Quaternary Research 81 (2014) 531–537

Contents lists available at ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

# Changes in the glacier extent and surface elevation along the Ningchan and Shuiguan river source, eastern Qilian Mountains, China

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ARTICLE INFO

*Article history:*
Received 6 August 2013
Available online 25 February 2014

*Keywords:*
GPS RTK
Glacier extent
Surface elevation
Qilian Mountains

ABSTRACT

We investigate the changes at nine glaciers in the Ningchan and Shuiguan river source, eastern Qilian Mountains, between 1972 and 2010. According to analysis of topographic maps and multispectral satellite data, all nine glaciers in the study area have retreated, by a maximum of 250 ± 57.4 m and a minimum of 91 ± 57.4 m. The total glacier area decreased by 1.20 $km^2$, corresponding to 9.9% of the glacierized area in 1972. Comparing the two DEMs generated from the topographic maps and Real-Time Kinematic GPS data, the mean glacier thinning rate was 0.64 m $yr^{-1}$ between 1972 and 2010. The most significant thinning generally occurred on the termini. The ice-volume loss was about $106.8 \pm 46.7 \times 10^{-3}$ $km^3$ (equal to $90.8 \pm 39.7 \times 10^{-3}$ $km^3$ w.e.), which suggested a mean water discharge of 0.1 ± 0.05 $m^3$/s during 1972–2010. Based on analysis of meteorological data, the summer temperature (June–August) tends to increase over a similar time period. The consistency of temperature increase and glacier shrinkage allows us to suggest that air temperature plays an important role in glacier changes in this region.

## Introduction

Melting of glaciers and polar ice caps is believed to significantly raise sea levels (Kaser et al., 2006; Meier et al., 2007; Gardner et al., 2013). To understand the changes in glacier length, areal extent and mass balance is thus important for reconstructing past climates and evaluating the contribution of glaciers to modern sea levels (Oerlemans, 2005; Meier et al., 2007; Ohmura, 2011). The key to understanding the mechanisms of glacier variation likely lies in a thorough analysis of glacier response to climate change (Lemke, 2007; Anderson et al., 2008). Glacier meltwater also plays an important role as a source of freshwater in arid and semi-arid areas, where it supports daily life and the development of agriculture, livestock and industry (Yao et al., 2004; Ding et al., 2006; Kaser et al., 2010). Mass loss of glaciers has wide-ranging consequences such as changing runoff distribution (Gao et al., 2012; Zhang et al., 2012), sea-level rise (Radić and Hock, 2011; Jacob et al., 2012) and increasing risk of glacial lake outburst floods (Bolch et al., 2011; Xie et al., 2013).

It has been suggested that the mid-latitude Asian glaciers have retreated continuously since the 1960s as a result of global warming (Liu et al., 2003, 2006; Shangguan et al., 2006; Aizen et al., 2007; Bolch, 2007; Gardner et al., 2013). In addition, Yao et al. (2012) reported ten of the 15 glaciers in the Tibetan Plateau (TP) exhibited a negative mass balance, the most negative being about 1.7 m $yr^{-1}$. Based on the mass balance measurements of the Qiyi, Small Dongkemadi and Kangwure glaciers, the glaciers have shown an accelerating trend of more negative mass balance in recent years (Yao et al., 2012), as also have the Akshiirak glaciers, Tien Shan, Central Asia (Surazakov and Aizen, 2006). However, due to the remote location and wide distribution of these glaciers, ice thickness and ice volume monitoring is sparse. Traditional ground-based techniques have played an essential role in measuring glacier mass balance directly, but they tend to be laborious, expensive and provide very limited spatial coverage (Keutterling and Thomas, 2006; Racoviteanu et al., 2008). Fortunately, studies of glaciers have improved due to novel, rapid and relatively inexpensive techniques such as remote sensing and aerial photography (Paul et al., 2004; Liu et al., 2006), GIS and GPS technologies (Kargel et al., 2005). Several studies have used digital elevation models (DEMs) based on remotely sensed data and GPS technologies to measure changes in glacier surface elevation (e.g. Rivera and Casassa, 1999; Rignot et al., 2003; Berthier et al., 2004; King, 2004; Rivera et al., 2005; Howat et al., 2007; Berthier and Toutin, 2008).

Monitoring the change in glacier area using remote-sensing data indicates that glaciers in the Qilian Mountains have tended to retreat during the past 50 yr (Liu et al., 2003; Ding et al., 2006; Shangguan et al., 2010). Glaciers in the Lenglongling Mountains, eastern Qilian Mountains, are small and their melt will not contribute significantly to global sea level rise. However, they are sensitive indicators of climatic change at a relatively short time scale (a few decades), and they serve as benchmark glaciers for many global applications. Their disappearance might have great economic and societal impacts, for example on

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http://dx.doi.org/10.1016/j.yqres.2014.01.011

the hydrologic regime and tourism in the Hexi Corridor. Pan et al. (2012) determined glacier area change in the western Lenglongling Mountains. Xie et al. (1985) and Liu et al. (1992) showed some glacier termini retreated in the Lenglongling Mountains from 1956 to 1984. Li et al. (2010) estimated an average thinning of 15 ± 8 m for Shuiguan (SG) river source glacier No. 4 using field measurements in 2007 and topographical map data from 1972. These studies are very important for understanding the response of glacier mass balance to climatic change in these areas. However, more data are needed to make a robust estimation. To update research on glacier mass balance in this region, we chose nine glaciers in the Ningchan (NC) and SG river source, which originate in the Lenglongling Mountains. The aim of this study is to gain a better understanding of glacier mass balance in terms of length, area and ice-surface elevation change from 1972 to 2010.

## Study location

The Lenglongling Mountains are located in the northeastern part of the TP (Fig. 1a). The Chinese Glacier Inventory (CGI) (Wang et al., 1981) shows that a total of 244 glaciers occur above 4000 m asl in the Lenglongling Mountains, covering a total area of 103.02 km$^2$ (Fig. 1b). Glaciers in this area are mainly influenced by the combined effects of the East Asian monsoon and the Westerlies (Chen et al., 2008), and are classified as subcontinental-type glaciers (Shi and Liu, 2000). Mean annual air temperature in the period 1980–2010 was about 1.17°C at Menyuan meteorological station (37°23′N, 101°37′E, 2924 m asl). The mean equilibrium line attitude (ELA) in the Lenglongling Mountains is about 4500 m (Wang et al., 1981) and, extrapolating with a standard atmospheric lapse rate of 0.72°C (100 m)$^{-1}$ (Wang et al., 2009), mean annual air temperature at the ELA is about −10.18°C (Pan et al., 2012).

There are ten glaciers in the NC and SG river source, located on the northern slope of the Lenglongling Mountains. The highest peak has an elevation of 5024 m asl. One of the glaciers is a hanging glacier with a terminus altitude of 4580 m asl. All the other glacier terminus altitudes are about 4100–4200 m asl (Wang et al., 1981); the area of these nine glaciers varies and the average area is 1.34 km$^2$. The largest glacier covers more than 3 km$^2$, and the smallest less than 0.5 km$^2$ (Fig. 1c).

## Data and methods

### GPS data

GPS measurement has been applied in glacier research for many years (King, 2004; Elizabeth et al., 2011; Kunz et al., 2012). A GPS-RTK (Real-Time Kinematic) survey of glaciers in NC and SG river source was conducted from 12 to 20 July, 2010 (Table 1) (Fig. 2a). Five Trimble 5800 dual-frequency GPS receivers were used to implement the RTK survey. The points shown in Figure 2a were obtained in RTK mode, with four receivers carried by four researchers, and the fifth receiver (used as the base station for differential correction of post-processing) installed on an outcrop. The survey areas shown in Figure 2 are accessible for fieldwork. The GPS-measured area covers about 38.8% of the total area in 2010.

The precisions of the vertical and horizontal measurements by GPS were about 0.1 m and 0.05 m, respectively. In glacierized areas, the precision may decrease for unavoidable reasons, such as clouds or

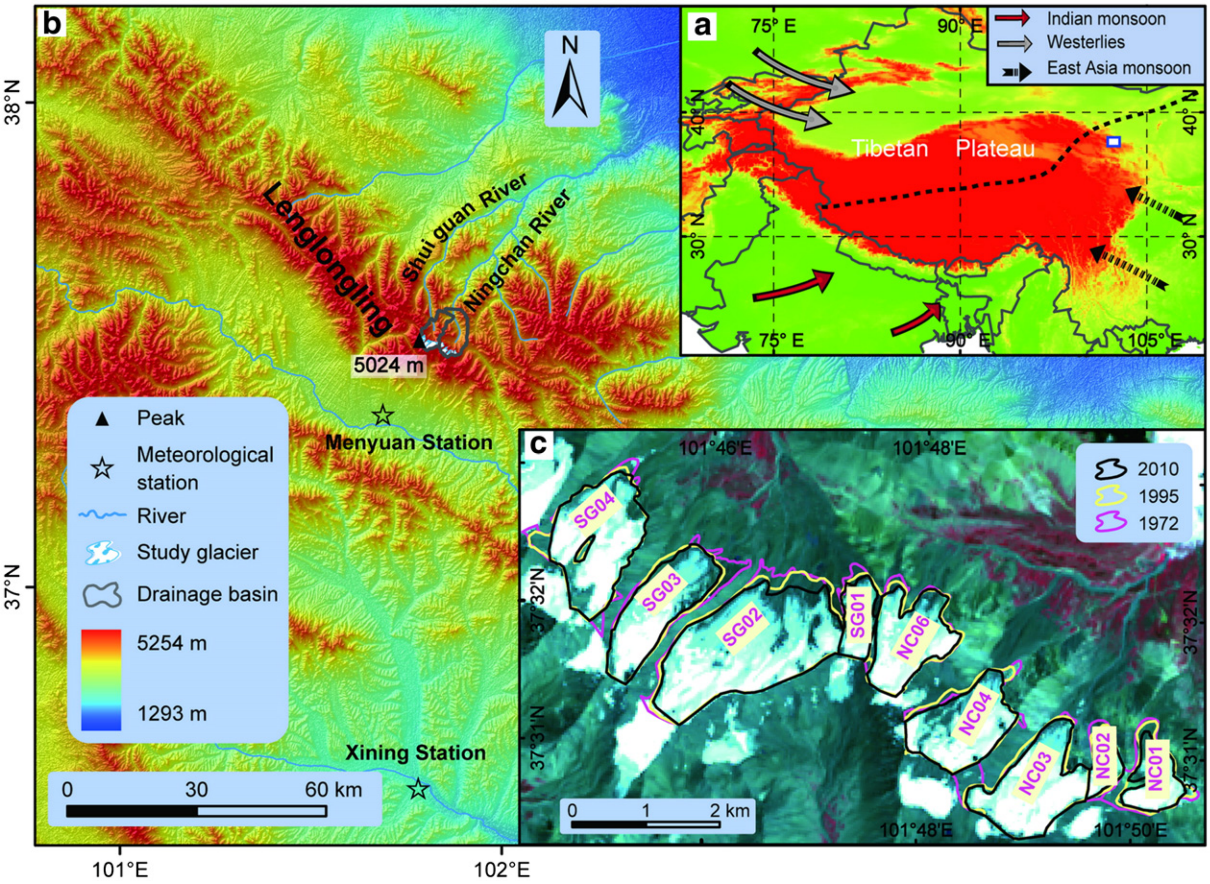

**Figure 1.** Location of the Ningchan and Shuiguan river source glaciers. (a) The inset shows the location of the study area within the TP. Dashed line shows the boundary between westerly and monsoon moisture (after Chen et al., 2008). (b) Overview of the study area overlaid on DEM. (c) Overview of the borderlines of the glacier with a Landsat image. NC01 stands for Ningchan river source glacier No. 01 and SG01 stands for Shuiguan river source glacier No. 01.

**Table 1**
Source of data used in this study.

| Data source | Date | Resolution | RMSE[b] | DEM error |
|---|---|---|---|---|
| Topographic map | 1972 | 5 m/1:50,000[a] | | <11 m |
| Landsat TM | 11 Jun 1995 | 28.5 m | <28.5 m | |
| Landsat TM | 08 Sep 2010 | 28.5 m | <28.5 m | |
| GPS measurements | 2010 | 0.3 m | | 0.5 m |

[a] According to the criteria of the State Bureau of Surveying and Mapping of China, the ground resolution of maps at scales of 1:50,000 is about 5 m.

[b] The RMSE of remote-sensing images is <1 pixel.

ionosphere error. However, the vertical accuracy is less than 0.3 m and horizontal accuracy is less than 0.1 m (Rivera et al., 2005). All GPS point data were re-projected to the Universal Transverse Mercator (UTM) coordinate system and referenced to the World Geodetic System 1984 (WGS84) and then the point data were interpolated by the Inverse Distance Weighted (IDW) method to produce the raster of DEM2010, with a grid resolution of 15 m (Fig. 2b).

### Aerial photograph and topographic maps

We used a map derived from aerial photographs at a scale of 1:50,000 acquired in 1972 by the State Bureau of Surveying and Mapping. Then we digitized the 20 m interval contours and spot heights in order to generate a Triangular Irregular Networks (TIN) map and create a DEM1972 based on Beijing54. The center and flattening of Beijing54 are different from the WGS84 UTM. In order to compare with other data, the DEM was re-projected to the WGS84 UTM datum using a seven-parameter datum transformation model with a 15 m resolution. The application of the seven-parameter datum transformation model has been discussed by Wang et al. (2003) and Zhang et al. (2010). The error using a seven-parameter datum transformation model is <0.002 m (Wang et al., 2003). The identified glacier outline was then digitized using GIS based on vector files.

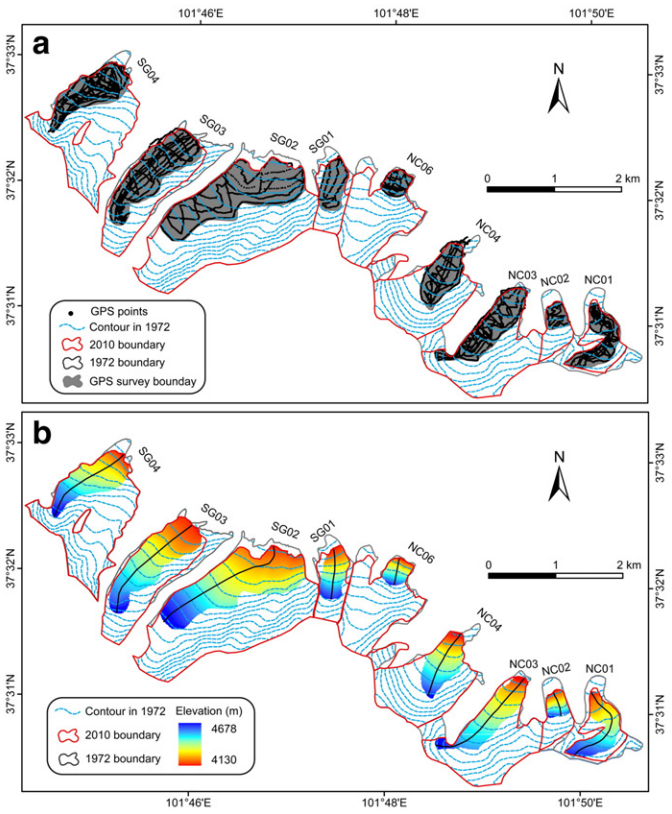

**Figure 2.** GPS-RTK survey in the study region. (a) Map of the surface points. (b) DEM generated by GPS survey data.

### Remote-sensing data

Two Landsat Thematic Mapper (TM) images (Path: 132, Row: 34, 11 June 1995; 08 September 2010) were obtained to identify the glacier borderline. Although some areas in the TM image 2010 were covered with seasonal snow, NC and SG river source glaciers can be distinguished clearly from other surface types (Pan et al., 2012). The Landsat TM data are obtained from the Global Land Cover Facility (GLCF) and the United States Geological Survey (USGS). They were all orthorectified to the WGS84 UTM datum. The best tool to extract more reliable information from satellite images for many glaciers is manual digitization (Raup et al., 2007).

### Surface elevation changes

The lower parts of each glacier were selected to calculate glacier surface elevation changes between 1972 and 2010 (Fig. 2a). Surface elevation or ice volume changes were derived from repeated comparisons of the DEMs for different years. Ice volume changes were calculated by multiplying the mean value of surface elevation change, $\Delta H$, by the glacier surface area, $S$.

## Results

### Changes in glacier terminus position and area

All nine glaciers retreated during the period 1972–2010, with a mean rate of 4.7 m $\text{yr}^{-1}$. The maximum and minimum values were 250 ± 57.4 m and 91 ± 57.4 m, respectively (Table 2). The maximum glacier length retreat occurred on NC04 glacier. In addition, several field campaigns to study the glaciers in this region have been carried out since 1956. These studies show glacier retreat of about 400 m (20 m $\text{yr}^{-1}$) during 1956–76 (Xie et al., 1985) and 71.2 m (8.9 m $\text{yr}^{-1}$) during 1976–84 (Liu et al., 1992). The glaciers have shrunk continuously since at least 1956.

Glacier terminus altitude rises as the glacier shrinks. The rise is rapid when the glacier terminus is steep, and slow when it is flat. The glacier terminus altitudes rose from 2 m (NC06) to 81 m (NC04) from 1972 to 2010 for nine glaciers (Table 2). The increase in mean terminus altitude is 39.3 m in NC and SG river source glaciers. The ELA has increased more than 100 m since 1972 as evidenced by field observation in 2007 (Li et al., 2010).

The total area decrease for these nine glaciers was 1.20 $\text{km}^2$, accounting for 9.9% of the total area in 1972 (Table 3). As each glacier has a different shape, the glacier retreat rates varied significantly. Some glaciers shrunk relatively faster, e.g. NC01 ($8.2 \times 10^{-3}$ $\text{km}^2$ $\text{yr}^{-1}$) and SG03 ($6.1 \times 10^{-3}$ $\text{km}^2$ $\text{yr}^{-1}$), while others retreated slowly, e.g. NC04 ($0.8 \times 10^{-3}$ $\text{km}^2$ $\text{yr}^{-1}$) and SG04 ($1.8 \times 10^{-3}$ $\text{km}^2$ $\text{yr}^{-1}$).

### Changes in glacier surface elevation and ice volume

The glaciers thinned by between 2 and 70 m between 1972 and 2010 (Fig. 3a). The trend of surface elevation change fluctuated with altitude. The mean elevation change was 24.5 m (0.64 m $\text{yr}^{-1}$) for nine glaciers for all surveyed areas (Table 4). The largest ice thinning was observed at NC01 glacier, 0.76 m $\text{yr}^{-1}$ from 1972 to 2010. Generally, most thinning occurred in the lower sections near the terminus area for 35 m in the study area (below 4250 m asl) (Fig. 3b). The thinning trend appears to decrease at higher altitudes.

Table 4 shows the ice volume loss of each glacier from 1972 to 2010. The total ice volume loss was $106.8 \times 10^{-3}$ $\text{km}^3$, corresponding to $90.8 \times 10^{-3}$ $\text{km}^3$ w.e. if the ice density is assumed to be $0.85 \times 10^3$ kg $\text{m}^{-3}$ (Huss, 2013).

**Table 2**
Changes in glacier terminus.

| Glaciers | | NC | | | | | SG | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 01 | 02 | 03 | 04 | 06 | 01 | 02 | 03 | 04 |
| Terminus altitude (m) | 1972 | 4170 ± 11 | 4175 ± 11 | 4140 ± 11 | 4160 ± 11 | 4158 ± 11 | 4158 ± 11 | 4117 ± 11 | 4172 ± 11 | 4193 ± 11 |
| | 2010 | 4225 ± 0.3 | 4237 ± 0.3 | 4156 ± 0.3 | 4241 ± 0.3 | 4160 ± 0.3 | 4205 ± 0.3 | 4130 ± 0.3 | 4198 ± 0.3 | 4245 ± 0.3 |
| Terminus change (m) | 1956–1976 | | | 400[a] | 400[a] | 200[a] | 310[a] | 450[a] | 360[a] | 320[a] |
| | 1976–1984 | | | | | | | | | 71.2 [b] |
| | 1972–1995 | 91 | 124 | 56 | 176 | 85 | 152 | 145 | 140 | 201 |
| | 1995–2010 | 79 | 40 | 35 | 74 | 54 | 51 | 32 | 50 | 55 |
| | 1972–2010 | 170 | 164 | 91 | 250 | 139 | 203 | 177 | 190 | 232 |
| Terminus retreat rate (m $yr^{-1}$) | 1956–1976 | | | 20.0 | 20.0 | | 15.5 | 22.5 | 18.0 | 16.0 [a] |
| | 1976–1984 | | | | | | | | | 8.9[b] |
| | 1972–1995 | 4.0 | 5.4 | 2.4 | 7.7 | 3.7 | 6.6 | 6.3 | 6.1 | 8.7 |
| | 1995–2010 | 5.3 | 2.7 | 2.3 | 5.0 | 3.6 | 3.4 | 2.1 | 3.3 | 3.7 |
| | 1972–2010 | 4.5 | 4.3 | 2.4 | 6.6 | 3.6 | 5.3 | 4.6 | 5.0 | 6.1 |

[a] After Xie et al. (1985).
[b] After Liu et al. (1992).

However, those parts of the glaciers that were lost due to terminus retreat were excluded from these ice volumes. Furthermore, glacier surface elevation changes were not determined for the higher-altitude areas of the glaciers. So, the ice volume loss from 1972 to 2010 was more than $106.8 \times 10^{-3}$ $km^3$ in the NC and SG river source glaciers.

## Discussion

### *Analysis of errors*

The accuracy in measuring glacier terminus positions extracted from multi-temporal satellite images primarily relies on the sensor resolutions (Williams et al., 1997; Racoviteanu et al., 2009; Paul et al., 2013) and the co-registration errors (Hall et al., 2003; Silverio and Jaquet, 2005). According to Ye et al. (2006) and Silverio and Jaquet (2005), the measurement uncertainty of the glacier terminus, $U_T$, can be calculated from

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

where $U_T$ is the measurement uncertainty of the glacier terminus in the study area, $\lambda$ is the original pixel resolution of each image and $\varepsilon$ is the co-registration error (<1 pixel) of each image to the topographic map generated in 1972. For the images in 1972, 1995 and 2010, the resolutions are 5 m, 28.5 m and 28.5 m respectively. According to Eq. (1), the uncertainties in measurement of the glacier terminus retreat were 57.4 m during the periods 1972–95 and 1972–2010, and 68.8 m between 1995 and 2010. The uncertainty in glacier area from 1972 to 2010 is calculated to be 0.004 $km^2$ from

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

where $U_A$ is the uncertainty in calculating glacier extent.

The vertical errors were generated from the DEM1972 and DEM2010. DEM1972 is the main source of systematic error in our analysis. The systematic vertical errors of the DEM generated from the 1:50,000 topographic maps were less than 11 m on slopes less than 15° (State Bureau of Surveying and Mapping, 2007). In order to calculate the accuracy error of the DEM1972, some points on the stable terrain were surveyed and the error was about 5 m in the vertical (Table 5). However, the points are too few to have statistical significance, so we use the maximum error of 11 m as the vertical error. The accuracy of the GPS surveys is 0.3 m; however, when we use these points to create a DEM, the error for the 2010DEM will be larger than 0.3 m, which was determined by the number of points and whether the distribution was uniform. Therefore we randomly chose 30 points from each glacier to examine the 2010DEM. The survey points are very dense and the glacier surface is relatively smooth in the study area. The mean elevation error was small, about 0.5 m.

The vertical error of these two DEMs was about 11 m as calculated by Eq. (3) (Barrand et al., 2010)

$$Error = \sqrt{Error^2{}_{DEM\ \ 1972} + Error^2{}_{DEM\ \ 2010}} = \sqrt{11^2 + 0.5^2} \approx 11\ \text{m}. \tag{3}$$

**Table 3**
Changes in glacier area.

| Glaciers | | NC | | | | | SG | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 01 | 02 | 03 | 04 | 06 | 01 | 02 | 03 | 04 |
| Area ($km^2$) | 1972 | 0.78 | 0.36 | 1.54 | 1.28 | 1.22 | 0.52 | 3.15 | 1.47 | 1.82 |
| | 1995 | 0.60 | 0.29 | 1.47 | 1.26 | 1.15 | 0.46 | 3.05 | 1.32 | 1.78 |
| | 2010 | 0.47 | 0.25 | 1.43 | 1.25 | 1.12 | 0.43 | 3.00 | 1.24 | 1.75 |
| | GPS measured | 0.34 | 0.11 | 0.52 | 0.37 | 0.13 | 0.25 | 1.24 | 0.77 | 0.52 |
| Area change ($km^2$) | 1972–1995 | 0.18 | 0.07 | 0.07 | 0.02 | 0.07 | 0.06 | 0.10 | 0.15 | 0.04 |
| | 1995–2010 | 0.13 | 0.04 | 0.04 | 0.01 | 0.03 | 0.03 | 0.05 | 0.08 | 0.03 |
| | 1972–2010 | 0.31 | 0.11 | 0.11 | 0.03 | 0.10 | 0.09 | 0.15 | 0.23 | 0.07 |
| Area retreat rate ($\times 10^{-3}$ $km^2$ $yr^{-1}$) | 1972–1995 | 7.8 | 3.0 | 3.0 | 0.9 | 3.0 | 2.6 | 4.3 | 6.5 | 1.7 |
| | 1995–2010 | 8.7 | 2.7 | 2.7 | 0.7 | 2.0 | 2.0 | 3.3 | 5.3 | 2.0 |
| | 1972–2010 | 8.2 | 2.9 | 2.9 | 0.8 | 2.6 | 2.4 | 3.9 | 6.1 | 1.8 |

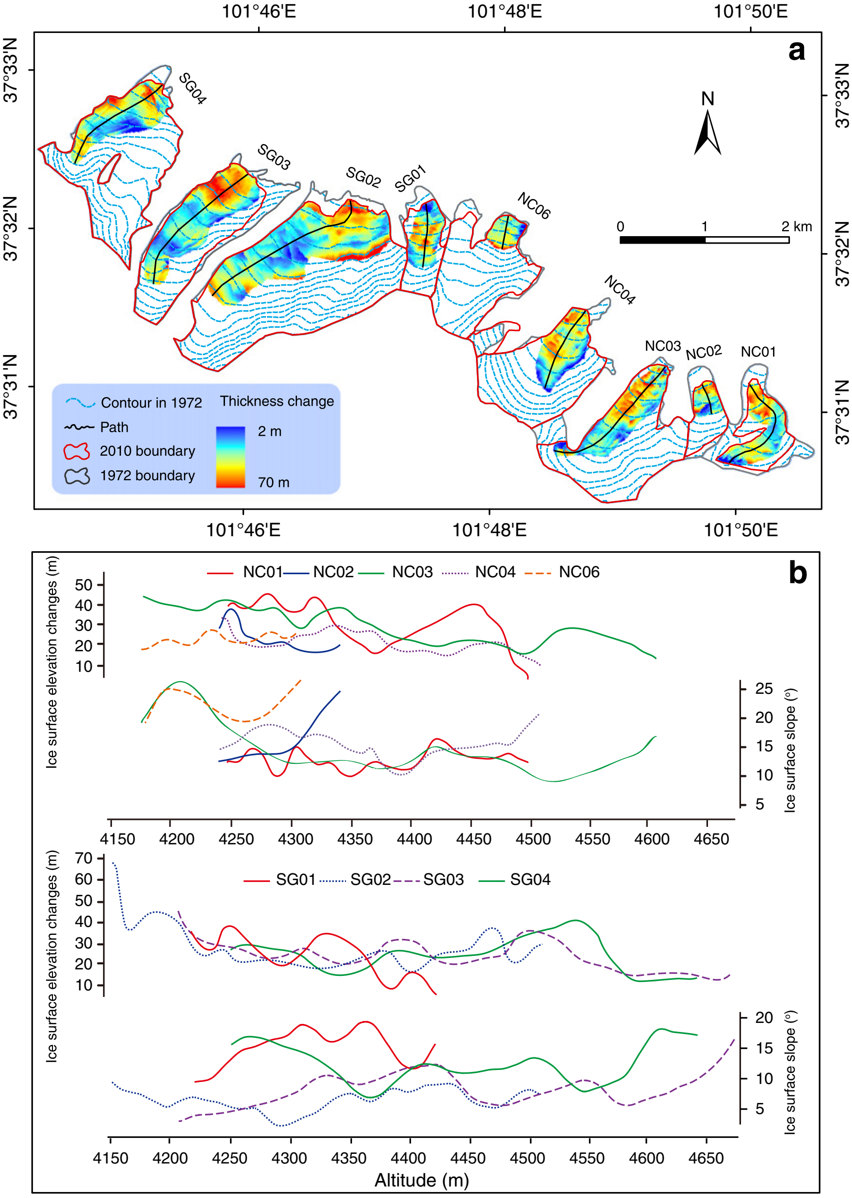

**Figure 3.** Glacier surface elevation change. (a) Changes in glacier surface thickness. (b) Ice thickness and slope changes along the paths on each glacier.

## *Reasons for glacier variation*

Precipitation and air temperature are the two main factors controlling glacier changes (Oerlemans, 2005). Precipitation determined the glacier's accumulation, while summer temperature determined the melt. Menyuan meteorological station and Xining radiosonde station (36°43′N, 101°45′E, 2295 m asl) are about 20 km and 100 km south of the study area, respectively. The meteorological data show that the annual precipitation presents a fluctuation but with no significant trend. However, the summer air temperature and freezing-level height (FLH) show a dramatic increase (Fig. 4) which causes high summer melt rates and negative glacier mass balance. Therefore, the glacier variations in the NC and SG river source appear to be concurrent with changes of summer air temperature and FLH during the period 1972–2010. Pan et al. (2012) pointed out that glaciers in the Western Lenglongling Mountains shrunk between 1972 and 2007, and the glacier shrinkage

**Table 4**
Glacier surface elevation and volume changes in GPS measured.

| Glaciers | NC | | | | | SG | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 01 | 02 | 03 | 04 | 06 | 01 | 02 | 03 | 04 |
| Area (%)[a] | 72 | 44 | 36 | 30 | 12 | 58 | 41 | 62 | 30 |
| Mean slope (°) | 13.8 | 17.6 | 15.1 | 15.7 | 21.7 | 21.6 | 14.2 | 16.9 | 17.1 |
| Elevation bands (m) | 4240–4508 | 4237–4350 | 4151–4602 | 4166–4520 | 4157–4337 | 4216–4500 | 4150–4550 | 4200–4678 | 4250–4644 |
| Mean surface elevation change (m) | 28.8 ± 11 | 23.7 ± 11 | 28.4 ± 11 | 22.0 ± 11 | 22.0 ± 11 | 24.0 ± 11 | 27.5 ± 11 | 22.7 ± 11 | 21.4 ± 11 |
| Mean thinning rate (m $a^{-1}$) | 0.76 ± 0.29 | 0.62 ± 0.29 | 0.75 ± 0.29 | 0.58 ± 0.29 | 0.58 ± 0.29 | 0.63 ± 0.29 | 0.72 ± 0.29 | 0.60 ± 0.29 | 0.56 ± 0.29 |
| Ice volume loss $\times 10^{-3}$ ($km^3$) | 9.8 ± 3.7 | 2.6 ± 1.2 | 14.7 ± 5.7 | 8.1 ± 4.1 | 2.9 ± 1.4 | 6.0 ± 2.8 | 34.1 ± 13.6 | 17.5 ± 8.5 | 11.1 ± 5.7 |

[a] GPS measured area covers the percentage of the total area in 2010.

**Table 5**
Errors between GPS survey and topographic map data.

| Point | Latitude (°) | Longitude (°) | Elevation (m) (GPS) | Elevation (m) (topographic map) | Error (m) |
|---|---|---|---|---|---|
| 1 | 37.5462 | 101.7810 | 3972.0 | 3977.1 | 5.1 |
| 2 | 37.5371 | 101.8011 | 4137.5 | 4140.0 | 2.5 |
| 3 | 37.5403 | 101.8041 | 4009.6 | 4010.0 | 0.4 |
| 4 | 37.5398 | 101.8145 | 3882.1 | 3880.0 | −2.1 |
| 5 | 37.5397 | 101.8146 | 3881.7 | 3883.5 | 1.8 |
| 6 | 37.5226 | 101.8369 | 4165.0 | 4163.0 | −2.0 |
| 7 | 37.5308 | 101.8381 | 3935.4 | 3940.0 | 4.6 |
| 8 | 37.5210 | 101.8382 | 4156.8 | 4168.8 | 12.0 |
| 9 | 37.5439 | 101.8521 | 3710.2 | 3720.0 | 9.8 |

can probably be attributed to the increase in air temperature. Thus, combined with the above analysis, we also believe that glacier shrinkage and thinning in this area is mainly caused by the increase in summer temperature and FLH during the period 1972–2010.

Rate of glacier variation is controlled not only by climate change but also by topographic setting (e.g. aspect and slope), especially for glaciers at the regional scale or in the same climate condition (Scherler et al., 2011; Venkatesh et al., 2013). The aspects of these nine glaciers are primarily north. Therefore, the difference in thinning rate cannot be well explained by the aspect individually. The mean slope in the GPS-measured area of each glacier is also calculated (Table 4). Generally, a higher mean thinning rate corresponded to a lower mean slope. In addition, the changes in thinning rate and slope for each glacier along paths are shown in Fig. 3b. The figure also shows a slightly negative relationship, with slope decreasing while thinning increases at each glacier. However, the high uncertainty of the vertical makes it of doubtful reliability for evaluating and discussing the correlation.

### *Glacier retreat and thinning in other mountains*

Many studies have shown that the TP glaciers have responded to rapid warming by decreasing in area and losing ice mass in recent decades, with varying shrinkage statuses from region to region. For example, glacier mean area decreased by 0.57% $yr^{-1}$ in the southeastern TP, 0.41% $yr^{-1}$ in the central Himalayas, 0.42% $yr^{-1}$ in the western Himalayas, 0.29% $yr^{-1}$ in the northeastern TP, and 0.07% $yr^{-1}$ in the northwestern TP (Yao et al., 2012). In the southeastern TP, the Hailuogou glacier of the Gongga Mountains experienced a high thinning rate (1.1 m $yr^{-1}$ between 1966 and 2009) (Zhang et al., 2010), and Parlung No. 12 glacier also shows a significantly negative mass balance (−1.7 m $yr^{-1}$ from 2005 to 2009) (Yao et al., 2012). Shangguan et al. (2010) found a thinning rate of about 0.4 m $yr^{-1}$ for two glaciers along the Yanglonghe river between 1956 and 2007, which is similar to the 0.41 m $yr^{-1}$ found in Dongkemadi Ice Field from 1961 to 2000 (Li et al., 2011) and slightly lower than rates in our study area (0.64 m $yr^{-1}$). However, Glacier No. 01 in the Urumqi river source of the Tien Shan had a much lower thinning rate of 0.24 m $yr^{-1}$ from 1962 to 2003 (Ye et al., 2005).

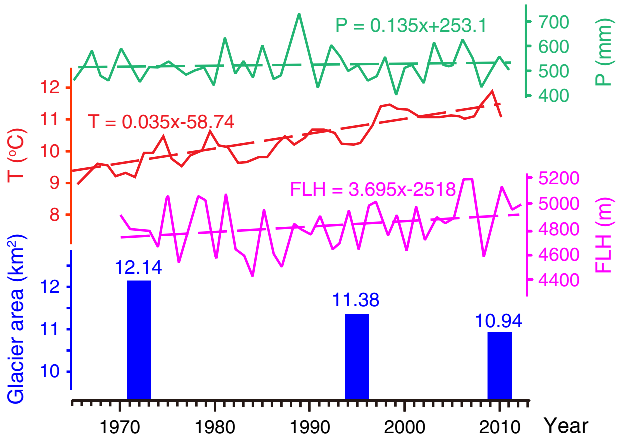

**Figure 4.** Changes in annual precipitation (*P*), summer (June–August) air temperature (*T*) at the Menyuan weather station (2924 m), freezing-level height (*FLH*) at the Xining radiosonde station (2295 m) and the glacier area in the study area.

## Conclusion

GPS is an efficient and accurate method for extracting data for glacier mass balance change. The nine glaciers in the NC and SG river source lost 9.9% of their total area in the period 1972–2010. The mean terminal altitude rose 39.3 m and glacier length retreated at a rate of 4.7 m $yr^{-1}$. The mean surface elevation decreased by 0.64 m $yr^{-1}$. Total glacier mass loss was at least $90.8 \pm 39.7 \times 10^{-3}$ $km^3$ w.e. ($0.1 \pm 0.05$ $m^3/s$) for 1972–2010 in NC and SG river source glaciers. The glaciers in the study area and in other mountains are retreating, decreasing in area and thinning in response to climate change during the past several decades.

## Acknowledgments

We thank G. Zhang, B. Huang, F. Liu, D. Chen and F. Li for their hard field work. This paper has benefited from valuable comments and constructive suggestions by F. Chen and two anonymous reviewers, whose efforts are gratefully acknowledged. This study is financially supported by the National Basic Work Program of the Ministry of Science and Technology of China (Grant No. 2013FY111400), the National Natural Science Foundation of China (Grant Nos. 91125008 and 41171063), and the Program for New Century Excellent Talents in University (Grant No. NCET-13-0263).

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