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Comparative study on observed mass balance between East and West Branch of Urumqi Glacier No. 1, Eastern Tianshan, China

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ABSTRACT

This paper is based on observed mass balance between East and West Branch of Urumqi Glacier No. 1, meteorological data during 1988–2010, comparative studies the mass balance variations, and analyses the mass balance sensitivity to climate change. Results show that average mass balance of East and West Branch was −532 mm/a and −435 mm/a, cumulative mass balance was −12,227 mm (ice thinned by 13.6 m) and −10,001 mm (ice thinned by 11.1 m), respectively, and mass loss of East Branch was 97 mm/a larger than West Branch. The East and West Branch ELA (equilibrium line altitude) ascended about 176 m and 154 m, analysis shows the steady-state ELA_0 was 3,942 m a.s.l. and 4,011 m a.s.l., and when East and West Branch mass balance decreased by 100 mm, ELA ascended 20 m and 23 m, respectively. The AAR (accumulation area ratio) of East and West Branch presented an obviously decreasing trend of 34.5% and 23%, equilibrium-state AAR_0 was 65% and 66%, when East and West Branch mass balance increased by 100 mm, AAR ascended 4.6% and 4.2%, respectively. Glacier mass balance was sensitive to change of net ablation, net ablation of East and West Branch increased 10×10^4 m^3, and mass balance decreased 110 mm and 214 mm, respectively. By analyzing mass balance sensitivity to climate change, results suggest that East and West Branch mass balance decreased (increased) 463 mm and 388 mm when ablation period temperature increased (decreased) by 1 °C, East and West Branch mass balance increased (decreased) 140 mm and 158 mm when annual precipitation increased (decreased) by 100 mm, and sensitivity of East Branch mass balance to climate change was more intense than that of West Branch.

Keywords: mass balance; sensitivity; Urumqi Glacier No. 1

1 Introduction

Glacier mass balance is an important index linking glacier change with climate change (Zemp *et al*., 2009; Xie and Liu, 2010; Wu *et al*., 2011), and mass balance is a direct response to climate change which affects the volume and timing of stream flow that provides water for hydroelectric power production, irrigation, and domestic water supplies (Ye *et al*., 2005; Yao *et al*., 2007). In 1987, climate conditions transformed from warm-dry to warm-wet in Northwest China (Shi *et al*., 2003), most glaciers experienced accelerated melting, the retreat phenomena existed mainly as glacier mass loss, the equilibrium line altitude ascended, glacier terminus retreated, and runoff increased. Glaciers in the Tianshan region are important water resources in arid and semi-arid regions of northwestern China, and it is estimated that glacial melt water accounts for 22% of river runoff in these regions (Li *et al*., 2011; Duan *et al*., 2012). Thus, the study of glacier mass balance has important scientific significance.

Urumqi Glacier No. 1 is a northwest-facing valley glacier which is composed of two ice streams. Due to rising air temperatures, negative balance increase, area reduction and glacier terminus retreat, the two branches of the former glacier became separate into two small glaciers in 1993. Some work has been carried out on glacier mass balance at Urumqi Glacier No. 1 during the past 20 years, but few have focused on the variations of East and West Branch. Whereas the East and West Branch separated completely, they have differences in terrain, slope, glacier area, and altitude. When studying mass balance change against the background of climate warming, it is necessary to compare the differences of East and West Branch. In this study, according to mass balance of East and West Branch and meteorological data, contrastive analysis was carried out on the variations of glacier mass balance, equilibrium line altitude, accumulation area ratio and net ablation, and the difference of mass balance sensitivity to climate change.

2 Study area and data

Urumqi Glacier No. 1 (43°08′N, 86°82′E), the best-monitored glacier in China and a reference glacier in the World Glacier Monitoring Service (WGMS) glacier monitoring network (Zhang *et al*., 2012), is located at the headwaters of the Urumqi River in the eastern Tianshan Mountains (Figure 1), and is the largest glacier in the Urumqi River Basin. Glacier area was 1.95 km^2 and minimum altitude was 3,637 m a.s.l. in 1959, and is a continental glacier according to ice physical characteristics. The photograph shown in Figure 1 was taken by ZhongQin Li in 2007, indicating that Urumqi Glacier No. 1 is a northeast-facing valley glacier with two branches, East Branch (the area was 1.163 km^2) and West Branch (the area was 0.677 km^2), which were separated in 1993. According to 2010 data, the East Branch has a total area of 1.068 km^2 with a length of 2.028 km, altitudinal range is between 3,743 m a.s.l. and 4,267 m a.s.l., and the median elevation is 3,978 m a.s.l. The West Branch has a total area of 0.577 km^2 with a length of 1.714 km, and altitudinal range is between 3,845 m a.s.l. and 4,484 m a.s.l., and median elevation is 4,087 m a.s.l. (WGMS, 2011).

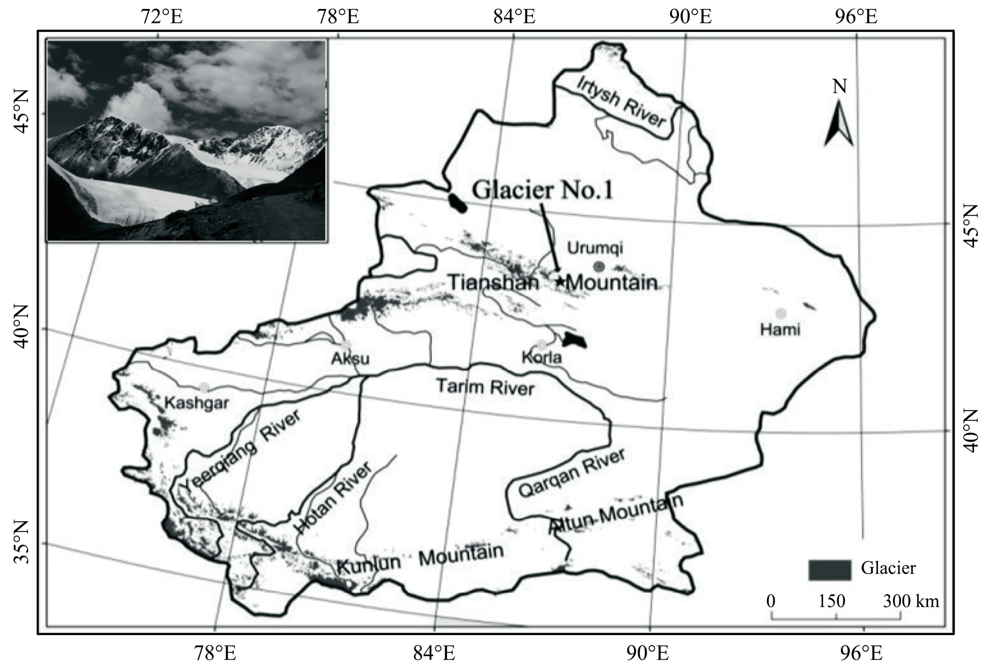

Figure 1 Location of the Urumqi Glacier No. 1 within Tianshan Mountain

Glacier mass balance is a traditional and basic observation that indicates the accumulation and ablation rates of the glacier. The mass balance observation to the Urumqi Glacier No. 1 that began in the summer of 1959 was measured by the stakes and snow pits method. There were 45–50 stakes and five snow pits over the entire glacier except the steep slopes. In the ablation zone, accumulation and ablation was measured by stakes' changes, in the accumulation area, they are measured by digging pits at each of the stakes. Based on mass balance of a single point and a standard glacier map, the isolines of mass balance can be drawn, and annual mass balance can be calculated by using the area weighted method. The altitude where annual mass balance was zero was defined as the equilibrium line altitude (ELA), the accumulation area ratio (AAR) through the location of ELA can be calculated.

The mass balance data of East and West Branch have been separately reported starting from 1987/88 in Annual Reports of the Tianshan Glaciological Station (TGS) with study period in 1988–2010 (Table 1). The main data source is the Annual Report of TGS, Glacier Mass Balance Bulletin, Fluctuations of Glaciers of WGMS, and meteorological data obtained from the vicinal Daxigou Meteorological Station (DMS; 3,539 m a.s.l.).

Table 1 Mass balance of East Branch and West Branch, Urumqi Glacier No. 1

Period	East Branch				West Branch			
	b_n (mm)	*ELA* (m)	*AAR* (%)	*A* ($\times 10^4$ m^3)	b_n (mm)	*ELA* (m)	*AAR* (%)	*A* ($\times 10^4$ m^3)
1987/1988	−646	4,050	32	81.2	−639	4,110	43	48.0
1988/1989	39	3,916	69	20.1	220	4,036	62	10.7
1989/1990	18	3,908	69	29.4	110	4,010	73	15.0
1990/1991	−734	4,110	25	87.7	−657	4,150	41	47.7
1991/1992	15	3,918	69	27.7	37	4,032	67	17.8
1992/1993	−34	3,932	69	31.9	−20	4,028	69	19.6
1993/1994	−384	4,037	37	59.8	−367	4,079	46	35.4
1994/1995	−225	4,021	49	39.7	−233	4,049	53	21.4
1995/1996	46	3,947	66	11.8	37	3,910	69	5.0
1996/1997	−773	4,079	25	91.5	−995	4,240	24	67.2
1997/1998	−826	4,055	28	97.1	−726	4,138	41	50.4
1998/1999	−825	4,095	28	97.0	−737	4,170	37	48.9
1999/2000	−379	4,048	47	51.1	−242	4,090	55	23.5
2000/2001	−915	4,115	35	107.2	−704	4,153	44	49.9
2001/2002	−871	4,140	31	101.8	−767	4,143	42	51.4
2002/2003	−387	4,066	45	54.0	−377	4,089	52	32.2
2003/2004	−706	4,096	42	86.4	−844	4,173	40	56.2
2004/2005	−480	4,045	48	62.2	−503	4,071	54	35.5
2005/2006	−920	4,086	19	104.3	−506	4,089	43	42.5
2006/2007	−696	4,060	28	82.5	−542	4,100	36	38.2
2007/2008	−1,046	4,152	10	121.5	−719	4,184	31	47.8
2008/2009	−57	3,975	56	26.1	289	4,010	81	9.7
2009/2010	−1,441	>4,267	0	154.1	−1,116	>4,484	0	64.4
Mean	**−532**	**4,049**	**40**	**70.7**	**−435**	**4,110**	**48**	**36.5**

b_n: mass balance; *ELA*: the equilibrium line altitude (> means *ELA* surpassed the glacier summit); *AAR*: the accumulation area ratio; *A*: net ablation.

3 Variations of mass balance

3.1 Mass balance and cumulative mass balance

The mass balance change is an undelayed response of the glacier to climate change, and it is also a sensitive indicator for climate change (Li *et al.*, 2008). Both mass balance and cumulative mass balance of East and West Branch have shown that mass loss is serious and increasing (Figure 2). During 1988–2010, East and West Branch mass balance varied between −1,441 to 46 mm and −1,116 to 289 mm, with average mass balance of −532 mm/a and −435 mm/a, and cumulative mass balance was −12,227 mm (ice thinned by 13.6 m) and −10,001 mm (ice thinned by 11.1 m), respectively. From 1988 to 1996 weak negative balance was typical, the average mass balance of East and West Branch was −212 mm /a and −168 mm/a, respectively. Especially in 1997–2010, it was characterized by strong negative balance, the minimum mass balance value of East and West Branch was −1,441 mm and −1,116 mm in 2010, the average mass balance sharply reduced to −737 mm/a and −606 mm/a, respectively, and cumulative mass balance accounted for 85% of total mass loss amount. The main reason for this loss is due to major worldwide weather events in 1997, with an average temperature of 16.9 °C, which is the highest average temperature during the 20th century, and the global climate continued warming (Li, 1998).

However, the mass loss amount of East and West Branch are different, the average mass loss of East Branch was 97 mm/a larger than West Branch, which means that East Branch was 2.5 m thinner than West Branch during the past 23 years.

3.2 Mass balance versus ELA

The equilibrium line altitude (ELA) is a theoretical line on a glacier at which annual mass accumulation equals annual mass loss (Dong *et al.*, 2012; Wang *et al.*, 2012), has a close relationship with glacier mass balance and local climate conditions, and its altitude depends on the interaction among climate, topography and glacier (Ju *et al.*, 2004). The ELA change is a reflection of glacier morphology for regional climate, and also is an important climate index to distinguish glacial properties, types and their activities. Figure 3a shows the ELA variations of East and West Branch: ELA descended slowly from 1988 to 1996, ascended promptly after 1996, then surpassed the glacier summit in 2010. Over the whole study period, ELA displayed a general ascending trend, with a linear regression of its variational trend, ELA of East and West Branch ascended about 176 m and 154 m, respectively. ELA of East Branch varied between 3,908 and 4,267 m a.s.l., with a mean of 4,049 m a.s.l., ELA of West Branch varied between 3,910 and 4,484 m a.s.l., with a mean of 4,110 m a.s.l.. ELA of West Branch was 61 m higher than East Branch, indicating that ELA of West Branch was generally higher than East Branch, this may be due to altitude, slope and surface morphology of the glacier.

Previous research indicated that ELA had negative correlation with mass balance (Liu *et al*., 1997; Wang *et al*., 1998). Figure 3b indicates the correlation between glacier ELA and mass balance during 1988–2010. Then we obtained the correlation models between the ELA and mass balance (b_n):

East Branch:

$$ELA = 3942 - 0.20b_n \quad (R = 0.95) \tag{1}$$

West Branch:

$$ELA = 4011 - 0.23b_n \quad (R = 0.83) \tag{2}$$

Results show that ELA has a strong negative correlation with mass balance. As the mass balance decreases, the ELA shows an ascending trend, exceeding the upper limit of the glacier when mass balance decreases to a certain extent. Analysis shows that if mass balance decreases 100 mm, and the ELA of East and West Branch would ascend by 20 m and 23 m, respectively. The average mass balance of East and West Branch were −532 mm/a and −435 mm/a during 1988–2010. Based on the aforementioned formulae, the ELA can be calculated as 4,048 m and 4,111 m, which are in accordance with the measured average ELA (4,049 m and 4,110 m). In addition, from Formulae *(1)* and *(2)*, we know that the ELA of East and West Branch was in a steady state, namely zero equilibrium line altitude (ELA_0) was 3,942 m and 4,011 m respectively, 107 m and 99 m lower than the mean ELA.

3.3 Mass balance versus AAR

The accumulation area ratio (AAR) is the ratio of accumulation area to total glacier area, and is one of the most important indicators of the weight variation of mass balance. The AAR of East and West Branch shows an obviously decreasing trend during 1988–2010 (Figure 4a), descended by 34.5% (slope is 1.5%/a) and 23% (slope is 1.0%/a), the slope of the regression line of East Branch AAR was larger, implying that the decreased amplitude of East Branch was greater than that of West Branch. The East Branch AAR varied between 0%–69% with an average value of 40%, the West Branch AAR varied between 0%–81% with an average of 48%.

Figure 4b indicates the correlation between glacier AAR and mass balance. We obtained the correlation models between the AAR and mass balance (b_n) as follows:

East Branch:

$$AAR = 65 + 0.046b_n \quad (R = 0.96) \tag{3}$$

West Branch:

$$AAR = 66 + 0.042b_n \quad (R = 0.92) \tag{4}$$

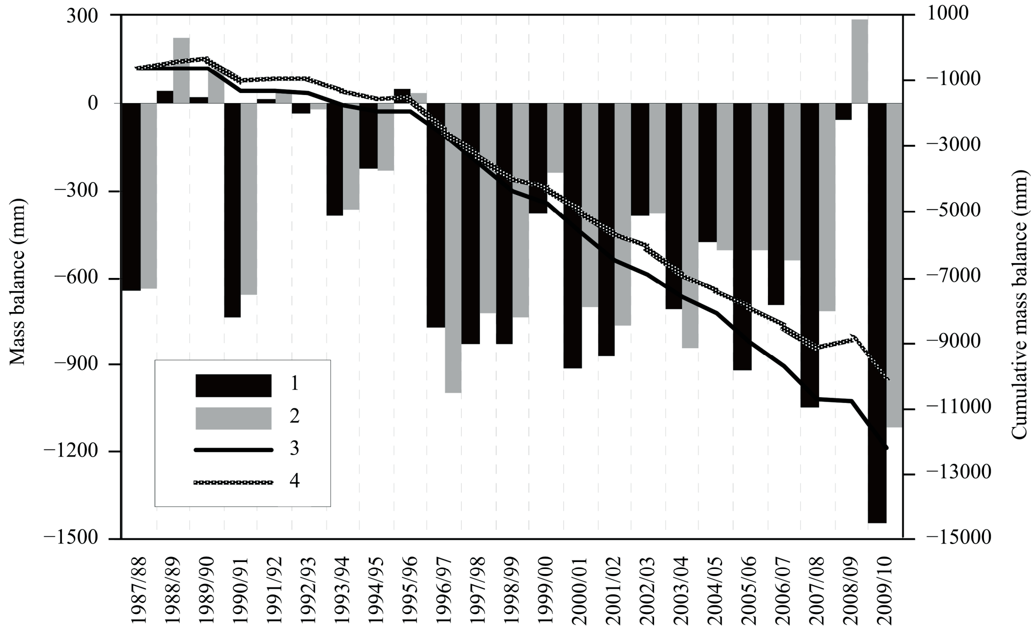

Figure 2 Multi-year course of mass balance and cumulative mass balance. 1: mass balance of East Branch; 2: mass balance of West Branch; 3: cumulative mass balance of East Branch; 4: cumulative mass balance of West Branch

Results show that AAR has a significantly positive correlation with mass balance. As the mass balance increases, the AAR also shows an ascending trend. Data analysis shows that if mass balance increases 100 mm, the AAR of East and West Branch would ascend 4.6% and 4.2%, respectively. The AAR of East and West Branch was in an equilibrium state, namely zero accumulation area ratio (AAR_0) was 65% and 66%, respectively, which was 25% and 18% larger than the average value (40% and 48%). We can draw a conclusion that the AAR synchronously changed with mass balance result, the possible reason is that accelerated glacier melt expands the ablation area, so accumulation area decreases, causing an accumulation area ratio decrease.

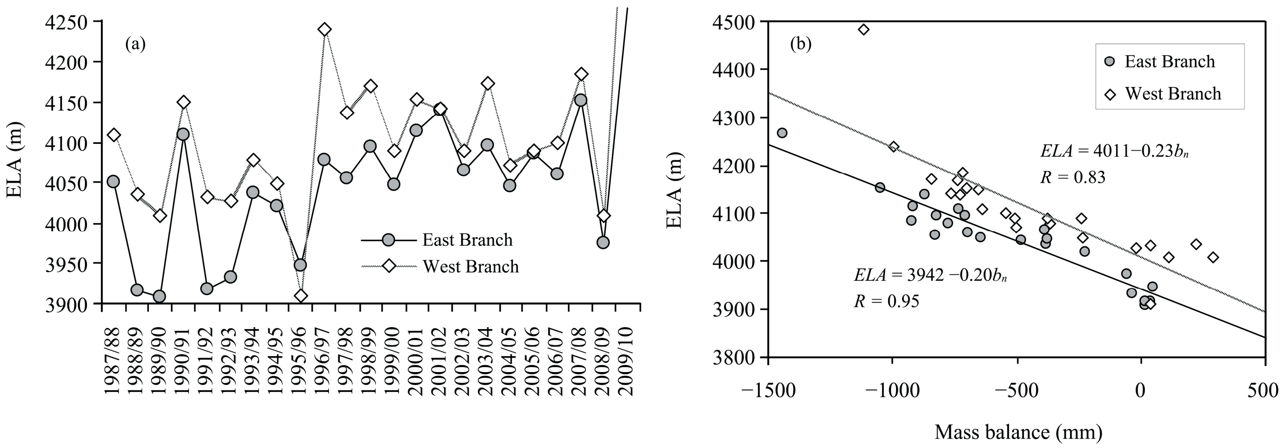

Figure 3 ELA variations (a) and mass balance versus ELA (b) of East and West Branch

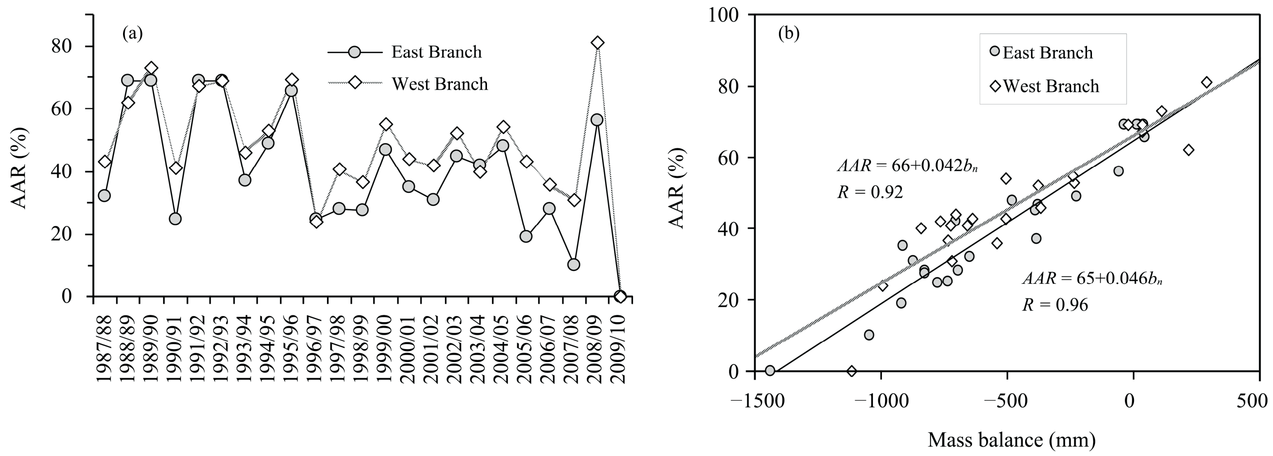

Figure 4 AAR variations (a) and mass balance versus AAR (b) of East and West Branch

3.4 Mass balance versus net ablation

Urumqi Glacier No. 1 is a summer-accumulation-type glacier, both accumulation and ablation occurs in the summer. The net ablation is directly related to the inter-annual change of mass balance (Shi *et al*., 2009). During 1988–2010, the net ablation of East and West Branch shows an obvious increasing trend, the net ablation of East Branch varied between 12×10^4 m^3 and 154×10^4 m^3, with an average value of 71×10^4 m^3, the West Branch varied between 5×10^4 m^3 and 67×10^4 m^3 with an average value of 37×10^4 m^3. Figure 5 shows the relationship between mass balance and net ablation (A). The correlation models are as follows:

East Branch:

$$b_n = 248-11.0A \quad (R = 0.99) \tag{5}$$

West Branch:

$$b_n = 367-21.4A \quad (R = 0.98) \tag{6}$$

Results show that mass balance has good correlation with net ablation, demonstrating that as net ablation increases, mass balance decreases, indicating that glacier mass balance was sensitive to change of net ablation. Data analysis shows that net ablation of East and West Branch increases 10×10^4 m^3, and mass balance decreases 110 mm and 214 mm, respectively. The average net ablation of East and West Branch was 71×10^4 m^3 and 36×10^4 m^3, according to the aforementioned analysis, mass balance was 534 mm and 403 mm, almost identical to measured average value (−532 mm and −435 mm).

4 Mass balance sensitivity to climate change

Climate conditions transformed from warm-dry to warm-wet in Tianshan Mountains since 1987, with Urumqi Glacier No. 1 swiftly contracting and thinning, especially in 1997–2010 with strong ablation and mass balance presented large losses, except for 2009 in which there existed a weakly positive balance (mass balance of 63 mm w.e.), the remainder of the balance year saw strong negative balance, which is caused by high temperatures in the ablation period. According to DMS records, during 1988–2010, ablation period mean temperature (May to August) ranged by 2.0–4.8 °C, the average value was 3.4 °C, and increased by 0.5 °C compared with the mean value in 1959–1987. Annual precipitation varied between 383–674 mm, the average value was 499 mm, and increased by 74 mm (17%) compared to average annual precipitation from 1959 to 1987. If the change fitted a linear trend, then temperature rose by about 1.7 °C, and precipitation increased by 45 mm during the period of 1988–2010.

Research has indicated that mass balance is negatively correlated with ablation period temperature and positively correlated with precipitation (Liu *et al.*, 1997; Wang *et al.*, 2012). Figure 6 shows the relationships among glacier mass balance, ablation period temperature, and precipitation during 1988–2010. To investigate the difference in mass balance sensitivity of East and West Branch responding to climate change, by using the linear regression analysis, based on the 23-year mass balance observations combined with climate data, we established correlations among mass balance (b_n), ablation period temperature (T_s) and annual precipitation (P):

East Branch:

$$b_n = 367-463T_s+1.40P \quad (R = 0.79) \tag{7}$$

West Branch:

$$b_n = 90.5-388T_s+1.58P \quad (R = 0.70) \tag{8}$$

The results show that mass balance of East and West Branch decreased (increased) 463 mm and 388 mm when ablation period temperature increased (decreased) by 1 °C, and mass balance of East and West Branch increased (decreased) 140 mm and 158 mm when annual precipitation increased (decreased) by 100 mm. It can be seen that mass balance sensitivity of East Branch to ablation period temperature was larger than that of West Branch, while mass balance sensitivity of East and West Branch to annual precipitation was equivalent, because precipitation increase was not obvious (only increased by 45 mm over the past 23 years). In addition, the sensitivity of glacier mass balance responding to ablation period temperature, and precipitation demonstrates that ablation period temperature controls mass balance change. Compared with mass balance sensitivity of East and West Branch to climate change, it suggests that sensitivity of East Branch is more intense than that of West Branch. According to the IPCC fourth assessment report (IPCC, 2007), global temperatures could rise by 1.1 to 6.4 °C in the next 100 years (Wang *et al.*, 2011). Thus, we can infer that glacier mass balance might continue to decrease in the future, and mass loss of East Branch is larger than that of West Branch.

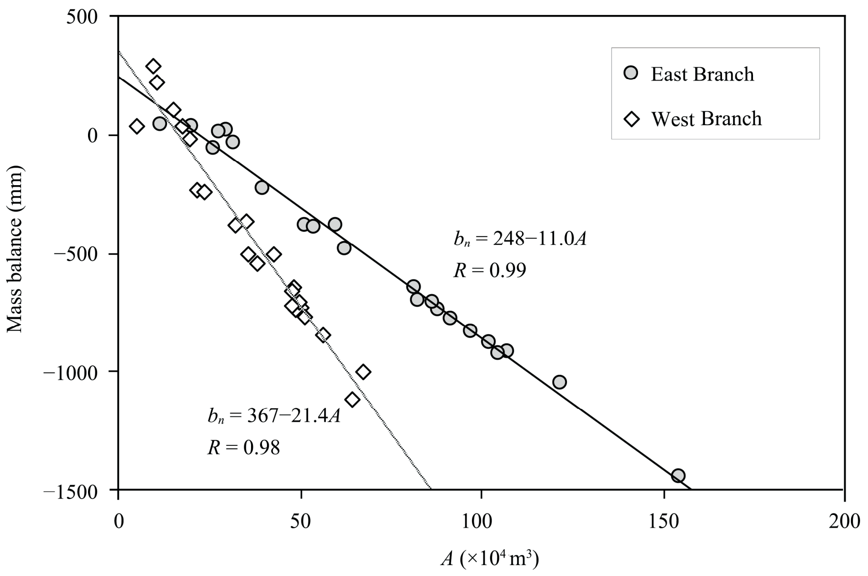

Figure 5 Mass balance versus net ablation (*A*) of East and West Branch

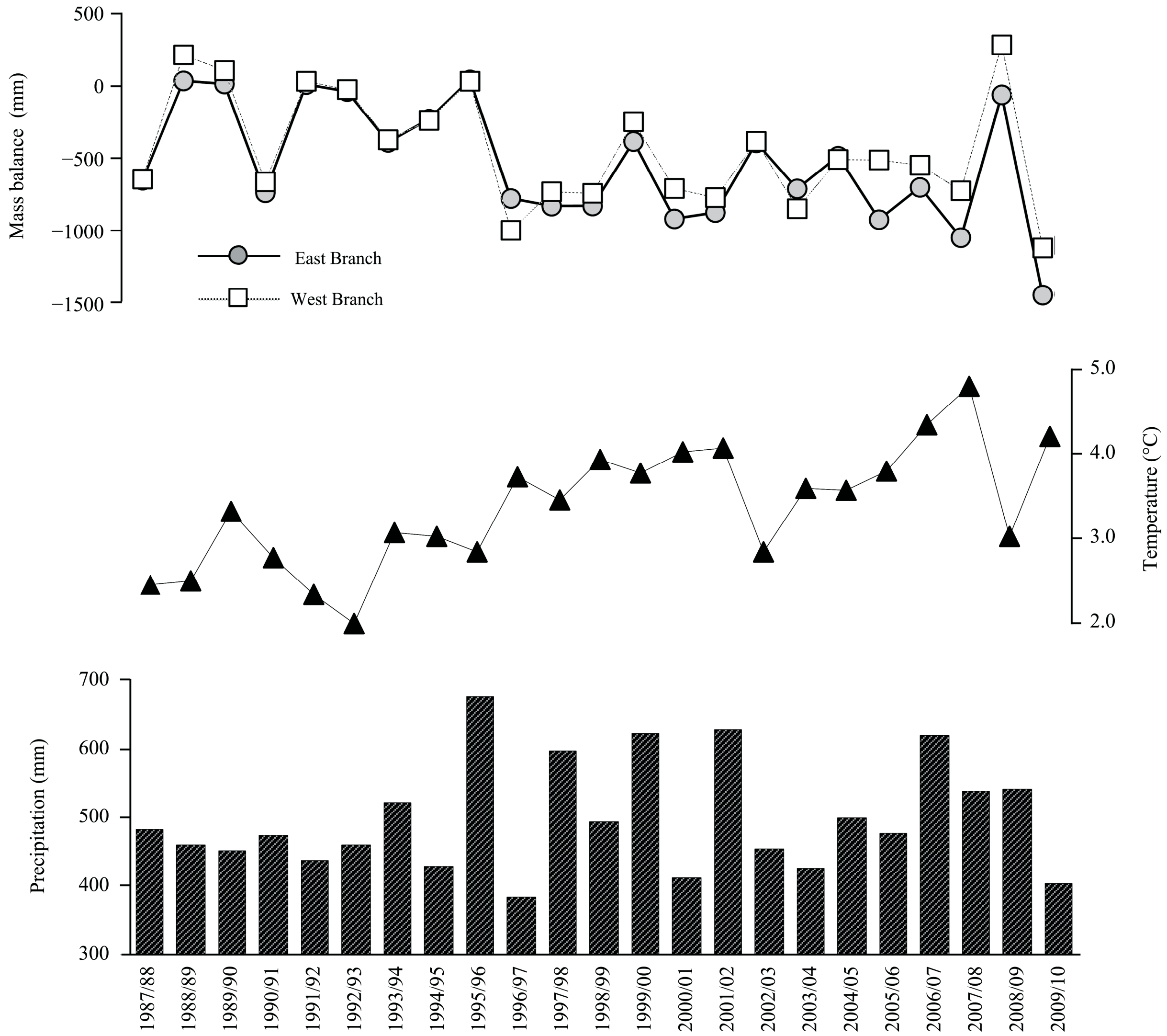

Figure 6 Mass balance versus precipitation and ablation period temperature

5 Conclusion

Based on observed mass balance data of East and West Branch and meteorological data during 1988–2010, by comparative study of mass balance variations and analysis of the sensitivity of mass balance to climate change, the following conclusions can be drawn:

(1) The average mass balance of East Branch was −532 mm/a, cumulative mass balance was −12,227 mm (ice thinned by 13.6 m), that of West Branch was −435 mm/a, cumulative mass balance was −10,001 mm (ice thinned by 11.1 m), and the mass loss of East Branch was 97 mm/a larger than West Branch.

(2) East and West Branch ELA ascended about 176 m and 154 m, respectively, analysis shows that steady-state ELA_0 was 3,942 m a.s.l. and 4,011 m a.s.l., with mass balance decrease, the ELA shows an ascending trend, and East and West Branch mass balance decreased 100 mm, ELA ascended 20 m and 23 m, respectively.

(3) East and West Branch AAR shows an obviously decreasing trend, descended by 34.5% and 23%, the equilibrium-state AAR_0 was 65% and 66%, with mass balance increase, the AAR shows an ascending trend, and East and West Branch mass balance increased 100 mm, AAR ascended 4.6% and 4.2%, respectively.

(4) Glacier mass balance was sensitive to change of net ablation, as net ablation increased, mass balance decreased, analysis shows that when net ablation of East and West Branch increased 10×10^4 m^3, mass balance decreased 110 mm and 214 mm, respectively.

(5) Analyzing results suggest that East and West Branch mass balance decreased (increased) 463 mm and 388 mm respectively when ablation period temperature increased (decreased) by 1 °C, East and West Branch mass balance increased (decreased) 140 mm and 158 mm respectively when annual precipitation increased (decreased) by 100 mm, and the sensitivity of East Branch mass balance to climate change was more intense than that of West Branch.

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REFERENCES

Dong ZW, Qin DH, Ren JW, Li KM, Li ZQ, 2012. Variations in the equilibrium line altitude of Urumqi Glacier No.1, Tianshan Mountains, over the past 50 years. Chin. Sci. Bull., 57(36): 4776–4783.

Duan KQ, Yao TD, Wang NL, Liu HC, 2012. Numerical simulation of Urumqi Glacier No.1 in the eastern Tianshan, central Asia from 2005 to 2070. Chinese Science Bulletin, 57: 4505–4509.

IPCC, 2007. Climate change 2007: The physical science basis. Report of Working Group II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Ju YJ, Liu GN, Zhang XY, Fu HR, Wei X, Cui ZJ, 2004. High Mountain glaciers' ELA_0 and climate. Progress in Geography, 23(3): 43–49.

Li XY, 1998. Significant climate events in the world during 1997. Meteorological Monthly, 24(4): 22–25.

Li ZQ, Li HL, Chen YN, 2011. Mechanisms and simulation of accelerated shrinkage of continental glaciers: A case study of Urumqi Glacier No.1 in Eastern Tianshan, Central Asia. Journal of Earth Science, 22(4): 423–430.

Li ZQ, Shen YP, Li HL, Dong ZW, Wang LW, 2008. Response of the melting Urumqi Glacier No. 1 in Eastern Tianshan to climate change. Advances in Climate Change Research, 4: 67–72.

Liu CH, Xie ZC, Wang CZ, 1997. A research on the mass balance processes of Glacier No.1 at the headwaters of the Urumqi River, Tianshan Mountains. Journal of Glaciology and Geocryology, 19(1): 17–24.

Shi YF, Huang MH, Yao TD, He YQ, 2009. Glaciers and Related Environments in China. Science Press, Beijing, pp. 1–539.

Shi YF, Shen YP, Li DL, Zhang GW, Ding YJ, Hu RJ, Kang ES, 2003. Discussion on the present climate change from warm-day to warm-wet in Northwest China. Quaternary Sciences, 23(2): 152–164.

Wang NL, He JQ, Pu JC, Jiang X, Jin ZF, 2012. Variations in equilibrium line altitude of the Qiyi Glacier, Qilian Mountains, over the past 50 years. Chin. Sci. Bull., 55: 3107–3115.

Wang NL, Yao TD, Tian LD, Liu SY, Duan KQ, 1998. Climate sensitivity of Glacier No.1 at the source of the Urumqi River in Tianshan Mountains. Arid Land Geography, 21(4): 34–40.

Wang PY, Li ZQ, Li HL, 2011. Ice volume changes and their characteristics for representative glacier against the background of climate warming—A case study of Urumqi Glacier No.1, Tianshan, China. Journal of Natural Resources, 26(7): 1189−1198.

Wang WB, Li ZQ, Zhang GF, Li XL, 2012. The processes and characteristics of mass balance on the Urumqi Glacier No.1 during 1958–2009. Sciences in Cold and Arid Regions, 4(6): 505–513.

WGMS, 2011. Glacier Mass Balance Bulletin No.11 (2008–2009). In: Zemp M, Nussbaumer SU, Gärtner-Roer I, Hoelzle M, Paul F, Haeberli W (eds.). ICSU (WDS) / IUGG (IACS) / UNEP / UNESCO / WMO, World Glacier Monitoring Service. Zurich, Switzerland, pp. 102.

Wu LH, Li HL, Wang L, 2011. Application of a degree—day model for determination of mass balance of Urumqi Glacier No. 1, Eastern Tianshan, China. Journal of Earth Science, 22(4): 470–481.

Xie ZC, Liu CH, 2010. Introduction to Glaciology. Shanghai Popular Science Press, Shanghai, pp. 1–490.

Yao TD, Pu JC, Lu AX, Wang YQ, Yu WS, 2007. Recent glacial retreat and its impact on hydrological processes on the Tibetan Plateau, China, and surrounding regions. Arctic Antarctic and Alpine Research, 39(4): 642–650.

Ye BS, Yang DQ, Jiao KQ, Han TD, Jin ZF, Yang HA, Li ZQ, 2005. The Urumqi River source Glacier No.1, Tianshan, China: Changes over the past 45 years. Geophysical Research Letters, 32(21): L21504−L21509.

Zemp M, Hoelzle M, Haeberli W, 2009. Six decades of glacier mass balance observations: a review of the worldwide monitoring network. Annals of Glaciology, 50(50): 101–111.

Zhang GF, Li ZQ, Wang WB, Wang WD, Li HL, Huai BJ, 2012. Change processes and characteristics of mass balance of the Urumqi Glacier No.1 at the headwaters of the Urumqi River, Tianshan Mountains during 1959–2009. Journal of Glaciology and Geocryology, 34(6): 1301−1309.