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Rapid decrease of observed mass balance in the Urumqi Glacier No. 1, Tianshan Mountains, central Asia

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ABSTRACT

The mass balance of Urumqi Glacier No. 1 located in Tianshan Mountains of central Asia has been monitored since 1959. Based on the long-term climate and glacier mass balance observation data for the period 1959–2010, analyses show that the glacier mass balance has decreased rapidly, the equilibrium line altitude (ELA) has ascended significantly and the glacier terminus has retreated continuously in response to climate change. The cumulative mass balance was −14,883 mm w.e., equivalent to glacier thinning of 16.5 m, with a mean value of 0.32 m/y. The ELA showed a significant ascending trend, ascending about 90 m. The averaged ELA was 4067 m a.s.l., and analysis shows the steady-state ELA (ELA_0) was 4018 m a.s.l., with the mass-balance gradient $\alpha = 5.9$ mm/m. The glacier terminus retreated by 199.3 m at the east branch and 241.3 m at the west branch. Linear regression analysis results suggest that 1 C° summer temperature increases leads to 440.6 mm mass balance decrease. Mass balance increases by 120 mm when annual precipitation increases by 100 mm. Mass balance decrease was controlled mainly by summer temperature. If such increased warming continues in the future, the glacier mass balance will form a strongly negative balance, the glacier will shrink, and the glacier terminus will continue to retreat.

1. Introduction

Glaciers are sensitive to changes in temperature and precipitation, which makes them important indicators of climate change. They are also inherent components of the economy, culture, and environment in high mountains. In addition, they represent a unique source of freshwater for agricultural, industrial and hydroelectric power production, which is especially important to arid area of northwestern parts of China where precipitation is limited (Yao et al., 2004). As a link connecting changes of glaciers with the changes of climate (Fischer, 2010; Wu et al., 2011), glacier mass balance changes are important, and can serve as a signal of local climatic change. In addition, mass balance is directly linked to glacier fluctuations, climate change and also directly reflects changes of glacier volume, melting, and runoff (Han et al., 2006; Xie and Liu, 2010). It is important to assess the response of glacier mass balance to climate change.

The rapid ablation and retreat of mountain glaciers in the 20th century has been occurring on a global scale, and a significant accelerating trend has appeared during the past two or three decades (Haeberli et al., 2000; Barry, 2006; Li et al., 2011). A recent study has shown that the Xiao Dongkemadi glacier mass balance has shown a deficit trend, the glacial terminus was also retreating, and the rapid decrease in the mass balance is related to summer season warming (Pu et al., 2008). However, the time sequence is short, and the sample size is just 13 (1988–2000), limiting the accuracy of the results. Most other Chinese glaciers have been monitored for only several years, but Urumqi Glacier No. 1 has the longest mass balance dataset. The rapid warming since 1985 has resulted in a sharp retreat of glaciers on the Tianshan Mountains (Li et al., 2010). In this study, we studied on the variations of glacier mass balance. Then, we established a statistical model, which is linking the mass balance and climatic factors (temperature and precipitation) based on continuous observation data during 1959–2010, to analyze the mass balance sensitivity to climate change.

2. Study area

As only the Chinese reference glacier in the World Glacier Monitoring Service (WGMS) glacier monitoring network, Urumqi Glacier No. 1 is representative for central Asia inland areas (Zemp

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et al., 2009). Urumqi Glacier No. 1 (43°07′N, 86°49′E) is located at the headwaters of the Urumqi River in the Tianshan range of central Asia (Fig. 1). Flanking Tianger Peak II (4484 m a.s.l.), the highest peak in the southeastern Tianshan, it is a typical continental mountain glacier. With climate warming, it has been shrinking, with mass negative balance increasing, the glacier area reducing, and glacier retreat. It separated completely and became two independent glaciers in 1993, but the fragments are still called the East and West Branch of Glacier No.1. Based on the glacial inventory of 1962, Urumqi Glacier No. 1 (numbered 5Y730C0029) at that time was 1.95 km^2, 2.25 km long, terminus altitude was 3730 m a.s.l., summit altitude was 4486 m a.s.l., and its average altitude was 4040 m a.s.l. According to the record in 2010, the lower boundary to upper boundary altitude for the East and West branches were 3743–4267 m a.s.l. and 3845–4484 m a.s.l., respectively. The glacier has a total area of 1.645 km^2, and is 2.028 km long (WGMS, 2012). This indicates that the glacier area reduced by 0.305 km^2 (15.6%) during 1962–2010.

3. Data and methods

Mass balance observations have been made every year since 1959, and there are 52 years of data of field work observation. The mass balance observation used measuring stakes. There were 45–50 stakes drilled into the glacier surface at different altitudes of the East and West branches using a steam drill, with a mean of three in every row (Fig. 1). The mass balance year of Urumqi Glacier No. 1 is defined from the previous September 1 to the next August 31. Observations of mass balance are conducted from May to September each year at intervals of one month. The measured items include the stake vertical height over the glacier surface, firn layer thickness and density, thickness of affiliated ice, and structure of snow pits profiles at each stake. The mass balance of a single point (b_n) was obtained by

$$b_n = b_{ice} + b_s + b_{si} \quad (1)$$

where b_{ice}, b_s and b_{si} are the mass balance of glacier ice, snow and affiliated ice, respectively. The mass balance has been calculated based on contour maps of the ablation stakes, accumulation stakes, and snow pits. The mass balance of the whole glacier was calculated by using the area weighted method:

$$B_n = \frac{1}{S}\sum s_i b_i \quad (2)$$

where s_i and b_i are the area and the corresponding mass balance of altitude zone i, respectively, and S is the total area of the glacier.

The annual mass balance data of Urumqi Glacier No. 1 have been internally published in Annual Reports of the Tianshan Glaciological Station, and submitted to WGMS, responsible for collecting and publishing worldwide standardized glacier data, which provides the longest glaciological and climatological monitoring record (Kaser et al., 2003). The glacier data series used in this research were extracted from Annual Report of Tianshan Glaciological Station and the Glacier Mass Balance Bulletin, Fluctuations of Glaciers, available at the website http://www.wgms.ch. Meteorological data come from the Daxigou Meteorological Station located at 3539 m a.s.l., about 3 km downstream of the glacier (Fig. 1). It has been operated by the Xinjiang Uygur Autonomous Region Meteorological Bureau since 1958, and a continuous time series of the temperature and precipitation data are available.

4. Results and discussion

4.1. Change of climate conditions

Climate in the Urumqi River source is affected mostly by the Tibetan Plateau monsoon in summer. Urumqi Glacier No. 1 is a

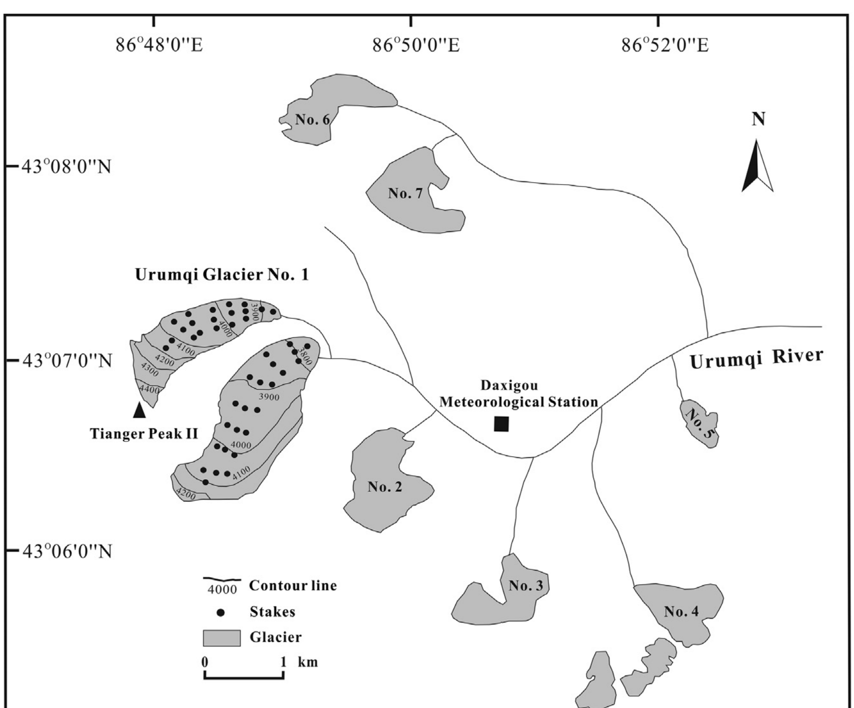

Fig. 1. Maps showing location of Urumqi Glacier No. 1 and the Daxigou Meteorological Station at the headwaters of the Urumqi River, showing the position of the stakes for Urumqi Glacier No. 1 in 2010 (black dots).

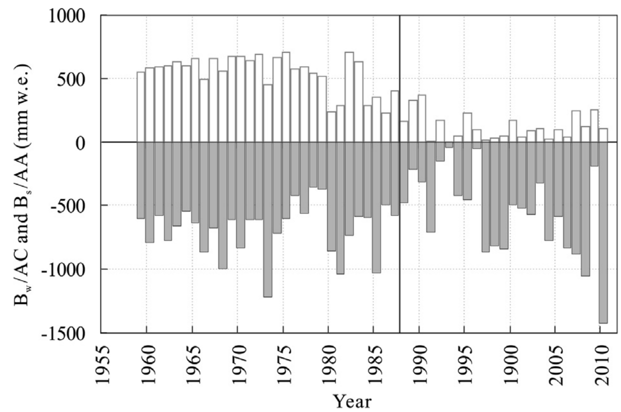

Fig. 2. Winter balance/annual accumulation (positive value), and summer balance/annual ablation (negative value) for Urumqi Glacier No. 1. The figure is divided into two parts: white and grey bars represent annual accumulation and annual ablation before 1988; and winter balance and summer balance for 1988–2010.

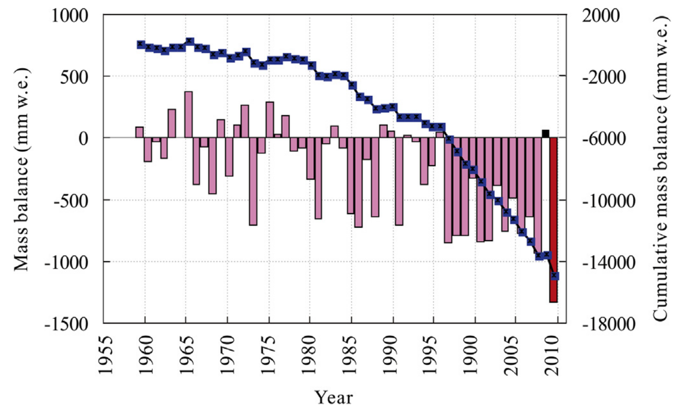

Fig. 3. Change of annual mass balance and cumulative mass balance of Urumqi Glacier No. 1 (bars represent the annual mass balance, block represents cumulative mass balance). Positive balance (63 mm w.e. in 2009) and Negative balance (−1327 mm w.e. in 2010) represent the extreme values of annual mass balance during 1997–2010.

summer-accumulation-type glacier because both accumulation and ablation occur in summer, and there is little snowfall in winter. According to the record in this region, during 1959–2010, the mean annual temperature was −5.1 °C, the monthly mean temperature was below zero for seven to eight months, the coldest month (January) average temperature was −15.5 °C, and monthly mean temperature of the hottest month (July) was 5.0 °C. The average annual precipitation was 467 mm, with annual precipitation mainly concentrated in summer (May to August). The glacier firn basin is at about 4030 m a.s.l., which is the maximum precipitation zone of the glacier. Averaged annual precipitation is 700 mm (Li et al., 2006). Precipitation increased with altitude at an average gradient of 22 mm/100 m (Yang et al., 1992). The average annual temperature decline rate was 0.65 C°/100 m in the non-glacier area, and was slightly larger in summer and smaller in winter.

Using the observation data derived from the Daxigou Meteorological Station, we analyzed the change rule of temperature and precipitation, and divided the period into three stages. Before 1986, the temperature and precipitation were relatively low with fluctuations. The annual average temperature was −5.4 °C and precipitation was 422 mm. However, the climate conditions for Urumqi River source underwent a shift from a warm-dry to warm-wet pattern (Shi et al., 2003). A significant rise in temperature and precipitation began to appear after 1986. During 1986–1996, annual mean temperatures was between −4.7 °C and −5.8 °C, an average of −5.2 °C. The summer mean temperature range was between 2.0 °C and 3.4 °C, with a mean value of 2.7 °C. The annual precipitation varied from 354 to 674 mm, the average was 469 mm. In 1997–2010, the changes were particularly strong: annual mean temperatures were between −3.5 °C and −4.8 °C. The average was −4.3 °C, corresponding to an increase of 0.9 C° (0.064 C°/y) compared with the mean value of 1986–1996. The average summer temperature was 3.8 °C, increasing by 1.1 C° (0.079 C°/y). Average precipitation was 506 mm, increasing by 37 mm. Therefore, the climate conditions of Urumqi River source have underwent a significant change. As a result, the glaciers of this region experienced accelerated melting and retreating.

4.2. Mass balance changes

Urumqi Glacier No. 1 has both accumulation and ablation in summer, and there is little snowfall in winter, unlike the glaciers in Europe and mid-America, which accumulate in winter and lose mass in summer (Li et al., 2008). Only annual accumulation and annual ablation were measured before 1988. The mass balance year is divided into winter and summer season, with the corresponding winter and the summer balance. The annual mass balance (B_n) of the whole glacier was calculated from:

$$B_n = B_w + B_s \tag{3}$$

where B_w and B_s denote the winter balance and summer balance. The winter balance predominantly consists of snow accumulation, but there may be short (unobserved) periods of melting, so that the observed winter balance is the net result of accumulation and ablation during the winter season. Similarly, summer balance is the net result of melting, offset by greater or smaller snowfalls during the summer (Braithwaite, 2002). Winter and summer balances involve essentially different processes, measured since 1988. Fig. 2 shows the winter balance (B_w)/annual accumulation (AC), and summer balance (B_s)/annual ablation (AA); results are converted to water equivalent.

Glacier mass balance reflects how the glacier is affected by regional hydrothermal conditions (Shi et al., 2005; Wang et al., 2012). Fig. 3 shows the change of annual mass balance and cumulative mass balance for Urumqi Glacier No. 1. Annual mass balance varies between 374 and −1327 mm w.e., with a mean of −286 mm w.e. Glacier mass balance has been decreasing almost monotonically in the last 52 years. Annual mass balance averaged −94 mm w.e. before 1986, then changed to −242 mm w.e. during 1986–1996. In 1997–2010, strong ablation occurred, with large mass losses. Although 2009 was a weak positive balance (63 mm w.e.), the rest of the 13 years showed strongly negative balance, averaging −701 mm w.e., and reaching a minimum value of −1327 mm w.e. in 2010. During 1997–2010, cumulative mass balance was −9676 mm w.e. (ice average thinning 10.8 m), accounting for 60% of the total mass losses during the past 52 years, indicating that this is the most intense period of mass loss of Urumqi Glacier No. 1 since 1959. Throughout the study period, cumulative mass balance was −14,883 mm w.e., equivalent to glacier thinning of 16.5 m, with a mean value of 0.32 m/y.

4.3. Equilibrium line altitude

The equilibrium line altitude (ELA) is the average altitude at which accumulation exactly balances ablation, over a period of one year. It separates the accumulation zone from the ablation zone (Benn and Lehmkuhl, 2000; Wang et al., 2010; Dong et al., 2012). This definition contains two meanings. First, the annual mass

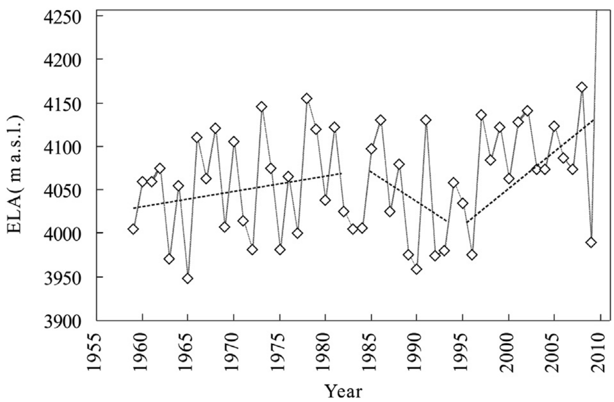

Fig. 4. ELA variations of Urumqi Glacier No. 1 during 1959–2010. Dashed line is the regression for ELA change trend.

balance was zero at the ELA. Second, ELA does not imply that the whole glacier is in equilibrium, and the whole glacier may be gaining or losing. Glacier behaviors such as advancing or retreating are controlled by ELA variations, and fluctuations of ELA provide an important indicator of glacier response to climate change. A strong melt corresponds to a higher ELA, conversely, greater accumulation causes ELA to fall accordingly.

During the period 1959–2010, ELA varied between 3948 and 4484 m a.s.l., with a mean of 4067 m a.s.l. The ELA of the positive and negative mass balance years varied over 3948–4066 m a.s.l., and 3984–4484 m a.s.l., respectively. The mean ELA value of the positive mass balance years (3995 m a.s.l.) was 104 m lower than the ELA of the negative mass balance years (4099 m a.s.l.). Fig. 4 presents Urumqi Glacier No. 1 ELA variations, with ELA divided into three stages for the whole observation period 1959–2010. During 1959–1985, ELA showed a slowly ascended trend within a normal fluctuation range, with a mean of 4051 m a.s.l. ELA descended slowly from 1986 to 1996, and the average ELA was 4035 m a.s.l. However, glacier ELA has ascended since 1997, with a mean of 4125 m a.s.l. In 2010, the highest observed value appeared, and ELA surpassed the glacier summit, which implies that the whole glacier was ablating in this year (Fig. 4). Over the whole study period, ELA displayed a generally ascending trend, ascending about 90 m.

Glacier ELA and annual mass balance have a significant linear relationship, with a correlation coefficient of Urumqi Glacier No. 1 of 0.80. The ELA associated with zero annual mass balance for the whole glacier is known as the steady-state ELA, which is thus a theoretical construct which may never actually occur in nature. A particular glacier may always be out of equilibrium with climate to greater or lesser degree (Benn and Lehmkuhl, 2000). The steady-state ELA (ELA_0) should ideally be based on observations of glacier mass balance over several years, indicated by the intersection of the best-fit line and the vertical axis (zero annual mass balance). ELA_0, is 4018 m a.s.l. and lies some 49 m below the mean ELA for the study period (Fig. 5).

Mass-balance gradient is used to reflect the change of annual mass balance with ELA in the study of glaciology. Equation (4) is used to calculate the mass-balance gradient (Wang et al., 2012; Zhang et al., 2012):

$$\alpha = B_n/(\mathrm{ELA}_0 - \mathrm{ELA}) \tag{4}$$

where, α is mass–balance gradient, B_n is annual mass balance and ELA_0 is the steady-state ELA. Based on the equation (4), we obtain the mass-balance gradient α = 5.9 mm/m. As the ELA ascends 100 m, the annual mass balance decreases by 590 mm. In practice, mass-balance gradient is also influenced by local factors (Mayo,

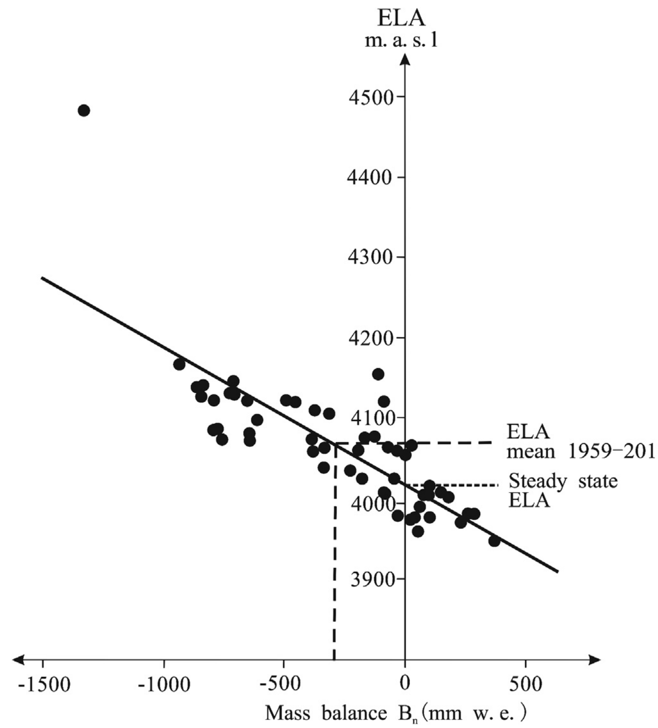

Fig. 5. Relationship between ELA and mass balance of Urumqi Glacier No. 1 for the observation period 1959–2010.

1984; Kaser, 1995). However, these values averaged over many years have been relatively stable.

4.4. Retreat of glacier terminus

The change of glacial mass balance results in changes in glacier movement patterns, terminal position, glacier area and ice reservation (Pu et al., 2008). The change of terminus thus provides reliable evidence of dimensional changes in the glacier. Fig. 6 shows the change of terminus retreat. Urumqi Glacier No. 1 terminus has been measured since 1980. The east and west branches of the glacier separated completely in 1993 due to melting. The total terminus retreat was observed as 139.72 m during 1962–1993, and an average retreat rate of 4.5 m per year (Li et al., 2008). From 1993 to 2010, the east branch retreated at an average rate of 3.5 m per year (a total of 59.6 m), and the west branch retreated at a rate of 6.0 m per year (a total of 101.6 m).

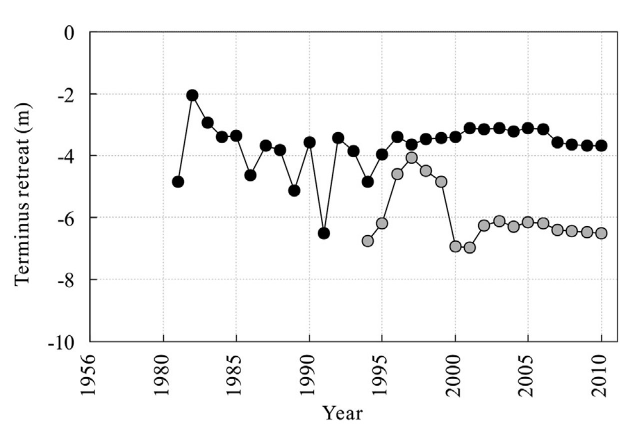

Fig. 6. Change of terminus retreat at the east and west branches of Urumqi Glacier No. 1. Black and grey circles represent the east and west branches, respectively.

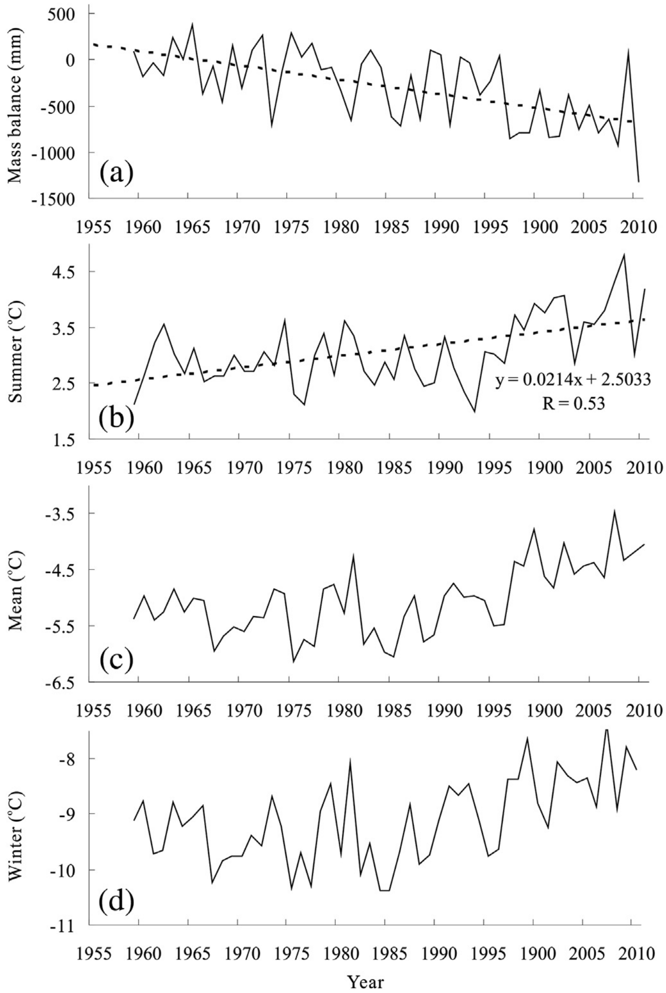

Fig. 7. Mass balance and its trend (a) of Urumqi Glacier No. 1, summer (b), annual mean (c) and winter temperature (d) at Daxigou Meteorological Station. The dash-dotted straight lines are the corresponding trend lines, and the linear regression equations are also shown.

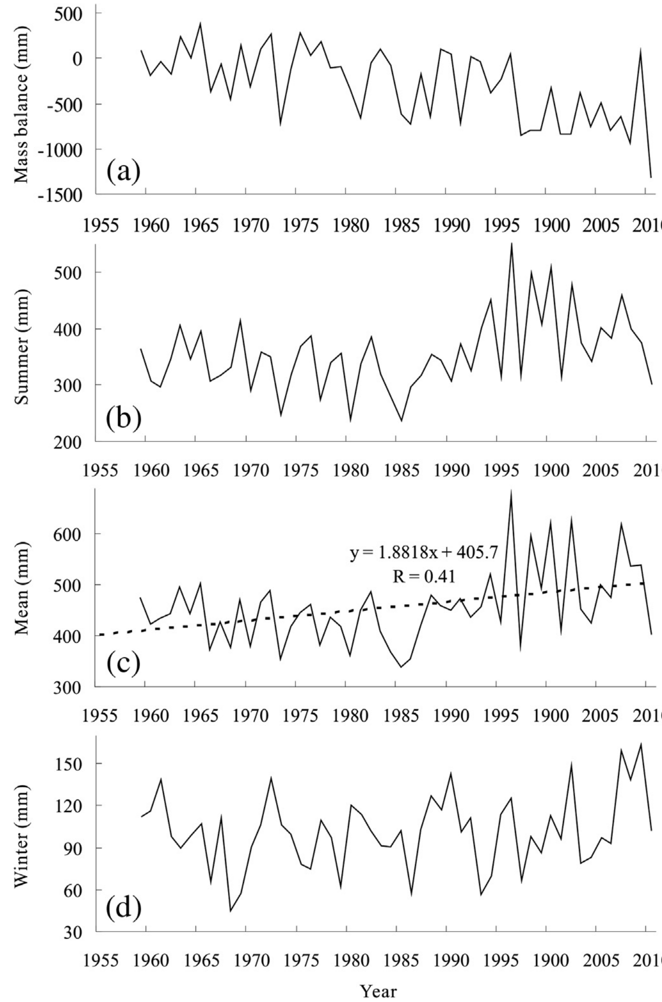

Fig. 8. Mass balance (a) of Urumqi Glacier No. 1, summer (b), annual mean (c) and winter precipitation (d) at Daxigou Meteorological Station. The dash-dotted straight line is the corresponding trend line, and the linear regression equation is also shown.

Throughout the study period, for the east branch, the terminus has retreated by 199.3 m, with an annual mean retreat of 3.83 m. The retreat speed was 5.96 m/y in 1963, 3.33 m/y in the 1970s, 3.7 m/y in the 1980s (Jing et al., 2006), 4.0 m/y in the 1990s, and 3.31 m/y in the 2000s. Similarly, the terminus retreated by 241.3 m at the west branch, with an annual average retreat of 4.64 m, and the retreat speed was 5.4 m/y in the 1990s, and 6.37 m/y in the 2000s. The changes in the glacier terminus of the east and west branches show a similar trend, although the retreat speed of the west branch terminus is greater. The main cause of this difference is that the East Branch is covered with debris and is partly dead. The west branch terminus is high and steep, and the main slope is between 15° and 30°, allowing basal ablation. When monitoring the glacier terminus began, the terminus positions of Urumqi Glacier No. 1 experienced rapid retreat in all the observation years. The terminus of the two branch glaciers showed relatively stable trends in recent years. The changes the terminus retreat corresponded to glacial mass balance variations.

4.5. Mass balance response to climate change

The heat and water conditions (temperature and precipitation) of glacierized regions are the main factors controlling glacier mass balance. Previous research has indicated that the mass balance and temperature have a weak negative correlation. Mass balance and precipitation have a clear positive correlation before 1986. Mass balance and temperature have a negative correlation and no correlation exists with precipitation since 1986 (Li et al., 2008; Wang et al., 2012; Zhang et al., 2013).

Fig. 7 shows the summer (b), annual mean (c) and winter (September to April) (d) temperatures over the period 1959 to 2010 at Daxigou meteorological station. To quantify the relationship between mass balance and temperature, we examined the relationships among summer (T_s), annual mean (T), winter temperature (T_w) and glacier mass balance:

$$B_n = -942.9 - 396.6\, T_s \quad (R = 0.62) \tag{5}$$

$$B_n = -2122.7 - 363.7\, T \quad (R = 0.58) \tag{6}$$

$$B_n = -2439.4 - 236.2\, T_w \quad (R = 0.45) \tag{7}$$

Results showed that mass balance has a very good negative correlation with temperature. With the increase of the temperature, mass balance shows a decreasing trend. Moreover, the summer temperature seems more important to mass balance change, showing a high correlation coefficient ($R = 0.62$). The slope of regression line of the correlation between mass balance and summer temperature is larger, implying that the mass balance will decrease more quickly when summer temperature increases. This result also reflects the significant sensitivity of the glacier mass balance to summer temperature change.

Besides the temperature, glacier mass balance was also influenced by precipitation in the glacial region (Dong et al., 2012). The summer (b), annual (c), and winter (d) precipitation over the period 1959 to 2010 are presented in Fig. 8. The maximum precipitation was 674 mm in 1996 and the minimum precipitation was 340 mm in 1985. The average precipitation was 457 mm during 1959–2010. Fig. 8c shows the variation of annual precipitation, and increasing trend of precipitation at Daxigou meteorological station. When the precipitation increased, the mass balance would increase. We then established the correlation among summer (P_s), annual mean (P), winter temperature (P_w) and glacier mass balance:

$$B_n = -286.9 + 0.001\, P_s \quad (R = 0.000) \tag{8}$$

$$B_n = -321.9 + 0.077\, P \quad (R = 0.014) \tag{9}$$

$$B_n = -347.7 + 0.603\, P_w \quad (R = 0.040) \tag{10}$$

These relationships are very weak statistically, especially as the summer precipitation shows zero correlation. However, studies have shown that over 95% of precipitation occurs from April to October, with the maximum precipitation observed in July and August (Li et al., 2008). Therefore, the analysis does not conform to the reality, and it is reasonable that higher precipitation leads to lower glacier melt, increasing the mass balance (Liu et al., 1997). The summer (Fig. 8b) and winter season (Fig. 8d) precipitation showed a weak increasing trend ($y = 1.5417x + 313.6$, $R = 0.354$, and $y = 0.3401x+92$, $R = 0.196$, respectively). These trends are not significant statistically. However, the annual precipitation (Fig. 8c) showed a relatively good increasing trend ($y = 1.8818x+ 405.7$, $R = 0.41$). If future precipitation is similar to that in the past 52 years, the linear increasing rate for annual, summer and winter seasons is 18.8 mm/10 y, 15.4 mm/10 y and 34 mm/10 y, respectively.

However, we need to consider both the temperature and precipitation factors, and establish a model to find out the sensitivity of the glacier mass balance to climate change. To investigate the sensitivity of Urumqi Glacier No. 1 mass balance to climate change, we established a correlation using the long time series data, between mass balance, summer temperature (T_s) and annual Precipitation (P) in 1959–2010:

$$B_n = 529.3 - 440.6\, T_s + 1.2\, P \quad (R = 0.654,\ n = 52) \tag{11}$$

We investigated the sensitivities of Urumqi Glacier No. 1 to variabilities in summer temperature and annual precipitation using equation (11). Regression results suggest that 1 C° summer temperature increases leads to 440.6 mm mass balance decrease. Mass balance increases by 120 mm when annual precipitation increases by 100 mm. The glacier mass balance is more sensitive to temperature variation than precipitation. The sharp decrease in mass balance in 2010 was related to the higher summer temperature and low precipitation, while the positive mass balance in 2009 was well correlated with the extremely low air temperature and increased precipitation. The high summer temperature caused the mass balance to decrease sharply in 2010.

Much work has been carried out on the glacier mass balance and climate change at Urumqi Glacier No. 1 during the past 20 years. The summer temperature controls glacier mass balance and runoff changes (Ye et al., 2005). Annual air temperature shows a stronger influence on the glacier mass balance than annual precipitation (Han et al., 2006). The annual mass balance was correlated with summer mean air temperature, suggesting summer temperatures are a major cause of the variation in mass balance. Although annual precipitation increased, the mass balance has become more negative with summer warming during the past two decades (Li et al., 2008). Many similar studies were carried out at Urumqi Glacier No. 1 show that mass balance is usually controlled by both temperature and precipitation, but it is controlled mainly by temperature when temperature rises to a certain level.

5. Conclusions

This study analyzed long-term climate and glacier records to examine climate change and glacier response in the Urumqi Glacier No. 1 over the past 52 years. The results show that the cumulative mass balance was −14,883 mm w.e., equivalent to glacier thinning of 16.5 m, with a mean value of 0.32 m/y. The ELA varied between 3948 and 4484 m a.s.l., with a mean of 4067 m a.s.l., displayed a generally ascending trend, and ascended about 90 m. The steady-state ELA (ELA_0) was 4018 m a.s.l., and the mass-balance gradient was 5.9 mm/m. The glacier terminus retreated by 199.3 m at the east branch and 241.3 m at the west branch. Using the linear regression analysis, 1 C° summer temperature increases leads to 440.6 mm mass balance decrease, increasing by 120 mm when annual precipitation increases by 100 mm. The mass balance decrease is controlled mainly by the summer temperature.

Urumqi Glacier No. 1 mass balance has decreased rapidly, the equilibrium line altitude has ascended significantly and the glacier terminus has retreated continuously in response to climate change. If such increased warming continues in the future, the glacier mass balance will be strongly negative balance, the glacier will shrink, and the glacier terminus will continue to retreat.

Acknowledgements

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