An inventory of glacier changes between 1973 and 2011 for the Geladandong Mountain area, China

by J. Zhang, D. Braaten, X. Li, and F. Tao

2013

Zhang et al. (2013). An inventory of glacier changes between 1973 and 2011 for the Geladandong Mountain area, China. *Cryosphere Discussions* 7(1)

Published version: http://www.dx.doi.org/10.5194/tcd-7-507-2013

The Cryosphere Discuss., 7, 507–531, 2013
www.the-cryosphere-discuss.net/7/507/2013/
doi:10.5194/tcd-7-507-2013

The Cryosphere
Discussions
Open Access

An inventory of glacier changes between 1973 and 2011 for the Geladandong Mountain area, China

J. Zhang[1,2], D. Braaten[2], X. Li[2], J. She[2,3], and F. Tao[1]

[1]Department of Geography, School of Geography, Nantong University, 999 Waihuan Road, Nantong, Jiangsu 226007, China
[2]Department of Geography, University of Kansas, 1475 Jayhawk Blvd Lawrence, KS 66045, USA
[3]School of Geographic and Oceanographic Sciences, Nanjing University, 22 Hankou Road, Nanjing, Jiangsu 210093, China

Received: 8 January 2013 – Accepted: 18 January 2013 – Published: 12 February 2013

Correspondence to: J. Zhang (sezjg@yahoo.com.cn)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The snow and ice of the Geladangong Mountain area supply the headwaters of the Yangtze River, and long-term changes to glaciers and ice masses in this region due to a warming climate are of great concern. An inventory of glacier boundaries and changes over decades for the Geladandong Mountain area in China has been conducted using remote sensing imagery from Landsat (MSS, TM, ETM+), CERBES CCD, and GIS techniques. Variations in glacier extent has been measured using a series of digital images since 1973, including Landsat MSS in 1973, Landsat TM in 1992, Landsat ETM+ in 2004, and CBERS CCD in 2011. All Landsat data are snow-free outside the glacier boundaries, allowing an unsupervised classification method to be used to extract glacier area. For the CBERS CCD data, some areas were covered by clouds and snow, requiring an initial unsupervised classification method to divide glacier, clouds and snow from other land types, followed by a supervised visual interpretation to extract glacier area. The results show a decrease in glacier ice cover in the study area during the past 38 yr. From 1973 to 2011, glacier area decreased from 107 105 hectares to 94 220 hectares, or a change of −12 %. The speed at which ice cover is being lost has been decreasing during the past 38 yr. The rate of glacier area loss was 0.47 % yr^{-1} from 1973–1992, 0.19 % yr^{-1} from 1992–2004, and 0.14 % yr^{-1} from 2004–2011. While most of the glaciers are shrinking, some are expanding. For the 1973 to 2004 period, retreating glaciers exposed 14 447 hectares of land, and advancing glaciers spread over 2682 hectares that were not covered by ice in 1973. The net glacier area decrease is 11 765 hectares from 1973–2004. For the 1973 to 2011 period, glaciers expanded over 3791 hectares, and retreated from 16 504 hectares.

1 Introduction

Often called the third pole of the earth, the Qinghai Tibet Plateau is one of the highest areas on earth and supports many glaciers including the Geladandong Glacier. The Qinghai Tibet Plateau is also known as the water tower of Asia, because many of Asia's great rivers originate here and provide an important source of fresh water for China and many other Asian countries. A majority of the population living in the surrounding area of the Qinghai Tibet Plateau depends on the glacier melt water for their everyday fresh water and hydroelectric energy needs. If these glaciers were to disappear, serious consequences related to water availability would challenge the massive human population that now depend on the runoff. Most non-ice-sheet-type glaciers on earth have receded during the 20th century (Shi and Cheng, 1991; Dyurgerov and Meier, 2000), and the glaciers on the Qinghai Tibet plateau have not been an exception. The headwaters of many great rivers, including the Yangtze and Yellow Rivers, are located in the Tibetan Plateau, and the potential loss of these glaciers is threatening the security of the water resources for China and other Asian countries. It is important to quantify glacier changes and trends in this region.

Mountain glaciers are extremely sensitive to environmental fluctuations, and are considered to be sensitive indicators of climate change (Barry, 2006), though their response is complicated (Oerlemans, 1987). Alpine glaciers, especially those in temperate zones, are also regarded as one of the best natural indicators of climate change (Houghton et al., 2001), and an increasing number of researchers are beginning to study glacier change. Climate in the Qinghai Tibet has shown a significant temperature increase since the mid-1950s (Liu and Chen, 2000; Frauenfeld et al., 2005; Kang et al., 2010), accompanied by an increase in average precipitation (Zhao et al., 2004; Chen et al., 2009; Liu et al., 2009). Many studies have shown that glaciers receded almost throughout the entire Tibetan Plateau during recent decades (Ding et al., 2006; Ye et al., 2006; Xiao et al., 2007; Li et al., 2008).

Developments in remote sensing have provided effective data sets to study glacial change in remote regions (Wang et al., 2005). Remote sensing has provided a set of tools, growing in sophistication over the years, for measuring and monitoring processes and phenomena on the Earth's surface (Rees, 2006). Sometimes remote sensing is the only method used to study glaciers in remote areas (Bolch and Kamp, 2005). Because multi-temporal and multi-spectral satellite data are ideal to study and monitor glacier changes simultaneously over larger areas in remote mountainous terrain and they allow for automated glacier mapping, these data can be used to quantify long-term trends of glacial extent (Hall et al., 1987; Paul, 2000; Silverio and Jaquet, 2005). A simple but robust glacier mapping method is unsupervised classification using 3 visible bands and a near-infrared band if the image is cloud free. The earliest imagery suitable for automated mapping is available after the launch of Landsat in 1972.

Geladandong Mountain, the highest peak in the Tanggula Mountains, with an elevation of 6621 m a.s.l., is located in the central Tibetan Plateau at 33.5° N, 91.1° E (Fig. 1). The Tanggula Mountains serve as an orographic boundary between the continental air masses to the north and the summer Indian monsoon to the south of the Tibetan Plateau (Zheng and Zhu, 2003). The two air masses meet between 32° and 34° N. Since the headwaters of the Yangtze River are located in the Geladandong Mountain region, the future of the glaciers in this area is critical to China. There is a need for a basic understanding of the sensitivity of these glaciers to long-term change, which can lead to a glacial change modeling approach that includes future climate scenarios and hydrologic modeling. While this study only examines long-term change in glacier extent, the findings allow inferences to be drawn on the future of frozen water resources in northwest China.

Previous work by Ye et al. (2006) reported glacier shrinkage for the Geladandong Range, but these studies are based on a comparison of satellite data with data from 1970s topographic maps. Frauenfelder and Kääb (2009) found uncertainties and location errors with these older data, which has also been made available in the GLIMS (Global Land Ice Measurements from Space) initiative database (Li, 2003). The recent speed up in decreasing glacier area reported by Ye et al. (2006) was not found in this study, and in fact, the ice area loss rate was found to be slowing down. Ice thickness information is unavailable, so these results do not allow us to assess the trend in ice volume loss. In this study, digital images of the Geladandong Mountain region obtained from Landsat Multispectral Scanner (MSS) (1973), Landsat Thematic Mapper (TM) (1992), Landsat Enhanced Thematic Mapper Plus (ETM+) (2004), and CBERS CCD (2011) were used to assess glacier change in this region over nearly 4 decades.

2 Study area

The study area chosen for this research (shown in Fig. 1) includes most of the Geladangong Mountain area and some nearby glaciers, including Gar Kangri and Kangchenchagzhong. This area was chosen based on the coverage of the imagery available. There are 3 large contiguous ice masses in the study area, and they are identified as A, B and C (see Fig. 1).

Changes in glacier extent over the entire study area and over each of these contiguous ice masses has been examined. The Geladandong Mountain region is located in the center of the Qinghai Tibet Plateau, south-western Qinghai Province of China near the border of Tibet (http://www.peakbagger.com/peak.aspx?pid=10590). Geladandong Mountain is the tallest mountain in the Tanggula Mountain Range of the Tibetan Plateau (ele 6621 m). The source of the Yangtze River is seasonal runoff and glacier melt water from this mountain. The Geladandong Peak is encircled by over twenty high mountain peaks, all exceeding 6000 m in elevation. Geladandong Mountain region is approximately 50 km long from north to south and approximately 20 km wide from west to east, covering an area of approximately 670 km^2, and includes over 40 glaciers. This area is directly across the border from Amdo County, Nagqu Prefecture, Tibet Autonomous Region, and the Qinghai-Tibet Railway crosses the Tanggula Mountain Range around 100 km to the east of Geladandong Peak.

Due to the area's arid climate, its annual mean precipitation is only 200 mm at the base. In the high-altitude areas with elevations over 5000 m, however, strong winds and frequent precipitation prevail, providing a yearly water-equivalent precipitation that is several hundred mm more than that in the foothill area. Thus, snow and hailstones frequently fall, feeding the development of glaciers. In the foothill area the average temperature is −5 °C, and the hottest months are from June to August with a temperature of over 20 °C, while the coldest month is January, with an average temperature of −18 °C. In the high-altitude areas over 5000 m, temperatures are much lower. (http://en.wikipedia.org/wiki/Geladaindong_Peak)

3 Data and methodology

Satellite-based remote-sensing techniques, including microwave data and optical imagery, have commonly been used in global-scale glacier surveys. Landsat imagery, including the Landsat MSS (images of four spectral bands in the visible/near-infrared (VNIR) region, with a pixel resolution of 79 m), the Landsat TM (images of seven spectral bands from visible to thermal-infrared with 28.5 m pixel resolution in the VNIR), and the Landsat ETM+ (images of eight discrete spectral bands with a 14.25 m pixel resolution in the panchromatic band), has been one of the primary data sources for glaciological research (Bindschadler et al., 2001; R. S. Williams, J. Rand, J. G. Ferrigno, http://pubs.usgs.gov/fs/2005/3056/pdf/fs2005-3056_508.pdf). Landsat data have provided glacier information in remote areas since the satellite was launched in 1972 (Meier, 1973). With the development and launch of remote-sensing satellites by China, the use of CBERS imagery for glaciological research has increased since 2000. CBERS imagery, especially the CBERS CCD images have five spectral bands (0.51–0.73 µm (panchromatic); 0.45–0.52 µm (blue); 0.52–0.59 µm (green); 0.63–0.69 µm (red); 0.77–0.89 µm (near infrared), with 20 m spatial resolution) that are used in developing glacier inventories.

The main source for the glacier inventory in this paper was Landsat MSS/TM/ETM+ and CBERS CCD scenes from different years, including Landsat MSS in 1973, TM in 1992, ETM+ in 2004 and CBERS CCD in 2011 (Table 1). The Landsat scenes were available from USGS (United States Geological Survey, http://glovis.usgs.gov/). The CBERS scenes were available from the China Centre for Resource Satellite Data and Application. In order to compare with Landsat data, we also did a geometric rectification for CBERS scenes by using 1992 Landsat TM data as a reference. All of the Landsat data are snow free beyond the glacier margins, but for CBERS data a small area was covered by seasonal snow and some cloud. In addition, the 2004 Landsat image was partly covered by cloud in a few areas. The spectral profile of glacial ice surfaces is totally different than other land types at bands blue (band1), green (band2), red (band3) and near infrared (band4), but has similar characteristics with the spectral profile of clouds. So for cloud-free Landsat images in 1973 and 1992, it is enough to extract the glacier information only by using data for bands 1–4. But because the 2004 Landsat images have some cloud cover, it is difficult to distinguish between glacier surface and clouds only using the bands 1–4 because of the spectral similarities. However, the glacier spectral profile is very different from the cloud spectral profile in near-infrared bands 5 and 7, so for the 2004 Landsat data, bands 1–5 and 7 are used to extract the glacier boundaries.

The multispectral classification methods used for glacier delineation with Landsat data and CBERS data include manual digitization, normalized difference snow index (Silverio and Jaquet, 2005), spectral-band ratio, and unsupervised and supervised classification techniques (Hall and Martinec, 1985; Pauland et al., 2002; GLIMS Algorithm Working Group, http://www.geo.unizh.ch/~kaeaeb/glims/algor.html). Although the unsupervised classification method may not be very accurate for extracting other land types that have similar spectral profiles in bands 1–4, it is a very useful method for extracting glacier information because the glacier has a very different spectral profile than the non-glaciated areas. Therefore, with Landsat data, we use the unsupervised classification method to extract glacier area. For CBERS CCD data, which was partly covered by clouds and snow, we first use the unsupervised classification method to divide glacier, clouds and snow from other land types, and then we use visual interpretation to extract glacier area. Finally, the distribution and the area of glaciers in each period in the Geladandong Mountain area were mapped and calculated (Fig. 2). The variation of glacier extent was quantified using overlay analysis for each period.

The potential error of the multi-temporal analysis mainly arises from positional and mapping errors (Bolch et al., 2010). Uncertainty of glacier mapping depends on the resolution of the utilized imagery and the conditions at the time of the acquisition (especially seasonal snow). Under optimum conditions, an accuracy of less than half a pixel can be achieved. MSS, TM and ETM+ scenes from the USGS used by us matched perfectly. We estimated the uncertainty by the buffer method suggested by Bolch et al. (2010) and Granshaw and Fountain (2006). We have chosen a buffer size of 30 m for the MSS image, and 15 m for the TM, ETM+ and CBERS CCD images. So when we extracted the glacier area, we calculated the perimeter of every polygon of glacier and multiply by the buffer size to get the uncertainty of the mapped glacier area. This led into an uncertainty of the mapped glacier area of 5 % for the MSS image, and 3 % for the ETM+ and CBERS CCD images on average.

4 Results

Our results show that the total glacier area has continually decreased over the past 38 yr (Figs. 3 and 4). In 1973, the total glacier area in study region is 107 105 ± 7817 hectares, which decreases to 97 546 ± 3925 hectares in 1992. In 2004 the total glacier area in study region is 95,340 ± 2508 hectares decreasing by about 2206 hectares from 1992. In 2011, the total glacier area in study region was 94 420 ± 2624 hectares, just 912 hectares less than 2004, which is within the uncertainty of the measurements. Over the entire period from 1973 to 2011, total glacier area decreased 12 685 hectares.

Our results show that the rate at which glacier area is decreasing is diminishing with time (Figs. 5 and 6). The trend is −503 hectares yr^{-1} during 1973–1992, or −0.47 % yr^{-1}. But during 1992–2004, this loss rate was reduced to −183.8 hectare yr^{-1}, or −0.19 % yr^{-1}, a 63 % drop in the loss rate compared to the 1973–1992 period. During 2004–2011, the loss rate was reduced to −130 hectares hectare yr^{-1}, or −0.14 % yr^{-1}, a 26.7 % drop in the loss rate compared to 1992–2004. The overall loss rate between 1973 and 2011 is −334.5 hectares yr^{-1}, or −0.31 % yr^{-1}.

Figure 7 summarizes the changes in perennial snow cover within the study area during each time interval and over the entire 38 yr period. Although most of the glaciers and ice masses were shrinking or being lost altogether, some glaciers were surging as depicted by the area colored in yellow. From 1973 to 1992, 3389 hectares of non-glacier area was covered by ice from surging glaciers. During this same period, 12 948 hectares of glacier area was lost, for a net change of −9559 hectares in glacier area. Between 1992 and 2004, surging glaciers claimed 2146 hectares of non-glacier area, and glaciers retreated from 4352 hectares, resulting in a net decrease of 2206 hectares of ice cover. Between 2004 and 2011, surging glaciers claimed 2015 hectares of non-glacier area, and 2928 hectares lost their ice cover, resulting in a net decrease of 913 hectares of ice cover. In total, from 1973 to 2011, there has been 3791 hectares of non-glacier area changed to glacier area from surging, and 16 504 hectares of glacier area lost by glacier retreat, so the net glacier decrease in glacier covered area is 12 713 hectares.

It is quite clear from Fig. 7 that many of the relatively small, isolated ice masses were lost during the first comparison period (1973–1992), and did not return. These small ice masses were more vulnerable to increasing temperatures than the large contiguous ice masses, and their loss accounts for the large ice area loss rate observed during the first comparison period. In order to examine the changes to the three large contiguous ice masses without the bias of the small ice masses, we converted the raster layer glacier map to arc coverage polygons. We then obtained the information on the three large contiguous ice masses by calculating the area and perimeter of these three largest polygons (see Table 2 and Figs. 8 and 9).

For the smallest of these three glaciers (A) with a size of ∼ 8000 hectares, a slight decrease in glacier area was observed between 1973 and 2004, but this change was less than the uncertainty of the measurements (Table 2). Between 2004 and 2011, the glacier area expanded slightly, but this change was still less than the uncertainty of the measurements. Between 1973 and 2011, the overall net negative change in glacier area was within the measurement uncertainty, and therefore we can consider it unchanged over the 38 yr period.

For glacier B, which has an area of more than twice the size of glacier A, its area decreased for all measurement intervals, however the observed changes were within the uncertainty of the measurements. The overall rate of glacier area changes was $-0.18\,\%\,\mathrm{yr}^{-1}$.

Glacier C is by far the largest of the three individually examined glaciers with an area of more than 60 000 hectares. This glacier was found to have a continual decrease in glacier area for all of the measurement intervals, but all changes were within the measurement uncertainty. The change in area from 1973 to 2011 was −3860 hectares, and the rate of change of ice area was found to decrease throughout the period. The overall rate in which area changed was −0.18 % per year, which was the same rate of change observed for glacier B.

5 Conclusions

Glacier variations in the Geladandong Mountain area have been measured by using a series of digital images since 1973. We have presented a method for investigation of glacier variations using Landsat data and CBERS data. Our results show that during a period of nearly 4 decades, the area covered by glaciers and ice masses has been continually decreasing in Geladandong mountain region. Although some glaciers in the Geladandong Mountain region of the central Tibetan Plateau have advanced over the past 38 yr, most of them have retreated. Between 1973 and 1992, many small ice masses were found to have disappeared, and they did not return by 2011. Over the entire period from 1973 to 2011, total glacier area decreased 12 685 hectares in study area. These results agree with other similar analyses on the Qinghai Tibet Plateau (Ye et al., 2006), but our results also show that the rate of glacier area change is decreasing in recent years as the small, isolated ice masses have disappeared. This decreasing trend of glacial area loss was also observed for the two largest ice masses of the Geladandong Mountain region. These results showing a decreasing area loss rate differ from previous studies. However, the change in the rate of glacier area loss may not reflect changes in ice volume, and we have no way of knowing whether the ice volume is increasing or decreasing with time. Ice thickness data or repeat ice surface elevation data are needed to begin to understand how ice volume and hence, water discharge, are changing over time. Quantifying ice volume changes is necessary to understand how this water resource is changing, and is the most important objective for future research.

Acknowledgements. This research is supported by the Jiangsu Government Scholarship for Overseas Studies (JS-2010–184).

References

Barry, R. G.: The status of research on glaciers and global glacier recession: a review, Prog. Phys. Geogr., 30, 285–306, 2006.

Bindschadler, R., Dowdeswell, J. A., Hall, D., and Winther, J. G.: Glaciological applications with Landsat-7 imagery: early assessments, Remote Sens. Environ., 78, 163–179, 2001.

Bolch, T. and Kamp, U.: Glacier mapping in high mountains using DEMs, Landsat and ASTER data, Proceedings of the 8th International Symposium on high mountain remote sensing cartography, 37–48, 2005.

Bolch, T., Yao, T., Kang, S., Buchroithner, M. F., Scherer, D., Maussion, F., Huintjes, E., and Schneider, C.: A glacier inventory for the western Nyainqentanglha Range and the Nam Co

Basin, Tibet, and glacier changes 1976–2009, The Cryosphere, 4, 419–433, doi:10.5194/tc-4-419-2010, 2010.

Chen, F., Kang, S., Zhang, J., and You, Q.: Glaciers and lake change in response to climate change in the Nam Co Basin, Tibet, J. Mt. Sci., 27, 641–647, 2009 (in Chinese with English abstract).

Ding, Y., Liu, S., Li, J., and Shangguan, D.: The retreat of glaciers in response to recent climate warming in western China, Ann. Glaciol., 43, 97–105, 2006.

Dyurgerov, M. B. and Meier, M. F.: Twentieth century climate change: evidence from small glaciers. Proc. Natl. Acad. Sci. USA, 97, 1406–1411, 2000.

Frauenfeld, O. W., Zhang, T., and Serreze, M. C.: Climate change and variability using European Centre for Medium-Range Weather Forecasts reanalysis (ERA-40) temperatures on the Tibetian Plateau, J. Geophys. Res., 110, D02101, doi:10.1029/2004JD005230, 2005.

Frauenfelder, R. and Kääb, A.: Glacier mapping from multitemporal optical remote sensing data within the Brahmaputra river basin, Proc. 33rd Int. Symposium on Remote Sensing of Environment, 4–8 May 2009, Stresa, Italy, Tucson, Arizona, International Center of Remote Sensing of Environment, Paper 299, 4 pp., 2009.

Granshaw, F. D. and Fountain, A. G.: Glacier change (1958–1998) in the North Cascades National Park Complex, Washington, USA, J. Glaciol., 52, 251–256, 2006.

Hall, D. K. and Martinec, J.: Remote sensing of ice and snow, Chapman and Hall Ltd., London and New York, 1985.

Hall, D. K., Ormsby, J., Binsdschdler, R. A., and Siddalingaiaha, H.: Characterization of snow and ice reflectance zones on glacier using Landsat Thematic mapper data, Ann. Glaciol., 9, 104–108, 1987.

Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A.: Climate cHange 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2001.

Li, X.: GLIMS Glacier Database, Boulder, CO, National Snow and Ice Data Center/World Data Center for Glaciology, Digital Media, 2003.

Li, X., Cheng, G., Jin, H., Kang, E., Che, T., Jin, R., Wu, L., Nan, Z., Wang, J., and Shen, Y.: Cryospheric change in China, Global Planet. Change, 62, 210–218, 2008.

Lihong, W., Lu, A., Liu, S., and Yao, T.: The Study of Glacier Fluctuations using Remote Sensing on the Mt. Geladandong and A'nyêmaqên in the Qinghai-Tibetan Plateau, IEEE, 2005.

Liu, J., Wang, S., Yu, S., Yang, D., and Zhang, L.: Climate warming and growth of high-elevation inland lakes on the Tibetan Plateau, Global Planet. Change, 67, 209–217, 2009.

Liu, X. and Chen, B.: Climatic warming in the Tibetan Plateau during recent decades, Int. J. Climatol., 20, 1729–1742, 2000.

Meier, M. F.: Evaluation of ERTS imagery for mapping and detection of changes of snow-cover on land and on glaciers, in: Symposium on Significant Results Obtained from Earth Resources Technical Satellite-1, (New Carrollton, Maryland), edited by: Freden, S. C., Mercanti, E. P., and Witten, D. E., Washington, DC, National Aeronautics and Space Administration, 863–875, 1973.

Oerlemans, J.: On the process of valley glaciers to climatic change, in: Glacier Fluctuations and Climatic Change, Proceedings of the Symposium on Glacier Fluctuations and Climate Change, Amsterdam, 1–5 June, Kluwer Academic Publishers, Netherlands, 1987.

Paul F.: Evaluation of different methods for glacier mapping using landsat TM, Proceedings of EARSeL-SIG-Workshop Land Ice and Snow, Dresden/FRG, 16–17 June, 239–245, 2000.

Paul, F., Kääb, A., Maisch, M., Kellenberger, T., and Haeberli, W.: The new remote-sensing-derived Swiss glacier inventory, I. Methods, Ann. Glaciol., 34, 355–361, 2002.

Qinghua, Y. E., Kang, S., Chen, F., and Wang, J.: Monitoring glacier variations on Geladandongmountain, central Tibetan Plateau, from 1969 to 2002 using remote-sensing and GIS technologies, J. Glaciol., 52, 537–545, 2006.

Rees, W. G.: Remote Sensing of Snow and Ice, Taylor and Francis, London, 2006.

Shi, Y. and Cheng, G.: Cryosphere and global climate change, Bull. Chinese Acad. Sci., 6, 287–291, 1991.

Silverio, W. and Jaquet, J. M.: Glacial cover mapping (1987–1996) of the Cordillera Blanca (Peru) using satellite imagery, Remote Sens. Environ., 95, 342–350, 2005.

Williams Jr., R. S., Hall D. K., and Chien, J. Y. L.: Comparison of satellite-derived with ground-based measurements of the fluctuations of the margins of Vatnajökull, Iceland, 1973–92, Ann. Glaciol., 24, 72–80, 1997.

Xiao, C., Liu, S., Zhao, L., Wu, Q., Li, P., Liu, C., Zhang, Q., Ding, Y., Yao, T., Li, Z., and Pu, J.: Observed changes of cryosphere in China over the second half of the 20th century: an overview, Ann. Glaciol., 46, 382–390, 2007.

Ye, Q., Kang, S., Chen, F., and Wang, J.: Monitoring glacier variations on Geladandong Mountain, central Tibetan Plateau, from 1969 to 2002 using remote-sensing and GIS technologies, J. Glaciol., 52, 537–545, 2006.

Zhao, L., Ping, C., Yang, D., Cheng, G., Ding, Y., and Liu, S.: Changes of climate and seasonally frozen ground over the past 30 years in Qinghai-Xizang (Tibetan) Plateau, China, Global Planet. Change, 43, 19–31, 2004.

Zheng, D. and Zhu, L. (Eds.): Formation, Environment and Development of the Tibetan Plateau, Shijiazhuang, Heibei Science and Technology Press, 2003.

Table 1. Utilized satellite imagery.

Data	Satellite and Sensor	Path/Row	Spatial Resolution	Spectral Bands	Source	Suitability
10 Jun 1973	Landsat MSS	149/37	60.00	3 VIS, 1 NIR	USGS	
31 Aug 1992	Landsat TM	138/37	28.50	3 VIS, 1 NIR,	USGS	
9 Sep 2004	Land ETM+	138/37	28.50	3 VIS, 1 NIR, 2 MIR	USGS	Cloud on NE part
9 Aug 2011	CBERS CCD	25/63	19.50	3 VIS, 1 NIR	CCRSDA	Off season snow and clouds on small part

Table 2. Area of three largest contiguous ice masses (unit: hectare).

Year	1973	1992	2004	2011
A	7802 ± 360	7812 ± 220	7619 ± 208	8101 ± 221
B	19 254 ± 920	18 587 ± 614	18 520 ± 457	18 226 ± 511
C	65 145 ± 2781	62 591 ± 1843	61 445 ± 1373	61 285 ± 1353

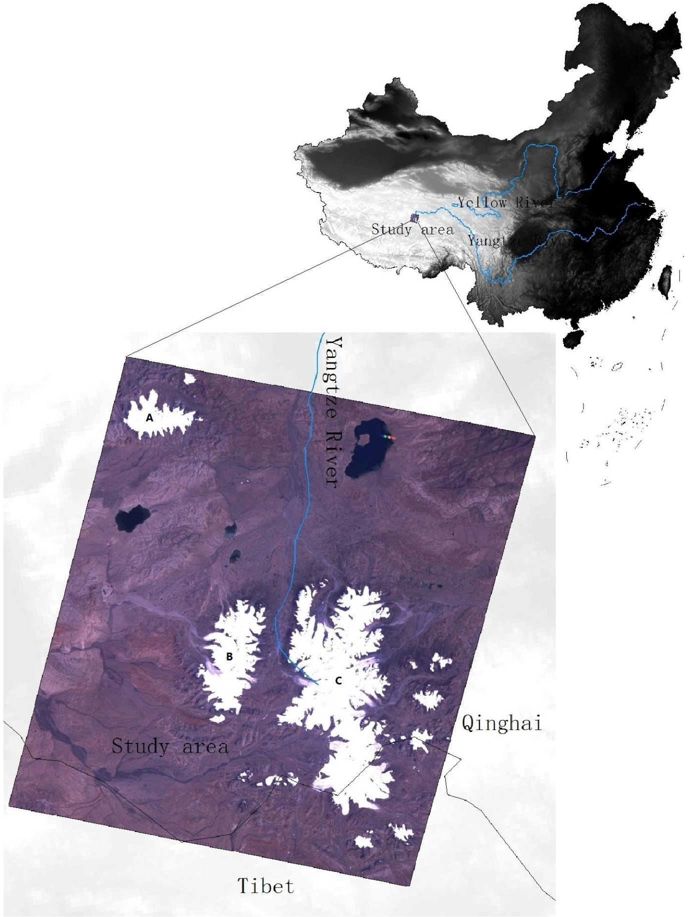

Fig. 1. Geladandong Mountain location and Landsat TM image taken on 31 August 1992.

1973 1992

2004 2011

Fig. 2. Geladandong Mountain area glacier coverage shown in blue for 1973, 1992, 2004 and 2011.

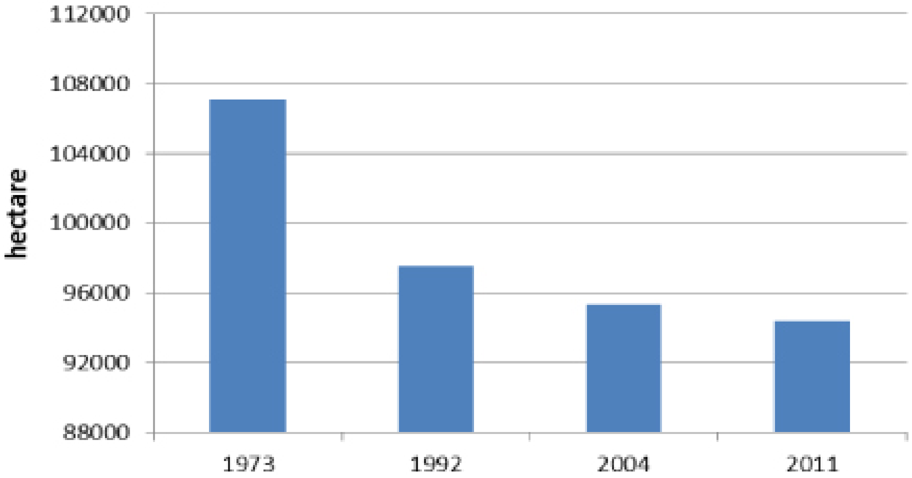

Fig. 3. Total glacier area in 1973, 1992, 2004 and 2011.

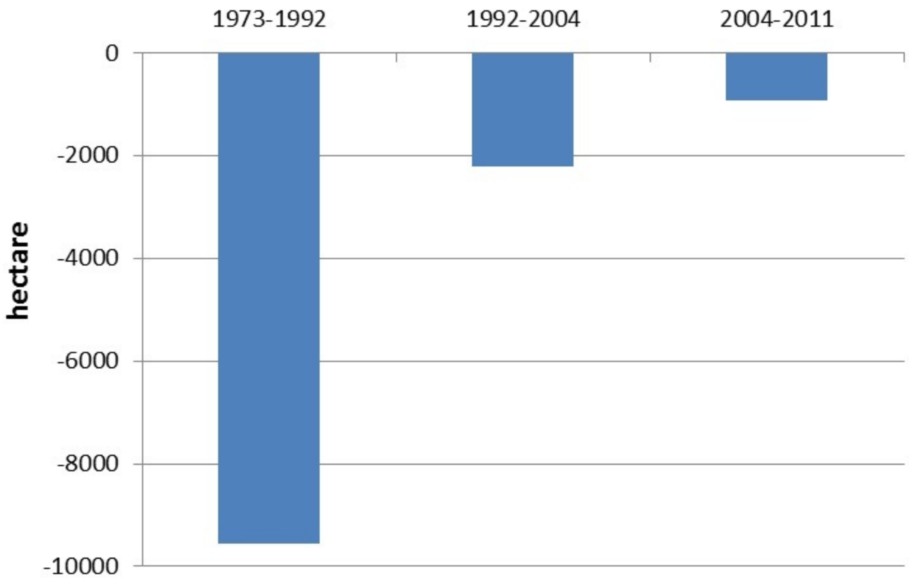

Fig. 4. The glacier area change between 1973–1992, 1992–2004 and 2004–2011.

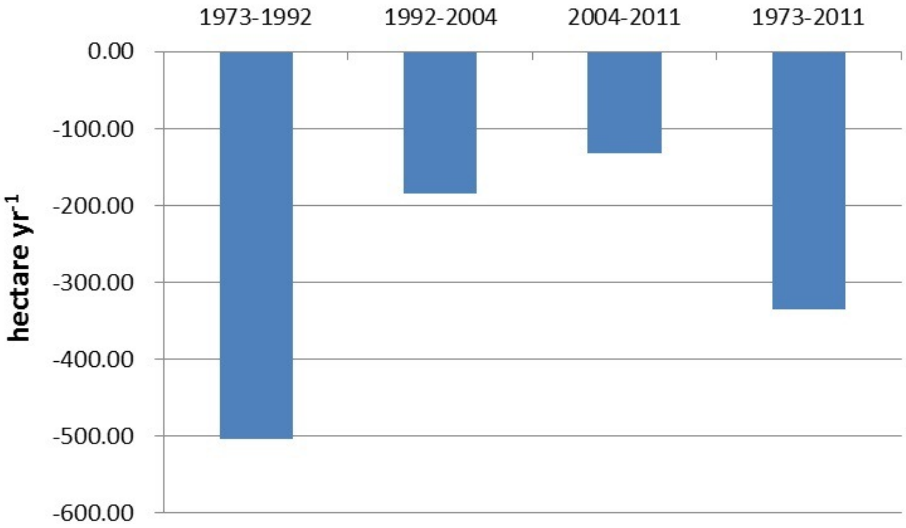

Fig. 5. Glacier area rate of change in hectare yr^{-1} in the Geladandong Mountain region.

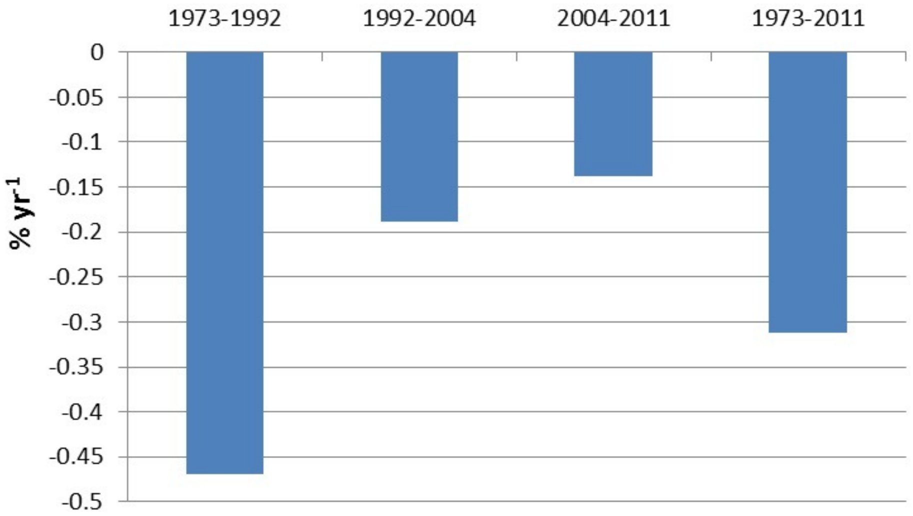

Fig. 6. Glacier area rate of change as a percentage of total area in the Geladandong Mountain region.

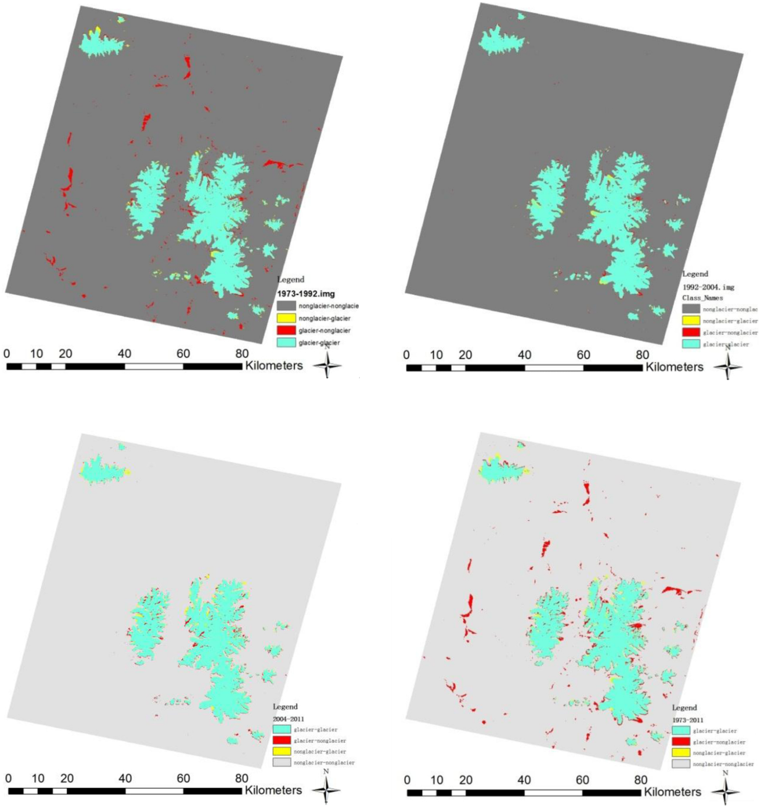

Fig. 7. Glacier change for 1973–1992, 1992–2004, 2004–2011 and 1973–2011 in the Geladandong Mountain area.

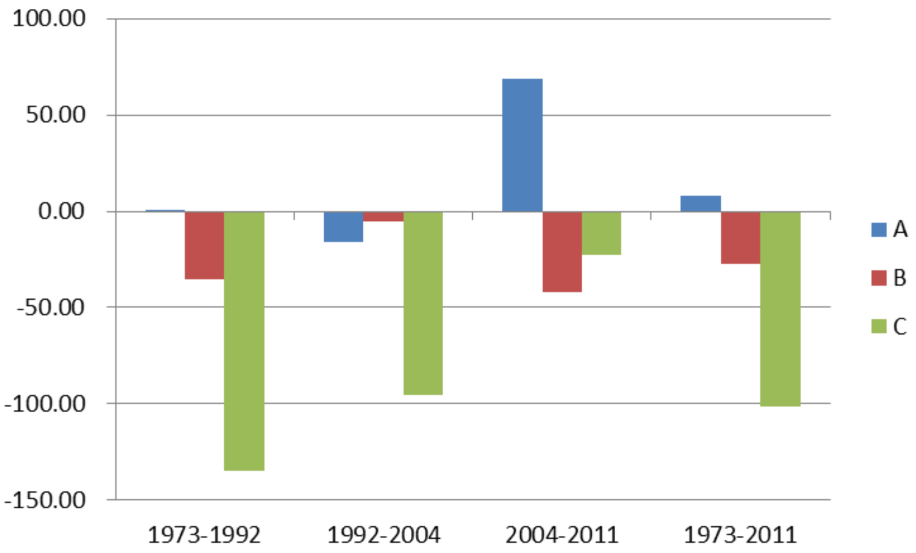

Fig. 8. The area rate of change of the three largest contiguous ice masses (unit: hectare yr^{-1}).

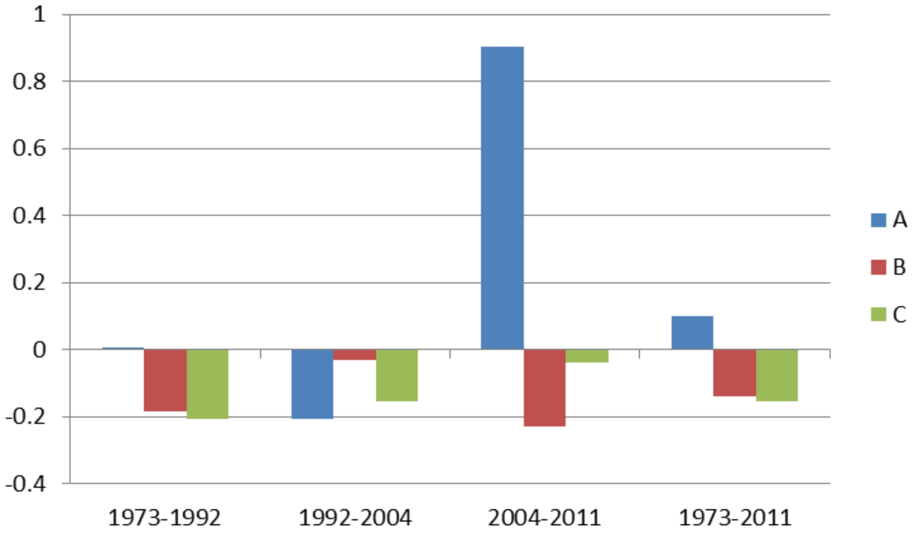

Fig. 9. The percentage rate of change the three largest contiguous ice masses (unit: % yr^{-1}).