HYDROLOGICAL PROCESSES
Hydrol. Process. **22**, 2953–2958 (2008)
Published online 8 October 2007 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/hyp.6865

Rapid decrease of mass balance observed in the Xiao (Lesser) Dongkemadi Glacier, in the central Tibetan Plateau

Jianchen Pu,[1,2] Tandong Yao,[2,1] Meixue Yang[1,2]* Lide Tian[2,1] Ninlian Wang,[1,2] Yutaka Ageta[3] and Koji Fujita[3]

[1] *Key Laboratory for Cryosphere and Environment, Cold and Arid Regions Environmental and Engineering Research Institute, CAS, Lanzhou 730000, China*
[2] *Environmental and Process Laboratory, Institute of Tibetan Plateau Research, CAS, Beijing 100085, China*
[3] *Graduate School of Environmental Studies, Nagoya University, Nagoya 464-8601, Japan*

Abstract:

The mass balance of the Xiao (Lesser) Dongkemadi Glacier located in the Tanggula Mountains, of the central Qinghai-Tibetan Plateau has been monitored since 1989. The results show that the mass balance of the glacier has recently shown a deficit trend, and that the glacial terminus was also retreating. Positive mass balance of the glacier was dominant during the period 1989–1993, and the accumulated mass balance reached 970 mm. However, negative mass balance of the glacier has occurred since 1994, except for the large positive mass balance year 1997. The mass balance was −701 mm in 1998, an extremely negative glacier mass balance year. The equilibrium line altitude showed a significant increasing trend. The mass balance of the glacier has changed from a significantly positive mass balance to a strongly negative mass balance since 1994. Meteorological data suggest that the rapid decrease in the mass balance is related to summer season warming. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS Xiao Dongkemadi Glacier; mass balance; glacier retreat; Tibetan Plateau

Received 12 January 2007; Accepted 5 July 2007

INTRODUCTION

The Tibetan Plateau, known as the roof of the world, has been experiencing rapid warming in recent decades, and this warming is more apparent at higher elevations (Liu and Chen, 2000). The alpine glaciers on the Tibetan Plateau have been substantially impacted by the warming trend. A recent study has shown that the rapid warming since the 1990s has resulted in a sharp retreat of glaciers on the Tibetan Plateau (Yao *et al*., 2004). The change in glacier mass balance on the Tibetan Plateau can serve as a signal of local climatic change. Studies have shown that the Qiyi glacier in the Qilian Mountains and the No.1 glacier at the headwater of the Urumqi River in Tianshan, Xinjiang, were experiencing negative mass balance owing to the recent warming (Li *et al*., 2003; Jiao *et al*., 2004; Pu *et al*., 2005). Continuous observation of the mass balance of the alpine glacier, Xiao Dongkemadi, in the middle of the Tanggula Montains, has been carried out since 1989 (Fujita *et al*., 1996, 2000). By 2003, mass balance records had been collected for 14 years, the longest data series for the Tibetan Plateau. Monitoring is ongoing, supported by the Natural Science Foundation of China. In this paper, variations in the glacier mass balance and glacier terminus of Xiao Dongkemadi glacier are discussed.

* Correspondence to: Meixue Yang, State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, CAS. E-mail: mxyang@lzb.ac.cn

LOCATION OF THE XIAO DONGKEMADI GLACIER AND MASS BALANCE OBSERVATION

The Xiao (Lesser) Dongkemadi Glacier (33°04′N, 92°05′E) is located at the headwaters of the Dongkemadi river, a tributary at the upper reaches of the Buqu river near the Tanggula pass (Figure 1). This Xiao Dongkemadi glacier converges with the Da (Greater) Dongkemadi glacier at the glacier terminus. The glacier area is 1·767 km^2, with a length of 2·8 km and an average width of 0·5–0·6 km. The elevations of the summit and the terminus of the glacier are 5926 and 5380 m a.s.l., respectively, with a relative height difference of 546 m. With a gentle surface and without any avalanche or surface moraines, the glacier is an ideal place for mass balance study (Pu and Yao, 1993). According to the automatic meteorological station data observed near the equilibrium line (5600 m a.s.l.) on the glacier, the annual precipitation and air temperature are 302 mm and −9·8 °C, respectively. Only 21 days showed a daily average air temperature above 0 °C, and maximum air temperature was 3·5 °C. The melting period of the glaciers in the Tanggula Mountains is very short (Pu *et al*., 1995). The mass balance of the Xiao Dongkemadi glacier has been monitored since 1989.

The mass balance of a glacier is the difference between the annual accumulation and ablation of a glacier in a mass balance year. Practically, a mass balance year usually starts at the end of the summer ablation in September/October. The mass balance, accumulation and

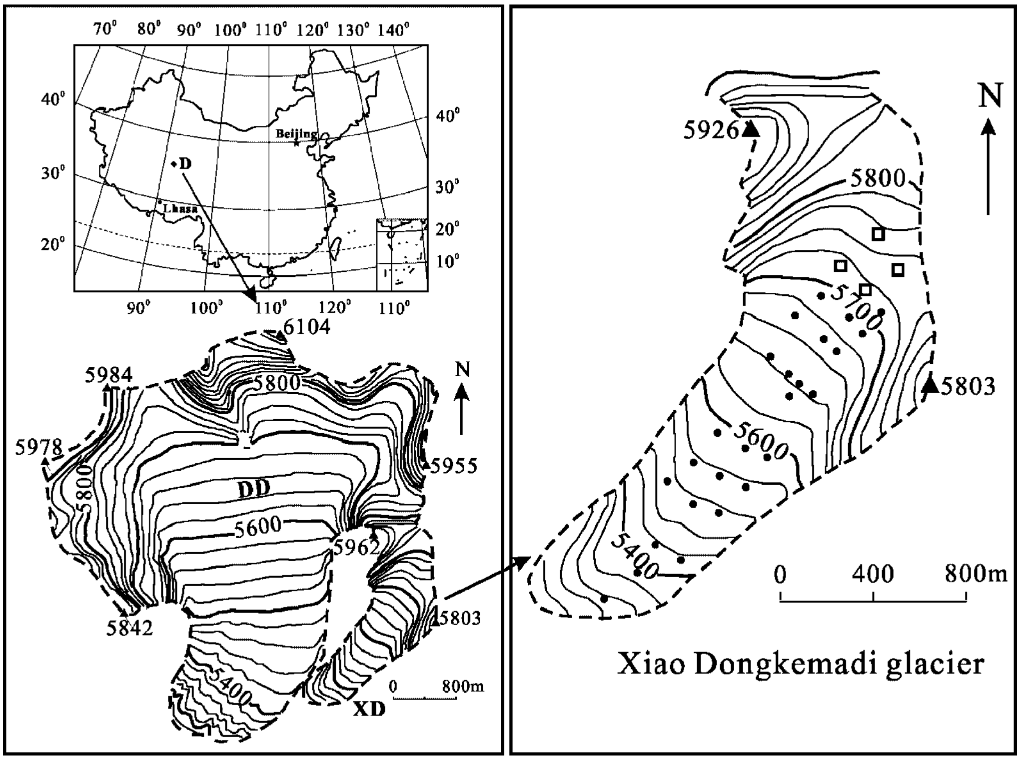

Figure 1. Geographical location of the Xiao Dongkemadi glacier. D in left upper figure refers to the Dongkemadi glaciers (Xiao Dongkemadi (XD) and Da Dongkemadi (DD) glaciers) in left lower figure. The right figure shows the Xiao Dongkemadi (XD) glacier with the stake sites (black circle) and snow pits (square). Note that the stake sites also serve as snow pits in the field

ablation of Xiao Dongkemadi glacier were measured by the stake method once or twice a year. In total, 25 stakes were set up on the glacier surface along 12 arrays covering both the accumulation and ablation area (Figure 1). The net ablation was acquired by measuring the stake heights and the firn pits in the glacial ablation zone. The net accumulation was obtained by measuring the snow-pit in the accumulation zone. At each site, the measured items include the stake height over the glacier surface, firn layer thickness and density, thickness of superimposed ice, and structure of snow-pit profiles.

Using the measured data at each stake site on the glacier surface, the annual net mass balance at each measuring site can be calculated. The mass balance b is obtained as:

$$b = \Delta F \rho_F + \Delta I \rho_I \quad (1)$$

where ΔF and ΔI are the thickness change of the firn and ice, respectively; and ρ_F and ρ_I are the firn density and ice density, respectively.

The calculated mass balance results at each stake site were labelled on the glacier map. Then the contour map of glacial accumulation and ablation were drawn on the map. Based on the mass balance contour map, the equilibrium line was drawn. The accumulation or ablation areas between two adjacent isoline intervals were estimated. Then the net glacial accumulation, net glacial ablation and mass balance of the whole glacier were calculated from:

$$B = C + A = \sum S_{cn} C_n + \sum S_{an} \alpha_n \quad (2)$$

where C and A denote the whole net accumulation and net ablation on the glacier; S_{cn} and S_{an} are the areas between adjacent isoline intervals in the accumulation and ablation areas; C_n and α_n are the averages of mass balance in the accumulation and ablation areas.

The surface of Xiao Dongkemadi glacier is relatively flat, with a fairly gentle slope from the terminus to summit. The distribution of the mass balance with elevation is relatively regular. Here we used the contour interval area to calculate the total mass balance of the Xiao Dongkemadi glacier. The changes of glacier terminus were determined by measuring the position of the glacier tongue, usually twice a year. Markers were placed in front of the glacier, and each time, the distance was measured between the markers (large boulders) and the glacier tongue. The movement of the glacier was estimated by calculating the average distance changes.

Annual variation of mass balance

Figure 2b shows mass balance fluctuations of the Xiao Dongkemadi glacier over the past 14 years (1989–2002). The annual mass balance varies significantly from a maximum of 525 mm water equivalent (1988/1989) to minimum of −701 mm water equivalent (1997/1998). The mass balance was positive in the first 5 years, followed by substantial negative mass balances (except for 1996/1997). Figure 2b also shows the mass balance trend at the Xiao Dongkemadi glacier, indicating a decrease of about 50·1 mm per year over the 14 years ($P < 0{\cdot}1$). Glacier No.1, Tien Shan, also experienced a mass balance decreasing trend over the past two

DOI: 10.1002/hyp

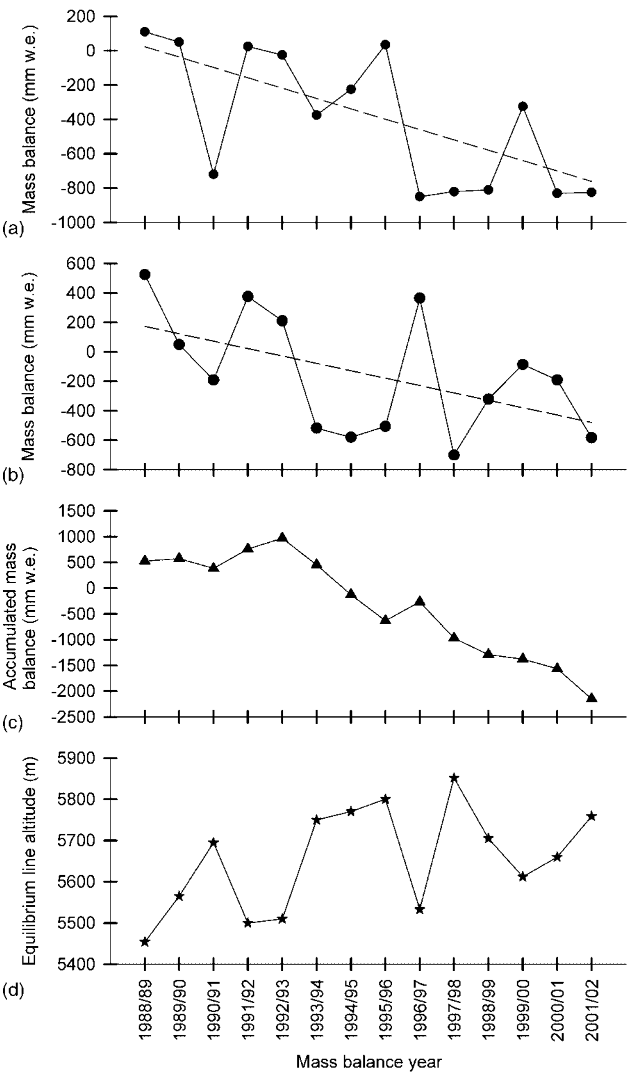

Figure 2. Annual variations of mass balance and its trend observed in Glacier No.1, Tienshan (a) (after Wang *et al.*, 2004), annual variations of mass balance and its trend (b), the accumulative mass balance (c) and the equilibrium line altitude (d) observed in the Xiao Dongkemadi glacier, central Tibetan Plateau. The significant level of the linear trend is $<10\%$ for Xiao Dokemadi glacier mass balance and $<1\%$ for Glacier No.1, Tien Shan. Note that the sample size for statistics here is different from Wang *et al.* (2004)

decades ($P < 0{\cdot}1$) (Wang *et al.*, 2004), and the decreasing trend has become more significant recently ($P < 0{\cdot}01$, Figure 2a). The accumulated mass balance (Figure 2c) during the first 5 years was 970·7 mm of water equivalent, corresponding to a glacier surface increase of 1·08 m (assuming an ice density of about 0·9 g cm^{-3}) on average (Pu *et al.*, 1996). From 1994 on, the glacier mass balance was in deficit, although 1996/1997 was an exception. The 9 years' (1994–2002) accumulated mass balance was −3119 mm in water equivalent, giving an average lowering of the glacier surface by about 3·5 m.

The Equilibrium Line Altitude (ELA) in the Xiao Dongkemadi glacier is shown in Figure 2d. The ELA has varied in the range 5450–5850 m a.s.l. during the past 14 years (1989–2002).

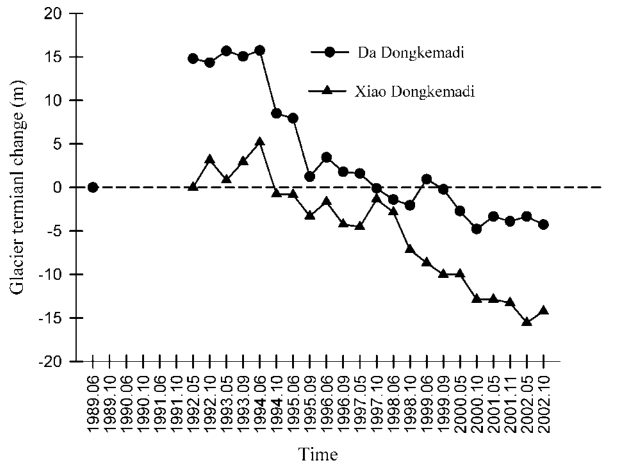

Figure 3. Glacier terminus changes of the Da Dongkemadi and Xiao Dongkemadi glaciers. The terminus changes are the terminal distance relative to the first observation time (June 1989 for Da Dongkema glacier and June 1992 for Xiao Dongkemadi glacier)

ADVANCE/RETREAT OF THE GLACIER TERMINUS

The change of glacial accumulation or ablation results in changes in glacier movement patterns, terminal elevation, glacier area and ice reservation. Because the Xiao Dongkemadi glacier converges with the Da Dongkemadi glacier at the glacier terminus, the terminal positions of both glaciers were measured. Figure 3 shows changes in the glacial terminus for both Xiao Dongkemadi glacier and Da Dongkemadi glacier over the past 14 years. The changes in the glacier terminus for both glaciers show a similar trend. However, the changes in the Xiao Dongkemadi glacier are more marked than those in the Da Dongkemadi glacier, and probably indicate patterns to come for the larger glacier in a year or two. Compared to the year (1989 at Da Dongkemadi glacier and 1992 at Xiao Dongkemadi glacier) when monitoring the glacier terminus began, the positions of the terminus of both glaciers experienced advance during the first several years and then rapid retreat in recent years. The Da Dongkemadi glacier advanced 14·18 m from 1989 to 1992. After that, the terminus of the two glaciers remained relatively stable from 1992 to 1994. From the summer of 1994 to 2003, the two glaciers retreated significantly. The changes in glacier terminus corresponded to glacial mass balance variations.

DISCUSSION AND CONCLUDING REMARKS

Air temperature and precipitation are the main factors controlling the glacier mass balance. Cold climate and high levels of precipitation will benefit the positive mass balance and vice versa. Previous statistical study showed that the main body of the Tibetan Plateau experienced significant warming in the 1990s (Liu and Chen, 2000; Gou *et al.*, 2007). Figure 4 shows the summer (May to September) (b), annual (c), and winter (October to April) (d) temperatures over the

DOI: 10.1002/hyp

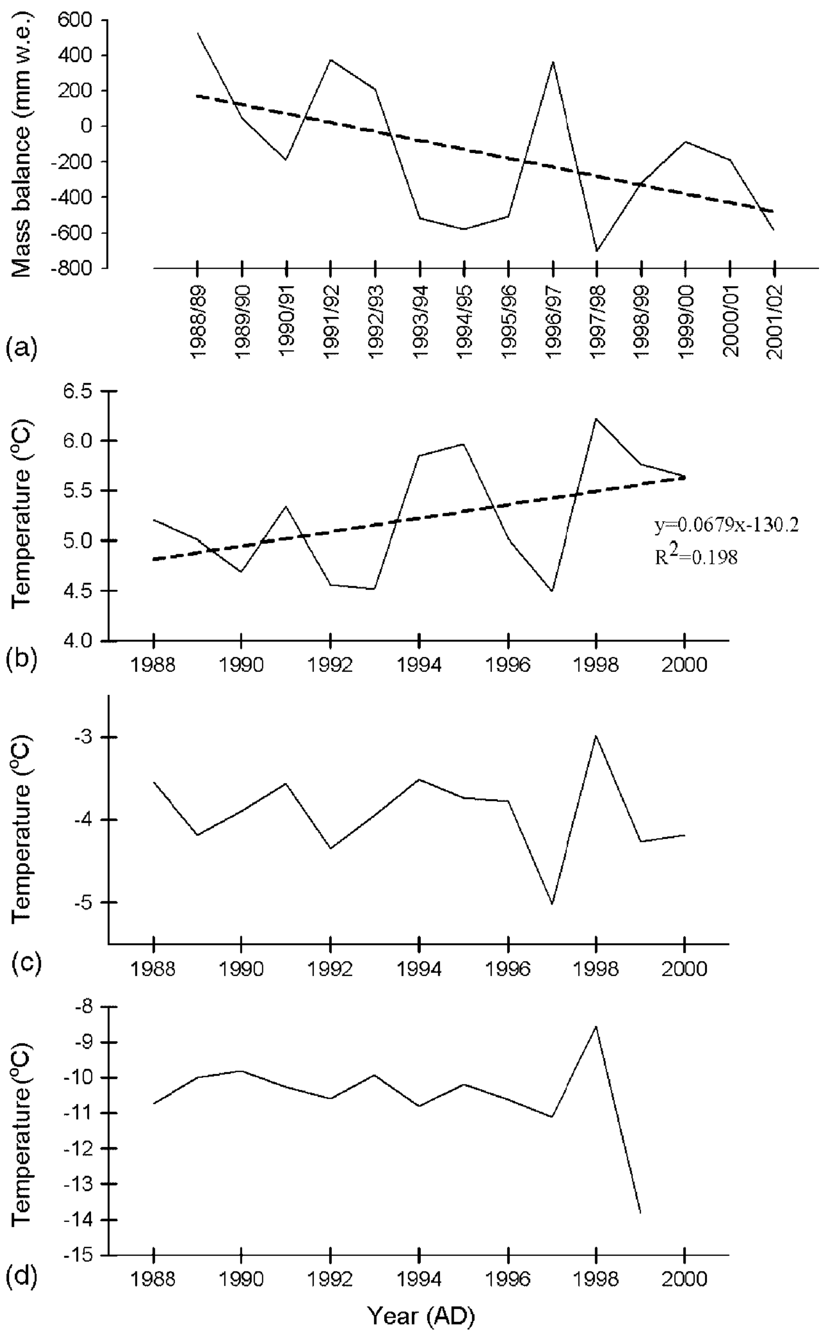

Figure 4. Mass balance and its trend (a) of the Xiao Dongkemadi glacier, summer (May to September) (b), annual mean (c) and winter (October to April) temperature (d) at Tuotuohe meteorological station. The dash-dotted straight lines are the corresponding trend lines and the linear regression equations are also shown, respectively

period 1988 to 2000 at Tuotuohe meteorological station (34°13′, 92°26′, 4534m) located to the north of the Xiao Dongkemadi glacier (Figure 1). The mean (Figure 4c) and winter (Figure 4d) temperatures experienced a very weak negative linear trend ($y = -0{\cdot}02x + 35{\cdot}93$, $R^2 = 0{\cdot}024$ and $y = -0{\cdot}11x + 209{\cdot}34$, $R^2 = 0{\cdot}105$, respectively). The summer temperature (Figure 4b) has a positive linear trend ($y = 0{\cdot}067x - 130{\cdot}2$, $R^2 = 0{\cdot}198$), but it is still not statistically significant. It is important to note that the sample size is just 13 (1988 to 2000). Taking account of the limited sample size, the positive linear trend is worthy of notice. The linear rates for annul mean and winter temperatures are −0·20 °C/10a and −1·10 °C/10a, respectively. However, the summer temperature was increasing at a linear rate of 0·68 °C/10a, indicating warmer summers. The warmest summer was 1998 with a temperature of 6·2 °C and the coldest was 1997 with a temperature of 4·5 °C. The warmest winter season was 1998/1999 with a temperature of −8·6 °C and the coldest was 1999/2000 with a temperature of −13·8 °C. The summer (May to September) (b), annual (c), and winter (October to April) (d) precipitation over the period 1988 to 2000 at Tuotuohe meteorological station are presented in Figure 5. The precipitation at Tuotuohe mainly occurred in the summer season, and this accounts for 91·5% of the annual total precipitation.

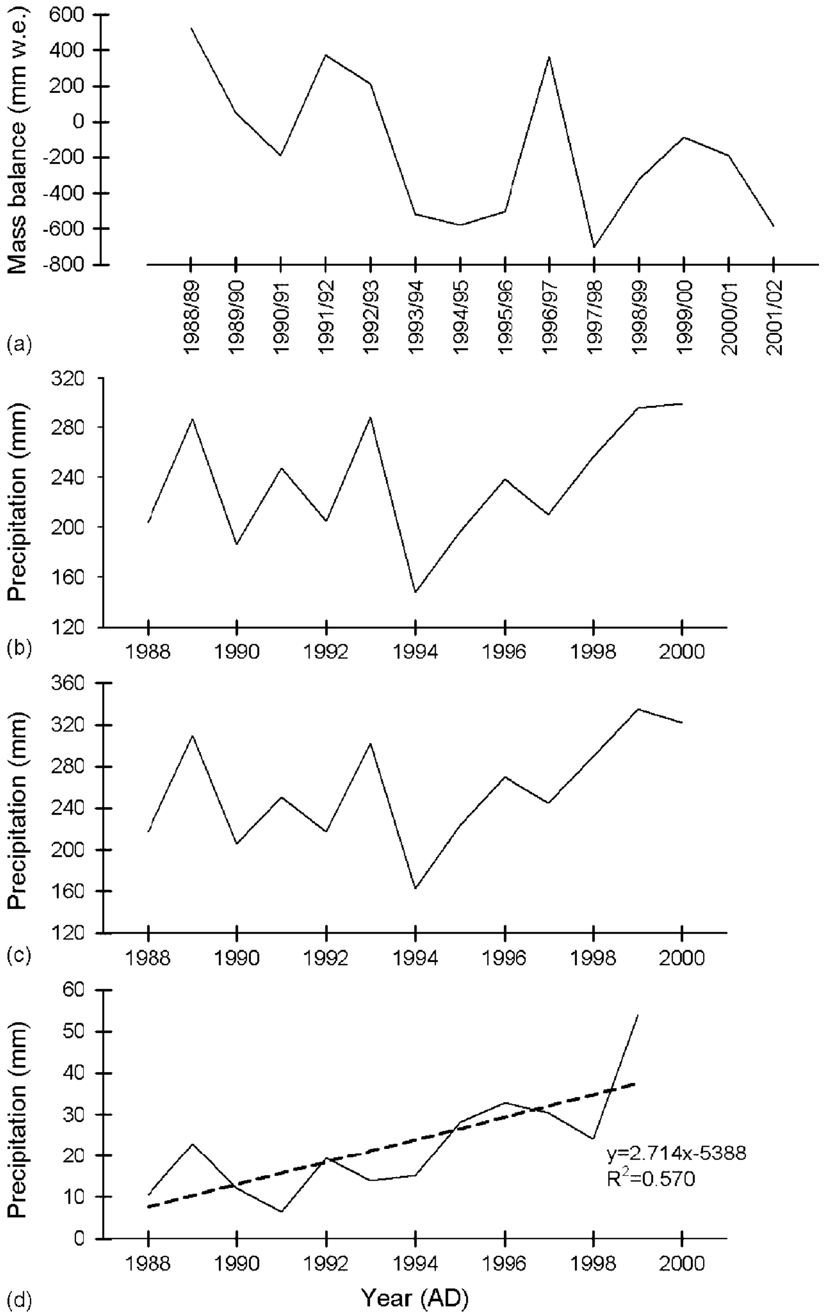

Figure 5. Mass balance (a) of the Xiao Dongkemadi glacier, summer (May to September) (b), annual mean (c) and winter (October to April) precipitation (d) at Tuotuohe meteorological station. The dash-dotted straight line is the corresponding trend line and the linear regression equation is also shown

The maximum precipitation in the summer season was 299·1 mm in 2000 and the minimum precipitation in the summer season was 147·9 mm in 1994. The average summer season precipitation during 1988 to 2000 was 235·9 mm. However, maximum precipitation in the winter season was 54·1 mm in 1998/1999 and the minimum precipitation was 6·5 mm in 1991/1992. The annual average precipitation during the winter season (October to April) was 22·6 mm. The summer (Figure 5b) and annual (Figure 5c) precipitation showed a weak increasing trend ($y = 4{\cdot}139x - 8017$, $R^2 = 0{\cdot}112$; $y = 6{\cdot}048x - 11\,803$, $R^2 = 0{\cdot}205$, respectively). These trends are not significant statistically. However, the winter season precipitation (Figure 5d) showed a significant increasing trend ($y = 2{\cdot}714x - 5388$, $R^2 = 0{\cdot}570$) with a significance level of $P < 0{\cdot}01$. The linear increasing rate for annul, summer and winter season is 60·5 mm/10a, 41·4 mm/10a and 27·1 mm/10a, respectively.

The sharp decrease in mass balance in 1993/1994 was related to the low precipitation and higher summer temperature in 1994 (Figure 4 and Figure 5), while the positive mass balance in 1996/1997 was well-correlated with the extremely low air temperature and reduced precipitation in 1997. Both the precipitation amount and air temperature could have affected the mass balance of

Xiao Dongkemadi glacier. The increased air temperature, especially in summer, will enlarge the glacial ablation area, lower the snow surface albedo, and enhance glacier melting. Tree ring records also showed that the major glacier advances in northeastern Tibetan Plateau correspond with cold periods of the summer maximum temperature (Gou *et al*., 2006). Wang *et al*. (2004) noted that the annual mass balance of Urumqi Glacier No. 1, Tien Shan, China, was correlated (significance level 1%) with summer mean air temperature, suggesting summer temperatures are a major cause of the variation in mass balance. Although precipitation increased, the mass balance of Urumqi Glacier No. 1 has become more negative with summer warming during the past two decades (Wang *et al*., 2004). The summer warming directly intensifies the ablation of alpine glaciers. Therefore, the mass balance of the glacier becomes negative and the glacier terminus will also retreat. The swift retreat of the glacier terminus in the Xiao Dongkemadi glacier is a response to the summer warming. The variation of glacier mass balance, ELA variation, movement of glacier terminus in Xiao Dongkemadi glacier, was a response to the summer warming in recent years. If such increased warming continues in the future, the glacier mass balance will become more negative, the glacier will be thinner, and the glacier terminus will keep on retreating.

ACKNOWLEDGMENTS

This work is supported by the National Basic Research Program of China (2005CB422002), the Innovation Program of Chinese Academy of Sciences (KZCX3-SW-339) and National Natural Science Foundation of China (40121101, 40571039, and 40571036).

REFERENCES

Fujita K, Ageta Y, Pu J, Yao T. 2000. Mass balance of Xiao Dongkemadi glacier on the central Tibetan Plateau from 1989 to 1995. *Annals of Glaciology* **31**: 159–163.

Fujita K, Seko K, Ageta Y, Pu J,Yao T. 1996. Superimposed ice in glacier mass balance on the Tibetan Plateau. *Journal of Glaciology* **42**(142): 454–460.

Gou X, Chen F, Jacoby G, Cook E, Yang M, Peng J, Zhang Y. 2007. Rapid tree growth with respect to the last 400 years in response to climate warming, northeastern Tibetan Plateau. *International Journal of Climatology* **27**: 1497–1503.

Gou X, Chen F, Yang M, Jacoby G, Peng J, Zhang Y. 2006. A comparison of tree-ring records and glacier variations over the past 700 years, northeastern Tibetan Plateau. *Annals of Glaciology* **43**: 86–90.

Jiao K, Jing Z, Han Q. 2004. Variation of the glacier No. 1 at the headwaters of the Urumqi river in the Tianshan mountains during the past 42 years and its trend prediction. *Journal of Glaciology and Geocryology* **26**(3): 253–260. (In Chinese with English summary).

Li Z, Han T, Jin Z. 2003. A summary of 40 years observed variation facts of climate and glacier No.1 at Headwater of Urumuqi river, Tianshan, China. *Journal of Glaciology and Geocryology* **25**(2): 117–123. (In Chinese with English summary).

Liu X, Chen B. 2000. Climatic warming in the Tibetan Plateau during recent decades. *International Journal of Climatology* **20**(14): 1729–1742.

Pu J, Yao T, Duan K, Sakai A, Fujita K, Matsuda Y. 2005. Mass balance of the Qiyi glacier in Qilian mountains: A new observation. *Journal of Glaciology and Geocryology* **27**(2): 199–204. (In Chinese with English summary).

Pu J, Yao T, Zhang Y, Seko K, Fujita K. 1995. Mass balance on the Dongkemadi and Meikuang glaciers in 1992/1993. *Journal of Glaciology and Geocryology* **17**(2): 138–143. (In Chinese with English summary).

Pu J, Yao T, Zhang Y. 1996. Study on the relation ship between mass balance and climatic factors on the Xiao Dongkemadi Glacier. *Cryosphere* **2**: 59–62.

Pu J, Yao T. 1993. Study on mass balance of Small Dongkemadi glacier. In *Glaciological Climate and Environment on Qing-zang Plateau*. Science Press: Beijing. (In Chinese with English summary).

Wang N, Jiao K, Li Z, Jing Z, Han T. Recent accelerated shringkage of Urumqi glacier No. 1, Tien Shan, China. *Journal of Glaciology* **50**(170): 464–466.

Yao T, Wang Y, Liu S, Pu J, Shen Y, Lu A. 2004. Recent glacial retreat in High Asia in China and its impact on water resource in Northwest China. *Science in China (Ser. D)* **47**(12): 1065–1075.