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The Glacier Area Changes in the Qangtang Plateau Based on the Multi-temporal Grid Method and its Sensitivity to Climate Change

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Abstract: Glacier area changes in the Qangtang Plateau are analyzed during 1970-2000 using air photos, relevant photogrammetric maps and satellite images based on the multi-temporal grid method. The results indicate that the melting of glaciers accelerated, only a few of glaciers in an advancing state during 1970-2000 in the whole Qangtang Plateau. However, the glaciers seemed still more stable in the study area than in most areas of western China. We estimate that glacier retreat was likely due to air temperature warming during 1970-2000 in the Qangtang Plateau. Furthermore, the functional model of glacier system is applied to study climate sensitivity of glacier area changes, which indicates that glacier lifespan mainly depends on the heating rate, secondly the precipitation, and precipitation increasing can slow down glacier retreat and make glacier lifespan prolonged.

Keywords: The Qangtang Plateau; Glacier change; Multi-temporal; Climate change; Functional model of glacier system; Simulation

Introduction

The mountain glaciers are considered as the wonderful proxy indicator to reflect climate change owing to their sensitivity to climate change. The Tibetan Plateau, also called the world's 'Third Pole', is the most glaciated mountain region in the middle and low latitude area of the world. Glaciers on the Tibetan Plateau play an important role in the Earth's climate system (Owen et al. 2008). Nevertheless, since the Little Ice Age (LIA), especially in the 20th century, the full-scale retreat of glaciers occurred in the Tibetan Plateau. Under the impact of climatic warming, the glaciers in the High Asia in China have been retreating continuously with negative glacial mass balance in recent several decades (Yao et al. 2004). Since the Maxima of the Little Ice Age (the 17th century), air temperature has risen at a magnitude of 1.3°C on average and the glacier area decreased corresponds to 20% of the present total glacier area in western China (Shi and Liu 2000). The glaciers in Mt. Qomolangma has retreated 170-270 m, equivalent to a retreat speed of 5.5-8.7 m/a during 1966-1997 and 6.4 m/a in Mt. Xixiabangma since the 1980s (Ren et al. 2004). In the Geladandong mountain region, the total glacier area has decreased from 889 km^2 in 1969 to 847 km^2 in 2002, an average of 1.29 km^2 /a (Ye et al. 2006). Compared with other areas of western China, the least change of glaciers since LIA happened in the Qangtang Plateau, the

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main part of the Tibetan Plateau, the retreating rate of only 7% (Qin et al. 2002; Li et al. 2009). However, in the Qangtang Plateau, it is scarce of systematic observation data and related records about local glacier changes until now due to poor natural conditions and inconvenient transportation.

Multi-temporal satellite image analysis is an important tool for monitoring the position of glacier front and its area variations (Hall et al. 2003; Kulkarni et al. 2011; Williams et al. 1997), and also gradually used to analyze glacier resource and its dynamic measuring in the Tibetan Plateau since the mid 20th century (Li et al. 1998; Wu and Zhu 2008; Kulkarni and Bahuguna 2002). In this paper, we discuss firstly glacier area changes in the Qangtang Plateau during 1970-2000 using satellite images based on the multi-temporal grid method. Secondly we analyzed the response of glacier to climate change during 1970-2000. Finally the climate sensitivity of glacier area changes in the 21 century is simulated in the Qangtang Plateau in terms of the functional model of glacier system.

1 Background

The Qangtang Plateau ranges from the south of the Kunlun Mountain to the north of the Gangdisê Mountain and from the east of the Karakorum Mountain to the west of the Tanghla Mountain (Figure 1). It is divided into Northern Qangtang Plateau and Southern Qangtang Plateau

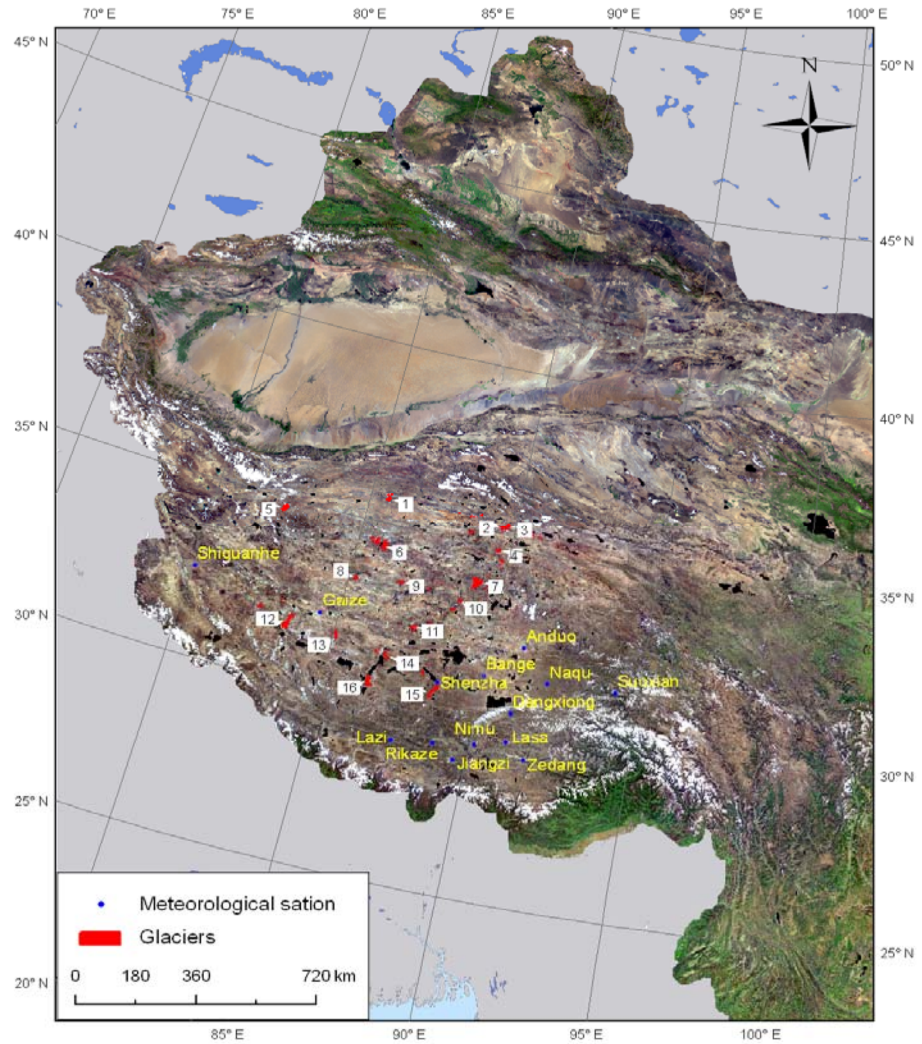

Figure 1 Sketch map of glacier distribution in the Qangtang Plateau (1 Songzhiling; 2 Gangzhari; 3 Jinyanggangri; 4 Ganggairi; 5 Tuzegangri; 6 Zangsergangri; 7 Puruogangri; 8 Duguer; 9 Mayigangri; 10 Xiyaergang; 11 Mugagebo; 12 Longger; 13 Xiakangjian; 14 Qingpagonglong; 15 Shenzhajiegang; 16 Bobogawu)

by Heihe-Ali Highway. The development of glaciers mainly depends on the factors including climate, surface relief and topography (Jiao and Zhang 1988a). The Qangtang Plateau is situated in hinterland of the Qinghai-Tibet Plateau and separated by surrounding high mountains with rare precipitation. In addition, the plateau face in latter tertiary was lifted by the strong tectonic movements， low relative altitude difference and few mountains of more than 7000 meters. On account of EW and NS major dislocations, NWW and NEE oblique crossing dislocations arising from many later-Cenozoic tectonic movements, the glaciers are heavy fragmentation distribution surrounding the high summits or large mountains, mainly ice-capped type and flat-topped type. The Glacier groups including Tuzegangri, Zangsergangri, Ser'ugangri, Puruogangri in the Qangtang Plateau are roughly in East-West direction, the largest ice-cap distribution area of the Northern Tibetan Plateau, about 40% of the whole glacier coverage in the Qangtang Plateau (Li et al. 1986). The Puruogangri is not only the biggest ice-cap in the Qangtang Plateau, but also is the biggest ice field in the Qinghai-Tibet Plateau (Shi et al. 2005, Yi et al. 2002).

Glacier area of different mountains in the Qangtang Plateau is illustrated in Table 3 (see 3.1 Changes of glacier in 1970-2000). In 2000 there are about 1006 glaciers covering nearly 1985.112 km^2 in the whole study area, which is least among the mountain systems of the Qinghai-Tibet Plateau due to those factors limiting the development of quaternary glaciers. The number of glaciers in the Northern and Southern Qangtang Plateau are 490 and 516, with the area of 1508.079 km^2 and 477.034 km^2, which accounts for 75.97％ and 24.03％ in total glaciers area, respectively.

2 Data Processing and Methods

2.1 Data sources

We use the 40 topographic maps of 1:100,000 in 1970/1971(unified to 1970), and two periods' orthorectified Landsat images (L1G) from the Global Land Cover Facility (GLCF: http://www.landcover.org) (Landsat TM in 1990±2 (unified to 1990), ETM+ in 2000±2 (unified to 2000)，see Table 1) to map the glacier extents in the Qangtang Plateau. As a result of the abominable natural environment and special traffic condition, the climatic records during 1970-2000 from only 14 meteorological stations of Shiquanhe, Gaize, Bange, Anduo, Naqu, Shenzha, Dangxiong, Lazi, Rikaze, Nimu, Lasa, Zedang, Jiangzi and Suoxian (Figure 1) are used for analyzing climate change in the region.

2.2 Data processing

The satellite images are orthorectified using a first-order polynomial technique to eliminate perspective distortion and displacement. The reported positional accuracy of the orthorectified TM /ETM+ data is with an RMSE(residual root mean square error) less than 50m (Tucker et al. 2004). In order to register Landsat images, we select the 1:100000 topographic maps as baseline. 40 ground control points (GCPs) are located on

Table 1 The remote sensing data used in the study area

Path/Row	TM yyyy-mm-dd	ETM+ yyyy-mm-dd	Path/Row	TM yyyy-mm-dd	ETM+ yyyy-mm-dd
139/35	1989-11-02	2000-10-17	141/38	1990-11-03	2001-09-22
139/36	1994-12-18	2001-09-24	141/39	1990-11-03	2001-09-22
139/37	1990-05-29	2000-10-07	142/35	1990-11-10	2001-07-11
139/39	1989-11-10	2000-11-08	142/36	1990-11-10	2002-05-27
140/35	1990-11-12	1999-08-25	142/37	1989-10-22	2000-10-28
140/36	1992-09-30	1999-08-25	142/38	1990-11-10	2000-10-28
140/37	1992-09-30	1999-08-25	143/36	1989-10-29	2001-09-20
140/38	1992-09-30	2000-10-30	143/37	1990-11-17	2001-09-20
141/36	1990-11-03	1999-09-17	143/38	1990-11-17	2001-09-20
141/37	1990-11-03	2001-09-22	144/36	1992-10-12	2001-10-13

which both topographic map and each image can be identified. The RMSE of check points is no more than 38.9 m for TM and 35.4 m for ETM+. The data are presented in a Gauss Kruger coordinate system and Krasovsky 1940 spheroid.

The multi-temporal accuracy of glacier front position is determined by the image resolution and coregistration error (Williams et al. 1997, Hall et al. 2003, Silverio and Jaquet 2005), and each position has an uncertainty (U_T) that can be calculated by the following formula (Ye et al. 2006):

$$U_T = \sqrt{\sum_1^n \lambda^2} + \sqrt{\sum_1^n \varepsilon^2} \quad (1)$$

where λ is the original pixel resolution of each image and ε is the registration error of each image to the topographic map. Thus the uncertainty for glacier front was 160.4 m during three periods (1970-1990-2000).

Changes in the areal extent of an individual glacier during three periods are measured with an accuracy of 0.037 km^2, and the following formula (Ye et al. 2006):

$$U_A = 2U_T\sqrt{\sum_1^n \lambda^2} + \sqrt{\sum_1^n \varepsilon^2} \quad (2)$$

2.3 Methods

2.3.1 Glacier changes based on the multi-temporal grid method

The multi-temporal grid method is a typical application of the Geo-information Tupu, which is a kind of methodology developed by Academician Chen Shupeng, supported by technologies such as Remote Sensing (RS), Geographical Information System (GIS), Internet Communication, Virtual Reality and Cartography by computer. Tupu is combination of "carto" of spatial units and "graph" of the beginning and process of events (Chen 1998, Chen et al. 2000). It can be expressed as spatial differences in temporal system and develop data mining methods in spatial differences (Zhou and Li 1998).

The multi-temporal grid method is used for studying glacier changes by means of GIS and RS, which is a combination of geospatial dynamics and temporal analysis based on a grid unit, and the multi-temporal grid unit is a synthesis of glacier characteristies of "Space-Attribute-Process" (Khalsa et al. 2004). The spatial-temporal information of glacier are recorded, transferred, extracted and processed using a regular grid unit with the defined resolution. The attribute of each grid unit assigns a single-digit value representative of surface cover type at sampling time. The specified method is as shown below.

(1) Three stages of glacier vector edges are obtained by manual delineation of 1:100,000 topographic maps (1970) and images (1990 and 2000) in Arc/Info.

(2) Three stages of glacier vector edges above are converted to grid format, and then resampled by grid unit of 28.5 × 28.5 m^2. A classification scheme is used in which glacier area is assigned a single-digit value of 1, and non-glacier area is assigned a single-digit value of 0.

(3) In Arc/Info grid module, the one digit value (i.e. 1, 0) from each grid unit is integrated over time the classification results from the topographic maps (1970) and images (1990 and 2000) by map algebra. A multi-temporal grid with a three-digit value is generated in each grid cell that simulates glacier changes during 1970–2000. This will enable us to track glacier changes both on maps and in tables during the corresponding period. The operational formula is as follows:

$$\text{Glacier\_Qt} = \text{Qt\_1970} \times 100 + \text{Qt\_1990} \times 10 + \text{Qt\_2000} \quad (3)$$

where Glacier_Qt is the multi-temporal grid value of glacier change in the Qangtang Plateau during 1970-2000, Qt _1970, Qt _1990, Qt _2000 are classification results of glacier coverage from the images of 1970, 1990 and 2000, respectively.

(4) The multi-temporal grid value could identify advancing glacier, where the early non-glacier grid unit becomes glacier one later (e.g., 011, 001), and retreating glacier, where the early glacier grid unit becomes non-glacier one later during different periods (e.g., 100, 110). However, instances in which the multi-temporal grid value indicates more rapid changes than usual (e.g., 010, 101 etc.) are considered to be "Noise". These may be caused by false information or changes outside the expected range, such as different data sources or seasonal differences in snow cover in non-glacierized areas (Ye et al. 2006). To correct the misclassified grid units, all glacier changes and identified noises are reclassed both in mapping

(Figure 2) and in quantity (Table 2) by the remap table in the Arc/Info Grid module.

2.3.2 Functional models of glacier systems variation

All glaciers are studied as a whole system by functional models of glacier system variation (Kotlyakov 1988), which is the study of how the change of mass balance affects variations of glacier area, glacier volume, annual glacier discharge runoff and the equilibrium line altitude with the rise of the mean summer temperature, using mass balance of the equilibrium line altitudes at the steady state (ELA_0) and Kotlyakov-krenke's equation (Kotlyakov and Krenke 1982) that relates the annual ablation of glacier to the mean summer temperature. Variations of glacier area, annual glacier discharge runoff and the equilibrium line altitude are respectively available by glacier median area representing glacier area, the equation between area and discharge runoff, and calculating the distribution change of glacier area with altitude of the region. And the mean summer temperature near the equilibrium line is acquired with the vertical lapse rate of summer temperature and jerking value of temperature under the influence of

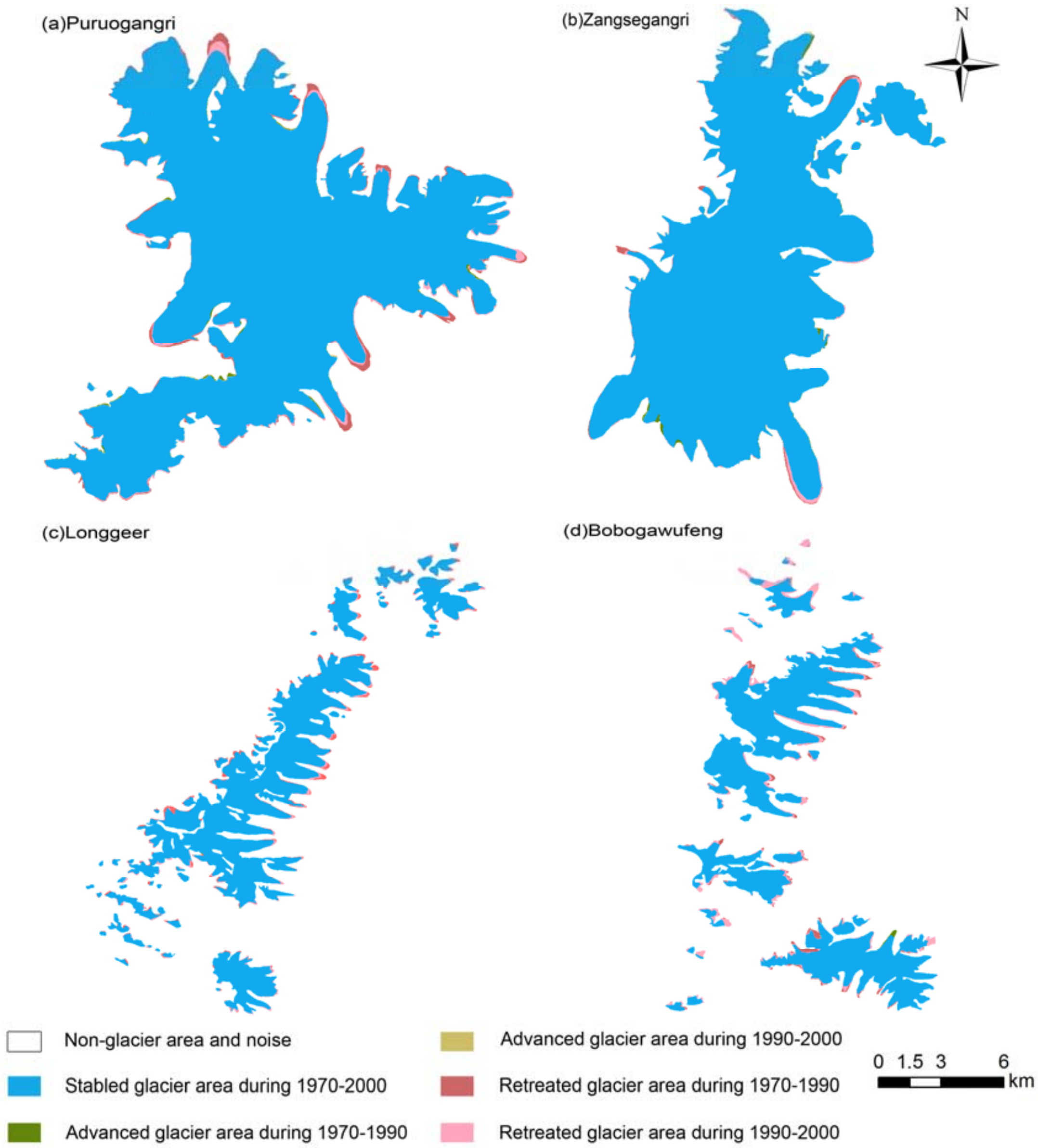

Figure 2 Glacier area changes during 1970-2000

Table 2 The remap table of the multi-temporal grid (MTG) of glacier changes process during 1970-2000 in the Qangtang Plateau

MTG	Recode	Glacier changes (km²)	Category of variation
000, 010, 101	0	419950.331	Non-glacier area and noise
111	1	1972.087	Stabled glacier area during 1970-2000
011	2	12.600	Advanced glacier area during 1970-1990
001	3	0.425	Advanced glacier area during 1990-2000
100	4	62.440	Retreated glacier area during 1970-1990
110	5	40.709	Retreated glacier area during 1990-2000

glacier surface cooling. Here, the vertical lapse rate of temperature in summer is 0.57 °C/100 m (Du et al. 2007).

On the basis of the structure of glacier system and the nature of the equilibrium line altitudes at the steady state (ELA_0), the functional models of glacier system to climate variation were established, and the details of these models can be referenced by others (Wang et al. 2005; Wang et al. 2008; Xie et al. 2002; Xie et al. 2007). The effect of both decreasing air temperature due to rising of ELA_0 and reduction of glacial area and precipitation rising rate due to climate warming were considered in these models simultaneously. The model is used to simulate directly the variation of glacier system responding to future climate change in the Qangtang Plateau.

3 Results and Discussion

3.1 Changes of glacier in 1970-2000

In the Qangtang Plateau, the glacier area in 1970 are respectively 2075.236 km² and 2070.45 km² by the multi-temporal grid method and glacier inventories (Jiao and Zhang 1988a; Jiao and Zhang 1988b; Yang and An 1988; Zhang and Jiao 1988a; Zhang and Jiao 1988b), with relative inconsistencies of 0.04% and 0.28% in comparison with glacier area of 2076.15km² by manual delineation. There are inconsistencies in the methodologies used to document and analyze glacier areas in previous inventories. The multi-temporal grid method could differentiate well between real glacier changes and noises during the observation based on characteristics of glacier dynamics (Ye et al. 2009). This study takes glacier area by the multi-temporal grid method as basis.

The number of glaciers in the study area was 1006 in which had both advanced and retreated ones , glacier retreat of 78.43% during 1970–2000, and the retreating glaciers was much larger than advancing ones (Table 2). The advancing and retreating glaciers area account for 0.63% and 4.97% in total glaciers area in 1970, respectively. Thus it can be seen, retreating glaciers were dominant, but a few of them were in an advancing state. After expansion of advancing glaciers offset reduction of retreating glaciers mutually, the whole glaciers were still in a shrinking state in the Qangtang Plateau, which agrees with climate warming and increasing melt of the glaciers in the region.

The results of glacier changes in the Qangtang Plateau during 1970–2000 by the multi-temporal grid method are shown in Table 3. The analysis indicates that the glaciers had decreased by a rate of 0.145%/a from 2075.236 km² to 1985.112 km² with an annual recession area of 3.004 km² during 1970–2000, by a rate of 0.120%/a from 2075.236 km² to 2025.397 km² with an annual recession area of 2.492 km² during 1970–1990, and by a rate of 0.199%/a from 2025.397 km² to 1985.112 km² with an annual recession area of 4.028 km² during 1990–2000, respectively. Accelerated recession of glacier area is clearly apparent. According to the annual percentage of area changes (APAC) in different regions, glaciers could be classified into three groups: class A (APAC≤0.1%/a), class B (0.1%/a<APAC≤0.2%/a), and class C (APAC> 0.2%/a) (Ding et al. 2006). Glaciers in the study area belonged to class B, and were still more stable than in most areas of western China. Researchers also found that the mass balance was negative in most of glaciers on the High Asia, which in the Qangtang Plateau was positive or between positive and negative from 1980s to early 1990s, within a small range of glaciers variation (Xie and Ding 1996; Su et al. 1999; Pu et al. 2002).

Table 3 Glacier area changes during 1970-2000 in the Qangtang Plateau

Region	Area (km²)			APAC (%/a)		
	1970	1990	2000	1970-1990	1990-2000	1970-2000
The Qangtang Plateau	2075.236	2025.397	1985.112	-0.12	-0.199	-0.145
Northern Qangtang Plateau	1553.923	1525.696	1508.079	-0.091	-0.115	-0.098
Hoh Xil	285.59	282.241	278.633	-0.059	-0.128	-0.081
Dongbule	83.469	78.671	77.658	-0.287	-0.129	-0.235
T-Z-P	980.457	969.048	960.203	-0.058	-0.091	-0.069
Puruogangri Ice field	429.212	420.758	414.852	-0.098	-0.140	-0.112
Mugagebo-gangribolu	77.021	71.624	70.296	-0.350	-0.185	-0.291
Duguer-Xiyaer	127.386	124.113	121.289	-0.128	-0.227	-0.160
Southern Qangtang Plateau	521.313	499.700	477.034	-0.207	-0.454	-0.289
Longger	229.280	218.762	212.172	-0.229	-0.301	-0.253
Xiakangjian	57.602	56.588	55.869	-0.088	-0.127	-0.100
Shenzhajiegang	103.487	97.631	93.651	-0.283	-0.408	-0.325
Qingpagonglong	32.666	30.837	27.427	-0.280	-1.106	-0.555
Bobogawufeng	98.277	95.882	87.915	-0.122	-0.831	-0.351

Abbreviation Used: APAC= the annual percentage of area changes, T-Z-P= Tuzegangri-Zangsergangri-Puruogangri

APAC in the Northern and Southern Qangtang Plateau were 0.098%/a and 0.289%/a during 1970–2000, respectively. According to glacier classification (Ding et al. 2006), the Northern Qangtang Plateau belonged to class A, whereas the Southern Qangtang Plateau belonged to class C. APAC in the Northern and Southern Qangtang Plateau were 0.091%/a and 0.207%/a during 1970–1990, and 0.115%/a and 0.454%/a during 1990–2000, respectively. The numerical results above show that the glacier area in the Northern Qangtang Plateau was much larger than in the Southern Qangtang Plateau, yet variation range in the former was much smaller than in the latter. Consequently the whole variation trend was increasing from north to south, glacier changes in the study area happened primarily in the Southern Qangtang Plateau, and glaciers in the Northern Qangtang Plateau was more stable, which was supported by the works of other researches (Kulkarni and Bahuguna 2002; Kääb et al. 2002), that is, smaller glacier is normally more sensitive to climate change than larger glaciers.

Meanwhile, except for in Dongbule and Mugagebo-gangribolu, glacier retreat in other sites accelerated during 1970–2000 and APAC was much smaller in Puruogangri than in the whole Qangtang Plateau. Therefore, although the Puruogangri ice field showed an accelerating retreat trend, it was relatively stable as compared with other glaciers during 1970–2000. The validity of our estimates is also confirmed by ground observation from glaciologists. The glacier in the west of the Puruogangri Ice Field retreated by 40-50 m with an average rate of 2 m/a from the 1970s to the end of the 1990s and retreated by 4-5 m from September 1999 to October 2000, showing a shrinking trend, but relatively stable as compared with other glaciers (Pu et al. 2002). Glacier changes differed during different periods and mountains in the study area. For instance, during 1970–1990, the greatest variation among the Northern Qangtang Plateau occurred in Mugageb-gangribolu with APAC of 0.350%/a, and among the Southern Qangtang Plateau occurred in Shenzhajiegang with APAC of 0.283%/a. During 1990–2000, the greatest variation among the former occurred in Duguer-xiyaer with APAC of 0.227%/a, and among the latter occurred in Qingpagonglong with APAC of 1.106%/a. However, no matter what period it was, the variation range was lowest in Tuzegangri-zangsegangri-puruogangri where glaciers were the stablest in the whole Qangtang Plateau.

3.2 Response of glaciers to climate change

In light of the time evolution of the averaged temperature change over China relative to years (1961 to 1990) of the SRES simulations A2 and B2 (Xu and Gao 2007), it will be in periodically persistent temperature rise in future. Furthermore, although the temperature rise plays a predominant part in glacier changes, the influence of precipitation should not be allowed to neglect (Anderson et al. 2010; Daniel et al. 2008). So this paper follows the climatic scenarios with the linear warming, the linear warming and precipitation increasing, periodical warming, and periodical warming and precipitation increasing (Li and Xie 2008), on the assumption of precipitation rising rate of 10%/K (Oerlemans et al. 1998), temperature rising rate of 0.01 K/a and 0.03K/a (Wang et al. 2005; Wang et al. 2008; Xie et al. 2007), and the range of temperature fluctuation of 1K and 3K.

Input parameters for glacier system variation against the coming year in the Qangtang Plateau are available on the basis of glacier inventories of China and mean summer temperature during 1960s and 1980s near meteorological stations provided by meteorological database of Chinese Academy of Sciences (Table 4). In this paper, simulating glacier changes is dated from 1970 in consideration of both glacier inventories of China and glacier changes of multi-temporal grid method from 1970. The mean summer temperature ($\overline{t_s}$) near the equilibrium line in the coming year is procured by the method as bellow. Firstly the mean summer temperature in 4500 m is figured out on the foundation of altitude and mean summer temperature in each observation station and the vertical lapse rate of summer temperature in the Tibetan Plateau. In ArcInfo, the contour of mean summer temperature is acquired with the mean summer temperature in 4500 m by Kriging method. It is by arithmetic mean value of longitude and latitude of those glaciers with accurate geographical location that the point is identified as measuring one in the Qangtang Plateau, and then figure out the mean summer temperature in 4500m of the measuring point. Finally, mean summer temperature ($\overline{t_s}$) near the equilibrium line in the coming year is acquired with the vertical lapse rate of temperature and jerking value of temperature under the influence of glacier surface cooling in the measuring point (Xie et al. 2007).

The parameters above are input as initial value into the functional model of glacier system variation, and then the calculated values are iterated annually as the next year' initial ones for simulating the glacier system' variation responding to climate change in the Qangtang Plateau.

Table 4 Input parameters for glacier systems variation against the coming year in the Qangtang Plateau

S_0 (km²)	V_0 (km³)	S_{med} (km²)	$\overline{ELA_0}$ (m)	AAR	$\overline{t_s}$ (°C)	a_0 (m)	W_0 (km³)
2070.45	188.431	7.7	5815.25	0.5794	0.21	0.91	1.87811

Note: S_0 = glacier area, V_0 = glacier volume, S_{med} = glacier median area, $\overline{ELA_0}$ = equilibrium line altitude in the coming year; AAR=accumulation area ratio, $\overline{t_s}$ =mean summer temperature near the equilibrium line, a_0 = annual ablation near the equilibrium line, W_0 = annual glacier discharge runoff.

Table 5 The variation simulation of glacier area in the Qangtang Plateau under different situations during 1970~2000

CS	Temperature rising rate	Area (km²)			APAC(%/a)		
		1970	1990	2000	1970-1990	1990-2000	1970-2000
L	0.01k/a	2070.45	2038.93	2019.99	-0.076	-0.093	-0.081
	0.03k/a	2070.45	2019.52	1979.22	-0.123	-0.200	-0.147
P	0.01k/a	2070.45	1983.41	2005.64	-4.388	1.121	-0.104
	0.03k/a	2070.45	1963.79	1964.20	-5.152	0.021	-0.171
L+P	0.01k/a	2070.45	2068.09	2059.91	-0.114	-0.396	-0.509
	0.03k/a	2070.45	2047.65	2017.31	-1.101	-1.482	-0.086
P+P	0.01k/a	2070.45	2010.30	2047.48	-2.905	1.849	-0.037
	0.03k/a	2070.45	1989.84	2003.60	-3.893	-0.692	-0.108

Abbreviation Used: CS= Climatic scenarios, L= Linear warming, P= Periodical warming, L+P= Linear warming and precipitation increasing, P+P= Periodical warming and precipitation increasing

Simulated results of glacier changes during 1970–2000 in the Qangtang Plateau are shown in Table 5, with the range of temperature fluctuation (ΔT) of 1K under periodical warming, periodical warming and precipitation increasing, and the temperature circle (ω) of 0.157 rad/a. When we compared the actual results (Table 3) with the simulated results (Table 5) of glacier changes in the Qangtang Plateau, the linear warming with the temperature rising rate of 0.03K/a is much more logical with the actual situation of glacier changes than other scenarios. Under the linear warming with the temperature rising rate of 0.03K/a and actual results, the glacier area had decreased by a rate of 0.147%/a from 2070.45 km² to 1979.22 km² with an annual recession area of 3.041 km² and by a rate of 0.145%/a from 2075.236 km² to 1985.112 km² with an annual recession area of 3.004 km² during 1970–2000, by a rate of 0.123%/a from 2070.45 km² to 2019.52 km² with an annual recession area of 2.546 km² and by a rate of 0.120%/a from 2075.236 km² to 2025.397 km² with an annual recession area of 2.492 km² during 1970–1990, and by a rate of 0.200%/a from 2019.52 km² to 1979.22 km² with an annual recession area of 4.030 km² and by a rate of 0.199%/a from 2025.397 km² to 1985.112 km² with an annual recession area of 4.028 km² during 1990–2000 respectively. This also shows the model of glacier system responding to climate change is feasible.

In various meteorological elements, temperature and precipitation have close relationship with glacier changes. Precipitation is the major factor in determining glacier accumulation, and temperature is also major factor in determining glacier ablation. Thereby, the changes of temperature and precipitation nearby 14 meteorological stations during 1970–2000 are respectively analyzed (see Figure 1) in order to understand exactly the response of glaciers to climate change.

Here, we define warm season as the mean monthly temperature ≥0°C, that is, from April to October. The cold season is defined as the mean monthly temperature <0°C, from November to next March. Changes in the annual mean temperature, the average temperatures in warm and cold seasons are obtained by moving mean method (Figure 3). According to Figure 3, the annual average temperature fluctuated upward during 1970–2000, which is consistent with the air temperature rising trend during 1971–2000 in the Qinghai-Tibet Plateau (Wu et al. 2007). The increase of the average temperature in warm season will obviously accelerate the glacier melting, while the increase of the average temperature in cold season shortens the shift time that the glacier varies from accumulation to melt, and protracts ablation period (Liu et al. 1999). Therefore, not only the increase of temperature in warm season led to quickening glacier ablation, but also the increase of the temperature in cold season protracted the ablation period, and accelerated glacier shrinking in the Qangtang Plateau.

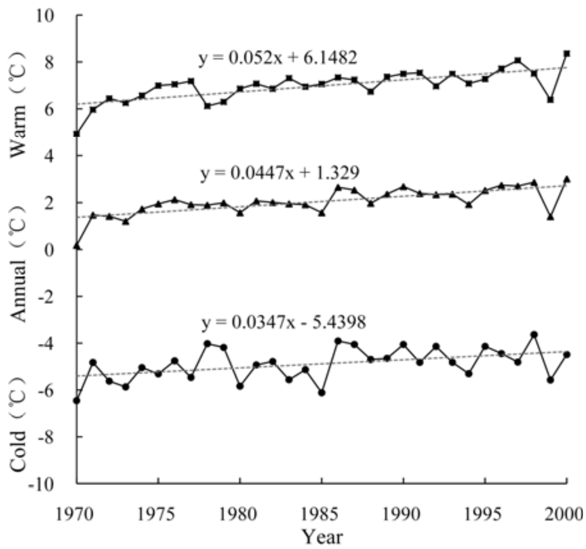

Figure 3 Interannual changes of annual average temperature and average temperature in cold and warm seasons

Based on spatial and temporal distributions of precipitation at 14 stations, we find that three lines of slide were ascending with a fluctuating trend, and precipitation in summer took up most of the total annual precipitation, and increase or decrease of precipitation mainly happened in July and August (Figure 4). During 1971–2000 the precipitation also presented an increasing trend in the Qinghai-Tibet Plateau (Wu et al. 2007). The precipitation increasing can cause more glacier accumulation, and make glacier thicken or advance. Therefore, the increase of precipitation during 1970–2000 helped to increase glacier accumulation in the Qangtang Plateau.

The analysis results of glacier changes indicate that glacier melting and shrinking occurred in the

Qangtang Plateau unceasingly during 1970-2000. Comparing figure 3 with figure 4, we can see precipitation increased with obvious trend, but strong warming played the leading roles in accelerated melting of glaciers during 1970–2000. Consequently, we consider it likely that glacier retreat was ascribed to climate warming, which conforms to the research that even a significant increase in precipitation cannot compensate for increased melting if the summer temperatures are high (Oerlemans and Fortuin 1992).

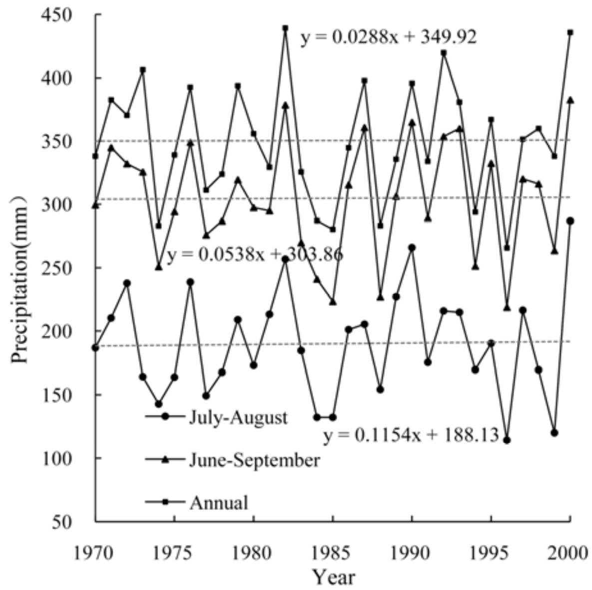

Figure 4 Interannual changes of the precipitation

3.3 Simulation of glacier variations in the 21th century

In order to understand climate sensitivity of glacier area changes in the 21 century, the changing rates of glacier area ($\Delta S/S_0$), volume ($\Delta V/V_0$), discharge runoff ($\Delta W/W_0$) and the rise of ELA_0 (ΔELA_0) are acquired by simulating with the range of temperature fluctuation (ΔT) of 1K under periodical warming, periodical warming and precipitation increasing, the temperature circle (ω) of 0.157 rad/a. Taking the temperature rising rate of 0.03K/a as an example, under the climatic scenarios with the linear warming, the linear warming and precipitation increasing, periodical warming, and periodical warming and precipitation increasing, by the end of the 21th century, glacier area will reduce to 44.24%, 39.57%, 45.08% and 40.33%, glacier volume will reduce to 59%, 53%, 61% and 55%, glacier discharge runoff increasing rate will be 20.52%, 31.41%, 46.63% and 60.27%, the ELA_0 will rise by 172.81 m, 168.26 m, 173.82 m and 168.91 m, respectively.

Figure 5 shows the simulated results under different scenarios with temperature rising rate of 0.01 K/a in the Qangtang Plateau in the 21 century. These scenarios indicate that the overall variation trend of glacier system in the Qangtang Plateau is uniform under different scenarios, and glacier lifespan mainly depends on the heating rate ($\overline{v}$), secondly the precipitation, but does not matter much with the pattern of temperature fluctuation (linear/periodical), and the pattern of temperature fluctuation only affects the specific process of the glacier systems variation and has little effect on the glacier lifespan. It is also found that precipitation increase can slow down glacier retreat and make glacier lifespan prolonged, because precipitation increase could counteract glacier ablation (Benn and Owen 1998).

4 Conclusion

Based on the above analysis, this paper comes to the conclusions as follows:

(1) A few of glaciers were actually advancing during 1970-2000 in the Qangtang Plateau. However, the glaciers tended to decrease by a rate of 0.145%/a from 1970 to 2000 with an annual recession area of 3.004 km^2 as a whole. The glacier melting accelerated during 1970-2000, but the retreat rate seemed much smaller in the study area than in most areas of western China.

(2) On the basis of the structure of glacier system and the nature of the equilibrium line altitudes at the steady state (ELA_0), the functional model of glacier system is established in order to study climate sensitivity of glacier area changes. The linear warming with temperature rising rate of 0.03K/a is much more logical with the actual situation. By analyzing the changes of temperature and precipitation nearby 14 meteorological stations during 1970-2000, glacier retreat was likely due to air temperature warming during 1970-2000 in the Qangtang Plateau.

(3) The climatic scenarios indicate that glacier lifespan mainly depends on the heating rate and the precipitation, and has little relationship to the

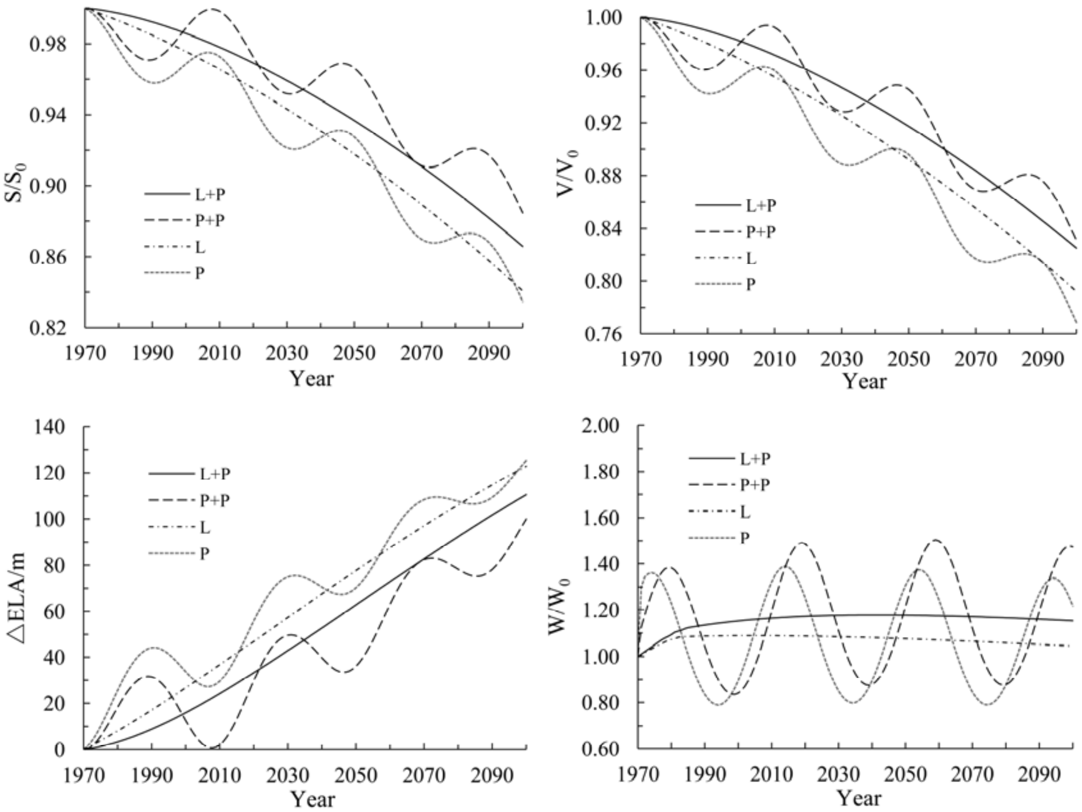

Figure 5 The comparative analysis on the variation simulation of the glacier system in the Qangtang Plateau under different situations in the 21th century. Linear warming (L); Linear warming and precipitation increasing (L+P); Periodical warming (P); Periodical warming and precipitation increasing (P+P).

pattern of temperature fluctuation (linear/ periodical).

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