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Glacier changes from 1966–2009 in the Gongga Mountains, on the south-eastern margin of the Qinghai-Tibetan Plateau and their climatic forcing

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Abstract

In order to monitor the changes of the glaciers in the Gongga Mountain region on the south-eastern margin of the Qinghai-Tibetan Plateau, 74 monsoonal temperate glaciers were investigated by comparing the Chinese Glacier Inventory (CGI), recorded in the 1960s, with Landsat MSS in 1974, Landsat TM in 1989, 1994, 2005, and ASTER data in 2009. The remote sensing data have been applied to map the glacier outline by threshold ratio images (TM4/TM5). Moreover, the glacier outlines were verified by GPS survey on four large glaciers (Hailuogou, Mozigou, Yanzigou, and Dagongba) in 2009. The results show that the area dominated by the 74 glaciers has shrunk by 11.3 % (29.2 km^2) from 1966 to 2009. Glacier area on the eastern and western slope of the Gongga Mountains decreased by 14.1 km^2 (5.5 % in 1966) and 15.1 km^2 (5.9 % in 1966), respectively. The loss in glacier area and length is respectively 0.8 km^2 and 1146.4 m (26.7 m yr^{-1}) for the Hailuogou glacier, 2.1 km^2 and 501.8 m (11.7 m yr^{-1}) for the Mozigou Glacier, 0.8 km^2 and 724.8 m (16.9 m yr^{-1}) for the Yanzigou Glacier, and 2.4 km^2 and 1002.3 m (23.3 m yr^{-1}) for the Dagongba Glacier. Decades of climate records obtained from three meteorological stations in the Gongga Mountains were analyzed to evaluate the impact of the temperature and precipitation on glacier retreat. During 1966–2009, the mean annual temperature over the eastern and western slope of the Gongga Mountains has been increasing by 0.21 °C/10 yr and 0.13 °C/10 yr, respectively. Moreover, it was stable in the mean annual precipitation. This evidence indicates that the warming of the climate is probably responsible for the glacier retreat in the study region.

1 Introduction

Glaciers are a critical component of the earth system and the present accelerated melting and retreat of glaciers has severe impacts on the environment and human well-being, including vegetation patterns, economic livelihood, natural disasters, and the water-energy supply (UNEP, 2007). Changes of glaciers in mountainous regions are widely recognized as one of the best natural indicators of global climate change (Oerlemans, 1994, 2005), and the decline in glacier extent in mountains and other regions also contribute to sea level rise (Arendt et al., 2002; Larsen et al., 2007; Schiefer et al., 2007). The response of a glacier to climate change depends on its geometry and on its climatic setting (Oerlemans, 2005). Extensive meteorological experiments on glaciers have shown that the primary source for melt energy is solar radiation but that fluctuations in the mass balance through the years are mainly due to temperature and precipitation (Oerlemans, 2005; Greuell and Smeets, 2001). Recently, many records of glacier changes in the global have been obtained by fieldwork investigation, ground and aerial photographic measurements, and high-resolution remote sensing monitoring (Barry, 2006; DeBeer and Sharp, 2007; Racoviteanu et al., 2008; Paul and Andreassen, 2009; Shangguan et al., 2007). All the results indicate the general trend of a glacier is recession, and only a few glaciers are advancing. The monsoonal temperate glacier, with a high rate of accumulation and ablation and a high mass-balance amplitude (Braithwaite and Zhang, 2000; Kaser et al., 2006), is more active than cold and continental glacier, and thus is more sensitive to the changing climate (Su and Shi, 2000).

In China, numerous glaciers exist within and around the Qinghai-Tibetan Plateau. Established in the 1960s, the first Chinese Glacier Inventory (CGI) was compiled using aerial photography data, and the results formed a significant step in integrating knowledge of glaciers in China (Shangguan et al., 2006). The data were subsequently abridged into a Concise CGI, published in Chinese (2005) and in English (2008) (Shi et al., 2009), in order to make the glacier inventory more accessible and better adapted for assessing glacier response to climate change (Shi et al., 2009). In order to know the accurate information of glacier status after 30–40 yr of pronounced glaciers changes in and respond to the USGS-led project GLIMS (Global Land Ice Measurements from Space) (Haeberli et al., 2000; Paul et al., 2004), the new Chinese Glacier Inventory was started in 2006 using the new multi-spectral satellite data with a high spatial resolution.

Glacier inventories in this region have existed in the Gongga Mountains where typical monsoon temperate glaciers are widely developed since the 1930s (Heim, 1936; Anderson, 1939). Cui (1958) reported comprehensive information relating to the glaciers investigations in the Gongga Mountains. In recent decades, more investigations have been conducted in different ways in this region. For instance, Su et al. (1992) presented new data about glaciers changes which was mainly based on the field investigations including repeated surveys expeditions to the Qinghai-Tibetan Plateau by the Chinese Academy of Sciences (1981–1983) and by Sino-Soviet joint glaciological expedition to the Gongga Mountains in 1990. Four years later, more glacier parameters in the Gongga Mountains were accomplished by Pu in 1994 (Pu, 1994), based on the topographic map derived from aerial photographs acquired in the 1960s. Using the steady-state equilibrium line altitude (ELA) method and the observed melting data, Xie et al. (2001) discovered that the mass-balance in Hailuogou (HLG) Glacier (one of the large glaciers in the Gongga Mountain) was about $-488\,\mathrm{mm\,yr^{-1}}$ from 1990 to 1998, and concluded that the negative mass balance of the HLG Glacier is caused by an increase in ablation. The elevation change of ablation area of HLG Glacier was measured as $-1.1 \pm 0.4\,\mathrm{m\,yr^{-1}}$ from 1966 to 2009 by GPS surveys (Zhang et al., 2009). The study on the relation between HLG Glacier shrinkage and hydrological response showed an increasing trend of storage loss during the last 20 yr (Liu et al., 2010). Li et al. (2010a) summarized the fluctuations of HLG Glacier during the Holocene and considered that the changes of HLG Glacier were mainly influenced by climatic fluctuation. However, most of these researches were focusing on a single glacier in the Gongga Mountains, and there was little systematic and comprehensive study on the change of length and area of glaciers, especially by using the remote sensing image. Using multi-temporal remote sensing data in different periods, including Landsat MSS (Multispectral Scanner), TM, ETM+ (Thematic Mapper Plus), ASTER (Advanced Spaceborne Thermal Emission and Reflection) and CGI data based on topographic maps derived from aerial photographs, this study is an attempt to accurately investigate changes of all of glaciers in the Gongga Mountains since the 1960s, and to discuss the reason for these changes, especially their relation to global climate change.

2 Study area

The Gongga Mountains (29° 20′ –30° 10′ N, 101° 30′ –102° 10′ E) is situated on the south-eastern margin of the Qinghai-Tibet Plateau (Fig. 1), the highest peak (Mount Gongga) has an elevation of 7556 m a.s.l. Geomorphologically, Gongga Mountains is located at the transition zone between the Sichuan Basin and the Qinghai-Tibet Plateau and climatically between the warm-wet monsoon climatic region of the eastern subtropics and cold-dry region of the Qinghai-Tibet Plateau. The Gongga Mountains is not only controlled by the monsoon of Southern Asia and the monsoon of Eastern Asia, but also influenced by the Qinghai-Tibet plateau monsoon and the westerly circulation (Li et al., 2010b). The annual precipitation is ∼ 1871 mm at 3000 m a.s.l. on the eastern slope of the Gongga Mountains and ∼ 1173 mm at 3700 m a.s.l on the western (Su et al., 1992). The mean annual air temperature is 3.7 °C on the eastern slope (3000 m a.s.l.) and only 1.9 °C on the western (3700 m a.s.l.) (Su et al., 1992).

According to the CGI (Pu, 1994), 74 glaciers with a total area of 257.7 km^2 are distributed in this region, containing five valley glaciers with lengths of more than 10 km, including Hailuogou (HLG) Glacier, Mozigou (MZG) Glacier, Yanzigou (YZG) Glacier, Nanmenguangou (NMGG) Glacier on the eastern slope and DaGongba (DGB) Glacier on the western slope. The glacier in this region is classified as summer-accumulation type (Su et al., 1996; Xie et al., 2001), which has more accumulation in summer than winter in the whole area of a glacier (Ageta and Higuchi, 1984). They are characterized by a high flow velocity, rich accumulation and heavy melting. Many moraines are

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distributed around the glacier snouts, and both terminal and lateral moraines along the western slope are more developed than those along the eastern slope.

3 Data sources and methods

The changes in the glaciers were determined by comparing glacier area and length for multi-temporal spaceborne images, including Landsat MSS, TM, ETM+, ASTER and CGI (Table 1). The glacier outlines from the CGI (Pu, 1994) were interpreted and measured by stereophotogrammetry from aerial photographs at a scale of 1 : 60 000 taken during 1966, and corrected by aerial photographs and field investigation. As the first CGI is the oldest archive to analyze changes of glaciers in the west of China (e.g., Shangguan et al., 2006, 2007 and 2009; Liu et al., 2010), we digitized the glacier outlines of the first CGI as vector files and took them as the basic and reference data to analyze later changes in the Gongga Mountains glaciers.

The used Landsat MSS/TM/ETM+ scenes were downloaded from USGS (United States Geological Survey) webserver. Their quality is good, details can be found in Table 1. These data include one Landast MSS image (1974), three Landsat TM images (1989, 1994 and 2005) and one Landsat ETM+ image (2002). Two ASTER images with no clouds and minimal seasonal snows were provided by the NASA (National Aeronautics and Space Administration) /METI (Ministry of Economy, Trade and Industry). Some historical data (e.g. mass balance data, meteorological data) were also summarized to analyze fluctuations of glaciers in the Gongga Mountains.

The DEM (Digital Elevation Model) at 20-m resolution, constructed from the digitized contour line of the topographic map from 1989 with a scale of 1 : 50 000, was used to analyze the topographic features of the glaciers (e.g. slope, aspect, elevation). All datasets (DEM, remote sensing images, results of CGI) were spatially referenced to the local Universal Transverse Mercator coordinate system (UTM zone 47N, WGS84), and resampled to 15 m resolution, in order to ease the calculation of changes in the glaciers. The residual Root Mean Square error (RMSe) of verification points, when compared with Landsat ETM+, was usually less than 1.2 pixels or 18 m.

In this study, automated glacier mapping from multi-spectral satellite data was applied to track the glacier change. This technique was developed Hall et al. (1987), who suggested that the ratio of TM band 4 to TM band 5 could provide improved contrast (relative to using a single TM band) between glaciers which are surrounded by ablation areas of debris, or till-laden glaciers. At present, the method of band ratio is widely used in the glacier inventory of the whole world (Khromova et al., 2003; Paul and Kääb, 2005; Aizen et al., 2006; Raup et al., 2007; Paul and Andreassen, 2009; Svoboda and Paul, 2009).

For the Landsat TM, the band ratio of TM3/TM5 or TM4/TM5 was selected for glacier mapping. A threshold (Table 2) was set by TM4/TM5 > 2.4, that was more accurate than TM3/TM5 in this region, and an additional threshold in TM1 (DNs > 59) was set to improve glacier mapping in cast shadow (Paul and Kääb, 2005). This method is simple to apply, and the result is accurate for debris-free glaciers (Albert, 2002; Andreassen et al., 2008). Glacier mapping by spectral band combinations image (TM3/TM5 or TM4/TM5) is accepted to be the most efficient method for debris-free glaciers (Paul, 2002), but it is not suitable for debris-covered glaciers, which are generally mapped manually. Glacier mapping with ASTER was done using threshold band ratio (Table 2) of the third band (red band) and the fourth band (SWIR band), a method which was already successful in other regions (e.g., Paul, 2002; Paul and Kääb, 2005; Raup et al., 2007; Svoboda and Paul, 2009). Svoboda and Paul (2009) have discussed glacier mapping with Landsat MSS, and obtained satisfying results on Southern Baffin Island, Canada. We chose their method to extract glacier extent from Landsat MSS. The specific method is as follows: a decision-tree classifier that utilizes multiple thresholds (Table 2) was used because MSS has no SWIR band; instead of a SWIR band, an NIR (near-Infrared) band was used for the band ratio (MSS3/MSS4); and an additional threshold in the first NIR band (MSS3) was applied to remove wrongly classified rocks in shadow (Svoboda and Paul, 2009).

However, many glaciers in the Gongga Mountains are debris-covered, and all methods mentioned above make it difficult to detect glacier outlines. Consequently, manual editing was implemented to correct the mapping results. Finally, we put all the digital glacier outlines into a Geographic Information System (GIS) and then calculated the changes during the years 1966–2009.

Analysis of the corresponding change in glacier area consistently indicates a great percentage of area loss in last 43 yr. However, some uncertainties and limitations of the glacier mapping could be derived. Generally, debris cover, snowfields, water bodies are the unavoidable factors affecting the accuracy of the mapping of glacier outlines and also hardly to evaluate. Another important uncertainty in the area change assessment is derived from the comparison of different data sources. Errors in glacier mapping were caused by low image resolution and by co-registration (Ye et al., 2006; Hall et al., 2003; Shangguan et al., 2009). The comparatively low resolution (80 m) of the Landsat MSS image is not as accurate as TM and ASTER images, especially for the smaller (area < 0.1 km^2) and debris-covered glacier outlines. Similar problems were also reported by Hall et al. (2003) in Austria and Svoboda and Paul (2009) in Canada, but they considered that Landsat MSS images are available for most parts of the world with an archive making up for the deficiency of data in the 1970s. In order to verify and improve the accuracy of glacier outlines, fieldwork was conducted (Fig. 1c). Five glaciers (HLG, MZG, YZG, DGB and XGB Glacier) were surveyed in April 2009 using dual differential GPS (SF-2040G, single-level positioning accuracy ≤ 10 cm), and, the results showed that there is about ± 30 m deviation in the length and 0.5 % in the area, when comparing our 100 surveyed points with glacier mapping generated from ASTER data in 2009.

4 Results

4.1 New glacier inventory data in 2009

The 76 glaciers in the Gongga Mountains (Fig. 2a), 51.3 % of all glaciers smaller than 1 km^2 and contribute to 7.1 % to the total area, while 6.5 % glaciers larger than 10 km^2 and contribute to 45.7 % of the total area. The distribution of the number and area of glaciers by covered by the median altitude is depicted in Fig. 2b. There are 25 glaciers with approximately 50 % of total area distributed between 5200 m and 5400 m. There is only one glacier reaching higher than 6000 m and one glacier reaching lower than 4000 m. On the eastern slope (Fig. 1b), there are 36 glaciers covering an area of 139.9 km^2, with a mean area of 3.9 km^2 and the mean climatic equilibrium line altitude (ELA) of ~ 4900 m. There are 40 glaciers with a total area of 87.6 km^2 distributed on the western slope, with a mean area of only 2.1 km^2 and a mean climatic ELA of ~ 5100 m. The mean aspect of each glacier is calculated following Paul (2007). The orientation of glaciers by number and area is shown in Fig. 3; south-western and south-eastern sectors make up half the number of glaciers, dominating 78 % of the area (Fig. 3a,b), and there are no glaciers in the northern and north-eastern sectors. Furthermore, the area of glaciers covered on the south-eastern sector obviously exceeded half of the total area (Fig. 3b), and the number of glaciers in the southern sector account for about 20 % of all glaciers, while their area contributes to 7.5 % (16.9 km^2) of total. The orientation distribution shows that the locations of glaciers dependent on local topographical constraints (Andreassen et al., 2008). The mean slope of glaciers in the study region is less than 45°, and most glaciers areas range between 25 and 40°.

4.2 Glacier changes

The analysis of glacier area from 1966 (CGI) to 2009 (ASTER) reveals some interesting changes, as shown in Tables 3 and 4. The sample of 74 glacier units from the 1966 CGI, covers a total area of 257.7 km^2 (mean glacier area: 3.5 km^2). The area of the largest glacier (YZG Glacier) is 30.1 km^2, and the minimum area of glacier is only 0.11 km^2. Whereas, the area of 76 glacier units from 2009 ASTER inventory is 228.5 km^2 (mean glacier area: 3.0 km^2), in which the maximum glacier is 25.5 km^2 and the smallest glacier is only 0.05 km^2. The total area loss of the glaciers is about 29.2 km^2 (11.3 % of total area in 1966) in a decreasing of 0.7 km^2 yr^{-1} from 1966 to 2009. The rate of area change (–1.3 km^2 yr^{-1}) during 2005 to 2009 is the fastest in the whole period, while the rate during 1994 to 2005 is the slowest, at –0.5 km^2 yr^{-1}.

Due to the effect of glacier retreat, one glacier on the western slope was separated into two smaller glaciers in 1974–1989 and two big glaciers (YZG Glacier) on the eastern slope were respectively separated into two and three ones in 1989–2009. Two small glaciers on the western slope with northern aspect disappeared between 1994 and 2005. Therefore, the number of glaciers has increased by two during the period 1966–2009. The trend that most of the glaciers covering the Gongga Mountains have decreased in size is remarkable (Fig. 2, Tables 3 and 4).

On the eastern slope of the Gongga Mountains, the sample of 33 glaciers with an area of 155.1 km^2 in 1966 has increased to 36 glaciers with an area of 139.9 km^2 in 2009, and the total area loss is 15.2 km^2 (accounting for 5.5 % of the area in 1966). On the western slope, the sample of 41 glaciers with a total area of 102.6 km^2 in 1966 has decreased to 40 glaciers with an area of 87.6 km^2 in 2009, and the area loss contributes to 5.9 % of total in 1966. Glacier size strongly affects the percentage loss of glacier area. From 1966 to 2009, the area loss in the size classes < 0.5 km^2, 0.5–1 km^2, 1–5 km^2, 5–10 km^2, and >10 km^2, equals 6.3 %, 10.8 %, 34.8 % , 21.3 % and 26.8 %, respectively (Table 4). The shrinkage of the glaciers in the size class of 1–5 km^2 contributes to about 1/3 of the total area loss, (Fig. 2a; Table 4). All glaciers in northwestern aspect are located on the western slope, and are small glaciers (< 5 km^2). The shrinkage of these glaciers is stronger than for other orientation in this region. The mean slope of all glaciers in this region ranges between 15 and 45°, and glaciers with the mean slope of 35–40° (covering an area of 37.9 % in 1966) exhibit the largest shrinkage.

4.3 Exemplary glacier change

Four glaciers with length of 10 km (the HLG, MZG, YZG and DGB Glaciers) are located in the investigation area and account for 39.4 % (89.6 km^2) of the total glacier area in 2009. We studied their area change and front variations in detail.

4.3.1 HLG Glacier

As a famous tourist attraction in China, the HLG Glacier have described by many glaciologists (Heim, 1936; Cui, 1958; Su et al., 1992; Liu et al., 2010) in different ways. For example, the length of the HLG Glacier was about 13 km in 1936 (Heim, 1936), decreased about 1 km from the 1930s to 1960s (Su et al., 1992), and further to only 11 km in 2009. Our investigation indicates that, from 1966 to 2009, the total retreat of the HLG Glacier is about 1146.4 m (about 26.7 m yr^{-1}), which can be separated into 336.5 ± 60 m, 393.4 ± 30 m, 188.3 ± 30 m, 103.8 ± 30 m, 124.6 ± 15 m, for periods of 1966–1974, 1974–1989, 1989–1994, 1994–2005 and 2005–2009, respectively (Fig. 4a,b; Table 5). The highest retreat rate occurred during the period 1989–1994. Our results are in agreement with previous studies (Su et al., 1992; He et al., 2008; Liu et al., 2010; Li et al., 2010a). Moreover, its area has shrunk by 3.1 % (from 26.1 km^2 in 1966 to 25.3 km^2 in 2009) since 1966 (Table 6).

4.3.2 MZG Glacier

The terminus of the MZG glacier retreated about 501.8 m from 1966 to 2009 (Fig. 4c,d; Table 5). This relatively low value may be attributed to its higher mean elevation and larger accumulation area ratio (0.75) than that of the HLG Glacier. The area shrinkage of 7.7 % from 1966 to 2009 (Table 6), however, is larger than that of the HLG and YZG Glaciers. By comparing remote sensing images from 1974, 1989, 1994, 2005 and 2009 with CGI, we found that some snowfields hide parts of the MZG glacier perimeter in the images before 2009, and the snowfields might be included in determination of the glacier outline. When the snowfields melted away in 2009 (Fig. 5a), the exact glacier outline exhibited a sudden shrinkage. In Fig. 5a (Uncertain area), although some glacier change was found, we could not confirm whether the MZG glacier has been already separated into two parts due to a steep cliff (Fig. 5b,c).

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4.3.3 YZG Glacier

The terminus of the YZG Glacier retreated 724.8 m (about 16.9 m yr^{-1}) during the period 1966–2009, including 204.9 ± 60 m, 181.7 ± 30 m, 97.8 ± 30 m, 172.8 ± 30 m, 67.6 ± 15 m in the periods 1966–1974, 1974–1989, 1989–1994, 1994–2005 and 2005–2009, respectively (Fig. 4e,f; Table 5). The terminus retreat rate (25 m yr^{-1}) was at its maximum between 1966 and 1974. The area of the glacier changed from 30.1 km^2 in 1966 to 20.2 km^2 in 2009. Furthermore, the YZG Glacier had been separated into three parts between 1966 and 2009, in which two glaciers were separated from the YZG Glacier during the period 1989–1994 (Fig. 6a,b) and 1994–2009 (Fig. 6b,c,d). The field photography in 2009 also illustrates this evidence (Fig. 6e). These three glaciers cover areas of 20.2 km^2, 2.9 km^2 and 6.0 km^2, respectively.

4.3.4 DGB and XGB Glaciers

The DGB Glacier and XGB Glacier formed one single glacier before 17th century. However, it separated into two independent glaciers during the early 17th to middle 19th century (Li, 1996). According to the description of Heim (1936), the DGB Glacier is about 10 km long, a tongue of 2 km, and the terminus ends at a height of 3800 m a.s.l. Su et al. (1992) have also described the situation of the glacier. They stated that the overlap of the fresh and the older moraines formed a great cone, which was about 240 m above the valley floor, and there was no distinct boundary between the present terminus and the fresh moraines around the DGB Glacier. According to our results, the terminus of the DGB Glacier has retreated about 1002.3 m (Fig. 4g,h; Table 5) from 1966 to 2009, and is located at a height of about 4000 m a.s.l. in 2009, which is approximately 200 m higher than that in 1936. The length of the glacier was reduced by about 685.7 m in the period 1966–1989 and 316.5 m in the period 1989–2009. The total area of DGB Glacier has reduced by 2.4 km^2 (11.2 %), from 21.5 km^2 in 1966 to 19.1 km^2 in 2009 (Table 6), the area shrinkage during the period 1966–1989 accounts for 78 % of the total area loss. Although the shrinkage rate on the western slope was generally higher than that on the eastern side, the terminus of DGB Glacier remained relatively stable during last decades, because the ablation zone was covered by a thick debris layer. The field investigation in 2009 showed that the surface elevation of DGB Glacier is about forty meters lower than its fresh lateral moraines. The XGB Glacier is smaller than the DGB Glacier, and is also debris-covered glacier. The terminus of the XGB Glacier retreated about 378 m in the last 43 yr, and total area had diminished by −14.6 % (from 6.7 km^2 in 1966 to 5.7 km^2 in 2009).

5 Discussion

5.1 Regional climate, topographic and glacier changes

In this study, temperature and precipitation data are from three meteorological stations (Fig. 1a,b), which are closely located to the glaciers in the Gongga Mountains. They are Hailuogou meteorological station (3000 m a.s.l.) on the eastern slope (Fig. 1b) and Jiulong meteorological station (2993 m a.s.l.) and Xinduqiao meteorological station (3640 m a.s.l.) on the western slope (Fig. 1a). Climate records of these stations (Fig. 7) were analyzed to evaluate the impact of the temperature and precipitation on glacier retreat. The mean annual temperature of all three stations has increased over the past 50 yr, and the warming rate of the HLG meteorological station (0.21 °C per decade) is faster than those of Jiulong and Xinduqiao meteorological station (0.13 °C per decade). In the south-eastern margin of the Qinghai-Tibetan Plateau, evidence of long-term climate change, derived from tree-rings (He et al., 2003) and the ice core (Thompson et al., 2000) also indicates that there is a rapid warming trend in past millennium. The mean annual precipitation data did not exhibit a significant incremental trend (Fig. 7) in the last 50 yr. Mass-balance modeling (Oerlemans, 2001; Braithwaite and Zhang, 2000), indicates that a 25 % increase in annual precipitation is typically needed to compensate for the mass loss due to a uniform 1 °C warming. In the Gongga Mountains, the mean annual temperature has increased by 0.5 °C since the

1960s, while the mean annual precipitation has increased by 1 %. As a consequence, the increasing amount of precipitation could not compensate for the mass loss due to the temperature increase in the Gongga Mountains. Therefore, we propose that the glacier area shrinkage of 11.3 % in the Gongga Mountains is attributed to the increase of temperature (Fig. 8).

Taking the topographical features of this region into account, the Gongga Mountains is approximately north-south, and the number of glaciers is respectively 36 and 40 on the eastern and western slope in 2009. The rate of area loss on the western slope (5.89 %) is a little bit faster than that on eastern slope (5.48 %) of the Gongga Mountains. However, the mean annual temperature rise is faster on the eastern slope than on the western slope. The mean glacier size on the western slope (2.2 km^2) is smaller than that on the eastern slope (3.9 km^2). The smaller glaciers on the western slope may be more sensitive to the changes of climate than the larger glaciers on the eastern slope. The different retreat rates on both slopes can be interpreted by the difference of glacier size. Considering the largest glaciers changes, climate warming has resulted in sustained glacier retreat through 43 yr, but the topographic factor is also not neglected. For example, the HLG, and YZG glacier are located on the eastern slope, but the terminus of HLG glacier (3015 m a.s.l.) is lower than YZG glacier (3726 m a.s.l.). Additionally, the orientation of HLG and YZG glacier is southeast and northeast. Those can explain that the shrinkage of HLG glacier is more intense than the YZG glacier.

The rate of glacier retreat in the Gongga Mountains (Table 3 and Fig. 8) was 0.6 $\text{km}^2\,\text{yr}^{-1}$ from 1966 to 1974, slightly slowed down during the period 1974–1989, and then became intensive in the period between 1989 and 1994. It was at its slowest (0.5 $\text{km}^2\,\text{yr}^{-1}$) from 1994 to 2005, and after 2005, became its most intensive, at 1.3 $\text{km}^2\,\text{yr}^{-1}$. In order to explore causes of glacier reduction in different time intervals, the meteorological data of Jiulong station, which has the longest and most reliable series data from 1953 to 2009, were averaged with the same time interval as glacier reduction (Fig. 8). In comparison with glacier reduction (Fig. 9), it is obvious that the annual temperature has the same trend as the glacier reduction (Fig. 8), and annual precipitation has a significant negative correlation with the retreat rate of glacier area. The increase of precipitation probably weakens the rate of glacier reduction; in contrast, the decrease of precipitation aggravates the rate of glacier reduction. Therefore, the decrease in precipitation and increase of temperature caused the largest rate of glacier reduction ($1.3\,\mathrm{km^2\,yr^{-1}}$) during the period 2005–2009 (Fig. 8). This result consolidates the research of Yao et al. (2004), who divided the glacier retreat into several stages when studying glaciers in the Southeast Tibetan Plateau and Karakorum Mountains.

In general, the quantitative relationship between the glacier termini fluctuations and climate change is complicated by a time lag between climate change and glacier response (Jóhannesson, 1989). The time lag is affected by several conditions, such as glacier size, glacier bed slope, and glacier type. Porter (1986) expressed a phase lag of about 10–15 yr by studying glacier changes in the Alps using acidity level variation method. Wang and Zhang (1992) considered that there was a phase lag of 12–13 yr for glacier advance to climatic change in the Northern Hemisphere by analyzing numerous glacier advance and positive mass-balance. The lag of the monsoonal temperate glaciers of the Gongga Mountains should be shorter than those of other glaciers because of the characteristics of the glaciers.

When the Gongga Mountains glaciers are grouped, according to size classes (according to their CGI area) (Table 4), it shows that glaciers with small sizes had a more notable reduction than large glaciers. For instance, the shrinkage of the small glacier (area $< 1\,\mathrm{km^2}$) was the most serious, and some of the smallest glaciers have vanished. Although the area of the large glaciers (area $> 10\,\mathrm{km^2}$) dominated the total area, the glaciers of $1–5\,\mathrm{km^2}$ contributed about 35 % to the total area recession. This evidence suggests that smaller glaciers are more sensitive to climate change, especially to short-period and small-amplitude climate change.

5.2 Comparison of glacier changes in Gongga Mountains with other regions

In the Gangrigabu Mountains, Liu et al. (2006) concluded that the glaciers, which are also monsoonal temperate glaciers, have retreated 13.8 % (about 2.1 % per decade) in area and 9.8 % (about 1.5 % pre decade) in volume, respectively, from 1915 to 1980. The glaciers in the West Kunlun Shan (WKS), which are extreme continental type glaciers, have decreased by about 0.4 % in area during the period 1970–2001 (Shangguan et al., 2007). According to Shangguan et al. (2006), the glacier (sub-continental type glacier) area has decreased by 4.1 % (about 1.4 km^2 per decade) in the Karakoram Mountains between 1969 and 1999. Li et al. (2008) summarized the current status of the cryosphere in China and its changes based on the latest available data. The investigation indicated that glacier areas in China have shrunk about 2–10 % over the past 45 yr and total area has receded by about 5.5 % (Li et al., 2008). Moreover, Kang et al. (2004) suggested that the area change of monsoonal temperate, sub-continental and extreme continental type glacier is −8.9 %, −6.0 % and −2.4 % from the 1960s to 2000, respectively. Those results indicate that the change of monsoonal temperate type glacier is remarkable. Comparing with above researches, the glacier retreat in the Gongga Mountains (11.3 % reduction in glacier area from 1966 to 2009, and about 2.6 % per decade) is similar to the same glacier type faster than continental glaciers type in the west of China. Glaciers in the Gongga Mountains, typical monsoonal temperate glaciers, have abundant summer precipitation and higher ice-layer temperature above −1 °C, by inference, larger flow velocity and ablation intensity (Su and Shi, 2002). Therefore, the glaciers in the Gongga Mountains are naturally sensitive to climatic change.

6 Conclusions

In this study, we present the results of the new glacier inventory of the Gongga Mountains, with area 228.5 km^2 of 76 glaciers in 2009, and serial glacier mapping results from different data sources since the 1960s, including a statistical analysis of the inventory data and a calculation of area and length changes from 1966 to 2009. The glacier area of 74 glaciers in the Gongga Mountains shrank by −11.3 % (about 29.2 km^2) or about −2.6 % per decade since 1966. The number of glaciers has shrunk from 76 to

74 in 1966, as two small glaciers (< 1 km^2) have vanished and four new glaciers were separated from large glaciers during the period 1966–2009. The retreat rate of glacier area during 1966–2009 is higher than most other regions in China. Moreover, the area loss is more notable on the western slope (–5.9 % in 1966) than on the eastern slope (–5.5 % in 1966). The rate of glacier reduction is notable between 1966 and 1994, became slower during the period 1994–2005, and reached its fastest during the years 2005–2009. This trend of glacier reduction is similar to other glaciers on the southeast of the Qinghai-Tibetan Plateau, and the reduction is mainly caused by the increase of temperature. Moreover, the glacier reduction on the western is faster than that on the eastern which can be explained by the difference of topography and glacier size. Although, the terminus and area of the largest glacier is a visible retraction, the smaller glaciers also make important contributions to area changes, especially to response to climate changes, because the smaller glaciers are more sensitive to climate change than larger glaciers in local region range and short timescale. However, we have procured many significative and interesting results. Many open questions still need to be solved (e.g. spatial resolution of remote sensing images; the different of fieldwork; accuracies of glacier mapping). In the future, the monitoring of the glacier changes will be a long-time and hard work, especially for alpine glaciers.

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Table 1. Data sources used in this study.

Image	Path/row	Date	Resolution or scale	Quality	Cloud cover	Source
Topographic map	–	1971	1 : 100 000		–	Chinese military geodetic service
DEM	–	1989	20 m or 1 : 50 000		–	Topographic map
CGI	–	1966	1 : 100 000		–	Aerial photographs
Landsat 2 MSS	140/39	21 Jan 1974	80 m	5	0 %	USGS/NASA
Landsat 5 TM	131/39	2 Jan 1989	30 m	9	0 %	USGS/NASA
Landsat 5 TM	131/39	5 Sep 1994	30 m	7	0 %	USGS/NASA
Landsat 5 TM	131/39	7 Feb 2005	30 m	7	11 %	USGS/NASA
Landsat 7 ETM+	131/39	6 Jan 2002	30 m	6	0 %	USGS/NASA
Terra ASTER	–	23 May 2009	15 m	7	3 %	NASA/METI

Table 2. Thresholds used for glacier mapping for all investigated sensors.

Sensor	Snow and ice*	Snow and ice in shadow
ASTER	AST3/AST4 $\geq$ 1.8	AST1 $>$ 47
TM	TM3/TM5 $\geq$ 2.4	TM1 $>$ 59
MSS	MSS3/MSS4 $\geq$ 2.0	MSS3 $>$ 22

*Partly includes rocks in shadow.

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Table 3. Results of glacier mapping in 1966–2009.

Time	Glacier count	Total area (km^2)	Mean glacier area (km^2)	Area change* (km^2)	Rate of area change ($km^2\ yr^{-1}$)
1966	74	257.7	3.5	–	–
1974	74	252.4	3.4	−5.2	−0.7
1989	75	242.8	3.2	−9.6	−0.6
1994	76	239.1	3.1	−3.8	−0.8
2005	74	233.6	3.1	−5.5	−0.5
2009	76	228.5	3.0	−5.1	−1.3
total				−29.2	−0.7

*Area change is obtained by subtracting total area from two neighboring periods.

Table 4. Comparison of glacier area for 74 glacier units from three different inventories: CGI (1966), Landsat MSS (1974), Landsat TM (1989,1994 and 2005) and ASTER 2009. The area in 1966 is used as reference for area comparisons.

Interval area (km^2)	Number in 1966 (*n*)	(%)	Area (km^2) 1966	1974	1989	1994	2005	2009	Area change (km^2) 2009 –2005	2005 –1994	1994 –1989	1989 –1974	1974 –1966	Total (km^2)	Area change (%)
< 0.5	22	29.7	6.9	6.6	6.5	5.9	5.5	5.1	−0.4	−0.4	−0.6	−0.1	−0.3	−1.8	−6.3
0.5–1.0	16	21.7	11.5	11.1	9.8	9.5	8.8	8.4	−0.4	−0.7	−0.3	−1.3	−0.4	−3.3	−10.8
1.0–5.0	24	32.4	63.5	61.9	58.3	56.9	55.1	53.4	−1.7	−1.8	−1.4	−3.6	−1.6	−10.1	−34.8
5.0–10.0	6	8.1	43.6	42.5	40.8	39.8	39.0	37.4	−1.6	−0.8	−1.0	−1.7	−1.1	−6.2	−21.3
> 10.0	6	8.1	132.2	130.3	127.4	127.0	125.1	124.3	−0.8	−1.9	−0.4	−2.9	−1.9	−7.8	−26.8
Total	74	100.00	257.7	252.4	242.8	239.1	233.5	228.6	−4.9	−5.6	−3.7	−9.6	−5.3	−29.1	−100
Area change (%)									−2.0	−2.1	−1.5	−3.7	−2.0	−11.3	–

Table 5. Terminal retreat of four typical glaciers.

Glacier name	Terminal retreat (m)					Total of terminal retreat (m)	Terminal retreat (m yr^{-1})
	1966–1974	1974–1989	1989–1994	1994–2005	2005–2009		
HLG	−336.5	−393.4	−188.3	−103.8	−124.6	−1146.4	26.7
MZG	−120.6	−87.9	−109.9	−61.5	−121.8	−501.8	11.7
YZG	−204.9	−181.7	−97.8	−172.8	−67.6	−724.8	16.9
DGB	−408.7	−277.0	−117.8	−131.0	−67.8	−1002.3	23.3

Table 6. Area changes of four typical glaciers.

Glacier name	Area of glacier (km^2)						Area change of Glacier (km^2)					Total of area changes (km^2)	Area change (%)
	1966	1974	1989	1994	2005	2009	1966–1974	1974–1989	1989–1994	1994–2005	2005–2009		
HLG	26.1	26.0	25.8	25.6	25.4	25.3	−0.1	−0.2	−0.2	−0.2	−0.1	−0.8	−3.1
MZG	27.6	27.3	26.2	26.1	25.9	25.5	−0.3	−1.1	−0.1	−0.2	−0.4	−2.1	−7.7
YZG*	30.1	29.7	29.6	26.6	20.3	20.2	−0.4	−0.1	−0.2	−0.3	−0.1	−1.1	−3.7
DGB	21.5	20.5	19.6	19.5	19.4	19.1	−1.0	−0.9	−0.1	−0.1	−0.3	−2.4	−11.2

* Including two small glaciers.

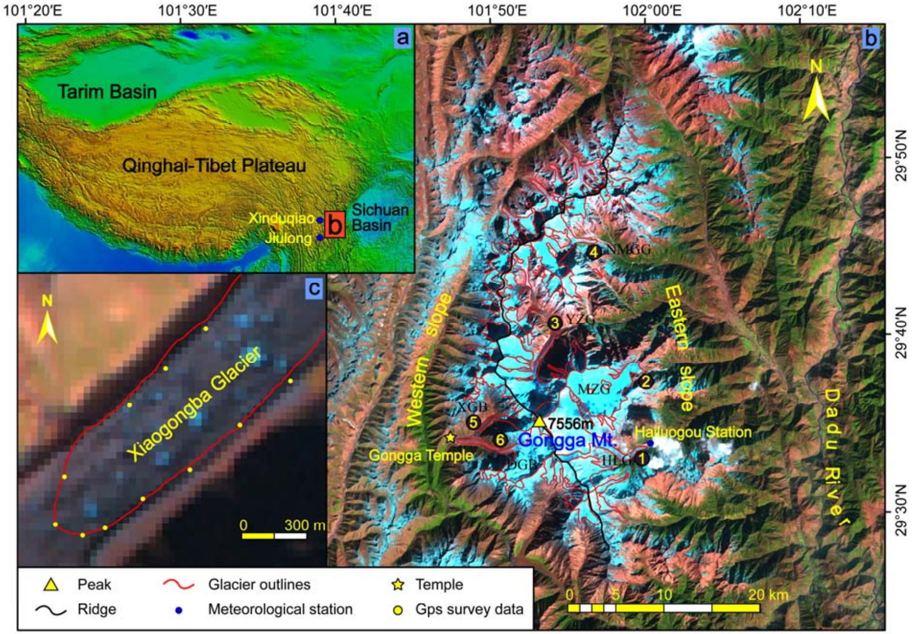

Fig. 1. (a) Showing the location of the Study region and two meteorological stations; **(b)** Glacier extent in Study region with Landsat TM band 543 (as RGB): No. 1 Hailuogou Glacier, No. 2 Mozigou Glacier, No. 3 Yanzigou Glacier, No. 4 Nanmenguangou Glacier, No. 5 Xiaogongba Glacier and No. 6 Dagongba Glacier; **(c)** Glacier outlines and field GPS survey data in 2009.

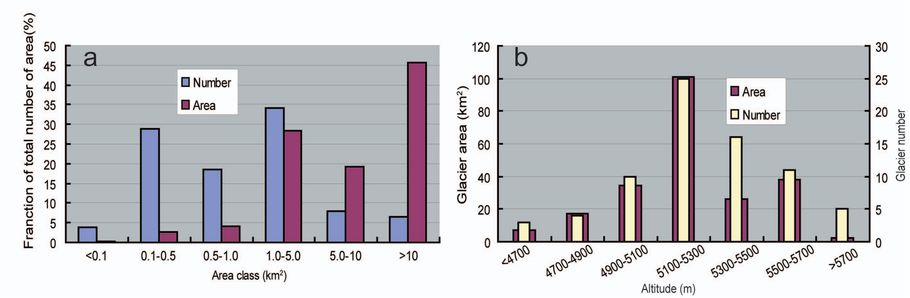

Fig. 2. **(a)** Bar graph showing the normalized part (total = 100 %) on the glacier area and number per size class for a sample of 75 glaciers, **(b)** Glacier area and number with zonal altitude at intervals of 200 m.

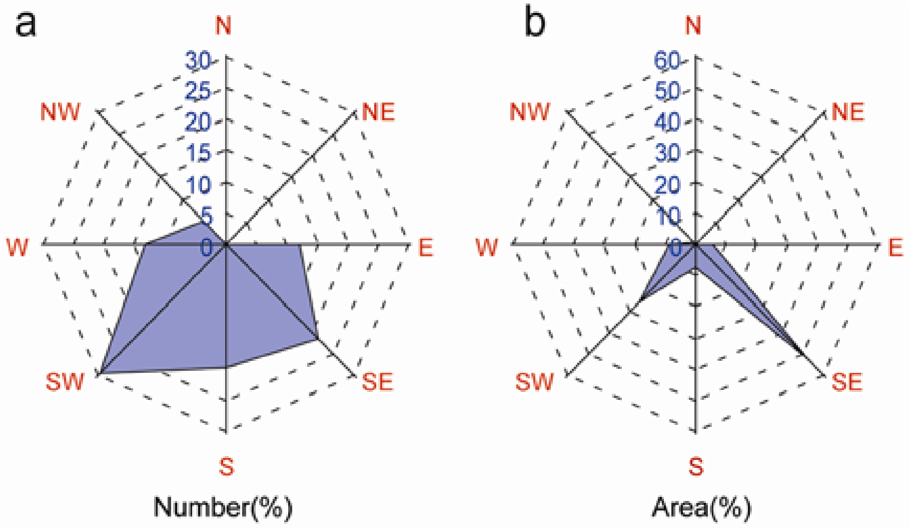

Fig. 3. **(a)** Distribution of glacier number percentage in different aspect. **(b)** Distribution of glacier area percentage in different aspect.

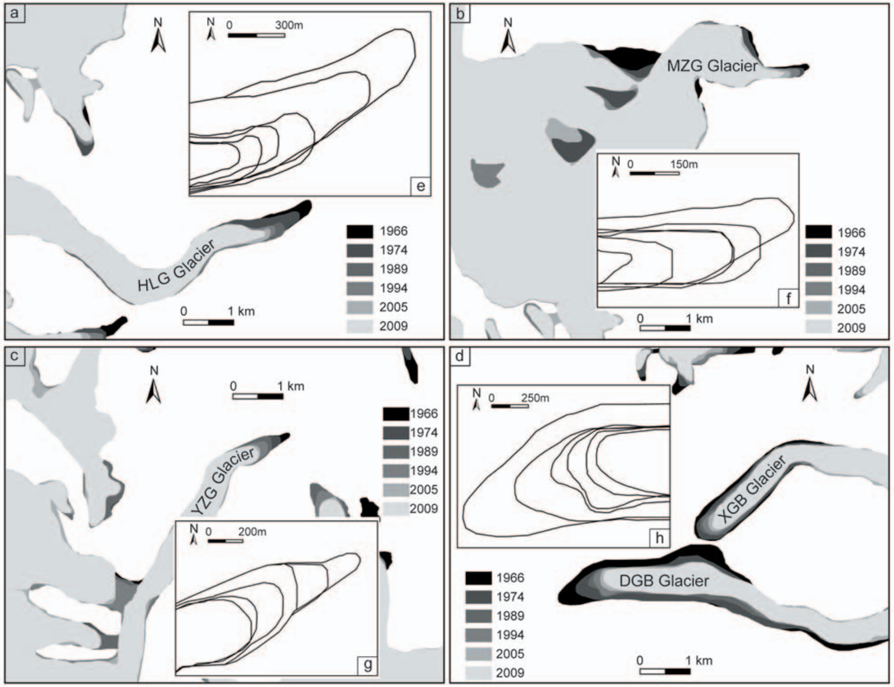

Fig. 4. Area changes and terminal retreat of the HLG (**a** and **b**), MZG (**c** and **d**), YZG (**e** and **f**) and DGB (**g** and **h**) Glaciers since 1966.

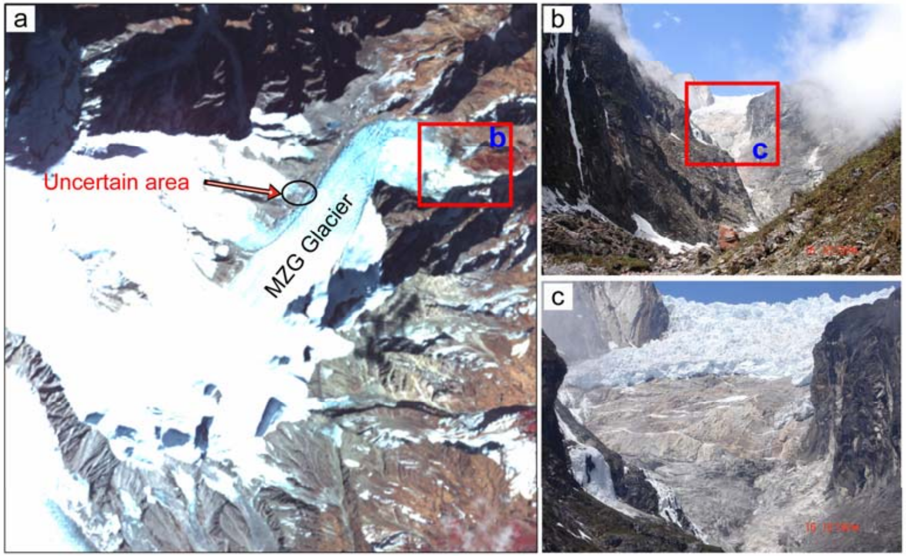

Fig. 5. (a) ASTER image showing the MZG Glacier in 2009 and the area where it is uncertain if the glacier has separated. (**b** and **c**). Field photo shows the terminus of the MZG Glacier in 2009.

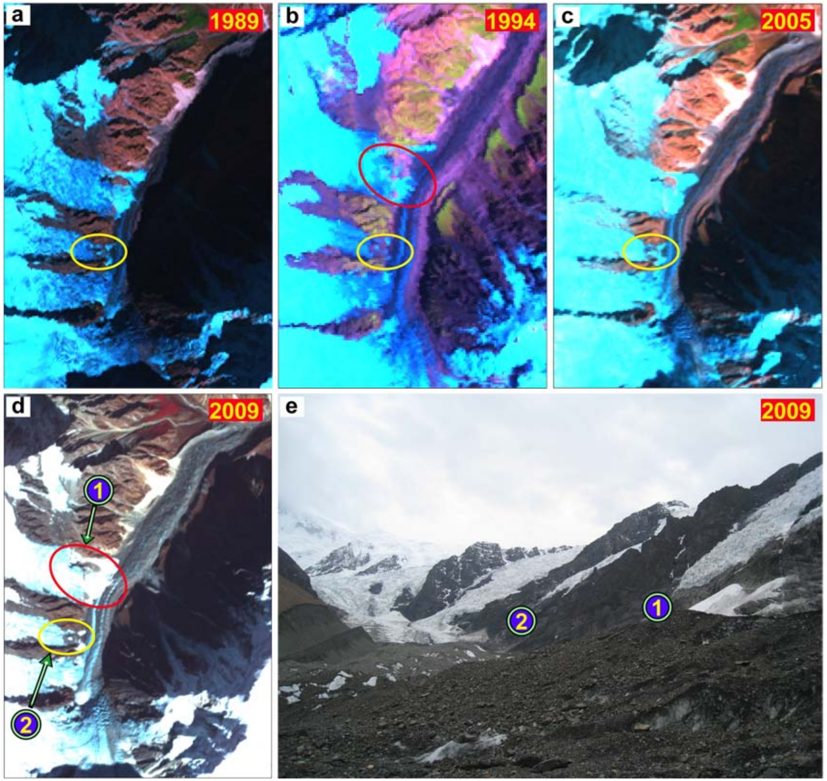

Fig. 6. The changes to the YZG Glacier between 1966 and 2009. **(a, b)** and **(c)** are TM image of the YZG glacier in 1989, 1994 and 2005, respectively. **(d)** is ASTER image of the YZG Glacier in 2009. **(e)** is Photo of the YZG Glacier in 2009. Yellow ellipse indicates one small glacier separated from the YZG Glacier between 1989 and 1994. Red ellipse indicates another small glacier separated from the YZG Glacier between 1994 and 2009; number 1 stands for red ellipse and number 2 stands for yellow ellipse in **(d)** and **(e)**.

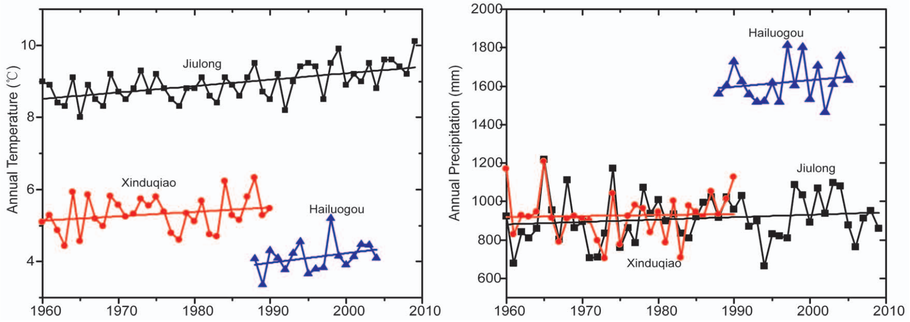

Fig. 7. The meteorological data of Gongga Mountain during 1960–2009.

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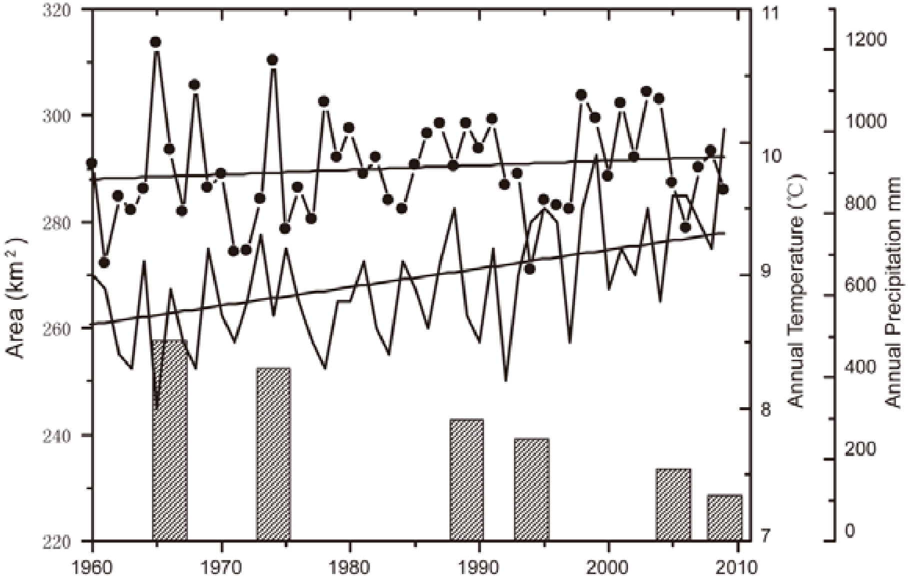

Fig. 8. The trend of glacier changes and meteorological data of Jiulong Station. The diagonal line stands for the total area in 1966, 1974, 1989, 2005 and 2009. The dot is precipitation. The polyline is temperature.

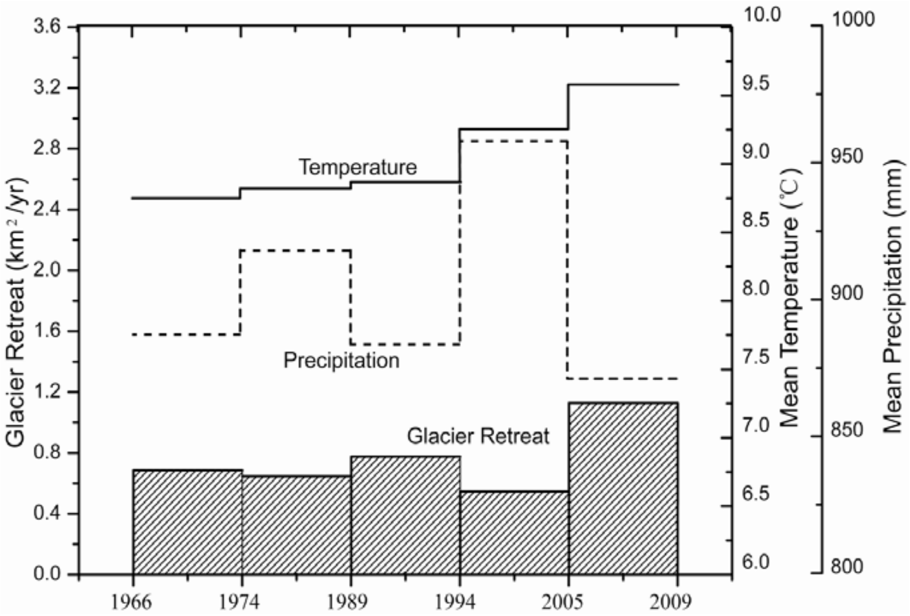

Fig. 9. The relation between glacier retreat and climate change. Bar is glacier retreat; black dash line is mean precipitation; black solid line is mean temperature.