

# Climate change and glacier area shrinkage in the Qilian mountains, China, from 1956 to 2010

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**ABSTRACT.** Glaciers in the Qilian mountains, located in the northeastern part of the Tibetan Plateau, constitute an important freshwater resource for downstream populations and natural systems. To enhance our understanding of the variability of the glaciers, temporally and spatially comprehensive information on them is needed. In this study, the glacier outlines of ~1990, ~2000 and ~2010 for the whole area were delineated in a semi-automated manner using band TM3/TM5 ratio images of Landsat ETM+ or TM scenes with the help of a merged ASTER GDEM/SRTM v4.1 digital elevation model. Combining our own results with those of previously published studies that span the period back to 1956, we found that the glacier area shrank by  $30 \pm 8\%$  from 1956 to 2010 and the shrinkage accelerated remarkably in the past two decades. The linear trends of annual air temperature and precipitation measured at weather stations within the glacierized areas were  $0.03\text{--}0.05^\circ\text{C a}^{-1}$  (significant only after 2000) and  $0.37\text{--}1.58\text{ mm a}^{-1}$  (not significant) respectively from 1961 to 2010. Glaciers shrank mainly due to the increasing temperature. Glaciers in the Qilian mountains are very unlikely to have experienced positive mass balance over the past decade. Moreover, given the trend toward higher temperatures, the glaciers in this region will continue to shrink.

**KEYWORDS:** mountain glaciers, remote sensing

## 1. INTRODUCTION

Glaciers present the most visible indicators of climate change (Solomon and others, 2007; Vuille and others, 2008; Kääb and others, 2012), and are considered key indicators for the early detection of global climate variations (Masiokas and others, 2008). The majority of mountain glaciers have been retreating worldwide since the end of the last century (Oerlemans, 2005; WGMS, 2008; Kaltenborn and others, 2010; Yao and others, 2012). Glacier variations can have strong impacts on water resources of downstream populations and natural systems, and are implicated in phenomena such as glacial lake outburst floods (GLOFs) and sea-level rise (Kääb and others, 2005; Meier and others, 2007; Bajracharya and Mool, 2009; Immerzeel and others, 2010; Jacob and others, 2012). However, changes to glaciers, and the resultant hydrological impacts are not homogeneous worldwide, but depend on the location, size and type of glacier.

In the arid and semi-arid regions of northwestern China, runoff has increased by  $>5.5\%$  since the 1990s due to glacier retreat (Yao and others, 2004). The Hexi Corridor is populated by  $>4.5$  million people, who depend for water mainly on the rivers originating from the glaciers and snow in the Qilian mountains (Fig. 1), and conflicts have taken place due to water crises in past and recent times (Wang, 2004; Qie, 2008). Thus, changes in glacier coverage in the Qilian mountains should be closely monitored as climate change continues.

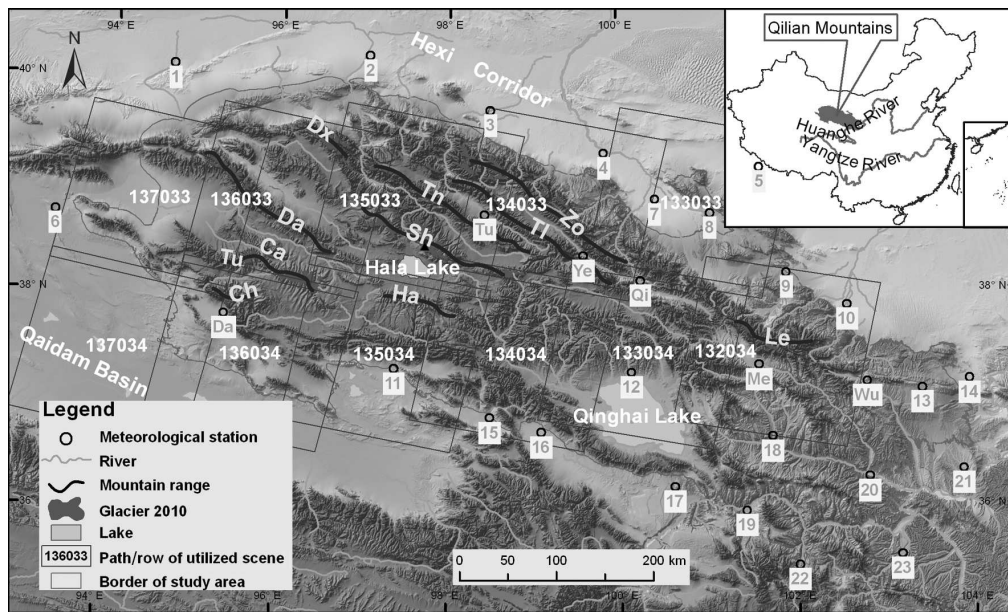
A recent study indicated positive glacial mass balance of  $\sim 7\text{ Gt a}^{-1}$  in Tibet and the Qilian mountains from 2003 to 2010 (Jacob and others, 2012), which appears inconsistent with previous studies that found decreasing glacier area or increasing equilibrium-line altitude (ELA) in recent decades (Liu and others, 2002; Du and others, 2008; Zhao, 2009; Cao and others, 2010; H. Zhang and others, 2010, 2011; P. Wang and others, 2011). However, as previous glacier

area studies either only investigated part of the Qilian mountains or spanned different time periods, direct comparison of these results with those of Jacob and others (2012) has been difficult.

Therefore, the aims of this study are to (1) generate a time series of glacier extents for the whole of the Qilian mountains, (2) provide information on the characteristics of glacier distribution and (3) analyze glacier changes during recent decades, with a view to re-examining the results of Jacob and others (2012), and discussing possible climatic drivers for, and possible impacts of, glacier changes.

## 2. STUDY AREA

The Qilian mountains are located in the arid and semi-arid region of northwestern China ( $38.0^\circ\text{ N}$ ,  $98.8^\circ\text{ E}$ ). The study area covers  $\sim 220\,000\text{ km}^2$  in the northeastern part of the Tibetan Plateau spanning an elevation range from 2000 to 5800 m a.s.l. (Fig. 1). The region is influenced by the interaction of the Siberian high, East Asian monsoon and westerly jet streams (Chen and others, 2011), with precipitation occurring mostly during the warm months owing to the East Asian monsoon and decreasing from east to west due to topography (Fig. 2; Table 1). There are two types of glaciers in the Qilian mountains: subcontinental (subpolar) and extreme continental (polar) (Shi and Liu, 2000). The subcontinental glaciers, characterized by annual precipitation ranges of  $500\text{--}1000\text{ mm a}^{-1}$ , annual average air temperature of  $-12$  to  $-6^\circ\text{C}$ , summer mean air temperature of  $0\text{--}3^\circ\text{C}$  at the ELA and ice temperature of  $-10$  to  $-1^\circ\text{C}$  within the upper 20 m ice layer, are mainly distributed in the eastern portion, whereas the extreme continental glaciers, characterized by annual precipitation of  $200\text{--}500\text{ mm}$ , annual air temperature of  $-10^\circ\text{C}$ , summer mean air temperature of  $<-1^\circ\text{C}$  at the ELA and extremely low ice temperature, are mainly distributed in



**Fig. 1.** Study area showing glacier coverage in 2010, path and row of the utilized Landsat scenes and meteorological stations. The red line indicates the border of the study area. Abbreviations of the names of mountain ranges are given in yellow (see Table 4 for full names). Numbered meteorological stations are those outside the glacierized area, and those within the glacierized area are denoted by abbreviations (see Appendix for the full names).

the western portion (Shi and Liu, 2000). There are effectively no debris-covered glaciers in this region, and only a very small number have small areas of marginal debris cover. The Datong river, a branch of the Huanghe river (Yellow River), originates in the Qilian mountains. The impacts of glacial melt on the Huanghe river are small because the river depends only marginally on glacial melt (Immerzeel and others, 2010). The share of glacier runoff in the other rivers varies from ~3% to ~60%, with a generally increasing share from east to west (Wang and others, 1981).

### 3. DATA AND METHODS

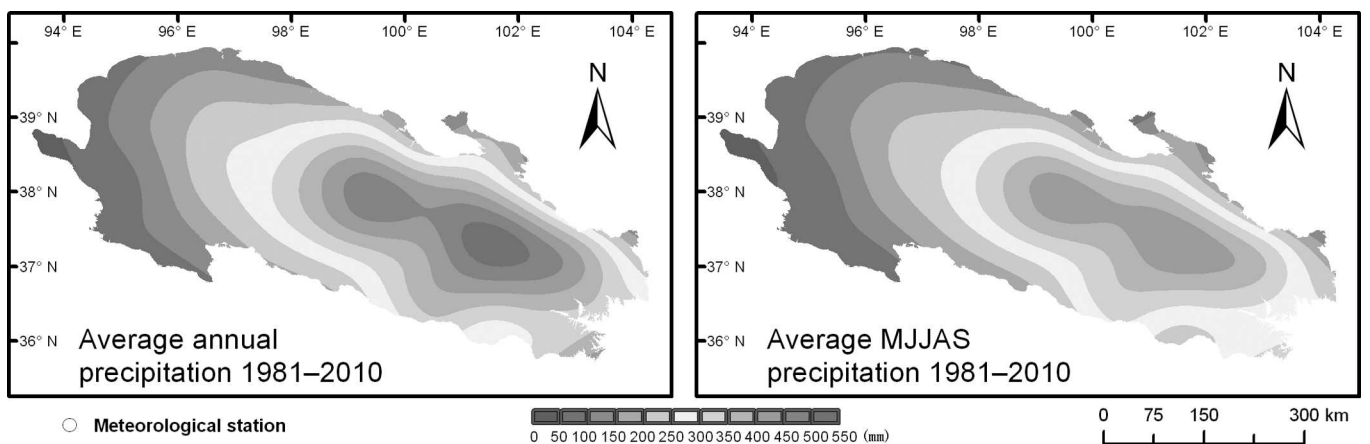
#### 3.1. Digital elevation model (DEM)

For elevation data, we used a combination of the Shuttle Radar Topography Mission (SRTM) v4.1, which has 90 m resolution, and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) global digital elevation model (ASTER GDEM), which has 30 m resolution

(<http://datamirror.csdb.cn>). The ASTER GDEM contains residual cloud anomalies and pervasive artifacts. In order to replace these anomalies and artifacts in the ASTER GDEM, the SRTM v4.1 data were first resampled to 30 m, and then the pixels in the ASTER GDEM were replaced with the resampled SRTM v4.1 data at locations where the elevation difference exceeded 200 m. These DEM data were used to delineate the glacier outlines and glacier basins, interpolate meteorological data and calculate statistics.

#### 3.2. Climate

Temperature and precipitation data (<http://cdc.cma.gov.cn/>) from 29 meteorological stations were selected to analyze climate trends (Fig. 1; Appendix). Because of the scarcity of observations before 1961, we only analyzed climate trends from 1961 to 2010. First, the climate data were processed using the software package RHtestV3 to make them homogeneous. Changepoints (shifts) in a time series of a station were detected and adjusted within the series using RHtestV3



**Fig. 2.** Average annual precipitation and average MJJAS precipitation during 1981–2010. Source: China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn/>).

**Table 1.** Climate characteristics at six meteorological stations. Seasonal precipitation shows the proportion of precipitation in each of the four seasons and MJJAS. The trends in temperature and precipitation show a linear relationship. For the location of the meteorological stations see Figure 1

Meteorological station	Symbol (Figs 1 and 4)	Elevation m a.s.l.	Ave. ann. air temp	Ave. ann. precip.	Seasonal precip.					Ann. air temp. trend	Ann. precip. trend	MJJAS air temp. trend	MJJAS precip. trend
			1981–2010	1981–2010	DJF	MAM	JJA	SON	MJJAS	1961–2010	1961–2010	1961–2010	1961–2010
			°C	mm	%	%	%	%	%	°C	mm	°C	mm
Wushangling	Wu	3029	0.4	407.0	2	18	59	21	84	0.03**	1.01	0.03**	0.52
Menyuan	Me	2882	1.2	531.2	2	23	55	21	83	0.04**	0.37	0.04**	0.24
Qilian	Qi	2721	1.4	415.1	1	16	64	18	90	0.03**	0.69	0.03**	0.81
Yeniugou	Ye	3224	−2.6	426.4	1	15	66	18	89	0.03**	1.58*	0.03**	1.32*
Tuole	Tu	3361	−2.2	309.7	1	15	70	13	92	0.04**	1.36*	0.03**	1.36*
Dachaidan	Da	3204	2.4	92.8	6	23	62	10	84	0.05**	0.41	0.04**	0.27

(\*\*) Significant at the 95% (99.5%) confidence level using an *F* test.

Source: China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn/>).

(X.L. Wang, 2008a,b). With temperature data, multiple regression analysis was performed for every year from 1961 to 2010 to obtain the relationship between temperature and longitude, latitude and elevation using MATLAB R2010. Temperature was then calculated based on the relationships for each pixel (500 m × 500 m) in the study area for each year from 1961 to 2010. This interpolation method was chosen because it has been attested to be superior to the other four conventional interpolation methods (i.e. inverse distance weighted, spline, ordinary kriging and trend) in the Qilian mountains (Zhao and others, 2006). For precipitation, a similar process was used, except that elevation was not chosen as an independent variable when performing multiple regression analysis because precipitation changes are not linear with elevation. If elevation were taken into account, anomalies would result at higher elevations. Finally, the mean temperatures and precipitation of areas covered by glaciers were calculated using the zonal statistic tool in ArcGIS 10. The calculated temperatures and precipitation of all gridpoints within the glacierized region were used to analyze the climate trend. Six meteorological stations (Dachaidan, Menyuan, Qilian, Tuole, Wushangling and Yeniugou) within the glacierized area were selected to analyze climate characteristics in detail (Fig. 1; Table 1).

Mann–Kendall analysis was used to detect climate trends (Mann, 1945; Kendall, 1975). A value greater than zero for the statistical index ( $UF_k$ ) indicates an increasing trend, and a value greater than 1.96 indicates a significant increasing trend at the 95% confidence level.

### 3.3. Glaciers

#### 3.3.1. Glacier outline extraction

Landsat Thematic Mapper (TM) and Enhanced TM+ (ETM+) imagery (Table 2) was used to extract glacier outlines for three periods, around 1990, 2000 and 2010. We solved the main problems of debris-free glacier delineation (e.g. snow and clouds) by selecting imagery taken during the melting season and using more scenes in similar time periods as alternatives. For example, if part of an image was influenced by snow or clouds, we used another image, in which this part was not influenced by snow or clouds, as an alternate image to delineate glaciers.

We extracted glacier extents using the following semi-automated method. First, a TM3/TM5 ratio image with a

threshold of 1.8 was used to delineate the glaciers in ENVI 4.5, and we used a minimum-elevation threshold of 3600 m to minimize misclassification. Then we manually reviewed and, where necessary, adjusted the glacier extents and deleted misclassified areas in ArcGIS 10 using the true-color image (bands 3, 2 and 1 as red, green and blue, respectively), false-color image (bands 5, 4 and 3 as red, green and blue, respectively) and the DEM as background. Modified areas included snow-covered areas, cloud-covered areas, debris-covered parts, shadow regions and termini ending in lakes. The manually adjusted glacier area differed from the automatically classified area by <3%, which is comparable to the 5% change in area reported by Bolch and others (2010a) for manual adjustment to automatic classification. We mapped only glaciers larger than 0.05 km<sup>2</sup>, in order to exclude features that were most likely snowpatches. We identified internal holes in the glacier polygons using an area threshold of 8100 m<sup>2</sup> (3 × 3 pixels) and deleted them, as these are usually misclassified pixels due to some surface debris. Because there is no effective method of delineating debris-covered glaciers based on Landsat data (Shukla and others, 2010; Bhambri and others, 2011), delineation of their outlines will introduce higher uncertainty into change analysis. If part of a glacier is covered by debris, the outline of clean ice was delineated in 1990 and held constant for the outlines 2000 and 2010 such that marginal change where there is some supraglacial debris is forced to be zero in this study. To separate connected glaciers into their basins, glacier basins were manually derived from the DEM using the Chinese Glacier Inventory as a reference.

#### 3.3.2. Error estimation

We compared our results with independently generated outlines from the China–Brazil Earth Resources Satellite-2B (CBERS2B) high-resolution (HR) imagery (resolution 2.36 m). The acquisition dates of the Landsat TM image and CBERS2B HR image were 29 July 2009 and 17 July 2009 respectively. The outlines of glaciers from the Landsat TM image were delineated using the above method without manual improvement. The area difference was about ±3%, which is consistent with previous studies that used a band ratio method to map glaciers (Paul and others, 2002, 2003; Bolch and others, 2010a,b). Because of data limitation, the range of data dates is greater than 1 year for each specified point in

**Table 2.** Landsat scenes used in the study

Path/row	~1990		~2000		~2010	
	Acquisition date	Sensor	Acquisition date	Sensor	Acquisition date	Sensor
132/034	11 Jun 1995	TM	1 Aug 1999	ETM+	10 Aug 2011*	TM
133/033	15 Aug 1987	TM	10 Aug 2000*	ETM+	26 Aug 2011	TM
			12 Jul 2001*	ETM+	11 Aug 2009*	TM
			13 Aug 2001	ETM+	14 Aug 2010	TM
133/034	5 Sep 1992	TM	8 Aug 1999	ETM+	14 Aug 2010	TM
	21 Aug 1995*	TM				
134/033	9 Oct 1987	TM	30 Jul 1999*	ETM+	5 Aug 2010	TM
	27 Aug 1992*	TM	3 Jul 2001	ETM+		
134/034	30 Aug 1990	TM	3 Jul 2001	ETM+	17 Jul 2009	TM
135/033	19 Aug 1995	TM	8 Aug 2000*	ETM+	9 Aug 2009	TM
	20 Jul 1996*	TM	21 Jul 1999*	ETM+	31 Aug 2011*	TM
135/034	28 Jun 1988*	TM	23 Sep 1999	ETM+	27 Jul 2010	TM
		TM			31 Aug 2011*	TM
		TM			2 Oct 2011*	TM
136/033	23 Aug 1994	TM	14 Sep 1999*	ETM+	27 Aug 2010*	ETM+
			14 Jul 2000	ETM+	23 Sep 2011	TM
			31 Aug 2000*	ETM+		
			3 Sep 2001*	ETM+		
136/034	13 May 1989	TM	14 Jul 2000*	ETM+	23 Sep 2011	TM
			21 Oct 2001	ETM+		
137/033	17 Sep 1989	TM	7 Sep 2000	ETM+	26 Aug 2010	TM
137/034	19 Aug 1990	TM	7 Sep 2000	ETM+	25 Jul 2010	TM

\*Alternate image.

time, which increases uncertainty in the calculated area change. Since the glaciers were shrinking during past decades, and both images from before and after each specified date were used, errors are likely to offset each other, but due to the ranges of image acquisition dates used, additional errors of ±2%, ±1% and ±1% were added to years 1990, 2000 and 2010 respectively.

In order to verify the horizontal accuracy of our results, GPS measurements of the outline of Qiyi glacier were performed on 31 August 2012. The horizontal precision of the GPS device is 15 m. The average distance between the 27 points measured by the GPS device and the outline of Qiyi glacier is 10.9 m, and the root-mean-square error (RMSE) is 15.4 m. The outline of Qiyi glacier was delineated from a Landsat ETM+ SLC (scan-line corrector)-off image from 25 August 2012 using the above method without manual improvement, and Qiyi glacier is not affected by scan-line errors of the SLC scene.

### 3.3.3. Calculation of glacier area variation

To enhance our understanding of the variability of the glaciers, temporally and spatially comprehensive information on them is needed. We used previously published results from the literature (Table 3) to obtain temporally comprehensive information on glacier changes. The earliest data were from 1956 (Liu and others, 2003; Yang and others, 2007; P. Wang and others, 2011; Yan and others, 2012) and the latest data were from 2010 (Tian and others, 2012a,b,c). Different data sources such as topographic maps, aerial photographs, Landsat and ASTER images, and different methods including unsupervised classification, supervised classification and visual interpretation were used in these studies. Some of these studies provided uncertainties which varied between <1% and 5% (Table 3).

In order to synthesize our results and previous results of glacier area variation, interpolation is required if the data overlapped. Suppose there were two studies A and B. The glacier area in study A changes from A1 to A3 during the period 1980–2005. The glacier area in study B changes from B1 to B3 during the period 1970–90. We interpolate linearly a glacier area A2 in 1990 to study A, as well as a glacier area B2 in 1980 to study B. If any study has more than one time overlap with other studies, we will interpolate linearly as many times as the number of time overlaps in the years. After interpolation of each study, the glacier area changes were calculated using the following method.

The area change for time period *i* (AC<sub>*i*</sub>) is

$$AC_i = \frac{\Delta S_i}{S_{0i}} = \frac{\sum_{j=1}^m \Delta S_{ij}}{\sum_{j=1}^m S_{0ij}}$$

where *j* is the order number of studies, Δ*S<sub>i</sub>* is the summary of the variation of glacier area (km<sup>2</sup>), *S<sub>0i</sub>* is the summary of the glacier area at the initial status (km<sup>2</sup>), Δ*S<sub>ij</sub>* is the variation of glacier area (km<sup>2</sup>), *S<sub>0ij</sub>* is the glacier area at the initial status (km<sup>2</sup>) and *m* is the number of studies for time period *i*.

The annual area change for time period *i* (AAC<sub>*i*</sub>) is

$$AAC_i = \frac{AC_i}{\Delta T_i}$$

where Δ*T<sub>i</sub>* is the time-span for period *i*.

The area change (AC) for the whole time period is

$$AC = \left[ \prod_{i=1}^n (AC_i + 1) \right] - 1$$

The accuracy of glacier delineation depends on the resolution of the utilized image, the conditions at the time of the acquisition, the knowledge of the operator, etc. The mapping uncertainty of our studies is <5%. However, it is

**Table 3.** Glacier area results used in this study. Beidahe basin is located at 38.4–40.7° N, 98.1–99.3° E (Yan and others, 2012). Yeniugou basin is located at 38.1–39.0° N, 98.5–100.0° E (Yang and others, 2007). AP: aerial photographs; map: 1:50 000 topographical maps; CGI: Chinese Glacier Inventory

Location (source)	Year	Glacier area km <sup>2</sup>	Error or data	Location (source)	Year	Glacier area km <sup>2</sup>	Error or data	
Daxueshan1 (Du and others, 2008)	1960	21.5	AP	Lenglongling6 (Liu and others, 2012)	1972	1.4	map	
	1976	21.5	AP		1995	1.3	< 2%	
	1985	21.5	AP		2009	1.2	GPS	
	1990	21.5	TM		Shulenshan1 (Zhang and others, 2011)	1970	428.3	map
	2000	22.1	ETM+			1995	403.4	TM
Daxueshan2 (Zhang and others, 2012)	1957	21.9	map	Shulenshan1 (Zhang and others, 2011)	1999	391.5	ETM+	
	1994	21.6	TM		2002	384.9	ETM+	
	2000	21.4	ETM+		2006	373.3	TM	
	2007	21.1	GPS	Shulenshan2 (Y. Wang and others, 2008)	1966	492.9	AP	
Lenglongling1 (Cao and others, 2010)	1972	103.0	map		1999	458.2	ETM+	
	1994	90.2	TM	Shulenshan3 (Tian and others, 2012a)	1976	171.7	MSS	
	2000	84.5	CBERS-2		1990	84.3	±3%	
2007	78.7	ASTER	2001		77.8	±3%		
Lenglongling2 (H. Zhang and others, 2010)	1970	53.6	map	2010	53.9	±3%		
	1995	46.2	TM	Western Qilian mountains (Liu and others, 2003)	1956	162.8	map	
	1999	36.1	ETM+		1990	155.1	TM	
	2002	32.3	ETM+	Middle Qilian mountains (P. Wang and others, 2011)	1956	397.4	map	
2009	30.2	ETM+	2003		311.0	ASTER		
Lenglongling3 (Pan and others, 2012)	1972	86.2	AP	Yeniugou basin (Yang and others, 2007)	1956	63.1	CGI	
	1995	70.5	TM		1971	57.0	map	
	1999	66.9	ETM+		2003	46.9	<1%	
	2002	64.6	ETM+		Tuegendabanshan (Tian and others, 2012b)	1974	68.8	MSS
2007	61.8	ASTER	1990	63.2		±3%		
Lenglongling4 (Zhao, 2009)	1956	103.0	CGI	1999		61.3	±3%	
	2002	73.2	ETM+	2010	59.3	±3%		
	Lenglongling5 (Tian and others, 2012c)	1973	78.1	MSS	Qilian mountains1 (R. Zhang and others, 2010a,b)	1975	2061.9	MSS
1999		51.0	±3%	2000		1847.1	ETM+	
2010		34.2	±3%	Qilian mountains2	This study	1990	2041.5	±5%
Beidahe basin (Yan and others, 2012)	1956	217.5	map			2000	1802.7	±4%
	2003	184.0	ASTER			2010	1575.8	±4%

difficult to evaluate the uncertainty of the results from previous studies, because different operators used different data sources and methods. The uncertainty is lower in recent times than earlier times due to the availability of higher-resolution images and better methods. Accordingly, the overall uncertainty of glacier area change from 1956 to 2010 is estimated to be no more than 8%.

## 4. RESULTS

### 4.1. Temperature and precipitation trends

The temperature analysis revealed an increase in temperature from 1961 to 2010 (Table 1; Figs 3 and 4). Annual air temperatures of the glacierized areas, and from each of the six stations have increased since the 1990s. The increase in these temperatures became significant after 2000. All MJJAS (May–September) air temperatures of glacierized areas, and from the six stations, increased in the late 1990s and this increase also became significant after 2000 (Fig. 4). However, the temperature increase varied spatially. In general, the increasing trends in both annual air temperature and MJJAS air temperature became stronger when moving from east to west (Fig. 3).

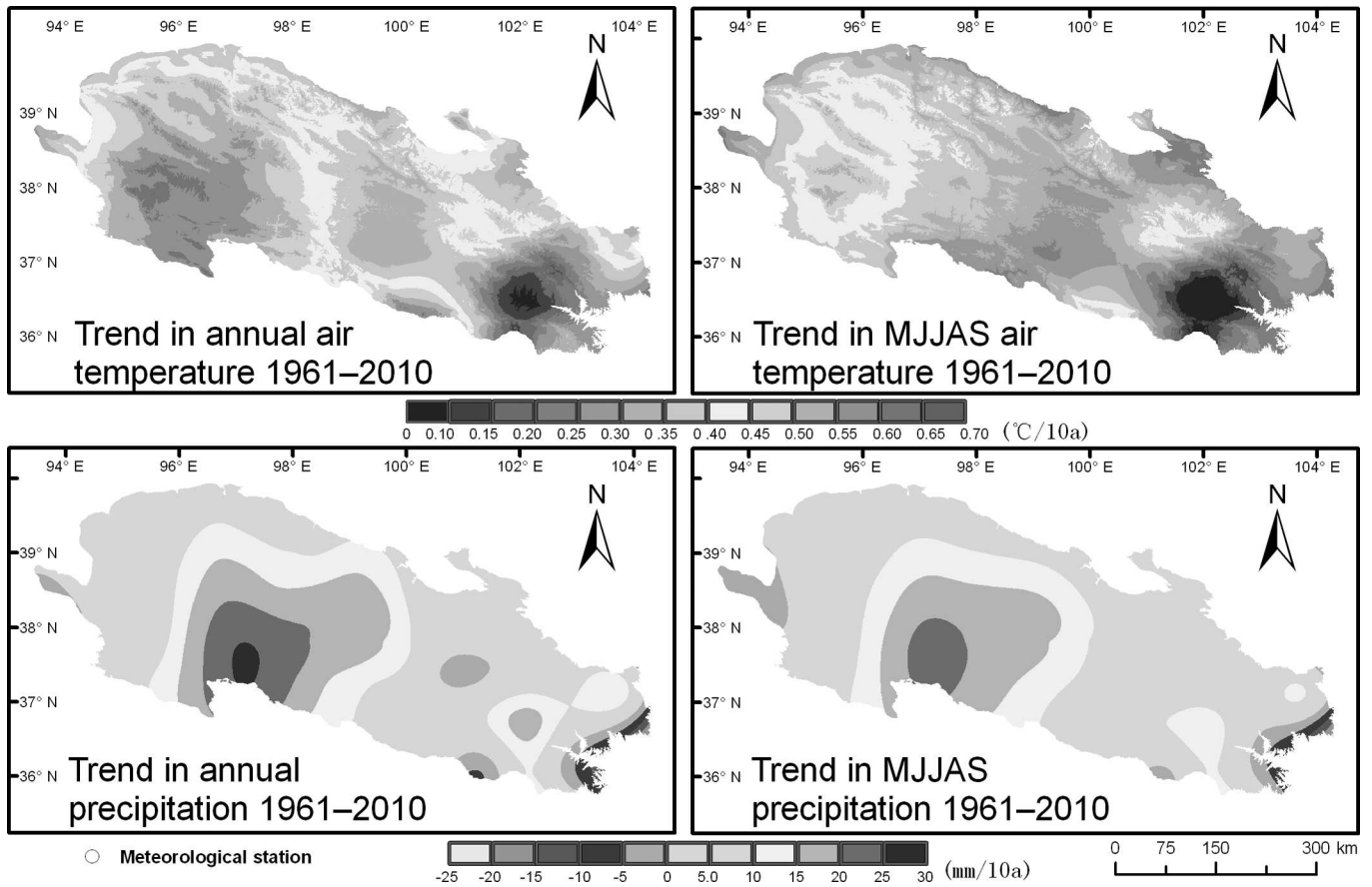
Both annual and MJJAS precipitation increased from 1961 to 2010, but the increase was not significant (Table 1; Figs 3 and 4). The greatest increase in precipitation occurred in the mid-southern portion of the Qilian mountains (Fig. 3).

### 4.2. Characteristics of glacier distribution

More glaciers are distributed in the western portion of the Qilian mountains than in the eastern portion (Table 4). The peaks of maximum glacier areas in 1990, 2000 and 2010 are at ~5000 m (Fig. 5a), which is close to the present ELAs (Wang and others, 2010). The altitude of glaciers ranges from ~3800 to ~5800 m. The glaciers in the eastern portion are at lower elevations than those in the western portion (Table 4). The glacier area increases with size class (Fig. 5b). Generally, glaciers in the eastern portion are smaller than those in the western portion (Table 4). There are more glaciers that have a north-facing aspect than a south-facing aspect (Fig. 5c).

### 4.3. Glacier change

Based on our data, the glacier area shrank  $23 \pm 5\%$  from 1990 to 2010, at an accelerating rate in the last decade. Based on previous studies and our data (Table 3), the glacier



**Fig. 3.** Trends in annual air temperature, MJJAS air temperature, annual precipitation and MJJAS precipitation during 1961–2010. Source: China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn/>).

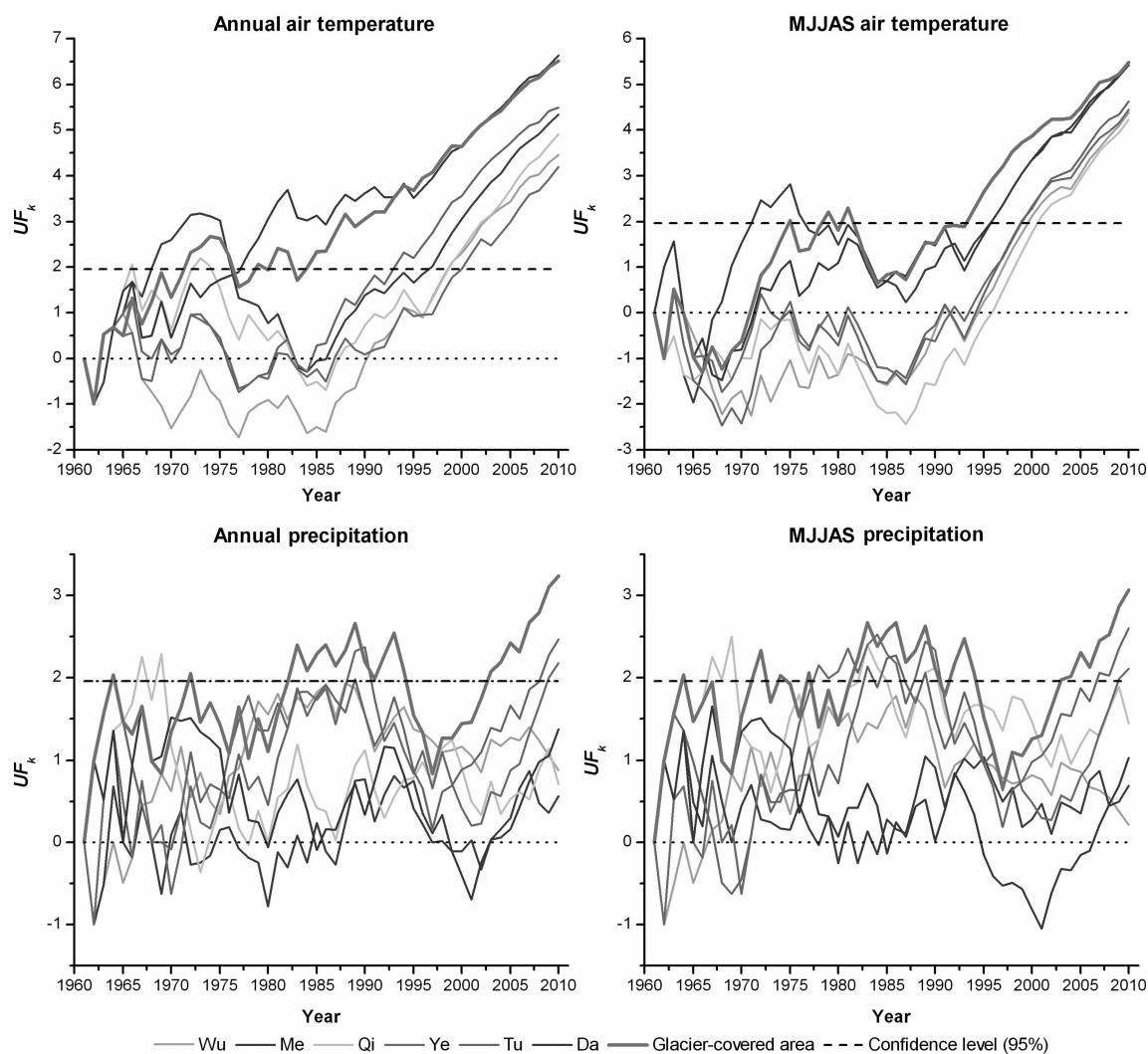
area shrank  $30 \pm 8\%$  from 1956 to 2010 and the shrinkage accelerated from 1990. We consider the almost constant rate of change from 1956 to 1965 and 1975 to 1985 to be mainly due to lack of data (Fig. 5d). The decrease in shrinkage rate from 1965 to 1975 may be related to the decreasing MJJAS air temperature in this time period (Figs 4 and 5d).

The pattern of the rate of change in glacier area below 4300 m is complicated because glacier distribution (Figs 5a

and 6a) is scarce and a variety of factors can influence the behavior of the glacier terminus. Accelerated shrinkage at middle elevations from 4400 to 4900 m a.s.l. (Fig. 6a) may be related to rising temperature. The decreasing shrinkage rate above 5000 m (Fig. 6a) may be the result of the recent increase in precipitation. In our opinion, glaciers at lower elevations (ablation zone) respond quickly to temperature changes while glaciers at higher elevations (accumulation zone) respond quickly to precipitation changes.

**Table 4.** Glacier area distribution in the Qilian mountains from 1990 to 2010 and glacier parameters for each mountain range in 1990. Mountain ranges are ordered from east to west. GA: glacier area

Mountain range	Symbol (Fig. 1)	GA in 1990 km <sup>2</sup>	GA in 2000 km <sup>2</sup>	GA in 2010 km <sup>2</sup>	Elevation in 1990			GA distribution (km <sup>2</sup> ) in 1990					
					Min. m	Ave. m	Max. m	<0.1 %	0.1–0.5 %	0.5–1 %	1–2 %	2–5 %	>5 %
Lenglongling	Le	100.69	60.82	47.90	3909	4448	5218	3.1	21.5	23.2	31.3	20.8	0.0
Zoulangnanshan	Zo	325.19	255.77	187.94	3819	4624	5571	2.5	20.4	21.2	26.6	24.9	4.4
Tuolaishan	Tl	42.15	30.95	18.31	4010	4515	5119	9.3	49.9	27.8	12.9	0.0	0.0
Tuolainanshan	Tn	117.12	111.59	91.76	3921	4670	5297	2.1	30.3	32.5	21.6	13.6	0.0
Shulenanshan	Sh	570.19	546.77	492.01	4194	4934	5789	0.5	6.2	8.8	12.7	33.0	38.7
Haerkeshan	Ha	18.53	17.62	13.16	4478	4775	5151	1.6	49.5	20.0	28.9	0.0	0.0
Daxueshan	Dx	173.15	153.72	141.54	4124	4845	5463	1.0	8.9	9.6	15.5	20.4	44.6
Danghenanshan	Da	189.41	161.73	153.49	4224	4944	5649	1.2	11.1	16.8	19.2	40.5	11.2
Chahanebotuling	Ca	21.77	16.27	14.17	4529	4912	5244	4.2	22.4	32.4	19.5	0.0	21.5
Tuergendabanshan	Tu	449.64	418.69	389.21	4473	5045	5698	0.4	4.3	9.4	15.8	18.2	51.9
Chaidamushan	Ch	33.66	28.77	26.33	4696	5160	5724	0.8	11.2	6.7	8.1	48.1	25.1
Whole region	–	2041.5	1802.7	1575.82	3819	4919	5789	1.6	15.1	15.5	19.2	23.8	24.9



**Fig. 4.** Mann-Kendall analysis of annual air temperature, MJJAS air temperature, annual precipitation and MJJAS precipitation during 1961–2010.

Small glaciers had higher relative change rates than larger glaciers from 1990 to 2010, which is consistent with previous studies (Bolch and others, 2010a; Narama and others, 2010) that suggest small glaciers are more sensitive to climate change than large glaciers. Shrinkage of glaciers of all sizes has accelerated during the past decade (Fig. 6b).

In addition, as shown in Figure 6c, west-, southwest-, south-, southeast- and east-facing glaciers shrank faster than the others from 1990 to 2010. Accelerated shrinkage in northwest-, north- and northeast-facing aspects has occurred mainly during the past decade (Fig. 6c). One reason for faster shrinkage of glaciers that have W-SW-S-SE-E aspects is that they are smaller than those with NW-N-NE aspects. Other factors (e.g. radiation, relative humidity and temperature) may also play a role, but analysis of these requires further research.

The shrinkage characteristics differed between the different mountain ranges. In particular, the Lenglongling, Zoulangnanshan and Tuolaishan have lost more area than the other ranges during the past two decades. The loss rate has accelerated in the past decade only for the Zoulangnanshan, Tuolaishan, Tuolainanshan, Shulenanshan, Haerkeshan and Tuergendabanshan (Figs 1 and 6d).

As seen in Figure 7, glaciers in the eastern part of the study area shrank more rapidly than those in the western

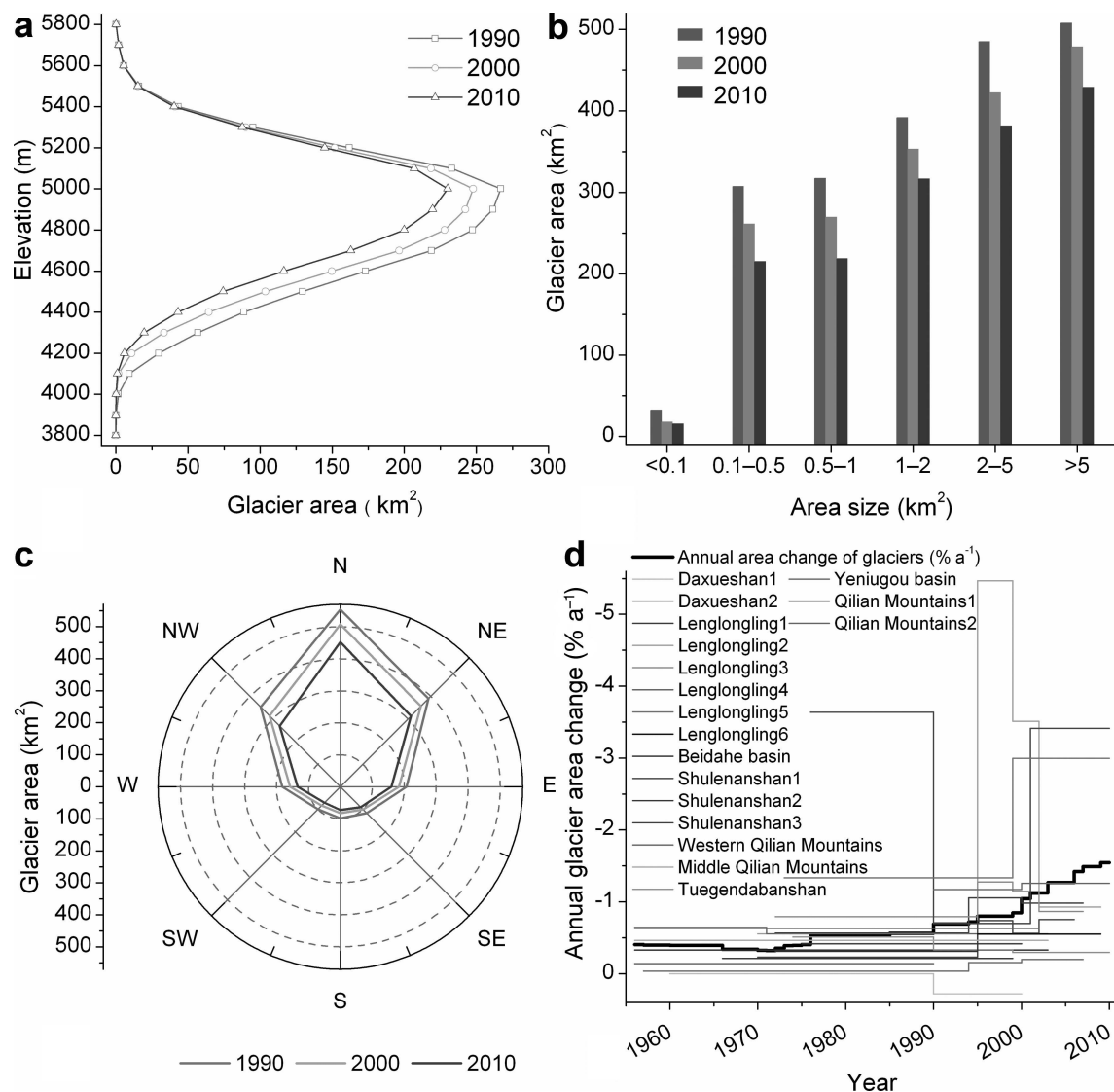
part. However, there are no obvious patterns of glacier area change from north to south from 1990 to 2010.

## 5. DISCUSSION AND CONCLUSIONS

Bolch and others (2010b) reported that the Chinese Glacier Inventory contains some inaccuracies and geolocation errors, and these are confirmed by our study. Geolocation errors are relatively common in the Chinese Glacier Inventory, and the data should be used with caution, especially in spatial change analysis (e.g. change with aspect), otherwise false results may be produced.

A recent study suggested the lag time between climate change and glacier response in the eastern Qilian mountains is probably ~5–8 years (Pan and others, 2012), although this varies with glacier size, type, location, altitude, etc. In accumulation zones, glacier area may respond quickly to precipitation changes. The decreasing shrinkage rate in accumulation zones may be the result of the recent increased precipitation (Fig. 4), which partly compensated for the melt effect of increasing temperature.

Contrary to the findings of Jacob and others (2012), the shrinkage of glaciers in the Qilian mountains during the past two decades (Figs 5d and 6a), the significant temperature increase after 2000 (Fig. 4), the rising ELA (Wang and others,



**Fig. 5.** (a) Glacier area distribution at different elevations. (b) Glacier area distribution by size. (c) Glacier area distribution by aspect. (d) Annual glacier area changes in the study area from 1956 to 2010. The bold black line shows annual glacier area changes in the whole Qilian mountains and colored lines show annual glacier area changes for each study (Table 3).

2010) as well as the observed mass balance (Yao and others, 2012) suggest that it is very unlikely the mass balance was positive in the study area from 2003 to 2010.

In general, the glacier shrinkage in the Qilian mountains is in line with increased air temperatures. Although precipitation increased slightly from 1961 to 2010 (Table 1; Figs 3 and 4), which helped glacier accumulation, increasing temperature appears to have led to significant melting of glacier ice, which exceeded snow accumulation. The ongoing trend of rapid glacier shrinkage will most likely continue given the temperature increase projected by the Intergovernmental Panel on Climate Change (Solomon and others, 2007).

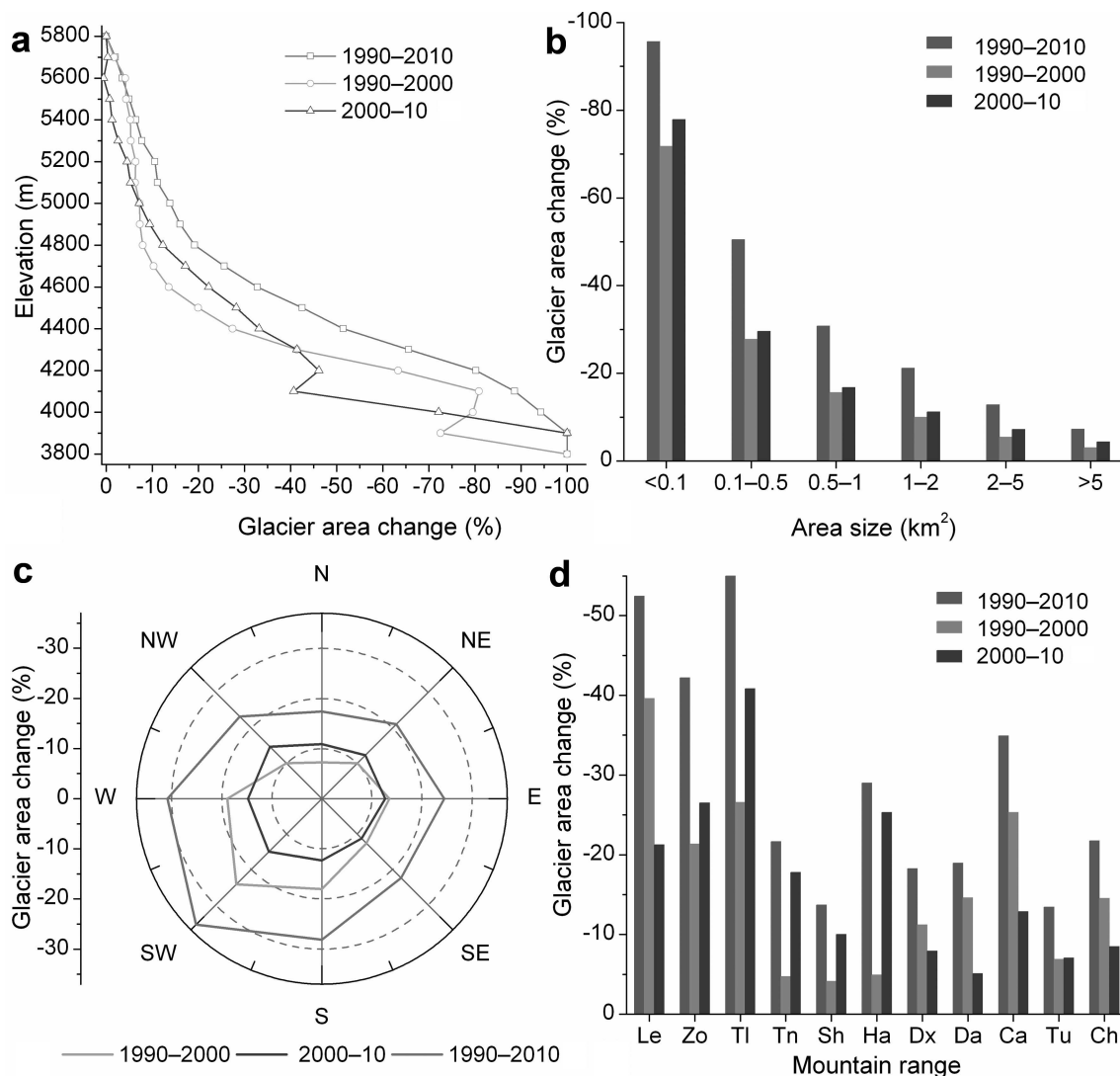
Although glaciers have generally shrunk under increasing temperatures, glacier area has decreased more in the eastern part of the study area than in the western part owing to the following factors:

1. The elevation of glaciers is generally lower in the eastern part than in the western part. Thus, glaciers in the eastern part experienced more significant ice melt due to higher air temperatures than in the western part at higher elevation (Table 4; Fig. 2).

2. The size of glaciers is generally smaller in the eastern part than in the western part. Smaller glaciers are more sensitive to climate change. Hence, when temperatures increased, they shrank more rapidly than larger glaciers.
3. Glaciers in the eastern part are mainly of the subcontinental type, whereas those in the western part are mostly of the extreme continental type. Subcontinental-type glaciers are more sensitive to climate change. Thus, as the temperature increased, glaciers in the eastern part shrank more rapidly than those in the western part.
4. The eastern part of the study area is influenced by the East Asia monsoon. The weakening of the East Asia monsoon might contribute to the rapid shrinkage of glaciers in this part (Yao and others, 2012).

The reason for the decreasing shrinkage rate in the Lenglongling mountains (symbol Le) may be that when glacier areas decrease, other factors (e.g. topography) become more important (DeBeer and Sharp, 2009). The decreasing shrinkage rate in mountain ranges in the western part (Fig. 6d) may be related to its high elevation where





**Fig. 6.** Glacier area changes (a) at different elevations, (b) for different area size, (c) in each direction and (d) in each mountain range from 1990 to 2010.

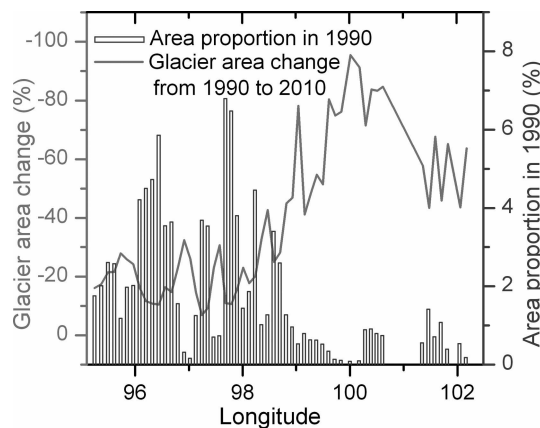
increasing precipitation more easily compensates for the melt effect of increasing temperature.

Our results ( $-12 \pm 4\%$  from 2000 to 2010) indicate that glacier changes in the Qilian mountains are smaller than those in the southeastern Tibetan Plateau (e.g. 16.6% shrinkage in Yulong mountain ( $27.4^\circ\text{N}$ ,  $100.2^\circ\text{E}$ ) between 2001 and 2009) (Du, 2011), but larger than those in the central Tibetan Plateau (e.g.  $\sim 2\%$  decrease in the Qiangtang plateau ( $34.4^\circ\text{N}$ ,  $86.1^\circ\text{E}$ ) between 1990 and 2000) (L.P. Wang and others, 2011).

Many factors (e.g. temperature, precipitation, wind speed, cloud coverage, relative humidity, elevation, aspect, glacier size and glacier type) can influence glacier change. The influence is very complicated, with the dominant factors varying with circumstances and time. Thus, evidently, accelerated shrinkage varied spatially.

Problems associated with glacier shrinkage include glacier hazards such as ice avalanches and GLOFs (Kääb and others, 2005; Narama and others, 2010; Bolch and others, 2011). Although detailed investigations are ongoing, we noticed from the imagery used in this study that proglacial lakes have developed rapidly during the past two decades. GLOFs may thus become an increasing threat

in the Qilian mountains. The above factors emphasize the need for strengthening research concerned with monitoring glacial recession, glacier-related hazards, effects of glacial recession on water sources, and sustainable water-use practices.



**Fig. 7.** Glacier area change with longitude from 1990 to 2010.

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## APPENDIX: LOCATIONS AND ELEVATIONS OF METEOROLOGICAL STATIONS UTILIZED

Meteorological station	Symbol	Lat. °N	Long. °E	Elevation m a.s.l.
Dunhuang	1	40°09'	94°41'	1145
Yumenzhen	2	40°16'	97°02'	1521
Jiuquan	3	39°46'	98°29'	1475
Gaotai	4	39°22'	99°50'	1350
Alashanyouqi	5	39°13'	101°41'	1530
Lenghu	6	38°45'	93°20'	2793
Zhangye	7	38°56'	100°26'	1481
Shandan	8	38°48'	101°05'	1772
Yongchang	9	38°14'	101°58'	1977
Wuwei	10	37°55'	102°40'	1527
Delingha	11	37°22'	97°22'	2966
Gangcha	12	37°20'	100°08'	3322
Songshan	13	37°07'	103°30'	2728
Jingtai	14	37°11'	104°03'	1638
Wulan	15	36°55'	98°29'	2962
Chaka	16	36°47'	99°05'	3090
Qiabuqia	17	36°16'	100°37'	2824
Xining	18	36°43'	101°45'	2298
Guizhou	19	36°02'	101°26'	2228
Minhe	20	36°19'	102°51'	1812
Gaolan	21	36°21'	103°56'	1672
Tongren	22	35°31'	102°01'	2495
Linxia	23	35°35'	103°11'	1911
Dachaidan	Da	37°51'	95°22'	3204
Menyuan	Me	37°23'	101°37'	2882
Qi	Qi	38°11'	100°15'	2721
Tuole	Tu	38°48'	98°25'	3361
Wushangling	Wu	37°12'	102°52'	3029
Yeniugou	Ye	38°25'	99°35'	3224