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Sensitivity analysis of glacier systems to climate warming in China

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Abstract: Data of 44 glacier systems in China used in this paper were obtained from Chinese Glacier Inventories and the meteorological data were got from Meteorological Atlas of Plateau of west China. Based on the statistical analysis and functional model simulation results of the 44 glacier systems in China, the glacier systems were divided into extremely-sensitive glacier system, semi-sensitive glacier system, extremely-steady glacier system and semi-steady glacier system in terms of glacier system's level of water-energy exchange, rising gradient of the equilibrium line altitudes and retreating rate of area to climate warming, their median size and vertical span distribution, and their runoff characteristics to climate warming. Furthermore, the functional model of glacier system to climate warming was applied in this paper to predict the average variation trends of the 4 types of glacier systems, which indicate that different sensitivity types of glacier systems respond to the climate warming differently.

Keywords: glacier system; functional model; response to climate warming; type of sensitivity

1 Introduction

Glacier system is regarded as multi-glaciers sharing the same region, influenced by the similar climate and organized by certain inside laws. It can be divided and sub-divided based on certain physical characteristics, mountain ranges, watershed boundaries and etc. (Kotlyakov *et al*., 1990). Glaciers in China have been dominantly retreating due to climate warming (Liu *et al*., 2002). As a result, many studies were carried out on the glaciers variation response to global warming (Shi *et al*., 2000; Ye *et al*., 2003; Xie *et al*., 2006; Wang *et al*., 2005). The models that can be used for glaciers responding to climate warming could be either used for a single glacier or for a glacier system. Models for the individual glaciers

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mainly involve the glacier melting calculation associated to temperature-index models (Hock, 2003; Brait *et al.*, 2000; Ohmura, 2001), dynamical models (Oerlemans *et al.*, 1998; Ye *et al.*, 2003), energy-balance models (Kang *et al.*, 1994; Oerlemans, 1993), glacier-runoff models and so on. The temperature-index models are established using positive accumulative temperature to calculate melting water of a glacier on the basis of meteorological data. The dynamical models and energy-balance models are both physically based process ones. Glacier-runoff models were set up based on the relationships between climate fluctuation and glacier runoff variation, such as SRM model (Martinec *et al.*, 1986), HYMET mode (Tangborn, 1984) and SHE model (Boggild *et al.*, 1999) and so on.

With the increasing demands of understanding a glacier system variation trend, some models were developed for simulating the glacier systems responding to climate warming, such as sensitivity of the mean specific balance models (Gregory *et al.*, 1998; Zuo *et al.*, 1997; Van de Wal *et al.*, 2001), girding the mass balance at the ELA model (Raper *et al.*, 2006), functional model for glacier systems (Xie *et al.*, 2002) and so on. It is not easy for to obtain the parameters that run the mean specific balance models and girding the mass balance at ELA model. Up to now the above two types of models have not been applied in China. The functional model of glacier system is established on the basis of the structure of glacier system and the nature of the equilibrium line altitudes at the steady state. The model was applied to simulate the glacier systems responding to climate warming in southern Tibet (Xie *et al.*, 2002), as well as the source regions of the Tarim (Wang *et al.*, 2006) and the Yangtze rivers (Wang *et al.*, 2005). It was further generalized to predict the variation trends of glacier systems to climate warming in China and evaluate the glacial runoff in the coming 50 years after some necessary verification work was carried out (Xie *et al.*, 2006a, b).

In this paper, we analyze the characteristics of 44 glacier systems in Chinese Glacier Inventory which were divided by watershed boundaries, apply functional model to simulate the glacier systems to climate warming, summary and classify the 44 glacier systems according to their sensitivities to climate warming, and predict different sensitivity types of glacier systems' variation trends under different climate warming events.

2 Data and method

The original data for the 44 glacier systems were obtained from the Chinese Glacier Inventories, supported by aero-survey photos and the topographic maps at a scale of 1:50,000 or 1:100,000 during the 1960s–1970s (some aero-survey photos of the Yarlung Zangbo River were taken in the early 1980s), and the original meteorological data came from the Meteorological Atlas of Plateau of west China (Lanzhou Institute of Plateau Atmospheric Physics, unpublished data), which were compiled from the high altitude meteorological survey data during the 1960s–1970s. So the two kinds of data can approximately reflect the physical state of glaciers and their meteorological conditions in the same period.

The temperature in west of China will rise at a range of 2.3–4.3℃ higher in 2050 than the average temperature of 1960–1990 (Zhao *et al.*, 2002; Li *et al.*, 1999). According to this prediction result, we make some assumptions about climatic scenarios with possible temperature rising rates of 0.01 K/a, 0.03 K/a and 0.05 K/a until the mid-21st century. We obtained the precipitation increasing rate also guided by Zhao *et al*. (2002) prediction results of about 19%–43% more precipitation in the next 50 years than the average precipitation in 1960–1990. At the same time, we noticed that Oerlemans (1998) committed the similar researches employing the way of every 1℃ higher accompanied by 10% precipitation increment. Furthermore, here we suppose the increasing precipitation is valid to glaciers, i.e., it takes solid form and supplies for glacier effectively both. We take the year 1980 as the original year and calculate the variations characteristics of glacier systems responding to possible climatic scenarios in this century.

The functional model of glacier system to climate warming is employed to analyze the sensitivities of glacier system in China in this paper since it was verified to be reliable and was widely applied in glaciated regions of China (Wang *et al*., 2005, 2006; Xie *et al*., 2006a, b).

3 An introduction to the functional model

3.1 Calculation of mass balance

The elevation of a glacier where the specific net mass balance is equal to mean net mass balance of the glacier is regarded as ELA_0. We suppose that the glacier systems remain steady state in the original year when ELA_0 coincides with ELA_h (Hess, 1904); while climate varies, the ELA_0 undoubtedly changes into ELA_{0i} in a given year i, and the specific net mass balance near ELA_{0i}, $b_n(ELA_{0i})$ is approximately equal to mean net mass balance of glacier, $\overline{b_{ni}}$ (Xie *et al*., 1996):

$$b_n(ELA_{0i}) = \overline{b_{ni}} \tag{1}$$

When summer temperature rises and precipitation increases simultaneously, employing the ablation formula by Kotlyakov *et al*. (1982), the net balance of a glacier, b_{ni}, in a given year i can be expressed as (Wang *et al*., 2005):

$$b_{ni} = 1.33[(9.66 + t_{s0})^{2.85} - (9.66 + t_{s0} + \Delta t_{si})^{2.85}] + \Delta p_i \tag{2}$$

where t_{s0} is the mean summer temperature at the ELA_0 in the original year; Δt_{si} is the increment of mean summer temperature and $\triangle P_i$ is the increment of solid precipitation which can effectively supply for the glacier in the given year i.

Then the ratio between $|b_{ni}|$ and a_0 of a glacier in the given year i, α_i, is:

$$\alpha_i = \frac{|b_{ni}|}{a_0} \tag{3}$$

where a_0 is the ablation of the glacier system in the original year.

3.2 Calculation of glacier runoff and area change for climate warming

When temperature rises accompanied with precipitation increasing, glacier melting will accelerate, negative mass balance will occur (Oerlemans, 1998; Wang *et al*., 2005) and therefore the depth of glacier runoff will increase. On the other hand, the glacier area will decrease for glacier retreating, then the total glacier runoff, w_i, in a given year i will be:

$$w_i = (r_0 + r_{di})(s_0 - s_{di}) \tag{4}$$

where r_0 and s_0 are the runoff depth and area of the glacier in the original year respectively; r_{di} and s_{di} are the increment of runoff depth and the decrement of glacier area due to climate warming in a given year *i* respectively. With temperature continuously rising, glacier runoff firstly increases for the increase of ablation, when it reaches the maximum amount, it will fall back because of the reducing too much glacier area; when it returns to the original amount of the glacial runoff again, we named it restoring original glacier runoff state (Xie *et al.*, 1996); at that time, if evaporation is neglected, we can get $r_0=a_0$, $r_{di}=\left|b_{ni}\right|$ then the decrement of glacier area s_{di} is:

$$s_{di} = \frac{s_0\alpha_i}{\alpha_i + 1} \tag{5}$$

The empirical format about relationship between the glacier area and thickness (Liu *et al.*, 1986) was widely used in Chinese glacier inventories:

$$\overline{h} = 53.21 s_i^{0.3} - 11.32 \tag{6}$$

We employed (6) to work out the time when glacier reaches restoring original glacier runoff state under continuously warming, T_{ei} (Xie *et al.*, 1996):

$$T_{ei} = \frac{1.8(\alpha_i + 1)}{\left|b_{ni}\right|(\alpha_i + 2)} \left\{ 53.21 s_i^{0.3} \left[1 - \left(\frac{1}{\alpha_i + 1} \right)^{1.3} \right] - \frac{11.32\alpha_i}{\alpha_i + 1} \right\} \tag{7}$$

Then the glacier area s_i in a given year *i* is:

$$s_i = s_{i-1} \left[1 - \frac{\alpha_i}{(\alpha_i + 1) T_{ei}} \right] \tag{8}$$

3.3 Calculating runoff of glacier system

What has been discussed above is about the variation laws of an individual glacier runoff. For the sake of calculating the runoff variation of a glacier system, the glacier system's median size (s_{med}) was utilized, which represents the glacier size when the percentage of cumulative glacier area reaching 50% in the glacier system. In a given year *i*, when the s_{medi} of the glacier system reaches T_{ei}, 50% of the glaciers smaller than s_{medi} in the whole system will reach or overpass T_{ei} successively, i.e., their total runoff is less than their original runoff. While the other 50% of the glaciers larger than s_{medi} in the glacier system has not reached T_{ei} i.e., their total runoff is still more than their original runoff; therefore when a glacier system's s_{medi} reaches T_{ei}, the runoff of the whole system is averagely to restore to the level of the original runoff of the whole system. Thus, when it comes to predict the variation of a glacier system, we can use s_{med} to represent the total area of the whole glacier system, and apply the laws mentioned above to reach the goals. If ignoring evaporation, the total runoff of a glacier system, W_i, in a given year *i* is:

$$W_i = \frac{a_i S_i}{1{,}000{,}000} \tag{9}$$

where S_i is the total area of the glacier system in a given year *i*; and the constant of 1,000,000 is involved to convert the criterion of mm to km.

3.4 Calculation of ΔELA_0 of glacier system

In order to compute the rising value of ELA_0 of a glacier system under the condition of climate warming, ΔELA_0, we make use of the altitude structure of the glacier system (Wang *et al*., 2004) to compute the accumulative area rate (AAR). AAR is the indicator of climate and immediate surroundings in a certain glaciated region; it is relatively by far less affected by climatic fluctuation. So when glacier retreating begins with the terminus, ELA_0 will rise simultaneously. The statistic results show that there exist polynomial relationships between ΔELA_{0i} and $\Delta S_i/S$:

$$\Delta ELA_{0i} = \mathrm{C}_1(\Delta S_i/S)^3 + \mathrm{C}_2(\Delta S_i/S)^2 + \mathrm{C}_3(\Delta S_i/S) \tag{10}$$

where $\Delta S_i/S$ is the retreating rate of the glacier system's area; C_1, C_2 and C_3 are empirical coefficients.

4 Sensitivity analysis of glacier system in China

4.1 Sensitivity types of glacier system

Combining the functional model results with the statistic characteristics of the 44 glacier systems in China, the indexes were summarized to rank the sensitivity of the glacier systems to climate warming which include the level of water-heat exchange (a_0), altitude range of glaciation ($\triangle$H, the difference of elevation between the mean highest altitude and the mean lowest altitude where the glaciers are distributed in a glacier system), the glacier area of median size (S_{med}), the rising rate of ELA_0 of a glacier system ($\triangle ELA_0$), the runoff increasing rate of a glacier system ($W_{\max}/W_0$, the ratio between the maximum runoff and original runoff of a glacier system), the area retreating rate of a glacier system (S_i/S_0, the ratio of glacier area in the year of *i* and in the original year), the signal runoff years of a glacier system (T_1 is the year when the runoff of a glacier system reaching its maximum runoff magnitude for climate warming; T_2 is the year when the runoff of a glacier system restoring its original runoff level). All the indexes indicating the sensitivities of glacier system to climate warming are shown in Table 1. According to criterion description of the indexes, we divided the 44 glacier systems in China into 4 types of glacier systems, extremely-sensitive glacier system, semi-sensitive glacier system, semi-steady glacier system and extremely-steady glacier system. The distribution and their amount of the 4 sensitivity types of glacier systems in China are shown in Table 2 and Figure 1.

Table 1 Indexes indicating sensitivities of glacier systems to climate warming

Type of glacier system	Level of water-heat exchange (a_0/mm)	Altitude range of glaciation ($\triangle H$/m)	Area of median size (S_{med}/km^2)	Rate of area retreating (S_i/S_0)	Rising value of ELA ($\triangle ELA_0$/m)	Increasing rate of runoff ($W_{\max}/W_0$)	Signal runoff year (Year)
Extremely-sensitive	1400–2000	600–1600	<1	0–0.1	400–600	1.01–1.15	T_1: 10–30 T_2: 30–50
Semi-sensitive	1000–1400	1500–3600	1–2	0.1–0.3	300–500	1.12–1.30	T_1: 15–30 T_2: 30–80
Semi-steady	600–1000	1800–4100	2–3	0.3–0.5	200–400	1.30–2	T_1: 50–100 T_2: 100–200
Extremely-steady	<600	2000–4900	>3	0.5–0.6	100–300	2–5	T_1: 100–150 T_2: 150–300

Table 2 Distribution of different sensitivity types of glacier systems in China

Type of glacier system	Area (km^2)	Volume (km^3)	Region of distribution
Extremely-sensitive	11559.32	1066.9579	Commonly distributing in low, marginal mountainous area with abundant precipitation, such as the eastern part of Qilian Mountains, southern Altay Mountains, Kaidou-Kongqi River Basin in southwest of Tainshan Mountains, interior drainage area of scattered flow in east and southeast of Tibet, etc.
Semi-sensitive	9363.37	622.7831	Commonly distributing in marginal mountainous area with relatively abundant precipitation but relatively higher altitude than that of the extremely-sensitive glacier systems', such as the middle of Qilian Mountains, Qinghai Lake, the middle part of northern slope of Tianshan, Altay Mountains, Yili River Basin, middle and eastern parts of northern slope of Himalayas, etc.
Semi-steady	19307.31	1846.7450	Mainly distributing in interior high mountains with relatively scarce precipitation, such as the western part of Qilian Mountains, A'nyêmaqên Mountains, Qaidam Basin, Weigan River Basin in southwest of Tianshan Mountains, Karakorum Mountains, Pamirs, upriver regions of Yarlung Zangbo, etc.
Extremely-steady	19170.06	2056.4085	Mainly distributing in the huge and arid mountains of Qinghai-Xizang Plateau and Tianshan, such as the west Kunlun Mountains, interior regions of Tibet, central mountains of Tianshan, east Pamirs, western part of Himalayas, etc.

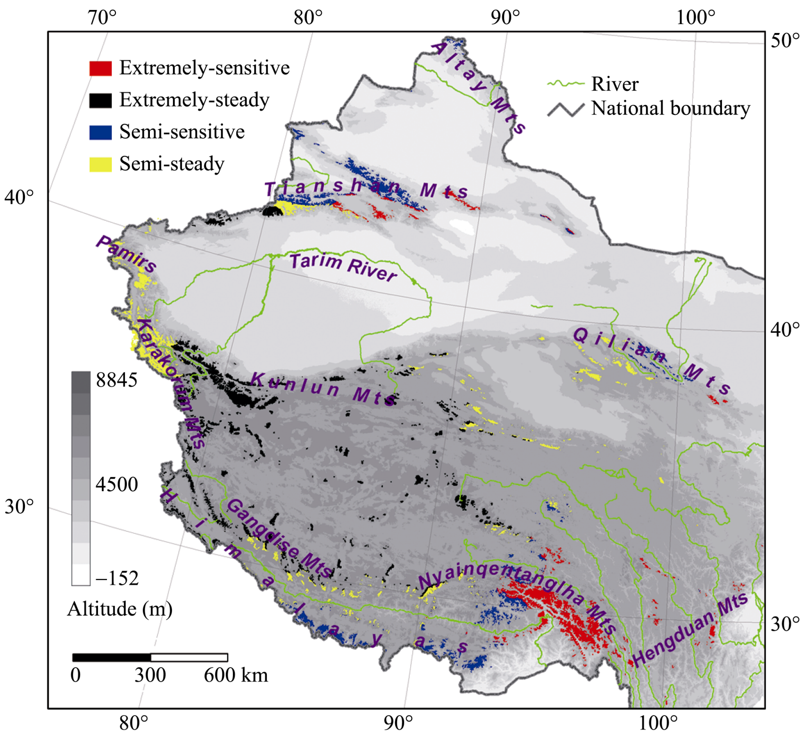

Figure 1 Sensitivity types of glacier systems and their distribution in China
(The altitude based on the SRTM data)

4.2 Variation trends of glacier systems in China to climate warming

Using functional model of glacier system and the data described above, the variation trends of different sensitivity types of glacier systems were shown in Figure 2 which reveals that, under three kinds of possible climate warming scenarios, different sensitivity types of glacier systems respond to climate changing in different ways.

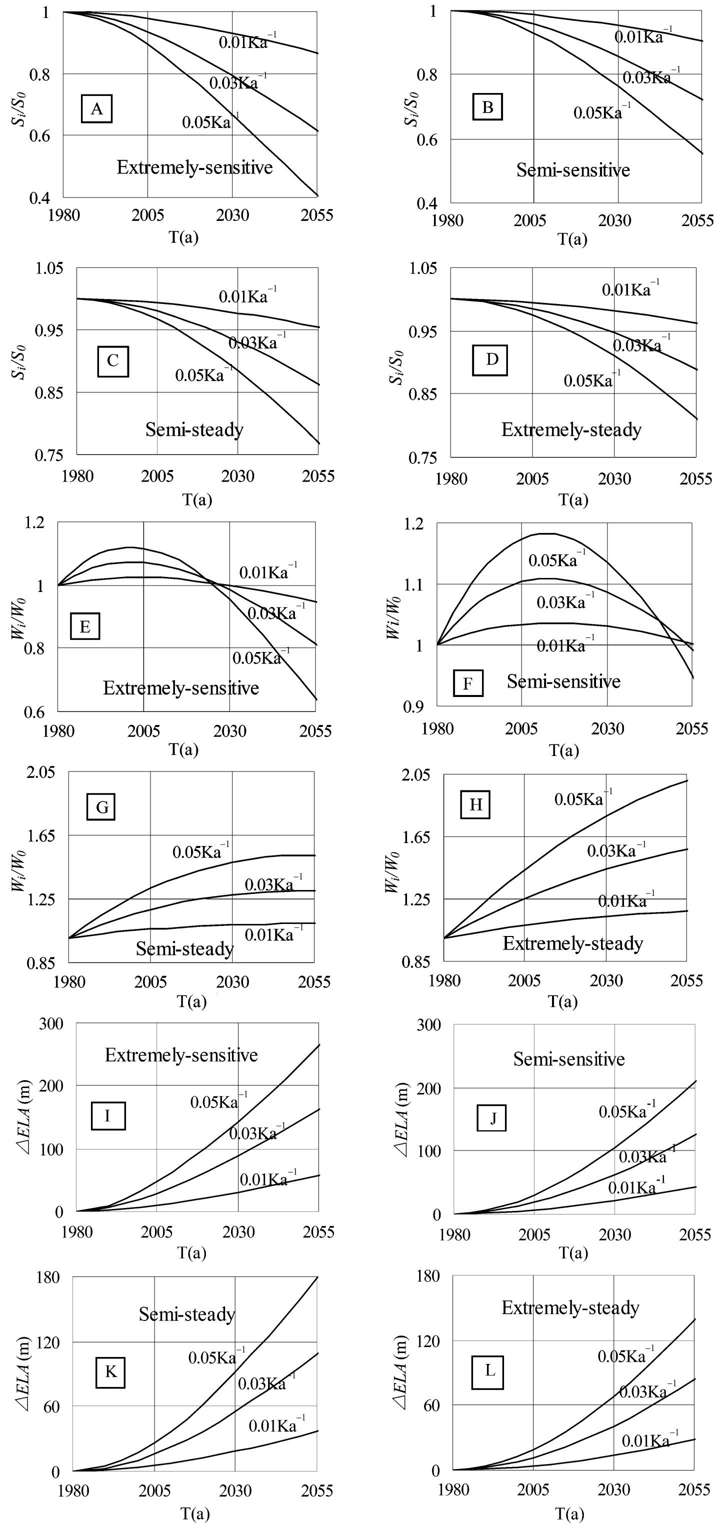

Figure 2 Variation processes of different sensitivity types of glacier systems' area retreating rate (S_i/S_0), A–D, runoff increasing rate (W_i/W_0) E–H, and equilibrium attitude line rising value ($\triangle ELA$), I–L, in China due to possible climate warming scenarios in the mid-21st century

5 Discussion

There are some similarities between the sensitivity glacier types and the water-exchange level glacier types (Shi *et al.*, 1964). Generally speaking, the maritime glacier systems with high water-heat exchange level are more sensitive than the continental glacier systems with low water-heat exchange level to climate changing. Yet, in this paper, the altitude range of glaciation (△H), area of median size (S_{med}), area retreating rate (S_i/S_0), rising value of ELA (△*ELA*), increasing rate of runoff (W_{max}/W_0) and signal runoff years (T_1, T_2) of a glacier system were involved as the indexes to classify the sensitivities of glacier systems to climate changing. Among the indexes, the S_{med} which reflects the individual glacier size characteristics of a glacier system and △H which reflects the vertical survival space of a glacier system play vital roles in the sensitivity classification. For example, the glaciers in north Xinjiang of China are sorted out as semi-continental glaciers; however, they were ranked as semi-sensitive glacier system because of their S_{med} were relatively small (<2 km^2), and some glaciers which survive at the edge of mountains with smaller S_{med} (<1 km^2) and narrow vertical survival space (<1000 m) are ranked as extremely-sensitive glacier system. On the other hand, the maritime glaciers in the middle Yarlung Zangbo are categorized into semi-steady glacier system as a result of large S_{med} (= 3.6 km^2) and wide vertical survival space (△*H* =3940 m) although with high water-exchange level. Recently, the researches on the relationship between glacier retreating rates and glacier sizes support the points of view (Liu *et al.*, 2002; Ye *et al.*, 2003; Su *et al.*, 2000; Wang *et al.*, 2002).

The fluctuation of a glacier system is influenced by many factors such as climatic factors, topographic factors, glacier supplying condition, etc. In many respects, the individual glaciers respond to the climate change inconsistently and the phenomenon is often examined that some of the glaciers remain advancing when most of the glaciers keep in a retreating state in a glacier system (Liu *et al.*, 2002; 2006). Therefore, it is not easy to obtain the average variation trend of a glacier system by knowing the fluctuations of an individual glacier or a few glaciers. And to understand the average variation process of the whole glaciers in a glaciated region, a more appropriate way is to simulate average variation trend of the whole glacier system. The functional model was established to simulate the average variation trend of a glacier system by averaging its parameters to minimize the roles of some special glaciers, which would be in favor of understanding the trends of the whole glacier system responding to climate change. So the functional model is a preferred model to simulate the glacier system's variation trend to climate change. However, one more needs to pay attention, there exists a lag time in glaciers response to climate change, especially for large and thick debris-covered glaciers. However, on one hand, with respect to alpine glacier system, the small or non-debris-covered glaciers usually prevail in China; on the other hand, the effects of climate warming would overwhelm the protection of surface debris of glaciers and once the debris-covered glaciers lost the protection of debris, they would retreat faster and tend to be the average variation rate of glacier system from a long period. So we can still argue the reliability of the model. Continuously increasing survey data of glacier variation and alpine meteorological data make it possible to verify the functional model simulating results (Table 3). The survey data were obtained from satellite images or aerophotographs. As shown in Table 3, the survey data about glacier variations rate are largely consistent with that of the model results under the temperature rising scenario 0.02–0.05 Ka^{-1}, which agrees well with the air temperature rising scenario of 0.02–0.05 Ka^{-1} (Shi *et al.*, 2003; Zhao *et al.*, 2002) in the last 30–40 years in the glaciated region of China (only Anyemaqen glacier system was an exception, for the survey result revealed that 17% of the glacial area of the Anyemaqen glacier system shrank in the last 35 years; however, the functional model indicates that the Anyemaqen glacier system only lost 16% of the glacial area for a period of 60 years even under the temperature rising scenario of 0.05 Ka^{-1}). So we can assume that the functional model simulating results are reliable as a whole.

Table 3 Verification of model results with data of the glacier system' area changes surveyed by remote sensing in western China in recent decades

Glacier systems	Survey data				Model results		
	Area (km^2)	Period (a)	Area retreating rate (%)	References	Temperature rising rate (Ka^{-1})	Period (a)	Area retreating rate (%)
Urumqi River Basin[a]	48.04	1964–1992	−13.8	Cheng *et al.*, 1996	0.03	28	−13.7
Gangrigabu[a]	3031.25	1915–1980	−47.9	Liu *et al.*, 2006	0.05	65	−54.2
Pengqu-Boqu Basin[b]	1642	1970–2001	−9.0	Rui Jin *et al.*, 2005	0.03	31	−11.3
Altay Mountains[b]	804.9	1952–1998	−7.1	Narozhniy *et al.*, 2003	0.02	46	−8.2
Kashen River Basin[c]	133.85	1962–1990	−3.5	Liu *et al.*, 1999	0.02	27	−3.5
Sikesu River Basin[c]	102.22	1962–1990	−2.6	Liu *et al.*, 1999	0.02	27	−3.1
West of Qilian Mountains[c]	162.8	1956–1990	−4.8	Liu *et al.*, 2002	0.03	34	−4.6
Anyemaqen Mountains[c]	125.5	1966–2000	−17	Liu *et al.*, 2002	0.05	60	−16.4
East Pamir[c]	1067.24	1962–1999	−7.9	Shangguan *et al.*, 2006	0.05	37	−7.2
Geladandong[d]	889	1969–2002	−4.8	Ye *et al.*, 2006	0.03	33	−3.5
Naimaona[d]	84.41	1976–2003	−3.8	Ye *et al.*, 2006	0.03	27	−3.0
Yulongkashi[d]	1776.96	1989–2001	−0.5	Shangguan *et al.*, 2007	0.03	12	−0.3

a: Extremely-sensitive; b: Semi-sensitive; c: Semi-steady; d: Extremely-steady

6 Conclusions

Based on the above analysis, the following conclusions can be drawn.

(1) The glacier systems of different characteristics respond to the climate warming differently, and the glacier systems in China could be divided into extremely-sensitive glacier system, semi-sensitive glacier system, extremely-steady glacier system and semi-steady glacier system in terms of glacier system's level of water-energy exchange, rising gradient of the equilibrium line altitudes and retreating rate of area to climate warming, their median size and vertical span distribution, and their runoff characteristics to climate warming.

(2) Functional model of glacier system to climate warming could be applied to predict the average variation trends of the 4 types of glacier systems, and the prediction results indicate that, in the mid-21st century, under the climatic warming scenario of 0.03 K/a, for the extremely- and semi-sensitive glacier systems, the glacier area ($\Delta S_i/S$) will reduce by

25%–35%, $\triangle ELA$ will rise by 100–150 m and the glacial discharge-runoff will reach their maximum amount before 2030; while as to the extremely- and semi-steady glacier systems, the glacier area will reduce only by 10%–20%, $\triangle ELA$ will rise less than 100 m and the glacial discharge-runoff will reach their maximum amount after 2050.

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