Modeling the response of glacier systems to climate warming in China

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ABSTRACT. A glacier system is regarded as the ensemble of many glaciers sharing the same region, influenced by a similar climate and organized by certain intrinsic laws. It can be either 'sensitive' or 'steady'. On the basis of the structure of the glacier system and the nature of the equilibrium-line altitudes at the steady state, functional models of a glacier system responding to climate warming were established, using the Kotlyakov–Krenke equation relating annual glacier ablation and mean summer temperature and the glacier system's median size. The modeling results under the climatic scenarios with a rate of temperature increase of 0.01, 0.03 and 0.05 K a^{-1} indicate that by the end of this century the glacial area of China will be reduced by –14%, –40%and –60% respectively. However, model results show distinct differences between the sensitive glacier system and the steady glacier system.

INTRODUCTION

A glacier system is regarded as the ensemble of many glaciers sharing the same region, influenced by a similar climate and organized by certain intrinsic laws; it can be divided and subdivided based on certain characteristics (e.g. mountain massif, watershed boundaries) (Kotlyakov and Smolyarova, 1990). There are 59 406 km^2 of glacial area and 5590 km^3 of glacial volume in China (C. Liu and others, 2000). Glaciers are a vital fresh-water resource in the arid western area of China. The recent temperature rise is the key factor in the variation of glaciers, which have been retreating since the middle of the last century due to global warming (Liu and others, 1999). As a result, many studies were carried out on the variation of glacier response to global warming (Kotlyakov and others, 1991, 2000; Shi and Liu, 2000; Ye and others, 2003).

The model of glacier system response to climate warming was previously applied on the glacierized regions of southern Tibet (Xie and others, 2002). In this paper, we improve our model further and apply it to glacier systems all over China and try to gain average results of glacier systems in China responding to climate warming during this century.

Table 1. Parameters of glacier systems in China for prediction

Glacier systems	S_0 km^2	V_0 km^3	S_{med} km^2	ELA$_0$ m	AAR$_0$	t_s °C	a_0 mm
Sensitive	20 923	1690	1.36	4794	0.65	2.63	1619
Steady	38 477	3903	8.74	5275	0.75	–1.24	596

Notes: S_0 and V_0: glacier area and volume; S_{med}: median size; ELA$_0$: equilibrium-line attitude during steady state; AAR$_0$: accumulation-area ratio; t_s: mean summer temperature near ELA$_0$; a_0: annual ablation.

PARAMETERS FOR MODELS

Glacier data (number, area, volume, etc.) were obtained from Chinese glacier inventories acquired from aerial surveys during the 1960s–80s. Glaciers were divided into 'sensitive' and 'steady' glacier systems (Fig. 1) based on the glacier system's mean summer temperature near the equilibrium-line altitude (ELA) and their median size. Temperature data were taken from the Climatic Atlas of Tibetan Plateau Climate which reflects meteorological conditions of the 1960s and 1970s. The parameters needed in order to run glacier system modeling are listed in Table 1.

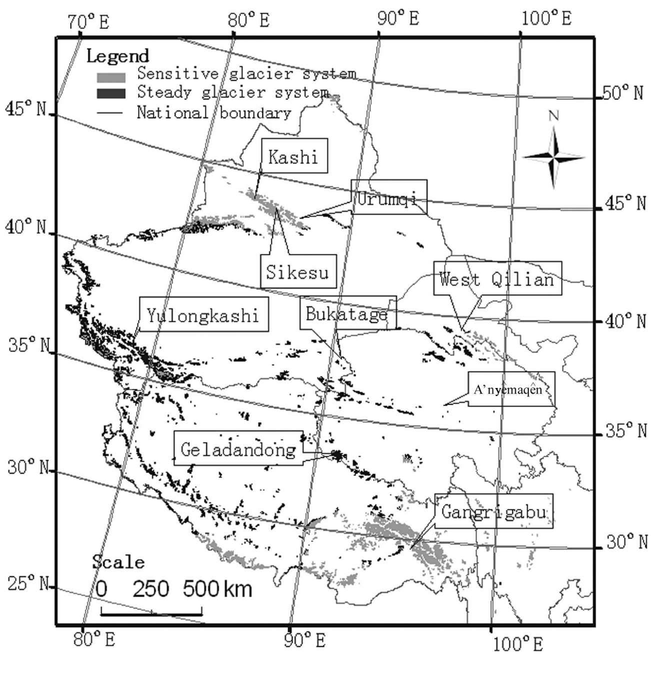

Fig. 1. Location and sensitivity to climate change of glaciers in China.

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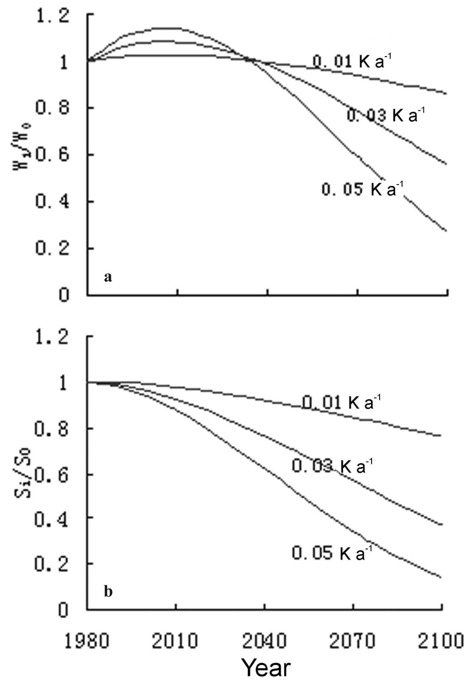

Fig. 2. Responses of a sensitive glacier system in China with respect to total runoff and glacier area in response to possible climatic scenarios in this century: (a) glacier runoff variation; and (b) glacier area variation.

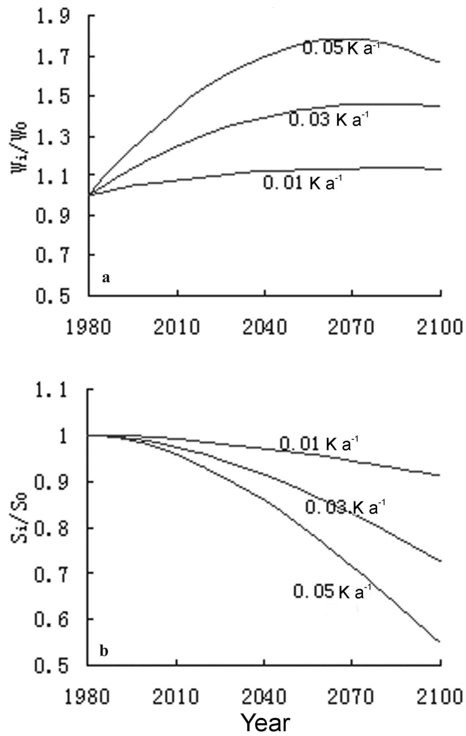

Fig. 3. Same as Figure 2, but for a steady glacier system.

MODELING

Calculation of mass-balance change

The specific net mass balance near ELA_0 is approximately equal to the average net mass balance of a glacier (Xie and others, 1996), and the depth of ablation and runoff are also approximately equal to their corresponding average values (Kang and others, 1994). These laws can also be applied to glacier systems (Xie and others, 2002). With a given temperature rise, employing the ablation formula by Kotlyakov and Krenke (1982), the net balance of a glacier system, b_{ni}, in a given year i can be expressed as:

$$\begin{aligned} b_{ni} &= a_0 - a_i \\ &= 1.33\left[(9.66 + t_{s0})^{2.85} - (9.66 + t_{s0} + \Delta t_{si})^{2.85}\right], \end{aligned} \quad (1)$$

where a_0 and a_i are ablation in the original year and in the given year i, t_{s0} is the mean summer temperature near ELA_0 in the original year and Δt_{si} is the increase of mean summer temperature in the given year i.

We define the ratio between $|b_{ni}|$ and a_0 of a glacier system in the year i as:

$$\alpha_i = \frac{|b_{ni}|}{a_0}. \quad (2)$$

Calculation of glacier runoff and area change for climate warming

When temperature rises, glacier melting will accelerate, negative mass balance will occur, and therefore glacier runoff will increase. On the other hand, glacier area will decrease as glaciers retreat, and the total glacier runoff, w_i, in a given year i will be:

$$w_i = (r_0 + r_{di})(s_0 - s_{di}), \quad (3)$$

where r_0 and s_0 are the depth of runoff and area of glacier in the original year, respectively, and r_{di} and s_{di} are the increase of runoff depth and the decrease of glacier area due to climate warming in a given year i, respectively. With the temperature continuously rising, glacier runoff will first increase due to the increase in ablation, and after reaching its maximum amount, it will decrease again because of the reduction in glacier area. When it returns to the original amount of glacial runoff, we call this 'restoring original glacier runoff state' (Xie and Feng, 1996). At that time, ignoring evaporation, we can set $r_0 = a_0$, $r_{di} = |b_{ni}|$ and the decrease of glacier area, s_{di}, is:

$$s_{di} = \frac{s_0 \alpha_i}{\alpha_i + 1}. \quad (4)$$

We employ the widely used empirical formula to relate glacier area and thickness (Liu and Ding, 1986) to determine the time when a glacier reaches restoring original glacier runoff state under continuous warming, T_{ei} (Xie and Feng, 1996). Then the glacier area s_i in a given year i is:

$$s_i = s_{i-1} - \frac{s_{di}}{T_{ei}} = s_{i-1}\left[1 - \frac{\alpha_i}{(\alpha_i + 1)T_{ei}}\right]. \quad (5)$$

When it comes to predicting the variation in the glacier system, we use s_{med} to replace the total area of the whole glacier system, S, and apply the laws mentioned above to arrive at the results. Ignoring evaporation, the total runoff of the glacier system, W_i, in a given year i is:

$$W_i = \frac{a_i S_i}{10^6}, \quad (6)$$

where S_i is the total area of the glacier system in a given year i, and the constant 10^6 is used to convert mm into km.

PREDICTION RESULTS

The global mean surface air temperature will rise this century (Houghton and others, 2001) and so will the

Table 2. Verification of model results with data of the glacier changes in western China in recent decades

Location of glacier systems	Survey data			Model results		
	Period	Retreat rate	Source	Rate of air-temperature increase	Period	Retreat rate
		%		$K a^{-1}$	years	%
Yulongkashi	1989–2001	0.3	Shangguan and others (2004)	0.03	15	0.3
Ürümqi	1964–92	13.8	Chen and others (1996)	0.05	30	13.4
Sikeshu	1962–90	2.6	Liu and others (1999)	0.03	27	3.1
West Qilian	1956–90	10.3	Liu and others (2002b)	0.03	45	10.1
Hashi	1962–89	3.5	S. Liu and others (2000)	0.02	27	3.3
Bukatage	1973–94	1.6	Li and others (1999)	0.02	20	1.7
Geladandong	1969–2000	1.7	Lu and others (2002)	0.02	31	1.7
A'nyêmaqên	1966–2000	17.0	Liu and others (2002a)	0.05	60	16.5
Gangrigabu	1980–2001	2.8	Liu and others (2005)	0.03	20	2.9

temperature in northwestern China and on the Tibetan Plateau (Zhao and others, 2002). Since the prediction for a climatic warming trend is accompanied by uncertainties, we have made some assumptions about climatic scenarios with possible rates of temperature increase of 0.01, 0.03 and 0.05 $K a^{-1}$ in this century. We take 1980 as the original year and calculate the tendency of glacier systems' variations in response to these possible climatic scenarios. By the end of this century, the glacier area of China ($\Delta S/S$) will on average be reduced by 14.2%, 39.7% and 59.7% under the climatic scenarios of 0.01, 0.03 and 0.05 $K a^{-1}$, respectively. However, there are distinct differences between the sensitive glacier system (Fig. 2) and the steady glacier system (Fig. 3).

VERIFICATION AND DISCUSSION

The continuous increase in the abundance of glacier variation observations and alpine meteorological data makes it possible to verify our models. However, care needs to be taken since there exists a lag time in glaciers' response to climate change, especially for large, thick debris-covered glaciers. But with respect to alpine glacier systems, the small and non-debris-covered glaciers which are sensitive to climate change are most prevalent in China, so we argue that our model is reliable. On the other hand, precipitation has been increasing in northwest China since the 1980s (Shi and others, 2003); but considering that the prediction of precipitation variation is accompanied by large uncertainties, we discuss the influence of precipitation on glacier systems under climate warming separately. The survey data for contemporary glacier variations (Fig. 1) and corresponding model results are compared in Table 2.

In the Northern Hemisphere, average air temperatures were 0.4 K higher in the 1980s than in the 1960s (Lin and Zhao, 1998). In Tibet the average rate of increase in air temperature was >0.02 $K a^{-1}$ (Kang, 1996) and it has been accelerating since the mid-1980s (Shi and others, 2002). On average, air temperatures were 0.5 K higher during 1985–2001 compared to 1958–85 in the glacierized source region of the Ürümqi river (Li and others, 2003), with air temperatures increasing by 0.03 $K a^{-1}$ from 1985 to 2001. Thus, the rate of air-temperature increase was on average 0.02–0.03 $K a^{-1}$ for the last 30–40 years in the glacierized region of China. The survey data for glacier variations largely reflect this temperature increase, and they agree well with the results of our model under similar temperature-rise scenarios (Ürümqi and A'nyêmaqên were exceptions). Thus, we suggest that our model is generally reliable.

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