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Glaciological observations on Rikha Samba Glacier in Hidden Valley, Nepal Himalayas, 1998 and 1999.

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Abstract

Glacier fluctuation, surface flow velocity and mass balance were observed at Rikha Samba Glacier in Hidden Valley, 1998 and 1999, which was selected as the representative glacier in the west Nepal Himalayas. The glacier terminus has shown a continuous retreat since 1974, and the retreat rate possibly increased in the 1990s. The analysis of surface flow velocity for one year, which was first obtained, suggests the large contribution of basal sliding. The flow speeds in 1998/99 were similar to those in 1974 though the glacier thickness has diminished. Mass balance and meteorological variables were also first observed for one year from October 1998. The finding of a large negative mass balance may support the shrinkage of the glacier. Preliminary results are presented in this paper.

1. Introduction

It should be noted that the Himalayan glaciers are very important for water circulation in the area as well as for changes in global sea level. In Nepal, for instance, most of the rivers are nourished by glaciers in the Himalayas, in particular during the dry season when water demand is intense. On the other hand, it is estimated that the shrinkage of glaciers in the Asian highland accounts for 20% of the increase in sea water (*e.g.,* Meier, 1984; United States Department of Energy, 1985). It remains unclear, however, how the glaciers contribute to the global and/or regional water circulation since the glaciological and meteorological information on this region has been quite limited.

Rikha Samba Glacier in Hidden Valley (28°50′N, 83°30′E; Fig. 1), which has been surveyed intermittently since 1974 (Nakawo *et al.,* 1976; Fujii *et al.,* 1996; Fujita *et al.,* 1997), was selected for glacier monitoring. Mass balance, surface flow and meteorological variables had also been observed on and around the glacier in 1974 (Fujii *et al.,* 1976; Nakawo *et al.,* 1976; Shrestha *et al.,* 1976). In order to clarify the recent fluctuations of the glacier in the 1990s, surveys of the glacier were carried out in October of 1998 and 1999. In addition, mass balance, surface flow velocity and meteorological variables were observed for one year. Changes in the glacier geometry, meteorological data and mass balance are presented in this paper.

2. Observations and results

2.1. Change in terminus position

Surveys of the terminus position were carried out in August 1974 (Nakawo *et al.,* 1976), October 1994 (Fujita *et al.,* 1997), 1998 and 1999 (this study). The change in terminus periphery shows the continuous retreat of the glacier terminus since 1974 (Fig. 2). Changes in horizontal distance along the bottom of a valley and retreat rates in each observation period are summarized in Table 1 which shows that the

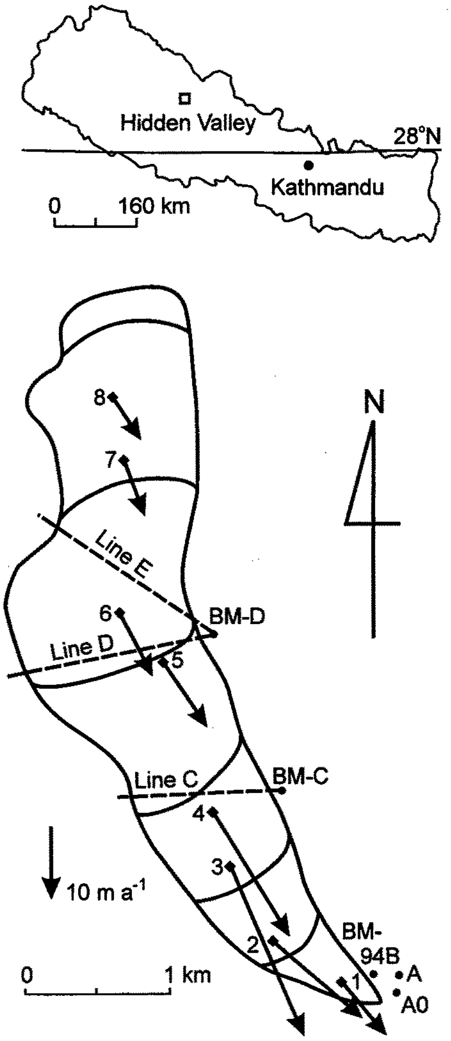

Fig. 1. Map of Rikha Samba Glacier. Surface profiles were surveyed along broken lines. Rhombuses with number and arrows denote mass balance stakes and surface flow velocities during 1998 and 1999. Circles denote bench marks.

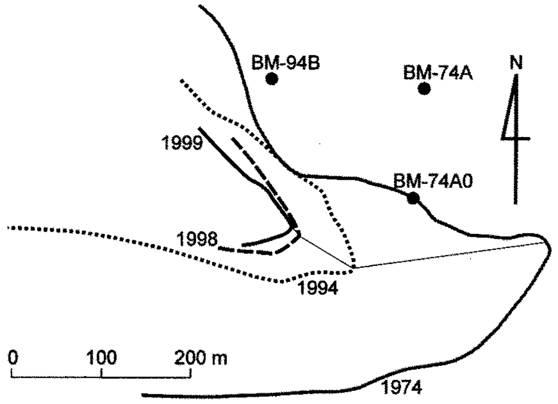

Fig. 2. Change in the terminus periphery of Rikha Samba Glacier since 1974. Circles denote bench marks. Change in horizontal distance was obtained along the thin line, which almost corresponds to the bottom of a valley.

Table 1. Change in horizontal distance and retreat rate of the terminus of Rikha Samba Glacier since 1974.

Period	Change in horizontal distance (m)	Retreat rate (m a^{-1})
1974 - 1994	215.8	10.8
1994 - 1998	72.8	18.2
1998 - 1999	11.5	11.5

retreat rate of the terminus position accelerated in the 1990s.

2.2. Change in surface elevation

Surface elevations along 5 straight lines had been surveyed in 1974 (Nakawo *et al.,* 1976). Three of them (shown in Fig. 1) were surveyed again in 1994 (Fujita *et al.,* 1997). In this study, only Line C was surveyed in 1999. Figure 3 depicts the changes in surface elevation along Lines C, D and E since 1974, showing increased, thinning at higher altitude. An additional profile along Line C in 1999 also suggests less thinning. It is remarkable that the surface elevation remained unchanged only around middle part of the glacier despite its shrinking tendency. It may be probable that longitudinal compression and/or kinematic waves might have prevented surface lowering around Line C. We have no evidence, however, to discuss these changes with glacier dynamics.

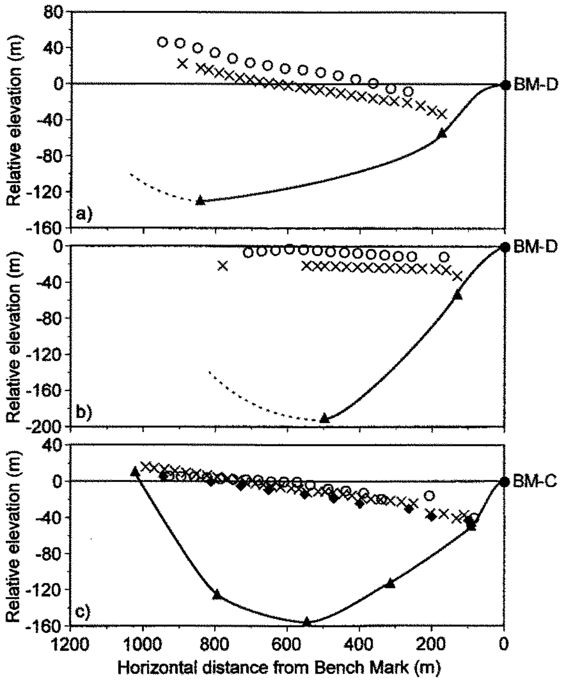

Fig. 3. Surface profiles for 1974 (circles), 1994 (crosses), 1999 (solid rhombus along Line C) and bed rock (triangles) along lines E (a), D (b) and C (c) of Rikha Samba Glacier looking upstream. The solid circle denotes bench mark for each line.

2.3. Surface flow speed

Surface flow speed on the Rikha Samba Glacier had been observed during the period from 10 July to 25 August 1974 (47 days; Nakawo *et al.,* 1976). In this study, surface flow velocities were observed at 8 altitudes by surveying the positions of mass balance stakes in October of 1998 and 1999. Surface flow velocity at each stake is shown in Fig. 1. Figure 4 shows the altitudinal distribution of surface flow speeds in 1974 and 1998/99. The actual annual flow speeds in 1974 should be smaller than those shown in the figure because the 1974 speeds were converted from the data measured in summer when the flow speed was considered higher. The figure suggests that the surface flow speeds on Rikha Samba Glacier in 1998/99 were equal or larger than those in 1974.

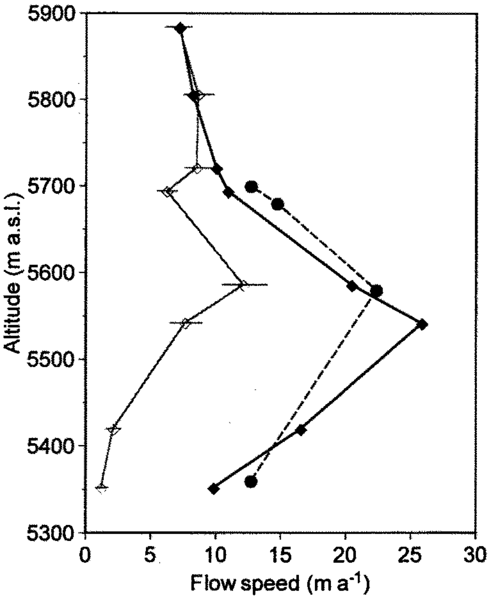

Fig. 4. Surface flow speeds in 1974 (solid circles with broken line; after Nakawo *et al.,* 1976) and in 1998/99 (solid rhombus with solid line) of Rikha Samba Glacier. Flow speed estimated from the ice deformation is also shown (open rhombus with gray line).

Surface flow speed due to ice deformation can be estimated from ice thickness h (m), surface slope α and ice temperature as (Paterson, 1994):

$$u_s - u_b = \frac{2A}{n+1}(\rho g \sin\alpha)^n h^{n+1}. \tag{1}$$

Here, u_s and u_b are the velocities at the surface and base. n, ρ and g are a constant (assumed to be 3), the density of ice (910 kg m^{-3}), and gravitational acceleration (9.8 m s^{-2}), respectively. Parameter A (s^{-1} kPa^{-3}) depends on ice temperature, which is assumed to be represented by temperature at 20 m depth. Ice temperature at a certain altitude was esti-

Table 2. Stake No., altitude, parameter A, ice thickness, slope angle, calculated and observed surface flow speed on Rikha Samba Glacier during 1998/99. Asterisks in ice thickness denote extra/interpolated values.

Stake No.	Altitude (m a.s.l.)	A ($\times 10^{-15}$ s^{-1} kPa^{-3})	Ice thickness (m)	Slope angle	Calculated flow speed (m a^{-1})	Observed flow speed (m a^{-1})
1	5353	2.26	54*	10.3°	1.2	9.8
2	5421	2.15	79	7.5°	2.1	16.5
3	5543	1.96	126*	6.4°	7.6	25.8
4	5586	1.89	143	6.4°	12.1	20.4
5	5694	1.71	161	4.5°	6.2	10.9
6	5721	1.67	170	4.7°	8.5	10.0
7	5806	1.54	154	5.5°	8.6	8.2
8	5884	1.44	140*	6.0°	7.1	7.2

mated from the bore hole temperature measured at 5780 m a.s.l. in 1994 (-5.1℃; Fujii *et al.*, 1996) and a lapse rate of ice temperature (assumed to be 6.0℃ km^{-1}). Ice thickness h (m) was obtained by using a 5 MHz radio-echo sounder (constructed at Ohio State University). Detailed methods are described in Casassa (1992). These values at each stake site are summarized in Table 2. Calculated surface flow speeds due to ice deformation are also shown in Fig. 4. The figure suggests the possibility of basal sliding below 5700 m a.s.l. The increase in surface flow speed under thinning ice thickness would be caused by a change in the basal sliding condition such as increase in meltwater, though we have no data to discuss this problem.

2.4. *Meteorological conditions during 1998/99*

An automatic weather station (Aanderaa Instruments, Norway) was installed near the terminus of Rikha Samba Glacier in October 1998 (5267 m a.s.l.). Air temperature, solar radiation, wind speed and precipitation were monitored during one year at intervals of one hour. Daily mean variables are shown in Fig. 5. Annual mean values are summarized in Table 3. Relative humidity and snow depth were not obtained. Although the meteorological observation had been conducted during a short period in 1974 (Shrestha *et al.*, 1976), the present observation provides the first meteorological data in this region for one year. The figure suggests the typical climate in the Nepal Himalaya such as clear sky and windy days during winter, while persistent clouds and calm days prevail during the monsoon summer.

Table 3. Annual average/total variables at 5267 m a.s.l. near the terminus of Rikha Samba Glacier, Hidden Valley for one year from 1 October 1998 to 30 September 1999.

	Average/total value
Air temperature	-4.6 (℃)
Solar radiation	263 (W m^{-2})
Solar radiation at the top of atmosphere	370 (W m^{-2})
Wind speed	4.4 (m s^{-1})
Precipitation	447 (mm w.e.)

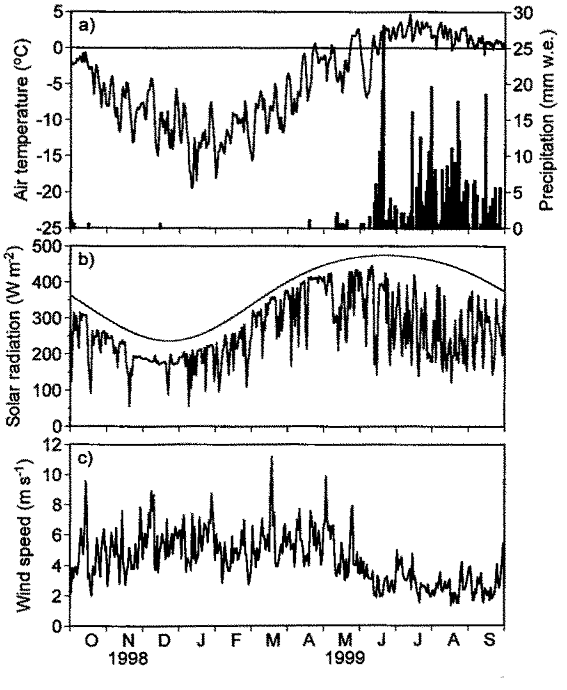

Fig. 5. Daily mean air temperature (line in a), solar radiation (black line in b), calculated solar radiation at the top of atmosphere (gray line in b), wind speed (line in c), and daily amount of precipitation (bars in a) observed at 5267 m a.s.l. near the terminus of Rikha Samba Glacier for one year from October 1998 to September 1999.

Since a tipping bucket does not detect solid precipitation, we can not affirm the absence of precipitation in winter as the figure shows. However, the annual amount of precipitation gathered by a totalizer (450 mm w.e.) installed near a AWS was nearly equal to that observed by a tipping bucket (447 mm w.e.). It is plausible, therefore, to assume few instance of precipitation in winter. It is a significant problem for the glacier mass balance whether precipitation occurred as rain or snow. Higuchi (1977) has also discussed the effect of snowfall during the night on the mass balance of Rikha Samba Glacier. Figure 6 shows the hourly averaged precipitation and air temperature during June to September 1999. It is considered that the high precipitation around 10 o'clock suggests the melt of snow fallen in the previous night. Our precipitation data, therefore, should be used carefully.

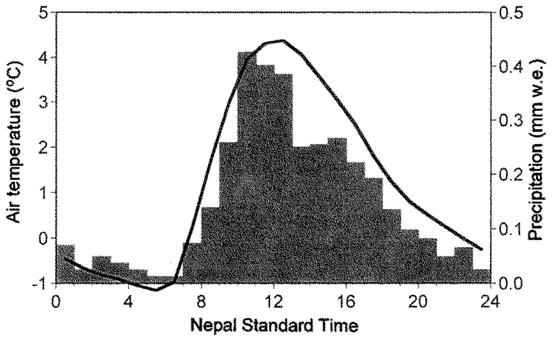

Fig. 6. Diurnal changes in hourly mean air temperature (solid line) and precipiation (gray histogram) at 5267 m a.s.l. near the terminus of Rikha Samba Glacier for the period from June to September 1999.

2.5. *Mass balance during 1998/99*

Eight stakes were installed on Rikha Samba Glacier in October 1998 (Fig. 1). Stake height and snow thickness were measured in October of 1998 and 1999. An ice core taken at 5780 m a.s.l. in 1994 suggested that the formation of superimposed ice occurred even in the accumulation area (Fujii *et al.*, 1996). Superimposed ice in the accumulation area implies that a significant amount of refrozen water contributes to the glacier mass balance (Fujita *et al.*, 1996) Specific mass balance (b mm w.e.) at a certain stake site is calculated based on the amount of superimposed ice as:

$$b = \rho_s \Delta S + \rho_i \Delta I. \qquad (2)$$

Here, ρ_s and ρ_i are the densities of snow (350 ± 50 kg m^{-3}). and ice (870 ± 40 kg m^{-3}). ΔS and ΔI are the changes in snow thickness (m) and ice level (m), which were obtained from stake and pit measurements.

The accumulation (c mm w.e.) at each stake site is evaluated from the daily precipitation record, daily mean air temperature (Fig. 5a.), lapse rate of air temperature (assumed to be 6.0℃ km^{-1}) and probability of snowfall depending on air temperature. The relationship between the percentage (%) of snowfall and air temperature is assumed to be expressed by a linear equation as:

$$P_s = \left[1 - \frac{T_a}{T_c}\right] \times 100 \qquad (0 < T_a < T_c). \qquad (3)$$

Here, P_s is percentage of solid precipitation. T_a and T_c are air temperature (℃) and a critical air temperature (℃) at which all precipitation falls as rain. This critical temperature T_c depends on the precipitation system in each region and season. Since T_c has not been observed in Hidden Valley, we evaluate the error associated with the assumption of critical temperature, which ranges from 3 to 6℃ (Ageta *et al.*, 1980; Ueno *et al.*, 1994). It is also assumed that the precipitation amount does not change with altitude. Ablation ($a = b - c$, mm w.e.) is obtained as a residual portion from mass balance and accumulation.

These values at each stake site and the altitudinal distribution are shown in Table 4 and Fig. 7. The mass balance profile during summer of 1974 (about 50 days from the middle of July to the end of August) is also shown *in the figure* (after Fujii *et al.*, 1976). A large negative balance during 1998/99 suggests the shrinking tendency of the glacier in the 1990s.

Table 4. Stake No., altitude, mass balance, accumulation and ablation at each stake site on Rikha Samba Glacier during 1998/99.

Stake No.	Altitude (m a.s.l.)	Mass balance (mm w.e.)	Accumulation (mm w.e.)	Ablation (mm w.e.)
1	5353	-3454 ± 159	356 ± 40	-3810 ± 164
2	5421	-3004 ± 139	391 ± 30	-3395 ± 142
3	5543	-1394 ± 62	432 ± 16	-1826 ± 64
4	5586	-936 ± 41	443 ± 12	-1379 ± 43
5	5694	-388 ± 9	459 ± 5	-846 ± 10
6	5721	-271 ± 0	461 ± 4	-732 ± 4
7	5806	27 ± 20	465 ± 1	-438 ± 20
8	5884	81 ± 18	466 ± 0	-385 ± 18

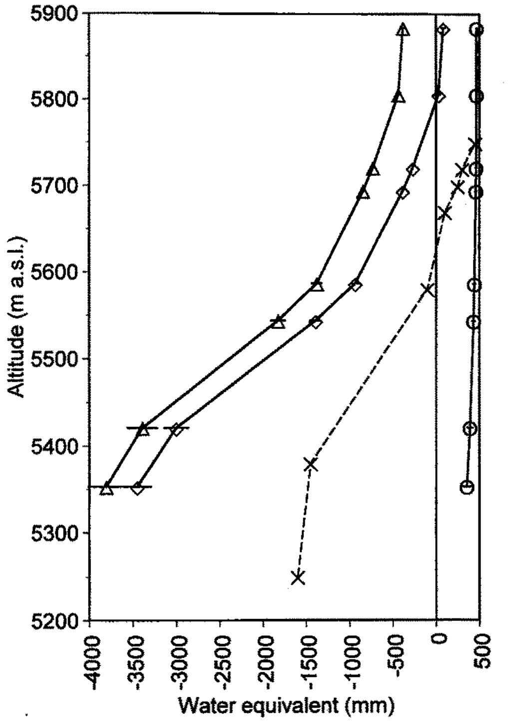

Fig. 7. Altitudinal profiles of mass balance (rhombuses), accumulation (circles) and ablation (triangles) during one year from October 1998 with error bars. Mass balance profile during summer of 1974 is also shown (crosses with broken line; after Fujii et al., 1976)

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