Bulletin of Glacier Research 10 (1992) *1–10*

Article

On the relation between climate and retreat of Glacier AX010 in the Nepal Himalaya from 1978 to 1989

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(Received August 15, 1991 ; Revised manuscript received January 16, 1992)

Abstract

During the period from 1978 to 1989, the terminus of Glacier AX010 in Shrong region, East Nepal, retreated about 30m. This retreat is equivalent to 12m thinning of ice thickness around the glacier terminus. For understanding of the relation between climate and glacier variation, this thinning is evaluated by using simple models of glacier mass balance and ice flow, and the average climatic condition around the glacier is estimated.

Calculated mean air temperature and mean precipitation during summer (June to September), which control annual mass balance in this area, are 2.5 ℃ and 140 cm, respectively, during this period at the terminus. These climatic conditions are similar to those in 1978. The glacier retreated under these climatic condition and possibly the rate of retreat was accelerated compared to that in the years before 1978 due to rising air temperature. On the other hand, mean summer temperatures at the meteorological stations at the non-glacierized area in East Nepal show increase by 0.2–0.4 ℃ since 1980 in comparison with that in 1978. This suggests that the local climate around glaciers did not fluctuate in the same way as did the climate at the non-glacierized region, or disregard of effects of winter snowfall in the model caused lower estimation of summer temperature at the glacier.

1. Introduction

Glaciers have been recognized as an indicator of changing climate, because glaciers change their dimensions responding to the surrounding climatic conditions. In discussing glacier variations, it is common to refer to the changing position of the terminus since this is commonly the most noticeable feature and can be easily monitored. In the Nepal Himalaya, however, there exist two types of glaciers, one is the D-type : large glaciers with lower part covered by debris, and the other is the C-type : small glaciers which are debris-free (Moribayashi and Higuchi, 1977). Kodama and Mae (1976) and Fushimi (1977) showed the lowest part of Khumbu Glacier, which is a typical D-type glacier, was considered as an inactive ice body having no direct relation to the glacier flow. As the present active termini of D-type glaciers are located in the debris-covered ice bodies, it is difficult to determine the exact active termini positions of D-type glaciers. Also D-type glaciers are considered less sensitive to the changing climate than C-type glaciers.

For this reason, terminus positions of C-type glaciers in Dudh Kosi region, East Nepal, have been monitored from 1970s and the results were reported by Higuchi *et al.* (1980) and Fushimi and Ohata (1980) and Yamada *et al.* (1992).

An investigation of the relation between terminus position and climate variations is useful for the prediction of future glacier extent as well as the reconstruction of past climate. To enable such an analysis, knowledge of the glacier regime, especially mass balance and ice flow, is necessary. For this reason, Glacier AX010 in Shorong region is the most suitable among the glaciers monitored in the Nepal Himalaya, because this glacier was well investigated in 1978/1979, and measurements included mass balance (Ageta *et al.*, 1980 ; Ageta, 1983), ice flow (Ikegami and Ageta, 1991).

In this paper, the observational results of the terminus change of Glacier AX010 is reported, and the relation between the terminus position of the glacier and the climatic condition during the period from 1978 to 1989 is discussed by the use of a combined model of local climate, glacier mass balance and ice dynamics.

2. Observational result of the glacier terminus change

The location of Glacier AX010 is shown in Fig. 1. Glacier AX010 starts from just below a rock peak (5381m) and ends in a small pond (4952m) with its length and area, 1.7km and 0.57km^2 respectively (Fig. 2).

In 1978, a reference point was set near the terminus and horizontal distances from this point to the glacier terminus were measured toward several directions at a level of pond surface.

In 1989, the distances and the water level were remeasured. Fig. 3 shows the change of terminal positions between 1978 and 1989. The terminus retreated about 30m during this period. As seen in Fig. 4, shrinkage of the glacier is evident.

As Glacier AX010 flows into the pond, this distance of retreat can be translated into ice thickness change by using a simple geometrical argument, namely 30m retreat is equivalent to 12m thinning of the ice thickness around the terminus, as shown in Fig. 5.

3. Modelling of the ice thickness change

Ice thickness change is a result of a glacier response to a changing climatic condition around a glacier, through the interrelation between mass-energy balance and the ice dynamics. A flow chart in Fig. 6 shows this relation. As shown in Fig. 6, this chart can be divided into two parts, the climate segment and the ice dynamics segment. At first we introduce the models for each segment and then combine the two.

a. Climate segment

Glacier AX010 is under the influence of the summer monsoon. Accumulation and ablation occur simultaneously and most of them concentrate in this season (June to September). Using observational data in 1978 and 1979, Ageta (1983) derived the empirical equations to calculate mass balance at a given point on this glacier. These equations are functions of mean summer temperature (hereafter T_s) and summer precipitation (hereafter P_s) at the given point, here summer means four months from June to September. These equations are as follows :

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 temperature (°C)
P_s : summer precipitation (cm)

Then

$$c_s = P_s(0.80 - 0.23T_s) \qquad (-0.8 \leqq T_s \leqq 3.4) \qquad (1)$$

$$c_s = P_s \qquad (T_s < -0.8) \qquad (2)$$

$$c_s = 0 \qquad (3.4 < T_s) \qquad (3)$$

$$a_s = -(T_s + 3.2)^{3.2} \qquad (-3.2 < T_s) \qquad (4)$$

$$a_s = 0 \qquad (T_s \leqq -3.2) \qquad (5)$$

$$b_s = P_s \qquad (T_s \leqq -3.2) \qquad (6)$$

$$b_s = P_s + a_s = P_s - (T_s + 3.2)^{3.2} \qquad (-3.2 < T_s < -0.8) \qquad (7)$$

$$b_s = c_s + a_s = P_s(0.80 - 0.23T_s) - (T_s + 3.2)^{3.2} \qquad (-0.8 \leqq T_s < 3.4) \qquad (8)$$

$$b_s = a_s \qquad (3.4 \leqq T_s) \qquad (9)$$

As seen in the above, this model treats T_s and P_s

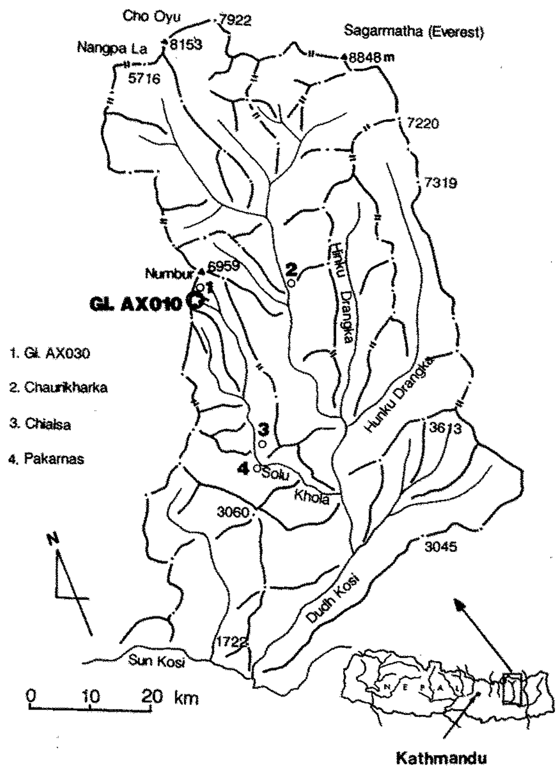


Fig. 1. The locations of Glacier AX010 and the meteorological stations in Dudh Kosi region, East Nepal.

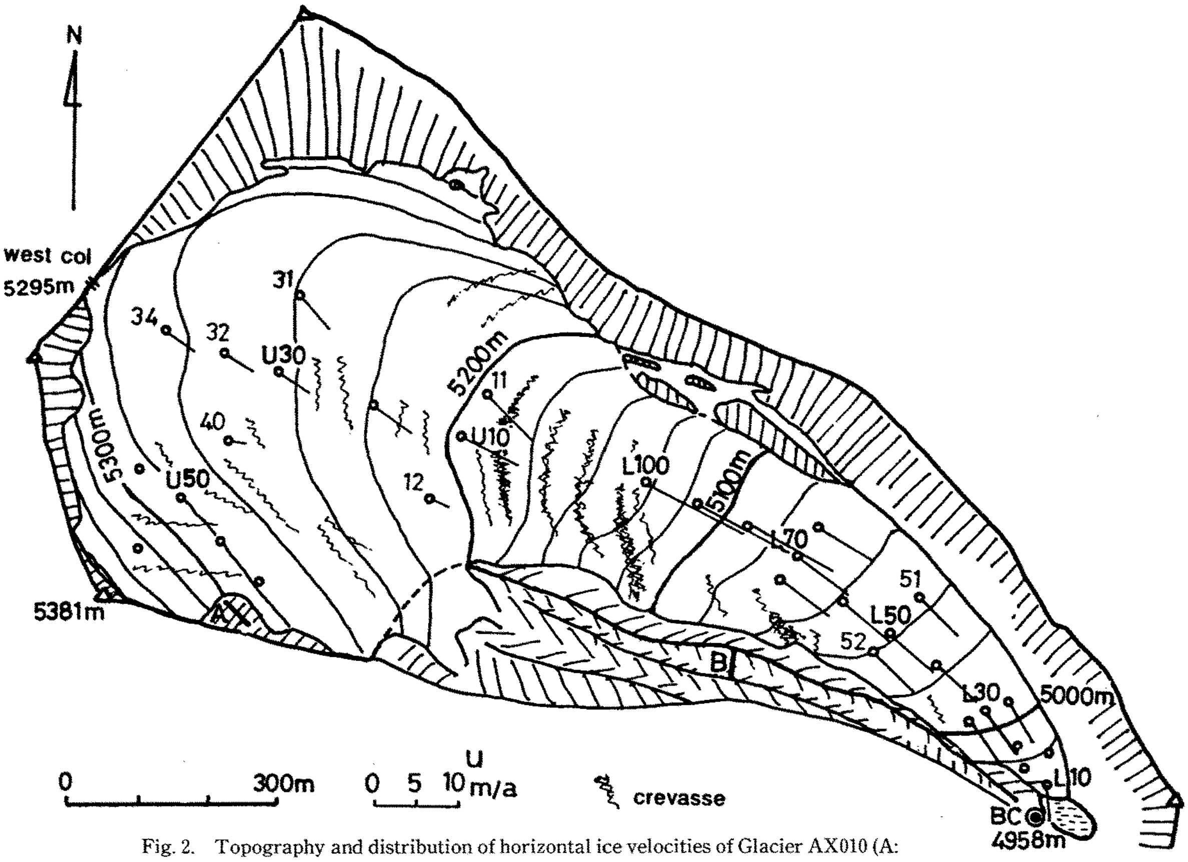


Fig. 2. Topography and distribution of horizontal ice velocities of Glacier AX010 (A: base line of survey for upper stakes, B: that for lower stakes). After Ikegami and Ageta (1991).

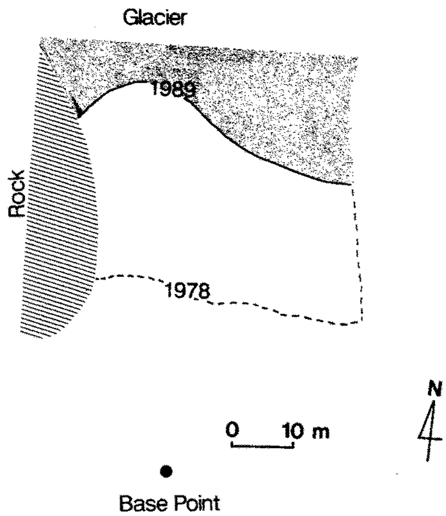


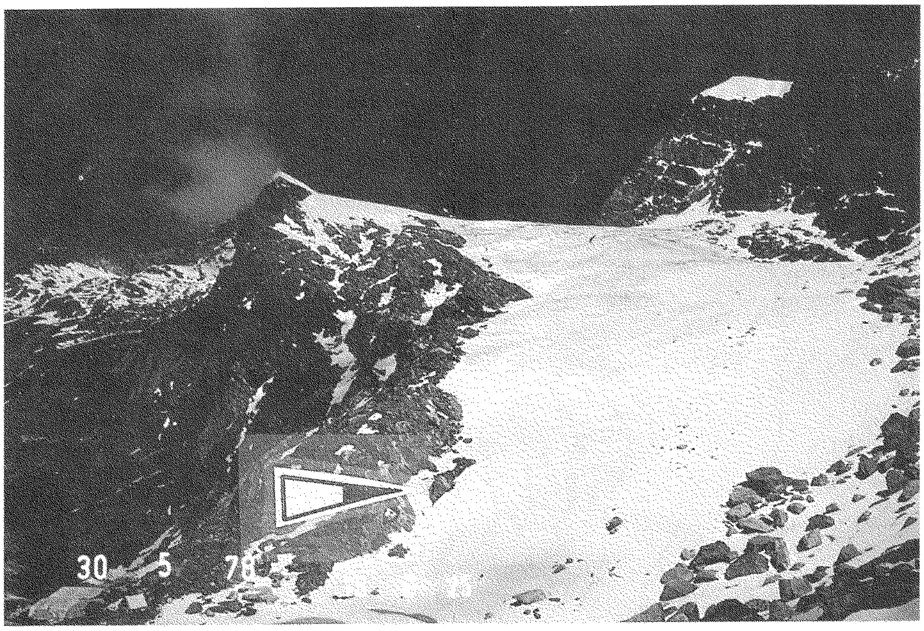
Fig. 3. The change of terminal positions of Glacier AX010 between 1978 and 1989.

as the representatives of the climatological factors which govern mass balance of the glacier. Ageta (1983) observed that as winter precipitation (less than 20% of annual precipitation) was blown away, it did not contribute to accumulation and that ablation in winter was negligible. Therefore, we treat balance in summer as to be almost equivalent to annual balance in this paper.

b. Ice dynamics segment

The surface ice flow was measured in 1978/1979 (Ikegami and Ageta, 1991). The distribution of annual flow velocity shows a normal pattern, that is, it increases from the upper reach and shows maximum speed around the equilibrium line then decreases toward the terminus (Fig. 2). The flow velocity should

(a)



(b)

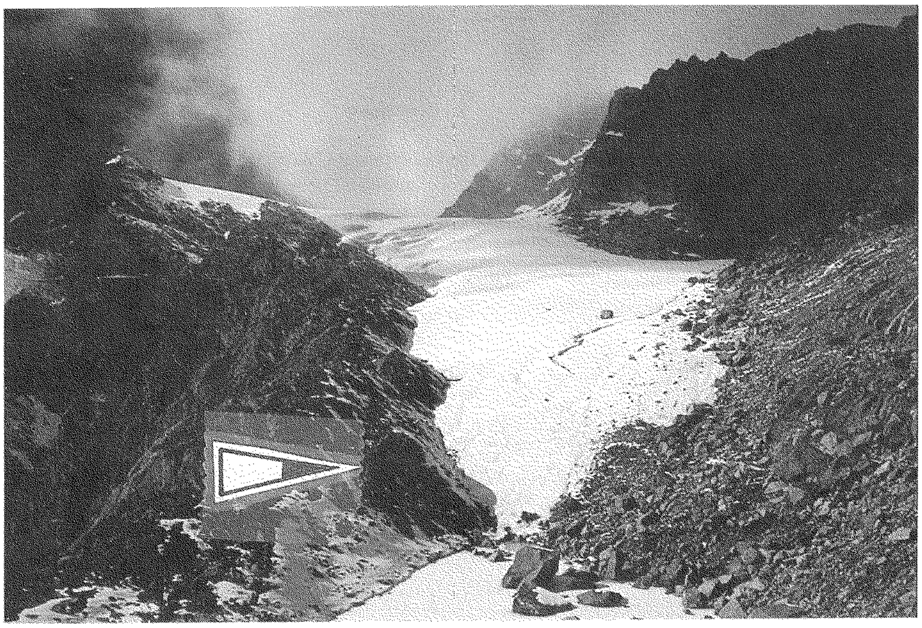


Fig. 4. Photographs of the lower part of Glacier AX010 taken in June 1978 (a), and in November 1989 (b). Shrinkage of the glacier is evident as shown by arrows in (a) and (b) at the same point.

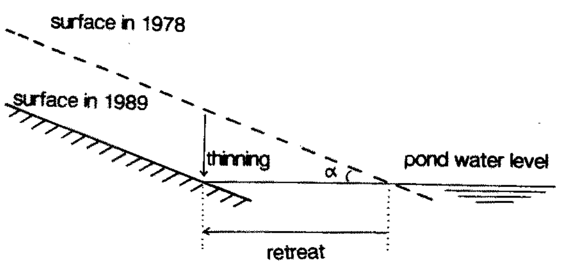


Fig. 5. A schematic profile of the terminus of Glacier AX010, which shows the relation between a distance of glacier retreat (30m) and thinning of ice thickness (12m) from 1978 to 1989. A slope of the terminus (α) was 22°.

change in accordance with thickening/thinning of the glacier ice. In order to evaluate this, the following simple flow model (Paterson, 1970, 1981) was used :

$$U = U_d + U_b \tag{10}$$
$$U_d = 2A(f_1 \rho g \sin \alpha)^n (Z \cos \alpha)^{n+1} / n+1 \tag{11}$$
$$U_b = 0.11(Z \cos\alpha)^{0.95} \tag{12}$$
$$U_s = U \cos \alpha \tag{13}$$

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 law parameter ($5. \times 10^{-15}$ $s^{-1}kPa^{-3}$ for n=3)
- g : acceleration due to gravity
- ρ : density of ice
- α : 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 (200m interval in horizontal length) along the center flow line as shown in Fig. 7 (a). At the each grid point, the ice thickness were calculated using the equations (10)−(13) so as to match the surface velocity value of 1978/1979 measurement. Fig. 7 (b) shows longitudinal cross-section along the center flow line of the glacier, which was obtained by the use of the calculated ice thickness.

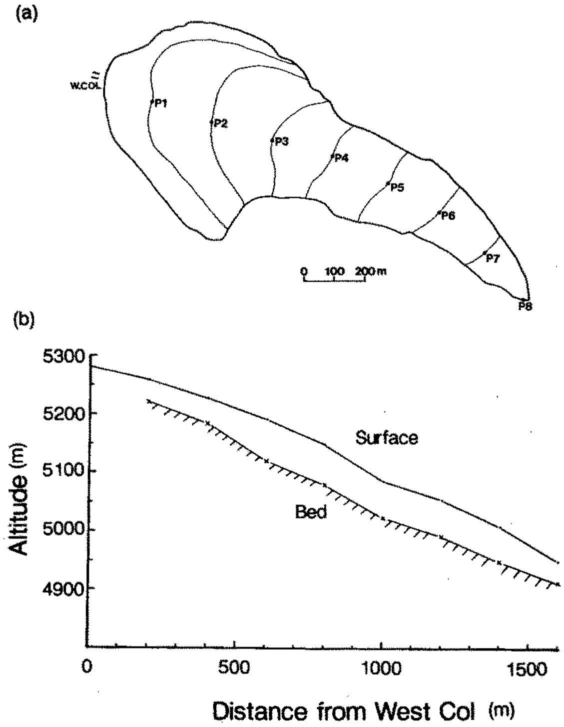


Fig. 7. Grid points setting at 200m interval in horizontal length along the center flow line of Glacier AX010 (a), and a longitudinal cross-section along that obtained from the calculated ice thickness (b).

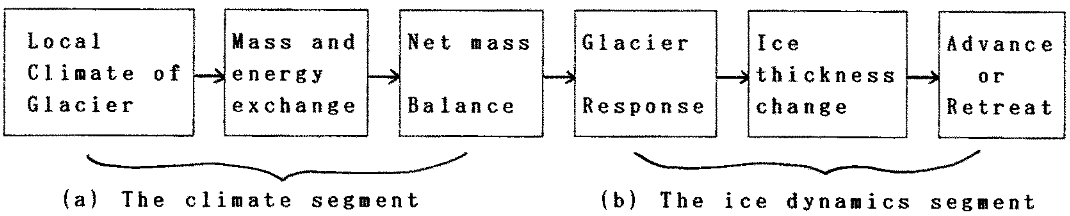


Fig. 6. The steps in the relation between the position of a glacier's terminus and the climate. After Meier(1965), modified.

c. Combined model

Figure 8 shows a schematic chart of a section of the glacier. Here $Q\mathrm{i}=f_2f_3U_s\mathrm{i}Z\mathrm{i}W\mathrm{i}$, then the ice dynamics segments can be combined with the climate segments through $b_s\mathrm{i}$ by the following equation :

$$\Delta\dot{Z}_i\mathrm{i}=\bar{b}_s\mathrm{i}+(Q\mathrm{i}\text{-}1-Q\mathrm{i})/S\mathrm{i} \qquad (14)$$

where

$Q\mathrm{i}$: ice flux through cross section at $P\mathrm{i}$

f_2, f_3 : shape factors

f_2, the cross section velocity factor,which relate the mean cross section velocity to the center line velocity

f_3, the valley factor, which relates the valley cross section to the centerline ice thickness Z, and the surface width, W.

$W\mathrm{i}$: surface width measured along the contour line through each grid point

$\Delta\dot{Z}\mathrm{i}$: area-averaged ice thickness change rate for each section

$\bar{b}_s\mathrm{i}$: area-averaged mass balance for each section

$S\mathrm{i}$: surface area of segment i

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

By the use of this model, we can obtain the preferable combination of T_s and P_s which give the ice thickness change fitted well to the observed value, i.e. 12m thinning around the terminus. Procedures of the calculation can be summarized as follows. Inputting T_s and P_s as variables of the model, the ice thickness change can be obtained. Practically, we input various combinations of T_s and P_n at the terminus of the glacier as shown in Table 1. T_s on the glacier was estimated from T_s at the terminus by assuming a constant lapse rate (−0.6°C/100m). The value of this lapse rate is taken to lie between that of a standard atmosphere and that of moist air at the air temperature/pressure around the terminus, and it can represent the condition during summer monsoon season on this glacier (Ageta, 1983). The distribution of P_s over the glacier was assumed to be uniform, which was observed in 1978 (Ageta *et al.*, 1980). These calculations were done in steps of one year, fixing each combination of T_s and P_s at the terminus throughout the 11-year run. Each combination of T_s and P_s was used as the mean values during the period from 1979 to 1989.

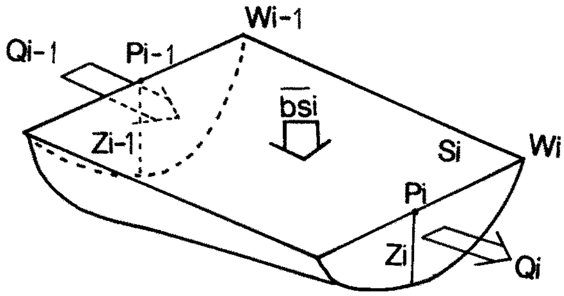


Fig. 8. A section of the glacier, as defined by the model with the symbols in the text. Glacier AX010 is devided into such eight sections (i : 1−8).

4. Discussion

4.1. Climate from 1978 to 1989 around Glacier AX010

In order to evaluate the result of calculation, the observed T_s and P_s at the glacier termini and at the meteorological stations in the same drainage and Kathmandu are shown in Table 2 and Table 3, respectively. The locations of the stations are shown in Fig. 1. Data after 1986 at these stations are not yet published.

In Table 2, the tendency of rise of T_s can be recognized from 1976 to 1978, and also T_s at the meteorological stations in East Nepal show rise from early 1970s to 1980s. On the other hand, no clear trend is found in P_s. Therefore, an average of T_s after 1978 should not be lower than 2.5°C and if T_s rose to 2.6°C, P_s should be 200cm as shown in Table 1. However, such an increase is not realistic according to the variation of P_s as shown in Table 3. Consequently, we can conclude that shrinkage of Glacier AX010 after 1978 occurred under the average climatic condition such that T_s had been 2.5°C and P_s had been 140cm around the glacier terminus. This combination is similar to that in 1978 when the observation on the glacier was carried out.

Actually, inter-annual fluctuation on T_s and P_s might exist. Figures 9 and 10 show the deviations of T_s and P_s from the 1978-1986 mean values at the meteorological stations, respectively. Although the inter-annual variations of T_s and P_s at the non-glacierized area may not be parallel to that at the glacierized area, we used these deviations to evaluate the inter-annual fluctuations. The result of this evaluation is that total ice thickness changes obtained by the

Table 1. Combinations of mean T_s (0.1 °C interval) and P_s at the terminus of Glacier AX010. which give 12 m thinning of the glacier terminus from 1979 to 1989.

T_s (°C)	2.2	2.3	2.4	2.5	2.6	2.7	2.8
P_s (cm)	10	50	90	140	200	280	370

Table 2. T_s (°C) at the glacier termini and at the meteorological stations in East Npal.

station	altitude	year						
	(m a.s.l.)	1976	1977	1978	1979	'71-'77	'78-'86	'80-'86
Glacier AX010	4958	–	–	2.4	–	–	–	–
Glacier AX030	4850	2.5	–	–	–	–	–	–
Chialsa	2770	13.7	14.1	14.9	14.9	14.2(0.5)	15.1(0.3)	15.1(0.3)
Kathmandu	1336	22.7	23.0	23.4	23.5	22.9(0.1)	23.7(0.2)	23.8(0.2)

( ) : standard deviation

Table 3. P_s (cm) at the glacier termini and at the meteorological stations in East Nepal.

station	altitude	year					
	(m a.s.l)	1976	1977	1978	1979	'71-'77	'78-'86
Glacier AX010	4958	–	–	145	–	–	–
Glacier AX030	4850	133	–	–	–	–	–
Chialsa	2770	146	169	182	165	153(20)	168(28)
Kathmandu	1336	118	104	118	112	119(20)	111(12)
Chaurikharka	2619	179	178	133	140	178(20)	161(33)
Pakarnas	1982	145	120	165	151	140(19)	149(17)

( ) : standard deviation

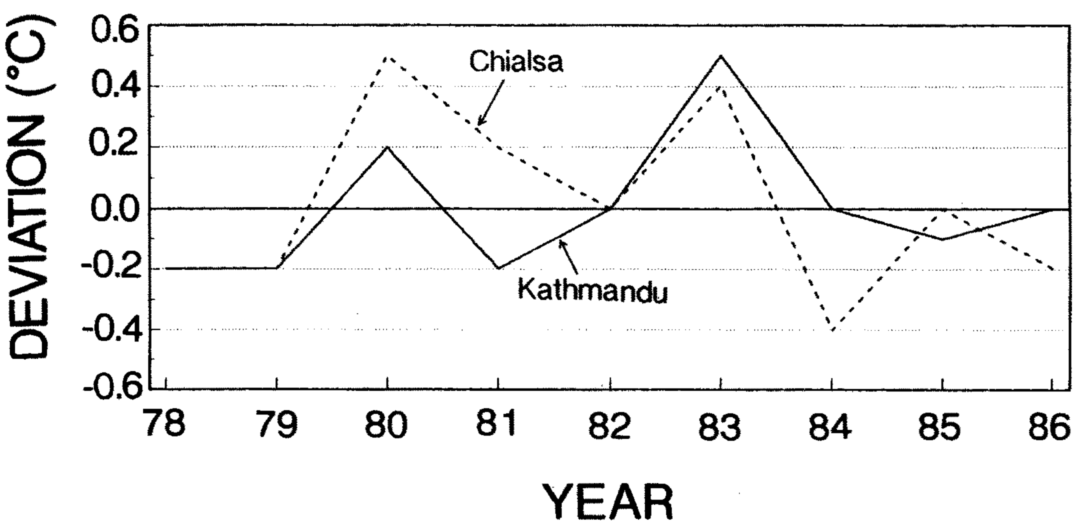


Fig. 9. Deviations of T_s from the 1978–1986 mean values at Kathmandu and at Chialsa.

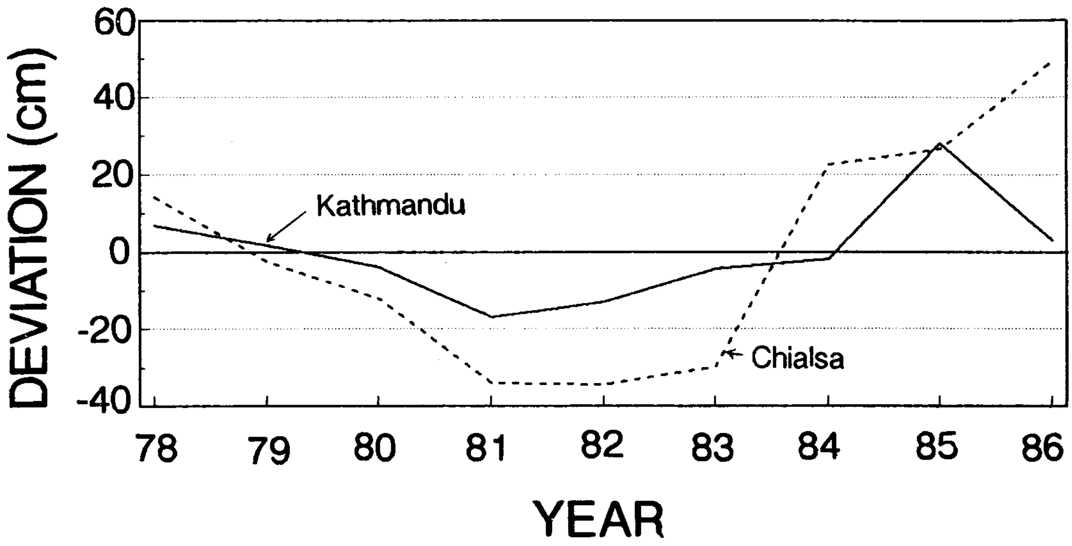


Fig. 10. Deviations of P_s from the 1978—1986 mean values at Kathmandu and at Chialsa.

models considering the inter-annual fluctuation of climatic condition at Chialsa and Kathmandu were 12.1m and 12.5m thinning, respectively. These results are almost equal to that obtained from the average condition. That is to say, the retreat of the glacier can be explained by the average climatic condition through the models.

Figure 11 shows the inter-annual courses of area-averaged annual values of b_s, ice flux and ΔZ around the terminus at the climatic condition mentioned above, which are obtained by the model. As the glacier is under the condition of shrinkage, negative

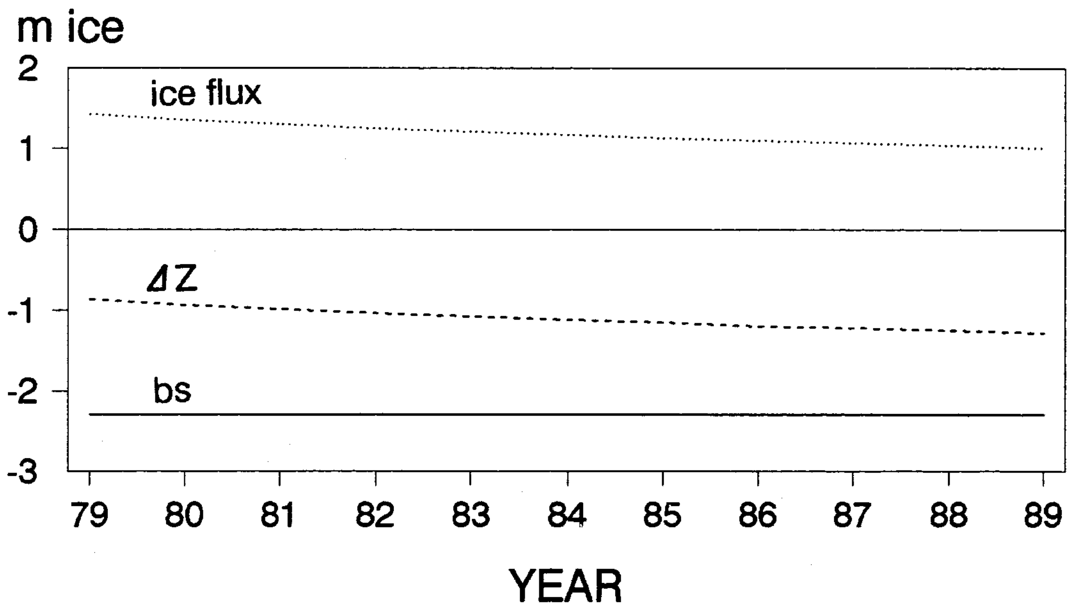


Fig. 11. Inter-annual courses of calculated area-averaged annual values of b_s (solid line), ice flux (dotted line) and ΔZ (broken line) around the terminus in the case that T_s and P_s are 2.5°C, 140cm respectively. Here T_s and P_s are estimated mean values during the period from 1979 to 1989.

balance is not compensated by ice flux from the upstream. Consequently, ice thickness of the glacier is reduced. The more ice thinning is, the less velocity becomes, that is, the less ice flux is led. Inter-relation between ice flux and ΔZ can be seen in this figure.

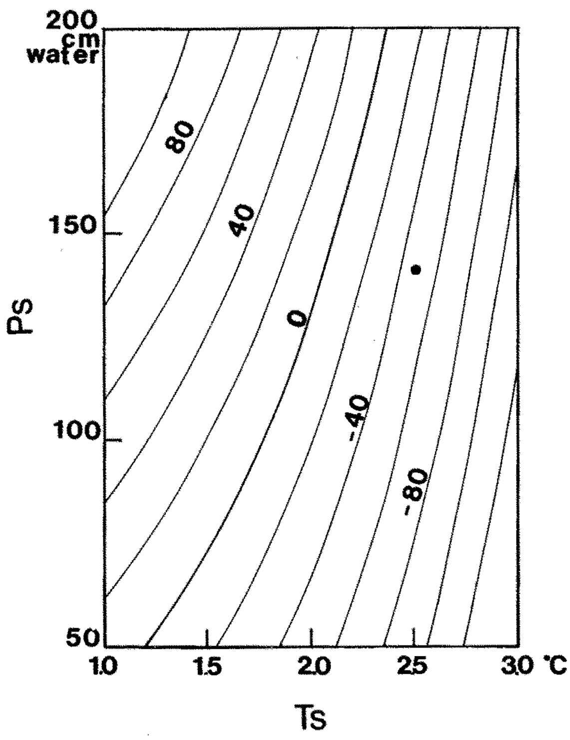


Fig. 12. The relation between combinations of T_s and P_s at the glaier terminus and area-averaged balance in summer ($\bar{b}_s$) for the whole area of Glacier AX010 (isolines of cm water in the figure). A solid circle indicates the average state of the glacier during the period from 1978 to 1989.

Figure 12 shows the relation between combinations of T_s and P_s at the glacier terminus and area-averaged balance in summer ($\bar{b}_s$) for the whole area of Glacier AX010. This result was derived from the equations from (1) to (9), assuming the area-altitude distribution of the glacier surface is steady at the condition in 1978. It can be seen in this figure that $\bar{b}_s$ depends on actual fluctuation of T_s strongly in comparison with that of P_s.

The average state of this glacier during the period from 1978 to 1989 ($\bar{b}_s$: -50 cm/yr) is indicated by a solid circle in Fig.12. The observed area-averaged mass balance for the whole area of the glacier in 1978 (T_s : 2.4°C, P_s : 145cm) and in 1979 were -45cm and -53cm, respectively (Ageta *et al.*, 1980 ; Ageta, 1983). Although T_s and P_s in 1979 at Glacier AX010 were not measured, those at Chialsa and Kathmandu were similar to those in 1978 as shown in Tables 2 and 3. Considering these values, the state of the glacier (T_s, P_s, $\bar{b}_s$) had not changed so much since 1978, and the rate of retreat since 1978 was possibly higher than that before 1978 due to T_s rising as shown in Table 2.

On the other hand, T_s at the meteorological stations in East Nepal increased from 1978 to 1980s by 0.2–0.4°C as shown in Table 2. If T_s around the glacier also had increased by 0.2–0.4°C, ice thickness decrease would be greater than that was observed. Consequently, there is a possibility that T_s at the glacierized area did not fluctuate parallel to T_s at the non-glacierized area. However, there are other possibilities which caused this discrepancy. We will discuss this point in the following section.

4.2. Evaluation of the models

In the present model, we assumed that balance in summer was almost equivalent to annual balance, as we mentioned in Chapter 3, and did not consider the climatic condition in winter from October to next May. However, if winter snowfall is enough to remain until summer monsoon season, snow cover on the glacier surface reduces ablation of the glacier ice due to its high albedo. In fact, heavy snowfalls in winters of 1979-80, 83-84 and 85-86 in Nepal have been reported by Takahashi *et al.* (1987) and Seko and Takahashi (1991). Therefore there is a possibility that winter snowfall increased accumulation in winter and reduced ablation in summer in several years during the studied period due to the above effect. In this case, T_s obtained by the model calculation is lower than the actual one. In order to evaluate the order of magnitude of this effect, we assume that 80% of annual precipitation is P_s and that the remainder falls as snow and accumulates on the glacier without ablation within the period from Oct. to May, every year. Put P_s as 140cm then surplus accumulation is led to 35cm. The result of the calculation of 11-year run shows preferable T_s is 0.2°C higher than that obtained by the procedure described in the former sections.

On the other hand, parameterization of the flow model used here is based on the flow survey results of one year only. Although this model consists of various parameters such as shape factors,flow law parameters and others, no verification on them was made. Lack of ice thickness and consecutive flow data of the glacier make it difficult to establish a concrete flow model. Since ice thickness estimation from surface velocity using flow law is dependent especially on the values of the parameters, direct measurement of ice thickness are highly required.

5. Conclusion and remarks

1) Glacier AX010 in Shorong Himal retreated about 30m from 1978 to 1989. This value of retreat can be translated into 12m thinning of ice around the glacier terminus by the use of a simple geometrical argument.

2) The ice thickness change was correlated with mean summer temperature (T_s) and summer precipitation (P_s), through the simple models of mass balance and ice flow. By the model calculation, it can be concluded that the shrinkage of the glacier was caused under the climatic condition similar to that in 1978, such as T_s 2.5°C, P_s 140cm in average since 1978 around the glacier terminus, and that the rate of retreat possibly increased relative to that in the years before 1978.

3) T_s at the meteorological stations in the non-glacierized area increased by 0.2−0.4°C in average since 1978, however, T_s around the glacier terminus obtained by model calculation increased by only 0.1°C. Although there remains a possibility that T_s at the glacierized area had not increased in the same way as that of the non-glacierized area had increased, it is probable that T_s obtained from the model calculation was lower than an actual one due to the heavy snowfall in several winters during the studied period.

The relation between the climate at the glacierized area and that at the non-glacierized area in the Nepal Himalaya may not be simple owing to complicated geographical situation. In order to link the state of glaciers and the climatic data at the non-glacierized area, further monitorings of glacier fluctuations and meteorological observations at glacierized area are required.

Acknowledgments

We wish to express our sincere gratitude to Dr. T. Ohata, Water Research Institute, Nagoya Univ. for many useful suggestions and comments on our first draft.

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