The Urumqi River source Glacier No. 1, Tianshan, China: Changes over the past 45 years

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[1] This study analyzes long-term climate and glacier records to examine climate change and glacier response over the past 45 years in Urumqi River source region, the Tianshan Mountains of China. The results show that summer temperature and annual precipitation near the glacier increased by 0.8°C and 87 mm (19%), respectively, during the study period. The glacier continuously retreated from 1962 to 2003, with the cumulated mass balance being −10,032 mm, or 20% of the glacier volume. Annual basin runoff has significantly increased by 413 mm or 62% during 1980–2003 due to precipitation increase and enhanced glacier melt caused by summer climate warming. Both summer precipitation and temperate are negatively correlated with mass balance and positively associated with runoff. Relative to precipitation-mass balance relation, the regression between temperature and mass balance is much stronger, indicating that summer temperature controls glacier mass balance and runoff changes. **Citation:** Ye, B., D. Yang, K. Jiao, T. Han, Z. Jin, H. Yang, and Z. Li (2005), The Urumqi River source Glacier No. 1, Tianshan, China: Changes over the past 45 years, *Geophys. Res. Lett.*, *32*, L21504, doi:10.1029/2005GL024178.

1. Introduction

[2] 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 [*Meier*, 1984; *Oerlemans and Fortuin*, 1992]. The small, mountain glaciers make up less than 3% of the earth's ice cover, they account for approximately 20–50% of the 10–15 centimeter rise in sea level over the last century [*Kuhn*, 1993; *Meier*, 1984], and the total glacier and ice cap volume is equivalent to 0.24–0.7 m sea level rise [*Meier and Bahr*, 1996; *Dyurgerov*, 2002; *Raper and Braithwaite*, 2005]. 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 [*Østrem*, 1991; *Yao et al.*, 2004].

[3] 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]. The Glacier No.1 located in the Urumqi River source has the longest monitoring records during 1958–2003 in China. *Jiao et al.* [2004] summarized the glacier mass balance results. This study systematically analyzes the long-term glacier, climate and hydrology records.

2. Site Description, Data Sets, and Method of Analyses

[4] The Glacier No.1 is located in the headwaters of the Urumqi River, Tianshan, China (43°05′N, 86°49′E) (Figure 1). It is a small valley glacier with two branches, the east and west branches. These two branches became separated into two small dependent glaciers in 1994 due to continued glacier shrinkage. The glacier is about 1.84 km^2 and 2.23 km long with elevation between 3740 and 4486 m a.s.l., the average ice thickness determined in early 1980's from the radar measurement is about 55 m [*Zhang et al.*, 1985].

[5] The glacier observation program at the Tianshan glacier station started in 1959 [*Xie and Ge*, 1965] and continued up to now with interruptions during 1967–1979. Field observations include glacier accumulation and ablation, equilibrium line altitude (ELA), changes in glacier length and area, and meteorological and hydrological data collections. Glacier data have been internally published in annual reports of the Tianshan Glacier Station from 1980–2004, and in the Glacier Mass Balance Bulletin (every two years) compiled by the World Glacier Monitoring Service of the International Commission on Snow and Ice [*World Glacier Monitoring Service*, 2003].

[6] Glacier mass balance is calculated by contour maps of accumulation and ablation, using data measured at the permanent stake network (about 45–80 stakes in 8–9 rows on the glacier) and additional snow pits. Comparisons of methods for mass balance calculations show that the stake network generally provides accurate estimates of glacier mass balance [*Elder et al.*, 1992]. The annual net accumulation, ablation and ELA also have been determined. The mass balance data are available from 1959 to 2003, except

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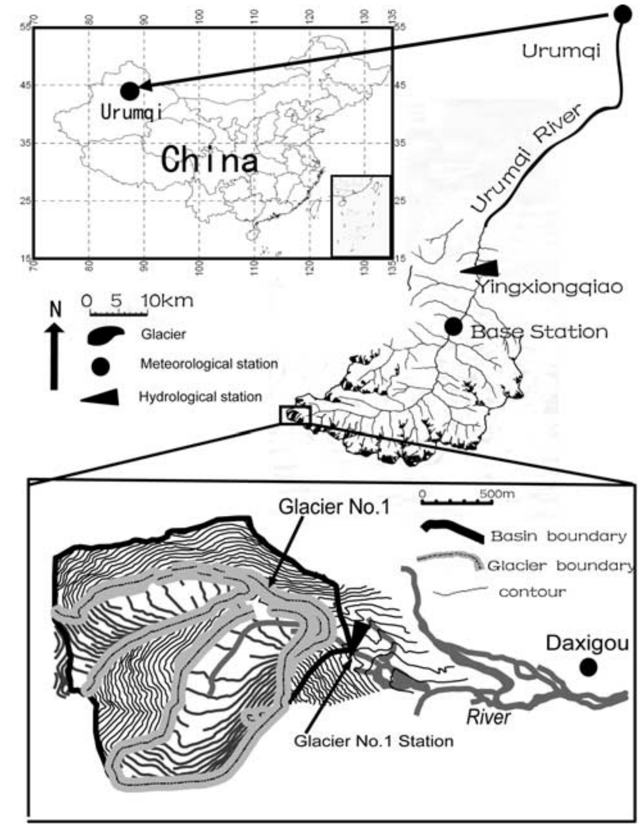

Figure 1. Locations of the Glacier No.1, and hydrologic and meteorological stations in the headwaters of the Urumqi River.

for 1967–1979. The missing data during 1967–1979 have been reconstructed, using the meteorological data [*Zhang*, 1981], based on the relationship between summer air temperature and mass balance during 1958–1966. The glacier length and areas have been determined using glacier maps made in 1962, 1964, 1986, 1992, 1994, 2000 and 2001. The retreat of the glacier snout is directly measured every year. The glacier ice thickness or glacier bed altitude was measured by radar and verified by borehole data in 1981 [*Zhang et al.*, 1985].

[7] The meteorological data during 1958–2003 have been collected at the Daxigou meteorological station located at 3539 m a.s.l., about 3 km downstream of the glacier (Figure 1). The mean annual temperature and precipitation there are −5.1°C, and 450 mm, respectively. A hydrologic station, the Glacier No. 1 Station with a contributing drainage area of 3.34 km^2, has been set up 200 m downstream of the glacier terminus at 3689 m a.s.l. The glacier coverage of the basin is about 53% (various from 55.6% in 1980 to 51.1% in 2001). Discharge has been observed there during the melt period (May–Sept.) from 1980 to 2003.

[8] We carried out trend analyses by the linear regression for the long-term meteorological, hydrological and glacier data collected at or near the Glacier No.1, and used the standard t-test to determine the statistical significance of the trends. We also analyze the relationship among summer temperature, precipitation, and glacier mass balance and runoff to quantify the impact of climate change to glacier change.

3. Climate Change and Glacier Response

[9] The seasonal regime of monthly temperature, precipitation and their trends is shown in Figure 2 (see auxiliary material[1])for the period 1958–2003. Monthly mean temperatures are −13∼−16°C in winter months (Dec–Feb) and 3∼5°C in summer months (Jun–Aug). Monthly temperatures during May to February have increased by 0.4–1.4°C over the last five decades, and the increases in June, July, September and November were statistically significant at 95% confidence. However, March and April became slightly cooler by about 0.3–0.9°C over the study period. As the result of the warming in most months, annual mean temperature has increased by about 0.8°C (95% significance level) over the last five decades. Temperature changes are particularly strong since 1997. For example, the summer (Jun–Aug) mean temperatures range from 3.0–4.6°C during 1958–1996, and vary from 4.4 to 5.8°C since 1997, indicating a step increase of 1.0°C since 1997 (Figure 3a).

[10] Monthly precipitation regime and its trend over the study period are also depicted in Figure 2. It shows that the monthly precipitation varies from 2–50 mm during September to May, and the summer months are relatively wet, with the peak amounts being 97–118 mm in July and August. Snowfall dominates in monthly precipitation, with only 17% rainfall in the warmest month of July. An upward trend was found in all months, except for September with a decrease of 6 mm. The increases are particularly significant (over 22 mm) in June and July, while trends in other months are 1–5 mm. Statistically, precipitation changes in July, November and December are significant at 95% confidence. The total trend of precipitation in summer reached 77 mm (25%) (above 95% significance level) during the study period. Annual total precipitation significantly increased by about 87 mm (19%) over the last several decades. Annual precipitation increases are very strong since 1987. The difference of mean annual precipitation between 1959–1987 and 1988–2003 is 76 mm or 17% of mean annual precipitation during the study period (Figure 3b).

[11] Yearly precipitation increase in the upper basin is very strong. To confirm this change, we examined precipitation data at two stations further downstream and found that the precipitation increase has occurred not only in upstream basin, but also in middle stream and even in downstream of the river basin. Furthermore, yearly runoff at the Yingxiongqiao station that controls the mountain portion of the basin also increased by 44 mm (or 11%) during 1959–2001, indicating consistency in precipitation and runoff change over the mountain regions of the basin. Temperature and precipitation changes reported here seem to suggest a regime shift from warm-dry to warm-wet pattern over northwest China [*Shi et al.*, 2003].

[12] Annual mass balance varies between 375 and −860mm during 1958–2003. Glacier mass balance has been decreasing almost monotonically in the last 45 years, especially in the most recent 10 years. The 5 years of most

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL024178.

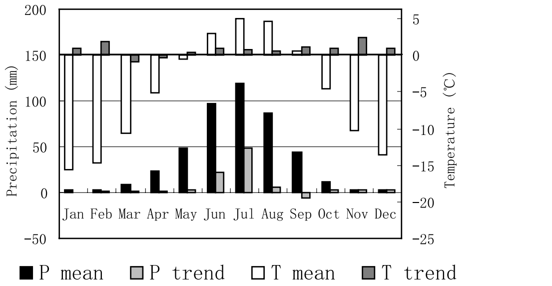

Figure 2. Long-term mean monthly temperature and precipitation, and their total trend at the Daxigou station during 1958–2003. Trends are in °C $(46a)^{-1}$ for temperature and mm $(46a)^{-1}$ for precipitation. See Table S1 of auxiliary material for data.

negative mass balance (over 790 mm) all appeared after 1997 (Figure 4). Cumulative mass balance reached –10,032 mm over the study period, equivalent to glacier thinning of 11.1 m (20% of average glacier thickness). Precipitation and temperature changes affect glacier mass balance differently. Precipitation increases enhance accumulation, and temperature warming enhances ablation. The negative mass balance, caused by higher ablation than the accumulation, is associated with precipitation increase and temperature warming over the study area. This result implies that the effect of warming may overcome the influence of precipitation increase.

[13] The mean ELA of the glacier is about 4056 m a.s.l. over 1959–2003. The ELA has moved up 37 m due to the climate warming. The ELA rise is strong since 1997 - it is above 4050 m a.s.l. with the mean of 4110 m a.s.l. Furthermore, the glacier length and area observations during 1962–2003 also show a steady retreat of the glacier over the observation period. The glacier length and area decreased

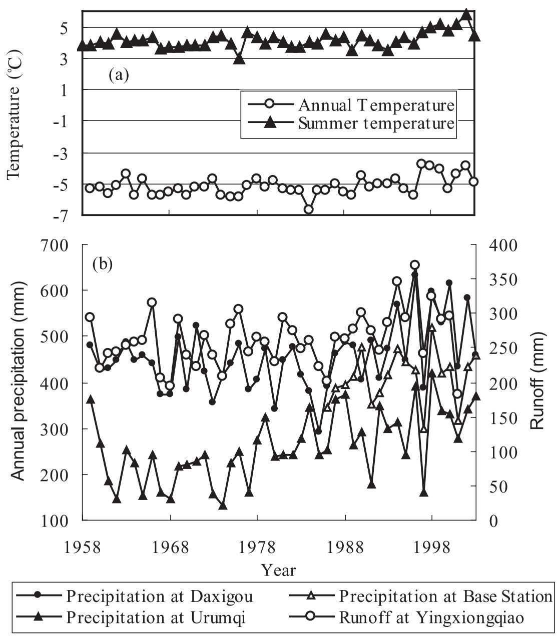

Figure 3. (a) Annual and summer (Jun–Aug) air temperature and (b) annual precipitation/runoff in the Urumqi River basin during 1958–2003. See Table S2 of auxiliary material for data.

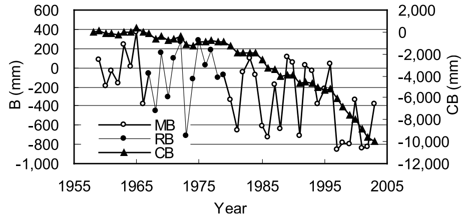

Figure 4. Annual and cumulative mass balance of the Glacier No.1 during 1959–2003. MB: measured mass balance, RB: reconstructed mass balance, CB: cumulative mass balance. See Table S3 of auxiliary material for data.

by 175 m (7.3%), and 0.24 km^2 (12.4%) during 1962–2003. Yearly runoff at the hydrologic station below the glacier ranges from 350–1030 mm, and has significantly increased by 413 mm (or 62%) during 1980–2003 (Figure 5). This increase is mostly from the glacier mass loss – total of 404 mm during the same period.

[14] To quantify the effect of climatic change on the glacier, we examine the relationships among summer temperature, precipitation and glacier mass balance and runoff. Figure 6a shows the relation between summer precipitation and mass balance/runoff. Summer precipitation is negatively correlated with mass balance and positively associated with runoff. These relationships, although very weak statistically, are reasonable, as higher precipitation leads to higher runoff and lower glacier melt [*Liu et al.*, 1998]. Similarly, summer temperature is negatively correlated with mass balance and positively associated with runoff (Figure 6b). These relationships, statistically significant at 99%, are expected for glacier basins, because higher temperatures lead to higher glacier melt (negative mass balance) and thus higher runoff. Regression results in Figure 6b suggest that the 1°C summer temperature change leads to 486 mm glacier mass loss and 250 mm runoff change over the basin. This result shows that mass balance of this small glacier (53% of the basin) is more sensitive than basin runoff to temperature variation.

4. Summary

[15] This study analyzes long-term climate and glacier records to examine climate change and glacier response over the past 45 years in the Urumqi River source area, the Tianshan Mountains of China. Trend analyses show the summer temperature, summer and annual precipitation near

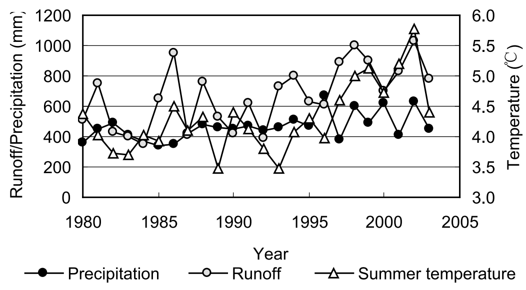

Figure 5. Summer (Jun–Aug) temperature, annual precipitation and runoff in the upper Urumqi River during 1980–2003. See Table S4 of auxiliary material for data.

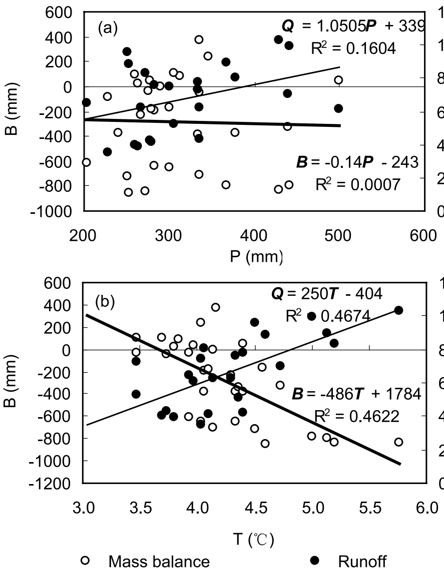

Figure 6. Regression relationships of summer temperature (T) and precipitation (P) vs. mass balance (B) and runoff (Q) during 1959–1966 and 1980–2003.

the glacier increased by 0.8°C, 77 mm (25%) and 87 mm (19%), respectively, during 1958 to 2003, with very significant changes over the most recent 8 years.

[16] The glacier has continuously retreated from 1962 to 2003. Its length and area have shortened by about 175 m (7.3%) and reduced by 0.24 km^2 (12%), respectively, during 1962–2003. The cumulative mass balance is −10,032 mm, equivalent to 11.1 m of glacier ice, or 20% of the glacier volume. Basin annual runoff has significantly increased by 413 mm or 62% during 1980–2003 due to precipitation increase and enhanced glacier melt caused by regional climate warming particularly in the summer season.

[17] Regression analyses show that summer precipitation is negatively correlated with mass balance and positively associated with runoff. These relationships are reasonable, as higher precipitation leads to higher runoff and lower glacier melt. On the other hand, summer temperature is negatively correlated with mass balance and positively associated with runoff. Relative to precipitation-mass balance relation, the regression between temperature and mass balance is much stronger. A 1°C increase in summer temperature leads to an increase of 486 mm glacier mass loss. This indicates that summer temperature controls glacier mass balance and runoff changes. It is important to note that, over the last 45 years, the negative mass balance, caused by higher ablation than accumulation, is associated with precipitation increase and temperature warming over the study area. This result suggests that the impact of warming (enhanced ablation) overcomes the effect of precipitation increase (enhanced accumulation) on glacier mass/runoff changes over the last 45 years.

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