Note:

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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 slopes of the Gongga Mountains decreased by 14.1 km^2 (9.8% since 1966) and 15.1 km^2 (14.6 % since 1966), respectively. The loss in glacier area and length is respectively 0.8 km^2 and 1146.4 m (26.7 m/yr) for the Hailuogou glacier, 2.1km^2 and 501.8 m (11.7m/yr) for the Mozigou Glacier, 0.8 km^2 and 724.8 m (16.9m/yr) for the Yanzigou Glacier, and 2.4 km^2 and 1002.3 m (23.3 m/yr) 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. The mean annual temperature over the eastern and western slope of the Gongga Mountains has been increasing by 0.34 K /decade and 0.24 K /decade (1988-2009), respectively. Moreover, mean annual precipitation was only increasing 1% in past 50 years. This evidence indicates that the warming of the climate is probably responsible for the glacier retreat in the study region.

Key words: Glacier change; GPS; RS; Climate change; Gongga Mountains

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 water-energy supplies (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 contributes 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 through 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 glacier recession with only a few glaciers advancing. The monsoonal temperate glaciers, with high rate of accumulation and ablation and a high mass-balance fluctuation (Braithwaite and Zhang, 2000; Kaser et al., 2006), are more active than cold and continental glacier, and thus 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). To the accurate information of glacier status after 30-40 years of pronounced glaciers changes in and response 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 changes in the Gongga Mountains were widely recorded since the 1930s (e.g. 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. 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 (1981-83) and by Sino-Soviet joint glaciological expedition to the Gongga Mountains in 1990. Four years later, more glacier parameters in the Gongga Mountains were measured 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 mm/yr from 1990 to 1998, and concluded that the negative mass balance of the HLG Glacier was caused by an increase in ablation. The elevation change of ablation area of HLG Glacier was measured as -1.1±0.4 m/yr from 1966 to 2009 from GPS surveys (Zhang et al., 2009). The study on the relation between HLG Glacier shrinkage and hydrological response showed increasing storage loss during the last 20 years (Liu et al., 2010). Li et al. (2010a) summarized the fluctuations of HLG Glacier during the Holocene and concluded that the changes of HLG Glacier were mainly influenced by climatic fluctuation. However, most of these researches focused on a single glacier in the Gongga Mountains, and there was little systematic and comprehensive study on the changes of length and area of glaciers, especially using the remote sensing images. 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 investigate 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) are 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, the Gongga Mountains are 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 climate of 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 ^{o}C on the eastern slope (3000 m a.s.l.) and only 1.9 ^{o}C on the western (3700 m a.s.l.) (Su et al., 1992). The altitudinal gradient of temperature described by Su et al (1993) by filed observation was -0.23ºC, -0.9 ºC and -0.2 ºC on the altitudinal belt 2880-3010m, 3010-3210m and 3210-3510m, respectively. Su et al (1993) and Gao and Peng (1994) indicated that the first maximum rainfall zone exists between 2900m and 3400m a.s.l. on the eastern slope and in the 3700 a.s.l. on the western slope; and the second maximum rainfall zone lies between 4900m and 6000m a.s.l., which is equal to the height of the present snow line with annual precipitation about 3000 mm.

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 the Hailuogou (HLG), Mozigou (MZG), Yanzigou (YZG), Nanmenguangou (NMGG) Glaciers on the eastern slope and the DaGongba (DGB) Glacier on the western slope. The glaciers in this region are classified as summer-accumulation type (Su et al., 1996; Xie et al., 2001), which has more accumulation in summer than winter (Ageta and Higuchi, 1984). They are characterized by a high flow velocity, rich accumulation and heavy melting. Many moraines are 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

3.1 Data Sources

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. The glacier outlines were corrected by aerial photographs and field investigation. As the first CGI is the oldest archive from which 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 reference data to analyze later changes in the Gongga Mountains glaciers.

The Landsat MSS/TM/ETM+ scenes used 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 snowcover 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 was constructed from digitized contour lines of a 1989 topographic map with a scale of 1:50000 and 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 Universal Transverse Mercator coordinate system (UTM zone 47N, WGS84), and was resampled to 15 m resolution, 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.

3.2 Methods

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 inventories 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, and 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. Terminal moraine, the head of glacier melt water, a glacial lake and lateral moraine are visual characteristics utilized in manual identification of the glacier perimeter. Finally, all the digital glacier outlines were placed into a Geographic Information System (GIS) to calculate the areal changes during the years 1966-2009.

3.3 Accuracy analysis

Analysis of the corresponding change in glacier area consistently indicates about 11.3% (29.2km^2) area loss over the last 43 years. However, some uncertainties and limitations of the glacier mapping could be derived. Generally, debris cover, snowfields and refreezing of water bodies are the unavoidable factors affecting the accuracy of the mapping of glacier outlines and also hardly to evaluate. In Gongga Mountains, the refreezing of water bodies could not occur in the ablation periods and we do not discuss this unavoidable factor. In order to verify and improve the accuracy of glacier outlines, fieldwork was conducted (Fig. 1b & c, Fig. 2). Five glaciers (HLG, MZG, YZG, DGB and XGB Glaciers) were surveyed in April 2009 using dual differential GPS (SF-2040G, single-level positioning accuracy ≤10cm), and, the results showed that there is about ± 30 m difference in the length and 0.5% in the area, when comparing our 100 surveyed points with glacier mapping generated from ASTER data in 2009.

Another important uncertainty in the area change assessment is derived from the comparison of different data sources. Errors in glacier mapping can be caused by low image resolution and by co-registration errors (Ye et al., 2006; Hall et al., 2003; Shangguan et al., 2009). Glacier area mapping from the comparatively low resolution (80m) of the Landsat MSS image are not as accurate as from TM and ASTER images, especially for the smaller (area < 0.1 km^2) and debris-covered glaciers. 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.

We calculated the errors of measure glacier outlines and co-registration as follows. The error of glacier area mapping, E, was estimated as the root sum squares (RSS) of uncertainty error

$$E=\sqrt{\lambda^2+\varepsilon^2} \quad (1)$$

Where λ is uncertainty for field survey, ε is the registration error of each image to the Landsat ETM+. In our case, according to the above equation, glacier terminus measurement uncertainty is 85.4 m, 42.4 m and 34.9 m for the periods 1966-1974, 1974-2005 and 2005-2009, respectively. Based on Hall et al. (2003) and Ye et al. (2006), the uncertainty in our estimation of glacier area is about 0.012 km^2.

4. Results

4.1. New glacier inventory data in 2009

The 76 glaciers in the Gongga Mountains (Fig. 3a), 51.3% of all glaciers are smaller than 1 km^2 and contribute to 7.1% to the total area, while 6.5% glaciers are larger than 10 km^2 and contribute 45.7% of the total area. The distribution of the number and area of glaciers by the median altitude is depicted in figure. There are 25 glaciers with approximately 50% of the total area distributed between 5200 m and 5400 m (Fig.3b). 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 a climatic equilibrium line altitude (ELA) (climatic snowline: a multi-year average of ELA in a plane and bare surface (Shi, Eds., 1988)) of ~4900 m. There are 40 glaciers with a total area of 87.6km^2 distributed on the western slope (Fig. 1b), 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 aspect of glaciers by number and area is shown in Figure 3c; south-western and south-eastern sectors make up half the number of glaciers, dominating 78% of the area (Fig. 3c), and there are no glaciers whose mean aspect is the northern or north-eastern sectors. Furthermore, the area of glaciers covered on the south-eastern sector obviously exceeded half of the total area (Fig. 3c), 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 aspect distribution shows that the locations of glaciers dependent on local topographical constraints (Andreassen et al., 2008). A dependence of glacier area and number on mean slope is observed as depicted in Figure 3d. The figure suggests the slope of glaciers in Gongga Mountains range from 15 to 45°.

4.2. Glacier changes

The analysis of glacier area from 1966 (CGI) to 2009 (ASTER) reveals some interesting changes, as shown in Table 3&4, Fig. 2. 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 29.2km^2 (11.3% of total area in 1966) in a decreasing of 0.7 km^2/yr from 1966 to 2009. The rate of area change (-1.3 km^2/yr) from 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. Due to glacier retreat, one glacier on the western slope was separated into two smaller glaciers in 1974-

1989 and two large glaciers (YZG Glacier) on the eastern slope were respectively separated into two and three from 1989-2009. Two small glaciers on the western slope with northern aspects 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 (Table 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 but with an area of 139.9 km^2 in 2009, and the total area loss is 15.2 km^2 (accounting for 9.8% 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 14.6 % of total in 1966. Glacier size strongly affects the percentage loss in 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. 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. 4d and Table 4). Most of glaciers in northwestern and east aspect are small glaciers (<5 km^2). The shrinkage of these glaciers in these aspects is stronger than for other glaciers with aspects in this region (Fig. 4a). Compared with glaciers changes in different median altitude, the glaciers area loss in the altitude 5100-5300 m and >5700 m is larger than the glaciers in others altitude (Fig. 4b). The mean slope of all glaciers in this region ranges between 15° and 45°, and glaciers with the mean slope of 15-20° and 35-40° (covering an area of 37.9% in 1966) exhibit the largest shrinkage (Fig. 4c).

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

In 1966, HLG glacier was 12 km long and 250–1200m wide, with an area of 26.1 km^2. The glacier flows eastwards as it descends from 7556 m to 3000 m. Four distinct zones can be recognized: the accumulation zone (from 7556 m to 4980 m), a large icefall zone (from 4980 m to 3850 m), a zone of glacier arches (from 3850 m to 3480 m) and a debris covered zone (from 3480 m to 3980 m). According to Li and Su (1996), the ELA of HLG is about 4900m a.s.l., and about 0.28 km^2 of glacial area is covered by thick debris. The HLG Glacier has 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 extended only 11 km in 2009. Our investigation indicates that, from 1966 to 2009, the total retreat of the HLG Glacier was about 1146.4 m (about 26.7 m/yr), which can be separated into five periods (Fig. 2a and e; 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; and 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 area of MZG glacier was 27.6km^2, with a length of 11.6 km in 1996. The terminus elevation of MZG glacier is 3600 m a.s.l., about 600 m higher than that of HLG glacier. The ELA is about 5240m a.s.l. and no debris covered on the glacier. The terminus of the MZG glacier retreated about 501.8 m in length from 1966 to 2009 (Fig. 2b and f; Table 5). This relatively slow retraction may be attributed to its higher mean elevation and larger accumulation area ratio (0.75). The terminus of glacier is quite steep and narrow (Fig. 6b and c), and was no debris covered on the ablation zone of glacier. The glacier change in MZG is different from other glaciers. This is an important question and we will explore it in the future works. From 1966 to 2009, the shrinkage area of MZG glacier is 7.7 % (Table 6) which is larger than that of the HLG and YZG Glaciers. By comparing remote sensing images from 1974, 1989, 1994, 2005 to 2009 with CGI, we found that some parts of the MZG glacier lay beneath a blanket of snow in the images except 2009; hence the snow fields should be included in the determination of the glacier outline. When the snowfields melted away in 2009 (Fig. 5a), the glacier outline exhibited a sudden shrinkage. In Figure 5a (Uncertain area), although some glacier change was found, we could not identify whether the MZG glacier has been already separated into two parts by a steep cliff (Fig. 5b and c).

4.3.3. YZG Glacier

The YZG glacier was 30.1 km^2 in area and 10.5km in length, with the terminus elevation of 3680m a.s.l. The ELA is about 4840 m a.s.l. for YZG glacier and about 0.81km^2 in the ablation area was covered by debris (Pu, 1996). The terminus of the YZG Glacier retreated 724.8 m (about 16.9 m/yr) during the period 1966-2009(Fig. 2d and h; Table 5). The terminus retreat rate (25 m/yr) was at its maximum between 1966 and 1974. The area of the glacier decreased from 30.1 km^2 in 1966 to 20.2 km^2 in 2009. Furthermore, the YZG Glacier separated into three parts between 1966 and 2009, in which two glaciers were separated from the YZG Glacier during the period 1989-1994 and 1994-2009 (Table 3). The fieldwork in 2009 also illustrates this evidence. 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 and XGB Glaciers formed a single glacier before the 17th century. However, they 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 was about 10 km long, and the terminus ended 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 recent and 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. 2d and h; Table 5) from 1966 to 2009, and in 2009 was located at an elevation of about 4000 m a.s.l., 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 decade, 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 years, and total area had diminished by -14.6% (from 6.7 km^2 in 1966 to 5.7 km^2 in 2009). In summary, the terminus of four glaciers has similar retreating (Table 5). We also found that the retreating of terminus in periods 1966-1974 is faster than that in others periods.

4.4 Comparison of glacier changes in Gongga Mountains with other regions

In this study, we make a portion statistics about glacier changes in China (Table 7). In the Gangrigabu Mountains, Liu et al. (2006) conclude 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 but faster than continental glaciers type in the west of China.

5. Discussion

In this study, temperature and precipitation data are from three meteorological stations (Fig. 1a and b), which are located close 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. 6) were analyzed to evaluate the impact of the temperature and precipitation on glacier retreat. The meteorological data was processed by Microsoft excel 2003, and the trend line was calculated by one-dimensional liner regression equation. The mean annual temperature of all three stations has increased over the last decades, and the warming rate of the HLG meteorological station (0.34 K/decade, 1988-2009) is faster than those of the Jiulong meteorological station (0.24 K/decade, 1988-2009) (Fig. 6). During 1966-2009, the warming rate of Jiulong and Xinduqiao meteorological data is about 0.14K/decade (Fig. 6). 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 an ice core (Thompson et al., 2000) also indicates a rapid warming trend in past millennium. The mean annual precipitation has only increased by 1% (Fig. 6) in the last 50 years. 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 K warming. In the Gongga Mountains, the mean annual temperature has increased by 0.5 K 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 mean air temperature (Fig. 7).

Taking the topographical features of this region into account, the Gongga Mountains run 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 (14.6%) is a little bit faster than that on eastern slope (9.8%) of the Gongga Mountains. According to meteorological data, the mean annual temperature rise is faster on the eastern slope than on the western slope. However, the difference of glacier area loss on both slopes could not be well interpreted by meteorological data as the length and operational period of the three weather stations differed significantly. The fact is that 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 different retreat rates on both slopes can be interpreted by the difference of glacier size. The smaller glaciers on the western slope may be more sensitive to the changes of climate than the larger glaciers on the eastern slope. Considering the largest glaciers changes, climate warming has resulted in sustained glacier retreat through 43 years, 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 aspect of HLG and YZG glaciers are southeast and northeast. Those responding can explain that the shrinkage of HLG glacier is quicker than the YZG glacier. Furthermore, the ablation of HLG glacier by Zhang et al (2011) note that about 67% of the ablation area on HLG glacier has undergone accelerated melting, whereas about 19% of the ablation area has experienced inhibited melting, and the sub-debris melt rate equals the bare-ice melt rate in only 14% of the ablation area, because of the inhomogeneous distribution of debris thickness. Although, the thick debris may give a crucial role in suppressing ablation in the terminus Zhang et al (2011), the ice crevasse and subglacial river also may cause the glacier accelerating ablation. The change of HLG glacier is a quite complex process.

The rate of glacier retreat in the Gongga Mountains (Table 3 and Fig. 7) was 0.6 km^2/yr 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 km^2/yr) from 1994 to 2005, and after 2005, became its most intensive, at 1.3 km^2/yr. In order to explore causes of glacier reduction in different time intervals, the meteorological data of Jiulong station, which is the longest and most reliable series data from 1953 to 2009, were averaged with the same time interval as glacier reduction (Fig. 7). In comparison with glacier reduction, the annual temperature exhibits similar trends as the glacier reduction (Fig. 7), and annual precipitation has a significant negative correlation with the retreat rate of glacier area (Fig. 8). 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 km^2/yr) during the period 2005 -2009 (Fig. 7). This result coincided with 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). According to Porter (1986), the small temperate glaciers in low-latitude and middle-latitude are especially sensitive to climate change; therefore the dynamic response of the terminus is generally rapid with a lag time of a decade or less. Wang and Zhang (1992) considered that there was a phase lag of 12-13 years for glacier advance to climatic change in the Northern Hemisphere by analyzing numerous glacier advance and positive mass-balance. The time lag is affected by several conditions, such as glacier size, glacier bed slope, and glacier type. Based on the study of Pelto and Hedlund (2001), HLG, YZG, MZG and DGB glaciers are all type 1 glacier, which is distinguished by steeper slope, extensive crevassing and higher terminus region velocities. The lag time of this type glacier should be 4 to 16 yr.

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 in area than large glaciers. For instance, the shrinkage of the small glacier (area < 1 km^2) was the quickest, and two smallest glaciers have vanished, which did not have consistent accumulation zones. According to Pelto (2010) study, the characteristics of substantial accumulation zone thinning, marginal recession or emergent bedrock areas in the accumulation zone are also found in less glaciers on Gongga Mountains. Although the area of the large glaciers (area > 10 km^2) dominated the total area, the glaciers of 1-5 km^2 contributed about 35% to the total area recession. This evidence suggests that smaller glaciers are responding more quickly, especially to short-period and small-amplitude climate change.

Monsoonal temperate glaciers in China mainly covered in the southeastern part of Qinghai (Tibetan) Plateau. The areas of monsoonal temperate glaciers is about 13203km^2, accounting for 22.2% of total glacier areas in China (Su and Shi, 2002). According to Thompson et al. (2000) study, Dasuopu cores suggested a large-scale, plateau-wide 20^{th}-century warming trend that appears to be amplified at higher elevations. Two records in southeastern Tibetan Plateau of temperate glaciers indicate a 0.8 K colder in the 17^{th} century than the present (Shi and Liu, 2000). However, the estimate of Jones et al. (1999) shows a worldwide temperature decrease in the same period is 0.5-0.8 K, which is just half of that occurring in western China. In this region, air temperature has risen to 0.8 K on average since the Maxima of the Little Ice Age and the glacier area has decreased by 3700 km^2, which corresponds to 29% of the area of existing glaciers (Shi and Liu, 2000). Glaciers in the Gongga Mountains are important monsoonal temperate glaciers. The glacier areas losses (11.3%) of Gongga Mountains are well response to the Shi and Liu (2000) results, and also prove the climate warming in this region.

6. Conclusion

In this study, we present the results of the new glacier inventory of the Gongga Mountains, with area 228.5km^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 slope is faster than that on the eastern slope 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. The glacier retreat in the Gongga Mountains is similar to the same glacier type but faster than continental glaciers type in the west of China. 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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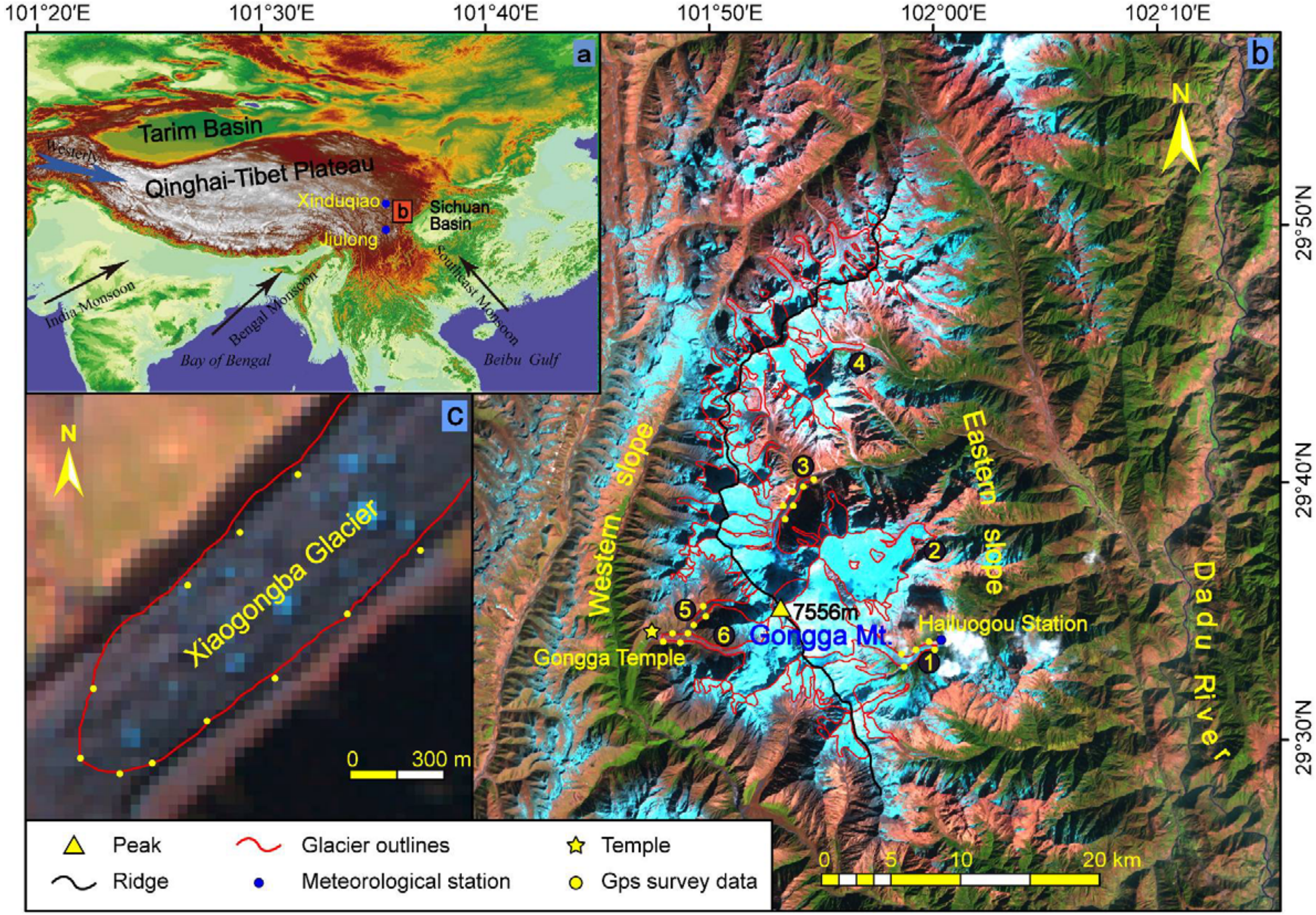

Fig.1. (a) Showing the location of the Study region and two meteorological stations; (b) Glacier extent in Study region with Landsat TM band 543 (as RGB): NO.1 Hailuogou Glacier, NO.2Mozigou Glacier, NO.3Yanzigou Glacier, NO.4Nanmenguangou Glacier, NO.5Xiaogongba Glacier and NO.6Dagongba Glacier; (c)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

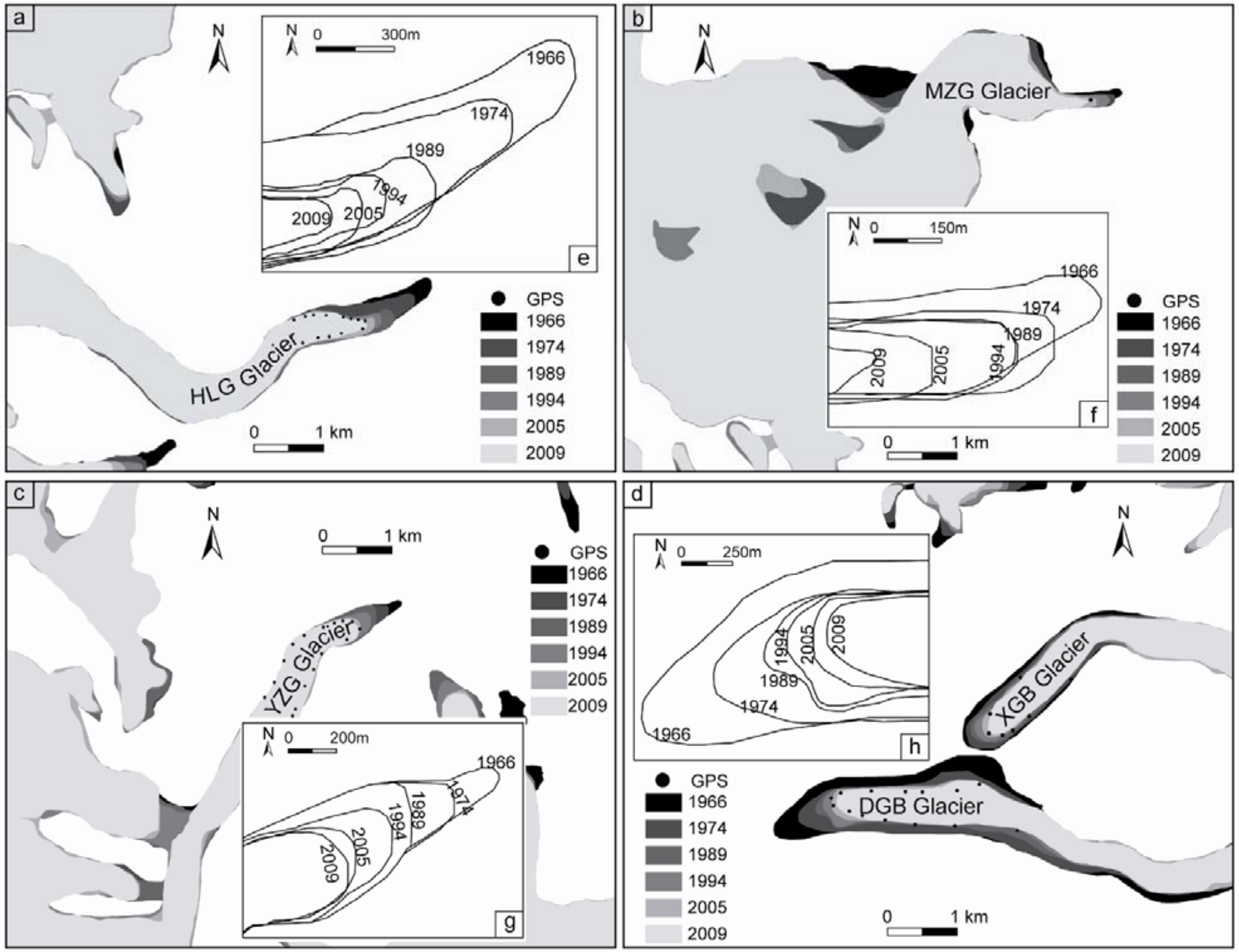

Fig. 2. Area changes and terminal retreat of the HLG (a and e), MZG (b and f), YZG (c and g) and DGB (d and h) Glaciers since 1966.

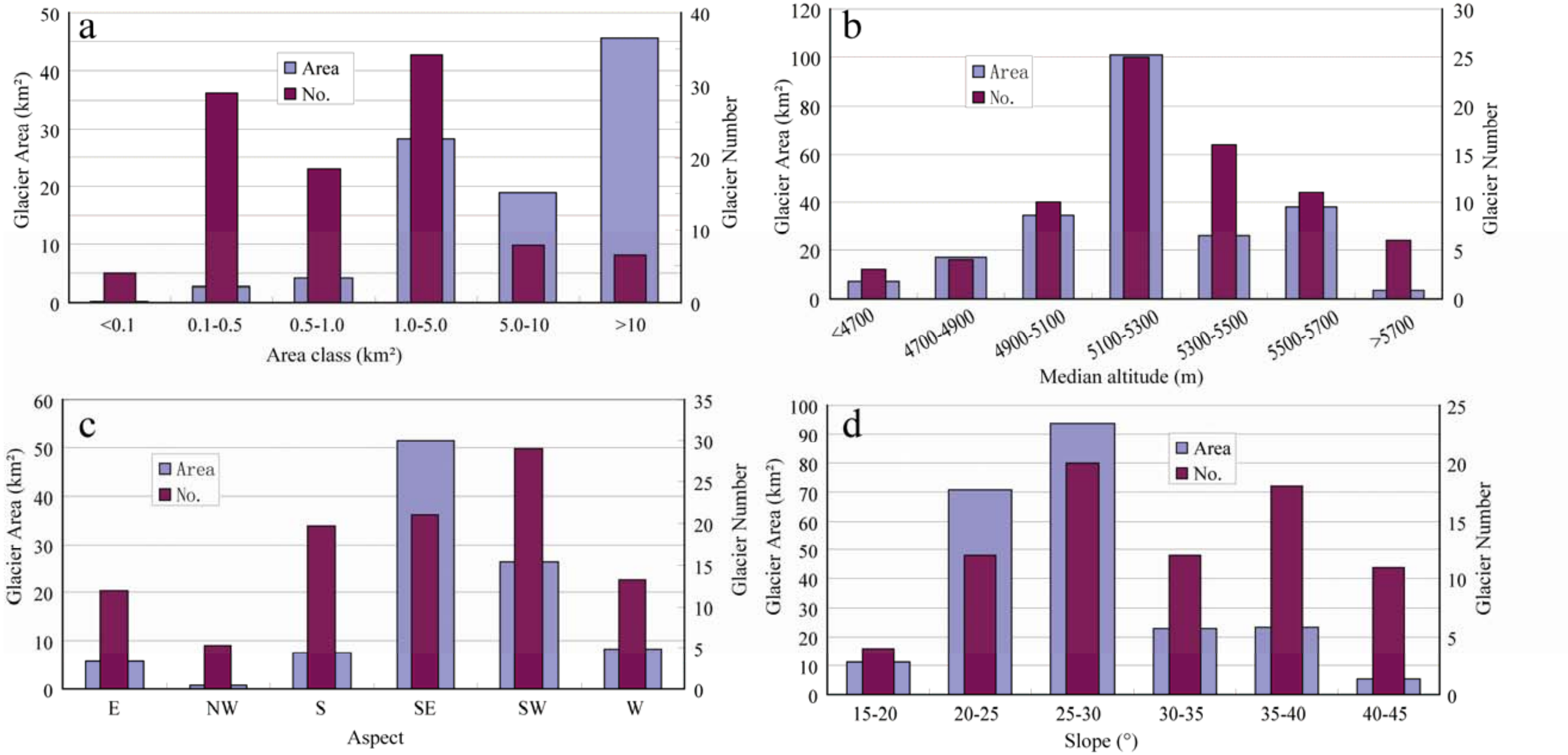

Fig. 3. Distribution of glaciers in 2009. (a) Distribution of glacier in different area class. (b) Distribution of glacier in different median altitude. (c) Distribution of glacier in different aspect. (d) Distribution of glacier in different slope.

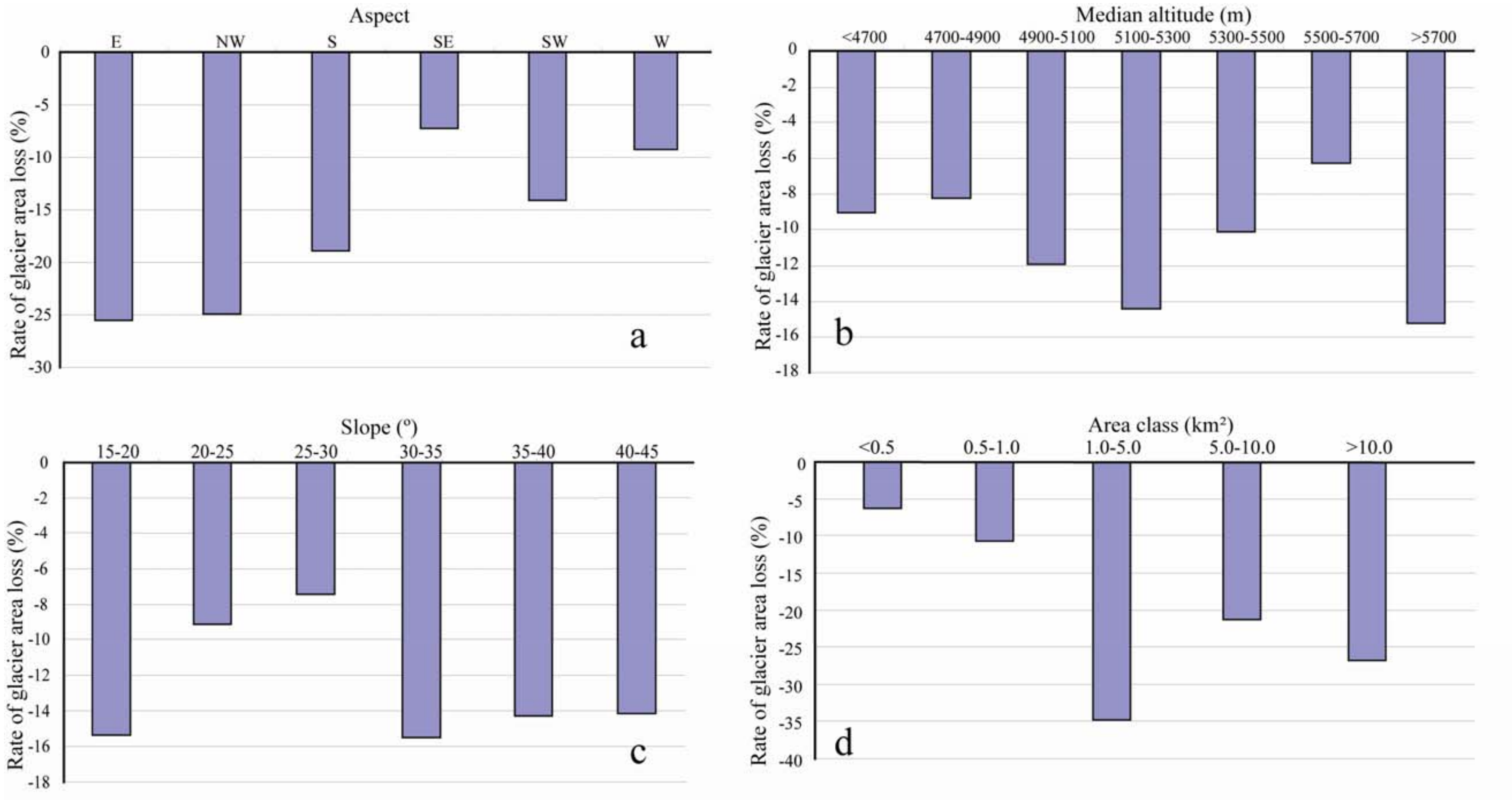

Fig. 4. The glacier changes between 1966 and 2009. (a) The relationship between area changes and aspect. (b) The relationship between area changes and median altitude. (c) The relationship between area changes and slope. (d) The relationship between area changes and area class.

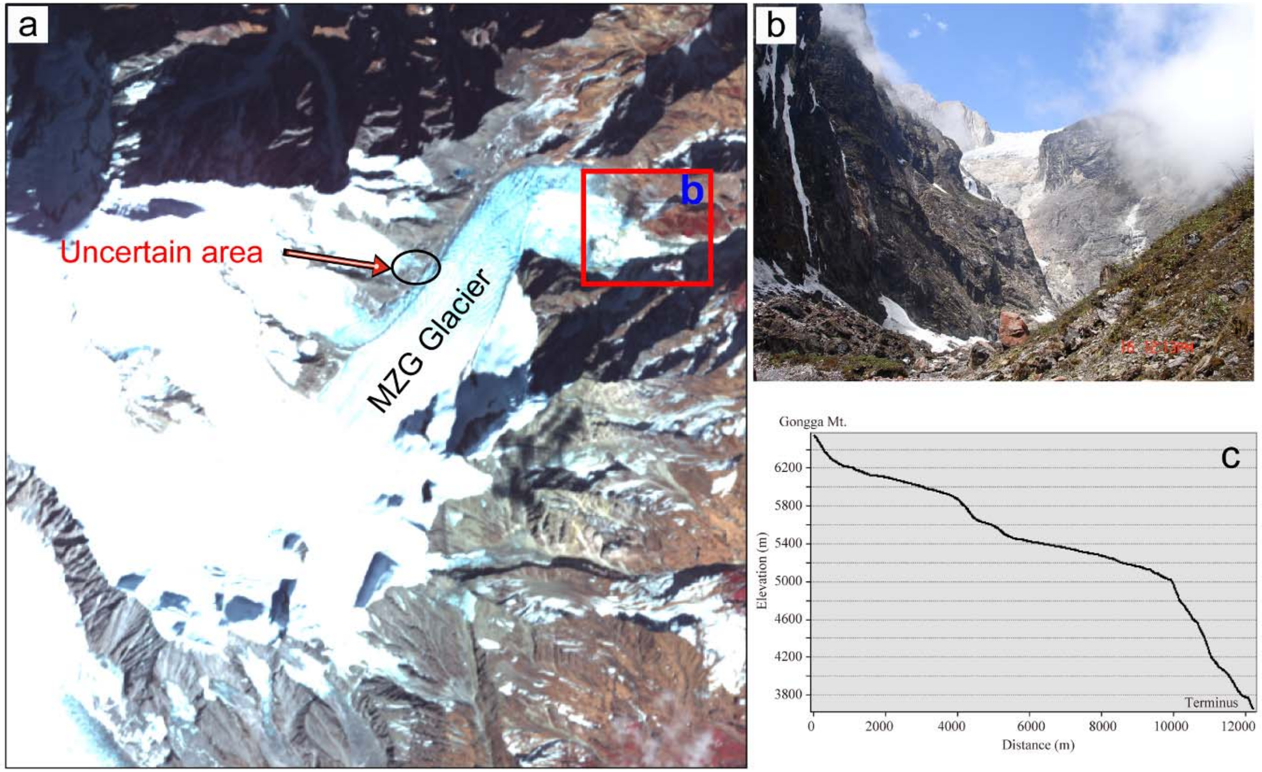

Fig. 5. (a) ASTER image showing the MZG Glacier in 2009. (b) Field photo shows the terminus of the MZG Glacier in 2009. (c) The longitudinal profile of MZG Glacier from DEM in 1989.

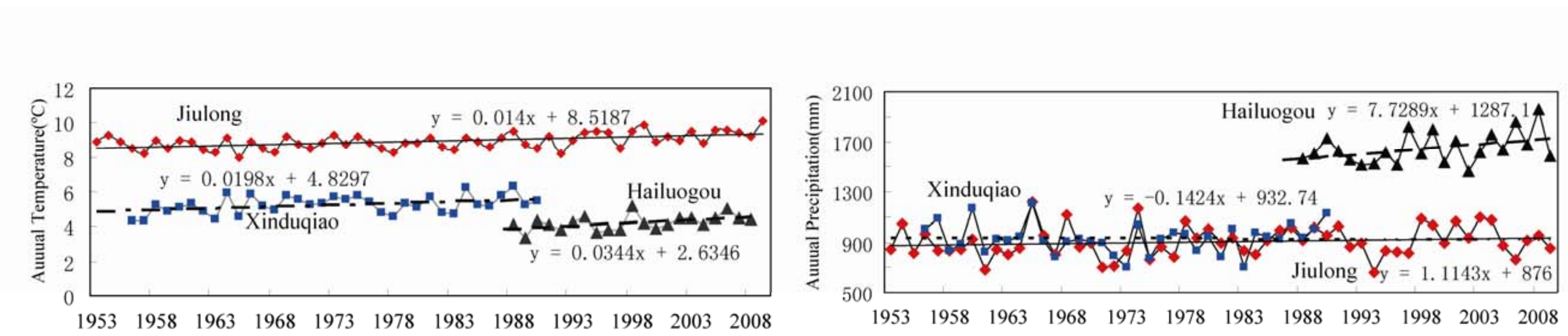

Fig.6. The meteorological data of Gongga Mountain during 1960-2009.

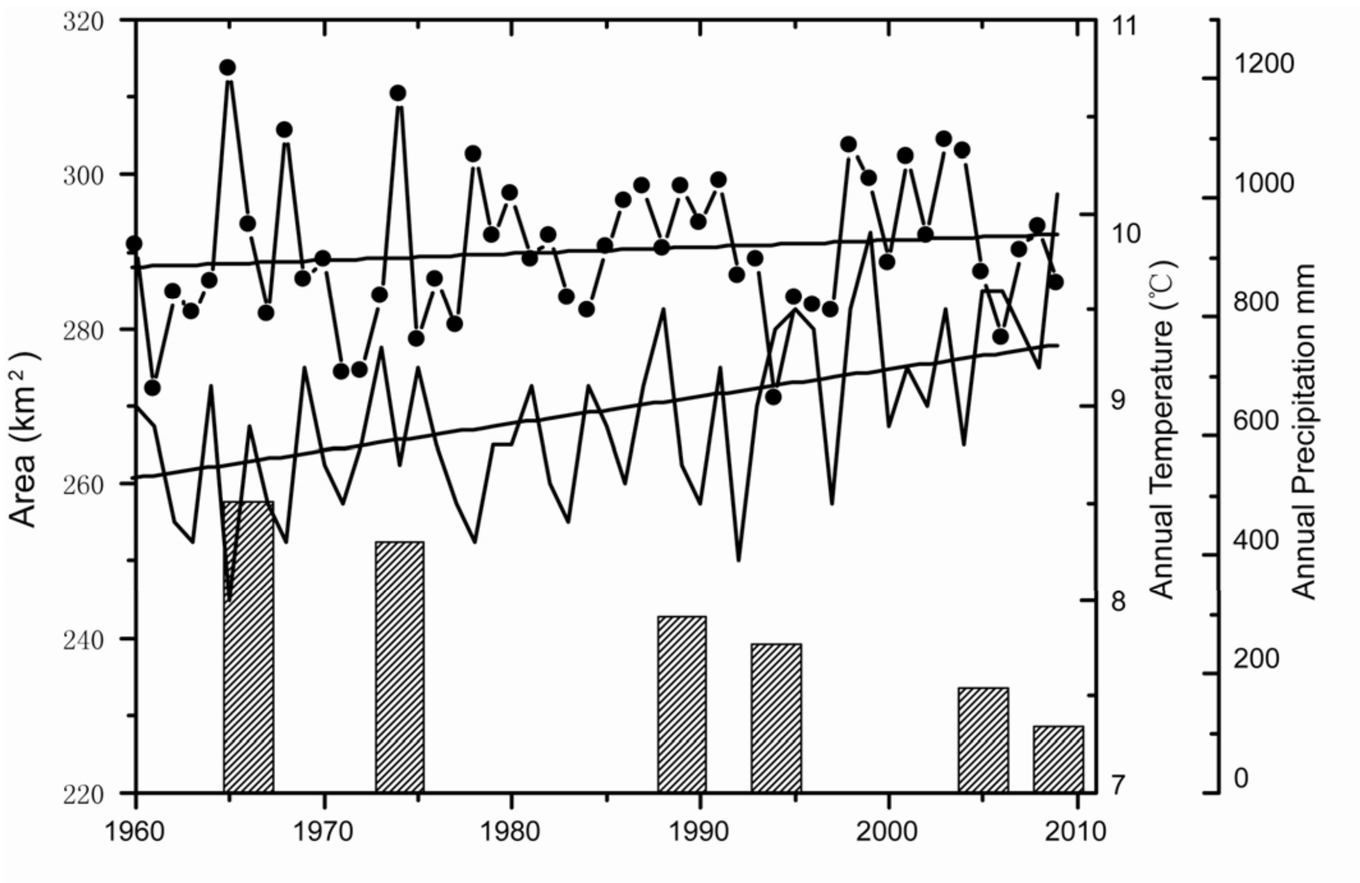

Fig. 7. The trend of glacier changes and meteorological data of Jiulong Station. The diagonal line stands for the total area in 1966, 1974, 1989, 2005 and 2009. The dot is precipitation. The polyline is temperature.

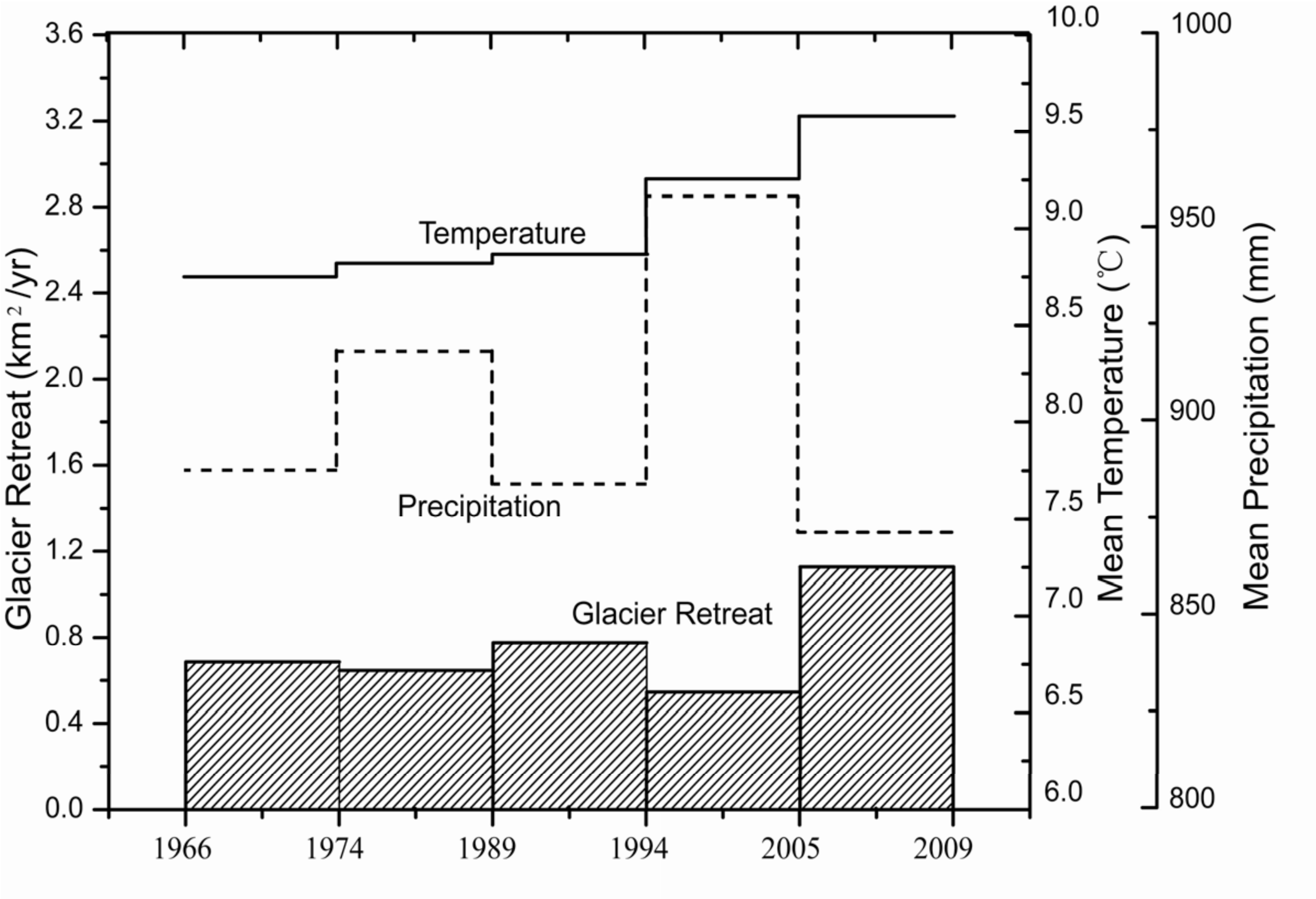

Fig. 8. The relation between glacier retreat and climate change. Bar is glacier retreat; Black dash line is mean precipitation; Black Solid line is mean temperature

Table 1 Data sources used in this study

Image	Path/row	Date	Resolution or scale	Cloud cover	Source
Topographic map	-	1971	1:100000	-	Chinese military geodetic service
DEM	-	1989	20m or 1:50000	-	Topographic map
CGI	-	1966	1:100000	-	Aerial photographs
Landsat 2 MSS	140/39	1974/01/21	80m	0%	USGS/NASA
Landsat 5 TM	131/39	1989/01/02	30m	0%	USGS/NASA
Landsat 5 TM	131/39	1994/09/05	30m	0%	USGS/NASA
Landsat 5 TM	131/39	2005/02/07	30m	11%	USGS/NASA
Landsat 7 ETM+	131/39	2002/01/06	30m	0%	USGS/NASA
Terra ASTER	-	2009/05/23	15m	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⩾1.8	AST1 > 47
TM	TM3/TM5⩾2.4	TM1> 59
MSS	MSS3/MSS4⩾ 2.0	MSS3 > 22

*Partly includes rocks in shadow.

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)
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	Number in 1966		Mean	Mean	Area (km^2)						Area change (km^2)						
area (km^2)	(n)	(%)	Terminus(m)	Elevation(m)	1966	1974	1989	1994	2005	2009	09-05	05-94	94-89	89-74	74-66	Total (km^2)	Area change (%)
<0.5	22	29.7	5090.4	5416.4	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	4956.9	5455.9	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	4388.6	5332.9	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	4320.7	5116.7	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	3616.6	5120.9	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)
	1966-74	1974-89	1989-94	1994-2005	2005-09		
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	1966-74	1974-89	1989-94	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

Table 7 The glacier changes of three types in China

Study Area	Glacier type	Periods	Glacier Changes (%)	Rate of glacier changes (%/a)	Document Source
The Western Kunlun Shan	Extreme continental	1970-2001	-0.4	0.01	Shangguan et al, 2007
The Western Nyainqêntanglha Range	Extreme continental	1970-2000	-5.7	0.19	Shangguan et al, 2008
Geladandong Mountain	Sub-continental	1969-2002	-4.7	0.16	Ye et al, 2006
Karakoram Mountains	Sub-continental	1969-1999	-4.1	0.14	Shanguan et al, 2006
Gangrigabu Range	Monsoonal temperate	1915-1980	-13.8	0.18	Liu et al, 2005
Gongga Mountain	Monsoonal temperate	1966-2009	-11.3	0.26	This study