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Comparison of changes in glacier area and thickness on the northern and southern slopes of Mt. Bogda, eastern Tianshan Mountains

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ABSTRACT

Rapid shrinkage and dramatic volume loss of the glaciers on Mt. Bogda in the eastern Tianshan Mountains have resulted in water shortages in the surrounding arid regions of China. Understanding ice thickness and its variation is important to the analysis of changes in glacial volume, which are directly related to regional hydrology and water resources. Fan-shaped Diffluence Glacier and Heigou Glacier No. 8 are located on the northern and southern slopes of Mt. Bogda, respectively. In this paper, the spatial distribution of the ice thickness of these two glaciers and the changes in their area and volume are discussed based on a 2009 survey result and comparison to previous investigations. The mean ice thickness of the tongue of Fan-shaped Diffluence Glacier was about 82.3 m and the calculated ice volume was 385.2×10^6 m^3 in 2009. It had thinned by 14 ± 8 m (0.30 ± 0.17 m a^{-1}) from 1962 to 2009, equivalent to an ice volume loss of $65.5 \pm 37.4 \times 10^6$ m^3. The mean ice thickness of the tongue of Heigou Glacier No. 8 was 58.7 m and the calculated ice volume was 115.1×10^6 m^3 in 2009. The tongue of Heigou Glacier No. 8 thinned by 13 ± 6 m (0.57 ± 0.26 m a^{-1}) from 1986 to 2009, which corresponds to an ice volume loss of $25.5 \pm 11.8 \times 10^6$ m^3. The greater thinning and retreat of Heigou Glacier No. 8 than those of Fan-shaped Diffluence Glacier is partially due to topographic characteristics. The difference can be attributed mainly to the greater increase in temperature on the southern slope than on the northern slope.

1. Introduction

The Fifth Assessment Report of the IPCC (IPCC, 2013) demonstrated that global warming has been increasing since the late 1980s. During the past 20 years, ice caps in Antarctica and Greenland, sea ice in the Arctic, and spring snow cover in the northern hemisphere have all been in shrinkage, while glaciers in the world continue to decrease in size. For the eastern Tianshan Mountains, the annual mean temperature and precipitation have experienced an increasing trend at a rate of 0.34 °C (10 a)$^{-1}$ and 11 mm (10 a)$^{-1}$ over the last five decades, respectively. The temperature in the dry seasons (from November to March) has increased significantly at a rate of 0.46 °C (10 a)$^{-1}$ (Wang et al., 2011). Climate warming has left most mountain glaciers, including glaciers in the Tianshan Mountains, in a state of rapid terminus retreat (Li et al., 2006; Aizen et al., 2007; Bolch, 2007; Kutuzov and Shahgedanova, 2009; Narama et al., 2010; Wang et al., 2013, 2014).

Mt. Bogda is the highest peak in the Bogda Mountains, belonging to the eastern Tianshan Mountains, surrounding which are extremely arid regions of China (location shown in Fig. 1). Glacial melt runoff is a very important water source for rivers on both the northern and southern slopes of the mountain. For example, before the 1980s glacial melt water supplied 37.6% of the runoff for the Baiyang River on the northern slope (Kang, 1983) and 49.6% of the runoff for the Heigou River on the southern slope before 1980s (Hu et al., 1990). Due to glacial retreat and excessive exploitation of ground water, the Karez water flow in Turfan basin has decreased in recent decades (Li et al., 2011) (Karez is a ground channel system that is generally used as a water supply for human settlements and irrigation in arid regions; it is also the name of a town in the Turfan basin.). If this continues, the lack of water will result in severe environmental and ecological damage.

Accurate assessment of ice thickness distribution is essential to modeling glacier dynamics (Gudmundsson, 1999). Understanding variation in ice thickness is vital to analyzing changes in glacial volume, since it is directly related to regional hydrology and water resources (Zhang et al., 1985; Sun et al., 2003; Farinotti et al., 2009; Fischer, 2009; Li et al., 2011; Kehrl et al., 2014). Changes in ice thickness can be assessed by comparing the thickness of ice surveyed in different

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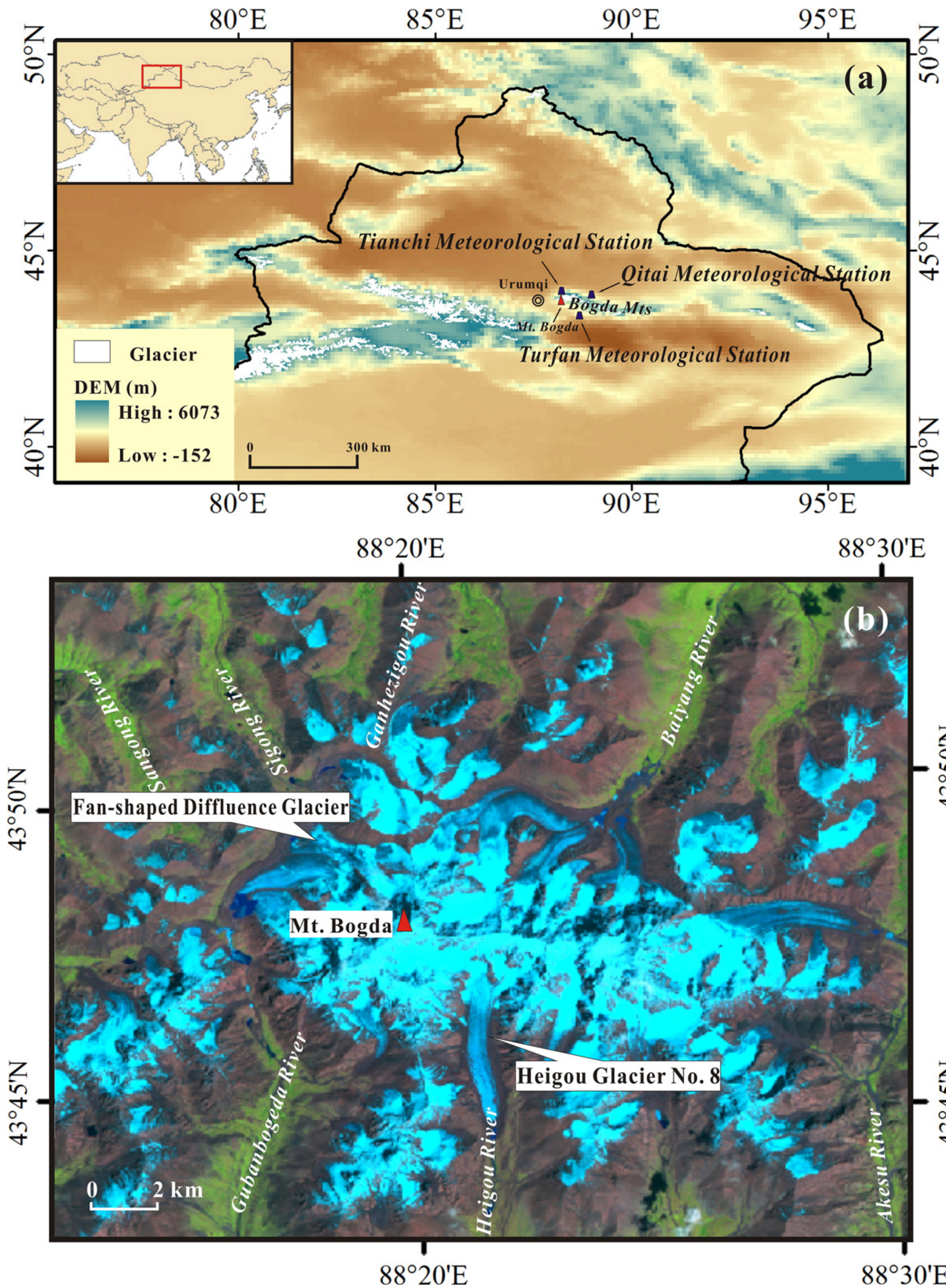

Fig. 1. (a) Location of Mt. Bogda and Bogda Mountains, the eastern Tianshan Mountains, and the related meteorological stations used in this study. (b) Fan-shaped Diffluence Glacier and Heigou Glacier No. 8 in the northern slope and southern slope of Mt. Bogda, respectively. The image is from Landsat ETM+ in 2009.

periods or at different parts of the glacial surface DEMs during different periods. Among the glaciers around Mt. Bogda, several were assessed in the 1980s, but the thickness of the ice was measured only at Heigou Glacier No. 8, which is on the southern slope of the mountain. In 2008 and 2009, ice thickness was measured for the Heigou Glacier No. 8 twice and the results were reported by Wu et al. (2013). Nevertheless, the late two measurements were limited to a smaller range than the earlier measurements. For this reason, the glacier was re-assessed and its thickness was surveyed again by the Tianshan Glaciological Station team in 2009 based on GPR. The Fan-shaped Diffluence Glacier on the northern slope was surveyed during this same season. Besides ice thickness, the surface elevation of the Fan-shaped Diffluence Glacier was surveyed using real-time kinematic (RTK)-GPS. The main objectives of this paper are to (1) present new data for glacial thickness obtained in 2009 and thickness data acquired during previous periods for Heigou Glacier No. 8; (2) analyze the variations in ice thickness and the corresponding changes in glacier volume; (3) compare the variations in glacier between the northern and southern slopes of Mt. Bogda; and (4) discuss possible explanations for observed changes.

2. Regional geography of study area

Located at the center of the arid and semi-arid regions of central Asia, the Tianshan Mountains contain 15,953 glaciers covering a total area of 15,416 km^2 (Liu, 1995; Shi, 2005). The Mt. Bogda region (43°44′–43°53′N, 88°12′–88°29′E) with a peak of 5445 m a.s.l., is the largest glaciated area in the eastern Tianshan Mountains. There are 113 glaciers with an area of 101.42 km^2 at the source of the Sangong River, Sigong River, Ganhezigou River, and Baiyang River in the northern slope and the Gubanbogeda River, Heigou River, and Akesu River on the southern slope. Fifty-four glaciers are located on the northern slope with an area of 44.82 km^2, accounting for 48% of the total number of glaciers and 44% of the glacier area. Fifty-nine glaciers are located on the southern slope with an area of 56.60 km^2, accounting for 52% of the total number of glaciers and 56% of the glacier area (Wang and Qiu, 1983; Wang, 1991). Both sides of Mt. Bogda are controlled by the Mongolia cold high pressure system in the winter, which results in low temperatures, and by the prevailing westerly jet stream position, high above the mountains, in the summer (Wu et al., 1983).

The Fan-shaped Diffluence Glacier (43°48′N, 88°20′E) is located on the northern slope of Mt. Bogda (as shown in Fig. 1). The total area was about 10.94 km^2 and the glacier ablation area was 3.42 km^2, making up 31.30% of the total glacier area (Shi, 2005). Its mass comes mainly from four avalanche troughs; so much of the accumulation area is steep. The upper limit of the glacier is near the peak of Mt. Bogda (5445 m) and the terminus is at about 3620 m a.s.l. The snow line has recently been around 3800–3900 m a.s.l. The glacier is named for the shape of its lower area, part of which flows down southern slope, resembling a fan. The glacier meltwater runs mainly into the Sigong River in the northern slope and part of it flows into the Gubanbogda River in the southern slope. The glacier's terminus is covered by debris and a moraine lake has formed at the glacier's terminus (Zhang and Xie, 1983).

Heigou Glacier No. 8 (43°46′N, 88°23′E) is located on the southern slope of Mt. Bogda (Fig. 1). It is a valley glacier with a long and narrow tongue facing the south and mainly replenished by avalanche from steep slopes. The area of Heigou Glacier No. 8 was 5.71 km^2 and the length was 7.1 km ranging from 5445 m at the top to 3380 m at the terminus as derived from a 1962 topographic map. Field investigation showed that the surface of the glacier tongue was irregular and plenty of superficial waterways were distributed over its surface.

3. Observations and approach

3.1. Radar survey

The thickness of the Fan-shaped Diffluence Glacier and Heigou Glacier No. 8 was surveyed using by ground-penetrating radar (GPR) in August 2009. A pulse EKKO PRO 100A enhanced GPR (Sensors and Software Inc., Mississauga, Canada) and a common-offset geometry with point-measuring mode and 100 MHz resistively loaded dipole antenna were used. The survey was performed on the Fan-shaped Diffluence Glacier from ~3850 m a.s.l to the glacier's terminus, and seven profiles were taken (Fig. 2a). For the tongue area of Heigou Glacier No. 8 (below ~3900 m a.s.l.), five profiles were taken to determine the distribution of the thickness of the ice in the tongue area, including four transverse profiles and one longitudinal profile (Fig. 2b). No measurements were carried out in the upper areas of the two glaciers due to the steep terrain. The transmitting-receiving antennae were arranged parallel to each other at an offset of 4 m and perpendicular to the profile direction. Two-dimensional images were produced. The relative error was estimated to be about 1.18%, which is within the accuracy requirement of glaciology (Sun et al., 2003).

The GPR survey data were analyzed using EKKO View Deluxe software (professional version) (Sensors and Software Inc., 1994). The thickness of the ice at the points of measurement of the different survey profiles for the two glaciers was determined by identification of the ice-rock interface in the radar images (Figs. 3 and 4) and calculation by multiplying radar-wave travel time with the velocity of the radar signal in the glacier (Sun et al., 2003). The velocity of 169 m μs^{-1} was used in this study from Kovacs et al. (1995).

The thickness of the ice of Heigou Glacier No. 8 was first measured in 1986 using an old radar-sounding system (Wang, 1991). During that expedition, the ice thickness of the ice was measured along the four transversal profiles and one longitudinal profile with a total of 68 survey points. The transversal profiles were located at altitudes of 3540 m, 3600 m, 3700 m, and 3840 m. The longitudinal profile was along the central flow line. The measurement error of the depth of the ice from the radar was determined to be within 1 m by comparing the results with concurrent borehole depths (Zhang et al., 1985). In 2008 and 2009, Wu et al. (2013) measured the thickness of the ice of Heigou Glacier No. 8 within a small range below 3690 m a.s.l.

3.2. GPS survey

The surface elevation of the tongue area of the Fan-shaped Diffluence Glacier (below ~3850 m) was surveyed in detail using a Global Positioning System (GPS) device (Unistrong E650) from Beijing UniStrong Science and Technology Co., Ltd. in August 2009. Survey lines are shown in Fig. 5. A real-time kinematic (RTK) differential mode was also used. GPS receivers were placed at fixed base points near the terminus of the glacier, and the rest of the receivers were used to perform manual simultaneous survey on and around the glacier at a sampling space of 20–50 m, with error of the obtained data between 0.10 and 0.30 m (Rivera et al., 2005). For Heigou Glacier No. 8, an RTK-GPS survey was performed to determine the location of the GPR survey profiles and the glacier terminus in 2009. These GPS survey lines are similar to the GPR survey lines shown in Fig. 2b. 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 using Unistrong Landtop software (version 2.0.5.1). The error using seven-parameter model in the space transform model was less than 0.002 m (Wang et al., 2003). A topographic map (1:50,000), derived from aerial photograph acquired in 1962 by the Chinese Military Geodetic Service, was also used in this study to analyze the glacier's terminus and area changes. These data are in the same coordinate system, i.e. BJ54 system. The DEM can be produced by digitizing the contours and spot heights from the topographic map, and then interpolated to a 5 × 5 m grid size.

3.3. Glacier thickness, subglacial topography, and glacier change

In order to determine the distribution of ice thickness of Fan-shaped Diffluence Glacier and Heigou Glacier No. 8, radar data were analyzed using ARCGIS 10.0 software. The value of the ice thickness of the glacier boundary including rock outcrops was assumed to be zero according to Huai et al. (2015). The Kriging interpolation method was used to determine the distribution of the ice thickness of these two glaciers. The ordinary kriging method was used in this study. The spherical semivariogram mode was adopted during the processing. In order to determine the advanced parameters, 5 m was set as the lag size, which is similar to the output raster cell size. Other parameters including major range, partial sill, and nugget, were estimated using the spatial analysis model.

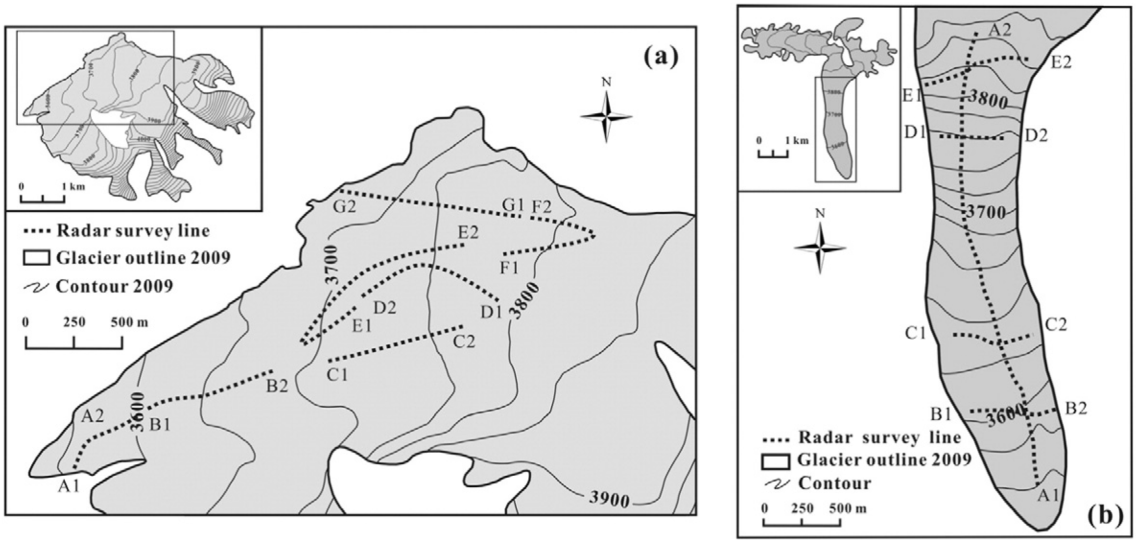

Fig. 2. Ground-penetrating radar survey lines on (a) Fan-shaped Diffluence Glacier and (b) Heigou Glacier No. 8 in 2009.

For the Fan-shaped Diffluence Glacier, the changes in the elevation of the surface of the ice (i.e., ice thickness change) were determined by comparison of the DEMs from 1962 and 2009. The 1962 DEM was established by digitizing the topographic map in 1962 at a scale of 1:50,000 originally derived from aerial photographs. The grid size was 5 m × 5 m. The systematic errors of the topographic map were below ±11 m for slopes below 15° and below ±19 m for slopes greater than 25° (State Bureau of Surveying and Mapping, 2007). First, the topographic map was scanned. Then, the geometry rectification was made, and error was less than one pixel. The 2009 DEM was generated by interpolating from the GPS data using a Kriging method with a resolution of 5 m × 5 m. Comparison was performed at 20 random independent points in the non-glaciated regions around the glacier terminus, and the vertical accuracy of the changes in the elevation of the ice surface of Fan-shaped Diffluence Glacier was estimated within 8 m. This method has been widely used in the previous studies (Raymond et al., 2005; Vanlooy and Forster, 2008; Wang et al., 2012). The subglacial topography of Fan-shaped Diffluence Glacier was obtained by subtracting the ice thickness grid from the 2009 DEM. The variation in the ice thickness of Heigou Glacier No. 8 during the period 1986–2009 was determined by assessing the differences in thickness grids from 1986 and 2009. The changes in terminus and area of the Fan-shaped Diffluence Glacier and Heigou Glacier No. 8 were also determined by comparison of the GPS survey data from 2009 to the topographic map from 1962.

4. Results and discussion

4.1. Ice thickness and subglacial map

The ice thickness distribution of the measured parts of Fan-shaped Diffluence Glacier and Heigou Glacier No. 8 are shown in Fig. 6. The subglacial topographic map of the tongue of Fan-shaped Diffluence Glacier is shown in Fig. 7. Because of the lack of detail in the surveys of surface elevation, the subglacial topographic map of Heigou Glacier No. 8 cannot be given here. The contour interval of ice thickness is 20 m. A closed area in the tongue of Fan-shaped Diffluence Glacier can be seen. There, the ice thickness was the largest at an altitude of ~3730 m (Fig. 3a) and the subglacial topography showed overdeepening (Fig. 7). The ice thickness of the tongue of Fan-shaped Diffluence Glacier (4.68 km^2) ranged from 0 to 221 m, with an average value of about 82.3 m. The calculated ice volume within the measured area of Fan-shaped Diffluence Glacier was 385.2×10^6 m^3, equal to a water equivalent of 346.6×10^6 m^3 assuming the ice density to be 0.9×10^3 kg m^{-3}.

For the tongue of Heigou Glacier No. 8, the ice was thinner towards the upper and lower areas in the longitudinal direction and thickest at the central flowline in the transverse direction. Two large and three small closed areas were found in the tongue area of Heigou Glacier No. 8, indicating the greatest distribution of ice thickness and bedrock depression, which may have been caused by pronounce erosion and glacial dynamic processes on the bedrock (Linton, 1963; Paterson, 1994; Sun et al., 2003). The pattern of ice thickness transversal profiles of Heigou Glacier No. 8 was similar to Urumqi Glacier No. 1 (Sun et al., 2003), from which the U-shaped valley feature can be seen. The ice thickness of the tongue of Heigou Glacier No. 8 (1.96 km^2) was between 0 and 178 m, with a mean value of about 58.7 m. The greatest ice thickness was measured at an altitude of ~3630 m. The calculated ice volume of the tongue of Heigou Glacier No. 8 was 115.1×10^6 m^3, corresponding to a water equivalent of 103.5×10^6 m^3 assuming ice density of 0.9×10^3 kg m^{-3}.

4.2. Changes in glacier area, thickness, and volume

Fan-shaped Diffluence Glacier and Heigou Glacier No. 8 were in a state of intensive thinning, retreat of the terminus, and area shrinkage. By comparison of 1962 DEM and 2009 DEM, the changes in the ice thickness of the Fan-shaped Diffluence Glacier were found to be from −50 to 0 m (Fig. 8a). On average, the ice thinned by 14 ± 8 m (0.30 ± 0.17 m a^{-1}) from 1962 to 2009, corresponding to a loss of volume of $65.5 \pm 37.4 \times 10^6$ m^3 and a water equivalent of $59.0 \pm 33.7 \times 10^6$ m^3 if assuming the ice density to be 0.9×10^3 kg m^{-3}. The glacier area decreased by 7.1% and the terminus retreated by 8.8 m a^{-1}.

As shown in Fig. 8b, the tongue of Heigou Glacier No. 8 below about 3900 m a.s.l. thinned by 13 ± 6 m (0.57 ± 0.26 m a^{-1}) from 1986 to 2009. This thinning corresponded to a loss of volume loss of $25.5 \pm 11.8 \times 10^6$ m^3, equal to a water equivalent of $22.9 \pm 10.6 \times 10^6$ m^3 if assuming an ice density of 0.9×10^3 kg m^{-3}. Wu et al. (2013) concluded that the ice thickness of this glacier decreased at a rate of 0.42 ± 0.56 m a^{-1} from 1969 to 2000 using DEM comparison of a topographic map made in 1969 to satellite images taken in 2000 and concluded a decrease rate of 1.92 ± 0.98 m a^{-1} during 2008–2009 within a small area of this glacier below 3690 m a.s.l. using GPR measurement. The present field observations also showed that the ice thickness has decreased substantially in the accumulation area, as indicated by the exposure of

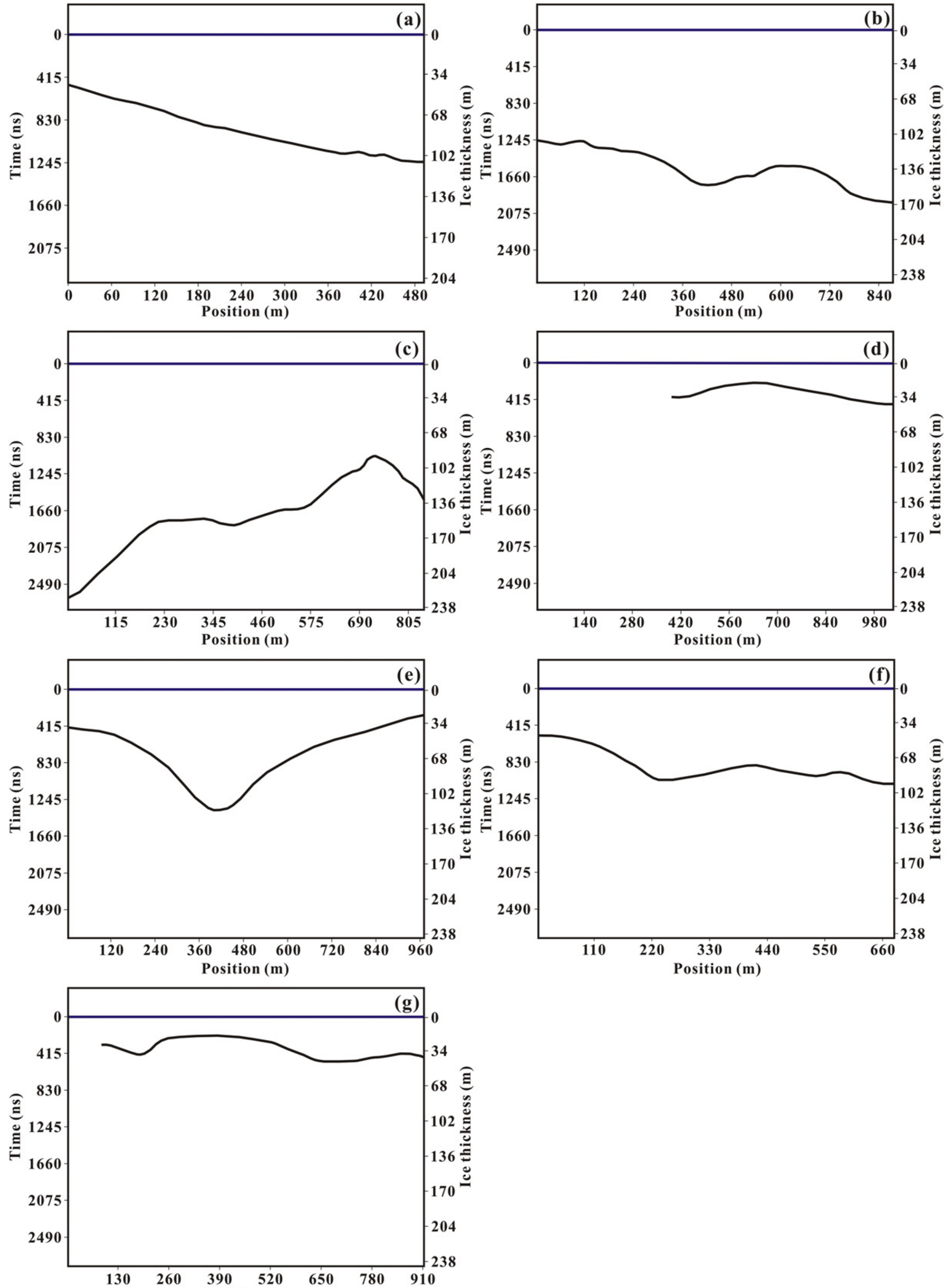

Fig. 3. Ice thickness profiles of Fan-shaped Diffluence Glacier along the survey lines ((a) A1-A2; (b) B1-B2; (c) C1-C2; (d) D1-D2; (e) E1-E2, (f) F1-F2; (g) G1-G2) by the ground-penetrating radar. The horizontal axis is the distance from the starting point of the radar survey (survey lines shown in Fig. 2a). The left and right vertical axes are the two-way travel time and ice thickness, respectively. The radar images of the profiles D1-D2 and G1-G2 are not clear or complete because of the presence of water caused by glacier melting.

fresh bedrock had already been exposed. All these findings indicate that this glacier has been thinning over the past decades, although the research results have various uncertainties. By comparing these observations to the 1962 topographic map, the area of Heigou Glacier No. 8 decreased by 1.3% from 5.71 km^2 to 5.63 km^2, with a terminus retreat of 11.0 m a^{-1} from 1962 to 2009. The changes in the glacier

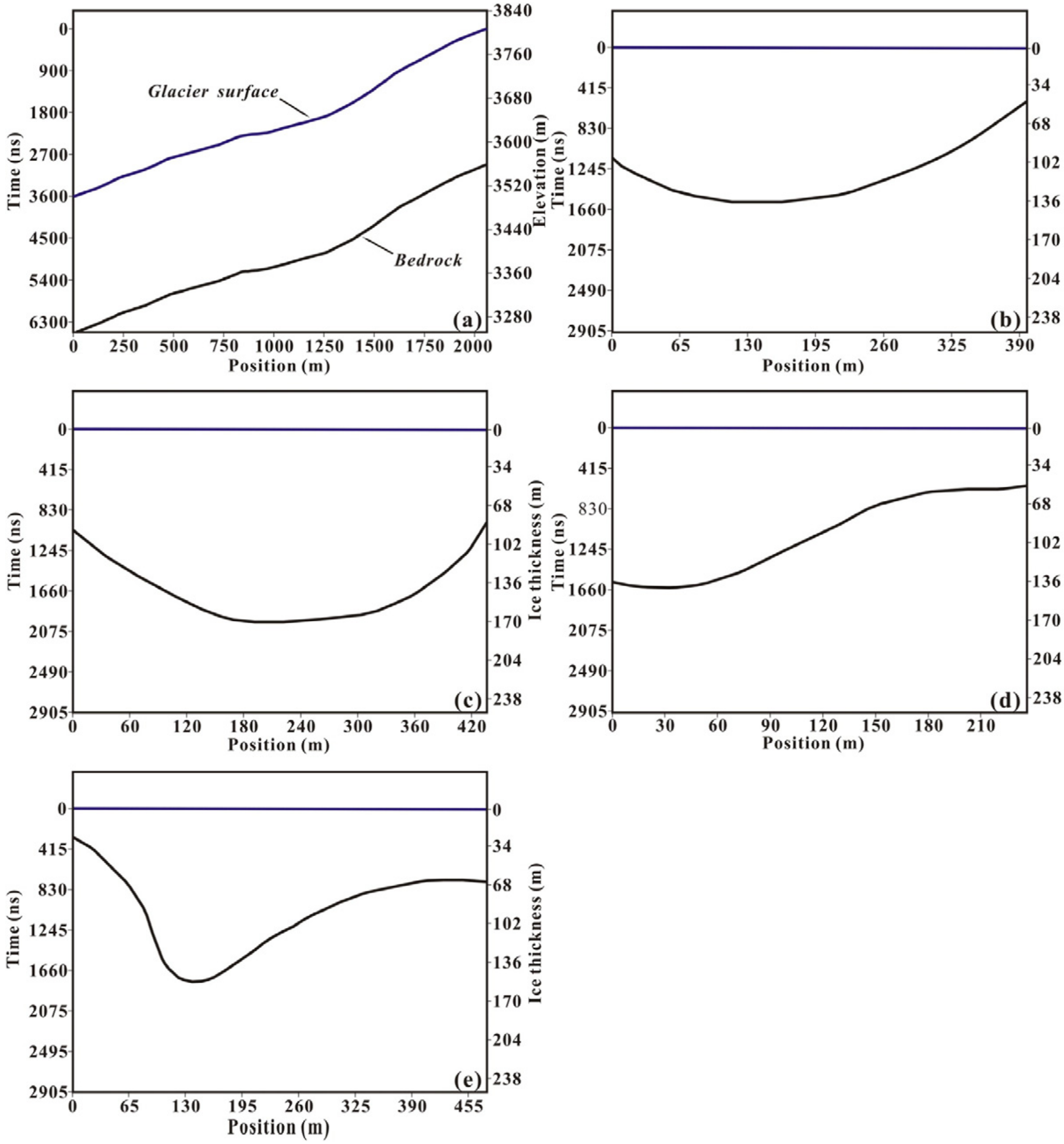

Fig. 4. Ice thickness along the ground-penetrating radar survey lines ((a) A1-A2; (b) B1-B2; (c) C1-C2; (d) D1-D2; (e) E1-E2) on the tongue of Heigou Glacier No. 8 in 2009. The horizontal axis is the distance from the starting point of the survey (survey lines shown in Fig. 2b). The left and the right vertical axes are the two-way travel time and ice thickness, respectively. Moreover, the right axis for (a) A1-A2 is the elevation after calibration.

were dominated by thinning and retreating, evidence of which mainly appeared at the terminus.

4.3. Comparison of glacier changes in the northern and southern slopes

Table 1 lists the measurements taken on the two glaciers named above and of another glacier, Sigong River Glacier No. 4, which is close to Fan-shaped Diffluence Glacier, located to the north. The change in the thickness of Sigong River Glacier No. 4 was obtained by Wang et al. (2012) from the comparison of DEM based on maps made at different times. As shown in Table 1, the retreat of the terminus and thinning of Heigou Glacier No. 8, which is on the southern slope of Mt. Bogda, was more intense than of the Fan-shaped Diffluence Glacier and Glacier No. 4 of Sigong River, which are on the northern slope of Mt. Bogda, even though the area shrinkage rate of Heigou Glacier No. 8 (1.3%) was small. This may have been because of topographic factors, such as the long tongue and low terminus altitude (~3380 m) of Heigou Glacier No. 8. Because of the large area of Fan-shaped Diffluence Glacier, the relatively small change in the area and thickness was associated with a large loss of ice volume.

More glaciers must be investigated to discuss the factors that affect. The results of some remote sensing investigations on glaciers also showed more pronounced shrinkage of glaciers on the southern slopes than on the northern slopes in the Bogda Mountains (Table 1). For example, Z.Q. Li et al. (2010) found that the area of 104 investigated glaciers on the southern slopes decreased by 25.3% from 1962 to 2006, with an average area shrinkage of 0.198 km^2 for individual glaciers and a terminus retreat rate of 4.5 m a^{-1}. However, the area of 99 investigated glaciers on the northern slopes decreased by 16.9%, with average individual glacier shrinkage of 0.107 km^2 and a terminus retreat of 3.6 m a^{-1}.

Climate change is undoubtedly the most important factor affecting changes in glaciers. Many studies have shown that the mass balance of glaciers is more sensitive to temperature than to precipitation, but

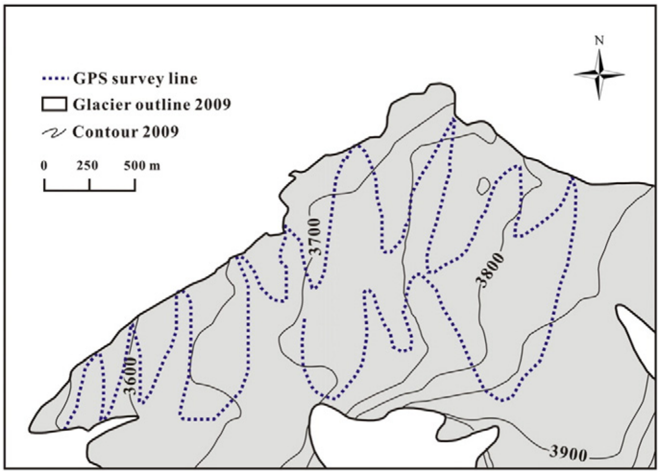

Fig. 5. GPS survey lines on the Fan-shaped Diffluence Glacier.

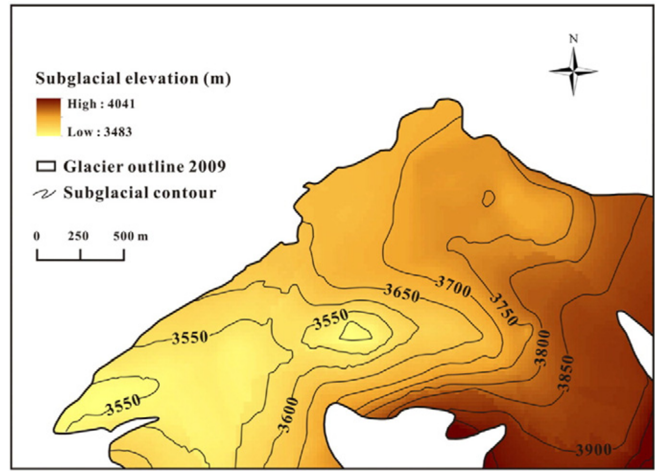

Fig. 7. Subglacial topographic map of the tongue of Fan-shaped Diffluence Glacier obtained by subtracting the ice thickness from the 2009 DEM.

the relative importance of temperature and precipitation differs across various regions due to local climate and topographic conditions (Oerlemans and Reichert, 2000; Anderson et al., 2010; Z.X. Li et al., 2010; Li et al., 2014), although some results have indicate that the mass loss caused by a 1 °C increase in air temperature would be offset by a 25% increase in precipitation typically (Oerlemans, 2005). For the Urumqi River Glacier No. 1, which is not very far from Mt. Bogda, to the west, Wang et al. (2016) reported that a 1 °C increase in temperature would cause a loss of about 400 mm water equivalent mass, nearly the average annual precipitation (400–500 mm) on the glacier (location is shown in Fig. 1). Ma et al. (2010) used data from the Tianchi Meteorological Station (located at a mountain lake with altitude of about 1920 m a.s.l) on the northern slope of Mt. Bogda in 1956–2007 to analyze changes in climate conditions of Mt. Bogda, and results showed that the average temperature increased during those 49 years at a rate of 0.18 °C $(10\ a)^{-1}$, which was consistent with the warming trend observed throughout the Tianshan Mountains in the past five decades. For the larger region, annual temperature and precipitation data from Qitai Meteorological Station to the north of Bogda Mountains and Turfan Meteorological Station to the south of Bogda Mountains are shown for 1959–2002 in Table 2 and Fig. 9 (locations are shown in Fig. 1). The Turfan Meteorological Station data indicates that there has been a rapid increase in air temperature at a rate of 0.42 °C $(10\ a)^{-1}$, which is notably higher than the increase of 0.25 °C $(10\ a)^{-1}$ recorded at the Qitai Meteorological Station. Both these stations are located in desert regions—Turfan Meteorological Station is in an extremely arid basin. There were very large differences in precipitation between the high mountain area and the deserts as well as between the two meteorological stations. Although the Qitai Meteorological Station data showed an obvious increase trend in precipitation with a rate of 24.8 mm $(10\ a)^{-1}$ and the Turfan Meteorological Station showed only a slight increase in precipitation, with a rate of 0.8 mm $(10\ a)^{-1}$, it is still hard to say how precipitation has changed in northern and southern slopes of Mt. Bogda. However, even if it is assumed that precipitation in the high mountain region has increased in past decades and that the increase is more pronounced on the northern slope than on the southern slope, its impact on changes in the glacier have still been found to be less pronounced than increases in temperature as indicated by the results recorded at Urumqi Glacier No. 1 (Wang et al., 2016). The thinning, retreat of terminus, area shrinkage, and volume loss of glaciers can be

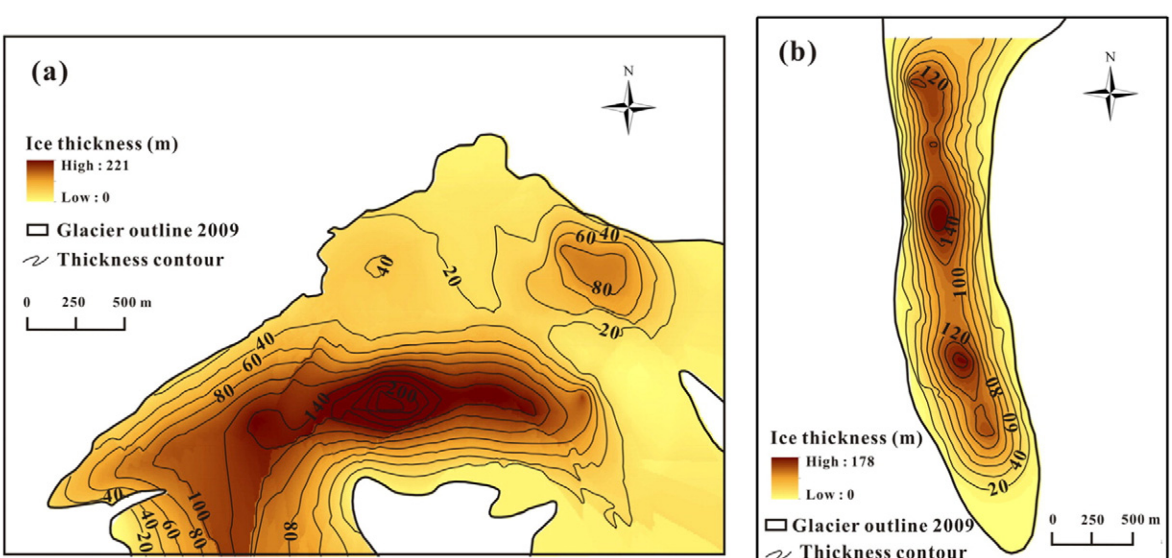

Fig. 6. (a) Ice thickness distribution of the tongues of (a) Fan-shaped Diffluence Glacier and (b) Heigou Glacier No. 8 interpolated from the radar survey data from 2009. The contour interval of ice thickness is 20 m.

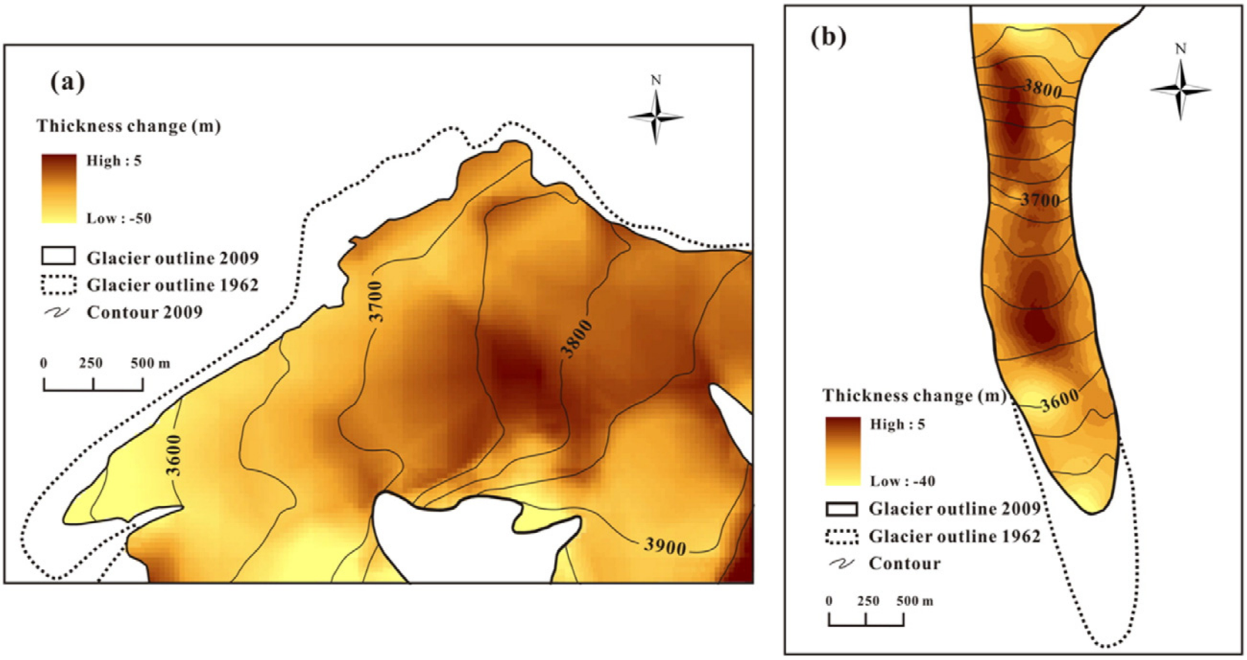

Fig. 8. Changes in the ice thickness of the tongues of (a) Heigou Glacier No. 8 from 1986 to 2009 and (b) Fan-shaped Diffluence Glacier from 1962 to 2009. The changes in terminus and area from 1962 to 2009 are indicated by different types of line.

attributed primarily to the rapid temperature increase in the Mt. Bogda region and the more pronounced increase in temperature may account for more intensive glacier shrinkage on the southern slope than on the northern slope.

5. Conclusion

The survey results showed that the maximum ice thickness of the tongue of Fan-shaped Diffluence Glacier was 221 m in 2009. The average ice thickness of the tongue of this glacier was 82.3 m and the calculated ice volume was 385.2×10^6 m^3, corresponding to the water equivalent of 346.6×10^6 m^3. It thinned by 14 ± 8 m (0.30 ± 0.17 m a^{-1}) during 1962–2009, corresponding to an ice volume loss of $65.5 \pm 37.4 \times 10^6$ m^3 and a water equivalent of $59.0 \pm 33.7 \times 10^6$ m^3. The glacier area decreased by 7.1% and the terminus retreated by 8.8 m a^{-1}.

The interpolation results showed that the maximum thickness of the tongue of Heigou Glacier No. 8 was 178 m with an average thickness of 58.7 m and an ice volume of 115.1×10^6 m^3, corresponding to a water equivalent of 103.5×10^6 m^3 in 2009. During the period 1986–2009, the tongue of Heigou Glacier No. 8 thinned by 13 ± 6 m with an average annual thinning of about 0.57 ± 0.26 m. The resulting ice volume loss reached $25.5 \pm 11.8 \times 10^6$ m^3 and the supply of glacier melt water to the runoff was $22.9 \pm 10.6 \times 10^6$ m^3 at minimum. The glacier area decreased by 1.3% from 5.71 to 5.63 km^2, with the terminus retreat of 11.0 m a^{-1} from 1962 to 2009.

The finding that the shrinkage of Heigou Glacier No. 8 was more pronounced than that of the Fan-shaped Diffluence Glacier was partially due to its long tongue and low terminus altitude. Remote sensing investigation of glaciers in the Mt. Bogda region also showed more shrinkage on the southern slope than on the northern slope. Because temperature is the most important factor influencing changes in glaciers on the regional scale, this difference in glacier shrinkage between the northern and southern slopes could be attributed to the more pronounced increase in temperature on the southern slope than in the northern slope. In view of large spatial variability of precipitation and lack of meteorological data for the mountain area, it is difficult to assess the impact of precipitation on change in glaciers in the region, although the effect of precipitation is believed to be less pronounced than that of temperature.

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Table 1
Changes in glaciers on the northern and southern slopes of the Bogda Mountains.

Region	Glacier	Glacier change							Source
		Area change		Terminus change		Thickness change		Volume change	
		Period	(%)	Period	(m a^{-1})	Period	(m a^{-1})	(10^6 m^3)	
Northern slope of Mt. Bogda	Fan-shaped Diffluence Glacier	1962–2009	−7.1	1962–2009	−8.8	1962–2009	0.30 ± 0.17	65.5 ± 37.4	This study
	Glacier No. 4 of Sigong River	1962–2009	−15.8	1962–2009	−8.0	1962–2009	0.32 ± 0.17	14.0 ± 8.0	Wang et al. (2012)
	99 glaciers	1962–2006	−16.9	1962–2006	−3.6	–			Z.Q. Li et al. (2010)
Southern slope of Mt. Bogda	Heigou Glacier No. 8	1962–2009	−1.3	1962–2009	−11	1986–2009	0.57 ± 0.26	25.5 ± 11.8	This study
	104 glaciers	1962–2006	−25.3	1962–2006	−4.5	–			Z.Q. Li et al. (2010)

Table 2
Changes in temperature and precipitation from Qitai Meteorological Station and Turfan Meteorological Station during the period 1959–2002. Data are from China meteorological data sharing service system (http://cdc.cma.gov.cn).

Station	Location	Elevation (m a.s.l.)	Mean annual temperature (°C)	Rate of increase (°C $10a^{-1}$)	Mean annual precipitation (mm)	Rate of increase (mm $10a^{-1}$)
Qitai Meteorological Station	44°01′N, 89°34′E	794	5.2	0.25	193.1	24.8
Turfan Meteorological Station	42°56′N, 89°12′E	345	14.4	0.42	16.3	0.8

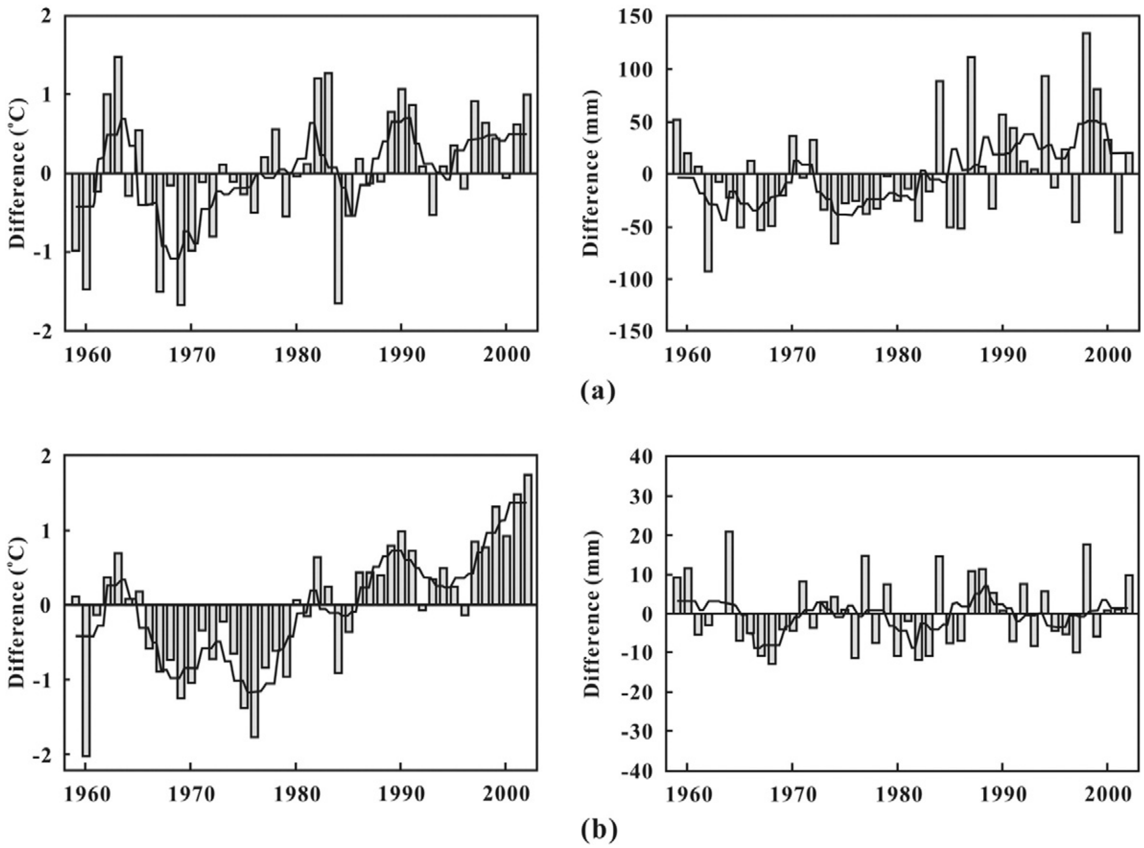

Fig. 9. Annual temperature and precipitation anomalies relative to the average over the period 1959–2002 at (a) Qitai Meteorological Station and (b) Turfan Meteorological Station.

References

Aizen, V.B., Kuzmichenok, V.A., Surazakov, A.B., Aizen, E.M., 2007. Glacier changes in the Tien Shan as determined from topographic and remotely sensed data. Glob. Planet. Chang. 56, 328–340.

Anderson, B., Mackintosh, A., Stumm, D., George, L., Kerr, T., Winter-Billington, A., Fitzsimons, S., 2010. Climate sensitivity of high-precipitation glacier in New Zealand. J. Glaciol. 56 (195), 114–128.

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.

Farinotti, D., Huss, M., Bauder, A., Funk, M., Truffer, M., 2009. A method to estimate the ice volume and ice-thickness distribution of alpine glaciers. J. Glaciol. 55 (191), 422–430.

Fischer, A., 2009. Calculation of glacier volume from sparse ice-thickness data, applied to Schaufelferner, Austria. J. Glaciol. 55 (191), 453–460.

Gudmundsson, G.H., 1999. A three-dimensional numerical model of the confluence area of Unteraargletscher, Bernese Alps, Switzerland. J. Glaciol. 45 (150), 219–230.

Hu, X.G., Li, N.J., Deng, S.M., 1990. Glacier meltwater runoff on the south slope of the Bogeda Mt.—taking the Heigou as an example. J. Glaciol. Geocryol. 12, 71–82.

Huai, B.J., Li, Z.Q., Wang, F.T., Wang, W.B., Wang, P.Y., Li, K.M., 2015. Glacier volume estimation from ice-thickness data, applied to the Muz Taw glacier, Sawir Mountains, China. Environ. Earth Sci. 74, 1861–1870.

IPCC, 2013. Working Group I contribution to the IPCC fifth assessment report (AR5). Climate change 2013: the physical science basis. http://www.climatechange2013.org/.

Kang, E.S., 1983. Glacial meltwater runoff on the north flank of Mt. Bogda in Tianshan and its contribution to river flow. J. Glaciol. Geocryol. 5, 113–122.

Kehrl, L.M., Hawley, R.L., Osterberg, E.C., Winski, D.A., Lee, A.P., 2014. Volume loss from lower Peyto Glacier, Alberta, Canada, between 1966 and 2010. J. Glaciol. 60 (219), 51–56.

Kovacs, A., Gow, A., Morey, R., 1995. The in-situ dielectric constant of polar firn revisited. Cold Reg. Sci. Technol. 23, 245–256.

Kutuzov, S., Shahgedanova, M., 2009. Glacier retreat and climatic variability in the eastern Terskey-Alatoo, inner Tien Shan between the middle of the 19th century and beginning of the 21st century. Glob. Planet. Chang. 69 (1–2), 59–70.

Li, B.L., Zhu, A.X., Zhang, Y.C., Pei, T., Qin, C.Z., Zhou, C.H., 2006. Glacier change over the past four decades in the middle Chinese Tien Shan. J. Glaciol. 52 (178), 425–432.

Li, Z.Q., Li, K.M., Wang, L., 2010. Study on recent glacier changes and their impact on water resources in Xinjiang, North Western China. Quat. Sci. 30 (1), 96–106.

Li, Z.X., He, Y.Q., Pu, T., Jia, W.X., He, X.Z., Pang, H.X., Zhang, N.N., Liu, Q., Wang, S.J., Zhu, G.F., Wang, S.X., Chang, L., Du, J.K., Xin, H.J., 2010b. Changes of climate, glaciers and runoff in China's monsoonal temperate glacier region during the last several decades. Quat. Int. 218, 13–28.

Li, K.M., Li, Z.Q., Gao, W.Y., Wang, L., 2011. Recent glacial retreat and its effect on water resources in eastern Xinjiang. Chin. Sci. Bull. 56 (32), 2708–2716.

Li, Z.X., Feng, Q., Liu, W., Wang, T.T., Chen, A.F., Gao, Y., Guo, X.Y., Pan, Y.H., Li, J.G., Guo, R., Jia, B., 2014. Study on the contribution from cryosphere to runoff in the cold Alpine Basin: a case study of Hulugou River Basin in the Qilian Mountains. Glob. Planet. Chang. 122, 345–361.

Linton, D.L., 1963. The forms of glacial erosion. Inst. Brit. Geogr. Trans. 3, 1–28.

Liu, C., 1995. Glacier resources and distributive characteristics in the Central Asia Tianshan Mountains. J. Glaciol. Geocryol. 17 (3), 193–203.

Ma, H.L., Ma, Y., Xue, F.M., 2010. Variation characteristics of climate change at Tianchi in Tianshan Mountains in recent 49 years. Meteorol. Sci. Technol. 38 (2), 209–213.

Narama, C., Kääb, A., Duishonakunov, M., Abdrakhmatov, K., 2010. Spatial variability of recent glacier area changes in the Tien Shan Mountains, Central Asia, using Corona (~1970), Landsat (~2000), and ALOS (~2007) satellite data. Glob. Planet. Chang. 71 (1–2), 42–54.

Oerlemans, J., 2005. Extracting a climates signal from 169 glacier records. Science 308, 675–677.

Oerlemans, J., Reichert, B.K., 2000. Relating glacier mass balance to meteorological data by using a seasonal sensitivity characteristic. J. Glaciol. 46 (152), 1–6.

Paterson, W.S.B., 1994. The Physics of Glacier. third ed. Pergamon Press, Oxford.

Raymond, C., Neumann, T.A., Rignot, E., Echelmeyer, K., Rivera, A., Casassa, G., 2005. Retreat of Glaciar Tyndall, Patagonia, over the last half-century. J. Glaciol. 51 (173), 239–247.

Rivera, A., Casassa, G., Bamber, J.L., Kääb, K., 2005. Ice elevation changes of Glaciar Chico, southern Patagonia, using ASTER DEMs, aerial photographs and GPS data. J. Glaciol. 51 (172), 105–112.

Sensors and Software Inc., 1994. Pulse EKKO 100 User's Guide, Version 1.1. Sensors and Software Inc., Mississauga, Ontario.

Shi, Y.F., 2005. Brief of Glacier Inventory of China. Shanghai Popular Science Press, Shanghai.

State Bureau of Surveying and Mapping, 2007. Technical Rules for Producing Digital Products of 1: 10 000 1: 50 000 Fundamental Geographic Information, CH/T1015.1-2007. State Bureau of Surveying and Mapping, Beijing.

Sun, B., He, M.B., Zhang, P., Jiao, K.Q., Wen, J.H., Li, Y.S., 2003. Determination of ice thickness, subice topography and ice volume at Glacier No.1 in the Tianshan, China, by ground penetrating radar. Chin. J. Polar Res. 15 (1), 35–44.

Vanlooy, J.A., Forster, R.R., 2008. Glacial changes of five southwest British Columbia icefields, Canada, mid-1980s to 1999. J. Glaciol. 54 (186), 469–478.

Wang, Z.T., 1991. A discussion on the questions of development of Heigou Glacier No.8, Bogda-peak Region. J. Glaciol. Geocryol. 13 (2), 141–158.

Wang, Y.S., Qiu, J.Q., 1983. Distributive features of the glaciers in Bogda Region, Tian Shan. J. Glaciol. Geocryol. 5 (3), 17–24.

Wang, J.X., Wang, J., Lu, C.P., 2003. Problem of coordinate transformation between WGS-84 and BEIJING54. J. Geod. Geodyn. 23 (3), 70–73.

Wang, S.J., Zhang, M.J., Li, Z.Q., Wang, F.T., Li, H.L., Li, Y.J., Huang, X.Y., 2011. Glacier area variation and climate change in the Chinese Tianshan Mountains since 1960. J. Geogr. Sci. 21 (2), 263–273.

Wang, P.Y., Li, Z.Q., Li, H.L., Cao, M., Wang, W.B., Wang, F.T., 2012. Glacier No.4 of Sigong River over Mt. Bogda of eastern Tianshan, central Asia: thinning and retreat during the period 1962–2009. Environ. Earth Sci. 66, 265–273.

Wang, P.Y., Li, Z.Q., Wang, W.B., Li, H.L., Zhou, P., Jin, S., 2013. 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. Quat. Int. 311, 123–131.

Wang, P.Y., Li, Z.Q., Li, H.L., Wang, W.B., Yao, H.B., 2014. Comparison of glaciological and geodetic mass balance at Urumqi Glacier No. 1, Tian Shan, Central Asia. Glob. Planet. Chang. 114, 14–22.

Wang, P.Y., Li, Z.Q., Li, H.L., Yao, H.B., Xu, C.H., Zhou, P., Jin, S., Wang, W.B., 2016. Analyses of recent observations of Urumqi Glacier s. Environ. Earth Sci. 75, 1–11.

Wu, G.H., Ageta, Y., Qiu, J.Q., 1983. Physical geographic features and climate conditions of glacial development in Bogda area, Tianshan. J. Glaciol. Geocryol. 5 (3), 5–16.

Wu, Z., Liu, S.Y., Zhang, S.Q., Shangguan, D.H., 2013. Accelerated thinning of Hei Valley No. 8 glacier in the Tianshan Mountains, China. J. Earth Sci. 24 (6), 1044–1055.

Zhang, W.J., Xie, Z.C., 1983. Features of accumulation and ablation of existing glaciers on the northern slope of Bogda, Tian Shan and an estimation of their mass balance. J. Glaciol. Cryopedol. 5 (3), 59–70.

Zhang, X.S., Zhu, G.C., Qian, S.L., et al., 1985. Radar measuring ice thickness of No. 1 Glacier at the source of Urumqi River, Tianshan. J. Glaciol. Geocryol. 7 (2), 153–162.