Journal of Geographical Sciences 14, 3 (2004) 296–302 ISSN: 1009–637X www.geog.cn

Remote sensing detection of glacier changes in Tianshan Mountains for the past 40 years

LI Baolin, ZHANG Yichi, ZHOU Chenghu
(State Key Laboratory of Environment and Resources Information System, Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China)

Abstract: Both marginal fluctuation and areal change were used to detect the accurate dynamics of glacier change in the study area using Landsat MSS, ETM, SPOT HRV and topographic maps based on GIS. From 1963 to 1977, four of eight glaciers advanced, two of them retreated and another two kept stable, the glacier advanced generally. From 1977 to 1986, four of eight glaciers retreated and the others kept stable, but the retreated glaciers were those which advanced from 1963 to 1977. From 1986 to 2000, seven of eight glaciers retreated and only one glacier kept stable, the retreating velocity was 10-15 m/a. Glacier recession in this period became very fast and universal. From 1963 to 2000, the area of glaciers decreased from 5479.0 ha to 4795.4 ha, up to 12.5%. It is alarming that most of glacier retreats happened from 1986 to 2000. This was very consistent with change process of summer mean temperature in this region and global warming beginning in the 1980s.
Key words: Tianshan Mountains; glacier; remote sensing; glacier retreat; global warming

1 Introduction

The piedmont area of Tianshan Mountains is one of the regions witnessing rapid economic development in arid area of China. Glacier meltwater provides the basis for the oasis ecosystems. With the acceleration of global warming in the 1980s, it has become more and more important to understand the ability of glaciers to provide water sources and the disasters related to glaciers and climate change (Mennis and Fountian, 2001). Thus, it is of great significance to obtaining the accurate information of glacier changes. Extensive researches on glaciers in Tianshan Mountains, especially on modern glacier processes have been carried out (Liu and Xie, 1998), the first glacier monitoring station of China was established in the source region of Urumqi River, and China Glacier Inventory of this area was finished in the 1980s (LIGG, 1987). Large scale research on frequent glacier change monitoring has been inadequately carried out because of the terrible natural environment and vastness of the glacier distributed area. Most work on glacier change monitoring by remote sensing techniques is focused on methods for glacier mapping and identification of glacier statistics index (Bayer *et al.*, 1994; Bishop *et al.*, 1999; Hall *et al.*, 1996; Klein and Isacks, 1999; Liu and Lu *et al.*, 2002). Certain work has been done on remote sensing detection of glaciers in the Tibetan Plateau, Tianshan Mountains and elsewhere in China (Liu and Lu *et al.*, 2002; Liu and Shen *et al.*, 2002; Lu *et al.*, 2002; Li *et al.*, 1998). Because debris cover, shadow and snowpack adjacent to the glaciers generally caused quite a few errors for understanding the changes of glaciers (Paul, 2002; Williams, 1997), it was still difficult to realize accurate and frequent detection of glaciers. This study seeks for the efficient and practical methodology to detect glacier change accurately based on marginal fluctuation and areal changes of firn in the study area using remote sensing data, including Landsat MSS, ETM, SPOT HRV and topographic maps from various sources with a monitoring time sequence of 40 years so that the trend of glacier and glacier runoff change can be predicted.

Received: 2004-03-13 **Accepted:** 2004-05-30
Foundation: National Natural Science Foundation of China, No.40101028; Knowledge Innovation Project of the Geographic Sciences and Natural Resources Research, CAS, No.CXIOG-D02-02
Author: Li Baolin (1970-), Associate Professor, specialized in environmental change and GIS and RS.
E-mail: libl@www.lreis.ac.cn

2 Methodology

2.1 Study area and data

The study area is located in Hejing County, Xinjiang Uygur Autonomous Region, China with center laying between 42°33'58"N and 85°28'35"E. Hejing County is situated in Albin Mountain, a sub-range of Tianshan Mountains on the east bank of Kaidu River (Figure 1). The landscape of Albin Mountain is typical in Tianshan Mountains, with elevations of 3000-5000 m. Three remotely sensed images were acquired for glacier change detection in this study (Table 1), including Landsat MSS, SPOT HRV and Landsat ETM multispectral images. In addition, two topographic maps which were compiled based on the 1:100,000 scale aerial photo in 1963 were also acquired. The SPOT HRV data with the highest spatial resolution are orthorectified using 18 Ground Control Points (GCPs) with RMS errors less than 0.5 pixels in both X and Y directions according to topographic maps and 1:250,000 DEM. The other two images were then geometrically orthorectified on the map coordinates using image-to-image registration of the master SPOT HRV image with RMS errors less than 0.5 pixels in both X and Y directions and 1:250,000 DEM (Table 2). The topographic maps were scanned and registrated, and the registrated data were exported to GIS and digitalized using GIS. In addition, the glacier distribution maps in China Glacier Inventory were also scanned and registrated (lower accuracy) which provided reference for other data.

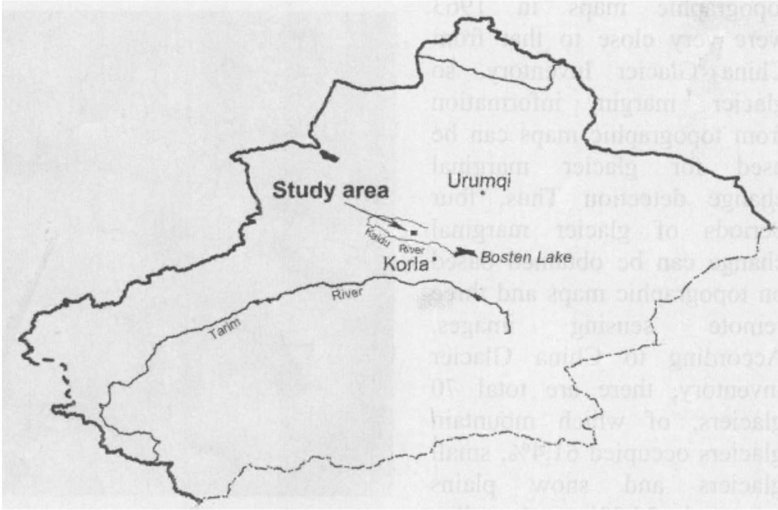

Figure 1 Location map of the study area

Table 1 Data used in this research

Satellite	Sensor	Path/row	Resolution (m)	Receiving data
Landsat 2	MSS	155/30	57*	15/8/1977
SPOT 1	HRV	215/264/4	20	30/8/1986
Landsat 7	ETM	144/30	30	7/8/2000

* Resampling resolution

2.2 Change detection

2.2.1 Marginal change Although all the remote sensing data were received in August, the seasonal snow was obvious on the images in 1977 and 1986 according to the glacier distribution map from China Glacier Inventory (LIGG, 1987). The glacier shapes from ETM in 2000 were very similar to those in China Glacier Inventory, but glacier retreat was quite obvious. Some had disappeared (Figures 2 and 3), for example, No. 9 and 10 (5Y696G-26, 5Y695B-20), and some nearly disappeared, for example, No.11, 12, 13, 14 and 15 (5Y695B-10, 21, 22, 23, 24). Although there was obvious seasonal snow on the images in 1977 and 1986, the glacial margins were not affected by seasonal snow because of the low elevation of glacier margins. After comparing with data in China Glacier Inventory, the elevations of glacier margins from

Table 2 RMS errors on geometric correction and registration of the images

	X (pixels)	X (m)	Y (pixels)	Y (m)	Total (pixels)	Total (m)
Topographic maps (1963)	1.2	10.7*	1.0	8.7*	1.6	13.9
LANDSAT MSS (1977)	0.3	18.2	0.2	13.7	0.4	22.8
SPOT HRV (1986)	0.5	9.6	0.3	6.4	0.6	11.6
LANDSAT ETM (2000)	0.4	13.2	0.3	9.3	0.5	16.2

*The resolution of scanned topographic maps is 8.6 m.

topographic maps in 1963 were very close to that from China Glacier Inventory, so glacier margin information from topographic maps can be used for glacier marginal change detection Thus, four periods of glacier marginal change can be obtained based on topographic maps and three remote sensing images. According to China Glacier Inventory, there are total 70 glaciers, of which mountain glaciers occupied 61.4%, small glaciers and snow plains occupied 34.3% and valley glaciers, 2.9% . Here eight large glaciers were selected to detect the glacier marginal changes (Figure 2 and Table 3).

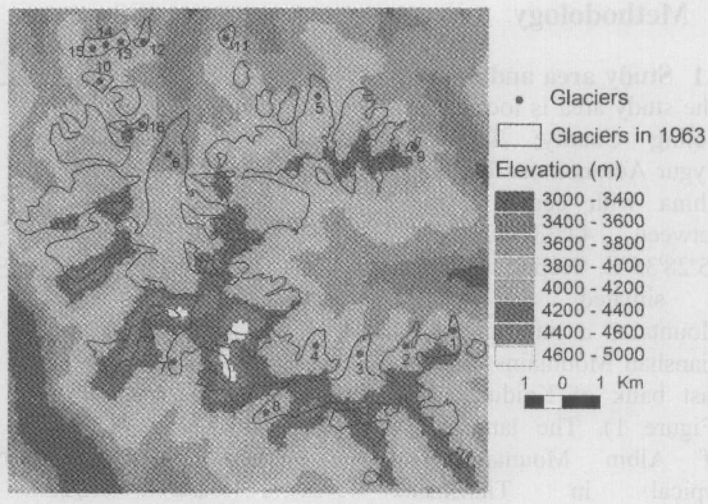

Figure 2 The glaciers for detecting changes of margins

Table 3 Glaciers for detecting marginal changes

Inventory number	Types	Area (km^2)	Margin elevation (m)
No.15Y696H-9	640110	0.55	3760
No.25Y696H-11	640110	1.22	3740
No.35Y696H-12	630110	2.3	3790
No.45Y696H-14	640110	0.88	3930
No.55Y695B-6	630110	2.01	3730
No.65Y695B-15	520110	8.51	3660
No.75Y695G-81	530110	2.29	4000
No.85Y695G-78	640110	1.83	4000

2.2.2 Accuracy assessment For glacier marginal accuracy assessment, the error of a series of measurements of similar quantities is $E\sqrt{n}$ if errors of all the measurements of margins are the same, where E is the error of measurements of glaciers and n is the number of measurements (Williams *et al.*, 1997). From Table 2 one can see the errors of different measurements of different glaciers vary, so the error of measurements of glaciers is $\sqrt{E_1^2 + E_2^2}$, where E_1 is the error of the measurement of series 1 and E_2 is the error of the measurement of series 2.

For glacier distribution accuracy assessment, we have chosen stratified random sampling scheme for selecting sample points of reference data for accuracy assessment. 500 sample points were generated and transferred to GIS. They were then overlaid on the classified images as well as on pseudo multispectral images. The ground truth data were obtained from visual interpretation. Kappa statistics and overall accuracy were taken as the accuracy index to evaluate the accuracies of all the methods to map glaciers and snow.

3 Results

3.1 Glacial marginal changes

Because the errors of glacier marginal accuracy varied between 20 m and 30 m and most of the changes of glacier margins were exceeded 70 m between two stages which were more obvious than errors (Table 4), this showed that the general trend of glacier marginal change can be detectable and the results were usable. From 1963 to 2000, six glaciers out of the eight retreated over 70 m and the diminishing velocity of the seven glaciers out of eight was generally 5 m/a, but the glacier change varied greatly in different stages. From 1963 to 1977, four of the eight glaciers advanced, two of them retreated and another two kept stable (Tables 4 and 5). Generally, the glaciers advanced. The glacier marginal changes of the eight glaciers were quite

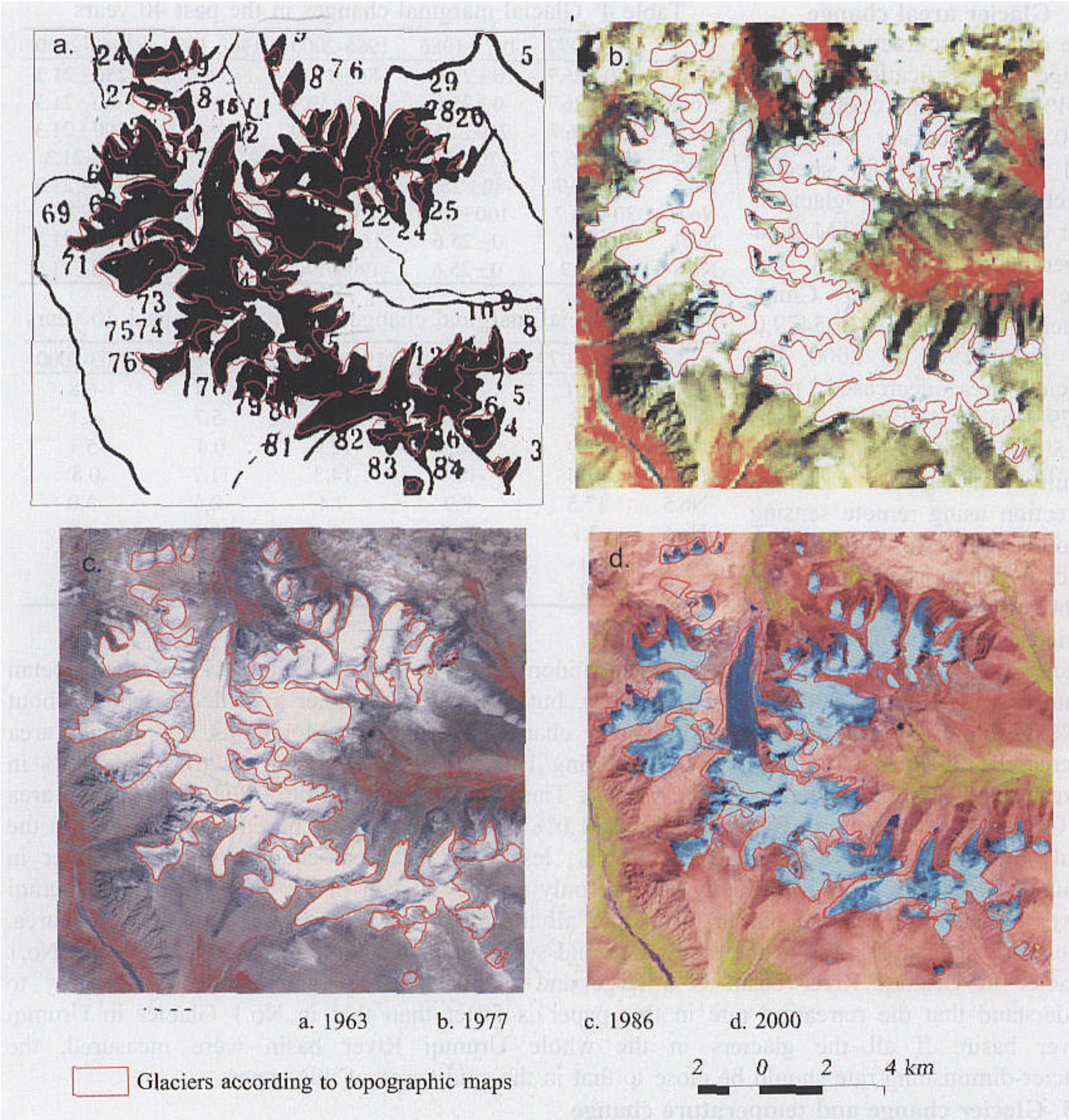

Figure 3 The glacier and snow change in the past 40 years

different. Glacier No.4 moved forward 31.4 m/a, but glacier No.1 retreated 12.1 m/a. From 1977 to 1986, four of the eight glaciers retreated and the others kept stable, and the retreating velocity was 10-30 m/a (Tables 4 and 5). However, the retreated glaciers were those advanced from 1963 to 1977. This showed that glacier retreat became obvious but not very great from 1963 to 1986. From 1986 to 2000, seven of the eight glaciers retreated and only one glacier kept stable (Tables 4 and 5), the retreating velocity was 10-15 m/a. This showed that the glacier retreat in this period became very fast and universal (Tables 4 and 5). From 1963 to 1986, only two of the eight glaciers retreated over 70 m and their retreating velocity was over 5 m/a. But from 1963 to 2000, six of the eight glaciers retreated over 70 m and their retreating velocity was over 5 m/a. This showed that the glaciers did not change much from 1963 to 1986 although glacier recession did exist and large scale glacier retreat happened in the past 15 years (Tables 4 and 5).

3.2 Glacier areal change

Table 4 Glacial marginal changes in the past 40 years

	1963-1977	1977-1986	1986-2000	1963-1986	1963-2000
No.1	-170±26.7	0±25.6	-80±19.9	-170±18.1	-250±21.3
No.2	-130±26.7	0±25.6	-170±19.9	-130±18.1	-300±21.3
No.3	250±26.7	-260±25.6	-180±19.9	-10±18.1	-190±21.3
No.4	440±26.7	-170±25.6	-200±19.9	270±18.1	30±21.3
No.5	70±26.7	-80±25.6	-100±19.9	-10±18.1	-110±21.3
No.6	30±26.7	-100±25.6	0±19.9	-70±18.1	-70±21.3
No.7	0±26.7	0±25.6	-160±19.9	0±18.1	-160±21.3
No.8	0±26.7	0±25.6	-190±19.9	0±18.1	-190±21.3

Table 5 Glacial marginal change velocity in the past 40 years

	1963-1977	1977-1986	1986-2000	1963-1986	1963-2000
No.1	-12.1	0	-5.7	-7.4	-6.8
No.2	-9.3	0	-14.1	-5.7	-8.1
No.3	17.9	-28.9	-12.9	0.4	-5.1
No.4	31.4	-18.9	-14.3	11.7	0.8
No.5	17.5	-8.9	-7.4	-0.4	-3.0
No.6	2.1	-11.1	0	-3.0	-1.9
No.7	0	0	-11.4	0	-4.3
No.8	0	0	-13.6	0	-5.1

The overall accuracy for ETM image classifications was 96.1% with Kappa coefficients 0.90. The accuracy was high and this may be for special spectral features of glaciers. The area based on ETM data supervision was 4795.4 ha. The area based on China Glacier Inventory was 5479.0 ha. From 1963 to 2000, the glacier area decreased from 5479.0 ha to 4795.4 ha, up to 12.5% (Figure 3). From other results of glacier change detection using remote sensing in other regions of China, most glaciers diminished from the 1960s to 2000, but change rate varied greatly (Table 6). The glacier area decreased only 1.7% in Geladandong area of the Yangtze River in the Tibetan Plateau from 1966 to 2000 (Lu *et al*., 2002), but most of the glacier area decreased by about 10% (Table 6). From the results of glacier change in Tianshan Mountains, the glacier area decreased 13.8% in Urumqi River basin during 1964-1993 (Chen *et al*., 1996), 2.6%-3.5% in Sikeshu and Kashi river basins in the west of Tianshan Mountains from 1962 to 1990, the area of Glacier No.1 in Urumqi River decreased 11.0% from 1962 to 2000 based on fieldwork. In the study area the glacier area decreased 12.5%, less than the areal change of No.1 Glacier in Urumqi River data. This is probably because only a valley glacier of the No.1 Glacier in Urumqi River basin was measured but in this paper all the glaciers were measured in the study area. There are diverse glaciers in the study area and some small glaciers are easier to melt but No.1 Glacier in Urumqi River basin is a large and relatively stable glacier, it is thus easy to understand that the retreating rate in this paper is faster than that in No.1 Glacier in Urumqi River basin. If all the glaciers in the whole Urumqi River basin were measured, the glacier-diminishing rate should be close to that in the study area of this paper.

3.3 Glacier change and temperature change

The glacier melting in the study area mainly took place from June to August in summer and are greatly affected by mean temperature in summer. Based on the meteorological data from Bayanbulak station in the middle reach of Kaidu River from 1958 to 2000, the mean temperature in summer generally increased (Figure 4). The mean summer

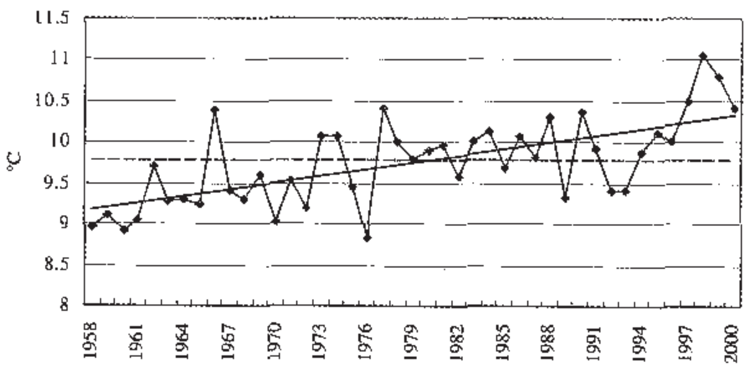

Figure 4 The summer average temperature in Bayanblak
(The average temperature from 1958 to 2000 is 9.8 °C.)

Table 6 Glacier change detection in other regions of China using RS

Author	Region	Period	Change rate	Trend
Liu and Lu *et al.*, 2002	Á Nyêmaên Mountains of the source area of the Yellow River	1966-2000	-17%	Retreat
Lu *et al.*, 2002	Geladandong area of the Yangtze River in the Tibetan Plateau	1969-2000	-1.7%	Stable
Liu *et al.*, 2002b	West of Qilian Mountains	1956-1990	-10.3%	Retreat
Li *et al.*, 1998	Bukatage Peak in the Middle of Kulun Mountains	1976-1987 1976-1994	-1.5% -1.7%	Retreat
Chen *et al.*, 1996	Urumqi River	1964-1992	-13.8%	Retreat
Shi Yafeng, 2000	Sikeshu River basin and Kashi River Basin in the West of Tianshan Mountains	1962-1990	-2.6%-3.5%	Retreat
Li *et al.*, 2003*	Glacier No.1 in Urumqi River	1962-2000	-11.0%	Retreat
The author	Kaidu River Basin in Tianshan Mountains	1963-2000	-12.5%	Retreat

* Data was measured in the field in Glacier No.1 of Urumqi River.

temperature was 9.4 ℃, 9.7 ℃, 9.9 ℃ and 10.1 ℃ in 1961-1970, 1971-1980, 1981-1990 and 1991-2000, respectively. The mean temperature in the past 40 years increased 0.7 ℃ and generally shows a linear increase.

The ability to respond to climate change was quite different for different types of glaciers.The response of oceanic glaciers to temperature rise is the quickest, then sub-continental glacier, and that of severe-continent glaciers is most slowly with a change rate being only about 1/3 of that of oceanic glaciers (Shi, 2000). The response period of continental glaciers in Tibetan Plateau to temperature change is 10 to 20 years (Su *et al.*, 1999). The change process of glaciers in Alps was very consistent with the temperature fluctuation with eight years lag (Jones and Briffa, 1992). The glaciers in the study area are sub-continental glaciers and the period of response to temperature may be 10 years. From the process of climate change, although the temperature began to increase since the end of the 1970s, the actual steady temperature increase began in the mid-1980s. Although the temperature was relatively low in the beginning of the 1990s, the general trend of temperature change was warming. Up to 1986, the glacier shapes have changed much because the period that temperature began to increase was short. Although the glacier area diminished, that did not change much. However, the glacier shapes changed and diminished quite obviously after the nearly 15-20 years temperature increased to 2000.

4 Conclusion and discussion

Owing to their synoptic, repetitive coverage and up-to-datedness, remote sensing materials become an unprecedentedly powerful and efficient media. Detecting the change of glaciers must eliminate accurately the effect of seasonal snow, which may be still obvious even if we used the images before the fresh snow fell down in autumn. Since the elevation of the glacier margin was lower and was affected less by seasonal snow generally, it is easy to detect the frequent change of glacier tongues. Thus, the detailed temporal dynamics of glacier change can be obtained based on multi-stage glacier marginal location. The few images, which were not affected by seasonal snow, can give detailed spatial distribution information of glaciers. It is a practical method to get detailed and accurate information of glacier dynamics using both glacier margin and area change detection based on a long series of remote sensing data.

From 1963 to 2000, all the eight glaciers except for one retreated over 70 m and the retreating velocity was generally 5 m/a, but the glacier change varied greatly in different stages. From 1963 to 1977, four of the eight glaciers advanced, two of them retreated and another two kept stable, the glacier advanced generally. From 1977 to 1986, four of the eight glaciers retreated and the others kept stable. The retreating velocity was 10-30 m/a. However, the retreated glaciers were those advanced from 1963 to 1977. This showed that glacier retreat became obvious but not very great. From 1986 to 2000, seven of the eight glaciers retreated and only one glacier kept stable, the retreating velocity was 10-15 m/a. This showed that the glacier retreat in this period became very fast and universal. From 1963 to 2000, the area of glacial snow decreased from 5479.0 ha to 4795.4 ha, up to 12.5%. It is alarming that most of the glacier decrease retreats happened from 1986 to 2000.

Temperature change is the direct cause for glacier change. Although temperature began to increase since the end of the 1970s, the actual steady temperature increase began in the mid-1980s. Although the temperature was relatively low at the beginning of the 1990s, the general trend of temperature change was warming. Up to 1986, the glacier shapes have not changed much because the period for temperature increase was short. Although the glacier area diminished, that did not change much. Up to 2000, the glacier shapes have changed and diminished quite obviously after the nearly 15-20 years temperature increase.

References

Bayer K J, Hall D K, Kovalick W M. Observations on glaciers in the eastern Austrian Alps using satellite data. *International Journal of Remote Sensing*, 1994, 15(9): 1733-1742.

Bishop M P, Shroder Jr J F, Hickman B. SPOT panchromatic imagery and neural networks for information extraction in a complex mountain environment. *Geocarto International*, 1999, 14(2): 17-26.

Chen Jianmin, Liu Chaohai, Jin Mingxie, 1996. Application of the repeated aerial photogrammetry to monitoring glacier variation in the drainage area of the Urumqi River. *Journal of Glaciology and Geocryology*, 18 (4): 331-336. (in Chinese)

Hall D K, Benson C S, Field W O. Changes of glaciers in Glacier Bay Alaska, using ground and satellite measurements. *Physical Geography*, 1995, 16(1): 27-41.

Jones P D, Briffa K R, 1992. Global surface air temperature variation over the twentieth century (part 1). *Holocene*, 254: 698-700.

Klein A G, Isacks B L. Spectral mixture analysis of Landsat thematic mapper images applied to the detection of the transient snowline on tropical Andean glaciers. *Global and Planetary Change*, 1999, 22: 139-154.

Lanzhou Institute of Glaciology and Geocryology (LIGG), CAS. China Glacier Inventory III, Tianshan Mountains, Southwest of Tarim River Inner Basin. Beijing: Science Press, 1987. (in Chinese)

Li Zhen, Sun Wenxin, Zeng Qunzhu, 1999. Deriving glacier change information on the Xizang (Tibetan) Plateau by integrating RS and GIS techniques. *Acta Geographica Sinica*, 54(3): 263-268. (in Chinese)

Li Zhongqin, Han Tianding, Jing Zhefan *et al.*, 2003. A summary of 40-years observed variation facts of climate and glacier No.1 at head water of Urumuqi River, Tianshan, China. *Journal of Glaciology and Geocryology*, 25 (2): 117-123. (in Chinese)

Liu Haichao, Xie Zichu, 1998. Glacial Activity in Tianshan Mountains. Beijing: Science Press, 1998. (in Chinese)

Liu Shiyin, Lu Anxin, Ding Yongjian *et al.*, 2002. Glacier fluctuations and the inferred climate changes in the A'Nyemaqen Mountains in the source area of Yellow River. *Journal of Glaciology and Geocryology*, 24 (6): 701-707. (in Chinese)

Liu Shiyin, Shen Yongping, Sun Wenxin *et al.*, 2002. Glacier variation since the maximum of the Little Ice Age in the Western Qilian Mountains, Northwest China. *Journal of Glaciology and Geocryology*, 24 (3): 227-233. (in Chinese)

Lu Anxin, Yao Tandong, Liu Shiyin *et al.*, 2002. Glacier change in the Geladandong area of the Tibetan Plateau monitored by remote sensing. *Journal of Glaciology and Geocryology*, 24(5): 559-562. (in Chinese)

Mennis J L, Fountian A G, 2001. A spatial-temporal GIS database for monitoring alpine glacier change. *Photogrametric Engineering & Remote Sensing*, 67(8): 967-975.

Paul F, 2002. Changes in glacier in Tyrol, Austria, between 1969 and 1992 derived from Landsat 5 Thematic Mapper and Austrian Glacier Inventory data. *International Journal of Remote Sensing*, 23(4): 787-799.

Shi Yafeng, 2000. Glaciers and Their Environments in China: The Present, Past and Future. Beijing: Science Press, 365-366. (in Chinese)

Su Zhen, Liu Zongxiang, Wang Wenti *et al.*, 1999. Glacier fluctuations responding to climate change and forecast of its tendency over the Qinghai-Tibet Plateau. *Advance in Earth Sciences*, 14(6): 607-612. (in Chinese)

Williams R S, Hall D K, Sigurddson O *et al.*, 1997. Comparison of satellite-derived with ground-based measurement of the fluctuations of the margins of Vatnajökull, Iceland, 1973-1992. *Annals of Glaciology*, 24: 72-80.