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Shrinkage of Glacier AX010 in Shorong region, Nepal Himalayas in the 1990s

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Abstract

Areal extent, terminus position, surface flow speed and mass balance were observed every year since 1995 at Glacier AX010 in Shorong region, Nepal Himalayas after the first observation in 1978. Areal extent and terminus position showed that the glacier has shrunk since 1978, and that the shrinkage rate has accelerated in the 1990s. The surface flow speed suggests the thinning of glacier thickness since 1978. Mass balance and air temperature data also support that the shrinkage tendency seemed to accelerate in the 1990s.

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 particular during the dry season when water demand is intense. On the other hand, it was estimated that the shrinkage of glaciers in the Asian highland accounted for 20% of the increase in sea water during the 20th century (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.

Glacier AX010 in Shorong region (27°42′N, 86°34′E; Fig. 1) is one of the most investigated glaciers in the Nepal Himalayas. Intensive observations related to mass balance (Ageta *et al.*, 1980), surface albedo (Ohata *et al.*, 1980), heat balance (Ohata and Higuchi, 1980), ice temperature (Tanaka *et al.*, 1980) and ice flow (Ikegami and Ageta, 1991) were first conducted in 1978. Changes in the glacier terminus and area have been monitored intermittently since 1978 and predicted by using a model for glacier flow (Kadota and Ageta, 1992; Kadota *et al.*, 1993; 1997). Ageta *et al.* (1980) observed and discussed the characteristics of mass balance of a summer-accumulation type glacier for the first time in the Himalayas, which was influenced by the summer monsoon. Based on the observational results, Ageta and Higuchi (1984) and Ageta and Kadota (1992) presented a simple mass balance model using precipitation and air temperature. They found the high sensitivity of mass balance to summer temperature due to summer accumulation. Kayastha *et al.* (1999) suggested the high sensitivity of mass balance to global radiation and surface albedo by using an energy-balance model for this glacier. Additionally, Kayastha *et al.* (2000) discussed the relationship between the positive degree-day sum of air temperature and the ablation of the glacier in order to evaluate glacier mass balance in the Himalayan region where meteorological data were limited. On the other hand, Takeuchi *et al.* (1998) discussed the relationship between snow algae community and glacier mass balance. They suggested that the snow algae community could be useful as an indicator of summer mass balance and the equilibrium line of the glacier.

In order to detect the recent fluctuation of the glacier in the 1990s, monitoring of the glacier was conducted every

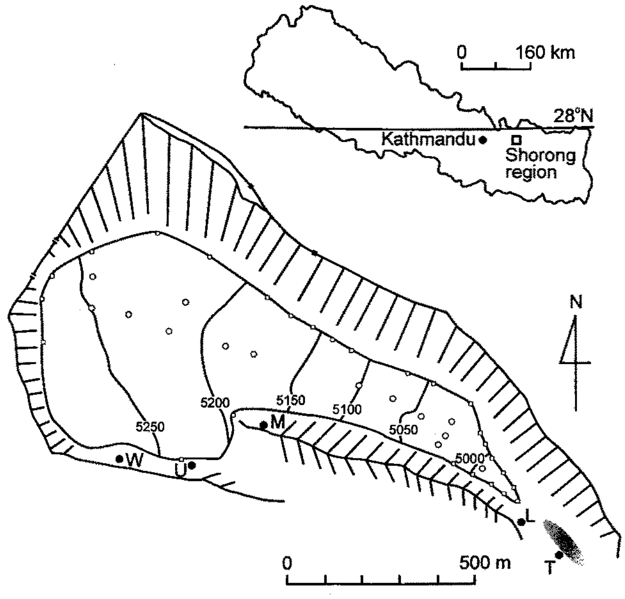

Fig. 1. Location of Shorong region and topographical map of Glacier AX010 surveyed in 1999. Solid and open circles denote the bench marks for survey and mass balance stakes in 1999. Open squares denote glacier boundary surveyed in 1999. Hatched gray denotes a pond located near the terminus.

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**Present address: Institute for Hydrospheric-Atmospheric Sciences, Nagoya University, Nagoya 464-8601 Japan year from 1995 to 1999. After the installation of mass balance stakes in June 1995, observations (mass-balance measurement and survey) and maintenance of stakes were carried out every October (except November of 1997). People who joined the observation of this glacier were listed in Nakawo *et al.* (1997) and Ageta *et al.* (2001). This paper presents preliminary results of glacier fluctuation, surface flow speed, mass balance and air temperature.

2. Observational results

2.1. Change in glacier extent

Areal extent of the glacier was measured intermittently in 1978, 1996 and 1999 by topographical survey (Fig. 2). Acceleration of shrinkage in the late 1990s is suggested by mean annual rate of the areal change in Table 1.

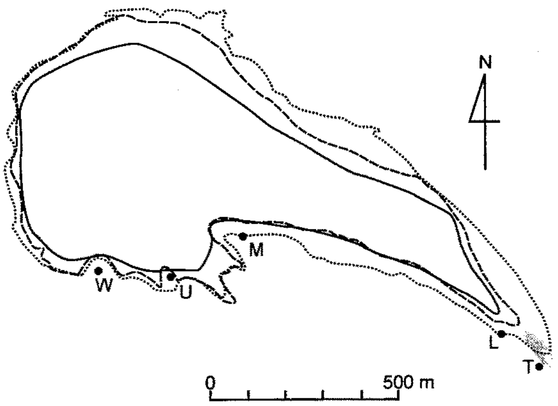

Fig. 2. Areal extents of Glacier AX010 surveyed in 1978 (dotted line; after Ageta *et al.*, 1980), 1996 (broken line; after Kadota *et al.*, 1997) and 1999 (solid line; this study). Solid circles denote the bench marks for survey. Hatched gray denotes a pond located near the terminus.

Table 1. Area, areal change and its annual rate of Glacier AX010 since 1978.

Year	Area (km^2)	Areal change (km^2)	Rate of areal change ($\times 10^4$ m^2 a^{-1})
1978	0.57*		
		-0.06**	-0.5
1991	0.51**		
		-0.03**	-0.6
1996	0.48**		
		-0.06	-2.0
1999	0.42		

*data from Ageta *et al.* (1980).
**data from Kadota (1997).

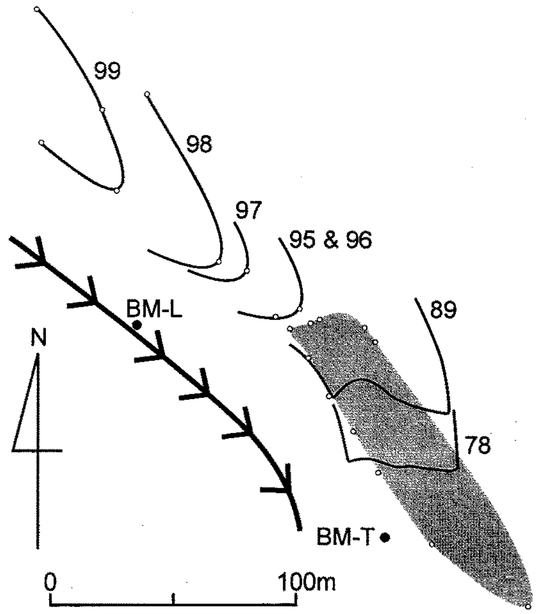

Fig. 3. Change in terminus periphery of Glacier AX010 surveyed in 1978 (after Ageta *et al.*, 1980), 1989 (after Kadota *et al.*, 1993) and every year from 1995 (this study). Peripheries in 1995 and 1996 are almost same position. Solid and open circles denote the bench marks for survey and surveyed points. Hatched gray denotes a pond located near the terminus. Thick solid line denotes ridge beside the glacier.

Table 2. Retreat in horizontal distance and its annual rate of the terminus of Glacier AX010 since 1978.

Year	Retreat distance (m)	Retreat rate (m a^{-1})
1978		
	} 30*	2.7
1989		
	} 28*	14.0
1991		
	} 12	3.0
1995		
	} ≈0	≈0.0
1996		
	} 26	25.9
1997		
	} 13	13.0
1998		
	} 51	50.9
1999		

*data from Kadota *et al.* (1997).

The change in terminus periphery shows the continuous retreat of the glacier terminus since 1978 (Fig. 3). Retreat in horizontal distance along stream line, and retreat rates of each observation period are summarized in Table 2. The effect of recent global warming in the Himalayas cannot be affirmed from the rapid retreat of the glacier terminus, because the terminus position would be affected by complex processes such as the mass balance, topography of bed rock and basal sliding. The retreat rates of the terminus position, however, seem to accelerate in the late 1990s.

2.2. Surface flow speed

Surface flow speeds were obtained by the survey of stakes installed on the glacier. Since the observation periods differ from year to year, annual flow speeds are converted from the average daily speed during each observation period as shown in Fig. 4. The figure, in which all data are plotted, shows that the surface flow speeds obtained in this study have clearly decreased rather than those observed in 1978/79 (Ikegami and Ageta, 1991) at all elevations. It is considered that thinning of glacier thickness would cause the decrease of flow speed. The flow speeds during the monsoon season of 1995 were the same as those observed in other years even though surface flow in the melting season is generally considered to be faster due to basal sliding than the annual ones. Since it was suggested that basal sliding would have a significant role in the surface flow speed of this glacier by Kadota *et al.* (1997), more detailed observation and analysis

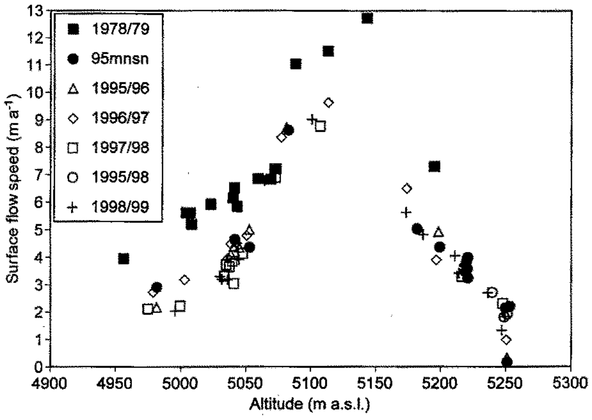

Fig. 4. Altitudinal distributions of surface flow speeds on Glacier AX010. '95mnsn' denotes the flow speed observed in the period of summer monsoon season from June to October in 1995. Annual flow speeds are converted from the average daily speed during each observation period.

concerning glacier dynamics are required in order to evaluate the relationship among glacier fluctuations such as mass balance, flow speed, ice thickness and terminus position.

2.3. Mass balance

Mass balances during each observation period were obtained by stake and pit measurements. Altitudinal distributions of specific mass balance (mass balance profile) are shown in Fig. 5. Distribution maps of specific mass balance are drawn for each observation period as shown in Fig. 6. Areal averaged mass balances are calculated from the area-balance relations in Fig. 6, and long-term mass balances since 1978 are calculated from the changes in the glacier volume assuming the ice density (870 kg m^{-3}) shown in Fig. 7. Mass balance between 1978 and 1979 and volume change from 1978 to 1996 are according to Ageta (1983) and Kadota (1997), respectively. No positive annual balance has been seen since 1978 (Fig. 7). It is considered that the drastic retreat of terminus between 1998 and 1999 would be caused by the large negative balance of 1997/98. The negative mass balances would clearly bring about shrinkage of the glacier area and the continuous retreat of the terminus since 1978.

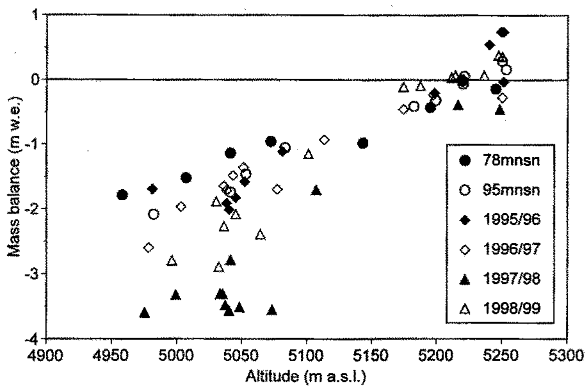

Fig. 5. Altitudinal distributions of specific mass balance of Glacier AX010. '78mnsn' and '95mnsn' denote the mass balance observed in the period of summer monsoon season in 1978 (June to September) and 1995 (June to October), respectively. Others correspond to the annual balance from October to next October (except November of 1997).

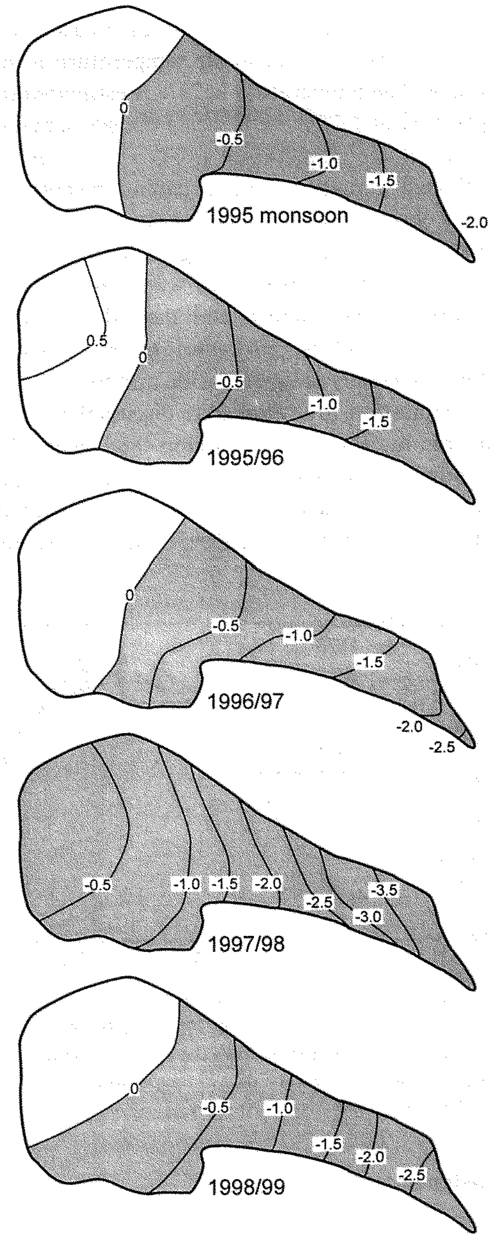

Fig. 6. Areal distributions of specific mass balances of Glacier AX010 since the monsoon season in 1995. A hatched part denotes the negative mass balance area. Contour lines denote the mass balance in m w.e. Measured periods are the same as in Fig. 5.

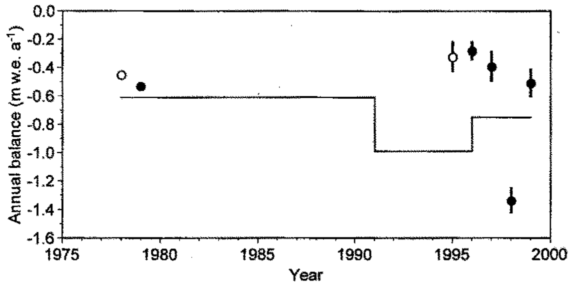

Fig. 7. Areal averaged annual balance of Glacier AX010 since 1978. Open and solid circles denote seasonal (monsoonal) and annual balances. Thick vertical bars denote the error range of calculations for the assumption of balance values at the highest and the lowest zones in Fig. 6. Connected solid line denotes averaged annual balance for each period obtained from the volume differences among 1978, 1991, 1996 and 1999.

2.4. *Air temperature*

Air temperature was observed at 5247 m a.s.l. beside the bench mark U. Monthly mean air temperature is summarized in Fig. 8. The temperature in 1978 is estimated from the air temperature at 4958 m a.s.l. beside the bench mark T and a lapse rate of air temperature (6.0℃ km^{-1}; Ageta *et al.*, 1980). Although 'climatic warming' can not be detected from a few years observation, the summer air temperatures (June to August) in the late 1990s were higher than in 1978. Therefore, these high air temperatures would have caused the large negative mass balance and then the rapid glacier shrinkage in the 1990s. However, other meteorological parameters, especially solar radiation and surface albedo as well as precipitation, are required to discuss the relationship between the meteorological forcing and mass balance, because it is pointed out that the radiative heat plays an important role in the heat balance on glaciers located in the lower latitude (Kayastha *et al.*, 1999; Fujita and Ageta, 2000).

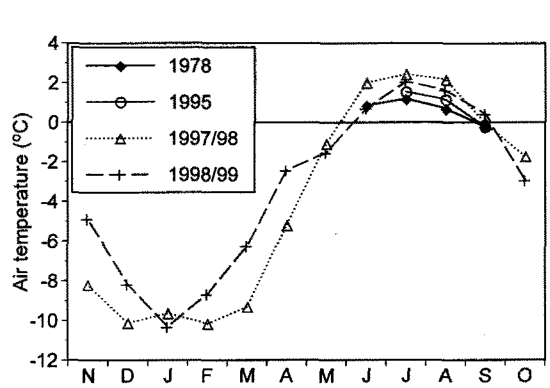

Fig. 8. Monthly mean air temperature obtained at 5247 m a.s.l. of Glacier AX010 in 1995, 1997/98 and 1998/99. Temperature in 1978 was estimated from the air temperature at 4958 m a.s.l. and a lapse rate of air temperature (6.0℃ km^{-1}; Ageta *et al.*, 1980).

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