier. We can identify various micro-morphological features on the glacier in the images such as ice pinnacles and supra-glacial ponds distributed over the lower part of the glacier. Different features have different color (spectral reflectance) from the surrounding debris covered surfaces with the false color multi-spectral satellite images (channel 3 (red), 2 (green) and 1 (blue)) : ice pinnacle was seen in light blue color and supra-glacial ponds dark blue color. They can be detected by their apparent coloration even when the ponds are frozen.

In order to compare the changes in surface features, we used the recent satellite image (1987, 1995) and detailed topographic maps of the glacier prepared in 1956 (Müller, 1959), 1978 (Iwata *et al.*, 1980), and

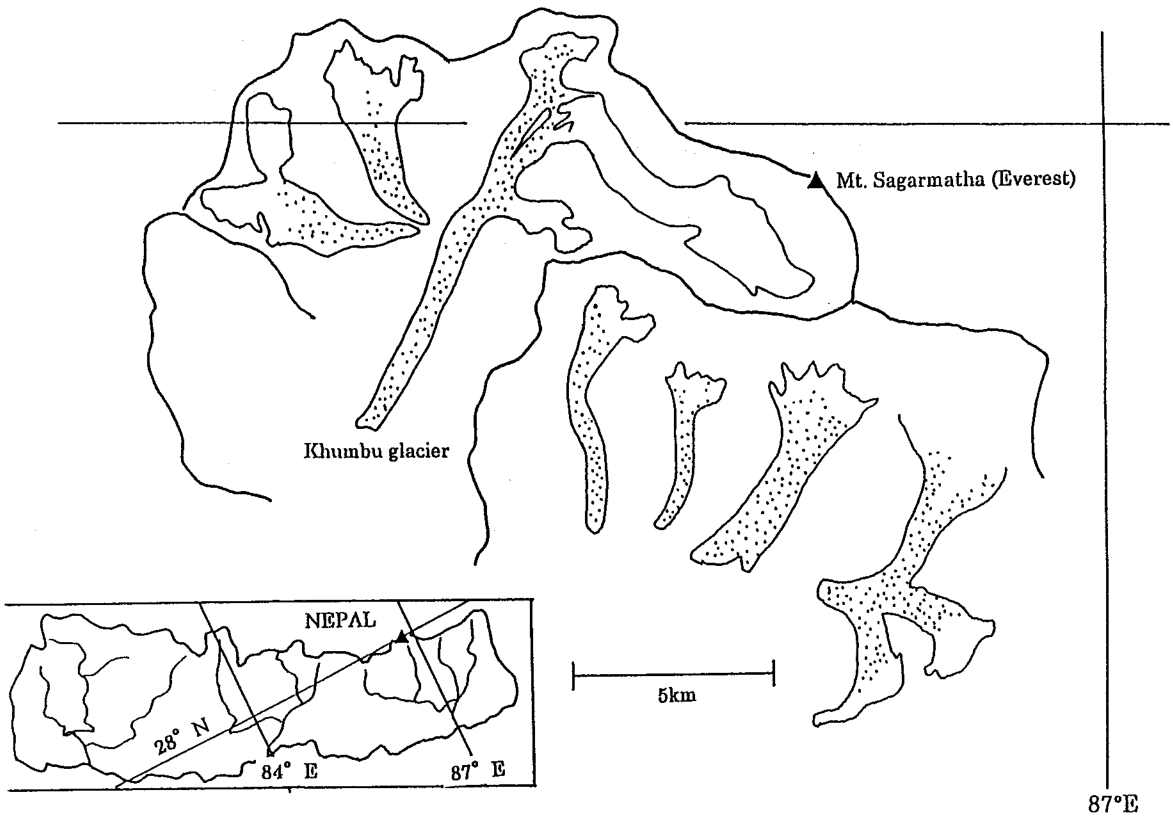

Fig. 1 Location of Khumbu Glacier, Nepal Himalayas. Stippled area denotes debris -covered zone of glaciers.

Table 1. Wave length and resolution of SPOT HRV

mode	Channel	observation wave length	resolution
Multi-spectral	1	0.50 ~0.59μm	20 m
	2	0.61 ~0.68μm	
	3	0.79 ~0.89μm	
Panchromatic	1	0.51 ~0.73μm	10 m

1984 (National Geographic Magazine, 1988). In case of satellite image in 1987, we could not detect ponds because this image is panchromatic data. The comparison is shown in Fig. 4.

3. Results and discussion

3.1. Ice pinnacles and ice flow

One of the characteristic micro-morphological features of the glacier is the ice pinnacles extending into the debris-covered regions (Fig. 5). The ice pinnacles gaps such as G1 and G2 in Fig. 5 are remarkable points on the debris covered glacier.

It is evident that the areal extent of the ice pinnacle zone has been gradually shrinking since 1956 as shown in Fig. 6. The lower end of the ice pinnacle zone retreated upstream by 1.5 km since 1956 to 1984, while the terminus position of the glacier did not change much.

The horizontal flow velocity of the ice pinnacles can be detected by tracing. There are two gaps in the pinnacle zone as designated G1 and G2 in Fig. 5. We assumed that the movement of the gaps is nearly equal to the ice flow velocity. Table 2 shows the ice flow velocities obtained from the change in location of the gaps formed on the maps and the satellite image, assuming the center of the upper and lower edges of each gap to be its location. It seems that the flow velocities estimated have decreased with time. By comparing the two satellite images of 1987 and of 1995, ice velocities were also obtained at several other sites at peaks of pinnacles. The results are shown in

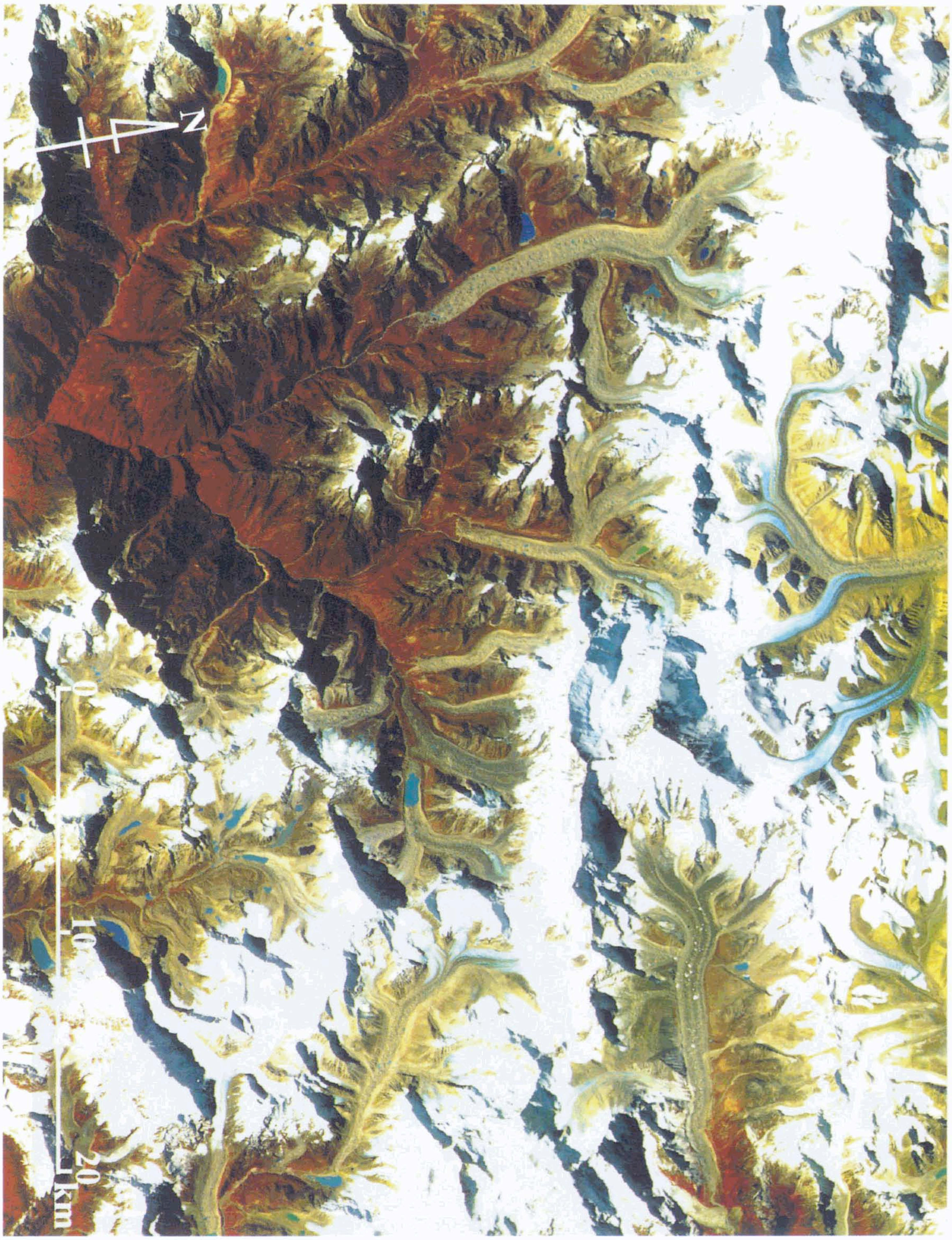

Fig. 2 A SPOT HRV multi-spectral image at Khumbu region taken in 7 Nov. 1995
(Scene ID ; 3 227-294 95/11/07 04 : 52 : 30 1 xs).

Fig. 3 A pick up image of Khumbu Glacier taken in 7 Nov. 1995 (Scene ID ; 3 227-294 95/11/07 04 : 52 : 30 1 xs).

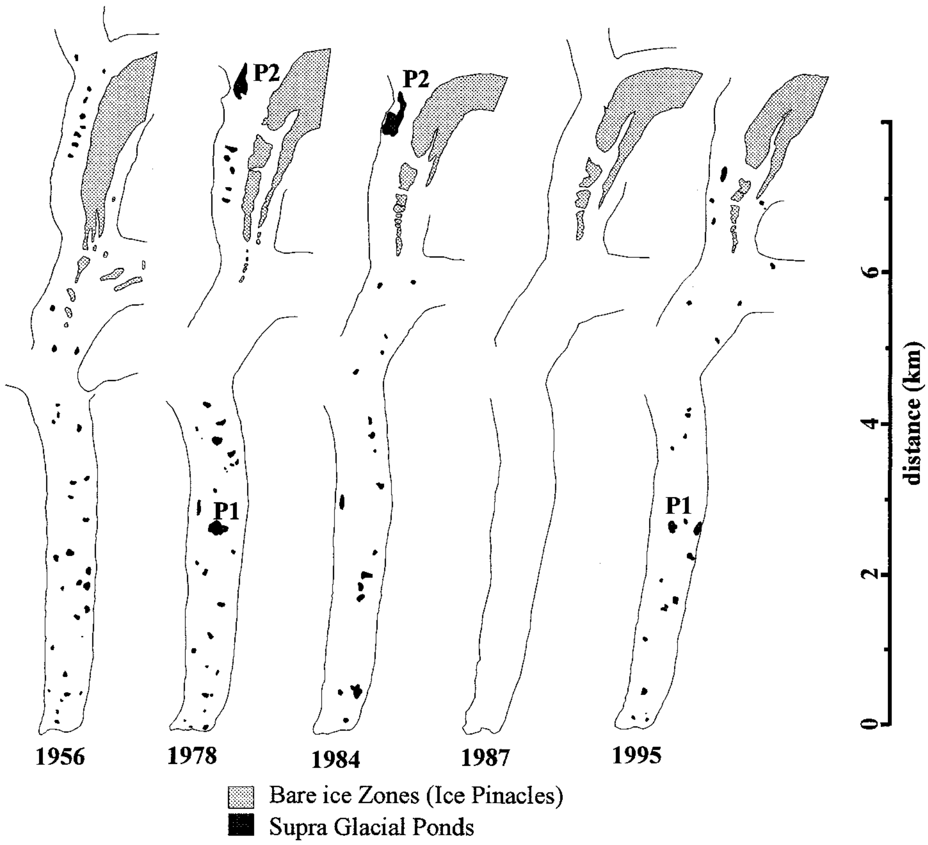

Fig. 4 Sketches of the surface features of the ablation zone traced from maps and the satellite image. The observation years are shown at the bottom of each. (P1 and P2 were big supra glacier ponds. These ponds recognized same one, respectively.)

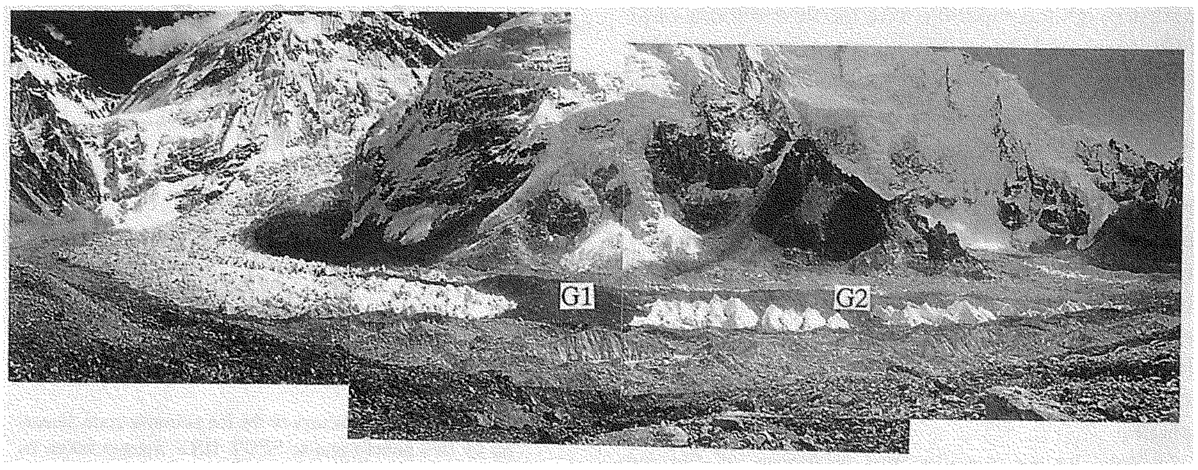

Fig. 5 A ground based photograph of ice pinnacles over the glacier (taken in Dec. 1991). G1 and G2 are gaps in the pinnacle zone (also shown in Fig. 6).

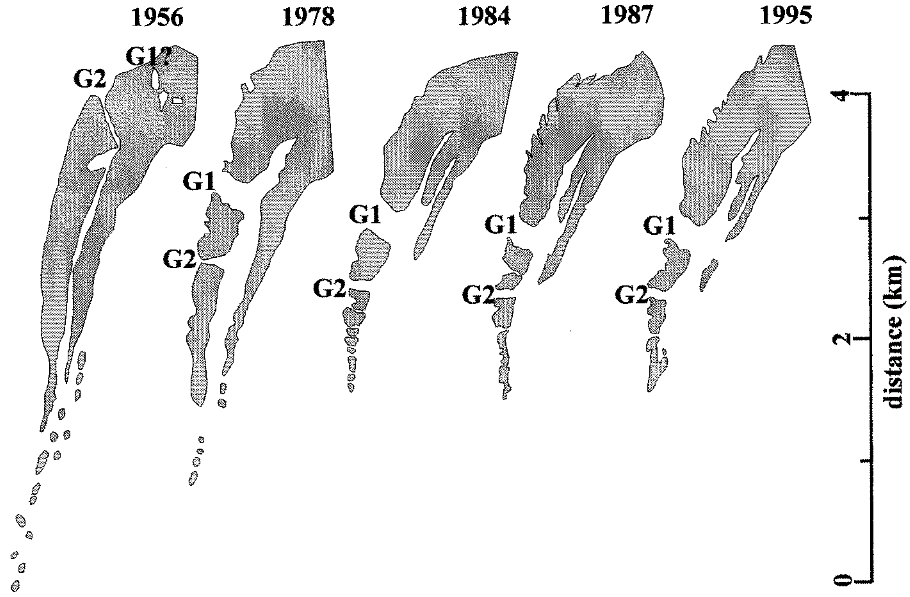

Fig. 6 The temporal variation of the ice pinnacle zone shown as gray areas (close up of Fig. 4).

Table 2. Ice flow velocities detected from the displacement the gaps

from	to	period (a)	G 1 (m/a)	G 2 (m/a)
1956	1978	22	****	56
1978	1984	6	41	41
1984	1995	11	26	26

(*** : no gap is shown for G1 on the map in 1956)

Fig. 7, where the speed ranges from 26 m/a to 57 m/a. It is roughly compatible with the flow velocity of 31 m/a measured by a triangulation survey in 1978 (Watanabe *et al.*, 1980). The figure showed that ice flow velocities were larger at upper stream side than at lower stream side.

All the flow speeds obtained are shown in Fig. 8 for the distance upward from the lower end of the pinnacle zone in 1987. At 2500–3000 m region, ice flow velocities was 68 m/a in 1956, 63 m/a in 1974, 56 m/a from 1956 to 1978 and 51 m/a from 1987 to 1995. This shows a temporal decreasing trend of the speed. Similar trend can be seen at lower sites, indicating the recent decrease in flow speed in the wide area of the glacier.

Now let us consider the evolution of the ice pinnacle zone extent along a longitudinal flow line. The relative height of pinnacles decreases down gla-

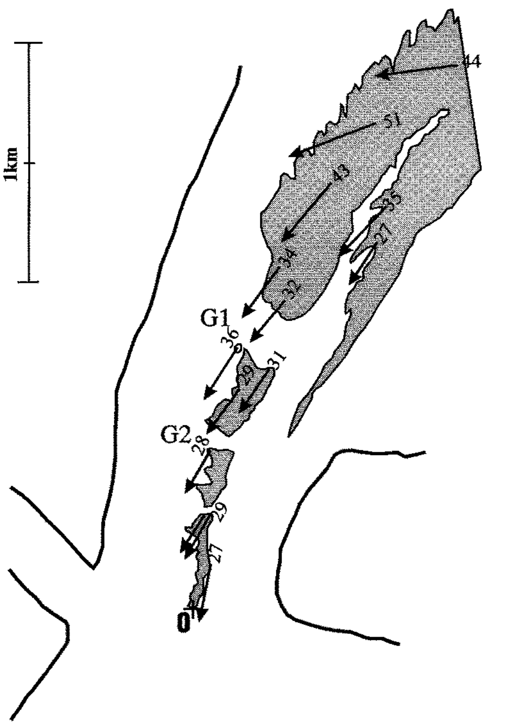

Fig. 7 The ice flow vectors in the ice pinnacle zone detected by two panchromatic SPOT HRV images taken in Jan., 1987 and Nov., 1995. (Numbers on figure are flow velocity (m/a). '0' in end of ice pinnacles is origin of Fig. 8.)

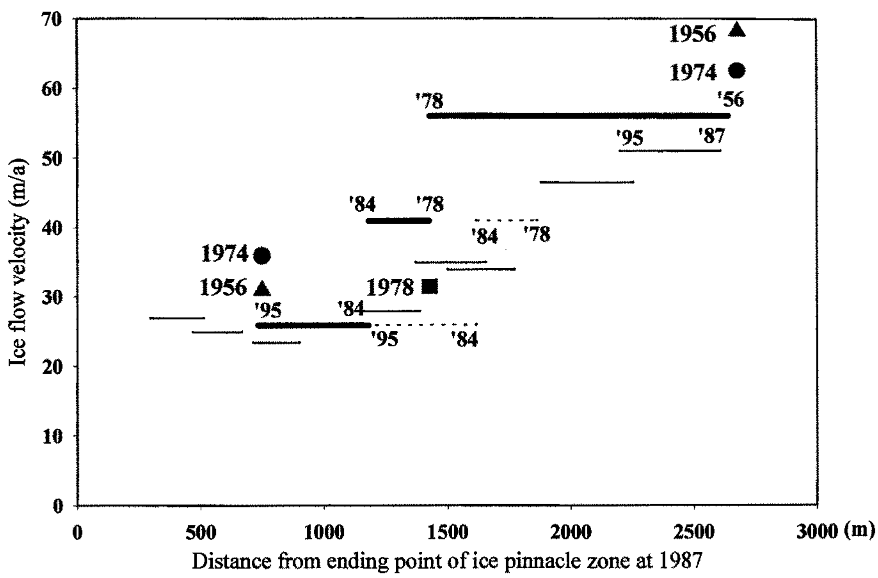

Fig. 8 Temporal variation of the ice flow velocities, measured by ground surveys in 1956 (solid triangle), 1974 (solid circle), 1978 (solid square). Dotted lines are the mean flow speeds from the displacement of G1, and thick lines from G2. Thin lines are the speeds from 1987 to 1995 shown in Fig. 6. Upper and lower ends of all the data lines correspond with the location of the respective markers at the beginning and the ending time of each observation periods respectively. The x-axis corresponds to the upward direction from the southernmost edge of the ice pinnacle zone in 1987 ('0' in Fig. 7).

cier in general. Taking x axis downward along a flow line, the pinnacle height $h(x)$ is given by

$$h(x) = h(0) - \int_0^x \frac{A_i - A_d}{V(x,t)} dx, \quad (1)$$

where $h(0)$ is the height at $x = 0$, which is the upper end of zone (G2). A_i and A_d are the ablation rate of ice pinnacles and of surrounding debris surface respectively. The flow velocity $V(x,t)$ is assumed, for simplicity, by

$$V(x,t) = ax + b(t), \quad (2)$$

where a is a constant. The value for a was obtained, from a linear regression analysis with the data from 1987 to 1995 (thin line in Fig. 8), resulting in -0.0136 a^{-1}. $b(t)$ is the ice flow velocity of G2 at respective time. The position of the ending point ($h(x) = 0$) of the ice pinnacle zone can be determined with the following equation derived from equations (1) and (2),

$$X_e = \frac{b(t)\left[\exp\left[\frac{h(0)a}{A_i - A_d}\right] - 1\right]}{a}, \quad (3)$$

where A_i-A_d is roughly 1 m/a (Inoue and Yoshida, 1980). $h(0)$ was about 30 m, and $b(t)$ about 41 m/a in the period of 1978-1984. With these figures, we obtained the result that X_e becomes 1010m the ending point of ice pinnacle zone. For 1987-1995, $h(0)$ was about 30 m and $b(t)$ was about 28 m/a, leading to X_e= 710 m. These results are roughly compatible with the observation.

3.2. Supra-glacial ponds

Another outstanding feature on the debris covered zone is supra-glacial ponds with dimensions of several tens of meters (Fig. 3). They have different color (spectral reflectance) from those for the surrounding debris covered surfaces.

The position and size of the ponds detected from the maps and the satellite image are shown in Fig. 4. There was a large pond (200 x 150 m) at about 3 km from the terminus in 1978 (P1 in the Fig. 4), while it was not found in 1984. It reappeared in 1995 as a smaller pond than in 1978. A similar case occurred in the upper part of the ablation zone where Khumbu Glacier meets with a tributary (Lingtren Glacier) ; a relatively large pond existed in 1978 and 1984, but not in 1956 and 1995 (P2 in the Fig. 4). The size and the position of ponds are thus highly variable.

Table 3 shows the variation of the ratio of the area covered by supra-glacial ponds to the total area of the glacier for each sub-section divided by 0.5 km interval from the terminus. The ponds area accounts for only about 1 % in each 0.5 km interval sub-area. Areal contribution is largest at around 3 km from the terminus, where a relatively big pond sometimes appears as in 1978. We see from Table 3 that no clear trend was found as for the total area of the ponds from 1956 to 1995. The areal fraction of supra-glacial ponds shows complex behavior since 1956 in contrast to the apparent shrinking trend of the ice pinnacle zone.

Table 3. Longitudinal variation of the ratio of the area covered by supra-glacial ponds to the total area of the glacier.

	Area	1956	1978	1984	1995	SD
distance from the terminus (km)	km^2	%	%	%	%	
0.0-0.5	0.25	0.04	0.09	0.02	0.08	0.03
0.5-1.0	0.30	0.14	0.09	0.26	0.03	0.08
1.0-1.5	0.31	0.08	0.08	0.00	0.04	0.03
1.5-2.0	0.31	0.07	0.15	0.12	0.23	0.06
2.0-2.5	0.30	0.22	0.13	0.20	0.02	0.08
2.5-3.0	0.29	0.19	0.10	0.06	0.51	0.18
3.0-3.5	0.29	0.08	0.75	0.08	0.03	0.30
3.5-4.0	0.29	0.08	0.11	0.07	0.03	0.03
4.0-4.5	0.29	0.02	0.33	0.06	0.03	0.13
4.5-5.0	0.29	0.17	0.16	0.02	0.01	0.08
5.0-5.5	0.32	0.00	0.00	0.02	0.02	0.01
5.5-6.0	0.36	0.04	0.02	0.05	0.06	0.01
6.0-6.5	0.34	0.03	0.00	0.03	0.04	0.02
6.5-7.0	0.31	0.08	0.00	0.08	0.00	0.04
7.0-7.5	0.39	0.06	0.00	0.00	0.03	0.02
7.5-8.0	0.46	0.02	0.06	0.00	0.08	0.03
Total	5.07	1.30	2.06	1.08	1.23	

SD : Standard deviation.

Large supra-glacial lakes of several kilometers in length and nearly 100 m in depth have developed over recent decades near the terminus of several large glaciers in the Himalayas. They have a potential for glacier lake outburst floods (GLOF), which is a primary concern for the resident people (*e.g.* Yamada and Sharma, 1993). These big glacier lakes are far larger than the supra-glacial ponds described in this paper, and the evolution of the supra-glacial lakes to large lakes with the potential disaster is to be examined further.

4. Concluding remarks

Surface morphological features on Khumbu Glacier, Nepal Himalayas were examined using high resolution satellite images (SPOT HRV). It was shown that we can detect the spatial and temporal variation of characteristic surface features such as bare ice zone and supra-glacial ponds. Further, glacier flow velocity can be monitored by tracing conspicuous features in the different images. Comparing satellite images and past topographic maps, it was shown that the ice pinnacle zone has shrunk since 1956 in its area. Ice flow velocities was found to have decreased since 1956, especially in upper stream part of the ablation zone.

By contrast, the supra-glacial ponds did not show any apparent trend. The behavior of the supra-glacial ponds is complex and their variation is possibly controlled not only by climatic factor but also by glacio-hydrological factors.

Recent high resolution satellite data provide quite valuable information on the variation of alpine glaciers in particular for those in this harsh environment. Remote sensing, however, has limitations. Changes of surface level and/or ice thickness, for example, cannot be detected by satellite sensors at present. We believe however that, utilization of satellite data, in addition to ground-based data can tell much about glacier variations in the Himalayas since now.

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