Ice thickness, volume and subglacial topography of Urumqi Glacier No. 1, Tianshan mountains, central Asia, by ground penetrating radar survey

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The results of radar survey for three times are presented, aiming to determine ice thickness, volume and subglacial topography of Urumqi Glacier No. 1, Tianshan Mountains, central Asia. Results show that the distribution of ice is more in the center and lesser at both ends of the glacier. The bedrock is quite regular with altitudes decreasing towards the ice front, showing the U-shaped subglacial valley. By comparison, typical ice thinning along the centerline of the East Branch of the glacier was 10–18 m for the period 1981–2006, reaching a maximum of ∼30 m at the terminus. The corresponding ice volume was 10296.2×10^4 m^3, 8797.9×10^4 m^3 and 8115.0×10^4 m^3 in 1981, 2001 and 2006, respectively. It has decreased by 21.2% during the past 25 years, which is the direct result of glacier thinning. In the same period, the ice thickness, area and terminus decreased by 12.2%, 10.3%, and 3.6%, respectively. These changes are responses to the regional climatic warming, which show a dramatic increase of 0.6°C (10 a)$^{-1}$ during the period 1981–2006.

1. Introduction

Mountain glaciers are not only indicators of climate change but also crucial for understanding the hydrological behaviour (Oerlemans and Fortuin 1992; Fountain *et al.* 1999; Haeberli *et al.* 2008). There are 15,935 glaciers with a total area of 15,416 km^2 in the Tianshan Mountains (39–46°N, 69–95°E), which is one of the largest mountain ranges in central Asia (Aizen and Aizen 1997; Aizen *et al.* 2007). The eastern Tianshan (Chinese Tianshan), located in China, contains 9035 glaciers with an approximate total area of 9225 km^2 (Shi *et al.* 2005, 2008). According to the 14 meteorological stations in this region, the temperature and precipitation showed remarkable increasing tendency from 1960 to 2009 at a rate of 0.34°C (10 a)$^{-1}$ and 11 mm (10 a)$^{-1}$, respectively. The temperature in the dry seasons increased more rapidly than in the wet seasons. The precipitation was exactly the opposite (Wang *et al.* 2011). The annual and seasonal climatic trends accelerated the shrinkage of glaciers in the Chinese Tianshan over the last century, particularly in the recent decades, causing a serious impact on the hydrological and ecological system of this region (Aizen *et al.* 1997, 2007; Li *et al.* 2010; Wang *et al.* 2011, 2012, 2013).

Length, area, ice thickness and volume are the key parameters for extracting glacier information. The determination of ice thickness, volume and subglacial topography are important for

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understanding the interactions between climate and the complex glacier system and essential for the development of projections of glacier extent, sea-level rise and mountain hydrology (Jevrejeva *et al.* 2008). Glacier length and area can be easily determined by remote sensing or field survey approaches. However, it is more difficult to obtain ice volume. It needs to be calculated based on ice thickness data, which requires extensive fieldwork that is expensive, laborious and difficult. So, in the previous studies, several empirical formulae have been developed to calculate ice volume from easily observed glacier area (e.g., Post *et al.* 1971; Driedger and Kennard 1986; Chen and Ohmura 1990; Meier and Bahr 1996; Trabant 1997; Liu *et al.* 2003). Bahr *et al.* (1997) theoretically investigated a relationship between glacier area and volume and found that scaling factors vary significantly (e.g., from one glacier to the others or on the same glacier under different climate conditions). The scaling relationship is confirmed by establishing empirically observed trends from over 100 different glaciers. Recently, Farinotti *et al.* (2009) proposed a method based on mass conservation and principles of ice flow dynamics to estimate the ice thickness distribution of alpine glaciers from surface topography. It has been validated on four alpine glaciers located in Switzerland, for which the bedrock topography is partially known from radio-echo soundings. Although the scaling approach is an easy and simple way to estimate the ice volume, it is not always feasible for specific glaciers and the relations would vary due to different times and places. Especially in the recent 20–30 years, glacier melting has increased because of climatic warming. Moreover, glacier dynamic models require many detailed glacial physical parameters, e.g., glacier surface, subglacial topography, ice thickness, etc., which are usually difficult to obtain at the same time. Thus both of the methods mentioned above have limitations in calculating glacier volume.

Urumqi Glacier No. 1 (43°06′N, 86°49′E) is located at the headwaters of Urumqi River within the Chinese Tianshan, central Asia. It had an area of 1.94 km^2 in 1964 and covered elevations between 4486 and 3730 m, according to the Glacier inventory of China III (LIGG 1986), as shown in figure 1. It is a small valley glacier, exposed to the northeast with two branches, East Branch and West Branch. Due to glacier retreat, the two branches became separated into two individual ones in 1993. The observations of Urumqi Glacier No. 1 were initiated in 1959. As a reference glacier in the WGMS (World Glacier Monitoring System), Urumqi Glacier No. 1 provides the longest glaciological monitoring record in China (Li *et al.* 2011). Since the 1950s, independent campaigns to measure ice thickness have been carried out systematically on the glacier three times (1981, 2001 and 2006). The repeated survey lines of the radar are also indicated in figure 1. A study of the Urumqi Glacier No. 1 is valuable because this glacier is well monitored in contrast to other glaciers in this vast region, and is representative of other unmonitored glaciers in central Asia. Taking this into account, in this paper we present and discuss the radar data collected for three times on the Urumqi Glacier No. 1. The ice thickness, volume and subglacial topography are further determined. Although this study does not focus on a large number of glaciers, it is of interest in order to realize the current ice volume and assess future glacier changes.

2. Data and methods

2.1 *Radar surveys*

Independent campaigns measuring ice thickness have been carried out systematically on Urumqi Glacier No. 1 in August 1981, October 2001 and October 2006, respectively. The first measurement was made with B-1 radar-sounding system, operated at 300 MHz central frequency, with theoretical error less than 3 m within measuring range of 150 m, which was designed at the Lanzhou Institute of Glaciology and Geocryology (LIGG), Chinese Academy of Sciences (now Cold and Arid Region Environmental and Engineering Research Institute, Chinese Academy of Sciences). Two longitudinal profiles and 14 transversal profiles of the two branches were constructed (one longitudinal profile and seven transversal profiles in the East Branch; others in the West Branch) (Su *et al.* 1984; LIGG 1986) and in 2006, two longitudinal profiles and 16 transversal profiles were established (one longitudinal profile and eight transversal profiles in the East Branch; others in the West Branch). Locations of the survey profiles are shown in figure 1. Practical uncertainty of the survey was tested by two borehole depths in field measurements, with the depth of 110 and 70 m respectively, drilled into the bedrock using a thermal steam drill. It was found that radar surveys agreed well with actual borehole depths, with error within 1 m (Zhang *et al.* 1985).

Ground penetrating radar (GPR) systems have improved the accuracy of ground-based measurements of ice thickness on alpine glaciers (e.g., Narod and Clarke 1994; Murray *et al.* 1997; Degenhardt 2009; Galley *et al.* 2009; Macheret *et al.* 2009; Shean and Marchant 2010). During the measurement in 2001, a pulse EKKO Pro GPR, made by Sensors and Software Inc., Canada

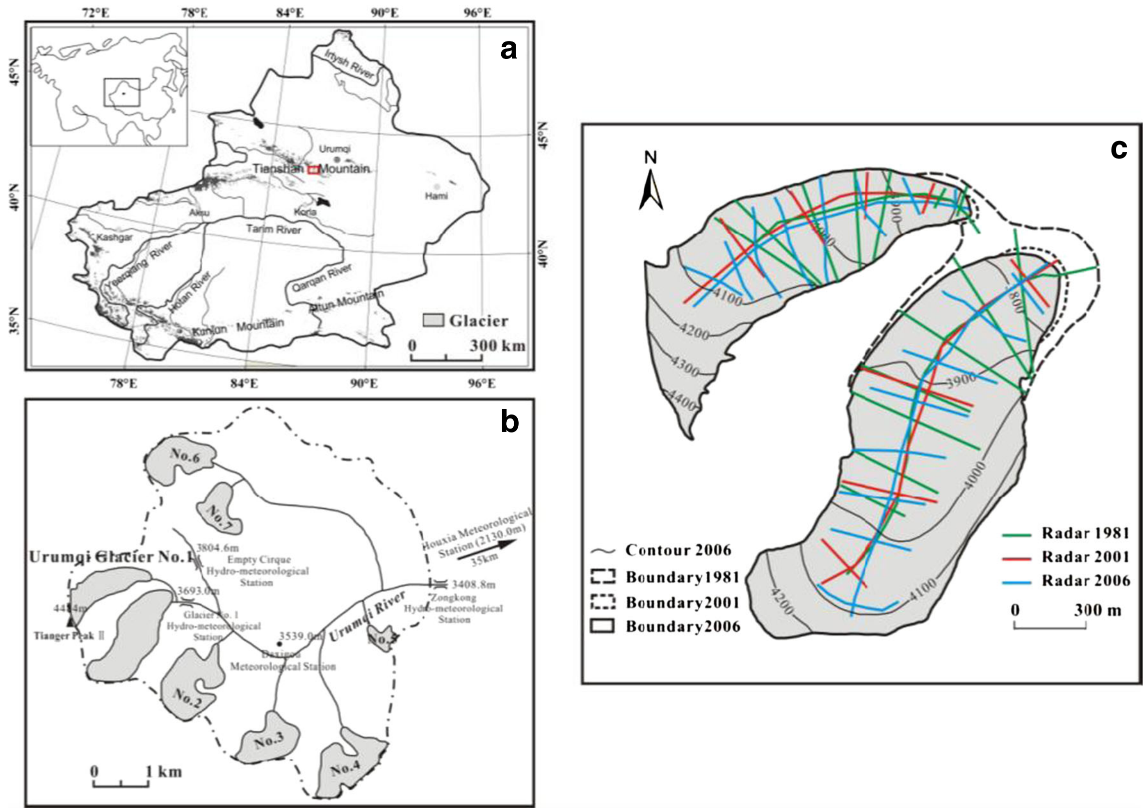

Figure 1. (**a**) Location of Urumqi Glacier No. 1 within the Chinese Tianshan, central Asia and (**b**) at the headwaters of Urumqi River. (**c**) The glacier surface topography, which is constructed by *in-situ* measurement in 2006. Contour interval is 100 m. The lines in different colours indicate the survey profiles of radar in 1981, 2001 and 2006, respectively. Glacier boundaries in different periods are denoted by different line types.

(SSI), was employed. Two longitudinal profiles and eight transversal profiles were generated from the measurement (one longitudinal profile and four transversal profiles in the East Branch; others in the West Branch). The locations of the GPR survey profiles were related to the surface relief, as shown in figure 1. In very steep and/or crevassed areas, no measurements were carried out. A common offset mode was used for the GPR profile survey and traces were artificially triggered. The profiles were obtained using a 100 MHz resistively loaded dipole antennae configuration lifted manually, vertical to the direction of movement. The transmitting-receiving antennae were arranged parallel to each other at a distance of 4 m and transverse to the profile direction. The radar diagram is shown in figure 2. The uncertainty of the survey had been reported to be less than 2% by Sun *et al.* (2003). In order to estimate the actual error of ice thickness measurement, a borehole (55.8 m) was drilled into the bedrock at the altitude of 3865 m in November 2009. However, it was a little shorter than the ice thickness (58 m) measured by GPR before the drilling. It was probably caused by the glacier ablation during 2006–2009 or influenced by significant thickness of sediment including sufficient coarse material.

The GPR data were processed in the software of EKKO View Deluxe (professional version) (Sensors and Software Inc. 1994; Murray *et al.* 1997). The ice thickness (h) can be calculated by the equation:

$$h = \frac{t_s}{2} \times v. \tag{1}$$

Here, t_s is the radar wave two-way travel time and v is the velocity of radar signal in the glacier. In all cases, a velocity of 169 m μs^{-1} (Kovacs *et al.* 1995) was used. This value is well within the range given in the literature (e.g., 167.7 m μs^{-1} (Glen and Paren 1975); 168 m μs^{-1} (Narod and Clarke 1994; Bauder 2001); 168.5 m μs^{-1} (Robin 1975)).

2.2 *Estimation of total volume and accuracy determination*

The ice volumes for 1981, 2001 and 2006 were estimated from the ice thickness maps retrieved from radar data in the same period. The surface topography maps of Urumqi Glacier No. 1 in 1981, 2001 and 2006 were determined from the digitized

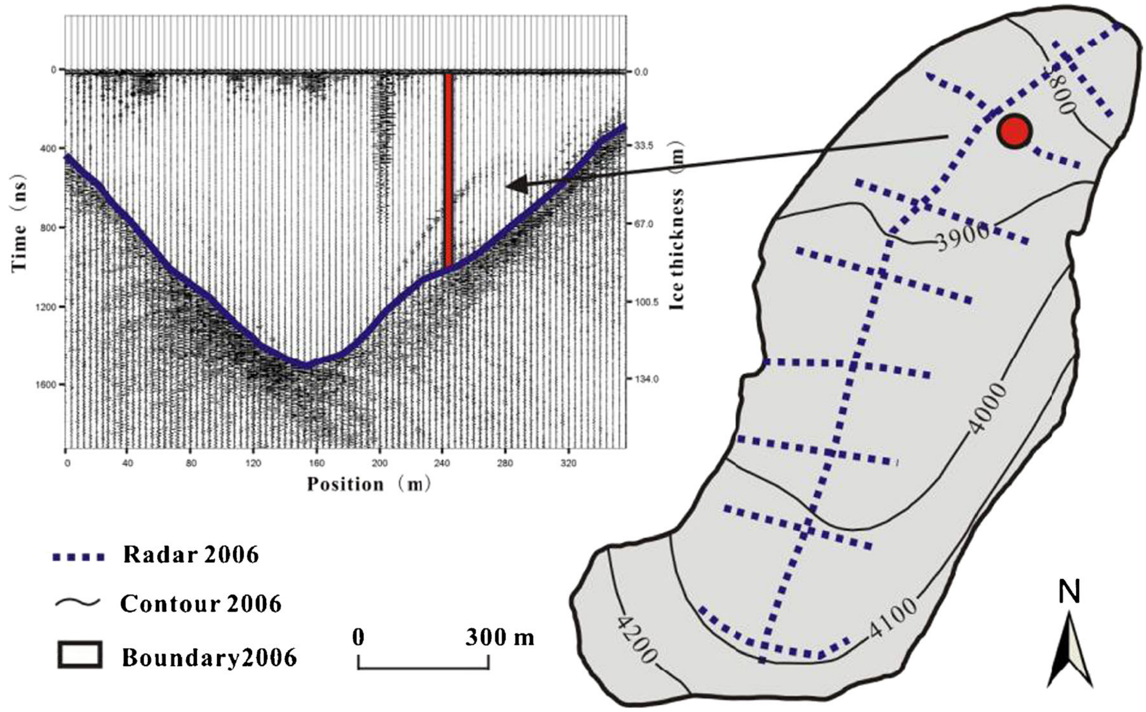

Figure 2. Radar diagram of the transverse ice thickness profile of the East Branch of Urumqi Glacier No. 1 surveyed in 2001. The x-axis is the distance from the starting point of the survey. The blue line is the bedrock topography before elevation-calibration. The red circle and line represent the drilling site and the drilled borehole to bedrock of the East Branch in 2009, respectively. Sun *et al.* (2003) estimated the uncertainty of the survey to be less than 2%. Comparison indicated that the difference between the GPR survey and drilled borehole was ∼2 m, probably caused by the glacier ablation or influenced by sediment.

topographic maps with the scaling of 1:50,000, 1:5000 and 1:5000, which was measured using aerial photograph, a theodolite and a total station, respectively, with a precision lower than 1 cm. A kriging interpolation algorithm was used to calculate the ice volume of Urumqi Glacier No. 1 in 1981, 2001 and 2006 based on a large number of ice thickness data by radar survey using ArcGIS 10.0 software. Such a method has been successfully used for Hurd Peninsula glaciers and Bowles Plateau ice cap of Livingston Island, Antarctica by Molina *et al.* (2007) and Macheret *et al.* (2009). The ice thickness was set to zero at the outline of the glacier. For the highly steep/crevassed area of Urumqi Glacier No. 1, where radar profiling was not possible, ice volume was estimated from the surface and bedrock topography determined by interpolating data from neighbouring areas (Navarro *et al.* 2005).

The accuracy of the ice volume is determined from two aspects: (1) the coverage (representative) and the numbers of the ice thickness measuring data. The completely independent radar data cover nearly 90% of the area of Urumqi Glacier No. 1. Therefore, these data were used to derive a volume which can be considered to be closer to reality; (2) the comparison of bedrock constructed by the three sets of surface topography and ice thickness data. This is because both the surface topography and ice thickness data existed for the three periods. The bedrock topography can be constructed by subtracting ice thickness from surface topography. It is assumed that the bedrock topography remained unchanged over these decades. Therefore, the difference of the bedrock constructed from the three sets of data compared with the value in 1981 can be deemed as the error. Results showed that the accuracy of ice thickness was 4.0% and 4.8% for 2001 and 2006, respectively, resulting in the accuracy of glacier volume within 6.0%. The assumption that the bedrock had remained unchanged would cause some error, but would be difficult to estimate. Nonetheless, we are certain that the error of ice volume calculation using this method is quite limited, which meets the requirement for the data processing and further analysis.

3. Results

3.1 *Ice thickness, glacier surface and bedrock topography*

The ice thickness distribution values of Urumqi Glacier No. 1 in 1981, 2001 and 2006 are similar.

Taking 2006 as an example, presented in figure 3(a), the maximum value of ice thickness, about 149 m, is found near the altitude of 3900 m, showing the pattern of thicker in the center and thinner at both ends. The average thickness was about 55.1, 51.5 and 48.4 m for 1981, 2001 and 2006, respectively (table 1). The generated DEM from glacier surface topographic map of Urumqi Glacier No. 1 in 2006 and the generated slope are shown in figure 3(b) and (c), respectively. It shows smooth surface slopes with the gradient of the West Branch ($\sim$22°) more than the East Branch ($\sim$14°). The higher angle makes the West Branch respond faster to the climate change than the East Branch (Xu *et al.* 2011). The bedrock topographic map obtained by subtracting the ice thickness from the glacier surface can be seen in figure 3(d). The bedrock is quite regular with altitudes decreasing towards the ice front and it shows U-shaped subglacial valley in the tongue area of the glacier. The bedrock topography is more undulating than the glacier surface, indicating that the amplitude of the bedrock undulation decreases with increasing distance above the bedrock. The difference in the undulation shapes of glacier surface and bedrock topography indicates that perturbations produced by Urumqi Glacier No. 1 bedrock undulations are damped out before they reach the glacier surface. Hutter (1983) predicted the undulated wavelengths of the bedrock as three to five times as the glacier thickness perturbs the ice surface topography directly and the bedrock undulation does not impact the surface topography when its wavelength is too long or too short.

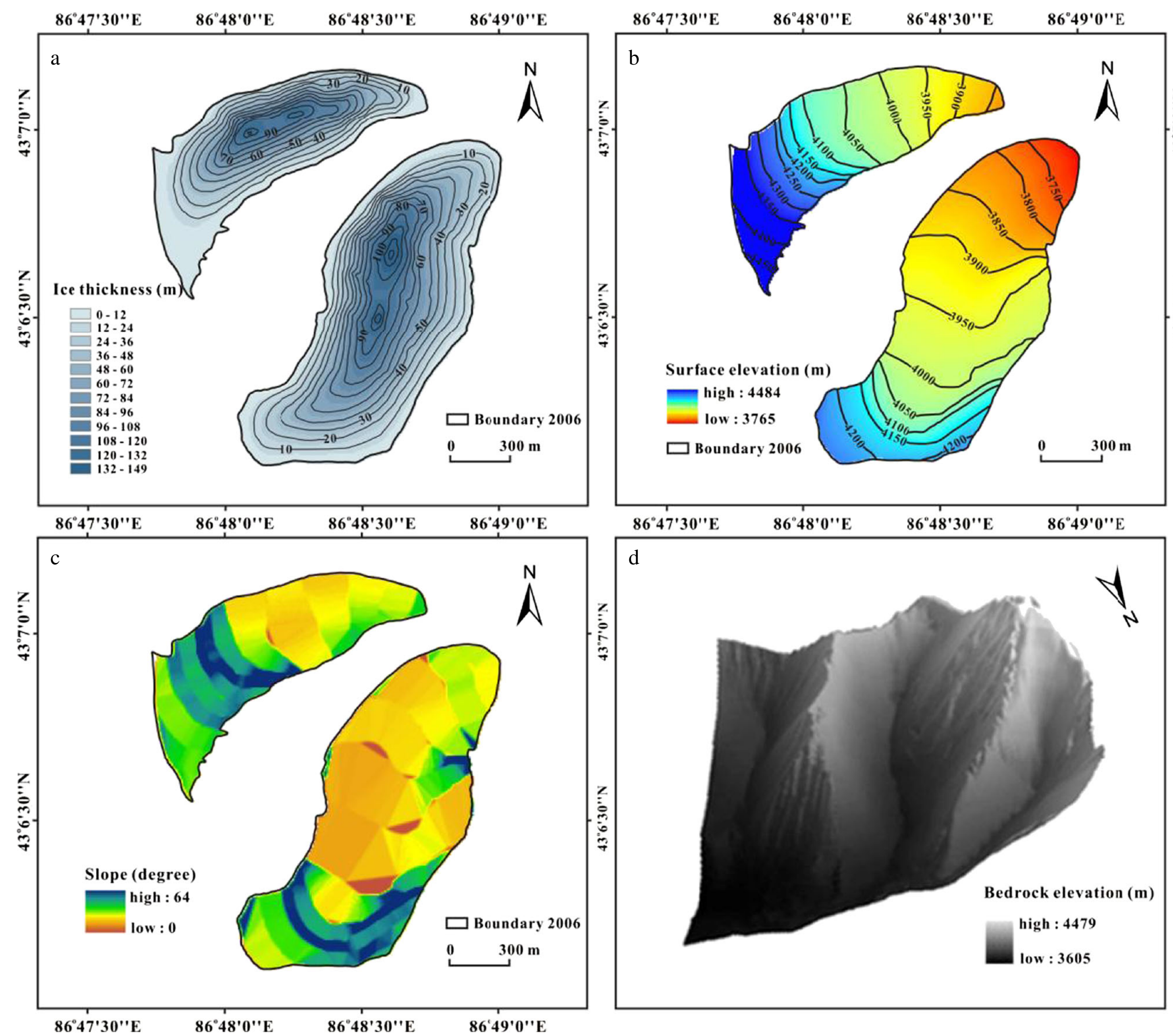

Figure 3. (**a**) Ice thickness and (**b**) the generated DEM from glacier surface topographic map of Urumqi Glacier No. 1 in 2006. (**c**) The glacier bedrock topography, constructed by subtracting the ice thickness from the glacier surface.

Table 1. *Ice volume, thickness, area and length of Urumqi Glacier No. 1 in 1981, 2001 and 2006, together with their cumulative changes. Note that the length in 2001 and 2006 is given maximum value of the two branches.*

					Glacier change			
Period	Volume (10^4 m^3)	Thickness (m)	Area (km^2)	Length (m)	Volume (%)	Thickness (%)	Area (%)	Terminus (%)
1981	10296.2	55.1	1.870	2117.5				
2001	8797.9	51.5	1.708	2057.5	−14.6	−6.5	−8.7	−2.8
2006	8115.0	48.4	1.677	2041.9	−21.2	−12.2	−10.3	−3.6

3.2 *Ice volume in different periods and their changes*

Ice volume, thickness, area, and length of Urumqi Glacier No. 1 in 1981, 2001 and 2006, together with their cumulative changes in the period 1986–2006, are shown in table 1 and figure 4. As shown in table 1, remarkable changes are observed for all parameters with different rates in the different periods. The volume of Urumqi Glacier No. 1 was 10296.2×10^4 m^3, 8797.9×10^4 m^3 and 8115.0×10^4 m^3 in 1981, 2001 and 2006, respectively. Ice volume had reduced by 21.2% of the value in 1981, with a mean annual reduction of 0.8% during the last 25 years, showing an even more accelerated decrease in ice volume. The decreasing rate of the ice volume was 74.9×10^4 m^{3}a^{-1} during 1981–2001. However, during 2001–2006, it increased to 136.6×10^4 m^{3}a^{-1} by nearly two times. Correspondingly, the ice thickness decreased by 0.18 ma^{-1} with the area reduction of 0.008 km^{2}a^{-1} and terminus retreat of 3.00 ma^{-1} during 1981–2001. For 2001–2006, the thinning increased to 0.62 ma^{-1}, which is more than three times the value in 1981–2001. However, the area and length show few changes.

Overall, the accumulative reduction rate of ice thickness (6.5%), area (8.7%) and length (2.8%) did not appear to be much different from each other during 1986–2001. Thus, the reduction in ice volume (14.6%) for this period was jointly caused by the reduction of ice thickness, area and length. However, after 2001, the accumulative reduction rate of ice thickness showed an increasing tendency and the differences between ice thickness (12.2%), area (10.3%) and length (3.6%) became larger. To that extent, a noticeable reduction (21.2%) in ice volume was due to accelerated decrease in ice thickness. The thinning was a major reason for the volume loss.

Temporal ice thickness change of Urumqi Glacier No. 1 has been examined by comparing centerline ice thickness longitudinal profiles between the site near the terminus to the upper reaches of the accumulation zone of the East Branch obtained in 1981, 2001 and 2006 (figure 5). It shows that during the 25-year period, relatively lower ice thickness thinning occurred on the accumulation zone, which was insufficient to be quantified because of the uncertainties in measurement and the comparison. However, pronounced thinning was found in the ablation zone from the terminus to an elevation of approximately 3910 m, whereas the greatest ice thickness loss in the vicinity of the terminus reached as much as ∼30 m. The average thinning along the centerline longitudinal profile of the East Branch was calculated as 10–18 m for the 25 years. Furthermore, detection of changes in ice thickness values will indeed help to observe which area is ablated more. Results indicated that the highest ablated values are achieved at the terminus. The rate of ablation at lower elevation was much more negative than those at higher elevations.

Changes in ice thickness along a longitudinal profile are particularly useful in understanding current and future glacier behaviour. A glacier adjusting to a new equilibrium will typically feature lower surface elevation change in the accumulation zone and considerable terminus thinning (Schwitter and Raymond 1993). The ongoing thinning behaviour on Urumqi Glacier No. 1 suggested that the glacier was not close to equilibrium and would continue to retreat in the foreseeable future.

4. Discussion

4.1 *Response of Urumqi Glacier No. 1 to climatic warming*

Changes in glacier volume, thickness, area, and terminus represent the integration of many climate-related events, occurring in as short a period as one year or over centuries (e.g., Harper 1993; Haeberli and Hoelzle 1995; Pelto and Hedlund 2001; Wang *et al.* 2013). Glacier change is predominantly influenced by temperature and annual precipitation. The relation between changes of Urumqi Glacier No. 1 and climate trends was studied based on meteorological data observed at the three gauging stations and two meteorological stations (table 2). Although the altitudinal elevation range covers 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

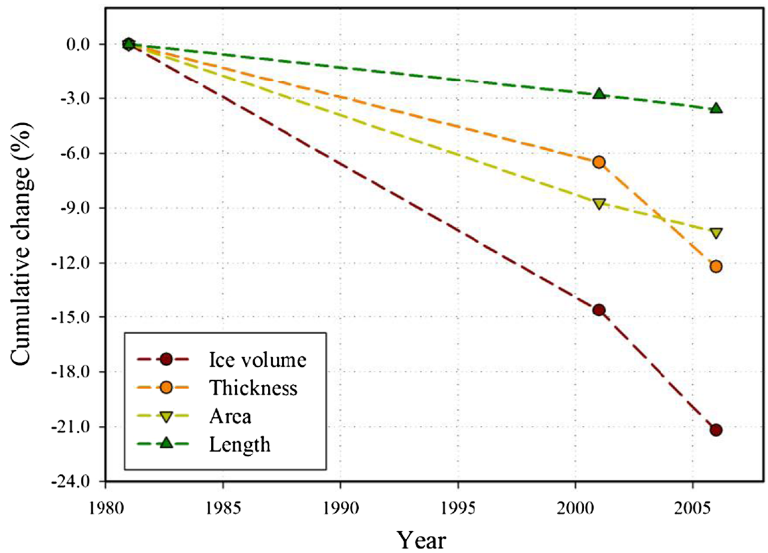

Figure 4. Cumulative changes of ice volume, thickness, area and length during 1981–2006, represented by various symbols in different colours.

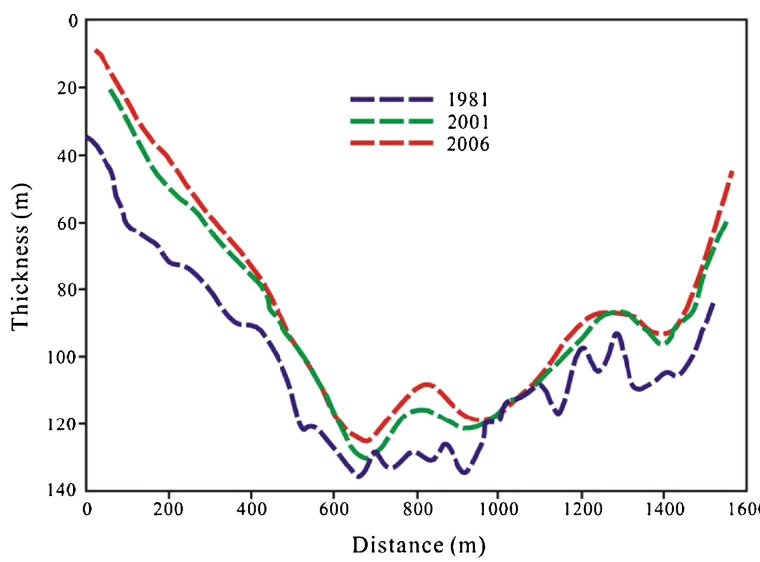

Figure 5. Changes in centerline ice thickness longitudinal profile of Urumqi Glacier No. 1 from 1981 to 2006. The horizontal axis shows the distance from the terminus. The vertical axis is the ice thickness in meter. The ice thickness in 1981, 2001 and 2006 are represented by lines in different colours. The greatest thinning occurred near the terminus.

Table 2. *Meteorological data from the five stations used in this study. Locations of the stations are shown in figure 1.*

Station	Elevation (masl)	Datasets	Time series (since the year)
Glacier No. 1 hydrometeorological station	3693.0	Temperature; precipitation	1959
Zongkong hydrometeorological station	3404.8	Temperature; precipitation	1981
Empty Cirque hydrometeorological station	3804.6	Temperature; precipitation	1981
Daxigou meteorological station	3539	Temperature; precipitation	1959
Houxia meteorological station	2130	Temperature; precipitation	1985

stations and at Daxigou Meteorological Station have similar annual fluctuations. Except for a slight dissimilarity between 1990 and 1996, the temperature at Houxia station (35 km away from Daxigou Meteorological Station) generally coincides with other four stations at headwaters of Urumqi River, indicating the consistency of air temperature at the Urumqi River basin.

As shown in figure 6, the observed temperature at Daxigou Meteorological Station demonstrates that the annual average value increased approximately 0.2°C $(10a)^{-1}$ from 1959 to 2006. Interestingly, the rate increased to 0.6°C $(10a)^{-1}$ for 1981–2006. During this period, the mean temperature was −4.96°C, compared to −5.29°C in 1959–1981, indicating an increase of almost 0.33°C. In a larger spatial scope, the air temperature in this area is generally in phase with that in other locations throughout Tianshan. According to Aizen *et al.* (1997), the average increase in air temperature over central and western Tianshan was 0.01°C a^{-1} with slightly lower value below 2000 m a.s.l. during the period 1940–1991, which is a little lower than that from Daxigou Meteorological Station, most likely because rapid temperature increase occurred after 1995, and also the elevation of the station is higher than the average. The annual precipitation series record shows that the increase averaged approximately 18 mm $(10a)^{-1}$ between 1959 and 2006 and 49 mm $(10)^{-1}$ between 1981 and 2006. The increased precipitation can probably add more or constant snow to the glacier increasing the accumulation. However, rapid reduction of ice volume, thickness, area and terminus has been observed in the past decades, which is closely related to climatic warming. The increased ablation has outweighed the accumulation for Urumqi Glacier No. 1. In addition, ice temperature of a glacier reflecting cold reserve in the glacier is closely related to the melting process of the glacier (Shumskii 1964; Cai *et al.* 1986; Mikhalenko *et al.* 2005; Li *et al.* 2007). Furthermore, with the temperature rising, the albedo is significantly reduced by the surface dust on this glacier (Takeuchi and Li 2008) which is also a factor leading to the accelerated glacier melt. According to the theory of glacier dynamics, the response of glacier change to the climate change indeed has a certain lag time. The response time depends on the glacier dimensions, such as ice thickness and length. According to Jóhannesson *et al.* (1989), the glacier will not stabilize unless it balances with the climatic conditions. At present, Urumqi Glacier No. 1 is in disequilibrium with the current climate. The change of ice volume, thickness, area and terminus illustrate the adjustments in response to climate changes from 1959 to 2006. In order to predict the changes of glaciers in the future, understanding the process of glacier change and the physical mechanism, and choosing suitable dynamic and climate models are very important.

Climatic warming has resulted in shrinkage of glaciers, which has a significant impact on water resources. Changes in glacier volume are directly related to the changes in glacial water resources and contribution of glacier changes to river runoff. Urumqi River is the mother river of Xinjiang Uygur Autonomous Region. Generally, glaciers

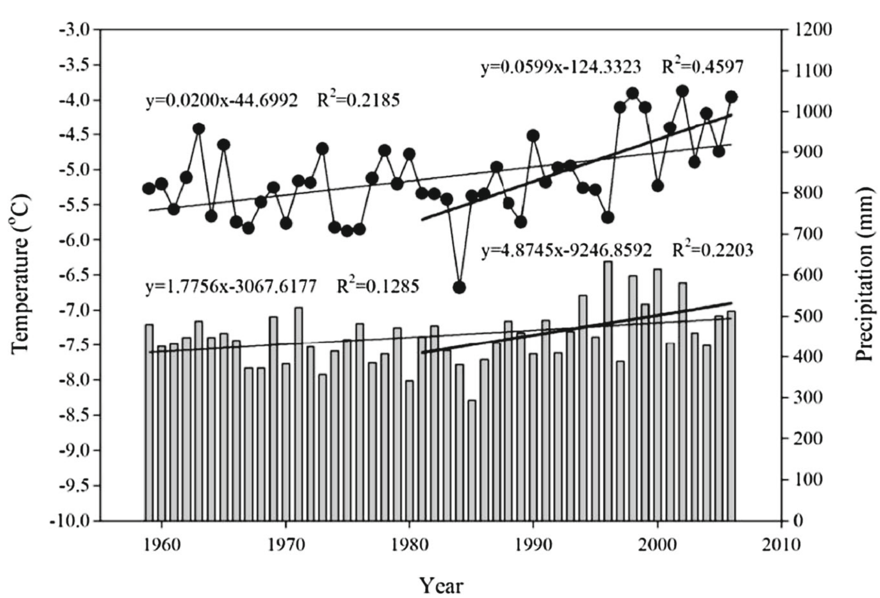

Figure 6. Variations in annual temperature and precipitation observed at Daxigou Meteorological Station in 1959–2006, showing a linear regression in different time periods.

collect solid precipitation in the winter or wet season and release melt water to supply rivers in the summer or dry seasons to stabilize river runoff. Glaciers at the headwater of the river are reliable water sources for oases and for the sustainable development of the ecological environment, industry, and agriculture in Xinjiang Uygur Autonomous Region.

5. Conclusion and outlook

Ice thickness of Urumqi Glacier No. 1 was systematically measured by radar survey three times (1981, 2001 and 2006). Based on these data, ice thickness, volume, and subglacial topography of Urumqi Glacier No. 1 are focused on in this study. The bedrock topography is obtained by subtracting the ice thickness from the glacier surface, appearing quite regular with altitudes decreasing towards the ice front. Ice volume was calculated to be 10296.2 $\times 10^4$ m^3, 8797.9 $\times 10^4$ m^3 and 8115.0 $\times 10^4$ m^3 in 1981, 2001 and 2006, respectively. Between 1981 and 2006, ice volume reduced by 21.2% or 2181.2 $\times 10^4$ m^3. Meanwhile, ice thickness, area and length decreased by 12.2%, 10.3% and 3.6%, respectively. The ice thickness reduction was the main reason for the volume loss. By comparing centerline ice thickness longitudinal profiles, it was found that the average thinning of the centerline of the East Branch was 10–18 m for the period 1981–2006. The greatest ice thickness loss, as much as $\sim$30 m was seen at the terminus. Climatic controls in this process are dominated by temperature, which significantly increased in the last 50 years, and particularly in the last 25 years. Precipitation increased as well, however, it could not compensate the mass loss caused by temperature increases.

Some problems still existed. On the one hand, the calculation of volume from ice thickness measured data seems to be an accurate way of monitoring volume change. However, the accuracy of volume changes calculated from radar measurements is highly dependent on the accuracy of positioning and the process is quite exhausting and time-consuming. This is especially true on a timescale of decades, since in the last decades GPR technology has developed rapidly and it might not be possible to revisit a site with the same measurement configuration. In the light of global change, the determination of glacier volume will be an important subject of research in future. On the other hand, glacier shrinkage, especially volume loss plays an important role in the water cycle of Xinjiang Uygur Autonomous Region. However, the influence of glacier change on river runoff has not been analyzed sufficiently. More detailed research is urgently needed in the future.

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