Shrinkage of Glacier AX010 since 1978, Shorong Himal, East Nepal

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Abstract The terminus of glacier AX010 retreated by 30 m and 28 m during the periods from 1978 to 1989 and from 1989 to 1991, respectively. The surface of the glacier lowered by more than 30 m around the terminus and about 20 m at the lower part of the glacier in average. Surface area is reduced to about 90% of the extent in 1978, which occurred mainly at the lower part. Resulting volume loss is roughly estimated to be $3 \times 10^6$ m$^3$ during the period from 1978 to 1991. Using an empirical mass balance model and flow model, the relation between retreat and climatic conditions during the period from 1978 to 1989 is discussed. As to retreat during the period from 1989 to 1991, drastic negative balance due to increase of summer air temperature should be a main cause, because this strongly affects the mass balance of the glacier. In the Nepal Himalaya, no other study relating to change of glacier volume has been done at present. The results presented here will be one of basic data for further study on the relation between climate and glaciers in the Himalaya.

INTRODUCTION

Variations in the position of glacier termini have been monitored world-wide. Especially in European countries there exist a series of data for many glaciers, including mass balance, ice flow, surface elevations, extent and so on. In the Nepal Himalaya, however, there are few studies of glacier fluctuation. Higuchi et al. (1978, 1980) compiled a glacier inventory for the Dudh Kosi region and compared the lowest elevations of glaciers with those compiled by Müller. They concluded that 85% of the 110 C-type glaciers (debris free glaciers) retreated during the period from 1960 to 1975. Fushimi & Ohata (1980) studied 14 C-type glaciers fluctuations from 1970 to 1978 and showed that seven glaciers retreated, three were stationary, three advanced and one glacier was irregular. Several of these glaciers were revisited in 1989 and were revealed to have been retreating during the last decade (Yamada et al., 1992). Up to this moment, monitoring of glaciers in the Nepal Himalaya has been limited to occasional survey of positions of a small number of glacier termini. In 1991, several glaciers were revisited and some brief topographical maps were
obtained by means of ground survey. In this paper we focus on Glacier AX010, one of the well-studied glaciers in the Nepal Himalaya, and discuss its shrinkage and relating climatic conditions around the glacier.

The location of Glacier AX010 is shown in Fig. 1. Glacier AX010 starts from just below a rock peak (5381 m) and ends in a small pond (4952 m) with its length and area, 1.7 km and 0.57 km² respectively (Fig. 2). In 1978, a reference point for monitoring the position of terminus was established near the terminus. A topographical map was also prepared. In November 1989 and October 1991, this glacier was revisited and remeasured.

Fig. 1 The locations of Glacier AX010 and the meteorological stations in Dudh Kosi region, East Nepal.
OBSERVATIONAL RESULTS

Terminus position

The terminus retreated by 30 m and 28 m during the period from 1978 to 1989 and from 1989 to 1991, respectively. Considering interval of the period, the retreating rate from 1989 to 1991 is remarkably large. Figure 3 shows terminus positions in 1978, 1989 and 1991. Remarkable shrinkage of the glacier can be seen in Fig. 4.

Area and volume change

The extent and surface elevations of the glacier were obtained in 1991 and compiled as a brief topographical map. Then these were compared with those
in 1978. The changes of extent and surface elevations are shown in Fig. 5. Surface area is reduced to about 90% of the extent in 1978, which occurred mainly at the lower part of the glacier. The surface of the glacier lowered by more than 30 m around the terminus and about 20 m at the lower part of the glacier in average. Figure 6 shows the longitudinal profile of the glacier along the centre line in 1978 and 1991. We can see the shrinkage occurred mainly at the lower part of the glacier. This suggests that increase of ablation is a main reason for the shrinkage on the basis of Ageta’s model in the following section.
Resulting volume loss is roughly estimated to be $3 \times 10^6$ m$^3$ during the period from 1978 to 1991. Although the ice thickness of the glacier has not been measured, assuming the average thickness to be 60 m from the flow model in the next chapter, it can be estimated glacier volume reduced to about 90% of that in 1978.

For understanding the climatic conditions which caused shrinkage of the glacier, we introduce models in the following chapter.
MODELS OF MASS BALANCE AND ICE FLOW

Mass balance

Ageta (1983) presented empirical formulae to estimate mass balance of this glacier based on the observational data obtained in 1978 and 1979. Summer (June to September) mass balance is given by functions of mean summer air temperature (hereafter $T_s$) and summer precipitation (hereafter $P_s$). As Glacier AX010 is under influence of summer monsoon, both accumulation and ablation concentrate in this season. Further, summer balance can be considered to be almost equivalent to annual one (Ageta, 1980). The equations are as follows:

\[ c_s = P_s(0.80 - 0.23T_s) \quad (-0.8 \leq T_s \leq 3.4) \quad (1) \]
\[ c_s = P_s \quad (T_s < -0.8) \quad (2) \]
\[ c_s = 0 \quad (3.4 < T_s) \quad (3) \]
\[ a_s = -(T_s + 3.2)^{3.2} \quad (-3.2 < T_s) \quad (4) \]
\[ a_s = 0 \quad (T_s \leq -3.2) \quad (5) \]
\[ b_s = P_s \quad (T_s \leq -3.2) \quad (6) \]
\[ b_s = P_s + a_s \]
\[ = P_s - (T_s + 3.2)^{3.2} \quad (-3.2 < T_s < -0.8) \quad (7) \]
\[ b_s = c_s + a_s \]
\[ = P_s(0.80 - 0.23T_s) - (T_s + 3.2)^{3.2} \quad (-0.8 \leq T_s < 3.4) \quad (8) \]
\[ b_s = a_s \quad (3.4 \leq T_s) \quad (9) \]

where:
- $c_s$: accumulation in summer (cm water);
- $a_s$: ablation in summer (cm water);
- $b_s$: balance in summer (cm water);
- $T_s$: mean summer air temperature ($^\circ$C);
- $P_s$: summer precipitation (cm).

Ice flow

Ikegami & Ageta (1991) reported the results of ice flow measurements from 1978 to 1979. Using the annual surface flow velocities 1978/79 as initial
conditions, Kadota & Ageta (1992) introduced an ice flow model for this glacier. The equations are based on Paterson (1970, 1981) and are as follows:

\[ U = U_d + U_b \]  
(10)

\[ U_d = 2A(f_1 \rho g \sin \alpha)^n(Z \cos \alpha)^{n+1}/n + 1 \]  
(11)

\[ U_b = 0.11(Z \cos \alpha)^{0.95} \]  
(12)

\[ U_s = U \cos \alpha \]  
(13)

where:

- \( U \): surface velocity parallel to the glacier surface;
- \( U_d \): deformational velocity;
- \( U_b \): basal sliding velocity;
- \( U_s \): horizontal surface velocity;
- \( A \): flow low parameter (5 \times 10^{-15} \text{ s}^{-1} \text{ kPa}^{-3} \text{ for } n = 3); 
- \( g \): acceleration due to gravity;
- \( \rho \): density of ice;
- \( \alpha \): surface slope of the glacier;
- \( Z \): ice thickness measured vertically;
- \( f_1 \): stress shape factor (Nye, 1965) — frictional effect of valley wall.

The glacier was divided into eight sections by setting eight grid points (200 m interval in horizontal length) along the centre flow line. Figure 7 shows a schematic chart of a section of the glacier. Here \( Q_i = f_2 f_3 U_s Z_i W_i \), then the ice flow model is combined with the mass balance model through \( b_{si} \) by the following equation:

\[ \Delta Z_i = b_{si} + (Q_{i-1} - Q_i)/S_i \]  
(14)

where:

- \( Q_i \): ice flux through cross section at \( P_i \);
- \( f_2, f_3 \): shape factors; \( f_2 \), the cross section velocity factor, which relate the mean cross section velocity to the centre line velocity; \( f_3 \), the valley

**Fig. 7** A section of the glacier, as defines by the model with the symbols in the text. Glacier AX010 is divided into such eight sections (i: 1-8).
factor, which relates the valley cross section to the centre-line ice thickness $Z$, and the surface width $W$;

$W_i$: surface width measured along the contour line through each grid point;

$\Delta Z_i$: area-averaged ice thickness change rate for each section;

$b_{si}$: area-averaged mass balance for each section;

$S_i$: surface area of segment $i$;

i: 1-8, number of grid point/section.

Then putting $T_s$ and $P_s$ as variables of the model, they could obtain ice thickness changes of the glacier for the years after 1978. Details are described in Kadota & Ageta (1992).

DISCUSSION

Climatic conditions during 1978-89

As the glacier terminates into a pond, the distance of retreat can be translated into ice thickness change by using a simple geometric argument, namely 30 m retreat is equivalent to 12 m thinning of the ice thickness. Using the model, a probable combination of $T_s$ and $P_s$ at the glacier terminus, which cause the said thinning of the ice, is derived as mean values for the period during 1978 to 1989, namely $T_s$ and $P_s$ to be 2.5°C and 140 cm respectively (Kadota & Ageta, 1992).

Climatic conditions during 1989-91

The rate of terminus retreat of the glacier after 1989 is remarkably larger than that from 1978 to 1989. When we visited the glacier at the end of October in 1991, at almost whole of glacier exposed bare ice and melting of glacier ice had still continued. It can be considered that increase of summer air temperature occurred and had been high enough to increase remarkably ratio of rain in summer precipitation. This reduces the albedo of the glacier surface then accelerates ablation of the glacier as well as decrease of accumulation. Therefore it can be concluded that drastic negative balance during 1989-91 should be a main cause for this significant retreat.

Evaluation of the models

Observed $T_s$ and $P_s$ at the glacier termini (1976 and 1978) and at the meteorological stations in the same drainage (1978-86) are investigated to evaluate the results of the model calculations. The locations of the stations are shown in Fig. 1. $T_s$ at the meteorological stations increased by 0.2-0.4°C from 1978 to 1980s. On the other hand, $T_s$ at the glacier terminus obtained by the
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The model shows almost unchanged or 0.1°C increase from 1978. This can suggest a possibility that $T_s$ at the glacierized area did not fluctuate parallel to $T_s$ at the non-glacierized area. Although the models have some assumptions on such as summer mass balance, flow law parameters and ice thickness, further verification is difficult at present due to lack of data.

CONCLUDING REMARKS

Glacier AX010 in Shorong Himal (East Nepal) has been retreating from the end of the 1970s, namely 30 m from 1978 to 1989 and 28 m from 1989 to 1991. In the latest two years, drastic ablation of the glacier might have occurred. Shrinkage of the glacier during 1978-91 is remarkable in the lower part of the glacier. The climatic data at the glacierized area, however, is limited for reliable estimation of the glacier variations. Monitoring of not only glaciers themselves but climatic conditions in glacierized regions is required. It should serve as data base for mountain hydrology in the Himalaya.

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REFERENCES


