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ORIGINAL ARTICLE

Characteristics of winter mass balance of Glacier No.1 at the headwaters of the Urumqi River, Tianshan Mountains

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Abstract This study analyzes the response of glacier to climate change during the past 49 years in Urumqi River source region, the Tianshan Mountains of China. The temporal and spatial variations of winter mass balance (bn-w) at different time scales were analyzed to identify their response to climate change during 1988–2006 (The observation of winter mass balance observation began in 1988) on the Glacier No.1 at the headwaters of the Urumqi River, Tianshan Mountains, China. The winter accumulation shows a significantly decreasing trend. The results show that the cumulative values on Glacier No.1 is 2,202 mm water equivalent during 1988–2006 and the mean values is 116 mm a^{-1}. Furthermore, the trend analysis of the winter mass balance indicates a rapid decrease since 1990, and the mean mass balance is only 79 mm a^{-1} during 1997–2006. Winter mass balance correlates well negatively with the total evaporation from September to April ($r = -0.68$, $\alpha = 0.01$), and positively with the total precipitation from September to April ($r = 0.74$, $\alpha = 0.01$). However, winter mass balance shows a weak correlation with mean minimum air temperature during September to April ($r = -0.35$), and runoff on September ($r = -0.13$).

Keywords Winter mass balance · Temperature · Precipitation · Glacier No.1 · Tianshan Mountains

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Introduction

Global warming has caused shrinking of most glaciers and ice caps in the world over the last century, especially in recent decades (Dyurgerov and Meier 2000). Small glaciers are highly sensitive to changes in temperature and precipitation, making them important indicators of climate change (Oerlemans and Fortuin 1992; Liu et al. 1997). Changes in the mass of these glaciers affect the volume and timing of stream flow that provides water for hydroelectric power production, irrigation, and domestic water supplies (Yao et al. 2004). Glacier runoff is an important water resource in the arid northwest China (Yang 1991). Mountain glaciers in western China have experienced losses of mass and volume over the last several decades (Yao et al. 2004).

Glacier mass balance (bn) reflects the changes of glacier-ice volume; it is also an indicator of glacier fluctuations and climate change. Therefore, many researchers have paid more attention to glacier mass balance since 1990s (Yang 1992; Fountain et al. 1999; Chinn 1999; Oerlemans and Reichert 2000; Schneider and Jansson 2004). Small glaciers are highly sensitive to changes in temperature and precipitation, it is therefore an important indicator of climate change (Meier 1984; Oerlemans and Fortuin 1992).

The annual mass balance does not relate to the ice mass changes to the weather conditions during the different seasons (Ohmura 2004). The separate determination of summer (bs) and winter (bn-w) mass balance will detect the signal of climate change at the seasonal time scale. Air temperature can be used as a proxy for analyzing the energy balance of the ablation processes, and solid precipitation as an indicator of accumulation.

The winter mass balance of the Glacier No.1 has been calculated from the difference of mass balance observed from the end of August to early May, which primarily reflects the accumulation in the non-ablation period. The winter mass balance calculation was conducted during the period of 1988–2006, which reveals the characteristics of mass balance in the cold seasons. This glacier has shrunk over many years and divided into two small glaciers in 1994 (Jiao et al. 2000). The glacier area was 1.742 km^2 in 1994, and 1.708 km^2 in August 2001 (Tianshan Glaciological Station 2002). The horizontal distance is 45 m between the tongues and the two branches in 2001 (Yang et al. 2005).

This study systematically analyzes the long-term glacier, climate, and hydrology records; and the effects of temporal and spatial variations of winter mass balance on different time scales were examined to identify their response to climate change over the past several decades.

Materials and methods

Study area and data

The Urumqi Glacier No.1 (43.05°N, 86.49°E) is at the headwaters of the Urumqi River, Tianshan Mountains, China (Fig. 1). It is a small cirque-valley glacier, comprising east and west branches with a total area of 1.95 km^2 in 1962 (Xie and Ge 1965). The Glacier No.1 has the longest monitoring records during 1958–2006 in China.

A standardized method for glacier mass balance measurements has been described by Meier (1962). Glacier mass balance has been calculated by contour maps of accumulation and ablation, using data measured at the permanent stake network, about 45 stakes in 8–9 rows on the glacier (in the east branch 23 points in 8 rows are from 3,800 to 4,050 m a.s.l., and in the west branch 22 points in 9 rows are from 3,850 to 4,100 m a.s.l.) and additional snow pits to observe the mass balance of glaciers (Han et al. 2006).

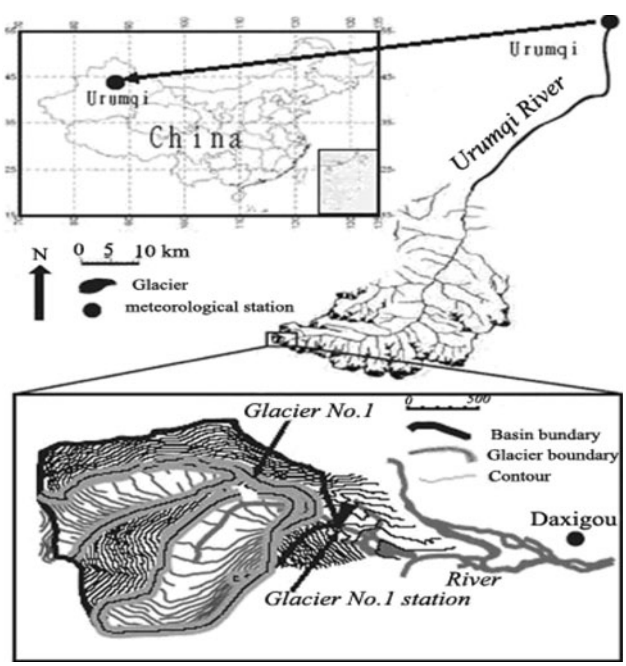

Fig. 1 Map showing the location of Urumqi Glacier No.1

The glacier observation program at the Tianshan glacier station was started in 1959 (Xie and Ge 1965) and continued to the present. Field observations included glacier accumulation and ablation, equilibrium line altitude (ELA), changes in glacier length and area, and hydrological data collections. Winter mass balance observation was launched in 1988. Glacier data have been internally published in annual reports of the Tianshan Glacier Station from 1980–2006.

The discharge data of the Glacier No.1 hydrological stations with 3.34 km^2 drainage area is located at the elevation of 3,659 m a.s.l. about 300 m downstream from the tongue of Glacier No.1. Temperature, precipitation and pan-evaporation data are available at the Daxigou meteorological station during 1958–2006. The station is located at the 3,539 m a.s.l. about 3 km downstream of the glacier tongue (Fig. 1).

Methods

The winter mass balance (bn-w) (mm) is determined as:

$$\text{bn-w} = P_{\text{ELA}} - Q_{\text{sept}} - E + \Delta M \quad (1)$$

$$P_{\text{ELA}} = P_{\text{dxg}} + P_{\text{dxg}} \times 14\% + (H_{\text{ELA}} - 3539) \times 22/100 \quad (2)$$

$$E_{\text{g}} = E_{\text{pan}} \times 0.4 \quad (3)$$

where P_{ELA} (mm) is the bias-corrected total precipitation during September to April at the ELA (Yang et al. 1991), it is as simulated the mean precipitation over the glacier surface; and P_{dxg} is the total precipitation during September to April at the Daxigou Meteorological station (about 3,539 a.s.l.); H_{ELA} is the mean ELA on the Glacier No.1; Q_{sept} is the glacier runoff for September; E_{g} and E_{pan} are the evaporation of glacier surface and the pan evaporation at the Daxigou Meteorological station from September to April, respectively (Yang and Zhang 1992); ΔM is the residual, including random errors.

The linear regression analysis was carried out for the long-term meteorological, hydrological, and glacier data collected at or near the Glacier No.1, and the standard t test was used to determine the statistical significance of the trends. Furthermore, the relationship among temperature, precipitation, and winter mass balance were analyzed to quantify the impact of climate change on glacier change.

Climate change and glacier response

This study analyzes long-term climate and glacier response over the past 49 years in the Urumqi River source area, the Tianshan Mountains of China. Trend analyses show that air temperature has been rising during 1958–2007 (Fig. 2), particularly in winter (Liu et al. 1999; Han et al. 2002). During the same period, the mean annual precipitation significantly increased at the headwaters of the Urumqi River.

However, the climate became slightly cooler, and air temperature decreases by 0.1°C on March (0.002°C $(10a)^{-1}$) during 1958–2007. An increasing trend in precipitation was found in all months except September, and a decrease of 3.5 mm occurs on September (0.7 mm $(10a)^{-1}$) during 1958–2007 (Fig. 3). In addition, a very significant change occurs over the most recent 20 years (1987–2007). The mean temperature has increased by 0.96°C (0.5°C $(10a)^{-1}$) and precipitation decreased by 30.9 mm (16.2 mm $(10a)^{-1}$) in the cold season from September to April (Fig. 3).

The gradual increase of air temperature leads to an enhanced glacier shrinkage (Li et al. 2003) although precipitation increased during the same period. Moreover, the mass balance exhibits an unprecedented negative balance. This indicates that the effects of temperature rise on the glacier mass balance are more predominant than that of the precipitation increase. The significantly negative mass balance (winter mass balance) is dominantly responsible for the strong melting of the glacier after 1997. Glacier thinning has been linked to a warmer climate, and mean air temperature in the cold season (September to April) has increased by 0.96°C in the source regions of Urumqi River over the last 19 years, which caused the melting of Glacier No.1 in the cold season (Fig. 2).

The winter mass balance has been decreasing in recent years. The cumulated winter mass balances of the Glacier No.1 was 2,202 mm water equivalent during 1988–2006, while the mean winter mass balance was 116 mm a^{-1}. The observed data showed that the winter mass balance presents an accelerated decreasing trend since 1990. The mean winter mass balance was only 79 mm a^{-1} (68% of mean winter mass balance) during 1997–2006 (Fig. 4).

In contrast, annual mass balance varies between 375 mm and −860 mm during 1958–2006 (Fig. 5). Cumulative mass balance reached −12,020 mm over the study period, equivalent to glacier thinning of −13.4 m (about 20% of average glacier thickness). Glacier mass balance has been decreasing almost monotonically in the past 48 years, especially in the most recent 10 years. The mean negative mass balance was −453.8 mm a^{-1} during 1988–2006. The 10 years of most negative mass balance

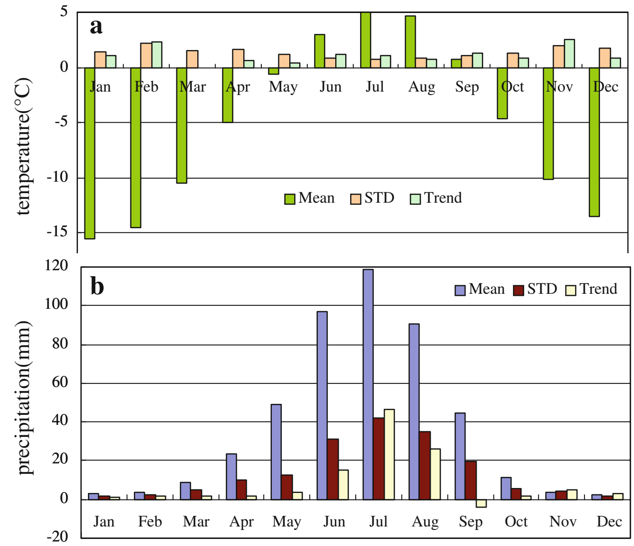

Fig. 3 Long-term mean monthly temperature (**a**) and precipitation (**b**), and their total trend at the Daxigou station during 1959–2007. Trends are in °C $(49a)^{-1}$ for temperature and mm $(49a)^{-1}$ for precipitation

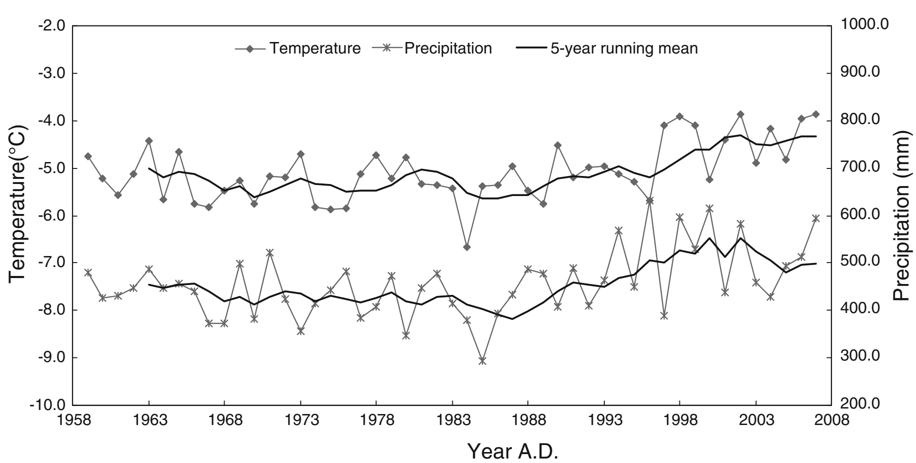

Fig. 2 Annual temperature and precipitation at Daxigou meteorological station since 1959 (showing mean values and a linear regression)

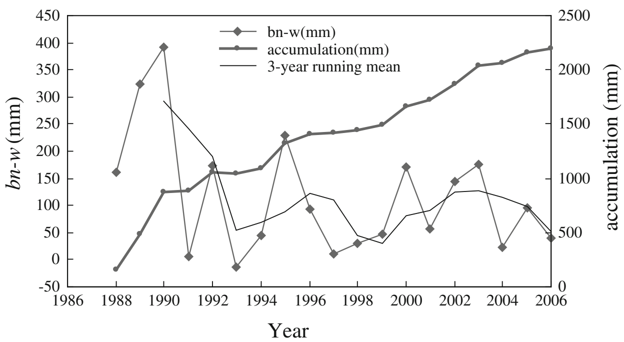

Fig. 4 Variations of Glacier No.1 winter mass balance (bn-w)

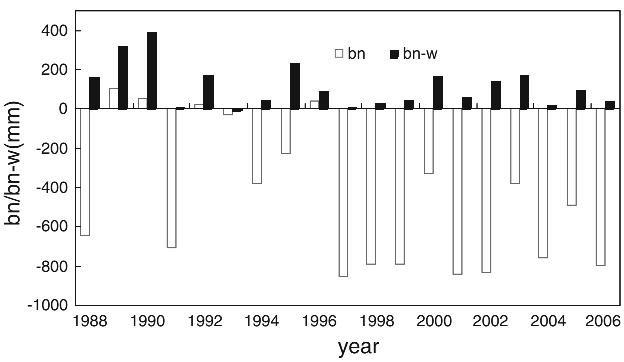

Fig. 5 Variations of Glacier No.1 bn and bn-w

(over −686 mm) all appeared during 1997–2006. The climate warming not only enhanced the ablation, but also increased the ablation area.

Results

To quantify the effect of climate change on the glacier, the relationships were examined among winter temperature, precipitation, evaporation, and winter mass balance of Glacier No.1 at the headwaters of the Urumqi River, Tianshan Mountains. Precipitation and temperature affect glacier mass balance differently. The increase of precipitation enhances the accumulation of glaciers, but the rise of temperature enhances ablation. The negative mass balance, mainly from a higher ablation rather than the lower accumulation, is associated with the increase of precipitation and the rise of temperature over the study area. This result implies that the effect of rising temperature on mass balance may be more significant than the influence of increasing precipitation.

The annual mass balance, different from the winter mass balance, is mainly influenced by summer mean air temperature from June to August. There is a good relationship between annual mass balance and air temperature in summer (the correlation coefficient is −0.62 with a significance of $\alpha = 0.01$) (Han et al. 2006). However, the correlation coefficient between annual mass balance and precipitation is 0.19 during the same period (Han et al. 2006). However, the correlation coefficient between winter and annual mass balance is still 0.60 ($\alpha = 0.01$; Table 1).

Though the winter mass balance could not completely explain the accumulation of glacier in winter, while the dominant factor is winter precipitation; there exists a poor relationship between winter mass balance and temperature over the same period. The winter mass balance roughly depends on the precipitation in the non-ablation period, especially from the period of September to April. As expected the significant correlation exists between winter mass balance and mean maximum air temperature ($r = -0.51$, $\alpha = 0.05$), and between winter mass balance and total precipitation ($r = 0.74$, $\alpha = 0.01$) during September to April (Fig. 6; Table 1). The correlation is less significant between winter mass balance and mean air temperature during September to April ($r = -0.35$).

Evaporation plays an important role in the ablation of the continental-type glaciers in China. Winter snowfall is low in the area; solar radiation causes the thawing of fresh snow and the shrinkage of glacial tongue. The wind is strong so that the evaporation of ice and snow surface becomes important. All these factors can affect the winter mass balance of the glaciers. The correlation coefficient between winter mass balance and evaporation is −0.68 ($\alpha = 0.01$; Table 1). In the ablation season, evaporation accounts for 12% of the ablation on the Glacier No.1

Table 1 The correlation coefficients between bn-w and different meteorological factors at the headwaters of the Urumqi River

	bn-w	E	T_{mean}	P	T_{min}	T_{max}	$Q_{Sept.}$	bn
bn-w	1							
E	−0.68**	1						
T_{mean}	−0.35	0.70**	1					
P	0.74**	−0.72**	−0.37	1				
T_{min}	−0.39	0.69**	0.91**	−0.42	1			
T_{max}	−0.51*	0.76**	0.90**	−0.54*	0.96**	1		
$Q_{Sept.}$	0.13	0.25	0.33	0.02	0.41	0.39	1	
bn	0.60	−0.49	−0.37	0.27	−0.41	−0.47	−0.31	1

** Correlation is significant at the 0.01 level (two-tailed)

* Correlation is significant at the 0.05 level (two-tailed)

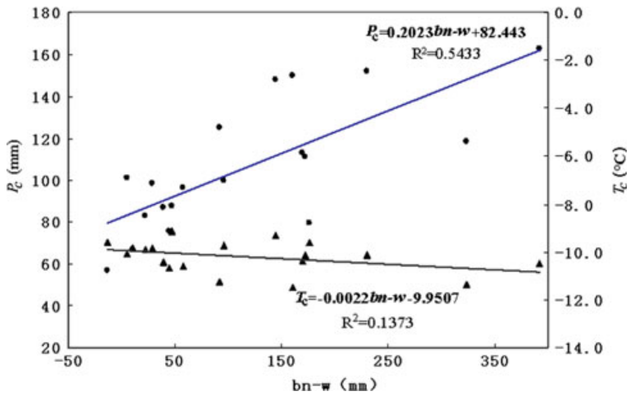

Fig. 6 Variations of winter mass balance and total precipitation (Pc) and mean temperature (Tc) in the cold season from September to April

(Zhang et al. 1996), but low correlation exists between the annual mass balance and evaporation (Han et al. 2006). Therefore, winter mass balance is determined not only by the winter accumulative rate of the glaciers mainly from precipitation, but also by ablation processes in winter mainly from evaporation (Fig. 7).

The equilibrium-line altitude (ELA) is the boundary between the accumulation and ablation zone, and is an important index of the glacier, which is sensitive to temperature and precipitation changes (Yao 1987; Wang 1995; Liu et al. 1998). The elevation of ELA is derived from a mass balance observation over the glacier.

In the past 20 years (1988–2006), the elevation of ELA of the glacier ranges from 3,771 to 4,058 m in winter, the mean ELA is about 3,923 m. The ELA shows a clear upward trend (the mean value is 3,936 m) since 1997. Analysis shows that a close relationship exists between the height of ELA and the winter mass balance (Fig. 8), which is primarily due to temperature rising during the same period.

Statistical analysis shows that winter mass balance depends primarily on precipitation and evaporation on the Glacier No.1 during the winter, and also correlates with the glacier melt on September.

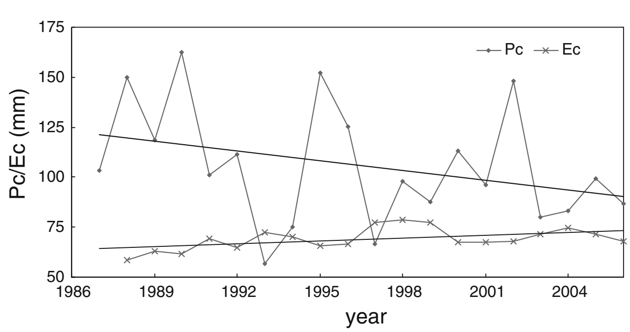

Fig. 7 Variation of total evaporation (Ec) and precipitation (Pc) in the cold season from September to April

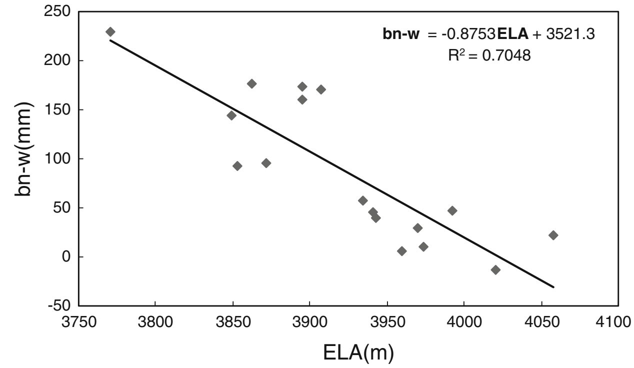

Fig. 8 The relationships between winter mass balance and ELA

Table 2 The observation and calculation winter mass balance of Glacier No.1 at the headwaters of the Urumqi River

Data	Observation (mm)	Calculation (mm)				
1991–2006	bn-w	P_{ELA}	$Q_{sept.}$	Eg	$P_{ELA} - Eg - Q_{sept.}$	ΔM
Mean	83	198	42	71	85	2

Based on Eq. (1), the average bn-w of the Glacier No.1 is 85 mm during 1991–2006 (Table 2), while the observed mass balance is 83 mm (relative error ΔM is about 2 mm, by 3%), so that the average winter mass balance bn-w can be obtained from Eq. (1) during the non-melting season.

Conclusion and discussion

The results of this study show that the cumulative values of winter mass balance of Glacier No.1 was 2,202 mm water equivalent during 1988–2006. The winter mass balance has decreased in the recent years. The mean mass balance was 116 mm a^{-1} during 1988–2006 while the mean mass balance was 79 mm a^{-1} during 1997–2006. Mass balance observations indicate that the winter mass balance of the Glacier No.1 presents an accelerated negative trend since 1990.

There are significant relationships of winter mass balance with total glacier surface evaporation and precipitation in the cold season from September to April. The correlation coefficients are 0.68 and 0.74, respectively. More important, this study reveals the dominance of precipitation and evaporation to winter mass balance from September to April.

It is important to point out that the winter mass balance is contributed from precipitation in winter season, but also is strongly affected by winter sublimation in the same season.

Variations of the winter mass balance are controlled mainly by precipitation and evaporation in the cold season. Furthermore, the additional factors include short-wave and long-wave radiation (especially related to cloud cover); although, wind speed, ice temperature, sublimation may also influence glacier mass balance. The calculation of the heat budget of the glacier will require precipitation and ice volume, in particular the volume of ice melting and runoff.

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References:

Chinn TJ (1999) New Zealand glacier response to climate change of the past 2 decades. Glob Planet Change 22:155–168

Dyurgerov MB, Meier MF (2000) Twentieth century climate change: evidence from small glacier. Proc Natl Acad Sci 97:1406–1411

Fountain AG, Lewis KJ, Doran PT (1999) Spatial climatic variation and its control on glacier equilibrium line altitude in Taylor Valley, Antarctica. Glob Planet Change 22:1–10

Han T, Ye B, Jiao K (2002) Temperature variations in the southern and northern slopes of Mt. Tianger in the Tianshan Mountains. J Glaciol Geocryol 24(5):567–570

Han T, Ding Y, Ye B et al (2006) Characteristics of mass balance of Glacier No.1 at the headwaters of the Urumqi River, Tianshan Mountains. Ann Glaciol 43:323–328

Jiao K, Wang C, Han T (2000) A strong negative mass balance appeared in the headwater of the Urumqi River. J Glaciol Geocryol 22(1):62–64

Li Z, Han T, Jing Z et al (2003) A summary of 40-year observed variation facts of climate and Glacier No.1 at the Headwater of Urumqi River Tianshan Mountains, China. J Glaciol Geocryol 25(2):117–123

Liu C, Xie Z, Wang C (1997) A research on mass balance processes of Glacier No.1 at the headwaters of the Urumqi River, Tianshan Mountains. J Glaciol Geocryol 19(1):17–24

Liu S, Ding Y, Wang L et al (1998) Mass balance sensitivity to climate change of the Glacier No.1 at the Urumqi River Head, Tianshan Mts. J Glaciol Geocryol 20(1):9–13

Liu S, Wang N, Ding Y (1999) The characteristics of glacier fluctuations during the last 30 years in Urumqi River basin and the estimation of temperature rise in the high mountain area. Adv Earth Sci 14(3):279–285

Meier MF (1962) Proposed definitions for glacier mass budget terms. J Glaciol 4(33):252–263

Meier MF (1984) Contribution of small glaciers to global sea level. Science 51:49–62

Oerlemans J, Fortuin JPF (1992) Sensitivity of glaciers and small ice caps to greenhouse warming. Science 258:115–117

Oerlemans J, Reichert BK (2000) Relating glacier mass balance to meteorological data by using a seasonal sensitivity characteristic. J Glaciol 46(152):1–6

Ohmura A (2004) Cryosphere during the twentieth century. In: The state of the planet: frontiers and challenges in geophysics, vol.19 Geophysical monograph 150, IUGG. pp 239–257 doi: 10.1029/150GM19

Schneider T, Jansson P (2004) Internal accumulation in firn and its significance for the mass balance of Storglaciären, Sweden. J Glaciol 50(168):25–34

Tianshan Glaciological Station ((2002)) Annual Report of Tianshan Glaciological Station. Lanzhou Institute of Glaciology and Geocryology, CAS, Lanzhou, pp 1–16

Wang N (1995) Grey relational analysis of the leading climatic factor influencing the changes of the equilibrium line. J Glaciol Geocryol 17(1):8–15

Xie Z, Ge G (1965) Accumulation, ablation and mass balance of the Glacier No.1 at the Urumqi River Head, Tianshan Mts. Study on glaciers and hydrology at the Urumqi River Head, Tianshan Mts. Science Press, Beijing, pp 24–34

Yang Z (1991) Glacier water resources in China. Gansu Science and Technology, Lanzhou, China, p 158

Yang D (1992) On the mass balance of 50 Mountain Glaciers in the Northern Hemisphere. Adv Water Sci 3(3):161–165

Yang D, Zhang Y (1992) Results of snow surface sublimation measurements in the Mountain area of Urumqi River. J Glaciol Geocryol 14(2):122–128

Yang D, Shi Y, Kang E et al (1991) Results of solid precipitation measurement intercomparison in the Alpine area of Urumqi River Basin. Chin Sci Bull 36(13):1105–1109

Yang H, Li Z, Ye B et al (2005) Study on mass balance and processes of Glacier No.1 at the headwaters of the Urumqi River in the past 44 years. Arid Land Geogr 28(1):76–80

Yao T (1987) The relationship between glacial mass balance equilibrium line and climate-Take Glacier No.1 at the head waters of Urümqi River as an example. J Glaciol Geocryol 9(4):290–300

Yao T, Liu S, Pu J, Shen Y, Lu A (2004) The recent retreat of glacier in High Asia and its effect on water resources. Sci China Ser D 34:535–543

Zhang Y, Yao T, Pu J (1996) The characteristics of ablation on continental-type glaciers in China. J Glaciol Geocryol 18(2):148–154