Arabian Journal of Geosciences (2018) 11: 716
https://doi.org/10.1007/s12517-018-4094-1

ORIGINAL PAPER

Glacier changes and its effect on water resources in Urumqi River Basin, Tianshan Mountains, China, from 1964 to 2014

Baojuan Huai[1] · Yetang Wang[1] · Zhongqin Li[2] · Weijun Sun[1] · Xiaoyan Wang[3]

Received: 13 December 2017 / Accepted: 16 November 2018 / Published online: 23 November 2018
© Saudi Society for Geosciences 2018

Abstract

This work investigated changes in glaciers over the Urumqi River Basin from 1964 to 2014, and its role in the local water resource. Based on the glacier outlines on 1964, 2005 and 2014 derived from topographical maps and satellite images, the glaciers shrank 32.51% of the surface area between 1964 and 2005, and 12.12% between 2005 and 2014, respectively. The corresponding area reduction rate increased from 0.77%/a in 1964–2005 to 1.21%/a in 2005–2014, suggesting accelerated glacier retreat in recent decades. Our results showed that hydrological regime variability in both glacierized and non-glacierized catchments of the Urumqi River Basin was dependent on the current glacier conditions. Furthermore, glaciers with the area of 1–2 km^2 contributed most to the water resources in this region, but their regulation effects to river runoff were weakening. Accordingly, the accelerated glacier retreat was a dangerous signal for local water resource, and the continuous future glacier monitoring under the global warming were desperately needed.

Keywords Glacier shrinkage · SPOT5 · Water resources · Urumqi Glacier No.1 · Urumqi River Basin

Introduction

Urumqi River Basin (URB) is an inland river basin in the arid of northwest China. Most glaciers in the URB experienced shrinkage in length and area since the last century, as did the glaciers in the Tianshan Mountains (Chen et al. 2016; Shangguan et al. 2009; Wang et al. 2008; Bolch 2007). Glacier melting water over the URB plays a key role in regulating and stabilizing river runoff, and increased river runoff is conductive for agricultural production and urban domestic water use in the short term (Wang and Su 2003; Han et al. 2005; Sun et al. 2013). Thus, knowing the present state of glaciers is essential for the sustainable development and utilization of regional water resources, and regional economic planning (Hagg et al. 2007; Li et al. 2010). Some previous studies have focused on the glacier changes in the URB (Chen et al. 1996; Liu et al. 1999; Li et al. 2010). The total glacier area in the URB decreased by 13.8% from 48.67 km^2 in 1964 to 41.96 km^2 in 1992, and to 32.05 km^2 in 2005 (Chen et al. 1996); however, studies about the recent glacier change in the URB are limited. In addition, some studies are concentrated on the glacier changes in Tianshan Mountains (Bolch 2007).

It was reported that annual melt water runoff of the Urumqi Glacier No.1 (UG1) distinctly increased in recent decades, especially after 1985 (Li et al. 2003; Ye et al. 2005; Han et al. 2006). Significant increased glacier melting affects the volume and timing of streamflow, which provides water for irrigation, and domestic water supplies (Yao et al. 2004; Ye et al. 2005), and also alters the seasonal distribution of runoff in the URB (Sun et al. 2013). Accordingly, assessment of glacier change and their contribution to changes in the URB runoff are extraordinarily required. To meet this demand, a relatively perfect observation system was established in this basin, and now becomes an important inland research base in hydrology, glacier changes, water resources, and other aspects of researches in cold regions (Shi and Su 1965; Li et al. 2003).

✉ Yetang Wang
wangyetang@163.com

[1] College of Geography and Environment, Collaborative Innovation Center of Human-Nature and Green Development in Universities of Shandong, Shandong Normal University, Jinan 250358, China

[2] State Key Laboratory of Cryosphere Science, Cold and Arid Region Environment and Engineering Research Institute/Tianshan Glaciological Station, Chinese Academy of Sciences (CAS), Lanzhou 730000, China

[3] Key Laboratory for Ecology and Environment of River Wetlands in Shaanxi Province, Weinan Normal University, Weinan 714000, China

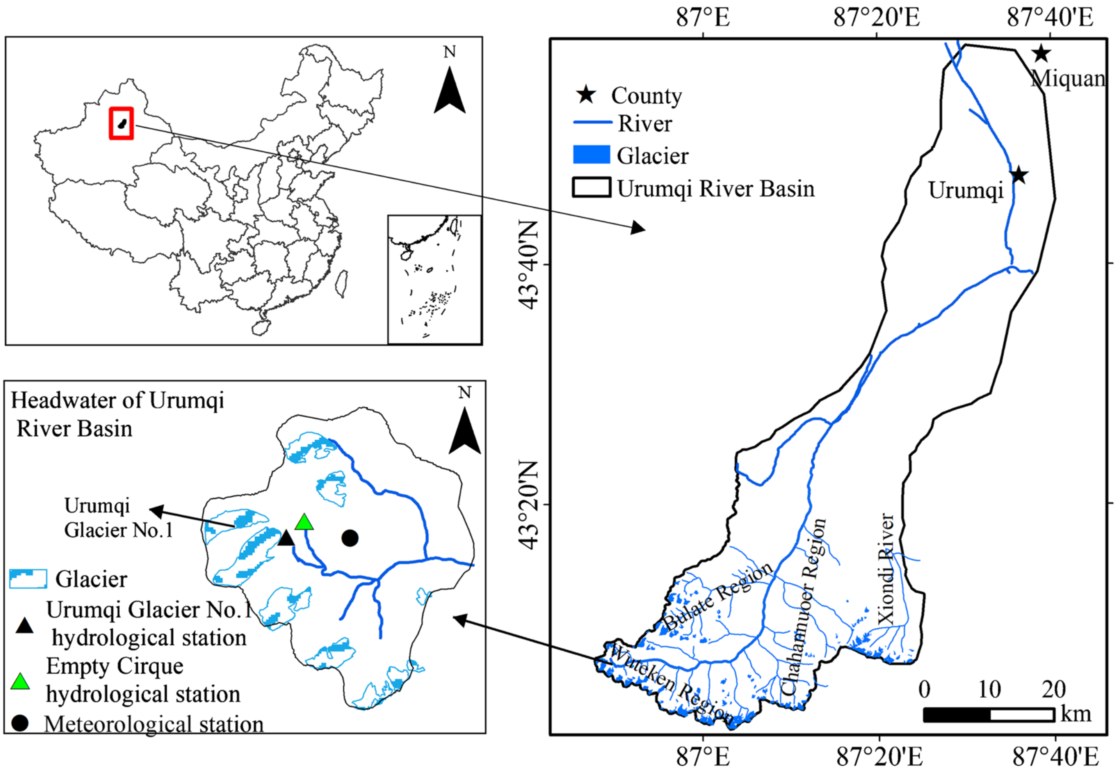

Fig. 1 Location of the URB and the UG1

The UG1 provides the longest glacier monitoring record in China (Han et al. 2006). Observations of UG1 were initiated in 1959, implemented by the Tienshan Glaciological Station (TGS), Chinese Academy of Sciences (CAS) (Li et al. 2003). The observed annual mass balance of UG1 was found to coincide with the mean annual mass balance of 30 reference

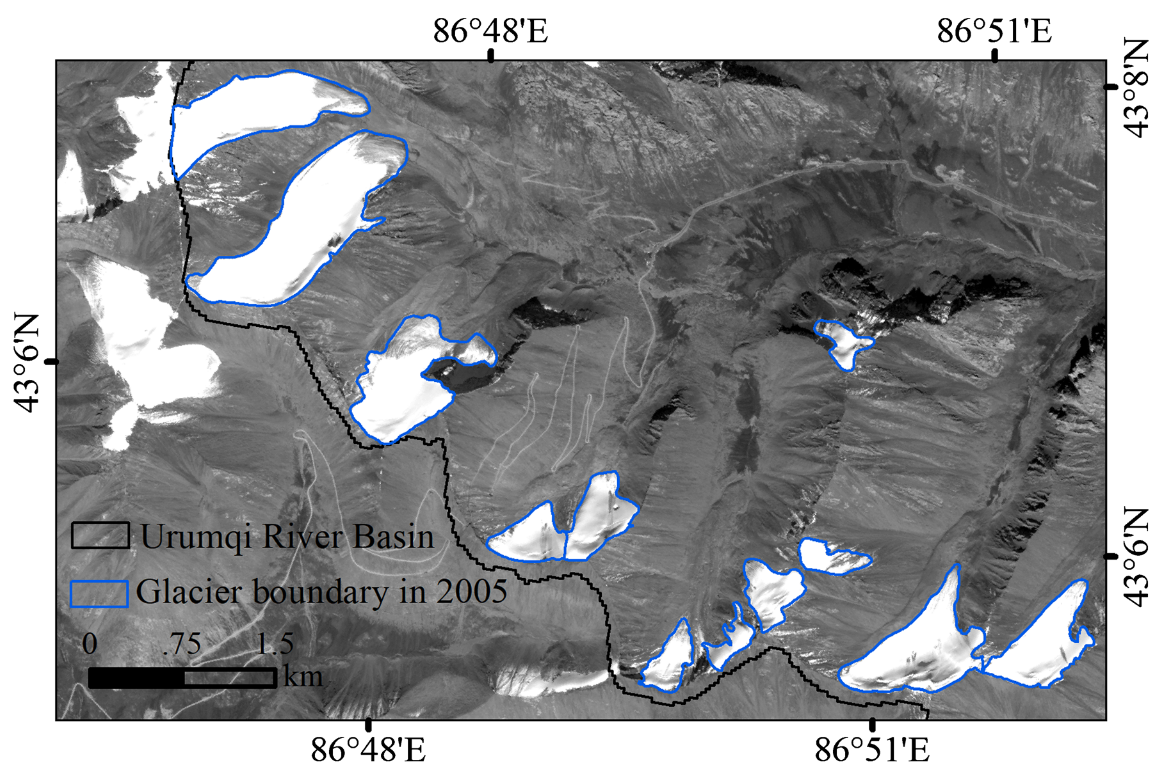

Fig. 2 Part of glaciers in the URB extracted by SPOT5

Table 1 Meteorological and hydrological stations used in this study (locations are shown in Fig. 1)

Station name	Longitude (°E)	Latitude (°N)	Altitude/m a.s.l.	Drainage area/km^2	Period
Daxigou M S	86.843	43.113	3539	–	1960–2010
Empty cirque hydrological station	86.833	43.100	3805	1.68	1982–2008
Glacier No.1 hydrological station	86.821	43.114	3695	3.34	1959–2008

glaciers worldwide (WGMS 2012). A great deal of mass balance studies was focused on the UG1, yet little research on the effects of the entire glaciers in the URB.

This work addressed on the current state of glaciers and potential problems related to the observed glacier shrinkage during the periods 1964–2005 and 2005–2014 in the URB. The main goals are: (1) to examine decadal area and volume change for glaciers; (2) to investigate and emphasize the changes of UG1; (3) to explore the effect on regional water resources; and (4) to give possible climatic drivers for glacier change.

Study area

The URB (86°45′E-87°56′E, 43°00′N-44°07′N) is located on the eastern Tianshan Mountains of the Xinjiang Uygur Autonomous Region (Fig. 1). The catchment area is about 4684 km^2 (Shi 1992), and its runoff reaches 2.44×10^8 m^3 $yr.^{-1}$(Wu et al. 2006). According to the first Glacier Inventory of China (GIC), there were 150 glaciers in the URB, with coverage of 45.99 km^2 in area and 1.54 km^3 in volume, respectively (GIC (ш)), and most of these glaciers were hanging and cirque glaciers (Chen et al. 1996). The UG1 (Fig. 1), a typical continental glacier, is located at the headwater of URB. The glacier, with an area of 1.65 km^2 and 2.23 km long in 2009, is a summer accumulation type glacier (Ageta and Fujita 1996). The elevation of UG1 spans between 3756 m and 4476 m, with an averaged elevation of 4130 m a.s.l. (Li et al. 2003).

Data and methods

Data acquisition

Six topographic maps at a scale of 1:50,000 were derived from aerial photographs in 1964. One SPOT5 image was obtained on October 2005 with a spatial resolution of 5 m, which covered the most heavily glaciated part of the URB (Fig. 2). Landsat 7 ETM+ image (receive date is 2014-08-05 and path row is 143/030) was used to extract the glacier boundary in 2014, and the data were acquired from U.S. Geological Survey (USGS, http://www.usgs.gov). Here we utilized SRTM DEM (the fourth version), which was jointly measured by National Aeronautics and Space Administration of USA (NASA) and the Department of Defense National Mapping Agency of USA (NIMA), to estimate the vertical variation of glaciers.

Two catchments, i.e., Glacier No.1 and Empty Cirque catchment, at the headwater of the URB were hydro-analyzed to obtain the glacier change effects on regional water resources. Glacier No.1 catchment, which is largely glaciated, covers a drainage area of 3.34 km^2, and Empty Cirque catchment, a small non-glacierized but barren rocked catchment, covers a drainage area of 1.68 km^2. The nearest long-term meteorological record is provided by Daxigou Meteorological Station (Daxigou MS). Daxigou MS which is located at 3539 m a.s.l. and about 3 km downstream of the UG 1 (Fig. 1). Data of these stations were provided by the TGS (Table 1).

Table 2 Glacier area and number change from 1964 to 2005 to 2005–2014 in the URB

Glacier area class (km^2)	Number of glaciers				Area of glaciers (km^2)			
	1964	2005	2014	Change (1964–2014)	1964	2005	2014	Change (1964–2014)
< 0.1	38	68	63	25 (65.79%)	2.22	3.21	3.36	1.14 (51.35%)
0.1–0.5	80	51	49	− 31 (− 38.75%)	18.74	11.99	11.79	− 6.95 (− 37.09%)
0.5–1	17	16	15	− 2 (− 11.76%)	11.99	10.97	9.99	− 2 (− 16.68%)
1–2	10	3	1	− 9 (− 90%)	12.37	3.81	1.03	− 11.34 (− 91.67%)
2–3	0	1	1	1 (100%)	0	2.92	2.74	2.74 (100%)
> 3	1	0	0	− 1 (− 100%)	3.43	0	0	− 3.43 (− 100%)
Total	146	139	129	− 17 (− 11.64%)	48.75	32.90	28.91	− 19.84 (− 40.7%)

Table 3 Glacier area and annual variation in the URB since 1964

Year	Area (km^2)	Annual variation rate (%/a)	Annual variation (km^2/a)
1964	48.75		
2005	32.90	0.77	0.38
2014	28.91	1.21	0.40

Methods

Topographic maps were scanned into digital products at a resolution of 600 dpi and geo-corrected to obtain digital raster graphics. Root mean square error (RMSE) of geometric correction was less than 1 pixel. Preprocessing of image data included accurate geometric correction and image enhancement. Twenty ground control points (GCPs) were selected from the topographic maps to orthorectify SPOT5 and Landsat image. All the data were presented in a Universal Transverse Mercator (UTM) coordinate system and World Geodetic System 1984 (WGS84) referenced to the topographic maps.

The glacier outlines of 1964 were interpreted from topographic maps. For 2005, the outline of glaciers was derived from a panchromatic SPOT5 image. A preliminary glacier boundary was generated automatically from the band ratio method for Landsat data in 2014. We applied the band ratio approach using the TM4/TM5 combined manual correction to extract glacier outlines in the URB (Williams et al. 1991; Jacobs et al. 1997; Bayer et al. 1994). To achieve maximum accuracy, manual checking on false color composites of 5, 4, and 3 bands with Landsat image was also used. "Calculate Geometry" tool, was used to calculate the areas in different periods. Errors in the glacier boundaries from remote sensing image were controlled by the image resolution and co-registration error. The uncertainty can be calculated by the following formulae (Hall et al. 2003; Silverio and Jaquet 2005; Ye et al. 2006):

$$U_T = \sqrt{\sum\lambda^2} + \sqrt{\sum\varepsilon^2} \tag{1}$$

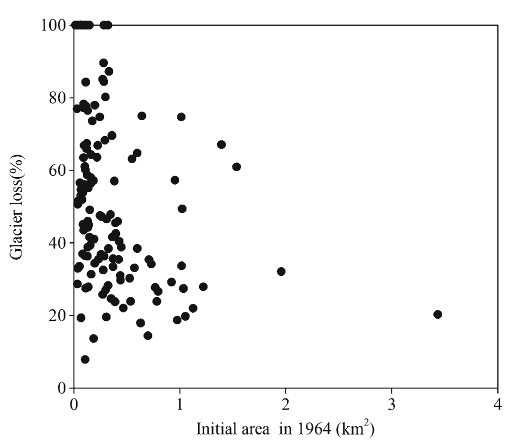

Fig. 3 Area change of individual glacier in the URB from 1964 to 2014

$$U_A = 2U_T\sqrt{\sum\lambda^2} + \sqrt{\sum\varepsilon^2} \tag{2}$$

where U_T is the uncertainty of glacier length; λ is the image resolution; ε is the co-registration errors of each image to the topographic map; and U_A is the uncertainty of glacier area. The accuracy of glacier length is ± 45 m for ETM+ data and ± 10 m for SPOT5 image. Glaciers area uncertainties were estimated to be ± 0.003 km^2 using ETM+ image and ± 0.0001 km^2 using SPOT5 image.

Results

Glacier area and number changes

Table 2 showed glacier area and number changes for the1964–2005 and 2005–2014 periods in the URB. The URB experienced seven glacier disappearances during the period 1964–2005, and another ten disappeared by 2014. Moreover, 21 glaciers smaller than 0.2 km^2 completely disappeared between 1964 and 2014. The total area of glaciers decreased from 48.75 km^2 in 1964 to 28.91 km^2 in 2014; that is, 19.84 km^2 or approximately 41% of glacier area were shrank.

The glaciers area change during the period 1964–2014 of the URB with area < 0.1, 0.1–0.5, 0.5–1, 1–2, 2–3 km^2, and > 3 km^2 were 1.14 km^2, − 6.95 km^2, − 2 km^2, − 11.34 km^2, 2.74 km^2, and − 3.43 km^2, respectively (Table 2). For the URB, glacier area and number increased in class < 0.1 km^2. The mean area for a single glacier from 0.33 km^2 during 1964 was reduced to 0.22 km^2 during 2014.

Overall, nearly doubling glacier shrinkage occurs in the URB, from an averaged area reduction rate of 0.77%/a in 1964–2005 to 1.21%/a in 2005–2014 (Table 3), and it appears that this was largely caused by small glacier shrinkage.

In terms of the relative changes in the glaciers with different glacier sizes (Jóhannesson et al. 1989), percentages of area reduction of small glaciers were usually higher than those of large glaciers. Taking into account the influence of the glacier size, we found there was a non-linear relationship between glacier initial size and percentages of area loss in the URB. Figure 3 shows that the relative glacier changes increased with decreasing glacier size. The shrinkage was very strong for glaciers with areas of 0–0.5 km^2 and its shrinkage accounted for 56.01% of the total glacier area loss.

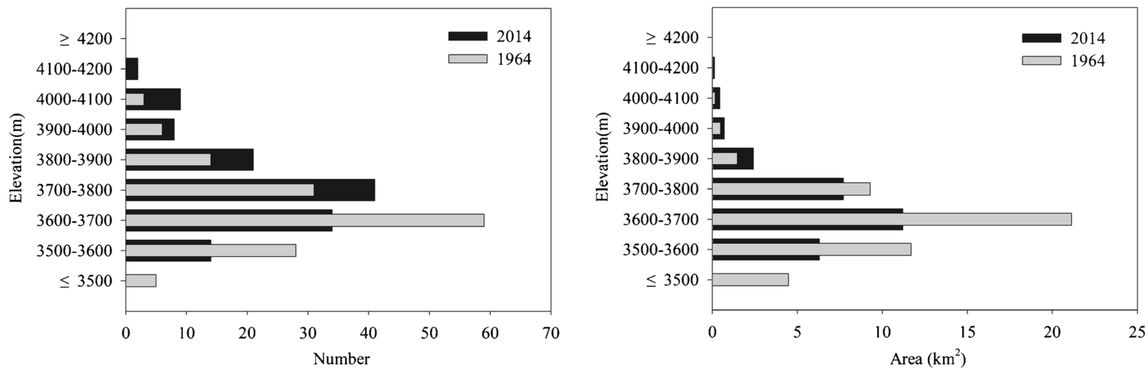

Fig. 4 Glacier area shrinkage in different elevation ranges in the URB from 1964 to 2014

Glacier variation in different altitude bins

Based on the topographic map, vertical variations were calculated for each 100 m elevation bin according to the elevation of glacier terminus. Statistical analysis was applied for two phases of the glacier data (Fig. 4): glacier terminus in the URB were mainly distributed in 3600–3700 m and 3700–3800 m, accounting for 26.36% and 31.78% in numbers, respectively. The most obvious reduction ranges are in the 3500–3600 m and 3600–3700 m bins. Obviously, the high shrinking rate of glaciers at the altitude range of 3500–3700 m directly led to an increasing trend at altitude range of 3800–4200 m.

Glacier distribution and regional differences

Glaciers in the URB are distributed in Xiondi River (5Y730A), Chahannuoer Region (5Y730B), Wuteken Region (5Y730C), and Bulate Region (5Y730D). Change in glacier area from different regions may be influenced by humidity, air temperature, precipitation, and terrain (Li et al., 2011). Average area of individual glacier in 2014 in Chahannuoer Region (5Y730B) was 0.29 km^2, and in Wuteken Region (5Y730C) was 0.41 km^2. Figure 5 shows that from 1964 to 2014, the greatest decrease was Chahannuoer Region (44.71%), followed by Xiondi River (42.33%), and Bulate Region (37.63%). Glacier area loss rates are different in different sub-regions, and regional differences are obvious. It is clear that both glacier distribution and glacier change in the URB have large regional differences.

Glacier volume change

According to previous studies (Liu et al. 2003; Xu et al. 2013), the empirical relation between glacier area and volume was founded by the Lanzhou Institute of Glaciology and Geocryology (LIGG) (1986), for glaciers in western China, which is expressed as follows:

$$H = -11.32 + 53.21S^{0.3} \tag{3}$$

$$H = 34.4S^{0.45} \tag{4}$$

$$V = S^{*}H/1000 \tag{5}$$

where S is the glacier area (km^2), H is mean thickness of glacier (m), and V is the glacier volume (km^3). Equation (3)

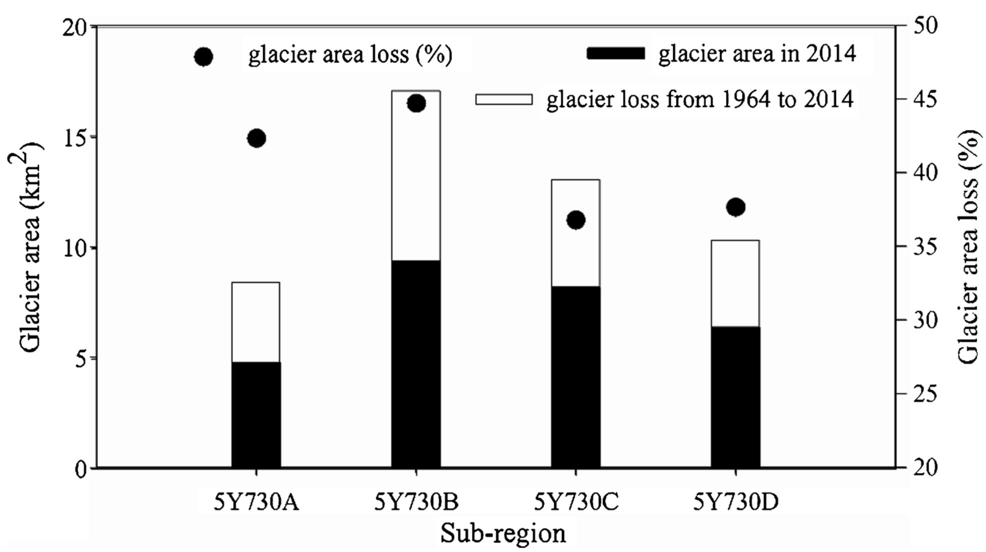

Fig. 5 Glacier area shrinkage of sub-region in the URB from 1964 to 2014

Table 4 Comparison of glacier recession in other mountain regions of the western China

Study areas	Area change (%)	Recession rate (%/a)	Period	Author
Yeniugou River Basin	− 25.71	0.54	1956–2003	Yang et al. (2007)
Heihe River Basin	− 29.6	–	1950s/1970s–2003	Wang et al. (2011)
Heihe River Basin	− 36.08	0.60	1960s–2007/2011	Huai et al. (2014)
Kaidu River Basin	− 11.6	0.31	1963–2000	Liu et al. (2006)
Gez River Basin	− 10	0.26	1960–1999	Liu et al. (2006)
Pumqu River Basin	− 8.98	0.30	1970s–2000	Jin et al. (2004)
UrumqiRiver Basin	− 13.8	0.45	1962–1992	Chen et al. (1996)
Urumqi River Basin	− 40.7	0.80	1964–2014	This study

is applicable for cirque, valley, and cirque-valley glaciers, and Eq. (4) is applicable for hanging glaciers. The formula was induced based on a statistical model and could be used to estimate the glacier volume change for a large region of glaciers instead of individual glaciers. After determining the mean thickness, glacier volume can be obtained by Eq. (5). These statistical formulas were applied to estimate glacier volume change for the 1964–2014 periods in the URB. Thus, ice volume shrinkage is estimated to be 49.94% over the 51 years, which is approximately 69.2×10^6 m^3 water equivalent (assuming an ice density of 900 kg/m^3). Considering the different periods (1964–2005 and 2005–2014) separately, the estimated volume losses are 36.62% and 13.32%, respectively.

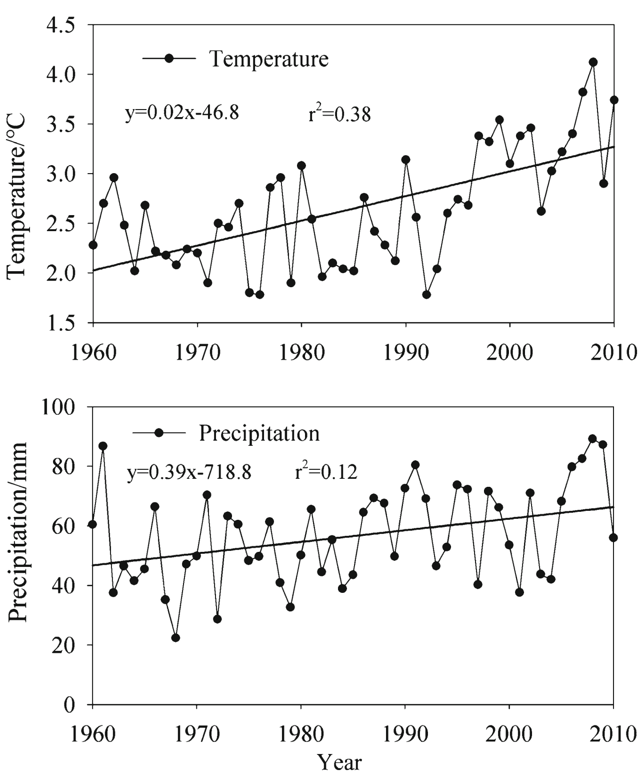

Fig. 6 The average temperature (from May to September) and total precipitation (from October to April) of Daxigou meteorological station in the URB

Change of Urumqi Glacier No.1

UG1 is representative in the URB in terms of area change, length change, surface elevation change, energy balance observation, ablation simulation, and mass balance observation. Several studies have been undertaken to calculate the glacier change of UG1 (Li et al. 2003; Wang et al. 2014; Sun et al. 2013), and here we summarize the length, area, volume, and mass balance change results. According to previous results, UG1 has experienced an accelerated shrinkage in the past several decades. The area has decreased by 0.30 km^2 (15.6%), from 1.95 km^2 in 1962 to 1.65 km^2 in 2009, which showed a remarkable shrinkage (Li et al. 2003). Except for climate warming reason, it may also be related to the increase in effective ablation area at the end of glacier after separating into two small glaciers with a consequent sudden increase in retreat speed in 1993 (Li et al. 2003; Ye et al. 2005). The retreat speed of the west branch terminus apparently more than that of the east branch. Published studies (Wang et al. 2014) suggested that the ice volume loss between 1962 and 2009 also showed an accelerating trend. Over the period of 1962–2009, UG1 lost a volume of 29.51×10^6 m^3 with the terminus retreat of 4.6 m/a and area reduction of 0.006 km^2/a (Wang et al. 2014). Both annual and cumulative mass balance of UG1 have shown negative increases since 1959 (Zhang et al. 2014).

Discussion

Comparison of glacier changes with other regions

Despite different measurement sites and periods and the meteorological conditions, general comparison is possible for glacier changes. It is found that compared with other glaciers in western mountain regions in China (Table 4), the rate of glacier retreat was significantly higher with 0.80%/a from 1964 to 2014 in this study. Compared with the study of Chen et al. (1996), the results indicated that glaciers in the URB are in a state of rapid recession, especially in the last

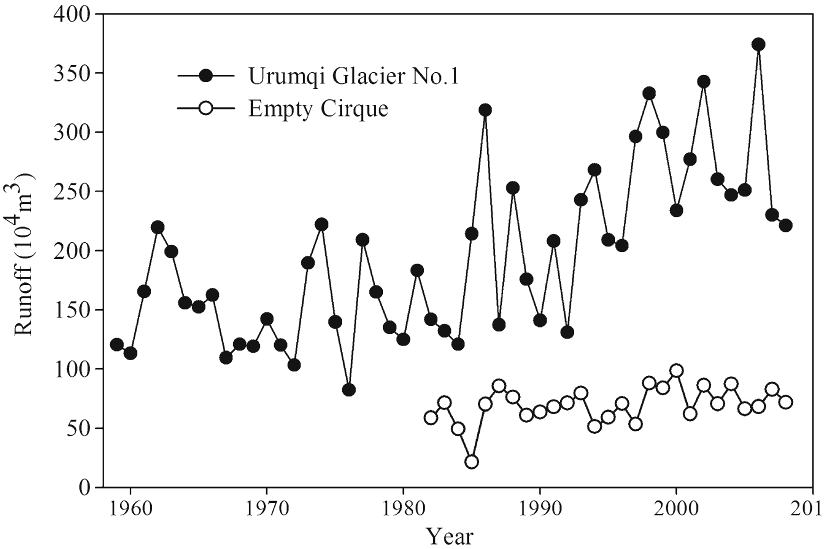

Fig. 7 Changes of annual runoff in Urumqi Glacier No.1 and Empty Cirque hydrological stations in the URB

two decades. By comparison, we see that there are significant differences of glacial recession in other regions of the western China, under the influence of climate change. To investigate reasons why glacier area reduced so fast in the URB, the regional climate change might be the main reason behind this relative higher reduction in glacier area while the glacier size also was a factor (Jóhannesson et al. 1989). As the average area of individual glacier in the URB was just 0.33 km^2, glaciers were more sensitive to climate change.

Response of glaciers change to climate

Figure 6 shows that the rate of average temperature in the glacier melting seasons (from May to September) increasing was more than 0.20 °C/10a (statistically significance at the 99% confidence level) during 1960–2010, and the precipitation in the accumulation seasons (from October to April) had been increasing rate of 3.9 mm/10a. The temperature trend magnitudes were higher than the rate of global average temperature increasing rate of 0.148 °C/10a (IPCC 2007). Previous study suggests that annual average precipitation was 294 mm during 1978–2000 and it was increased by 27.3% compared with 231 mm during 1951–1977, according to the data of Urumqi meteorological station (Han et al. 2005). Liu et al. (1999) demonstrated that glacier shrinkage in the last 30 years corresponded to an air temperature rise of about 0.35 ± 0.27 °C in the high mountain region of the URB. Obviously, temperature in the melting seasons have increased significantly, although precipitation in the accumulate seasons also showed slight increase; the sensitivity of glaciers on temperature became stronger. With temperature rising, the supply from increased precipitation cannot compensate for the loss of glacier mass ablation, thus resulting in the continued shrinkage for glaciers in the URB.

Effects on regional water resources

Figure 7 presents annual runoff at the Empty Cirque and Glacier No.1 hydrological stations from 1959 to 2008. The annual runoff of the Empty Cirque station has an evident low value compared with the Glacier No.1 station. It is illustrated that the change of hydrological regime in the URB was greatly linked to the glacier conditions, which further emphasized the fact that of great importance of glacier meltwater to local water resource. The measured annual runoff of Glacier No.1 station was 200 × 10^4 m^3, minimum occurred in 1976 and maximum occurred in 2006, inter-annual change was larger. Furthermore, the runoff of 1995–2008 was significantly higher than in 1959–1984 in Glacier No.1 hydrological station, which showed that the runoff has increased. On the contrary, the non-glacierized Empty Cirque station had relatively small variation amplitude and had a significant low runoff. Obviously, glacier meltwater in summer is the vital source for the URB upstream and has an important role in stabilizing runoff. Currently, glaciers less than 0.5 km^2 are rapidly melting in the URB, adding to the flow of downstream rivers. The glaciers with area 1–2 km^2 making the biggest contribution to water resources as the area change was − 11.34 km^2 during 1964–2014, which has the higher retreat rate. Undoubtedly, if climate warming causes ice loss to continue at rates like those reported in the present study, the regulation effect of glaciers to river runoff would be weakening.

The shortage of water in the Urumqi is a puzzling problem. With the economic activities and population increase, the water shortage in the URB will limit economic development and security of human life. It is necessary to take measures to make efficient use of limited water resources in the URB, and the glacier monitoring under the climate change should be taken seriously.

Conclusions

This paper studied the glacier change information in the URB from 1964 to 2014. Some conclusions can be drawn as follows:

(1) The area reduction rate increased from 0.77%/a during 1964–2005 to 1.21%/a during 2005–2014 in the URB, indicating that the melting of glaciers in the URB is becoming more and more intense.
(2) Ice volume loss is estimated to be 49.94% from 1964 to 2014, which is approximately 69.2×10^6 m^3 water equivalent. Glacier area between 1 and 2 km^2 are making the biggest contribution to water resources, but the regulation effect of such glaciers to river runoff is weakening.
(3) The accelerated glacier retreat was a dangerous signal for local water resource in the URB, and the continuous future glacier monitoring under the global warming were desperately needed.

Acknowledgements We thank the Tienshan Glaciological Station for the data collection.

Funding information This work was funded by the Natural Science Foundation of China (41701059; 41401040), the Postdoctoral Science Foundation of China (40411594), and Scientific Research Foundation for the introduction of talent by Shandong Normal University.

References

Ageta Y, Fujita K (1996) Characteristics of mass balance of summer-accumulation type glaciers in the Himalayas and Tibetan Plateau. Zeitschrift Fuer Gletscherkunde und Glazialgeologie 32:61–65

Bayer KJ, Hall DK, Kovalick WM (1994) Observations on glaciers in the eastern Austrain Alps using satellite data. Int J Remote Sens 15(9): 1733–1742

Bolch T (2007) Climate change and glacier retreat in northern Tien Shan (Kazakhstan/Kyrgyzstan) using remote sensing data. Glob Planet Chang 56(1–2):1–12

Chen J M, Liu C H, Jin M X (1996) Application of the repeated aerial photogrammetry to monitoring glacier variation in the drainage area of the Urumqi River. J Glaciol Geocryol,18(4):331–336 (in Chinese)

Chen YN, Li WH, Deng HJ, Fang GH, Li Z (2016) Changes in Central Asia's water tower: past, present and future scientific reports, vol 6, p 35458. https://doi.org/10.1038/srep35458(2016)

Hagg W, Braun LN, Kuhn M, Nesgaard TI (2007) Modelling of hydrological response to climate change in glacierized Central Asian catchments. J Hydrol 332:40–53

Hall DK, Bayr KJ, Schfner W, Bindschadler RA, Chien JYL (2003) Consideration of the errors inherent in mapping historical glacier positions in Austria from ground and space (1893-2001). Remote Sens Environ 86:566–577

Han TD, Ye BS, Ding YJ, Jiao KQ (2005) Increasing runoff in the Urumqi River basin since 1980s. J Glaciol Geocryol 27(5):655–659 (in Chinese)

Han TD, Ding YJ, Ye BS, Liu SY (2006) Mass_balance characteristics of Urumqi Glacier No.1, Tien Shan, China. Ann Glaciol 43(6):323–328

Huai BJ, Li ZQ, Wang SJ, Sun MP, Zhou P, Xiao Y (2014) RS analysis of glaciers change in the Heihe River basin, Northwest China, during the recent decades. J Geogr Sci 24(6):993–1008. https://doi.org/10.1007/s11442-014-1133-z

IPCC (2007) The fourth assessment report of the intergovernmental panel on the climate change. Cambridge University Press, Cambridge, pp 1–996

Jacobs JD, Simms EL, Simms A (1997) Recession of the southern part of Barnes Ice Cap, Baffin Island, Canada, between1961 and 1993, determined from digital mapping of Landsat TM. J Glaciol 43(143):98–102

Jin R, Che T, Li X (2004) Glacier variation in the Pumqu Basin derived from remote sensing data and GIS technique. J Glaciol Geocryol 26(3):261–266 (in Chinese)

Jóhannesson T, Raymond C, Waddington E (1989) Time-scale for adjustment of glaciers to changes in mass balance. J Glaciol 35:355–369

Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences (1986) Glacier inventory of China (ш): Tianshan Mountains (interior drainage area of Junggar Basin in northwest). Science Press, Beijing, pp 1–206 (in Chinese)

Li ZQ, Han TD, Jing ZF, Yang HA, Jiao KQ (2003) A summary of 40-year observed variation facts of climate and Glacier No.1 at headwater of Urumqi River, Tianshan, China. J Glaciol Geocryol 25(2): 117–123 (in Chinese)

Li ZQ, Li KM, Wang L (2010) Study on recent glacier changes and their impact on water resources in Xinjiang, northwestern China. Quat Sci 30(1):96–106 (in Chinese)

Liu SY, Wang NL, Ding YJ (1999) On the characteristics of glacier fluctuations during the last 30 years in Urumqi river basin and the estimation of temperature rise in the high mountain area. Adv Earth Sci 14(3):279–285 (in Chinese)

Liu SY, Sun WX, Shen YP, Li G (2003) Glacier changes since the Little Ice Age maximum in the western Qilian Shan, Northwest China, and consequences of glacier runoff for water supply. J Glaciol 49:117–124

Liu SY, Ding YJ, Zhang Y (2006) Impact of glacier change on water resources in the Tarim River Basin. Acta Geograph Sin 61(5):482–490 (in Chinese)

Shangguan DH, Liu SY, Ding YJ, Ding LF, Xu JL, Li J (2009) Glacier changes during the last forty years in the Tarim InteriorRiver basin, Northwest China. Prog Nat Sci 19:727–732. https://doi.org/10.1016/j.pnsc.2008.11.002

Shi YF (1992) The formation and estimation of water resources in Urumqi River Basin. Science Press, Beijing

Shi Y F, Su Z (1965) The glaciers features and the glaciers evolution history at the headwater of the Urumqi River, Tianshan Mountains[C]//The Study of Glaciers and Hydrology of Urumqi River, Tianshan Mountains. Beijing: Science Press, 83–87 (in Chinese)

Silverio W, Jaquet JM (2005) Glacial cover mapping (1987-1996) of the Cordillera Blanca (Peru) using satellite imagery. Remote Sens Environ 95(3):342–350

Sun MP, Li ZQ, Yao XJ, Jin S (2013) Rapid shrinkage and hydrological response of typical continental glacier in the arid region of Northwest China-taking Urumqi Glacier No. 1 as an example. Ecohydrology 6(6):906–916

Wang ZT, Su HC (2003) World and China's glacier distribution and water resources significance. J Glaciol Geocryol 25(5):500–503 (in Chinese)

Wang X, Xie ZC, Li Q (2008) Sensitivity analysis of glacier systems to climate warming in China. J Geogr Sci 18(2):190–200 (in Chinese)

Wang PY, Li ZQ, Gao WY, Yan DH, Bai JZ, Li KM, Wang L (2011) Glacier changes in the Heihe River basin over the past 50 years in the context of climate change. Resour Sci 33(3):399–407 (in Chinese)

Wang PY, Li ZQ, Li HL, Wang WB, Yao HB (2014) Comparison of glaciological and geodetic mass balance at Urumqi Glacier No. 1, Tian Shan, Central Asia. Glob Planet Chang 114(2014):14–22

WGMS (2012) Fluctuations of glaciers 2005e2010. In: Zemp, M., Frey, H., Gärtner- Roer, I., Nussbaumer, S.U., Hoelzle, M., Paul, F., Haeberli, W. (Eds.), ICSU (WDS)/IUGG (IACS)/UNEP/UNESCO/WMO, vol. X. World Glacier Monitoring Service, Zurich, Switzerland, p.336. Publication based on database version https://doi.org/10.5904/wgms-fog-2012-11

Williams RS, Hall DK, Benson CS (1991) Analysis of glacier facies using satellite techniques. J Glaciol 37(125):120–128

Wu SF, Lui ZH, Han P (2006) Impact of climate change on water resources of the Brômqi River Basin. J Glaciol Geocryol 28(5):703–706 (in Chinese)

Xu JL, Liu SY, Zhang SQ, Guo WQ, Wang J (2013) Recent changes in glacial area and volume on Tuanjiefeng Peak Region of Qilian Mountains, China. Plos One 8(8):e70574

Yang Y, Chen RS, Ji XB (2007) Variations of glaciers in the Yeniugou watershed of Heihe River Basin from 1956 to 2003. J Glaciol Geocryol 29(1):100–106 (in Chinese)

Yao TD, Liu SY, Pu JC (2004) Glacier retreat in high Asia and their impacts to water resource of Northwest China. Science of China D 34(6):535–543

Ye BS, Yang DQ, Jiao KQ (2005) The Urumqi River source Glacier No.1, Tianshan, China: changes over the past 45 years. Geophys Res Lett 32:L21504. https://doi.org/10.1029/2005GL024178

Ye QH, Kang SC, Chen F, Wang JH (2006) Monitoring glacier variation on Geladandong mountain,central Tibetan Plateau, from 1969 to 2002 using remote sensing and GIS technologies. J Glaciol 52(179):537–545

Zhang GF, Li ZQ, Wang WB, Wang WD (2014) Rapid decrease of observed mass balance in the Urumqi Glacier No. 1, Tianshan Mountains, Central Asia. Quat Int 349:135–141