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Climate change and glacier area variations in China during the past half century

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Abstract: Glacier variations in the Tibetan Plateau and surrounding mountain ranges in China affect the livelihood of over one billion people who depend on water from the Yellow, Yangtze, Brahmaputra, Ganges and Indus rivers originating in these areas. Based on the results of the present study and published literature, we found that the glaciers shrank 15.7% in area from 1963 to 2010 with an annual area change of -0.33%. The shrinkage generally decreased from peripheral mountain ranges to the interior of Tibet. The linear trends of annual air temperature and precipitation at 147 stations were 0.36°C $(10a)^{-1}$ and 8.96 mm $(10a)^{-1}$ respectively from 1961 to 2010. The shrinkage of glaciers was well correlated with the rising temperature and the spatial patterns of the shrinkage were influenced by other factors superimposed on the rising temperature such as glacier size, type, elevation, debris cover and precipitation.

Keywords: Glacier area; Climate change; Air temperature; Precipitation; China

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Introduction

Glacier variations can influence water resources of downstream populations and natural systems, and can influence phenomena such as glacial lake outburst floods (GLOFs) and sea-level rise (Meier et al. 2007; Jacob et al. 2012). The glaciers, with a total area of 59,425 km², in the Tibetan Plateau and surrounding mountain ranges in China, constitute the most extensive glacier cover outside Alaska and the Arctic (Dyurgerov and Meier 2005; Shi 2008; Zhang et al. 2012). Over one billion people depend on water from the Yellow, Yangtze, Brahmaputra, Ganges and Indus rivers originating in the region known as the Asian water towers (Immerzeel et al. 2010). Recent controversy about the glacier changes in this region has exposed major gaps in our knowledge of their behavior (Bolch et al. 2012; Gardelle et al. 2012;

Jacob et al. 2012; Yao et al. 2012). To enhance our understanding of the variability of the glaciers in the region, temporally and spatially comprehensive information is essential (Salzmann et al. 2014). Glacier variations are inextricably linked with climate change (Tennant et al. 2012). To better understand the behavior of the glaciers, the characteristics of climate change in this region should be analyzed. The objectives of this study are: (1) to generate up-to-date information on glacier extent in China; (2) to synthesize the results of the present study with published literature; (3) to analyze climate change in this region over the past decades; (4) to discuss possible factors influencing variability in glacier extent.

1 Study Area

The study area is located in west China (between 26.9°-49.2°N and 73.5°-104.7°E) where all the glaciers in China exist. The mountainous region of the study area can be subdivided into fourteen mountain ranges where glaciers can be found (Figure 1). There are 46,377 glaciers, with a total area of 59,425 km² and a total volume of 5600 km³ in the study area (Shi 2008). The area is influenced mainly by two climate systems, the Indian Monsoon in summer and the Westerlies in winter (Yao et al. 2012) with generally decreasing precipitation trends from the southeast to the northwest.

2 Data and Methods

Landsat images were used to delineate glacier outlines with the help of digital elevation model (DEM) data to obtain the latest glacier extent information. Subsequently, the results of the

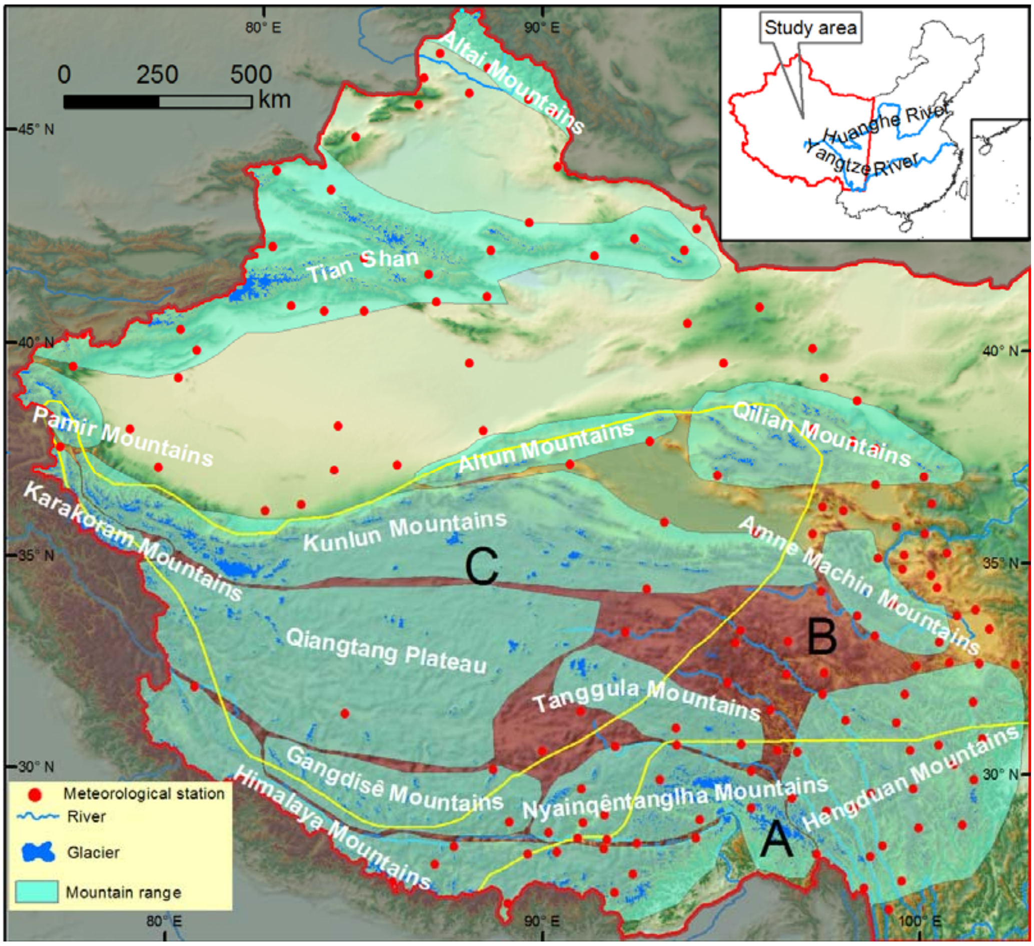

Figure 1 Study area showing glacier coverage, mountain ranges and meteorological stations. Glaciers in region A, B and C are maritime type, sub-continental type and extreme continental-type respectively (Shi 2008). Mountain range borders only show the approximate location where glaciers can be found.

present study and published literature were compiled to acquire temporally and spatially comprehensive information on glacier variations using a method that previously proved useful in the Qilian Mountains, one of the mountain ranges in the present study (Tian et al. 2014). Climate data were analyzed to better understand the background of variability in glacier extent.

2.1 Digital elevation model

For elevation data, we used a combination of Shuttle Radar Topography Mission (SRTM) v4.1 digital elevation model (DEM), which has a 90 m resolution, and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM), which has a 30 m resolution (http://datamirror.csdb.cn). ASTER GDEM contains residual cloud anomalies and pervasive artifacts due to different stack numbers when generating the final GDEM from variable number of individual Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Digital Elevation Models (DEMs). In order to replace these anomalies and artifacts in ASTER GDEM, SRTM v4.1 data were first resampled to 30-meter grid using bilinear interpolation, and then the pixels in ASTER GDEM were replaced with these resampled SRTM v4.1 data at locations where the elevation difference was greater than 200 m.

2.2 Glacier area data

Two sources of glacier areas are used in this study. One is from the present study (See section 2.2.1), and the other from published literature (Listed in Table 1).

2.2.1 Delineation of glaciers and error estimation

Landsat Multispectral Scanner (MSS), Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) images (http://www.usgs.gov/) were used to extract glacier outlines because they are suitable for glacier surface classification (Paul et al. 2002 a,b; Bolch et al. 2010a; Pope and Rees 2014). If an image is not available for a specified point in time, the one with the closest acquisition date was selected. With MSS imagery, maximum likelihood classification was used, and then the outlines of the glaciers were manually improved (Tian et al. 2012a).

We extracted glacier extents from TM and ETM+ imagery using the following semi-automated method. First, a band ratio (TM3/TM5) image with a threshold (varied from 1.8 to 2.1 in different regions) was used to delineate the glaciers in ENVI 4.5 using a minimum-elevation threshold to minimize misclassification. Then, we manually improved 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. We only mapped glaciers larger than 0.05 km^2 as a smaller threshold would include many features that were most likely snow patches. We identified internal holes in the glacier polygons using an area threshold of 8100 m^2 (3×3 pixels) and deleted them as these are usually misclassified pixels due to glacier debris. Because there is no effective method of delineating debris-covered glaciers based on Landsat data, they were not considered in this study (Paul et al. 2004; Shukla et al. 2010; Bhambri et al. 2011; Bhardwaj et al. 2014).

We compared our results with manually generated outlines from China Brazil Earth Resources Satellite-2B (CBERS2B) High Resolution (HR) imagery (resolution: 2.36 m) to check on the data quality. The images from the Landsat TM and CBERS2B HR were acquired on 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.

In order to verify the horizontal accuracy of our results, measurements using a Global Positioning System (GPS) device of the outline of Qiyi Glacier were performed on 31 August, 2012. The horizontal precision of the GPS device is 15 m. The outline of the Qiyi Glacier was delineated from a Landsat ETM+ Scan Line Corrector Failed (SLC-off) image from 25 August, 2012 using the above method without manual improvement and the Qiyi Glacier is not affected by scan line errors of the SLC scene.

2.2.2 Collection of information on glacier area from literature

We divided the whole region into 14 mountain ranges. Documents published before January 2013 were collected to obtain information on glacier area change in China (Table 1). Most data were derived from remote sensing data such as Landsat MSS/TM/ETM+ imagery and Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery. The mean glacier altitude and mean glacier area of each mountain range were calculated using data from the Glacier Inventory of China (GIC) (Wu and Li 2004; Shi 2008).

2.2.3 Calculation of the glacier area variation

In order to merge glacier area data, first we interpolated glacier areas when there were time overlaps between studies. In this report, when mentioning previous published studies as a source of data, they refer to previously published literature which covered at least two time periods of glacier extent at one or more glacierized regions. Suppose there were two studies, A and B. The glacier area in study A changed from A1 to A3 during the period 1980-2005. The glacier area in study B changed from B1 to B3 during the period 1970-1990. We interpolated linearly a glacier area A2 in 1990 to study A as well as a glacier area B2 in 1980 to study B. If a study has more than one time overlap with other studies, we interpolate linearly as many times as the number of the overlaps in the years.

Then we calculated the glacier area change using the following method. The area change for time period i (AC_i) is

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

where j is the order number of studies, ΔS_i is the summary of the variation of glacier area (km^2), S_{oi} is the summary of the glacier area at the initial status (km^2), ΔS_{ij} is the variation of glacier area

Table 1 Data source of glacier area from published literature

Mountainrange	Study period	Source
Nyainqêntanglha Mountains	1970–2009	(Liu et al. 2005; Shangguan et al. 2008; Wu and Zhu 2008; Chen et al. 2009; Xin et al. 2009; Bolch et al. 2010b; Zhang et al. 2010a, b; Zhang et al. 2011; Wang et al. 2012)
Tian Shan	1955–2009	(Liu et al. 1999; Li et al. 2003; Li et al. 2004; Jiao et al. 2004; Ding et al. 2006; Li et al. 2007; Song 2008; Wang et al. 2008; Wang et al. 2008b; Shangguan et al. 2009; Yao et al. 2009; Gao et al. 2011; Li et al. 2011a, b; Li et al. 2011; Qian et al. 2011; Wang et al. 2011a; Xu et al. 2011)
Qilian Mountains	1956–2010	(Liu et al. 2003; Yang et al. 2007; Du et al. 2008; Wang et al. 2008a; Zhao 2009; Cao et al. 2010; Zhang et al. 2010; Zhang et al. 2010a,b; Wang et al. 2011b; Zhang et al. 2011; Liu et al. 2012; Pan et al. 2012a; Tian et al. 2012a,b,c; Yan et al. 2012; Zhang et al. 2012)
Altai Mountains	1952–2008	(Wang et al. 2011; Bai et al. 2012; Yao et al. 2012)
Qiangtang Plateau	1970–2000	(Li et al. 2009; Zhang et al. 2010a,b; Wang et al. 2011a,b)
Kunlun Mountains	1968–2001	(Li et al. 1998; Li et al. 1999; Xu et al. 2006; Shangguan et al. 2007, 2009; Zhang et al. 2010a, b)
Himalaya Mountains	1970–2010	(Jin et al. 2004; Che et al. 2005; Chen et al. 2005; Ye et al. 2006b; Chen et al. 2007; Ye et al. 2007a, b; Wang et al. 2008; Ye et al. 2009a, b; Li et al. 2010; Nie et al. 2010a, b; Zhang et al. 2010a, b; Li et al. 2011; Liu and Xiao 2011)
AmneMachin Mountains	1966–2000	(Liu et al. 2002)
Hengduan Mountains	1957–2009	(Zheng et al. 1999; Liu et al. 2010; Zhang et al. 2010; Zhang et al. 2010a, b; Du2011; Wang et al. 2011; Pan et al. 2012b)
Pamir Mountains	1963–2001	(Shangguan et al. 2005; Cai et al. 2006; Shangguan et al. 2006; Shangguan et al. 2009; Zhang et al. 2010a, b)
Tanggula Mountains	1969–2007	(Lu et al. 2002; Yang et al. 2003; Lu et al. 2005; Ye et al. 2006a; Qiao 2010; Zhang et al. 2010a, b)
Karakoram Mountains	1968–2004	(Zhang et al. 2010a,b; Liu et al. 2011)
Altun Mountains	1975–2000	(Zhang et al. 2010a,b)
Gangdisê Mountains	1975–2009	(Zhang et al. 2010a,b; Zhang et al. 2012)

(km²) of study j in time period i, S_{oij} is the glacier area at the initial status (km²) of study j in time period i, and m is the number of studies for time period i.

The annual area change for time period i (AAC_i) is

$$AAC_i = \frac{AC_i}{\Delta T_i} \quad (2)$$

where ΔT_i is the time span for time period i. As can be seen from the above formula, annual area change for time period i (AAC_i) refers to the average annual change between two epochs.

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

$$AC = \left[\prod_{i=1}^{n}(AC_i + 1)\right] - 1 \quad (3)$$

where n is the number of time periods.

2.3 Climate

Annual and monthly temperature and precipitation data (http://cdc.cma.gov.cn/) from 147 meteorological stations (Figure 1) and CRU TS3.1 (http://www.cru.uea.ac.uk/) (Mitchell 2005) were selected to analyze climate trends. Climate data from meteorological stations were processed using software package RHtestV3 to make them homogeneous (Wang 2008a,b). In order to detect climate trends, First Difference Method (Petersonet al. 1998; Vuille 2000; Freeet al. 2004) and Mann–Kendall analysis (Zhang et al. 2011) were used in this study. Here a value greater than zero for the statistical index (UF_k) represents an increasing trend, and a value greater than 1.96 indicates a significant increasing trend at the 95% confidence level.

3 Results and Discussion

3.1 Climate changes

3.1.1 Temporal changes of climate

The analysis of air temperature revealed an overall increase from 1961 to 2010. The increases of annual and summer (JJA) air temperature became significant after the years 1988 and 1998 respectively. The annual precipitation also increased from 1961 to 2010 and the increase became significant after 1989. The summer precipitation increased slightly from 1999 to 2010 but the increase was not significant (Figure 2). The linear trends of annual temperature and precipitation were 0.36°C (10a)⁻¹ and 8.96 mm (10a)⁻¹ respectively from 1961 to 2010.

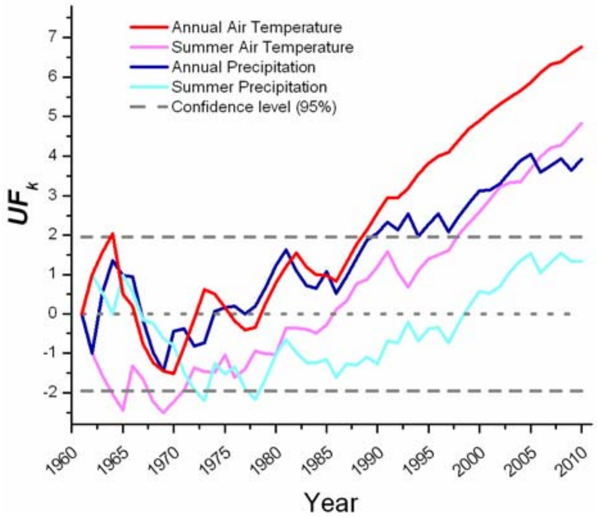

Figure 2 Mann–Kendall analysis of trends of annual air temperature, summer (JJA) air temperature, annual precipitation, and summer (JJA) precipitation during 1961–2010.

Air temperature increased significantly in every month from 1961 to 2010. Precipitation decreased in January, June and September during the same time period, but the decreases were not significant (Table 2).

Air temperature increased significantly in every season from 1961 to 2010. Precipitation also increased in every season during the same time period, but the increase was significant only in spring (Table 3).

3.1.2 Spatial changes of climate

The annual air temperature increased in most regions of West China, while the increase was dramatic in the Altai Mountains and the Middle Tian Shan (Figure 3a). Figure 3b shows an insignificant decrease in the summer air temperature in some regions in West China. The annual and summer precipitation increased in West China from 1961 to 2010 but the increase was insignificant in most regions. Both annual and summer precipitation decreased in the Middle Himalaya Mountains (Figure 3c and Figure 3d).

Table 2 Trends in monthly air temperature and precipitation during 1961-2010. (The trends in air temperature and precipitation show a linear relationship)

Month	1	2	3	4	5	6	7	8	9	10	11	12
Air temperature trend (°C (10a)$^{-1}$)	0.57**	0.61**	0.34**	0.19*	0.12*	0.23**	0.17**	0.15**	0.26**	0.29**	0.51**	0.54**
Precipitation trend (mm (10a)$^{-1}$)	-0.03	0.24	0.74	0.51	1.06*	-0.25	1.36	1.56	-0.16	0.1	0.25	0.15

Table 3 Trends in seasonal air temperature and precipitation during 1961-2010. (The trends in air temperature and precipitation show a linear relationship.)

Season	Spring	Summer	Autumn	Winter
Air temperature trend(℃ (10a)$^{-1}$)	0.22**	0.19**	0.36**	0.57**
Precipitation trend (mm (10a)$^{-1}$)	2.33**	2.68	0.2	0.37

Notes: *(**) Significant at the 95% (99%) confidence level using an F test. Source: China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/)

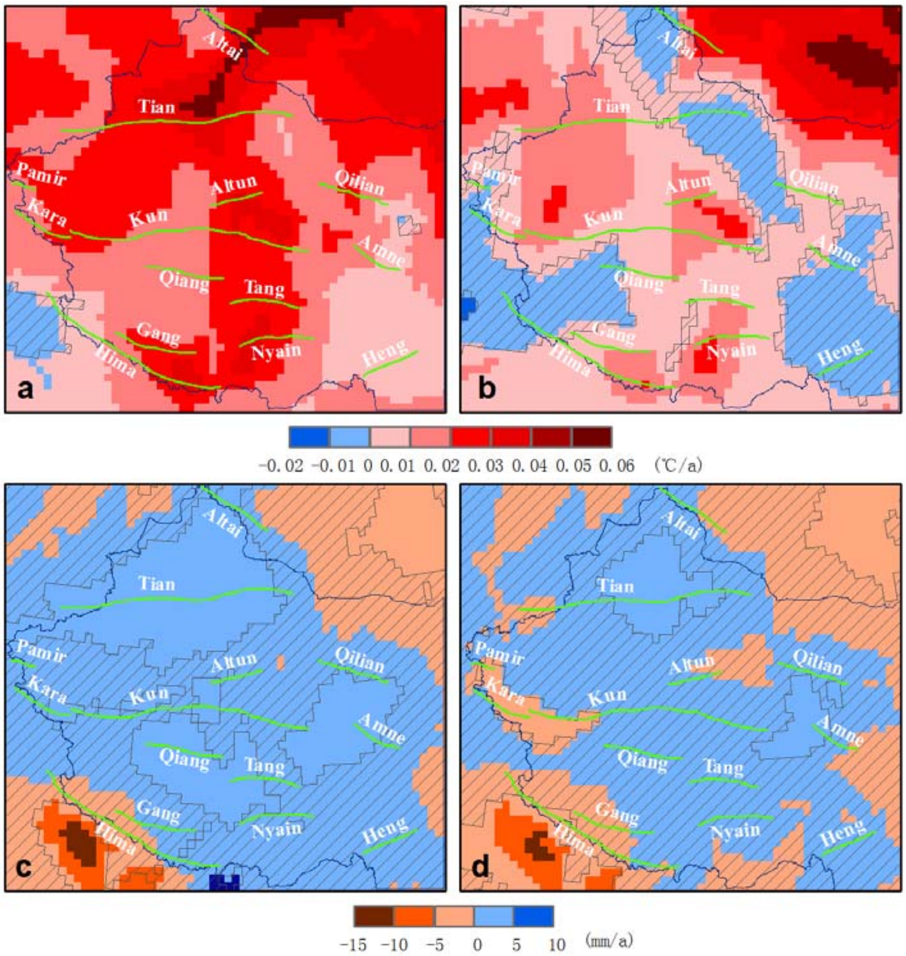

Figure 3 Trends in annual air temperature (a), summer (JJA) air temperature (b), annual precipitation (c), and summer (JJA) precipitation (d) in the CRU TS 3.1 dataset during 1961–2010. Regions where the trend is not significant at the 95% level are hatched. Source: CRU TS3.1 (http://www.cru.uea.ac.uk/). Abbreviations of the names of mountain ranges are given in white (see Table 5 for full names).

3.2 Glacier area variations

Table 4 shows the results of glacier area delineated from Landsat imagery using methods mentioned in section 2.2.1. The difference between glacier extent delineated from the Landsat TM image and CBERS2B HR image is approximately ±3%, which is consistent with previous studies that used a band ratio method to map glaciers (Paul et al. 2002a, b; Andreassen et al. 2008; Bolch et al. 2010a, b). The average distance between the 27 points (not including three points in the middle of the glacier) measured by the GPS device and the outline of the Qiyi Glacier is 10.9 m and the root-mean-square error (RMSE) is 15.4 m (Figure 4).

3.2.1 Temporal variations of glacier area

The total glacier area shrank 15.7% in China from 1963 to 2010. In order to obtain reliable results of glacier area change for all of China, we only used time periods when the number of studies was greater than 18 (Figure 5), the total glacier area studied was greater than 10,000 km², and the studies covered more than five mountain ranges. Yao et al. estimated glacier area in China decreased in the

Table 4 The results of glacier area

Mountain range	Area	Year	Glacier area (km²)
Nyainqêntanglha Mountains	West Nyainqêntanglha Mountains	1976, 1991, 2000, 2011	931.5, 878.4, 852.0, 737.6
Tian Shan	North Tian Shan	1989, 1998, 2011	2214.8, 2078.7, 1884.2
	Central Tian Shan	2000, 2011	889.5, 790.9
Qilian Mountains	Qilian Mountains	1990, 2000, 2010	2041.5, 1802.7, 1575.8
Altai Mountains	South Altai Mountains	1972, 1989, 2000, 2011	633.9, 452.5, 386.1, 329.0
	North Altai Mountains	1980, 2000, 2010	666.0, 614.3, 584.0
Kunlun Mountains	East Kunlun Mountains	1990, 2000, 2010	2197.4, 2047.0, 1933.1
	Malan	1973, 1976, 1994, 2002,2010	203.8, 201.4,196.1, 192.8,191.4
	Bukatage Peak	1973, 1976, 1994, 2002, 2010	430.6, 432.9, 414.0, 410.5, 407.2
	West Kunlun Mountains	1990, 1999, 2011	2986.7, 2984.2, 2979.0
Hengduan Mountains	Gongga Mountain	1974, 1989, 2002, 2010	252.1, 234.7, 236.1, 227.2
	Xuebaoding	1973, 1994, 2002, 2007	9.1, 8.7, 5.5, 6.0
	Yulong Mountain	1974, 1989, 2002, 2009	15.4, 13.4, 13.1, 13.0
Pamir Mountains	East Pamir Mountains	1972, 2000, 2011	1794.8, 1700.1, 1690.8
Altun Mountains	Altun Mountains	1973, 1999, 2010	348.0, 313.6, 293.8

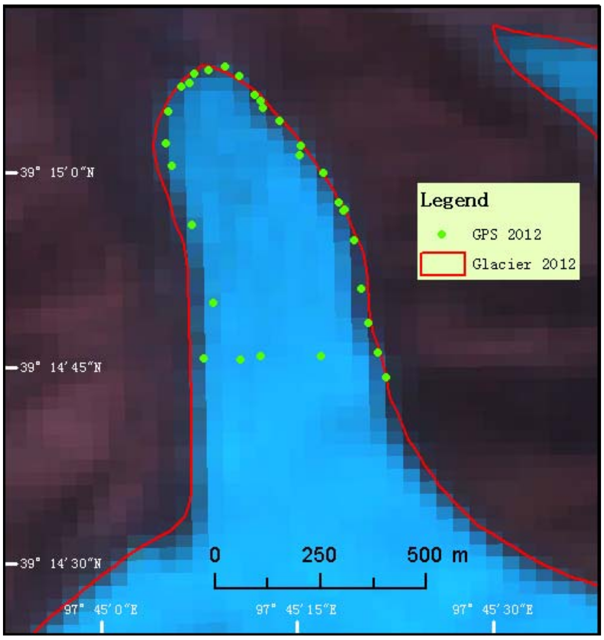

Figure 4 Outline of the Qiyi Glacier and measured points using a GPS device superimposed on the Landsat ETM+ SLC-off image of 25 August, 2012.

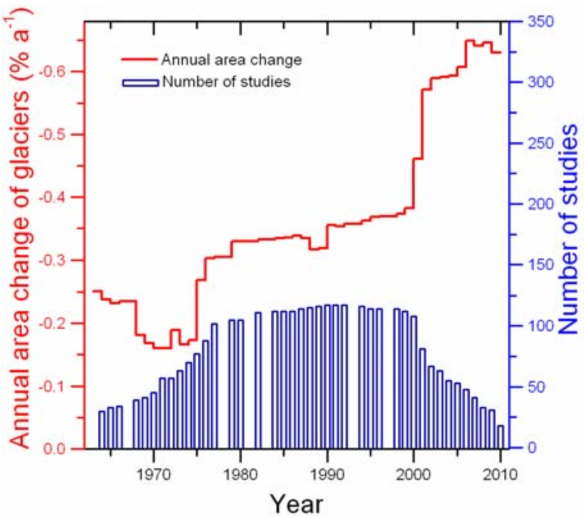

Figure 5 Annual area changes of glaciers in China from 1963 to 2010.

range of 5.8% to 9.1% based on different methods (2004). Ding et al. reported a total area reduction by 4.5% during the past 50 years (2006). Li et al. reported that glaciers have shrunk 5.5% in China since 1960s (2008). Zhang et al. calculated that the area-weighted shrinkage rate of glaciers was 10.1% in China since 1960 (2012). Our value is higher than the results of previous studies (Yao et al. 2004; Ding et al. 2006; Li et al. 2008; Zhang et al. 2012). The main reason for the difference is that our study includes more results of recent years and the shrinkage of most glaciers in China has accelerated in recent years. From 1963 to 2010, the annual area change was -0.33% a^{-1}, which is consistent with -0.3% a^{-1} by Zhang et al. (2012).

Many factors can affect glacier area variations at different scales, such as temperature, precipitation, wind speed, cloud coverage, relative humidity, sublimation, topography, debris cover, glacier size and glacier type (Scherler et al. 2011; Yao et al. 2012). The glacier area change was associated with a stronger trend in temperature than precipitation in China during the past several decades.

The annual area change of glaciers generally accelerated from 1963 to 2010 (Figure 5), but the annual area change patterns were varied among the mountain ranges (Figure 6). Glacier area expanded shortly in only two mountain ranges in the past, namely Karakoram and Kunlun Mountains.

3.2.2 Spatial variations of glacier area

Area shrinkage was substantial in the peripheral areas of the Tibetan Plateau and surroundings (TPSs) such as the Tian Shan, Altai, Altun, Qilian, AmneMachin, Hengduan, Nyainqêntanglha, Gangdisê, and Himalaya Mountains, with area shrinkage of more than 15% over the last several decades (Figure 7). The glaciers were relatively stable in the interior area of TPSs such as the Kunlun and Tanggula Mountains, and the Qiangtang Plateau, with area shrinkage less than 10% over the last several decades (Figure 7). The shrinkage patterns are consistent with previous studies (Yao et al. 2004; Ding et al. 2006;

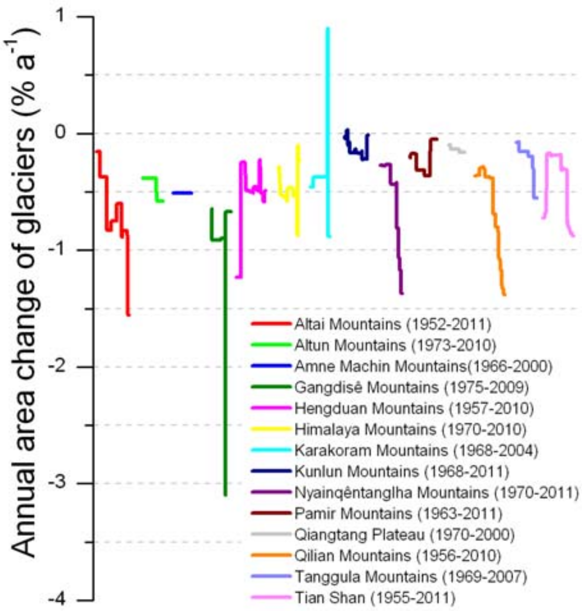

Figure 6 Annual area changes of glaciers in different mountain ranges.

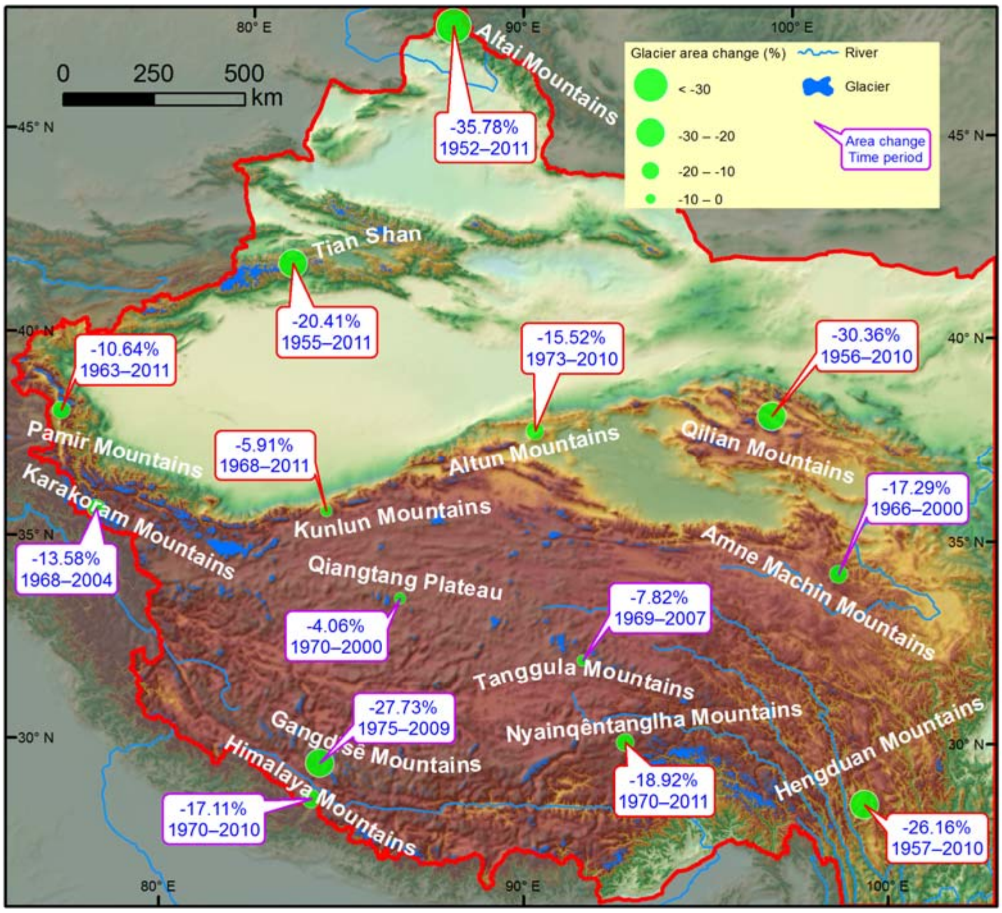

Figure 7 Glacier area changes in China (Dot size denotes the magnitude of glacier area change, and the number with the dot shows the percentage of glacier area change and its time period. Callouts with red outlines denote mountain ranges with both published glacier area data and updated glacier area data by the present study and callouts with violet outlines denote mountain ranges only with published glacier area data).

Li et al. 2008; Yao et al. 2012; Zhang et al. 2012). The change in the equilibrium line altitude between the Last Glacial Maximum (LGM) and present in West China was approximately 1000 m at the margin of the Tibetan Plateau and only 500–300 m or less in the interior of the Plateau (Shi 2002). The pattern of glacier variations in the last several decades was thus similar to the pattern at glacial-interglacial time scale.

Although the shrinkage of the glaciers was mainly influenced by rising temperatures, other factors such as precipitation, topography, debris cover, glacier size and glacier type also affected glacier area variations. These factors appear to be the main reason why the shrinkage varied spatially. For example, the rapid shrinkage in the Qilian Mountains was related to small glacier size and low elevation (Table 5), while in the Altun Mountains, shrinkage was influenced mainly by the rapid rising temperature (Figure 3). Rapid shrinkage in the Altai Mountains was due mainly to rising temperature, small glacier size and low elevation (Figure 3 and Table 5). The rapid shrinkage in the Tian Shan was caused by the rising temperature and low elevation (Figure 3 and Table 5), while the shrinkage in the Gangdisê Mountains was the result of rapidly rising temperature, a decrease in precipitation and small glacier size (Figure 3 and Table 5). The Himalaya Mountains experienced shrinkage due to rapid temperature increases and precipitation decreases (Figure 3). The rapid shrinkage in the Nyainqêntanglha and Hengduan Mountains was due mainly to the type of most of their glaciers, namely maritime type, which are sensitive to climate change (Figure 1).

Table 5 Mean altitude, mean area and number of glaciers in each mountain range

Mountain range	Symbol	MG-Al(m)	MG-Ar (km^2)	No-G
Nyainqêntanglha Mountains	Nyain	5278	1.51	7080
Tian Shan	Tian	3995	1.02	9035
Qilian Mountains	Qilian	4789	0.69	2815
Altai Mountains	Altai	3036	0.69	403
Qiangtang Plateau	Qiang	5293	1.88	958
Kunlun Mountains	Kun	5497	1.59	7697
Himalaya Mountains	Hima	5511	1.30	6472
AmneMachin Mountains	Amne	5185	1.87	76
Hengduan Mountains	Heng	5244	0.92	1725
Pamir Mountains	Pamir	4995	2.09	1289
Tanggula Mountains	Tang	5502	1.45	1530
Karakoram Mountains	Kara	5489	1.76	3563
Altun Mountains	Altun	5254	1.17	235
Gangdisê Mountains	Gang	5900	0.50	3554

Notes: MG-Al = Mean glacier altitude; MG-Ar = Mean glacier area; No-G = Number of glaciers. Source: Glacier Inventory of China (GIC) (Wu and Li 2004; Shi 2008).

The shrinkage in the AmneMachin Mountains was related to the type of most of the glaciers in this area, namely sub-continental type, which are quite sensitive to climate change (Figure 1). The small shrinkage in the Qiangtang Plateau was due to the prevalence of large, extreme continental-type glaciers which are not sensitive to climate change (Figure 1 and Table 5), while the small shrinkage in the Tanggula Mountains was related to high elevation (Table 5). The small shrinkage of glaciers in the Kunlun Mountains was influenced by high elevation, being of extreme continental type (Figure 1 and Table 5). However, the small shrinkage in the Pamir Mountains was related to large glacier size (Table 5), while the small shrinkage in the Karakoram Mountains was related to large glacier size including high elevation (Figure 3 and Table 5).

4 Conclusions

We provided new information on glacier extent and compiled information on glacier area from different studies. From 1963 to 2010, the total glacier area shrank 15.7% (-0.33% a^{-1}) in China. Area shrinkage generally decreased from peripheral mountain ranges to the interior of Tibet. The shrinkage of glaciers was attributed mainly to rising temperature. Other factors superimposed on the rising temperature influenced the spatial variability of glacier changes.

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