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Observed changes in streamflow at the headwaters of the Urumqi River, eastern Tianshan, central Asia

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Abstract:

The runoff records of streams draining basins with between 0 and approximately 54% glacier cover, located at the headwaters of the Urumqi River in eastern Tianshan, central Asia, have been examined for the purpose of assessing climatic and glacial influences on temporal patterns of streamflow for the period 1959–2006. Runoff in the highest glacierized basin is found to be inversely correlated with the glacier mass-balance data and increased by $165{\cdot}1 \times 10^4$ m^3 or 1·5 times on average from 1959 to 2006, whereas flow from a glacier-free basin reflects precipitation changes associated with temperature that may enable either ground ice formation or ice storage release. For the basin with a glacier cover of 18·5%, the runoff increased approximately $355{\cdot}4 \times 10^4$ m^3 or 29·6% on average from 1983 to 2006, which underscores expected results based on glacier melt and precipitation increase, especially after 2000. This is due to several possible reasons including enhanced evaporation, groundwater percolation, increased water consumption due to plant colonization and runoff decrease from glacier basins subject to area reduction. From the measurement at Urumqi glacier No. 1 gauging station and a simple water balance model, the glacial runoff during the period 1959–2006 was calculated and found to have increased by $145{\cdot}5 \times 10^4$ m^3 a^{-1} (a factor of 2) over the 48-year span. A significant amount of the increase occurred after 1987, particularly after 1995, and coincides with increases in both temperature and precipitation.

KEY WORDS streamflow; glacial runoff; Tianshan; glacier melt

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INTRODUCTION

Over the past few decades, global warming has resulted in substantial landscape changes, particularly through the loss of the mass and volume of most alpine glaciers. Small glaciers are highly sensitive to changes in temperature and precipitation, and their runoff has contributed to approximately one-quarter to one-third of the 7 cm rise in sea level that took place during the last century (Oerlemans and Fortuin, 1992; Kuhn, 1993; Meier and Bahr, 1996; Dyurgerov and Meier, 1997; Dyurgerov, 2002; Raper and Braithwaite, 2005; Intergovernmental Panel on Climate Change (IPCC), 2007). Presently, worldwide examination and prediction of glacier area and volume change are based on detailed observations from a rather small number of glaciers (Dyurgerov and Meier, 2000; Zemp *et al*., 2008). Consequently, detailed individual glacial runoff observation is imperative for the evaluation of glacier recession and water resource change on both a regional and global scale.

Located at the headwaters of the Urumqi River in eastern Tianshan, the core area of arid and semiarid central Asia, Urumqi glacier No. 1 (43°06′ N, 86°49′ E) has the longest observation record of all the glaciers in China, covering the period from 1958 to the present. Originating from the thawing of glaciers, glacial runoff is sensitive to climate warming. As an important water supply for Urumqi, the provincial capital city of Xinjiang Uyger Autonomous Region, glacial runoff from Urumqi glacier No. 1 and its change as well as its sustainability have drawn wide attention in recent years. Previous studies carried out on this glacier have focused on mass balance, runoff, area and terminus changes (Li *et al*., 2003, 2007; Li, 2005; Ye *et al*., 2005; Han *et al*., 2006, 2007; Jing *et al*., 2006). This study analyses the long-term changes in climate and streamflow at the headwaters of the Urumqi River and pays particular attention to the change in glacial runoff of Urumqi glacier No. 1.

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SITE DESCRIPTION, DATA SETS AND METHOD

The source area of the Urumqi River is located in eastern Tianshan, which contains 9035 glaciers with a total area of 9225 km^2 and approximately 1011 km^3 in volume (Shi *et al*., 2007). The area is bordered by three deserts: the Taklimakan to the south, the Junggar Basin to the north and the Gobi Desert to the east (Figure 1). There are seven glaciers at the headwaters of the Urumqi River. Urumqi glacier No. 1, a northeast-facing valley glacier, is the largest. It is composed of east and west tributaries currently covering 1·7 km^2 (Figure 2), which flank Tianger Peak II, the highest peak in southeastern Tianshan, with an elevation of 4484 m above sea level

Figure 1. Location of study site, Tianshan and the surrounding geographic environment. The shaded areas designate deserts (Des)

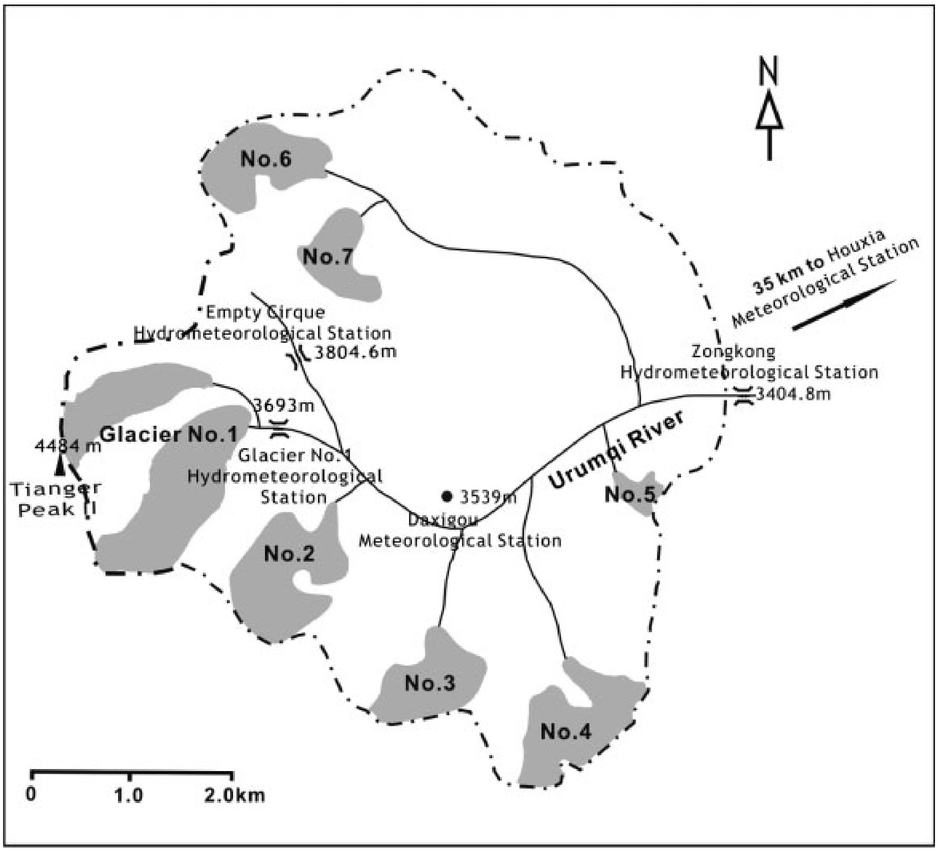

Figure 2. Locations of hydrometeorological stations and meteorological stations at the headwaters of the Urumqi River. The shaded areas designate glaciers

(m asl). The glaciers are surrounded by barren rock with sparse vegetation on the valley floor, but the mountain environment in the region includes a forest zone from 1500 to 2900 m, alpine meadows above 2900 m, bare rock, glacial deposits and permafrost above 3000 m.

Streamflow and meteorological parameters are measured at three hydrometeorological stations as well as at two meteorological stations at the headwaters of the Urumqi River (Table I and Figure 2). The Urumqi glacier No. 1 hydrometeorological station was established in

Table I. Information from the hydrometeorological and the meteorological stations

Station		Elevation (m asl)	Catchment area (km^2)	Glacierized area (%)	Starting year of observation
Hydrometeorological station	Urumqi glacier No. 1	3693·0	3·34	54·0	1959
	Zongkong	3404·8	28·9	18·5	1981
	Empty Cirque	3804·6	1·68	0	1981
Meteorological station	Daxigou	3539			1959
	Houxia	2130			1985

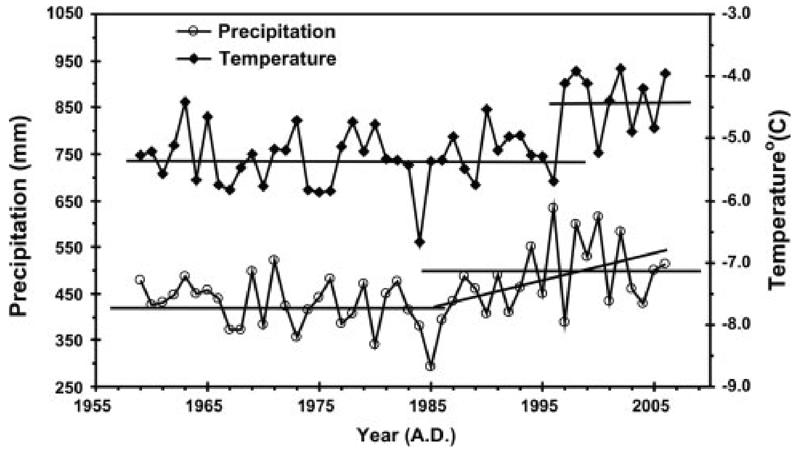

Figure 3. Annual temperature and precipitation at Daxigou meteorological station since 1959, showing mean values and a linear regression in different time periods

1959 at the front of Urumqi glacier No. 1 for the purpose of measuring glacial runoff. The runoff measurements were interrupted during 1967–1979, but the data were subsequently reconstructed using the meteorological data (Yang, 1991). The other two hydrometeorological stations, Zongkong and Empty Cirque, were constructed in 1981 to measure the runoff from all the seven Urumqi glaciers and from the non-glacial alpine permafrost zone, respectively. The runoff data from the Empty Cirque station after 1994 are excluded from this study because permafrost deformation perturbed the gauging structure and may have thereafter affected the reliability of the data. The Daxigou meteorological station, which is located 3 km downstream of Urumqi glacier No. 1, began operation in 1958. Observation at the Houxia meteorological station, situated 35 km northeast and downstream of the Glacier No. 1, began in 1982.

The observations at the three gauging stations are carried out from May to September each year, where the observed water level records are converted to discharges based on rating curves, and then converted into total daily, seasonal and annual volumes in cubic metres or annual runoff depths (dividing annual volumes by catchment areas) in mm. Over 95% of the annual runoff at the stations occurs during the observation period, whereas for the rest of the year, the streams are mostly frozen. Glacier mass-balance data have been published in annual reports of the Tianshan Glacier Station from 1980 to 2006. To minimize the inherent temporal noise of high-resolution time series, we analyse the annual periods in this study.

RESULTS AND DISCUSSIONS

Climate variability

The changes of streamflow in this mountain area are found to be driven by climate variations. In spite of the altitudinal elevation range of 400 m, with an air temperature gradient of approximately 0·0044 °C m^{-1} (Li *et al.*, 2003), the annual temperatures observed at the three gauging stations and at Daxigou meteorological station within the Urumqi glacier basin have similar annual fluctuations. Except for a slight dissimilarity between 1990 and 1996, trends also coincide with the temperature fluctuation observed at Houxia station, approximately 35 km to the northeast, downstream from these four stations, indicating the consistency of air temperature variation in this area. The observed temperature at Daxigou meteorological station (Figure 3) demonstrates an overall increase, especially during the period of 1997–2006. The annual average values increased approximately 0·9 or 0·019 °C a^{-1} from 1959 to 2006. During the period 1997–2006, the mean temperature was −4·4 °C, compared with −5·3 °C from 1959 to 1996, indicating an increase of almost 1 °C. The lowest annual temperature, −6·7 °C, was observed in 1984, and the highest, −3·9 °C, in 2002. Particularly low temperatures occurred during the period 1974–1976. The air temperature observed in this area is generally in phase with other parts of Tianshan. According to Aizen *et al.* (1997), the average increase in air temperature over the central and the western Tianshan was 0·01 °C a^{-1} during the period 1940–1991, with slightly lower values below 2000 m asl.

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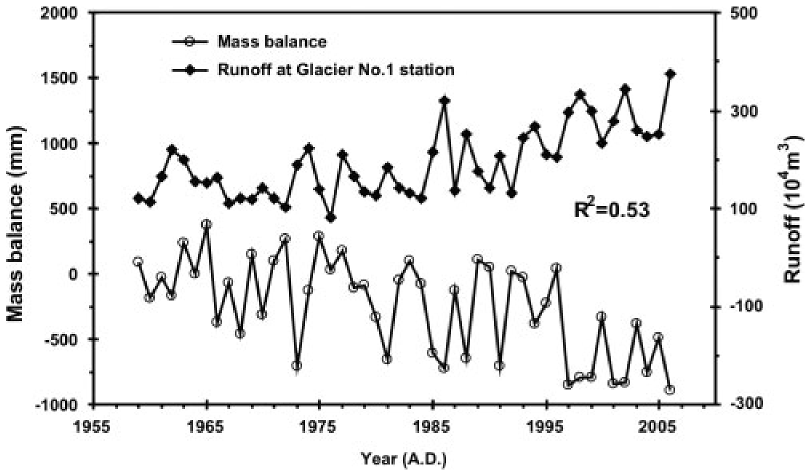

Figure 4. Comparison of runoff at Urumqi glacier No. 1 hydrometeorological station together with the annual mass balance of Urumqi glacier No. 1, illustrating that they have an explicit inverse correlation

The value is a little lower than our observations at eastern Tianshan, which is considered a result of more rapid temperature increase after 1995 and the relatively higher elevations of our stations.

Over 90% of the precipitation in the headwaters of the Urumqi River occurs during April through September. Annual precipitation series measured at the four stations located at the headwaters are found to have similar fluctuations, although there is an apparent discrepancy with the data at Houxia station during the period 1990–1994, which indicates that the precipitation is spatially variable.

The precipitation series at Daxigou station shown in Figure 3 is the longest record at the headwaters of the Urumqi River. According to this record, the increase in precipitation averaged approximately 83·4 mm (1·7 mm a^{-1}) or 20·3% in the past 48 years. The lowest (293·4 mm) and the highest (634·4 mm) occurred in 1985 and 1996, respectively. The precipitation has practically no recognizable trend during the period 1958–1986 and increased rapidly from 1987 to 2006. The mean precipitation was 491·1 mm during the period 1987–2006, compared with 424·8 mm from 1959 to 1986, an increase of 15·6%. The remarkable rise in both temperature and precipitation after 1996 indicates the warm-humid climate pattern over this area, which is experiencing the wettest and warmest climate over the past 48 years.

Long-term changes in streamflow

The streamflow in the headwaters of the Urumqi River depends on both the timing and magnitude of precipitation and temperature (Kang *et al.*, 1997). While precipitation determines the quantity of water entering the watershed, air temperature controls the amount of meltwater from the nival glacial zone. Due to the coincidence of spring–summer maximum precipitation with glacial and snow cover melt, over 90% of the runoff through the three gauging stations at the headwaters of the Urumqi River occurs from May through September.

Urumqi glacier No. 1 hydrometeorological station. The catchment area is 3·34 km^2 for the gauging station, of which approximately 54% is covered by Urumqi glacier No. 1. The runoff at the gauging station demonstrates a significant amplification and an increase of $165·1 \times 10^4$ m^3 or 1·5 times on average from 1959 to 2006. Compared with the period 1959–984, the average runoff during 1985–2006 has increased by 66%. The temporal variation during the period 1959–2006 is inversely correlated with the glacier mass balance of Urumqi glacier No. 1 ($R^2 =$ $0·53$; $N = 48$; $P < 0·01$), as shown in Figure 4, which suggests that the escalating runoff largely originates from the increased meltwater production as a result of the mass loss of the glacier.

Figure 4 also shows that the negative mass-balance year increases modestly from 1959 to 1985 and rapidly from 1986 to 2006. Before 1985, the mass balance was determined by both precipitation and temperature, whereas after 1986 it is mainly controlled by the temperature, even under a high-precipitation regime (Li *et al.*, 2007). Several previous studies (Li *et al.*, 2003, 2007; Han *et al.*, 2006; Jing *et al.*, 2006) have indicated that the recession of Urumqi glacier No. 1 resulting from climate warming prevails throughout the entire period of observation and has shown an accelerated tendency since the mid-1980s, particularly after 1995. The area of the glacier has reduced a total of 0·27 km^2 or 14·0% from 1962 to 2006, especially in the last 14 years from 1992 to 2006, whereby the reduction totalled 0·16 km^2, an amount greater than the area reduction from the last 30 years during 1962–1992. The terminus has undergone a constant recession since 1958, which has accelerated ever since the mid-1990s from 4·5 to 5 m a^{-1}. The continuous mass reduction led to the separation of the two glacier tributaries in 1993, which increased the terminus area of the glacier and in turn enhanced glacial melting. Furthermore, the radar sounding measurements demonstrated that ice thinning occurred from 1980 to 2001 and became more remarkable from 2001 to 2006. Consistent with glacier thinning, the maximum surface velocity has exhibited a decreasing trend since the 1980s.

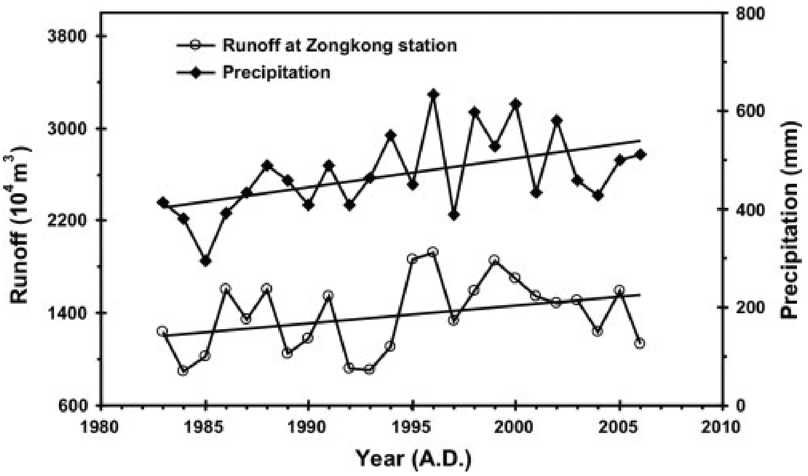

Figure 5. Runoff records at Zongkong hydrometeorological station and precipitation observed at Daxigou meteorological station from 1983 to 2006 with corresponding linear regressions

In contrast to a steep temperature rise during 1997–2006, the runoff demonstrates a gradual increase since 1986. This is not only produced by enhanced melt due to warming, but also by an increase in precipitation from 1986, which has a dual effect: direct increase in runoff and enhanced ice melt due to heat transfer by liquid precipitation.

Zongkong hydrometeorological station. The runoff at Zongkong hydrometeorological station shows a similar annual fluctuation compared with the precipitation trend (Figure 5), indicating a major contribution from precipitation. With an approximate 18·5% glacierized area in the catchment, glacial melt is considered an important component of the runoff, which is revealed by the observed runoff ratio (runoff/precipitation) average value of 1·1 at the station, a value much higher than in the nearby non-glacierized catchment of Empty Cirque where it is approximately 0·7. The annual runoff at the station demonstrates an overall ascending trend and increased approximately $355{\cdot}4 \times 10^4$ m^3 or 29·6% on average from 1983 to 2006. Nevertheless, considering the 34·7% increase in precipitation and escalating glacial melting during the same period, the runoff did not rise to a higher-than-expected level, especially after 2000. Further analysis shows that the average runoff ratio actually reduced by 3%, indicating the inefficient tendency of precipitation in contributing to runoff and/or the reduction of glacial melting. Similar cases have been observed in other areas of Tianshan during the last decade, where the increase in precipitation and temperature did not lead to an apparent increase in surface runoff (Aizen *et al.*, 1997).

A possible explanation of the smaller predicted runoff is that the increased precipitation is lost predominantly as enhanced evaporation resulting from temperature rise or is percolated to the groundwater system. The enhanced ecological development, perhaps mainly the plant colonization resulting from temperature rise may also raise the water consumption as well in the catchment. In addition, despite the increase in meltwater from Urumqi glacier No. 1, the glacial runoff from the other six small glaciers (0·61 km^2 for each glacier on average) in the catchment may have started to decline in recent years as a result of decreased glacierized area and corresponding reduction in glacial melting.

Empty Cirque hydrometeorological station. Due to the absence of glacier cover in the catchment, the major water source for this station is seasonal snowmelt. The annual snowfall in the catchment after applying a wind correction averages approximately 560 mm a^{-1} (Wang and Zhang, 1985; Yang *et al.*, 1988), which is about 33% higher than at the Daxigou meteorological station. The annual runoff (Figure 6) is found to be well correlated to the precipitation ($R^2 = 0{\cdot}53$; $N = 12$; $P = 0{\cdot}07$) and associated with the temperature from 1982 to 1993. The water balance at the gauging station can be simply described by the following equation:

$$R = P - E - \Delta S \tag{1}$$

where R is runoff at the station, P is precipitation, E is evaporation (including sublimation) and ΔS is the change in the storage of snow, ground ice and soil moisture in the catchment (Woo *et al.*, 1994). The coarse materials of the catchment ground facilitate rapid infiltration and exfiltration rendering a large ΔS. Compared with P and ΔS, the magnitude of E is insignificant. Under normal air temperatures, the runoff ratio R/P is calculated as 0·75 indicating a very efficient P to R transit. At abnormally low or high temperatures, the meltwater from the snow cover enables ground ice formation or ice storage release, respectively. This case was found during the period 1984–1987. The runoff in 1985 was a record low, inexplicable because of the low precipitation. Note that the air temperature in the previous year (1984) was extremely low, which might have possibly contributed to the transformation of meltwater infiltration to ground ice, effectively storing water in the active layer of the catchment ground. As the temperature rose in subsequent years, the stored water from previous years was released due to the melting of ground ice and resulted in a

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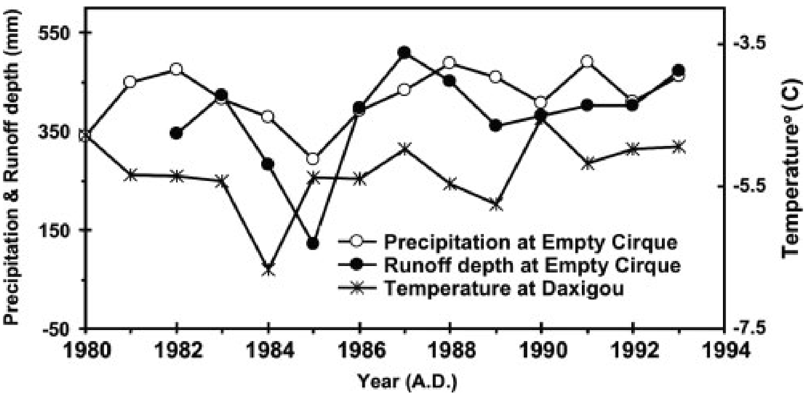

Figure 6. Runoff depth and the precipitation records at Empty Cirque hydrometeorological station, and air temperature observed at Daxigou meteorological station from 1980 to 1993

subsequent increase in runoff. Therefore, the record high of annual runoff in 1987 is considered to be a combined result of high precipitation and groundwater exfiltration.

Long-term change in glacial runoff

Glacial runoff is defined as the runoff solely from a glacier-covered area. The glacial runoff from Urumqi glacier No. 1 can be determined from the measurements gathered at the Urumqi glacier No. 1 hydrometeorological station, which is less than 1 km away from the terminus of the glacier. Annual water balance at this station can be described by

$$R_a = R - R_b \tag{2}$$

where R_a is glacial runoff, R is total runoff measured at the station and R_b is the non-glacial runoff in the basin. In a simplified condition, R_b can be calculated from

$$R_b = P^* \ (A_c - A_g)^* \alpha \tag{3}$$

where P is precipitation in the catchment area, A_c and A_g are the areas of the total catchment and of the glacier, respectively, and α is the runoff ratio (ratio of observed runoff and precipitation over the non-glacial surface). The observed runoff ratio in this area is 0·7 (Yang, 1991). The annual glacial runoff values during 1959–2006 were calculated using Equations (2) and (3) (Table II). The results give an average glacial runoff of $134{\cdot}3 \times 10^4$ m^3 a^{-1} during the 47-year period with a minimum of $22{\cdot}8 \times 10^4$ m^3 a^{-1} in 1976 and a maximum of $304{\cdot}5 \times 10^4$ m^3 a^{-1} in 2006. High glacial runoff is generally associated with high temperatures as well as high precipitations, while the minimum value in 1976 is found to coincide with a low temperature period from 1974 to 1976. The second highest value in 1986 is likely related to previous record low temperatures in 1984, which facilitated snow storage on the glacier surface. As the temperature rose in subsequent years, the stored snow melted and led to a rapid increase in glacial runoff. The maximum value in 2006 and the third highest value in 2002 are considered to be in agreement with the high temperatures observed in the same years.

From 1959 to 2006, the average annual glacial runoff increased by a factor of over 2, to $145{\cdot}5 \times 10^4$ m^3 a^{-1}.

Table II. Calculated glacial runoff of Urumqi glacier No. 1

Year	Glacial runoff (10^4 m^3)	Year	Glacial runoff (10^4 m^3)
1958–1959	63·0	1982–1983	78·5
1959–1960	61·7	1983–1984	72·4
1960–1961	112·5	1984–1985	169·5
1961–1962	165·5	1985–1986	272·2
1962–1963	138·7	1986–1987	82·0
1963–1964	101·8	1987–1988	187·6
1964–1965	91·2	1988–1989	113·2
1965–1966	116·9	1989–1990	79·9
1966–1967	57·3	1990–1991	143·7
1967–1968	74·9	1991–1992	71·7
1968–1969	61·9	1992–1993	180·7
1969–1970	95·9	1993–1994	197·6
1970–1971	63·6	1994–1995	151·0
1971–1972	43·8	1995–1996	112·7
1972–1973	146·5	1996–1997	244·3
1973–1974	171·1	1997–1998	251·6
1974–1975	82·3	1998–1999	232·7
1975–1976	22·8	1999–2000	149·6
1976–1977	159·5	2000–2001	221·4
1977–1978	108·4	2001–2002	257·7
1978–1979	80·4	2002–2003	198·7
1979–1980	76·7	2003–2004	189·1
1980–1981	124·3	2004–2005	183·3
1981–1982	78·1	2005–2006	304·5

A significant portion of the increase occurred after 1987, particularly after 1995 (Figure 7). The average value from 1986 to 2006 is $182{\cdot}2 \times 10^4$ m^3 a^{-1}, compared with the average value of $97{\cdot}0 \times 10^4$ m^3 a^{-1} from 1959 to 1985, thus showing an increase of $85{\cdot}1 \times 10^4$ m^3 a^{-1} or 87·8%.

The mass balance of Urumqi glacier No. 1 was calculated by comparing observed precipitation and runoff values with the annual water balance at the hydrometeorological station. The results suggest an average annual mass balance of −246·1 mm water equivalent (w.e.) and a cumulative mass balance of −11 812·2 mm w.e. from 1959 to 2006. Taking into consideration infiltration of the runoff before reaching the gauging station, these values are comparable with the observed average and cumulative mass-balance values, −252·4 and −12 115·4 mm, respectively (Tianshan Glaciological Station, 1980–2006).

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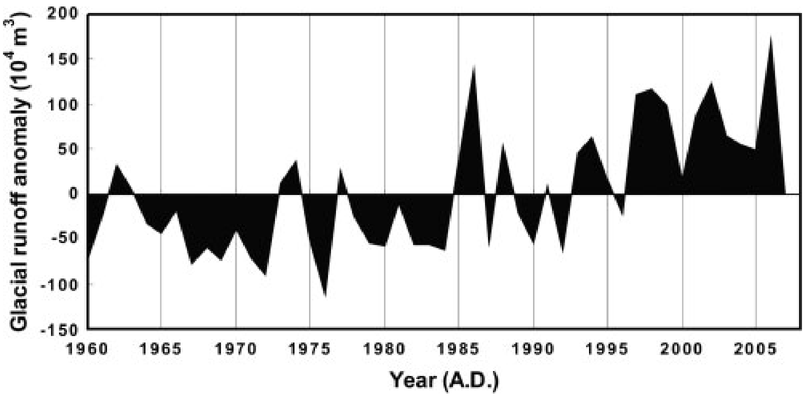

Figure 7. Annual glacial runoff anomaly of Urumqi glacier No. 1, indicating a significant increase in glacier melting since the mid-1980s

Whether glacial runoff is related to climate change can be evaluated by the precipitation and glacier melt, which are in turn controlled by temperature. During the period 1959–2006, the annual mean temperature and the annual precipitation increased by 0·9 °C and 83·4 mm, respectively. This is a major reason for the glacial runoff increase. Several previous studies (e.g., Shi *et al.*, 2002, 2003) have suggested that a climatic shift from a dry to a wet pattern has been occurring in eastern Tianshan since 1987. This is characterized by the continuous increase in precipitation and runoff from glaciers and rivers, which is consistent with our results and indicates a significant increase in glacial runoff after 1986.

SUMMARY AND CONCLUSION

The Urumqi River headwater region includes the longest record of any glacier in China, providing the best data set for climate and streamflow in the region. This study analyses the long-term changes in climate, streamflows and glacier runoff, as well as their relationships. The results reveal that at the headwaters of the Urumqi River, the annual temperature increased approximately 0·9 °C or 0·019 °C a^{-1} from 1959 to 2006, with a steep increase of almost 1 °C during the period 1997–2006. The increase in precipitation averaged approximately 83·4 mm (1·7 mm a^{-1}) or 20·3% during the past 48 years. The precipitation had normal fluctuations during the period 1958–1986 and then increased rapidly from 1987 to 2006. The mean precipitation was 491·1 mm during the period 1987–2006, compared with 424·8 mm from 1959 to 1986, increasing by 15·6%. The remarkable augmentations in both temperature and precipitation after 1996 indicate the warm-humid climate pattern over this area, which is experiencing the wettest and warmest climate over the past 48 years.

For Urumqi glacier No. 1 hydrometeorological station, where 54% of its catchment is covered by the glacier, the runoff demonstrates a significant amplification, particularly after 1984, with an increase of $165{\cdot}1 \times 10^4$ m^3 or 1·5 times on average from 1959 to 2006. This increase is inversely correlated with the glacier mass-balance data and associated with precipitation, indicating that both the mass reduction of the glacier and the elevated precipitation are contributors.

With an approximately 18·5% glacierized area in the catchment of Zongkong hydrometeorological station, the runoff (determined from precipitation and glacial runoff) demonstrates an overall ascending trend and increase of approximately $355{\cdot}4 \times 10^4$ m^3 or 29·6% on average from 1983 to 2006. This increase is less than hypothesized considering a 34·7% increase in the precipitation as well as the accelerated melting of glaciers in the same period, especially after 2000. The possible reasons are: (1) the increased precipitation is lost as enhanced evaporation resulting from temperature rises or is percolated into the groundwater system; (2) the plant colonization resulting from the temperature rise may have also raised water consumption in the catchment; and (3) as a result of strong glacierized-area reduction, the runoff contribution from the other six small glaciers in the catchment may have started to decline in recent years.

The runoff at Empty Cirque hydrometeorological station is correlated to the precipitation and also associated with temperature from 1980 to 1993. If the temperature is abnormally low or high, the meltwater from the snow cover enables ground ice formation or ice storage release, which evidently has an effect on the runoff.

The annual glacial runoff calculated at the Urumqi glacier No. 1 hydrometeorological station has increased by $145{\cdot}5 \times 10^4$ m^3 a^{-1}, a factor of 2, over the 48-year span from 1959 to 2006. A significant increase in runoff occurred after 1985, particularly after 1995 due to an increase in both temperature and precipitation in the area.

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REFERENCES

Aizen VB, Aizen EM, Melack JM, Dozier J. 1997. Climatic and hydrologic changes in the Tien Shan, Central Asia. *Journal of Climate* **10**(6): 1393–1404.

Dyurgerov MB, Meier MF. 1997. Year-to-year fluctuations of global mass balance of small glaciers and their contribution to sea-level changes. *Arctic and Alpine Research* **29**(4): 392–402.

Dyurgerov MB, Meier MF. 2000. Twentieth century climate change: evidence from small glaciers. *Proceedings of the National Academy of Sciences of the United States of America* **97**(4): 1406–1411.

Dyurgerov MB. 2002. Glacier Mass Balance and Regime: Data of Measurements and Analysis. Institute of Arctic and Alpine Research, University of Colorado, Boulder. Occasional paper No. 55, 268–275.

Han TD, Ding YJ, Ye BS, Liu SY, Jiao KQ. 2006. Mass-balance characteristics of Urumqi glacier No. 1, Tien Shan, China. *Annals of Glaciology* **43**: 323–328.

Han TD, Ding YJ, Xie CW, Ye BS, Shen YP, Jiao KQ. 2007. Analysis on the facts of runoff increase in the Urumqi river basin, China. In *Glacier Mass Balance Changes and Meltwater Discharge*, selected papers from sessions at the IAHS Assembly in Foz do Iguaçu, Brazil, 2005, Ginot P, Sicart J (eds). IAHS Publication: UK; 86–94.

Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Solomon S, Qin DH, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds). Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.

Jing ZF, Jiao KQ, Yao TD, Wang NL, Li Z. 2006. Mass balance and recession of Urumqi glacier No. 1, Tien Shan, China, over the last 45 years. *Annals of Glaciology* **43**: 214–217.

Kang ES, Shi YF, Yang DQ. 1997. An experimental study on runoff formation in the mountains basin of the Urumqi river. *Quaternary Sciences* **2**: 139–146.

Kuhn M. 1993. Possible future contributions to sea level change from small glaciers. In *Climate and Sea Level Change, Observations, Projections, and Implications*, Warrick RA Barrow EH, Wigley TM (eds). Cambridge University Press: Cambridge; 134–143.

Li ZQ, Han TD, Jing ZF, Yang HA, Jiao KQ. 2003. 40-year observed variation facts of climate and Urumqi glacier No. 1 at the headwaters of Urumqi river. *Journal of Glaciology and Geocryology* **25**(2): 117–123.

Li ZQ. 2005. A glacier melt water pool was discovered at summit of east branch of Glacier No.1 at source of Urumqi river, Tianshan, Xinjiang. *Journal of Glaciology and Geocryology* **27**(1): 150–152.

Li ZQ, Shen YP, Wang FT, Li HL, Dong ZB, Wang WB, Wang L. 2007. Response of glacier melting to climate change-take Urumqi glacier No. 1 as an example. *Journal of Glaciology and Geocryology* **29**(3): 333–342.

Meier MF, Bahr DB. 1996. Counting glaciers: use of scaling methods to estimate the number and size distribution of the glaciers of the world. In *Glaciers, Ice Sheets and Volcanoes: A Tribute to Mark F. Meier*, CRREL Special Report, Colbeck SC (eds). US Army Cold Regions Research & Engineering Lab: Lab, Hanover, NH; 89–94.

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

Raper SCB, Braithwaite RJ. 2005. The potential for sea level rise: new estimates from glacier and ice cap area and volume distribution. *Geophysical Research Letters* **32**: L05502. DOI: 1029/2004GL021981.

Shi YF, Liu CH, Wang ZT, Liu SY, Ye BS. 2007. *The Concise Glacier Inventory of China*. Shanghai Science Popularization Press: Shanghai; 1–194.

Shi YF, Shen YP, Hu RJ. 2002. Preliminary study on signal, impact and foreground of climate shift from warm-dry to warm-humid in northwest China. *Journal of Glaciology and Geocryology* **24**(3): 220–226.

Shi YF, Shen YP, Li DL, Zhang GW, Ding YJ, Kang ES. 2003. *An Assessment of the Issues of Climatic Shift from Warm-Dry to Warm-Wet in Northwest China*. Meteorological Press: Beijing; 1–124.

Tianshan Glaciological Station. 1980–2006. *Annual Report of Tianshan Glaciological Station, vol. 1–18*. Tianshan Glaciological Station Press:Lanzhou.

Wang DH, Zhang PY. 1985. Climate in Urumqi river valley, Tianshan. *Journal of Glaciology and Geocryology* **7**(3): 239–247.

Woo MK, Yang ZN, Xia ZJ, Yang DQ. 1994. Streamflow processes in an alpine permafrost catchment, Tianshan, China. *Permafrost and Periglacial Processes* **5**: 71–85.

Yang DQ, Jiang T, Zhang YS, Kang ES. 1988. Analysis and correction of errors in precipitation measurement at the head of Urumqi river, Tien Shan. *Journal of Glaciology and Geocryology* **10**(4): 384–399.

Yang ZN. 1991. *Glacier Water Resources in China*. Gansu Science and Technology Press: Lanzhou; 1–158.

Ye BS, Yang DQ, Jiao KQ, Han TD, Jin ZF, Yang HA, Li ZQ. 2005. The Urumqi river source Urumqi glacier No. 1, Tianshan, China: changes over the past 45 years. *Geophysical Research Letters* **32**: L21504. DOI: 10.1029/2005GL024178.

Zemp M, Roer I, Kääb A, Hoelzle M, Paul F, Haeberli W. 2008. *Global Glacier Changes: facts and figures*. WGMS, UNEP, World Glacier Monitoring Service: Zurich, Switzerland; 45–88.