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Glacier Changes on the Qiangtang Plateau between 1976 and 2015: A Case Study in the Xainza Xiegang Mountains

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Abstract: Xainza County on the Qiangtang Plateau (QP) spans a transitionally climatic and eco-environmental zone and is therefore a very sensitive region. Glaciers in this area are one of the most important kinds of land cover as well as key water resources, yet our understanding of their current status and spatio-temporal change remains limited. Using Landsat images, this study investigated the current distribution of glaciers (2015) in the Xainza Xiegang Mountains as well as the spatio-temporal changes that took place over six time periods between 1976 and 2015. Results show that, in 2015, 131 glaciers covered a total area of 74.59 ± 5.25 km^2, mainly located between 5,600 and 6,000 m above sea level (a.s.l). Between 1976 and 2015, the total number of glaciers increased by 12, while their areas decreased by 24.98% (24.83 km^2). Glacial retreat has induced a loss of water resources of 11.77 × 10^8 m^3 over the last 39 years, while spatial heterogeneities in glacial changes across various sub-basins, aspects, and altitudinal zones are also clearly observed. Climate warming is the key factor driving this continuous glacial retreat; the high-quality dataset presented in this paper for the Xainza Xiegang study area is crucial for the ongoing assessment of climatic and eco-environmental changes.

Key words: Glacier; water resources; remote sensing; Landsat images; Qiangtang Plateau

1 Introduction

As glaciers are amongst the most important water resources globally, they are also sensitive indicators of climate change (Kääb *et al.*, 2012). The Tibetan Plateau (TP) (Zhang *et al.*, 2002), which is known as the world's third pole, contains the largest area of glaciers outside the Arctic and Antarctic (Gardner *et al.*, 2013; Yao *et al.*, 2012). Measurements show that glaciers on the TP are gradually losing their mass balance (Bolch *et al.*, 2012; Kääb *et al.*, 2012; Li, 2014; Yao *et al.*, 2012), which will affect regional water availability (Immerzeel *et al.*, 2013), increase the risk of outburst floods from glacial lakes (Chen *et al.*, 2015; Nie *et al.*, 2013; Nie *et al.*, 2017; Wang *et al.*, 2012; Wang *et al.*, 2013; Yao *et al.*, 2012), and impact decision making for the sustainable management of ecology and environment (Nie *et al.*, 2010). Global and regional glacier inventory data, including global land ice measurements from space (Armstrong *et al.*, 2011; Kargel *et al.*, 2005), the Randolph glacier inventory (RGI) (Pfeffer *et al.*, 2014), the China glacier inventory (CGI) (Guo *et al.*, 2015; Shi *et al.*, 2010), and the Gamdam glacier inventory (GGI) (Nuimura *et al.*, 2015) all lend strong support to global modeling efforts aimed at improving our understanding of the status of glaciers and their responses to climate change. However, the productions of large-scale glacier inventories, of global, continental, and national scope, are extremely time-consuming, and global dynamic

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monitoring of glaciers currently remains incomplete. Recently, Chinese researchers completed the second CGI (Guo *et al.*, 2015; Liu *et al.*, 2014) and they applied these data to the analysis of dynamic changes in some areas (Liu *et al.*, 2015; Liu *et al.*, 2016), increasing our knowledge of spatio-temporal glacier changes.

Satellite remote sensing is considered to be the most appropriate technique for monitoring glacial changes in high mountainous areas. Of these, the Landsat series were first launched in 1972 with the most recent, Landsat 8, was launched in 2013 (Roy *et al.*, 2014). Landsat products provide the longest continuous record of the earth's surface and they have been widely applied in glacier change analyses, including at Bugyai Kangri, southeast Tibet (Liu *et al.*, 2016), in the Lancang river basin (Liu *et al.*, 2015), in the Qomolangma mountain (Everest) region (Nie *et al.*, 2010), at seven sites in the Hindu Kush Himalayas (Gardelle *et al.*, 2011), in the Qilian Mountains (Xu *et al.*, 2013), and in the western Canada (Bolch *et al.*, 2010). The latest Landsat 8 images have also begun to be used to map the extent of glaciers (Ke *et al.*, 2015) and they can provide up-to-date data on their state, which is important for studies of climate change, ecology, and the environment.

Xainza county on the middle TP (also the southern QP), encompassing a transitional zone between alpine meadow and steppe grassland, is one of the best places to monitor the ecological and environmental changes that have taken place as the result of the construction of the national ecological security barrier in Tibet. Thus, in order to monitor and assess the status of ecosystems in this region and to determine how they have been affected by global change and human development, the Chinese Academy of Sciences sponsored and built the Xainza Alpine Steppe and Wetland Ecosystem Observation Station near Xainza city in 2010. Glaciers in Xainza County are one important constituent of the terrestrial environment, contributing significantly to local water resources and ecology. However, the most recent status and spatio-temporal heterogeneity of glaciers in Xainza County has not been systematically investigated.

The objectives of this study are therefore: 1) To investigate the current distribution (2015) of glaciers in this region using Landsat 8 images; 2) To determine the changes in glaciers as well as their spatial heterogeneity using a series of consistent Landsat images encompassing the six time periods, 1976, 1989, 2000, 2007, 2009, and 2015, and 3) To promote our knowledge of the relationship between glacier changes, water resources, and associated eco-environmental effects.

2 Materials and methods

2.1 Study area

This study focuses on the glaciers in the Xainza Xiegang (abbr. XX) Mountains in Xainza County (Fig. 1). This county encompasses an area of 23 × 10^3 km^2, has a mean altitude of 4700 m a.s.l., and is located between Nyima and Baingoin in the west and east, and between Namling, Xaitongmion and Shuanghu in the north and south. A number of lakes are located in this area, including Siling Tsho, Kering Tsho, and Uru Tsho, while the climate is typical of a plateau, subfrigid and semi-arid, with an average annual temperature of 0.33℃ and a mean annual precipitation of 324 mm between 1976 and 2015. The highest peak in the XX Mountains is Mount Jiagang (6444 m a.s.l., located at 88.6°E, 30.8°N), 10 km from Xainza city. A number of endorheic rivers, including Xainza Zangbo and Baru Zangbo, run into Kering Tsho from the south, while glacial meltwater is a key water resource for the nearby settlements. According to the Sixth National Census, 20,285 people live in Xainza County, animal husbandry is their chief source of income, and major land uses are alpine grasslands and meadows.

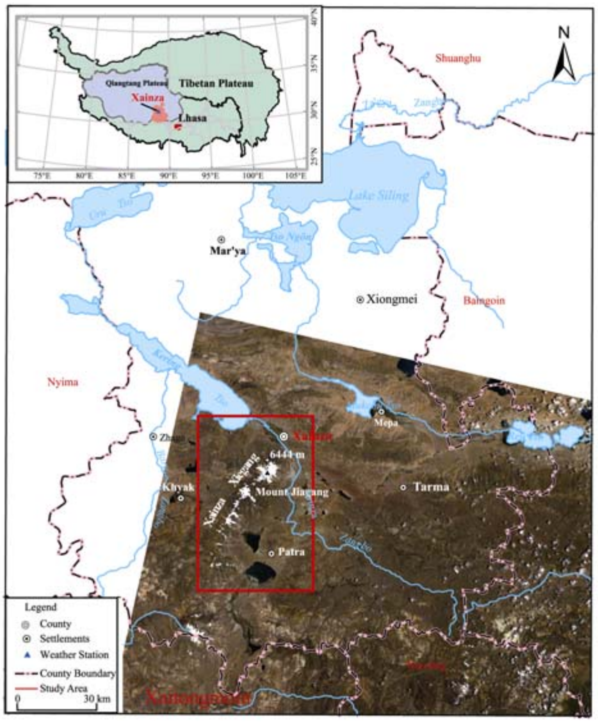

Fig.1 Location of the study area

2.2 Data

We downloaded Landsat satellite images from the United States Geological Survey and used them to map the extent of glaciers in 1976, 1989, 2000, 2007, 2009, and 2015 (Table 1). These images are the best available data across our study area after searching the Landsat archives. With the exception of the Multi-Spectral Scanner (MSS), which has a spatial resolution of 57 m, images from other sensors, including Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI), all have a consistent spatial resolution of 30 m. Different spatial resolutions may cause uncertainty in glacier change analysis (Nie *et al*., 2017). It is arduous to quantitatively analyze the uncertainty from the difference of spatial resolution of source data. The uncertainty due to the difference in spatial resolution seems to be negligible in accordance to the comparison among Landsat images in the study area. The valuable Landsat MSS data are the earliest record for earth land surface and help extend research period as long as 1970s. To reduce the effects of differences in acquisition date on glacier changes, we used images from similar seasons, mostly acquired in November, although one was taken in October and another in December (Table 1). All the images used in this study were the best available and largely cloud free.

Additional datasets used in this study include meteorological measurements from Xainza station provided by the China Meteorological Administration, shuttle radar topography mission digital elevation model (SRTM DEM) data with a 3-arc second (90 m) resolution (Jarvis *et al*., 2008), CGI (Guo *et al*., 2015; Shi *et al*., 2010), the GGI (Nuimura *et al*., 2015) and RGI (Pfeffer *et al*., 2014) data, high-resolution images from Google Earth, as well as data from a 2012 field survey and thematic data encompassing roads, rivers, and lakes.

2.3 Methods

We extracted the extent of glaciers for the six time periods between 1976 and 2015 using the object-oriented automatic mapping and human validation methods proposed by Nie *et al.* (2010). The normalized difference snow/ice index (Andreassen *et al*., 2008; Hall *et al*., 1998) was an optimal parameter to extract glacial extent during processing; our automatic mapping tended to generate good glacial extents as corroborated via source images. Nevertheless, visual inspection and correction based on high-quality Landsat images, DEM, or high-resolution Google Earth images are necessary steps to avoid the misclassification of glaciers as a result of topographic shadows, snow or cloud cover. It is also difficult to map debris-covered glaciers using satellite images (Racoviteanu *et al*., 2008) because they have similar spectra compared to other moraines, bare soils, and rocks. However, because Landsat and Google Earth images show that these kinds of debris-covered glaciers are rare in the study area, this reduces workload and enhances mapping accuracy. An additional step incorporated into this analysis involved cross-checking each glacier data over six episodes using multi-temporal images. Although this further inspection step is time-consuming, we consider it to be essential to generate high-quality glacier data.

Table 1 List of Landsat images used in this study

Order	Acquisition date	Path	Row	Sensor	Resolution/m
One	12/19/1976	150	39	MSS	57
Two	11/10/1989	139	39	TM	30
Three	11/8/2000	139	39	TM	30
Four	10/27/2007	139	39	ETM+	30
Five	11/25/2009	139	39	TM	30
Six	11/15/2015	139	39	OLI	30
Seven	07/05/2015*	139	39	OLI	30

*Auxiliary image used for interpretation

Topological validation, including the elimination of small sliver polygons and repeat removals, was also conducted with the minimum mapping unit of nine pixels, 0.0081 km^2, used in this study. All images were also exactly ortho-rectified; our data show that image registration error has little effect on glacial change, while uncertainty in glacial area was estimated using an error of ± 0.5 pixels and perimeters as reported in previous studies (Bolch *et al*., 2010; Liu *et al*., 2016; Wei *et al*., 2014). Glacier volume (*V*) was calculated using the regression equation between *V* and glacial surface area (*S*) (Liu *et al*., 2003), as follows:

$$V = 0.04S^{1.35} \qquad (S \text{ in km}^2,\ V \text{ in km}^3) \qquad (1)$$

3 Results

3.1 The distribution of glaciers between 1976 and 2015

Our mapping result shows that 119 glaciers covering an area of 99.43 ± 5.85 km^2 were observed in 1976. The total volume of these glaciers was 4.67 ± 0.09 km^3, equating to an equivalent volume of water of (42.07 ± 0.79) × 10^8 m^3. In 1989, 128 glaciers were present covering an area of 92.56 ± 6.16 km^2, while 133 were present in 2000 covering an area of 85.73 ± 6.07 km^2, 135 were present in 2007 covering an area of 79.03 ± 5.65 km^2, and 131 glaciers were present in 2009 covering an area of 75.75 ± 5.48 km^2. Our glacier mapping technique, based on Landsat-8 images, revealed 131 glaciers in 2015, covering a total area of 74.59 ± 5.25 km^2 (Table 2). Thus, the estimated glacier volume in 2015 was 3.37 ± 0.08 km^3, which was equivalent to (30.30 ± 0.70) × 10^8 m^3 of water.

Because our image data reveal that glaciers were located in a number of different watersheds, we divided the study area into five (Fig. 2). Overall, glaciers were distributed mainly in sub-watersheds one, two, and three (Table 3), with those in one and three accounting for 65.79% of entire glacial area, 68.54% of glacier volume, and supplying freshwater to Xainza city.

Table 2 Area of glaciers and equivalent volumes for the six time periods in this study

Year	Number	Area (km^2)	Volume (km^3)	Water equivalent (m^3)
1976	119	99.43 ± 5.85	4.67 ± 0.09	(42.07 ± 0.79) × 10^8
1989	128	92.56 ± 6.16	4.23 ± 0.09	(38.11 ± 0.84) × 10^8
2000	133	85.73 ± 6.07	3.87 ± 0.09	(34.80 ± 0.82) × 10^8
2007	135	79.03 ± 5.65	3.52 ± 0.08	(31.79 ± 0.75) × 10^8
2009	131	75.75 ± 5.48	3.41 ± 0.08	(30.67 ± 0.73) × 10^8
2015	131	74.59 ± 5.25	3.37 ± 0.08	(30.30 ± 0.70) × 10^8

Table 3 Distribution of glaciers and water resources within the five sub-watersheds in 2015

Sub-watershed	Area		Volume		Equivalent water
	km^2	%	km^3	%	m^3
One	31.26 ± 1.81	41.91 ± 5.24	1.64 ± 0.03	48.61 ± 1.83	$(14.73 \pm 0.27) \times 10^8$
Two	17.06 ± 1.02	22.87 ± 4.73	0.81 ± 0.02	23.98 ± 1.93	$(7.27 \pm 0.14) \times 10^8$
Three	17.82 ± 1.49	23.89 ± 3.76	0.67 ± 0.02	19.93 ± 3.06	$(6.04 \pm 0.18) \times 10^8$
Four	6.16 ± 0.63	8.26 ± 3.21	0.20 ± 0.01	5.88 ± 4.08	$(1.78 \pm 0.07) \times 10^8$
Five	2.30 ± 0.30	3.08 ± 2.35	0.05 ± 0.00	1.60 ± 5.97	$(0.49 \pm 0.03) \times 10^8$
Sum	74.59 ± 5.25	100.00 ± 4.51	3.37 ± 0.08	100.00 ± 2.30	$(30.30 \pm 0.70) \times 10^8$

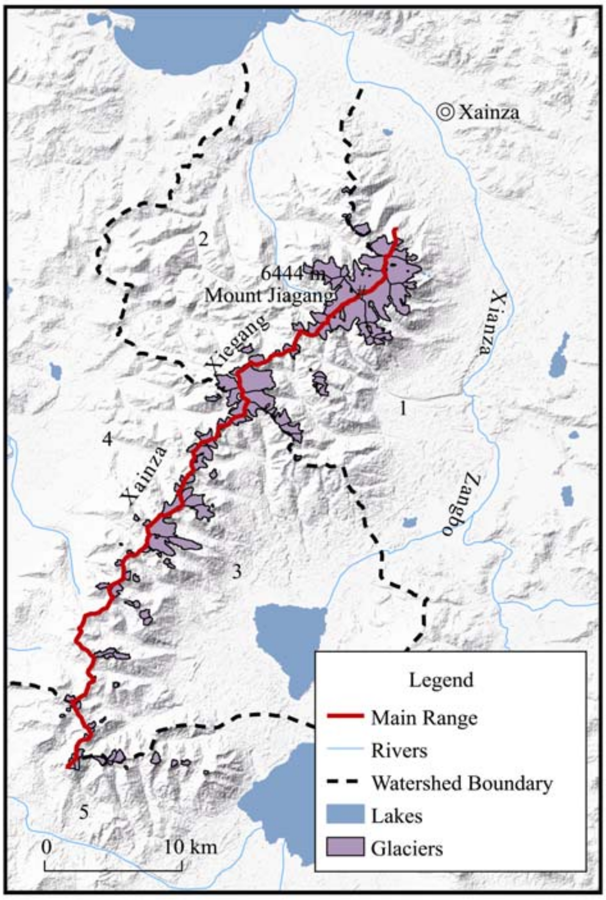

Fig.2 Distribution of glaciers in 2015

Data show that there is a distinct distribution to the gradients of glaciers in this study (Fig. 3). Overall mean gradient was 20°, most glaciers (80.26%) had gradients between 5° and 35°, while just 3.42% were located in flat areas where the slope was less than or equal to 5°. In contrast, those in steep areas, where the slope was greater than or equal to 45°, accounted for 3.19%.

Because of the northeast-to-southwest orientation of the XX Mountains, the glaciers in this study were predominantly orientated northwest and southeast (Fig. 4). Glaciers with a southeast facing aspect encompassed the maximum area in 2015, with smallest areas facing to the northwest and northeast.

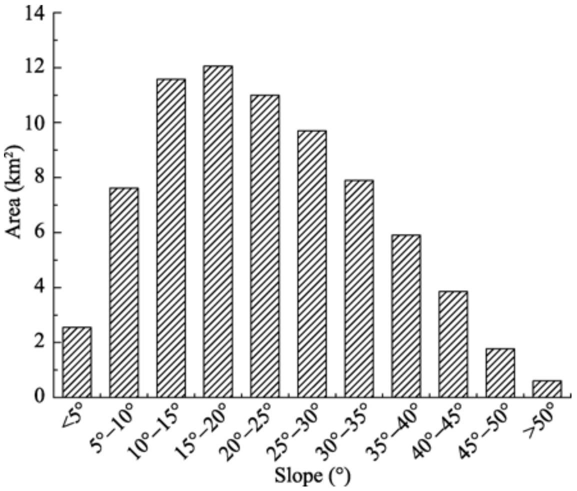

Fig.3 Gradient characteristics of glaciers in 2015

The numerical distribution of these glaciers was almost entirely consistent with their area allocation in 2015, with the largest number facing southeast and the smallest facing north.

3.2 Glacier variation between 1976 and 2015

3.2.1 Changes in glacier numbers and areas

Our results show that the number of glaciers has continued to increase over the last 39 years, while glacier area has decreased (Fig. 5 and table 4). Indeed, the number of glaciers in the study area increased by 12 between 1976 and 2015, partly because several were subdivided into independent entities as a result of shrinkage. Data show that the number of glaciers increased continuously between 1976 and 2007, decreased between 2007 and 2009, and remained stable between 2009 and 2015. Both the decrease and increase of glacier numbers occurred continuously between 1976 and 2015 (Table 4), while glacial area continued to shrink between 1976 and 2015, decreasing by 24.83 km^2 (24.98%). The rate of glacial shrinkage accelerated between 1976 and 2009, with maximum annual shrinkage rate (1.64 $km^2 \cdot yr^{-1}$) between 2007 and 2009, and minimum annual shrinkage rate (0.26 $km^2 \cdot yr^{-1}$) between 2009 and 2015. The mean shrinkage rate reached as high as 0.64 $km^2 \cdot yr^{-1}$ between 1976 and 2015, while the glacial water resource volume reduced during the study period, an inevitable response to

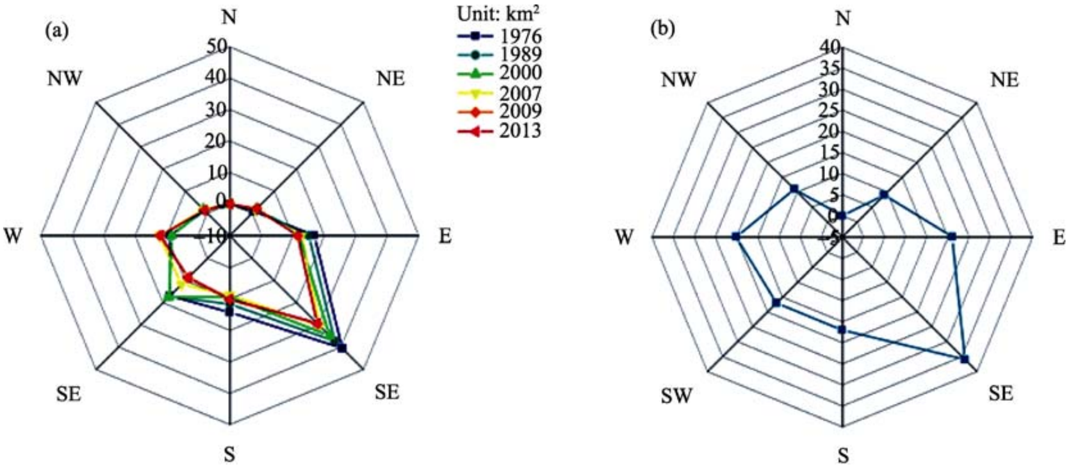

Fig.4 Distributions of glaciers in various aspects (a) glacial areas between 1976 and 2015, (b) glacier numbers in 2015

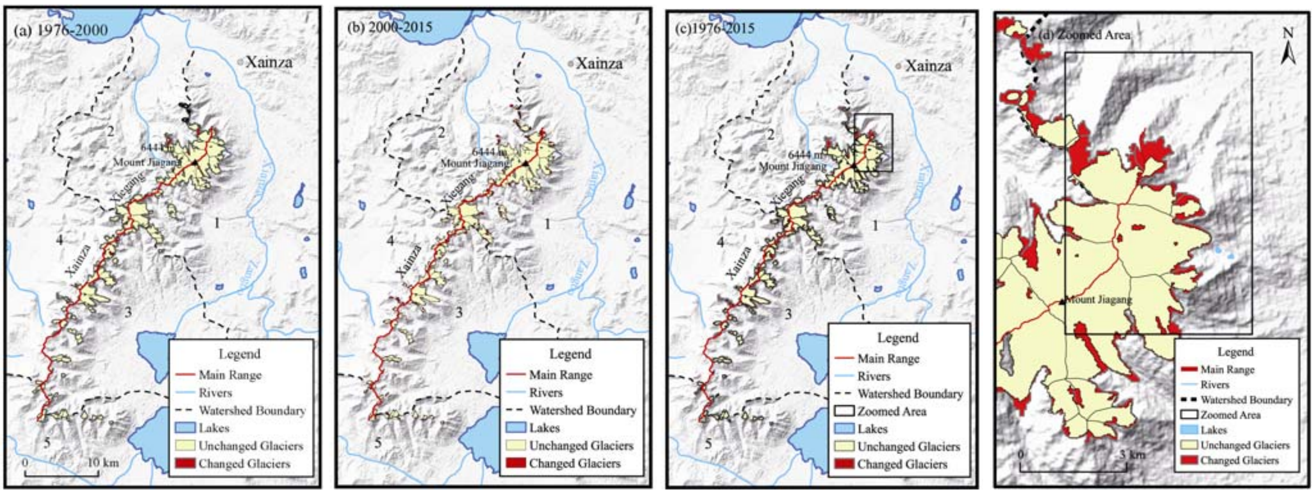

Fig.5 Glacial changes between 1976 and 2000 (a), between 2000 and 2015 (b), between 1976 and 2015 (c), and a close-up of the area (d) in the black box within (c)

Table 4 Glacier changes between 1976 and 2015 over six time periods

Period	Years	Numbers (increase/decrease) of glaciers	Area change (km^2)	Area change (%)	Annual rate (km^2·yr^{-1})	Water resource change (m^3)
1976–1989	13	9 (12/–3)	–6.88	–6.91	–0.53	-3.96×10^8
1989–2000	11	5 (7/–2)	–6.82	–7.38	–0.62	-3.31×10^8
2000–2007	7	2 (4/–2)	–6.71	–7.82	–0.96	-3.01×10^8
2007–2009	2	–4 (3/–7)	–3.27	–4.15	–1.64	-1.12×10^8
2009–2015	6	0 (1/–1)	–1.15	–1.53	–0.26	-0.37×10^8
1976–2015	39	12 (27/–15)	–24.83	–24.98	–0.64	-11.77×10^8

continuous glacial shrinkage.

Data show that the area of glaciers distinctly reduced between 1976 and 2015 for all size classes (glacier area greater than 0.1 km^2). Specifically, larger-sized glaciers, with areas greater than 1 km^2, continued to shrink over those time periods, making up 74.54% (18.52 km^2) of the total area loss between 1976 and 2015. Similarly, glaciers with areas between 0.5 km^2 and 1 km^2 contributed a decrease of 5.45 km^2, while those with areas between 0.1 km^2 and 0.5 km^2 contributed to a reduction of 2.00 km^2. The area of smallest glaciers, those with surface areas of less than 0.1 km^2, increased between 1976 and 2015 as a result of the continued retreat and splitting of their larger counterparts (Fig. 6).

3.2.2 The spatial heterogeneity of glacier changes

Data show that within each sub-watershed, glaciers consistently retreated with spatial heterogeneity between 1976 and 2015 (Fig. 7). Overall, glacier area decreased the most in sub-watersheds one (loss of 7.79 km^2) and three (loss of 7.47 km^2), followed by sub-watersheds two and four (Fig. 7). The least shrinkage of area was seen in sub-watershed five.

Results show that the retreat of glaciers varies across the study area, depending on aspect (Fig. 4). For example, those facing southeast shrunk most noticeably between 1976 and 2015 (loss of 11.33 km^2), followed by those facing southwest, east, and south. At the same time, glaciers facing

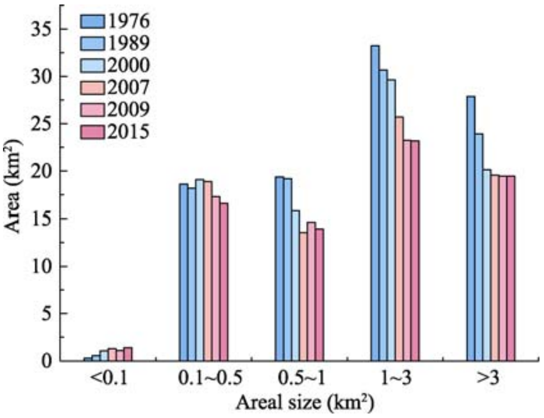

Fig.6 The areas of glaciers between 1976 and 2015 in various size classes

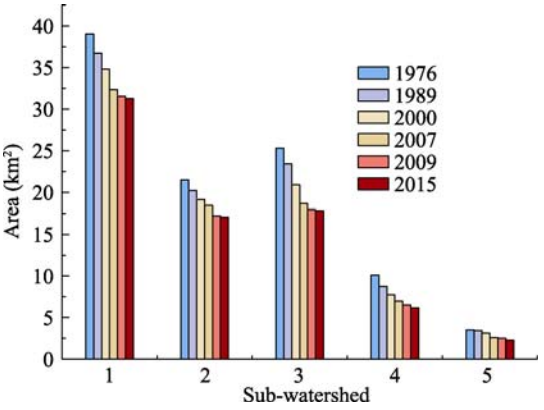

Fig.7 Areal changes in glaciers within different sub- watersheds

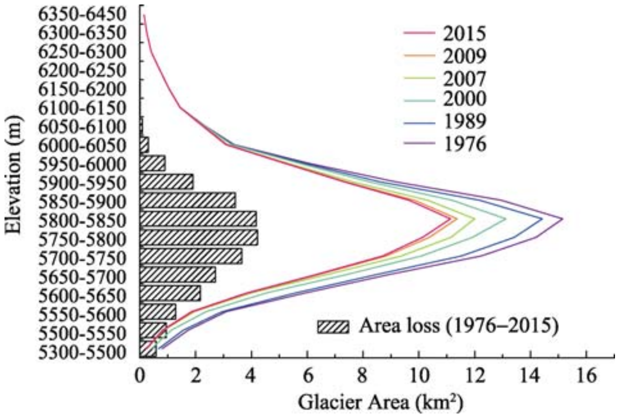

Fig.8 Changes and distributions of glaciers in various altitudinal zones

northwest, north, and northeast remained relatively stable over the study period.

Glaciers across the study area also exhibit distinct altitudinal distributions and changes (Fig. 8). The altitudes of all glaciers mapped in 2015 ranged from 5300 m a.s.l. to 6450 m a.s.l., with 83.53% occurring between 5600 m a.s.l. and 6000 m a.s.l. (mean altitude, 5800 m a.s.l.). Between 1976 and 2015, however, glaciers across this entire zone shrunk, with altitudes of glacial retreat highly consistent with altitudinal distributions. Retreated glaciers were located predominantly in the range between 5300 m a.s.l. and 6050 m a.s.l., with the greatest retreats seen in the altitudinal zone between 5750 m a.s.l. and 5850 m a.s.l. Based on remote sensing data, glaciers above 6000 m a.s.l. appear to have remained stable.

4 Discussion

4.1 Glacier mapping

Global and regional glacier inventory data have an important role in understanding changes in climate, water resources, and the eco-environment. However, currently, the available data on glaciers at global or regional scales (e.g. CGI, GGI and RGI) differs (Table 5) because of heterogeneous data sources, acquisition dates, and processing methods. Consequently, because the use of such data to monitor glacial changes causes uncertainties at local scales, we employed a consistent data source, mapping method and workflow in this study to generate reliable information on the status of the glaciers in the XX Mountains over six time periods. Our data for the glaciers in 1976 are close to those of the first CGI (1970s) which was sourced from topographic maps, while our data for 2000 are very close in numbers to the GGI but quite different in estimated area. This latter discrepancy is likely because GGI data did not include a number of glaciers covered partly under mountain shadows. At the same time, our glacier data for 2007 are almost identical in both number and area to the second CGI

Table 5 Different glacier dataset statistics in the study area

Data	Period	Data source	Number	Area (km^2)	Reference
First CGI	1970s	Topographical maps	144	95.07 ± 5.06	Shi *et al.* (2010)
This study	1976	Landsat images	119	99.43 ± 5.85	–
GGI	2000, 2003	Landsat images	132	66.85 ±4.28	Nuimura *et al.* (2015)
This study	2000	Landsat images	133	85.73 ± 6.07	–
Second CGI	2004	Landsat images	128	74.34 ± 4.09	Guo *et al.* (2015)
This study	2007	Landsat images	135	79.03 ± 5.65	–
RGI	Unknown	Unknown	90	137.23 ± 4.89	Pfeffer *et al.* (2014)

in 2004, while RGI data for this area remain extremely different. The above analysis implies that quality validation for the free global glacier datasets in a study area is compulsory before the utility. Selecting satellite images at the relatively consistent acquisition date to validate the glacier datasets is a reliable way. Using different global glacier datasets to analyze glacial dynamics may result in quite a few uncertainties. At local scale, we have to develop new glacier dataset, especially the latest glacial data, and should encourage academic communities to share these data for updating global glacier datasets.

4.2 The influence of climate on glacier change

Climate warming is of fundamental importance to the retreat of glaciers. Meteorological station data for Xainza County (Fig. 9) show that mean annual temperature increased by 0.35℃· $(10yr)^{-1}$ (adjusted R^2 value, 0.47) between 1976 and 2015, while annual precipitation only slightly increased by 20.60 mm· $(10yr)^{-1}$ (adjusted R^2 value, 0.07). Over the last 39 years, mean annual temperature has continuously increased while glaciers have continued to retreat; data show that glaciers are extremely sensitive to temperature fluctuations (Nie *et al.*, 2010; Yao *et al.*, 2012). The increasing precipitation may also have led to a positive glacier mass balance, however, satellite observations show that most glaciers have actually lost mass; this implies that variations in rainfall have made a limited contribution to glacial change while temperature increase has clearly and critically led to shrinkage between 1976 and 2015.

Nevertheless, the impact of climate change on glaciers is complex, and their response is strongly influenced by debris coverage (Scherler *et al.*, 2011). As these kinds of debris-covered glaciers are uncommon in this region, at least based on high spatial resolution images from Google Earth, this simplifies our glacier mapping and analysis of glacial changes.

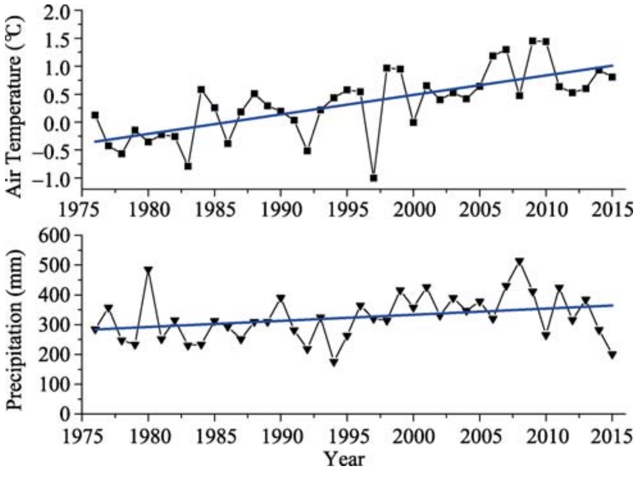

Fig.9 Changes in air temperature and mean annual precipitation for Xainza County between 1976 and 2015

The darkening of glaciers as the result of the incorporation of black sooty particles (Xu *et al.*, 2009) has also been considered as a contributor to accelerate glacial retreat on the TP. However, the absence of similar studies in this region constrains our analysis of glacial change. Under current condition of climate warming, glacial retreat might accelerate on the TP (Yao *et al.*, 2012). In any event, enhanced glacial retreat is possible to play an increasingly important role in the availability of water resources locally, as well as impacting the ecology and environment of Xainza County. Further quantitative assessment of glacial changes, and their ecological and environmental impacts, should thus be conducted in this area.

5 Conclusions

This study reports on a 2015 inventory of glaciers based on Landsat 8 images. In addition, changes in glaciers in the XX Mountains are systematically revealed using Landsat images over the past 39 years. Results show that the glaciers in this region rapidly shrunk (24.98%) between 1976 and 2015, with the specific characteristics of each glacier also revealed by Landsat images. At the same time, glacier evolution in this region is complex, involving disappearance and emergence induced by splitting. Overall, glacial recession in the XX Mountains has resulted in a loss to water resources of 11.77×10^8 m^3, clearly affecting the downstream supply of freshwater to Xainza city. We recommend that the continued monitoring and detailed assessment of glacial changes in this high mountain area is urgent as it will lead to a more explicit understanding of how glacier change affects the local ecology and environment.

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1976–2015 年羌塘高原冰川变化遥感分析：以申扎杰岗为例

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摘　要：羌塘高原的申扎县处于青藏高原的气候和生态环境过渡带，该区域对环境变化非常敏感。冰川是该区域重要的土地覆被类型之一，也是重要的淡水资源。目前对该区域冰川的最新状况和时空变化的理解非常有限。本研究选用 6 期陆地卫星遥感影像，完成了 2015 年申扎杰岗山脉冰川调查及 1976~2015 年间冰川时空变化分析。结果显示：2015 年研究区有 131 条冰川（74.59 ± 5.25 km^2），主要分布在海拔 5600–6000 m。1976–2015 年，研究区冰川面积退缩了 24.98%（24.83 km^2），冰川分裂导致冰川总条目增加了 12 条。据估算，过去的 39 年冰川退缩导致 11.77 × 10^8 m^3 的冰川水资源损耗。冰川在不同的子流域、坡向和海拔段存在显著的变化差异。气候变暖是冰川持续退缩的关键驱动因子。本研究构建的数据集可为羌塘高原的气候、生态和环境变化研究提供重要的支持。

关键词：冰川；水资源；遥感；陆地卫星影像；羌塘高原