

# Glacier variations and their response to climate change in an arid inland river basin of Northwest China

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**Abstract:** Glaciers are a critical freshwater resource of river recharge in arid areas around the world. In recent decades, glaciers have shown evidence of retreat due to climate change, and the accelerated ablation of glaciers and associated impacts on water resources have received widespread attention. Glacier variations result from climate change, so they can serve as an indicator of climate change. Considering the climatic differences in different elevation ranges, it is worthwhile to explore whether different responses exist between glacier area and air temperature in each elevation zone. In this study, we selected a typical arid inland river basin (Suganhu Basin) in the western Qilian Mountains of Northwest China to analyze the glacier variations and their response to climate change. The glacier area data from 1989 to 2016 were delineated using Landsat Thematic Mapper (TM), Enhanced TM+ (ETM+) and Operational Land Imager (OLI) images. We compared the relationships between glacier area and air temperature at seven meteorological stations, in the glacier-covered areas and in the Suganhu Basin, and further analyzed the regression relationship between glacier area and mean air temperature of the glacier surfaces in July–August in the elevation range of 4700–5500 m a.s.l. by the linear regression method and correlation analysis. In addition, based on the linear regression relationship established between glacier area and air temperature in each elevation zone, we predicted glacier areas under future climate scenarios during the periods of 2046–2065 and 2081–2100. The results indicate that the glaciers experienced a remarkable shrinkage from 1989 to 2016 with a shrinkage rate of  $-1.61 \text{ km}^2/\text{a}$  ( $-0.5\%/a$ ), and the rising temperature is the decisive factor dominating glacial retreat; there is a significant negative linear correlation between glacier area and mean air temperature of the glacier surfaces in July–August in each elevation zone from 1989 to 2016. The variations in glaciers are far less sensitive to changes in precipitation than to changes in air temperature. Due to the influence of climate and topographic conditions, the distribution of glacier area and the rate of glacier ablation first increased and then decreased in different elevation zones. The trend in glacier shrinkage will continue because air temperature will continue to increase in the future, and the result of glacier retreat in each elevation zone will be slightly slower than that in the entire study area. Quantitative glacier research can more accurately reflect the response of glacier variations to climate change, and the regression relationship can be used to predict the areas of glaciers under future climate scenarios. These conclusions can offer effective references for assessing glacier variations and their response to climate change in arid

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inland river basins in Northwest China as well as other similar regions in the world.

**Keywords:** glacier variations; climate change; glacier area; remote sensing; regression relationship; elevation zone; Qilian Mountains

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## 1 Introduction

Glacier variations result from climate change, so they can serve as an important indicator of climate change. The melting of glaciers accelerated by rising temperature has seriously affected the composition, annual distribution and stability of water resources of basins (Naz et al., 2014; Gan et al., 2015; Zhu et al., 2017). Even with the decrease in glaciers, the annual cycle of runoff is transformed from an ice-melt-dominated to a snow-melt-dominated regime (Horton et al., 2006). In arid inland regions, glaciers are often the main source of runoff for rivers (Sun et al., 2013). Therefore, monitoring the characteristics of glacial variations and their volatility trends, quantitatively analyzing the relationship between glacial area and climate factors and predicting the possible changes in future glacial areas are of great significance for the utilization of glacier resources and sustainable development of the ecology and economy in arid inland regions.

The study of modern glaciology began in the early 19<sup>th</sup> century. Before the 1980s, the majority of glacier mass balance monitoring abroad occurred in Europe, North America and the territory of the former Soviet Union (Dyurgerov, 2001). Aerial photographs were collected in a few typical areas to measure glacier area and assess volume changes, thickness variations and glacier responses to climate change (Nye, 1960; Bradley and Miller, 1972; Kite and Reid, 1977). The findings indicated that the global glaciers were generally retreat since the 1960s (Mu et al., 2018). From the 1980s to the early 21<sup>st</sup> century, with the development of remote sensing technology and Digital Elevation Model (DEM), studying the characteristics of glaciers and dynamic changes in high-altitude mountains has become an important trend (e.g., Dwyer, 1995; Casassa et al., 2002; Paul, 2002). During this period, a sharp retreat in global glaciers was observed, which greatly encouraged researchers to study the intrinsic influences of glacier variations in different regions under different climate conditions (Dowdeswell et al., 1997; Liu et al., 2003). During the early part of the 21<sup>st</sup> century, the widespread application of high-resolution remote sensing images, drone technology and radar thickness measurements played a significant role in studying global-scale and long-term glacier variations. Apart from the characteristics of glaciers, most researchers have gradually shifted to studying and forecasting glacier runoff, and identifying the impact of glacier variations on water resources and ecological stability of basins (e.g., Sorg et al., 2012; Gan et al., 2015).

With global warming, glaciers in northwestern China have undergone significant changes since the 1990s (Yao et al., 2010), and these will have a comprehensive impact on the ecological environment and water resource safety in arid areas (Zhu et al., 2017). The glacier area decreased by 10%–14% from 1970 to 2012 in northwestern China (Liu et al., 2015), and the glacier volume decreased by 29% in the past half-century in the Qilian Mountains (Sun et al., 2018), all of which has caused a clear change in runoff, especially for glacier-fed rivers (Hagg et al., 2007; Sun et al., 2013; Wang et al., 2017). During dry periods, glacial meltwater is the only and most important water source keeping rivers flowing (Singh and Kumar, 1997; Stahl et al., 2008; Sorg et al., 2012).

Numerical simulations of glacial change and its prediction are the frontiers of cryospheric science; in particular, simulations of glacier flow velocity and glacier mass balance based on climate factors have attracted increasing attention from scholars (Duan et al., 2012; Liu et al., 2019). However, current research regarding glacier flow velocity and glacier mass balance is limited to the monitoring of typical individual glaciers, which is not suitable for the study of glaciers in basins. As one of the important indicators of climate change, the glacial area can be easily obtained. It can also be used to simulate and predict glacial variations with climate change by establishing a

regression model among temperature, precipitation and glacier area. Moreover, previous studies of glaciers also have certain limitations: First, almost all research has focused on the relationship between glacier area variations and climate change at the basin scale or at several meteorological stations (e.g., Sorg et al., 2012; Rabatel et al., 2013; Wang et al., 2017). There is no quantitative analysis of the relationship between glacier area and climate factors. Second, previous studies have not analyzed the relationship between glacier area and air temperature in each elevation zone (e.g., Sakai et al., 2006; Tian et al., 2014; Sun et al., 2018). Changes in glaciers depend mainly on the climate of the glacier-covered area. The relationship between glacier area and air temperature exhibits different characteristics in different elevation zones due to different climate and topographic conditions.

The Qilian Mountains are located on the northern margin of the Tibetan Plateau in an arid to semi-arid region of northwestern China. Glacier and snow runoff in the Qilian Mountains nourishes the "Silk Road Economic Belt", which is very important for trade and cultural communication between Europe and Asia (Sakai et al., 2006; Sun et al., 2018). Monitoring the glacier resources of the region is of great significance to the implementation of the national "Belt and Road Initiative". In recent years, the accelerated ablation of glaciers has made the conflict between the water crisis and ecological degradation more prominent in arid areas (Bolch et al., 2010a; Pan et al., 2012; Zhu et al., 2017).

Therefore, this study selected a typical arid inland basin in the Qilian Mountains with the aim of (1) using remote sensing images to monitor glacial variations in the study area, (2) quantitatively analyzing the response of glacial area to climate factors, (3) comparing the variation characteristics of glaciers in different elevation zones and (4) establishing a regression relationship between glacier area and air temperature for glacier-covered areas in each elevation zone and predicting the future glacier area based on the above relationship.

## 2 Study area and data collection

### 2.1 Study area

The Suganhu Basin is a typical arid inland river basin located in the western Qilian Mountains (38°00'–39°30'N; 93°30'–97°20'E) in northwestern China. The study area covers an area of  $20.17 \times 10^3$  km<sup>2</sup>. It consists of the Haltang River, Danghenan Mountain and Tergun Daban Mountain (Fig. 1). The upper basin has an alpine and semi-arid climate while the middle and lower basins are characterized by a temperate arid climate. This region is mainly influenced by westerly winds and the Asian Monsoon; thus, most of the precipitation occurs in summer, infrequent and unsteady rains occur in spring and autumn, and rare precipitation events occur in winter. In addition, precipitation decreases from upstream to downstream, whereas evaporation presents the opposite trend. The annual precipitation ranges from 50 to 100 mm and the average annual evaporation is approximately 2400 mm (Ma et al., 2015). The annual mean air temperature ranges from  $-0.9^\circ\text{C}$  to  $3.0^\circ\text{C}$ .

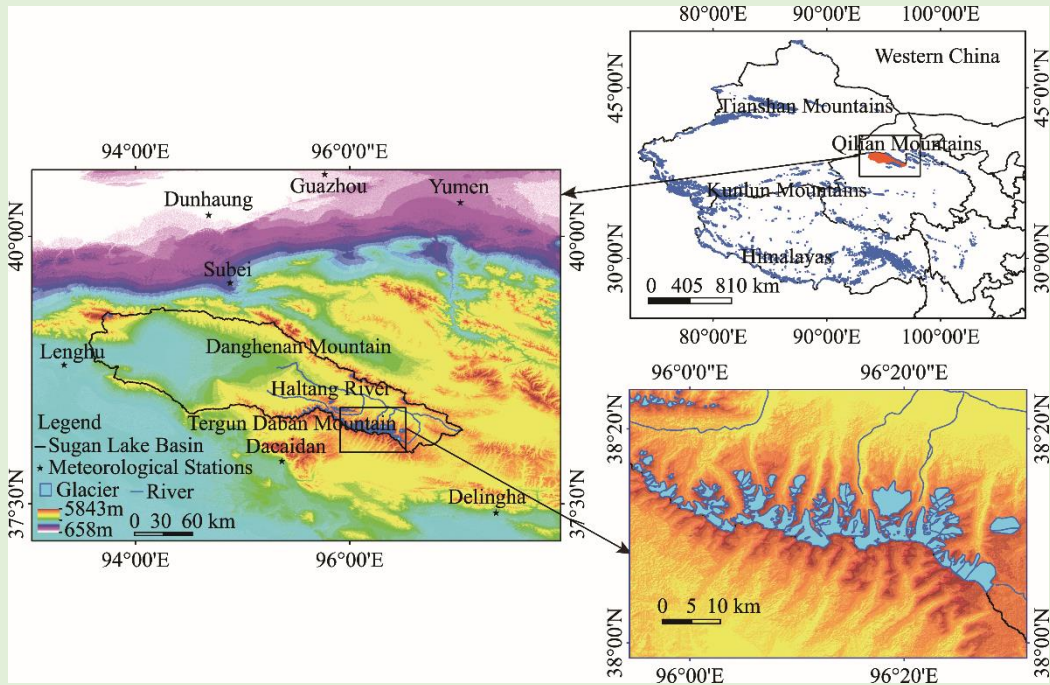
The latest authoritative data on the number of glaciers and their area in the Qilian Mountains were included in the Second Chinese Glacier Inventory (SCGI) (<http://westdc.westgis.ac.cn/data/>). In the SCGI, the glacier data in the Suganhu Basin encompassed the period 2006–2009 and were mainly derived from remote sensing data in 2007. In addition, the SCGI shows that the glaciers in the Suganhu Basin are mainly distributed along the Haltang River, which is located in the southeastern part of the study area. The Suganhu Basin presents a total number of 350 glaciers covering an area of 317.57 km<sup>2</sup>, and the glacier surface elevations range from 4500 to 5800 m a.s.l. The glaciers are well developed and glacial meltwater nourishes the Dunhuang oasis. For the glaciers in the Qilian Mountains, their average area was the largest and the ice volume was the second largest in the Haltang River Basin despite the fewer number of glaciers, compared to the Beidahe River Basins, Heihe River Basins and Danghe River Basin (Sun et al., 2018). Therefore, the Suganhu Basin can be selected as a typical representative arid inland river basin in the Qilian

Mountains of northwestern China.

## 2.2 Data collection

### 2.2.1 Remote sensing data acquisition

Landsat Thematic Mapper (TM), Enhanced TM+ (ETM+) and Operational Land Imager (OLI) images were used to delineate glacier outlines in the study area from 1989 to 2016. They were



**Fig. 1** Geographical overview of the Suganhu Basin and major glacier distribution

accessed from the United States Geological Survey (USGS) (<http://glovis.usgs.gov/>) and the Geospatial Data Cloud website (<http://www.gscloud.cn/>). The images were subjected to radiation correction and geometric correction, and terrain correction was also performed using DEM data. The study area covered the scenes of path 136 and 137 and row 033. We obtained the monthly temperature of the glacier surfaces in the Suganhu Basin based on the air temperature of national meteorological stations (shown in Fig. 1). The mean air temperature of the glacier surfaces is above  $0.0^{\circ}\text{C}$  in July–August (ablation period) and below  $0.0^{\circ}\text{C}$  during other months (accumulation period) in the Suganhu Basin. The time of the selected remote sensing images and the presence of snow often affect the reliability of the glacier extraction results. To obtain more accurate data and to ensure the time consistency of the remote sensing scenes, we selected dates mostly in August–September, i.e., the end of the ablation season without remnant fresh snow. In addition, we controlled for the cloudiness of each remote sensing image within 3%. A total of 20 high-quality remote sensing images were finally selected for the period 1989–2016 (Table 1). In addition, the SCGI was accessed from the Environment and Ecological Science Data Center for West China (<http://westdc.westgis.ac.cn/data/>).

**Table 1** Landsat scenes utilized in this study

Path	Acquisition date	Sensor	Path	Acquisition date	Sensor
	25 Aug 1989	TM		16 Aug 1989	TM
136/033	14 Jul 1991	TM	137/033	7 Sep 1991	TM
	26 Aug 1995	TM		1 Aug 1995	TM

31 Aug 1997	TM	22 Aug 1997	TM
23 Aug 2000	TM	14 Aug 2000	TM
16 Aug 2003	TM	15 Aug 2003	TM
27 Aug 2007	TM	26 Aug 2007	ETM+
27 Aug 2010	ETM+	26 Aug 2010	TM
11 Aug 2013	OLI	2 Aug 2013	OLI
2 Jul 2016	OLI	25 Jul 2016	OLI

Note: TM, Thematic Mapper; ETM+, Enhanced TM+; OLI, Operational Land Imager.

### 2.2.2 Climate and DEM data acquisition

Seven national meteorological stations near the study area were selected to analyze climate change in this study (Fig. 1). They are in Dunhuang, Guazhou (formerly known as Anxi), Yumen (formerly known as Yumen Town), Subei, Lenghu, Dachaidan and Delingha, with elevations of 1139, 1171, 1526, 2137, 2770, 3173 and 2982 m a.s.l., respectively. We acquired daily air temperature and precipitation data from the seven national meteorological stations for the period 1989–2016, which were provided by the China Meteorological Administration ([http://data.cma.cn/data/cdcdetail/dataCode/\\_SURF\\_CLI\\_CHN\\_MUL\\_DAY\\_V3.0.html](http://data.cma.cn/data/cdcdetail/dataCode/_SURF_CLI_CHN_MUL_DAY_V3.0.html)). The DEM is based on Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) data (<http://www.gscloud.cn/>) with a spatial resolution of 30 m. It is used to delineate glacier outlines and correct the climate data within the glacier-covered area.

## 3 Methodology

### 3.1 Glacier delineation and extraction of ice divides

The methods for glacier delineation using Landsat data can generally be divided into several categories, i.e., supervised classification (Sidjak, 1999), the normalized-difference snow index (Hall et al., 1995) and the band ratio method (Andreassen et al., 2008; Racoviteanu et al., 2009). Among them, the band ratio method has been proven to be an efficient method for mapping the extent of glaciers, even for small alpine glaciers (Paul, 2002). Images of the ratio between the Red and SWIR bands are usually created and analyzed to delineate glacier boundaries (Bayr et al., 1994; Jacobs and Alvin, 1997; Andreassen et al., 2008). All images were preprocessed with the Environment for Visualizing Images (ENVI). This detailed process can be observed in Figure 2. First, damaged Landsat 7 (2003–) images were repaired using the Landsat gapfill tool of ENVI, and the image preprocessing steps included radiometric calibration, FLAASH atmosphere correction and customize map projection. Then, the glacier boundaries were extracted by the band ratio method. For the TM, ETM+ and OLI images, the threshold (Threshold=Red/SWIR) is usually near 2.0 (Cao et al., 2010; Zhou et al., 2017; Han et al., 2018). A threshold of 2.0 (multiple tests) was used to clearly distinguish glaciers from other features, and the thresholds were similar in different years in this study. The glacier binary map was filtered by the median-filtered tool in a 3×3 window, which not only reduces the noise in shadows but also eliminates some seasonal snow (Andreassen et al., 2008). After the glacier outline was derived by raster-vector conversion from the binary map above, it could be opened in ArcGIS to obtain the glacier area. In addition, manual editing and correction were needed to remove incorrect water, snow areas and mountain shadows from glaciers using high-resolution Google Earth images (with a spatial resolution of 14.92 m) and SCGI data as the reference.

The extraction of ice divides is vitally important for glacier studies (Kienholz et al., 2013). In this study, we divided each glacier using the partitioning tool in ArcGIS based on the delineation results of the SCGI. Specific implementation methods can be found in Guo et al. (2011). To avoid

interference from moraines, we only included ice bodies of more than 0.01 km<sup>2</sup>. Thus, polygons with areas of 0.01 km<sup>2</sup> or smaller were excluded.

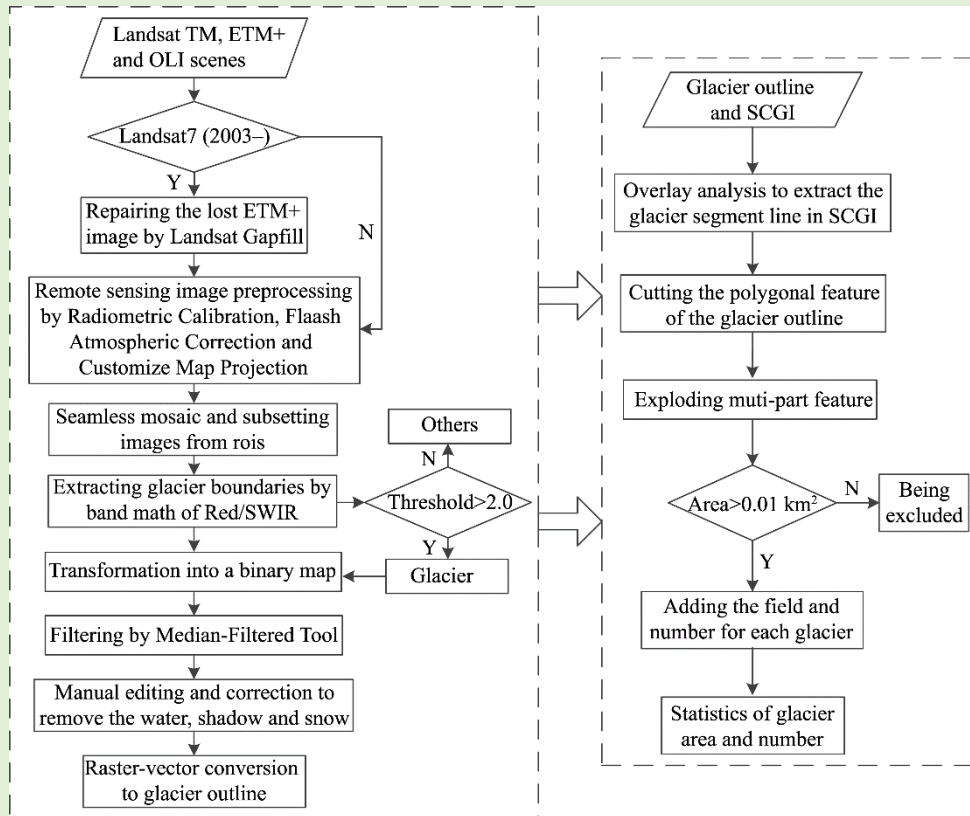
### 3.2 Indicators for glacier area change analysis

Generally, the percentage of area changes (PAC; %) and the annual percentage of area changes (APAC; %/a) can be used to quantify changes in glacier areas. The PAC is defined as the ratio of the change in glacier area to the glacier's initial area over a period of time. The APAC is a common indicator used to assess the annual percentage of glacier area changes. These values can be used to compare glacier variations on different time scales. They are calculated using the following formulas:

$$PAC = \Delta S_n / S_0 \times 100\%, \quad (1)$$

$$APAC = (\Delta S_n / S_0 \times 100\%) / n \times 100\%, \quad (2)$$

where  $S_n$  represents the glacial area in the  $n^{\text{th}}$  year (km<sup>2</sup>);  $S_0$  is the initial glacier area (km<sup>2</sup>); and  $n$  represents the time interval (a).



**Fig. 2** Flow chart of the algorithm used to extract glacier outline and to divide each glacier. The left panel is implemented using ENVI (Environment for Visualizing Images), and the right panel uses the spatial analysis modules in ArcGIS. SCGI, Second Chinese Glacier Inventory.

### 3.3 Interpolation and correction of air temperature and precipitation data

Because the air temperature and precipitation data at several meteorological stations or in the entire basin usually cannot directly represent the climatic conditions within the glacier-covered areas, the station data were further interpolated and corrected to better represent the glacier surfaces. Moreover, considering the large terrain fluctuations in the study area, it is necessary to perform terrain correction for temperature and precipitation.

For temperature, we first estimated the mean monthly air temperature at seven stations at the

same elevation during the period 1989–2016 based on both the elevation of each meteorological station and an air temperature lapse rate of  $-0.6^{\circ}\text{C}$  per 100 m (Jin et al., 2019). Then, we interpolated the air temperature of the study area using the Kriging method in ArcGIS, and used the elevation correction to obtain the actual air temperature of glacier surfaces. Furthermore, we plotted the monthly isothermal chart with  $1.0^{\circ}\text{C}$  of temperature difference in the study area, and calculated the glacier area at each air temperature range. For precipitation, we interpolated the annual precipitation from each meteorological station during the period 1989–2016 in the study area using inverse distance weighting, and then used the multi-year average precipitation contour map of the study area for terrain correction of precipitation.

### 3.4 The Mann-Kendall trend test

The Mann-Kendall trend test is based on the correlation between the ranks of a time series and their time order (Mann, 1945; Kendall, 1990). It has been widely used to detect climate trends by analyzing statistical variables. The methodology is described in greater detail elsewhere (e.g., Burn and Elnur, 2002; Hamed, 2008). Statistically significant trends were evaluated using the statistical index  $u$ . In this paper, the long-term trends of the meteorological time series were investigated using the Mann-Kendall trend test, and a significance level  $P=0.05$  and a critical value  $U_{0.05}=\pm 1.96$  were applied. A value of  $|u|>|U_{0.05}|$  indicates a significant change. In addition, positive  $u$  values indicate an increasing trend in the time-series, whereas negative values indicate a decreasing trend.

## 4 Results

### 4.1 Variations in glacier area and number

The glacier number and area data from 1989, 1997, 2007 and 2016 were selected to analyze the inter-annual variations of glaciers (Table 2). The results show that the number of glaciers with areas of  $\leq 1.0 \text{ km}^2$  was dominant and accounted for 76.0% of the total number but only 21.0% of the total area. Due to climate change, the number of glaciers decreased from 417 to 318 during the period 1989–2016, and the area decreased from 345.3 to 302.2  $\text{km}^2$  ( $-12.2\%$  PAC) (Table 2). The glacier area decreased mainly because glaciers with areas of  $>0.1 \text{ km}^2$  decreased in both number and area. The reduction rate of the number of larger glaciers ( $>5.0 \text{ km}^2$ ) was smaller than that of small glaciers ( $\leq 5.0 \text{ km}^2$ ). In contrast, glaciers with areas of  $\leq 0.1 \text{ km}^2$  increased in both number and area due to the melting of larger glaciers. The changes in glaciers differed in the three historical periods of 1989–1997, 1997–2007 and 2007–2016, and the rate of glacial retreat has accelerated (Table 3). Comparatively speaking, based on the APAC after 1997, glaciers retreated at a slightly faster rate than before 1997.

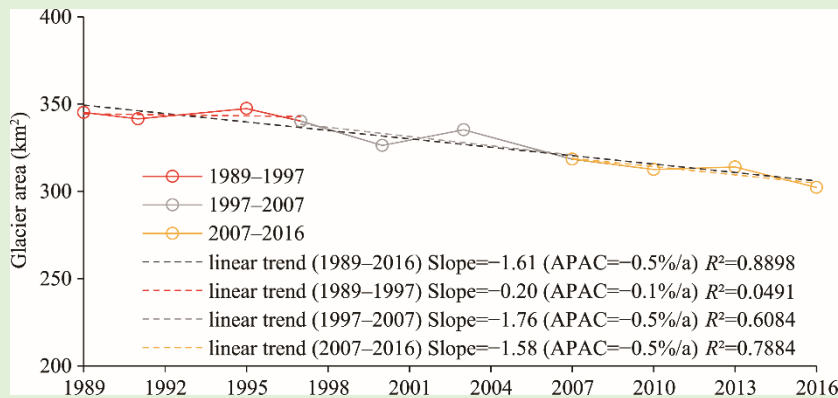
**Table 2** Glacier number and area in different classes in 1989, 1997, 2007 and 2016

Glacier class ( $\text{km}^2$ )	1989		1997		2007		2016	
	Number	Area ( $\text{km}^2$ )	Number	Area ( $\text{km}^2$ )	Number	Area ( $\text{km}^2$ )	Number	Area ( $\text{km}^2$ )
$\leq 0.1$	47	2.2	55	2.9	63	3.5	69	4.2
0.1–0.5	189	39.0	161	37.9	140	35.9	121	33.4
0.5–1.0	85	37.3	81	36.6	64	30.3	55	28.2
1.0–5.0	80	132.5	77	129.5	69	123.5	61	119.3
5.0–10.0	9	56.1	9	55.5	7	48.8	7	45.8
$>10.0$	7	78.2	7	77.9	6	76.4	6	71.3
In total	417	345.3	390	340.3	350	318.5	318	302.2

**Table 3** Annual percentage of area changes (APAC) in different classes during the period 1989–2016

Glacier class (km <sup>2</sup> )	1989–1997	1997–2007	2007–2016	1989–2016
	APAC (%/a)	APAC (%/a)	APAC (%/a)	APAC (%/a)
≤0.1	4.4	1.9	2.4	3.5
0.1–0.5	−0.3	−0.5	−0.8	−0.5
0.5–1.0	−0.2	−1.7	−0.8	−0.9
1.0–5.0	−0.3	−0.5	−0.4	−0.4
5.0–10.0	−0.1	−1.2	−0.7	−0.7
>10.0	0.0	−0.2	−0.7	−0.3
In total	−0.2	−0.6	−0.6	−0.5

In this study, we selected data with a short time interval (3 a) to more closely analyze the change trend in glacier area. The glacier area variations in the Suganhu Basin are depicted in Figure 3. The variations in glacier area over the entire study area exhibited a noticeable decreasing trend, with a shrinkage rate of approximately  $-1.61 \text{ km}^2/\text{a}$  ( $-0.5\%/a$ ). Comparing the results shown in Table 3, the APAC obtained by considering multiple remote sensing images in the same time period was slightly smaller. *R*



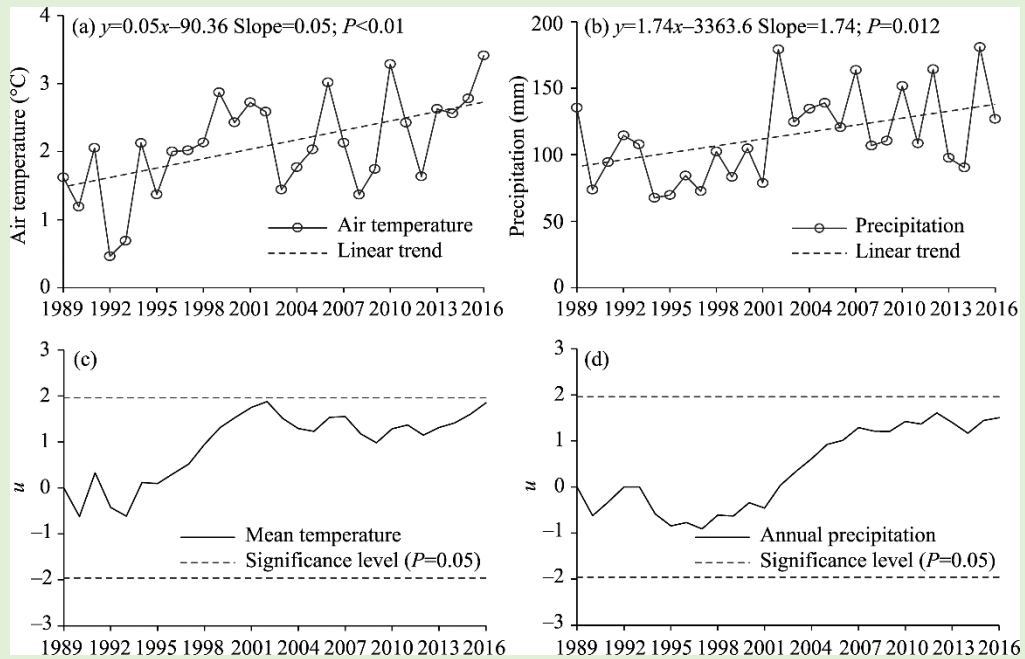
**Fig. 3** Variations in glacier area in the Suganhu Basin from 1989 to 2016. The dashed lines indicate the linear trend of glacier area variations for different periods. Slopes are the variation trend in glacier area, and the *P* values indicate statistical significance. APAC, annual percentage of area changes.

## 4.2 Glacier variations in response to climate change

### 4.2.1 Temperature and precipitation trends in glacier-covered areas

The mean air temperature of the glacier surfaces in July–August was greater than the freezing temperature, and the mean air temperatures in other periods was below  $0.0^{\circ}\text{C}$ . This study focused on the mean air temperature change at the glacier surfaces in July–August. As illustrated in Figure 4a, the air temperature exhibited a remarkable upward trend from 1989 to 2016, with an increasing rate of  $0.5^{\circ}\text{C}/10\text{a}$ . From 1989 to 2016, the precipitation of glacier-covered areas increased at a rate of  $1.74 \text{ mm}/\text{a}$  (Fig. 4b). From 1989 to 1994, the surface air temperature of the studied glaciers was slowly reduced, thus showing a slight volatile trend. Since 1995, the air temperature has rapidly increased (Fig. 4c). The annual precipitation decreased from 1989 to 2002 but exhibited an upward trend after 2003 (Fig. 4d).



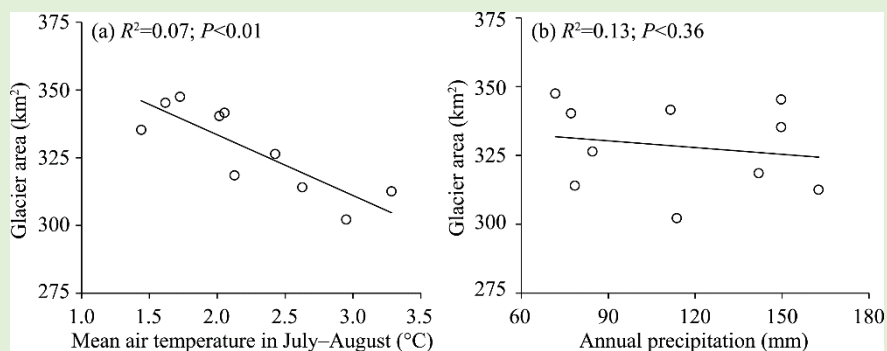


**Fig. 4** Variations in temperature and precipitation in glacier-covered areas from 1989 to 2016. (a), variations in mean air temperature of the glacier surfaces in July–August from 1989 to 2016 (the dashed line indicates the linear trend in air temperatures; (b), variations in annual precipitation of glacier-covered area from 1989 to 2016 (the dashed line indicates the linear trend in annual precipitation; (c), Mann-Kendall trend test of air temperature; (d), Mann-Kendall trend test of annual precipitation.  $u$ , statistical index.

#### 4.2.2 Correlations of glacier area with air temperature and precipitation

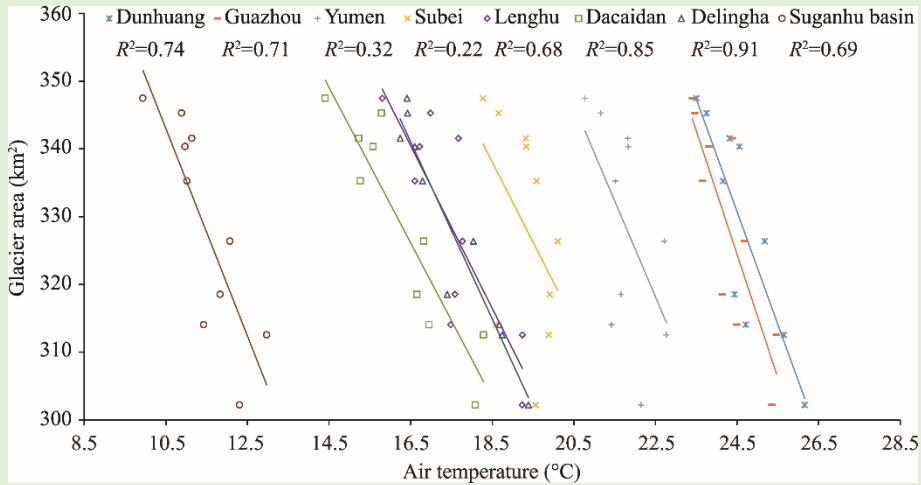
Water (precipitation), heat (temperature) and their combination are the main climate factors that affect the development and evolution of glaciers (Shi, 2000). Rising temperatures contribute to the melting of glaciers, and increasing precipitation contributes to the accumulation of glaciers. In this study, a significant negative correlation ( $P < 0.01$ ) was observed between glacier area and mean air temperature of the glacier surfaces in July–August (Fig. 5a). Meanwhile, the glacier area was poorly correlated ( $P = 0.36$ ) with the precipitation trend (Fig. 5b). The analysis of meteorological data revealed that the rising temperature has been the major controlling factor for glacier retreat in the Suganhu Basin since 1989, whereas the variations in glaciers were less sensitive to precipitation changes than to air temperature changes.

The linear coefficient of determination between glacier area and mean air temperature in July–August in the glacier-covered areas ( $R^2 = 0.70$ ) was slightly greater than that in the entire basin ( $R^2 = 0.69$ ) (Figs. 5a and 6). The correlation coefficients between glacier area and air temperature at each meteorological station differed considerably.



**Fig. 5** Relationships of glacier area with mean air temperature of the glacier surfaces in July–August (a) and

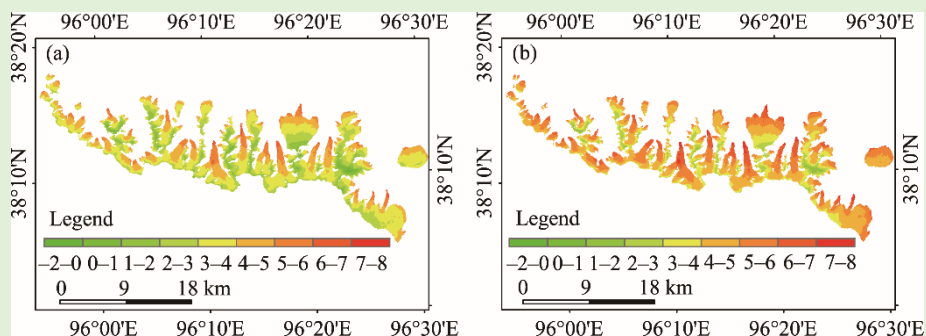
annual precipitation (b) in the glacier-covered areas. The solid lines indicate the linear trends of glacier area variations with air temperature and precipitation changes.



**Fig. 6** Relationships between glacier area and mean air temperature of the glacier surfaces in July–August at 7 meteorological stations and in the entire Suganhu Basin. The solid lines indicate the linear trends of glacier area variations with air temperature changes.

#### 4.2.3 Glacier area and coverage trends in different temperature ranges

The mean air temperature of the glacier surfaces was mainly between 0.0°C and 8.0°C in July–August in the Suganhu Basin. To investigate the relationship between glacier area distribution and different temperature ranges, we divided the air temperature into different temperature ranges with a difference of 1.0°C, and calculated the glacier area and coverage for each temperature range. As revealed in Figure 7, the glacier area of the higher air temperature ranges became larger with increasing air temperature, and the mean air temperature in July–August in 2016 increased by approximately 1.0°C compared with that in 1989. The elevation line corresponding to a temperature of 0.0°C exhibited a significant upward trend. As shown in Table 4, the glacier coverage gradually decreased with rising temperature. When the temperature was below -3.0°C, the average coverage of glaciers was 100.0%; when the temperature exceeded 8.0°C, the glacier coverage was close to zero. Over the past several decades, the mean glacier coverage in the Suganhu Basin ranged from 1.35% to 2.07%, with a multi-year average coverage of 1.69%.



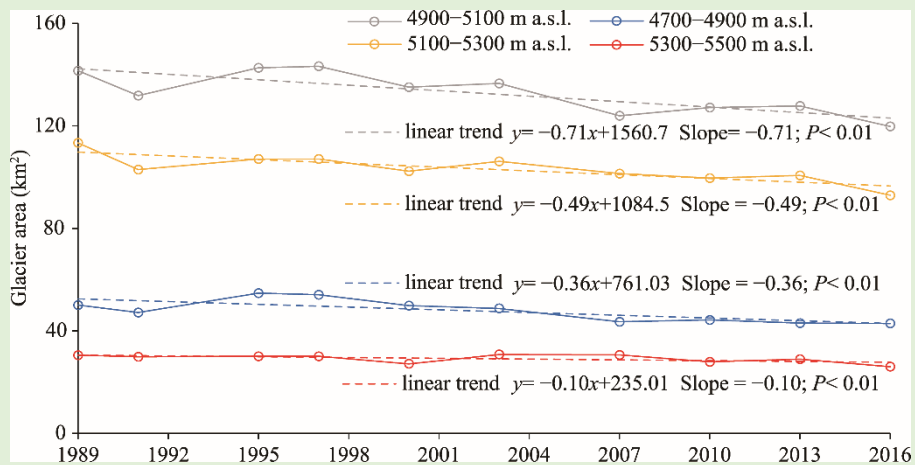
**Fig. 7** Spatial distributions of the mean air temperature of major glacier surfaces in July–August in 1989 (a) and 2016 (b)

**Table 4** Multi-year average glacier coverage distribution in different temperature ranges in the Suganhu Basin

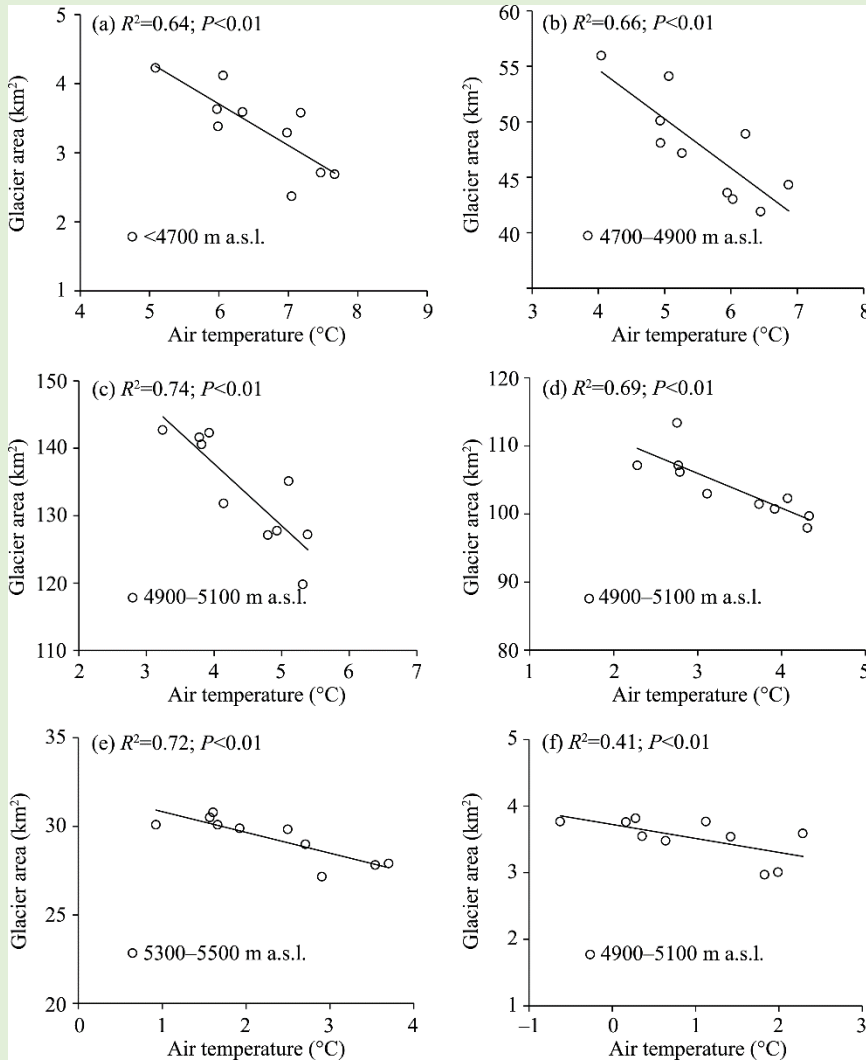
Temperature range (°C)	Glacier coverage (%)	Temperature range (°C)	Glacier coverage (%)
−∞−−3.0	100.00	3.0−4.0	32.30
−3.0−−2.0	97.00	4.0−5.0	14.30
−2.0−−1.0	88.86	5.0−6.0	4.33
−1.0−0.0	83.86	6.0−7.0	0.94
0.0−1.0	77.12	7.0−8.0	0.13
1.0−2.0	66.47	8.0−9.0	0.00
2.0−3.0	51.04	9.0−10.0	0.00

### 4.3 Relationship between variations in glacier area and air temperature in different elevation zones

The terrain condition, moisture and heat determine the glacier distribution. The glacier area was concentrated in the elevation range of 4700–5500 m a.s.l. The glacier area was approximately normally distributed, increasing first and then decreasing with elevation. In this study, the Suganhu Basin was divided into six different elevation zones. As shown in Figure 8, in recent years, the inter-annual variation of glacier area in each elevation zone showed a downward trend. In addition, the elevation zones with more glacier area always exhibited a larger deceleration rate. The areas with glaciers above 5100 m a.s.l. and below 4900 m a.s.l. were considerably small such that the trend was not obvious. In addition, there was a significant negative linear correlation ( $P < 0.01$ ) between glacier area and air temperature in each elevation zone (Fig. 9). The decrease in the glacier area in different elevation zones was mainly determined by the increase in air temperature, while the rate of glacier retreat was also affected by elevation. The more concentrated the area of glaciers, the more sensitive the glaciers to air temperature. Especially in the elevation zone of 4900–5100 m a.s.l., the glaciers exhibited the largest spatial distribution, and the variations in glacier area were most sensitive to air temperature changes; the ablation rate of glaciers was also the largest.



**Fig. 8** Inter-annual variations of glacier area in the 4700–5500 m a.s.l. elevation zones. The dashed lines indicate the linear trends of glacier area variations.



**Fig. 9** Relationships between glacier area and mean air temperature of the glacier surfaces in July–August for each elevation zone. The solid lines indicate the linear trends of glacier area variations with air temperature.

#### 4.4 Glacier area predictions

The Fifth Assessment Report of IPCC Working Group I in 2013 covered the following four RCP (Representative Concentration Pathway) scenarios of future climate change: RCP2.6, RCP4.5, RCP6.0 and RCP8.5 (IPCC, 2013). The assessment results show that the global mean surface air temperature is expected to increase by 1.0°C–2.0°C in 2046–2065 and by 1.0°C–3.7°C in 2081–2100 compared with the period 1986–2005 (Table 5).

**Table 5** Projected changes in global mean surface air temperature for the mid- and late 21<sup>st</sup> century compared with the period 1986–2005 (IPCC, 2013)

Variable	Climate scenario	2046–2065		2081–2100	
		Mean (°C)	Likely range (°C)	Mean (°C)	Likely range (°C)
Global mean surface temperature change (°C)	RCP2.6	1.0	0.4–1.6	1.0	0.3–1.7
	RCP4.5	1.4	0.9–2.0	1.8	1.1–2.6
	RCP6.0	1.3	0.8–1.8	2.2	1.4–3.1

Note: RCP, Representative Concentration Pathway.

A significant negative linear correlation was observed between glacier area variations and air temperature of the glacier surfaces in each elevation zone (Fig. 9). To analyze the relationship between glacier area and air temperature in various elevation zones, we established regression models based on the glacier area and mean air temperature of the glacier surfaces in July–August in each elevation zone and in the entire basin, as shown in Table 6. The correlations of the regression models established in some elevation zones were higher than those in the entire basin.

**Table 6** Regression models of glacier area and mean air temperature of the glacier surfaces in July–August in different elevation zones

Elevation zone (m a.s.l.)	Regression model	Coefficient of determination ( $R^2$ )	$P$ value
<4700	$A = -0.87 \times T + 9.27$	0.64	0.005
4700–4900	$A = -4.11 \times T + 70.83$	0.66	0.004
4900–5100	$A = -7.32 \times T + 166.25$	0.74	0.002
5100–5300	$A = -4.40 \times T + 118.99$	0.69	0.003
5300–5500	$A = -1.70 \times T + 33.05$	0.72	0.002
$\geq 5500$	$A = -0.29 \times T + 3.79$	0.41	0.047
In total	$A = -22.38 \times T + 378.20$	0.69	0.003

Notes:  $A$  is the glacier area ( $\text{km}^2$ ) and  $T$  is the mean air temperature of the glacier surfaces in July–August ( $^{\circ}\text{C}$ ).

The mean air temperature of the glacier surfaces in July–August and glacier area distribution in different elevation zones during the period 1986–2005 are presented in Table 7. In this study, the increase in the global mean surface air temperature reported in Table 5 represents the change of mean air temperature in July–August. Based on the regression models described in Table 6, we predicted the corresponding glacier areas under the four climate scenarios (Table 8). The trend in glacier shrinkage will continue because the air temperature will continue to increase in the future. Under the four scenarios of future climate, for the period 2046–2065, the average glacier area in the Suganhu Basin in different elevation zones was estimated to be  $304.55 \text{ km}^2$ , and the average glacier area for the entire basin was estimated to be  $298.14 \text{ km}^2$ ; for the period 2081–2100, the average glacier area in the Suganhu Basin in different elevation zones was estimated to be approximately  $290.53 \text{ km}^2$ , and the average glacier area in the entire basin was estimated to be  $281.07 \text{ km}^2$ . Based on the projected global mean surface air temperature, the prediction results of glacier area show that glacier retreat in different elevation zones will be slightly slower than that in the Suganhu Basin (Table 8).

**Table 7** Mean air temperature of the glacier surfaces in July–August and glacier area in different elevation zones during the period 1986–2005

Period	Elevation zone (m a.s.l.)	Mean air temperature ( $^{\circ}\text{C}$ )	Glacier area ( $\text{km}^2$ )
1986–2005	<4700	6.10	3.77
	4700, 4900	5.08	50.78
	4900, 5100	3.95	138.52
	5100, 5300	2.92	106.52
	5300, 5500	1.73	29.75

≥5500	0.44	3.56
Entire basin	1.77	332.89

**Table 8** Results of future glacier area predictions under four climate scenarios

Period	Climate scenario	Glacier area (km <sup>2</sup> )						Sum	Entire basin
		<4700 m	4700–4900 m	4900–5100 m	5100–5300 m	5300–5500 m	≥5500 m		
2046–2065	RCP2.6	3.09	45.86	130.02	101.74	28.41	3.37	312.49	308.53
	RCP4.5	2.74	44.21	127.09	99.98	27.73	3.26	305.01	298.61
	RCP6.0	2.83	44.62	127.82	100.42	27.90	3.29	306.88	301.22
	RCP8.5	2.22	41.75	122.70	97.34	26.71	3.08	293.80	284.19
2081–2100	RCP2.6	3.09	45.86	130.02	101.74	28.41	3.37	312.49	308.53
	RCP4.5	2.39	42.57	124.16	98.22	27.05	3.14	297.53	288.90
	RCP6.0	2.05	40.92	121.23	96.46	26.37	3.02	290.06	279.64
	RCP8.5	0.74	34.76	110.25	89.86	23.82	2.59	262.02	247.21

## 5 Discussion

### 5.1 Error estimation of glacier area extraction

The use of high-resolution remote sensing images to manually extract glacier areas and assess the accuracy of Landsat images is widely used to evaluate individual errors in glacier identification (Bolch et al., 2010b). Figure 3 shows that glacier areas fluctuated within a few years, and the area of glaciers in 2003 changed more significantly compared with that in 2000. To confirm the reliability of the extraction results, we used Google Earth images to verify the two Landsat images for 2000 and 2003. The glacier boundaries in 2000 and 2003 were manually obtained by Google Earth images in this study. In addition, the calculated glacier area derived from Landsat images in 2007 was compared with that obtained from the SCGI data. Taking the three glacier areas as an example, we performed an error analysis by comparing the results obtained by different data sources. The results are shown in Table 9. The glacier areas calculated from Landsat images were slightly larger than those from Google Earth images and SCGI data, and the relative error was within 0.5%. This error can likely be attributed to the different data sources and processing means.

**Table 9** Error estimation of glacier area from different data sources

Period	Glacier area (km <sup>2</sup> )		Absolute error (km <sup>2</sup> )	Relative error (%)
	Landsat data	Other data sources		
2000	326.4	326.1 <sup>a</sup>	0.3	0.1
2003	335.3	333.8 <sup>b</sup>	1.5	0.4
2007	318.5	317.6 <sup>c</sup>	0.9	0.3

Note: <sup>a</sup> and <sup>b</sup> mean that the data were from the Google Earth images; <sup>c</sup> means that the data were from the Second Chinese Glacier Inventory (SCGI).

### 5.2 Response of glacier variations to climate change

The increasing trends in annual air temperature and precipitation of glacier-covered areas during 1989–2016 were 0.50°C/10a in July–August and 1.74 mm/a, respectively. However, although the annual precipitation has decreased from 1989 to 2002, it has been on an upward trend since 2003. This result is consistent with the findings of Shi et al. (2007), who showed that the climate regime has begun to shift from warm-dry to warm-wet in the arid areas of Northwest China since the 1980s. While Tian et al. (2014) found that the increasing trends in annual air temperature and precipitation

measured at meteorological stations were  $0.30^{\circ}\text{C}/\text{a}$ – $0.58^{\circ}\text{C}/\text{a}$  and  $0.37$ – $1.58$  mm/a from 1961 to 2010, respectively. The discrepancy may be due to climate change and statistical spatial and temporal scale differences. Based on the data in Table 7, we can estimate the temperature lapse rate in glacier-covered areas. Due to the differences in topography, the temperature gradient between different elevation zones was approximately  $0.52^{\circ}\text{C}$ – $0.65^{\circ}\text{C}$  per 100 m, and the temperature gradient increased with elevation in glacier-covered area. The higher the elevation increased, the faster the air temperature declined.

Sun et al. (2018) found that glaciers rapidly shrank in the east but slowly decreased in the west-central region of the Qilian Mountains. In addition, the results in this study ( $-12.2\%$  from 1989 to 2016) indicate that glacier variations in the Suganhu Basin were close to those in Daxueshan in the central Qilian Mountains (e.g., decreasing rate of  $-4.9\%/10\text{a}$  between 2004 and 2015; Wang et al., 2017a) and smaller than those in the entire Qilian Mountains (e.g.,  $-(23\pm 5)\%$  shrinkage from 1990 to 2010; Tian et al., 2014) and the eastern Qilian Mountains (e.g., between  $-14.21\%/10\text{a}$  and  $-19.97\%/10\text{a}$  in the Datong River Basin and Shiyang River Basin from 1956 to 2010; Sun et al., 2018). This trend can be explained by the increasing median glacier elevation from east to west or the differences in latitude and longitude. Moreover, Liu et al. (2019) proposed that the glacier mass balance indicated a huge loss in glaciers in different areas of western China after 1997. However, in our study, we found that the APAC after 1997 exhibited slightly faster rates than that before 1997 in the Suganhu Basin. In addition to rising temperature during the melting season, this finding may also be related to the increase in temperature of glaciers (Sun et al., 2013).

In the Suganhu Basin, the rising air temperature during the melting season was the factor governing the glacial retreat. By comparing the coefficient of determination between glacier area and air temperature at the meteorological stations over the entire basin as well as in the glacier-covered areas, refined research regarding glacier variations can more accurately and stably reflect the sensitivity of glacier area to temperature changes. Therefore, it is necessary to analyze the relationship between glacier area and air temperature of the glacier surfaces instead of just the air temperature at meteorological stations or across the entire basin. The research results above show that the distribution of glacier area increased initially and then decreased with elevation increases. In the elevation zone of 4900–5100 m a.s.l., the glaciers exhibited the largest distribution, and the change in glacier area was the most sensitive to temperature change; the ablation rate was also the largest. The development and evolution of glaciers are influenced by topography and climatic conditions, and a mountain is a necessary condition for the formation of glaciers. In this elevation range ( $\geq 5100$  m a.s.l.), the mountain has a small distribution area, the cutting intensity is large, the terrain is broken and the steep terrain is not conducive to glacier development. Shi et al. (1982) stated that in a certain elevation range, the climate gradually develops in a wet and cold direction with increasing elevation, which is very beneficial for the development of glaciers. However, with further increases in elevation, the precipitation exhibits a decreasing trend, gradually moving toward dry and cold, which will inhibit the development of glaciers to some extent. The glaciers in the study area increased initially and then decreased with elevation increases, and the glacier area reached a maximum in the elevation range of 4900–5100 m a.s.l. With increasing elevation, the temperature gradually decreases and the precipitation first increases and then decreases. The increasing precipitation makes the glaciers in the study area more developed. The upper limit of the wet and cold zone is generally the most developed glacier area. For the Suganhu Basin, the upper limit of the wet and cold zone was found to be approximately 4900–5100 m a.s.l. The melting of glaciers is a bottom-up process, and in general, smaller glaciers are more sensitive to climate warming than larger ones. As the temperature increases, the area in which the glaciers are concentrated is more intense, and the sensitivity to temperature is stronger. The reason for this phenomenon may be that the melting of glaciers reduces the reflection of shortwave radiation of the original ice-snow covered area, thereby causing the area to absorb more solar radiation. The accumulation of heat exacerbates the heating rate of the glacier surfaces and accelerates melting.

The glacier volume is a potential water resource, and glacier meltwater accounts for 39%–56%

of the total river runoff in the western Qilian Mountains (Shi et al., 2003). Therefore, in the future, the meteorological monitoring of different elevation zones in the glacier-covered area should be strengthened, and the relationship between glacier volume and air temperature should be further studied.

## 6 Conclusions

In this study, we selected the Suganhu Basin of the western Qilian Mountains as a typical arid inland basin to analyze glacier variations under climate change. The glacier data from 1989 to 2016 were delineated using Landsat images over the past several decades. The Suganhu Basin had experienced a significant rise in temperature of  $0.50^{\circ}\text{C}/10\text{a}$  and an increasing precipitation trend of  $1.74\text{ mm/a}$ . Overall, there has been a warm and wet tendency in the region over the past 28 a. Glaciers experienced a remarkable shrinkage from 1989 to 2016, with a shrinkage rate of  $-1.61\text{ km}^2/\text{a}$  ( $-0.5\%/a$ ), and the glacier area variations fluctuated slightly within a few years. In addition, the rising air temperature in the melting season was the factor governing glacial retreat, whereas increasing precipitation was less relevant to the changes in glacier area. The linear coefficient of determination between glacier area and mean air temperature of the glacier surfaces in July–August in the glacier-covered areas was slightly larger than that in the entire basin. Quantitative glacier research can more accurately reflect the response of glacier variations to climate change. The glacier area had a significant negative linear correlation with the mean air temperature in July–August in different elevation zones, and the elevation zones with a larger area distribution had a larger deceleration rate of glaciers. The more concentrated the area of glaciers, the more sensitive the glaciers to temperature. The prediction of glacier area variations under future climate scenarios reveal that the trend in glacier shrinkage will continue under increasing air temperatures in the future.

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