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Changes of six selected glaciers in the Tomor region, Tian Shan, Central Asia, over the past ~50 years, using high-resolution remote sensing images and field surveying

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ABSTRACT

As the major water resource of the Tarim River, glaciers in the Tomor region have suffered major losses of ice in the last several decades. Based on topographic maps, high-resolution remote sensing image, field survey data and previous studies, changes of the six selected glaciers in the Tomor region (Qingbingtan Glacier No.72, Qingbingtan Glacier No.74, Keqikekuzibayi Glacier, Tomor Glacier, Keqikar Glacier and Qiongtailan Glacier) over the past ~50 years were analyzed in this study. Analysis shows that all of the six glaciers showed continuous shrinkage. The reduction rate of Glacier No.72 (terminus retreat of 41 m a^{-1} and area loss of 21.5% during 1964–2009) was higher than the others, with a dramatically increased rate. This dramatic ice thinning, related glacier front retreat and area loss of the six glaciers, suggests that glaciers in the Tomor region might currently be suffering negative mass balance in response to the ongoing temperature rise. Differences in changes of the six glaciers are influenced by debris cover and other topographical factors.

1. Introduction

The mountain ranges of Central Asia function as water towers for millions of people. Glacier runoff thereby is an important freshwater resource in arid regions, as well as during the dry seasons in monsoonal affected regions (Barnett et al., 2005). Furthermore, glaciers are sensitive to climate change (Global Climate Observing System, 1995; Li et al., 2010a,b; Wang et al., 2011a,b, 2012). Global climate warming has accelerated since 1910 (IPCC, 2007) and annual mean temperature increased by 0.4–0.5 C° from 1860 to 2005 in China (China Meteorological Administration, 2006). On the whole, precipitation has increased by 2%, whereas the frequency of rainy days in China decreased by 10% from 1960 to 2000 (Liu et al., 2005). The increasing trend is more remarkable in western China, especially in the northwest (Ye et al., 2004). The climatic warming observed in northwestern China during the 20th century is thought to have driven the fluctuations of glaciers, which have been suffering frontal retreat, area shrinkage and ice thinning in the recent decades. As a result of climatic warming, glaciers in the Tian Shan have also experienced significant shrinkage (Bolch, 2007; Li et al., 2007; Niederer et al., 2007; Aizen et al., 2007a,b; Narama et al., 2009; Shangguan et al., 2009).

Tian Shan (approximately 40°–45° N; 67°–95° E) is the main glaciated region of Eurasia. According to the Catalogue of glaciers of the USSR and the Glacier Inventory of China, compiled using data from the 1950s–1970s, there were just under 16 000 glaciers in the Tian Shan occupying about 15 400 km^2 during that period (Katalog Lednikov SSSR, 1967–1980; Shi et al., 2005). The foothills are densely populated, and with mean annual precipitation of 200–600 mm, local, predominantly agricultural economies rely on the glacier-fed rivers for irrigation. In the foothills, glacier nourishment contributes at least 30% to the total river discharge (Dikich and Hagg, 2004) and an accurate estimation of glacier retreat is important in terms of water resources prediction and planning (e.g. Hagg and Braun, 2005). In spite of the importance of the state of glaciers for regional economies, regular glacier mass balance and other ground-based glaciological measurements were discontinued both in the Tian Shan and the neighbouring Pamir Mountains in the 1990s. This encouraged assessments by the integration of ground-based measurements and remote sensing techniques.

Tomor is the largest glaciated region in the Tian Shan, which contains 1858 glaciers in the Chinese territory covering a total area

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of 4195 km^2 (Shi et al., 2005). Among these glaciers, there are six glaciers with individual areas larger than 100 km^2. Glaciers in the Tomor region are characterized by supraglacial moraine that affects surface energy balance and thus runoff generation. Glacial runoff is the main water source of Aksu River, which accounts for about 70% of the surface runoff of Tarim River, and plays an important role in the sustainable development of the ecological environment, industry and agriculture, especially in the arid and semi-arid "Xinjiang Uygur Autonomous Region" (Yang, 1991; Kang et al., 2002). In addition, higher temperature causing the intensive ablation of glaciers will induce disasters occurring with increasing frequency that will potentially influence human welfare in the downstream regions. Examples of such disasters include glacier lake outburst floods (GLOFs) and glacier surging in the Yarkant River and Pamirs of China (Shen et al., 2004). The glaciated area of the Tomor region is extensive: however, field observations are sparse. Taking this into account, it is important to carry out field measurements and document glacier changes in the Tomor region, and to understand the impact, trends and rates of ongoing climatic change. Tianshan Glaciological Station implemented a field campaign during 2007–2009. Qingbingtan Glacier No.72 (Glacier No.72), Qingbingtan Glacier No.74 (Glacier No.74), Keqikekuzibayi Glacier and Tomor Glacier have been surveyed as representative glaciers in the Tomor region. Furthermore, Keqikar Glacier and Qiongtailan Glacier have been focused on by previous studies (Zhu, 1982; Wang and Su, 1984; Su et al., 1985; Wang, 1987; Xie et al., 2007; Zhang et al., 2006, 2007).

The objectives of this study are:

a) to study changes of the investigated glaciers based on field survey data, remote sensing image, topographic maps and the previous studies. The six investigated glaciers are considered to be representative for glacier changes in this region, in that the lengths and areas of the glaciers varied from 7.4 km to 41.5 km and from 7.27 km^2 to 310.14 km^2, representing different scales of glaciers in the study area;
b) to document the local climate changes over the past several decades using temperature and precipitation data from the five meteorological stations of this region; and
c) to investigate the impacts of topographical factors on glacial response to climate change.

2. Study area

This study focused on six glaciers in the Tomor region of Tian Shan (Qingbingtan Glacier No.72, Qingbingtan Glacier No.74, Keqikekuzibayi Glacier, Tomor Glacier, Keqikar Glacier and Qiongtailan Glacier). The topography, debris-covered area and some landmark locations of these six glaciers are shown in Fig. 1.

Fig. 1. Geographical location of the Tomor region, Tian Shan and outlines of the six investigated glaciers (including debris-covered area): (a) Qingbingtan Glacier No.72, (b) Qingbingtan Glacier No.74, (c) Keqikekuzibayi Glacier, (d) Tomor Glacier, (e) Keqikar Glacier and (f) Qiongtailan Glacier, the scales of which are different. Rectangle represents the meteorological stations. The glacier extent is based on the SPOT 5 image in 2003.

Qingbingtan Glacier No.72 (41°45′N, 79°54′E) is a cirque-valley glacier, 7.4 km long and covering a surface of 7.27 km^2 in 1964. This type of glacier accounts for 80% of the total number of glaciers in the Tomor region (Shi et al., 2005). The coordinates of Qingbingtan Glacier No.72 are located between two glacier tongues and it extends from 5986 m to 3560 m a.s.l. at the terminus. It has a south aspect and is mainly nourished by icefall and avalanche. Qingbingtan Glacier No.74 (41°45′N, 79°57′E), located close to Glacier No.72, is a valley glacier with an area of 9.55 km^2 and a length of 7.5 km in 1964. It ranges from 5600 m to 3680 m a.s.l. with exposure to the south. Keqikekuzibayi Glacier (41°57′N, 80°34′E) is a southeast-exposed valley glacier with an area of 25.77 km^2 and a length of 10.2 km in 1964. Its elevation ranges from 4600 m to 3320 m a.s.l. at the terminus. Tomor Glacier (41°55′N, 80°00′E) is a large compound valley glacier in the Tomor region with an area of 310.14 km^2 and a length of 41.5 km in 1964, fed by several tributaries. It has a great altitude range of 7434–2780 m and an exposure to the southwest. Keqikar Glacier (41°49′N, 80°10′E) is a typical continental glacier with a length of 26 km and total surface area 83.6 km^2, ranging in altitude from 3020 to 6342 m a.s.l. (Zhang et al., 2007). According to the Glacier Inventory of China (Shi et al., 2005), Qiongtailan Glacier (41°57′N, 80°8.41′E) extends from 3080 to 7434 m a.s.l. with a length of 23.8 km and an area of 165.38 km^2.

The climate of this region is mainly affected by mid-latitude westerlies coming from the Atlantic Ocean. The snowline of the Tomor region is between 3900 and 4500 m a.s.l. The average annual temperature is between −7 and −11 °C and precipitation is 750–1000 mm close to the snowline. More than 70% of the yearly total precipitation falls from May to September in this region (Lanzhou Institute of Glaciology and Geocryology, 1987).

3. Data and methods

For the analysis of the change of six glaciers, a variety of datasets were employed. Changes of Qingbingtan Glacier No.72, Qingbingtan Glacier No.74, Keqikekuzibayi Glacier and Tomor Glacier are assessed using field survey data (including GPS, mass balance and thickness of debris cover), topographic maps, remote sensing images, and digital elevation model (DEM). Data related to variation of Keqikar Glacier and Qiongtailan Glacier has been reported by many previous studies made by Zhu (1982), Wang and Su (1984), Su et al. (1985), Wang (1987), Xie et al. (2007) and Zhang et al. (2006, 2007). Temperature and precipitation data and thickness of debris cover have also been used.

The availability of cloud- and snow-free, and high-resolution remote sensing image required for glacier mapping is usually very limited. For the study area, a pan SPOT-5 image obtained in September 2003 with the resolution of 5 m was used ensuring clear glacier boundary determination. In order to analyze recent changes in glacier terminus and area, alternative data had to be sought and tested. This resulted in the use of eight topographic maps with the scale of 1:50 000 derived from aerial photographs acquired in 1964 by the Chinese Military Geodetic Service. The planimetric and altitudinal accuracy of the topographic maps are $<\pm0.5$ mm and <4 m as for mountainous area, which can meet the analytical requirement. The topographic maps were georeferenced using thirty GCPs with an average rectification error of about 3 m root mean square error (RMSE). Then, a digital elevation model for 1964 (DEM-1964) with a cell size of 5 m was generated based on interpolation of 20 m interval digital contours and spot heights from the topographic maps in 1964. This product was used for the orthorectification of SPOT-5 image. Clearly distinguishable terrain features (e.g. peak) were selected for GCPs from the topographic maps that could be identified on the image. Thirty ground control points (GCPs) were collected with the root mean square error (RMSE) value <0.8 pixel (5 m) in both of the x and y directions (Richards, 1993). Topographic maps and remote sensing image were presented in the 1954 Beijing Geodetic Coordinate system (BJ54) GEOID.

In this study, all of which have a debris-covered terminus, were mapped manually with the DEM. The debris-covered areas were included in the glacier outline if they appeared to be underlain by active ice as determined by the presence of surface flow features. The glacier outlines in the upper parts are assumed to have not changed, and the studies of glacier area changes are only concentrated in the tongue area. Changes of glacier area are mainly caused by terminus changes (Lopez et al., 2010). To determine changes in glacier terminus, the length of ten lines drawn along the flow direction between the old and new terminus locations were averaged. For Glacier No.72, Glacier No.74, Keqikekuzibayi Glacier and Tomor Glacier, terminus positions were surveyed in July–August 2009 by GPS survey (Unistrong E650). The horizontal error of the GPS points reach to ±1 cm + 1 ppm $\times D$ and the vertical error is ±2 cm + 1 ppm $\times D$ (D is the distance (km)). The method of measuring a surface point in RTK (Real Time Kinematic) differential mode results in a survey error of ∼0.10–0.30 m for geodetic-quality GPS receivers (Rivera et al., 2007). All GPS data, measured with respect to the Universal Transverse Mercator (UTM) World Geodetic System 1984 ellipsoidal elevation (WGS84), were re-projected and transformed to the 1954 Beijing Geodetic Coordinate system (BJ54) GEOID. The datum level was the mean sea level of the Yellow Sea, namely, Qingdao Tidal Observatory in 1956. The error using a seven-parameter space transform model was <0.002 m (Wang et al., 2003). Frontal ablation data of Qingbingtan Glacier No.72 were reported by Wang et al. (2011a,b). Data related to changes of Keqikar Glacier and Qiongtailan Glacier had been published in the previous studies (Zhu, 1982; Wang and Su, 1984; Su et al., 1985; Wang, 1987; Xie et al., 2007; Zhang et al., 2006, 2007).

Based on the field measurements on debris thickness during the period May 2008 to September 2009 and the mass balance observation by six ablation sticks drilled in the glacier of the same altitude with different debris-cover thickness, the relation of glacier ablation and debris thickness have also been analyzed. It is difficult to measure debris thickness of Keqikekuzibayi Glacier and Tomor Glacier because of their large areas. Therefore, observation of debris thickness was only carried out at the glacier terminus.

The uncertainty of the mapped glacier outlines is an important but difficult topic in glacier mapping from satellite imagery. Numerous error terms need to be considered for a sound assessment of the uncertainty. Most of these errors have two parts: one that is comparably small and can be calculated by statistical means (technical error), and the other large and difficult to assess (methodological or interpretation error). The former includes the uncertainty related to the spatial resolution of the image and uncertainty due to errors in imagery registration. Thus, the uncertainty in the glacier extent for an individual glacier can be estimated referring to the uncertainty formulas as below (Hall et al., 2003; Silverio and Jaquet, 2005).

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

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

Where λ is the resolution of the image and ε is the registration error of the image to the topographic map. The mean uncertainty for the length U_T and area U_A can be calculated by the Formula (1) and (2), respectively. The latter includes the correct interpretation of debris-covered regions, seasonal/perennial snowfields (possibly attached to a glacier), and the position of ice divides in the accumulation area, which can be made better estimates with the experts' help. Another type of error is related to the applied glacier mapping algorithm, which is very small for clean to slightly dirty ice.

The relationship between climate variability and glacier changes were explored by examining daily mean temperature and precipitation data from the closest meteorological stations to the six selected glaciers in the Tomor region with a long period of observations, due to no meteorological observations in the glaciated areas (Table 1). All the data used were from 1961 to 2000. The Mann–Kendall trend test, one of the most widely used non-parametric tests for detecting trends in time series, was applied to analyze the temperature and precipitation data.

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

Meteorological station	Lat (N)	Lon (E)	Altitude (m)	Observation period
Aksu	41°10′	80°14′	1103.8	1961–2000
Wushi	41°13′	79°14′	1395.8	1961–2000
Akeqi	40°56′	78°27′	1984.9	1961–2000
Kalpin	40°30′	79°03′	1161.8	1961–2000
Alaer	40°30′	81°03′	1012.2	1961–2000

4. Results and discussion

4.1. Glacier changes

All of the six selected glaciers are experienced terminus retreat, area loss and thinning (Fig. 2; Table 2). Strikingly, the previous study indicated that the terminus of Glacier No.72 retreated by 1852 m at the rate of 41 m a^{-1} between 1964 and 2009 and the total area loss was 21.5% of the value in 1964 with the average reduction rate of 0.034 km^2 a^{-1} (Wang et al., 2011a,b). The rate of the terminus and area changes varied during 1964–2009, estimated for two periods: (1) in 1964–2003, the recession of the terminus and area was 40.1 m a^{-1} and 0.034 km^2 a^{-1} by comparing topographic map in 1964 and SPOT-5 image in 2003, and (2) the recession proceeded until recently with the terminus retreat rate of 48.0 m a^{-1} which showed a ~8.0 m a^{-1} increase in average terminus retreat rate and area shrinkage of 0.033 km^2 a^{-1} in 2003–2009 by comparing SPOT-5 image in 2003 and survey data during the field campaign. Correspondingly, the ice surface-elevation of the tongue decreased by 0.22 ± 0.14 m a^{-1} from 1964 to 2008, with the ice volume loss of 0.014 ± 0.009 km^3, which represented a ~20% decrease from the 1964 volume. Furthermore, the annual velocity of Glacier No.72 reached ~70 m a^{-1} (Wang et al., 2011a,b).

The terminus retreat rate of Glacier No.74 was 29.2 m a^{-1} in 1964–2003, and it increased up to 35.0 m a^{-1} in 2003–2009. The glacier lost about 14.7% of its area from 1964 (9.55 km^2) to 2009 (8.15 km^2) with a retreat rate of 0.031 km^2 a^{-1}. The glacier area decreased at the rate of 0.033 km^2 a^{-1} in 1964–2003 and 0.031 km^2 a^{-1} in 2003–2009, respectively. For Keqikekuzibayi Glacier, the terminus retreated at the rate of 22.9 m a^{-1} with the area loss of 6.8% (0.041 km^2 a^{-1}) from 1964 to 2007. The retreat rate was 22.8 m a^{-1} (0.039 km^2 a^{-1}) in 1964–2003 and 23.6 m a^{-1} (0.063 km^2 a^{-1}) in 2003–2007. Field survey showed that the terminus and area retreat rate of Tomor Glacier was lower than the three glaciers above, but the retreat still tended to accelerate. From 1964 to 2009, the area of Tomor Glacier reduced by 0.3% (0.021 km^2 a^{-1}) of the value in 1964 with the terminus retreat of 3.0 m a^{-1}. The retreat rates were 2.9 m a^{-1} and 3.5 m a^{-1} in 1964–2003 and 2003–2009, respectively. The area decrease varied from the rate of 0.020 km^2 a^{-1} in 1964–2003 to 0.025 km^2 a^{-1} in 2003–2009. Keqikar Glacier advanced or remained stationary for three periods: 850 m advance for 1942–1976; stationary for 1976–1981; stationary or 2 m slight advance for 1985–1989 (Wang and Su, 1984; Su et al., 1985; Xie et al., 2007). The terminus retreated since the 1980s, with the retreat rate of 4 m a^{-1}, 18 m a^{-1}, 20 m a^{-1} and 30 m a^{-1} for 1981–1985, 1989–1999, 1999–2002 and 2003–2005, respectively (Zhu, 1982; Wang, 1987; Xie et al., 2007). The thickness of the ice tongue decreased with a speed of 0.5–1.5 m a^{-1} during 1981–2004 by comparison of repeated radio echo sounder data (Xie et al., 2007). Qiongtailan Glacier has retreated 600 m with the rate of 17.6 m a^{-1} during 1942–1976 (Su et al., 1985). It retreated by 858 m with the rate of 22 m a^{-1} for 1964–2003.

The six glaciers showed continuous terminus retreat and area loss, although the change is complicated for Keqikar Glacier (Fig.2; Table 2). The retreat rate of Glacier No.72 was higher than the others with a dramatically increased rate.

4.2. Relationship between glacier change and climate fluctuation

The temperature and precipitation changes were recorded by 5 meteorological stations in the Tomor region of Tian Shan. Fig. 3 presents the trends in temperature and annual precipitation over

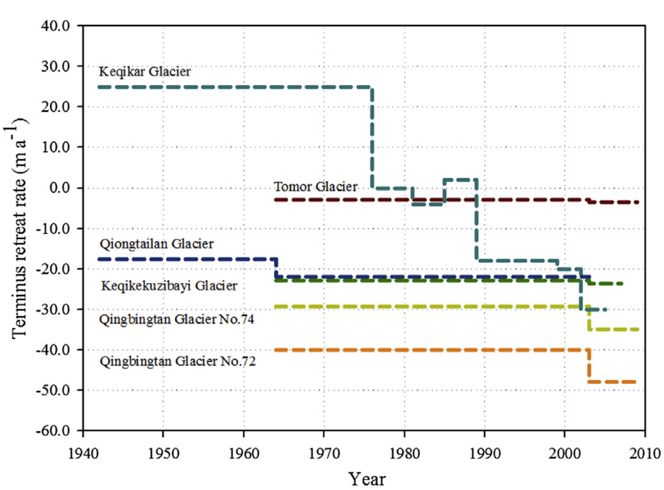

Fig. 2. Terminus retreat of the six selected glaciers in the Tomor region, plotted in dashed lines with different colors.

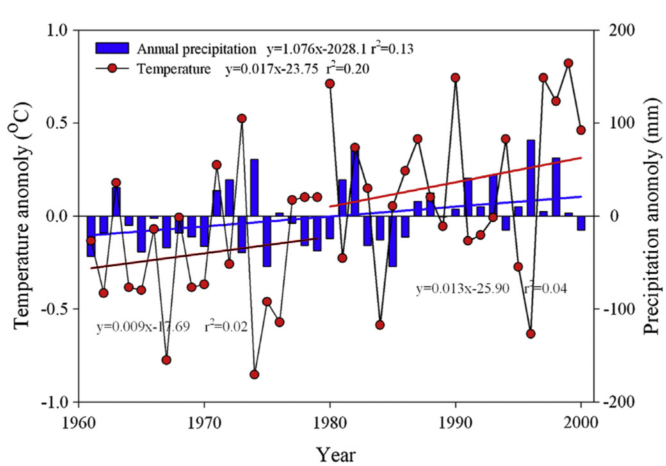

Fig. 3. Mean temperature and annual precipitation recorded at the five meteorological stations in the study area over the period 1961-2000, and linear fit to the data.

Table 2
Changes of terminus, area and ice thickness for the six selected glaciers during the past ~50 years.

Glacier	Terminus change			Area change			Ice thickness change		
	Period	m a^{-1}	Sources	Period	km^2 a^{-1}	Sources	Period	m a^{-1}	Sources
Qingbingtan	1964–2003	−40.1	This study	1964–2003	−0.034	This study	1964–2008	−0.22 ± 0.14	This study
Glacier No.72	2003–2009	−48.0	This study	2003–2009	−0.033	This study			This study
Qingbingtan	1964–2003	−29.2	This study	1964–2003	−0.033	This study	–		This study
Glacier No.74	2003–2009	−35.0	This study	2003–2009	−0.031	This study	–		This study
Keqikekuzibayi	1964–2003	−22.8	This study	1964–2003	−0.039	This study	–		This study
Glacier	2003–2007	−23.6	This study	2003–2007	−0.063	This study	–		This study
Tomor Glacier	1964–2003	−2.9	This study	1964–2003	−0.020	This study	–		This study
	2003–2009	−3.5	This study	2003–2009	−0.025	This study	–		This study
Keqikar Glacier	1942–1976	25.0	Su et al., 1985	–			1981–2004	0.5–1.5	Xie et al., 2007
	1976–1981	0.0	Wang and Su, 1984	–					
	1981–1985	−4.0	Zhu, 1982; Wang, 1987	–					
	1985–1989	0 or 2	Xie et al., 2007	–					
	1989–1999	−18.0	Xie et al., 2007	–					
	1999–2002	−20.0	Xie et al., 2007	–					
	2003–2005	−30.0	Xie et al., 2007	–					
Qiongtailan	1942–1976	−17.6	Su et al., 1985	–			–		
Glacier	1964–2003	−22.0	This study	1964–2003	−0.119	This study	–		

the period 1961–2000. The trend indicated that the temperature for the study region had significantly increased at the rate of 0.17 °C $(10a)^{-1}$ and was statistically significant at the 0.01 level checked by Mann–Kendall test, which was consistent with the climate change in Xinjiang Uygur Autonomous Region (Shi et al., 2007). As Fig. 3 shows, two time periods with different increase rates have been roughly identified, i.e. 1961–1979 with 0.09 °C $(10a)^{-1}$ and 1980–2000 with 0.13 °C $(10a)^{-1}$. The records at the five stations displayed a gradual increase in annual precipitation during the corresponding period with the average rate of 10.8 mm $(10a)^{-1}$, and the trend was also statistically significant.

Changes of the glaciers in the study area were predominantly influenced by temperature and annual precipitation. Climate warming and increasing precipitation had been reported at most stations in northwestern China, and there was a notable regional change from warm and dry to warm and wet in 1978 owing to the westerly circumfluence (Shi et al., 2007). Increasing temperature leads to an increased amount of energy available for ice and snow melt, decreased snow accumulation (and increased portion of liquid precipitation), and lower albedo of the glacier surface, which comes from the albedo difference between snow and ice. Temperature increase leads to an ELA rise and therefore to more snow-free ice, which caused the decrease of the overall albedo of the glacier (Ageta and Kadota, 1992; Fujita and Ageta, 2000; Dikich and Hagg, 2004; Hagg and Braun, 2005). The increase of precipitation provided good conditions for the glacier accumulation. However, the increase of temperature probably caused the increase of liquid precipitation instead of solid precipitation in the high-altitude glaciated area, leading to the reduction of glacier accumulation and the acceleration of ablation. Although increased precipitation has occurred since the late 1990s, it has not halted the glacier retreat as ablation has exceeded accumulation.

In warmer condition, as the equilibrium-line altitude increases, the ice thickness becomes thinner, and the ice velocity changes. As glaciers become thinner, narrower and shorter, changes of internal and upper surface morphology occur, providing evidence of the response to climatic warming. These changes may become evident on higher parts of the glaciers.

With the intensive ablation, the morphologic feature of Glacier No.72 changed correspondingly. Recent observations of widespread supraglacial rivers and lakes at Glacier No.72 are indicative of the effects of a warming climate. Streams are common on the glacier tongue because of the high rate of ablation, and these will cause further ablation, erosion and disintegration of the glacier surface (e.g. the disintegration of the southeast corner from the glacier terminus during 2008–2009). There is a large meltwater pool on the tongue of Glacier No.72 and the area of the pool showed an increase in the recent years. Moreover, ice pillars are widespread on the glacier tongue as a result of differential ablation. Crevasses are widely distributed on the surface of the glacier. Based on the field investigation, the crevasses are broadening, caused by intensive ablation at the glacier surface accompanied by substantial erosion by englacial water. A large amount of water is found to surge from sub-glacier channels, and braided streams have been well developed near the glacier tongue. Changes of englacial flow within the glacier result in further erosion (Fig. 4).

4.3. Impact of topographical factors on spatial differences of glacier change

It is well known that mountain glaciers are widely recognized as excellent indicators of climate change over recent centuries (Haeberli and Hoelzle, 1995). Most of the glaciers in the world show a decreasing trend over the twentieth century, and substantial and statistically significant change started in 1988, which can be considered as a shift in glacier regime at the global scale with no delay to a new mode of global climate (Dyurgerov, 2003). Changes of the six glaciers are synchronous to this trend. Highest mass change was found for the six glaciers in the lower elevations, which is typical for retreating mountain glaciers and was also present in the Western Himalaya (Berthier et al., 2007). Although changes of glacial area were little different, there was an obvious difference in the terminus retreat with the fastest retreat rate by Glacier No.72 (41 m a^{-1}). However, its surface lowering is quite moderate. Assuming that the surface changes in the accumulation area are smaller, the mean lowering for the whole glacier would also be considerably smaller than 0.22 m a^{-1}. By comparison, the thinning rate of Keqikar Glacier appears to be very similar to the observations of Ürümqi Glacier No. 1, the thickness of which reduced nearly 12 m (~0.26 m a^{-1}) during 1958–2004 (Li et al., 2008). For Akshiirak glaciers in Central Tian Shan, the rate of glacier thinning is about 0.24 ± 0.12 m a^{-1} (1943–1977) and 0.69 ± 0.37 m a^{-1} (1977–2003), respectively (Aizen et al., 2007b).

The topographic features of the glaciers have crucial impact on their dynamics, which can result in adjacent glaciers showing different specific mass-balance responses to climatic change (Kuhn et al., 1985). All the topographical factors jointly influence the glacier response to climate change.

Fig. 4. ice streams (left) and sub-glacier channel (right) on Qingbingtan Glacier No.72, 2008.

Firstly, melt rates of glaciers are strongly influenced by the existence of a debris cover. One of the most common characteristics of the Tomor region is the presence of debris masking a large portion of the tongues (Mountaineering and Expedition Term of Chinese Academy of Science, 1985; Shi et al., 2005; Li et al., 2010a,b). The distribution of debris will provide an important basis for the glacier change and application of the melting mode (Ohmura, 2001). In Central Asia, glacier degradation is accompanied by increasing debris cover on many glacier termini and the formation of glacier lakes (Ageta et al., 2000). In general, the debris cover partially or completely masks the tongue of a glacier by medial moraines converging downglacier and forming a continuous debris cover, or by rock falls from the surrounding slopes and therefore significantly influences the energy balance. It also partially controls the ablation rate and the discharge of meltwater (Nakawo et al., 2000). A general increase in debris cover over time was observed in Central Asia (e.g. Ageta et al., 2000; Benn et al., 2005; Owen and Benn, 2005; Shroder et al., 2006).

Observation indicates that Glacier No.72 is laterally debris-covered (Fig. 1), which accounts for 16% of the total glacier area. The thickness of debris is constantly thin, with the average value of ~10 cm. It was nearly debris free in the central part of the tongue. In the horizontal direction, debris in the west side of the glacier is thicker than the east side. Due to the different thickness of the debris cover in the tongue area, glacier melt rate was also different. In order to analyze the differences, ablation of Glacier No.72 was measured from 29 June, 2008 to 1 September, 2008 at six stakes that were placed into the ice using a steam drill at the altitude of 3950 m. Fig. 5 shows the relation between the thickness of debris and glacier ablation. At the six ablation stakes with varying debris thickness from bare ice to 45 cm, mean melt rate from 1.2 to 5.9 cm d^{-1} has been observed. Observations of ice ablation under a debris layer suggest that a very thin debris cover may accelerate melting, while an increasing thickness of debris, when in excess of a threshold thickness, inhibits melting. This agrees well with findings from other investigations (Østrem, 1959; Loomis, 1970; Fujii, 1977; Mattson et al., 1993; Hagg et al., 2008). The hyperbolic dependence between debris thickness and melt was theoretically explained by Khodakov (1972) and experimentally confirmed by many researchers, but the critical thickness found in literature range from 2 cm on Dome glacier in the Canadian Rockies (Mattson, 2000) to 7–8 cm on Djankuat glacier, Caucasus (Popovnin and Rozova, 2002). As soon as the debris cover reaches a thickness of about 1.5–2 m, ice melt practically stops (Hagg et al., 2008). Specifically, a sharp in ablation with debris thickness from 0 to 4 cm is followed by a decrease in ablation with thickness beyond 4 cm for Glacier No.72 (Fig. 5).

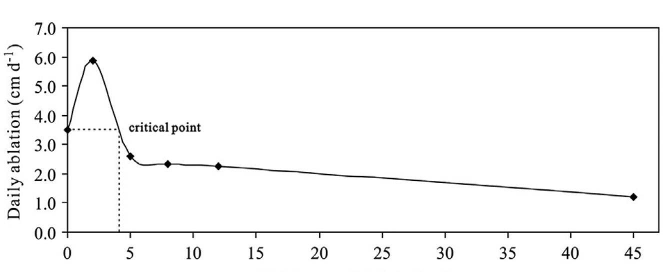

Fig. 5. Correlation between the thickness of debris and glacier daily ablation. The rhombuses represent the observation of six ablation stakes.

The tongue of Glacier No.74 is almost completely debris-covered accounting for 31% of the total area with the average thickness of ~15 m. The thickness of debris increases downwards and reaches the maximum at the snout. Moreover, the uneven debris cover is thin in the middle and thick in the both sides of the glacier. It is difficult to measure debris thickness of Keqikekuzibayi Glacier and Tomor Glacier because of their large areas. Therefore, observation of debris thickness was only carried out at the glacier terminus. The debris thickness of both glaciers is relatively thicker than Glacier No.72 and Glacier No.74, which is an essential component influencing the changes of glacier front. Tomor glacier has thickest and most widespread supraglacial debris. For the overall distribution from the remote sensing data, the debris of Tomor Glacier is concentrated in the tongue with the area of 48.53 km^2, which accounts for 15.6% of the glacier area. Below such thick debris cover, ice melt is practically stopped and the surfaces of such snouts are very stable. Supraglacial debris covers 83% of the total ablation area of Keqikar Glacier, with thicknesses ranging from <0.01 m on the upper reach of the ablation area and on ice cliffs to >2.0 m near the terminus (Han et al., 2006).

Three different sites with debris cover of ~8, ~15 and ~21 cm were chosen to make an experiment. A considerable difference in energy supplied to the base of the debris layer in the three cases, 26.9, 9.8 and 6.9 W m^2, respectively by the theoretical calculations of heat transfer (Han et al., 2005; Zhang et al., 2007). Wang (1987) reported that, at locations around 4000 m a.s.l. on Qiongtailan Glacier, ice ablation was 20–30% less under a 10 cm thick debris cover, and about 50% less under a 20 cm thick debris cover, than under a clean ice layer. The above implies that, compared with glaciers covered by clean ice and snow, glaciers with extensive supraglacial debris cover may be more stable against the warming climate, in terms both of dimensions (length, area and thickness) and of meltwater production.

Secondly, glacier initial area is a key factor to influence glacier response to climate change and plays an important role in the subsequent shrinkage process (Xu et al., 2010). In this case, the higher rates of surface loss are associated with smaller glaciers. This finding highlights the marked sensitivity of the smaller glaciers (which usually have a reduced altitude range) to changes in the main climatic factors, which always exhibit a strong vertical gradient and thus control the accumulation and ablation processes (Jóhannesson et al., 1989; Knight, 1998; Nesje and Dahl, 2000). Moreover, the response time of small glaciers is slower than for large glaciers (Oerlemans, 2005). As seen from the case of the six glaciers, the relative slow change of the Tomor glacier is also significantly affected by the initial large glacial area.

Thirdly, the slope of a glacier is another important factor influencing the glacier's response to the climate change (Haeberli, 1990; Hoelzle et al., 2003). At a steep glacier with positive mass balance, the excessive ice can be transferred rapidly from the accumulation area to the ablation area. For a negative mass balance, the steep slope can also cause high velocity, and the ice moves rapidly from the accumulation area to ablation area to be eventually lost (Xu et al., 2010). In both situations, steep glaciers have a quicker response to climate change than gentle glaciers. The slopes of the whole glacier areas were calculated using the DEM. The slopes of Glacier No.72 ($\sim 25^{\circ}$) were slightly steeper than the others, implying a more dynamic response. Hoelzle et al. (2003) examined area classes of 90 glaciers worldwide and also suggested that large flat glaciers have weak fluctuations, while small steep glaciers have high-frequency and large-amplitude variability. The area distribution with altitude may also have an impact on the glacier response to climate change (Kuhn et al., 1985; Barry, 2006). The fraction of the glacier tongue to total glacier length of Glacier No.72 ($\sim$74%) is higher than the others, with a large part of the glacier exposed to strong ablation.

Furthermore, glacier orientation, to a great extent, controls the effects of solar radiation. Exposed bedrock and glacier orientation to the south probably make Glacier No.72 and Glacier No.74 receive more solar insolation. So, it is reasonable to believe that terminus changes of Glacier No.72 and Glacier No.74 were most sensitive, followed by the three other glaciers. Glacier No.72 shows a lowering pattern similar to a debris-free glacier.

In conclusion, there are three typical features of glaciers' response to the climate change in the Tomor region: a) the melting of glaciers was extremely serious. Although the relative area reduction of glaciers was smaller, it exhibited larger absolute loss, such as Tomor Glacier and Keqikekuzibayi Glacier; b) the change rate of glacier area (or terminus) largely depends on thickness of debris cover on the glacier tongue which is accumulated with glacier shrinkage. In terms of glacier melting, changes of glacier volume are determined by area (or terminus) and thickness change. However, it is controlled by the different factors and has its own specific regulations. Debris covered glaciers are common in the Tomor region and the thinning rate is leading a role in the ablation of glaciers. The thickness of glaciers had become reduced (based on ground penetrating radar data, e.g. Qingbingtan Glacier No.72 and Qingbingtan Glacier No.74); and c) the temperature increase has an important influence on the lower valley glaciers. The type of valley glacier had occupied a very major part in this region, in the bottom of the valley with a lower terminus altitude, more sensitive to climate change.

Li et al. (2010) estimated that the total glacier area of 483 glaciers (1964–2003) in the Tomor region has decreased by 8.8% from 1964 (2267.71 km^2) by comparing aerial photographs, topographic maps and remote sensing images. The area reduction is 0.42 km^2 for individual glacier and the terminii have an average retreat rate of 6.2 m a^{-1}. Considering that these debris-covered glaciers in the Tomor region have been in a state of rapid melting during recent decades, it can be speculated that in the future the glacier retreat will be enhanced in response to the increase of temperature, directly resulting in the temporary increase of significant glacial runoff and final losses. Such glacial runoff is of vital significance to water resources in the Tomor region where the water supply is extremely limited, directly affecting human activities and environmental preservation efforts. Of 26 large rivers in Xinjiang Uygur Autonomous Region, 18 that originate in the Altai Shan, the Tian Shan, the east Pamirs and Karakoram have experienced runoff increases of 5–40% over the period 1987–2000 compared to 1956–1986 (Zhang et al., 2003). This increase is very evident in rivers from the south slope of the southwestern Tian Shan (Zhang et al., 2003). With exception of the influence of increasing precipitation, significant runoff increases with most rivers could be the result of an increase in glacial runoff, which is directly related to the proportion of glacial runoff supply in a watershed (Yang, 1991). Estimation by a degree-day meltwater model shows the positive anomaly in stream runoff of the Tailan river, a tributary of the Aksu River, can be partly attributed to the increase in glacier runoff (amounting to one-third of the stream discharge) (Liu et al., 2006).

5. Conclusions and future work

In this study, topographic maps, remote sensing image and the field survey data were used to study changes of six selected glaciers over a time period of $\sim$50 years. Shrinkage of the six selected glaciers (Qingbingtan Glacier No.72, Qingbingtan Glacier No.74, Keqikekuzibayi Glacier, Tomor Glacier, Keqikar Glacier and Qiongtailan Glacier) is primarily attributed to the significant increase in temperature. However, behaviors of the six glaciers are different, and depend on the local topographic effects including debris cover, slope, exposition and altitude. It is worthwhile to keep observing the intensive melt situation reflected by these representative glaciers.

With respect to the methodological approach, the combination of field survey with remote sensing, digital terrain information and GIS technology allows for comprehensive study of glacier changes. In order to improve the investigation of glacier changes, two elements must be improved: 1) Most of recent glaciological studies regarding mountain glaciers in Central Asia have concentrated on low altitude changes, however, in order to better understand the individual glacier changes, new data are necessary, especially from the accumulation areas, and 2) new data (e.g. continuous mass balance observation data) and repeated field survey are necessary. In this respect, the ASTER sensor with its along-track stereo capabilities offers the possibility of DEM generation and simultaneous glacier mapping (Kääb et al., 2002; Bishop et al., 2004). This could be the basis for an extensive and long period analysis of glacier changes for the Tomor region. In addition, Qingbingtan glacier No.72, monitored continuously since 2007, was selected as a reference glacier of this region, and further investigations should be done to look at the evolution of the glacier and the driving meteorological forces.

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