

Modeling the variation trends of glacier systems

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The basic principles and methods for a functional glacier systems model are introduced and applied for glaciers of Northwest China. When running the model we assume that a glacier system is under steady state conditions in the initial year. The median size of a glacier system is used as representative for the system. The curve of glacier area distribution against elevation is used to compute the increase in equilibrium line altitude (*ELA*), and the annual glacier ablation is calculated using a global formula $a = 1.33(9.66 + t_s)^{2.85}$ [4, p. 96]. The net mass balance near the *ELA* under steady state conditions represents the net mass balance of the whole glacier system, and the time required for glacier runoff to return to the initial year level is calculated according to the law of glacier runoff variation, and used to calculate the variation of glacier area. The variation of glacier runoff is modeled according to ablation at the *ELA*, and the variation of glacier volume is modeled according to the absolute value of the mass balance. The observed changes in surveyed glaciers in China over recent decades were broadly consistent with predictions of the glacier system model. The model therefore offers a reliable method for the prediction of changes in glacier systems in response to changing climate.

Introduction

As a result of continued global warming, many glaciers are retreating, with important effects on the natural environment. Therefore, studies on glacier variation, and the prediction of trends in glacier variation, have been a focus of research in the field of glaciology. Many methods have been developed to predict trends in glacier variation in response to climate warming, including models of response to climate change, dynamical models, and hydrological models. Models based on glacier energy balance can be applied to single glaciers that have been surveyed in detail [19]. However, other approaches are required for the prediction of glacial variation across large spatial scales without detailed field observation. The World Glacier Inventory provides data on many glaciers globally, and the application of satellite remote sensing technology enables the detection of large-scale glacier variation. Recently, several models simulating large-scale glacier variation have been developed. Paul et al. [20] used data on glacier accumulation area to predict glacier variation in several areas of Switzerland. Glazyrin and Kodama [12] used three phases of glacier inventory data for four basins in the Pamir Mountains of Central Asia, and developed a method to simulate changes in glacier

area. Kuzmichenok [8] developed a statistical method to simulate the runoff and evolution process for glaciers in Kyrgyzstan. According to the theory of glacier systems, a functional model was developed [5, 31] and applied to glacier systems in China [27, 36]. The modeled results of trends in glacier variation were close to observational results of glacier variation over recent decades [33]. In this paper we present a general introduction to a new functional model for glacier systems.

Principles of the glacier system functional model

Median size of the glacier system. A glacier system is a group of glaciers in the same region, influenced by similar climate patterns and intrinsic physical laws. A system can be divided and subdivided based on features including physical characteristics, mountain ranges, and watershed boundaries [13]. The concept of glacier systems has been widely applied in analyzing glacier distribution laws from glacier inventory data [1, 2]. The median size (S_{med}) of a glacier system is defined as the size when the cumulative glacier area reaches 50% of the glacier system as a whole. Median size was used to study the structure of glacier systems in Southern Tibet, and results confirmed that the median size of the glacier

system could appropriately represent the typical glacier area of the whole glacier system [17].

Glacier area distribution with elevation. Changes in glacier equilibrium-line altitude (*ELA*) have been calculated based on the curve of glacier area distribution against elevation. Kuzmichenok [7] developed a formula for calculating the glacier area distribution against elevation, which has been widely applied in China [16, 27, 32]. Recently, characteristics of Himalayan glacier systems were studied using ArcGIS software to obtain information on glacier area distribution against elevation [38].

Equilibrium-line altitude. The net mass balance close to the elevation of the *ELA* in steady state conditions, $bn(ELA_0)$, is equal to the mean net mass balance of the glacier, \overline{bn} :

$$bn(ELA_0) = \overline{bn}. \quad (1)$$

This relation has been explained in detail in a previous paper [30]. When the climate fluctuates normally, changes in ELA_0 are relatively small and stable, though the *ELA* in any one year (ELA_a) is variable as a result of annual climate fluctuations. The amplitude of the fluctuation in ELA_0 is smaller than that of ELA_a . Consequently, the net mass balance at ELA_0 was used to represent the mean net mass balance of the whole glacier in the model. ELA_0 is essentially an abstract concept obtained through computer analysis. For a glacier with a long time series of mass balance observations, the formula devised by Braithwaite [10] can be used to estimate ELA_0 :

$$bn = \alpha(ELA_0 - ELA_a), \quad (2)$$

where α is the gradient of effective mass balance.

We can also obtain the elevation of ELA_0 using the curve of net mass balance changes against altitude [30]. For glacier systems, the mean of ELA_0 , $\overline{ELA_0}$, can theoretically be derived from the ELA_0 of each glacier in a glacier system. The concept of the reduced snowline presented by Seversky [21], is similar to the concept of the $\overline{ELA_0}$. Analysis of *ELA* data from the Chinese Glacier Inventory showed that an empirical formula could be used to calculate the mean snowline altitude for a basin or a mountainous region:

$$ELA_k = aH_{me} + b, \quad (3)$$

where ELA_k is the computed *ELA*; H_{me} is the average of the highest and the lowest elevation of the glacier, and a and b are empirical constants.

Statistical analysis was conducted on exterior drainage data from the glacier inventory of Southern Tibet, and the correlation coefficients for ELA_k and

H_{me} (formula (3)) ranged from 0.8–0.88 for the glacier systems of the Indus, Ganges and Yarlung Zangbo Rivers [31]. For the Chinese Glacier Inventory, *ELA* was measured using the method devised by Hess (ELA_h), determined according to changes of contour lines in the central glacier. In fact, ELA_h is close to the dynamic *ELA*, ELA_d , which is related to the period of the glacier cycle. A.N. Krenke [6] reported that the average cycle time of glacier water is approximately 100 years in mountain glaciers. Therefore, ELA_h is relatively stable, and close to the concept of ELA_0 . However, ELA_h was only recorded for about 10–12% of glaciers in the Chinese Glacier Inventory. Formula (3) was used to calculate the ELA_d of all glaciers in the system, and the average value was denoted as the mean *ELA*, $\overline{ELA_k}$ for the glacier system. The $\overline{ELA_k}$ can therefore approximate the mean ELA_0 of glacier systems, namely:

$$\overline{ELA_k} \approx \overline{ELA_0}. \quad (4)$$

Ablation at ELA_0 . Currently, many models are available to describe and compute the process of glacial ablation. Models based on energy balance can be used for single glaciers if enough observational parameters exist. Degree-day models based on temperature can also be applied to single glaciers [11], and degree-day factors can be changed for large scale regions [38]. We therefore selected the Krenke–Khodakov model [5, p. 96; 14] based on the mean summer temperature:

$$a = 1.33(9.66 + t_s)^{2.85}, \quad (5)$$

where a is the ablation (mm w. eq.) at ELA_0 ; t_s is the mean summer temperature (June–August) at ELA_0 (°C).

This model has been widely used in the former Soviet Union [3, 5] and China [16, 37], with some modifications to its empirical constants. Recently, Kotlyakov and Lebedeva [5] demonstrated that under various climatic conditions the ablation curve could be different even if the value of t_s is the same. However, computing ablation using mean summer temperature had common implications, and formula (5) was designated as a global formula, suitable for application in large glaciated regions. We therefore used Formula (5) in this paper.

Mean summer temperature at ELA_0 . To calculate the mean summer temperature at ELA_0 , the temperature from June to August at 600 MPa was obtained from the Meteorological Atlas for the Qinghai-Xizang Plateau [10]. The Meteorological Atlas was compiled on the basis of meteorological survey data recorded between the 1960s and 1970s (Lanzhou Institute of

Plateau Atmospheric Physics, Chinese Academy of Sciences, unpublished data). Using the mean summer temperature at 600 MPa, t_{pa} , according to the vertical lapse rate and taking in to account jumps in temperature of the glaciers, Δt_j , the mean summer temperature at \overline{ELA}_0 was calculated:

$$t_s = t_{pa} + \Delta h \gamma + \Delta t_j, \quad (6)$$

where $\Delta h = h_{pa} - \overline{ELA}_0$; γ is the vertical lapse rate of temperature, ranging from 0.55–0.75 K/100 m.

The corrected temperature of the glaciers Δt_j was arbitrarily assumed to be -0.5 , -1.0 and -1.5 K according to the S_{med} of the glacier systems. Most of the original aerial photos used for the Chinese Glacier Inventory were taken in the 1960s and 1970s, which was coincident with the time that the mean summer temperature at 600 MPa was surveyed. The summer temperatures obtained as described above can therefore be regarded as initial temperatures (t_s) to predict changes in the Qinghai–Xizang Plateau glacier systems. When the glacier system functional model was used to predict the changing trends in the Altai Mountain glacier systems, the summer temperature field was established at 3000 m with $\gamma = 0.6$ K/100 m and $\Delta t_j = 0.5$ K, on the basis of ground-recorded meteorological data [34].

Net mass balance at the ELA_0 . Theoretically, the net mass balance b_n at the ELA_0 should be zero under steady state conditions. When the temperature of t_s rises, b_n can be computed using the following formula:

$$b_{ni} = 1.33[(9.66 + t_{s0})^{2.85} - (9.66 + t_{s0} + \Delta t_s)^{2.85}], \quad (7)$$

where b_{ni} is the net mass balance after the changes of t_s in a given year i ; t_{s0} is t_s at the steady state; Δt_s is the change in the value of t_s .

If the precipitation changed at the same time in a certain year i , the accumulation amount of the glacier (Δc_i) affected by solid precipitation could be added to formula (7) directly:

$$b'_{ni} = 1.33[(9.66 + t_{s0})^{2.85} - (9.66 + t_{s0} + \Delta t_s)^{2.85}] + \Delta c_i, \quad (8)$$

where b'_{ni} is the net mass balance of the glacier under the climatic scenarios of both temperature and precipitation changing simultaneously in a given year.

In the continental glacier systems of High Asia, where the precipitation is predominantly in solid form, the elevation of ELA_0 is relatively high. In maritime glacier systems, such as in the south of the Qinghai–Xizang Plateau, where liquid precipitation occurs often, the elevation of ELA_0 is hundreds of meters lower than for the continental glaciers.

Therefore, some meteorological methods should be applied to allow for the amount of solid precipitation. In the glaciated regions, accumulation at the ELA_0 does not equal to precipitation because of the influence of wind and snow drift. A correction coefficient for glacier accumulation of about 1.4 was introduced, based on observational data [6]. Generally, Δc_i in formula (8) can be expressed by the percentage of accumulation c_i . The c_i of glaciers under steady state conditions can be calculated using Formula (7), and the depth of glacier ablation at the ELA_0 should be equal to the depth of accumulation.

Variation of glacier runoff. When temperature rises, glacier melting accelerates, and a negative mass balance occurs resulting in an increase in the depth of glacier runoff, referred to as glacier retreating runoff [4]. As the glacier retreats, the area of the glacier also decreases. The total glacier runoff, w , can be expressed as:

$$w = (r_0 + r_d)(s_0 - s_d), \quad (9)$$

where r_0 and s_0 are the runoff depth and the area of the glacier in the initial year, respectively, and r_d and s_d are the increment of runoff depth and the decrement of glacier area resulting from climate warming, respectively.

As temperature rises, glacier runoff initially increases with acceleration of glacier melting. When the temperature reaches a maximum, runoff falls back secondary to a loss in glacier area, that is, the glacier runoff is characterized by an initial increase then subsequent decrease under the scenario of continuous warming. When the total glacier runoff returns to the original level (w_0), the decrement of glacier area can be calculated using:

$$s_d = s_0 r_d / (r_0 + r_d). \quad (10)$$

If evaporation is disregarded, then $r_0 = a_0$, $r_d = |bn|$, $\alpha = |bn|/a_0 = r_d/r_0$, and the decrement in glacier area s_d can be rewritten as:

$$s_d = s_0 \alpha / (\alpha + 1). \quad (11)$$

At the time when the total glacier runoff returns to the original level w_0 , the glacier area s_e is:

$$s_e = s_0 / (\alpha + 1). \quad (12)$$

To determine the time that it takes for the glacier to revert to the original runoff state T_e , the empirical formula for the relationship between mean glacier thickness and glacier volume, which was widely used in Chinese Glacier Inventories [22], was applied:

$$\bar{h} = 53.21s^{0.3} - 11.32, \quad (13)$$

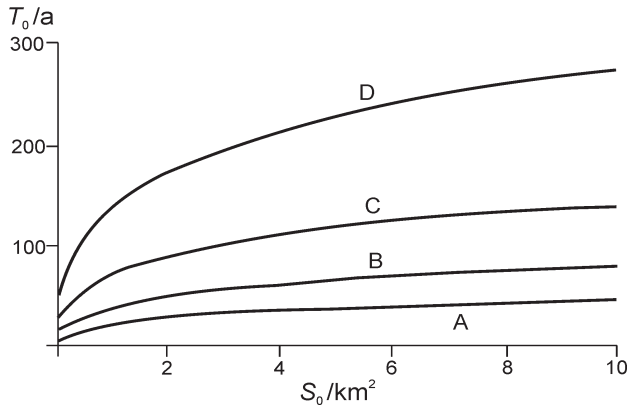


Fig. 1. Relationship between the time which needs for a glacier to revert to its original runoff T_e and glacier area in the year S_0 .

A, B, C, and D indicate glaciers with negative mass balance at extremely strong, strong, weak, and extremely weak rates, respectively.

Рис. 1. Соотношение между временем, необходимым для достижения исходных значений стока T_0 , и площадью ледника в начальный год S_0 .

A, B, C, D – соответственно ледники с экстремально высоким, высоким, низким и экстремально низким негативным балансом массы

where \bar{h} is the mean glacier thickness, and s is the glacier area. Considering the absolute value for net mass balance $|bn|$, formula (13) can be expressed as:

$$T_e = \frac{1.8(\alpha+1)}{|b_n|(\alpha+2)} \left\{ 53.21s^{0.3} \left[1 - \left(\frac{1}{\alpha+1} \right)^{1.3} \right] - \frac{11.32\alpha}{\alpha+1} \right\}. \quad (14)$$

Area variation of glacier systems. As is shown in formula (14), T_e increases exponentially with s_0 (Fig. 1) [31]. The discussion above has focused on the relationships for variation of individual glacier runoff, but for predicting the variation of glacier systems, the following formula should be applied:

$$S_{med0} = S_0, \quad (15)$$

where S_{med0} is the medium size of the glacier system in the initial year.

When the S_{med} of the glacier system reaches T_e , 50% of glaciers smaller than the S_{med} for the system as a whole will reach or pass T_e , and the total runoff will be less than the original runoff. The other 50% of glaciers larger than S_{med} will not have reached T_e and total runoff for these glaciers will still be higher than original levels. Therefore, when S_{med} for the glacier system reaches T_e , the runoff for the entire system is averaged to restore levels to the original values, and S_{med} can be used to represent the total area of the glacier system, and to predict the variation in area of the system. If the temperature continues to rise, each parameter in formula (14) varies

year by year, and the total area of the glacier system S_i in a given year i is:

$$S_i = S_{i-1} \left[1 - \frac{\alpha}{(\alpha+1)T_{ei}} \right]. \quad (16)$$

If climate warming persists T_{ei} will eventually reach close to zero, and at that time the total area of the glacier system S_i will also be close to zero, and the glaciers will disappear.

Volume variation of glacier systems. As climate warming continues, the variation of volume for a glacier V_{di} in a given year will be:

$$V_{di} = |b_{ni}|S_i/900\,000, \quad (17)$$

where V_{di} is the variation of glacier volume in a given year i ; $|b_{ni}|$ is the constant of net mass balance; S_i is the glacier area in a given year i and 900 000 is the conversion coefficient.

The average density of ice is 0.9 g/cm³, and the dimensions of glacier area and volume are km² and km³, respectively. The total accumulative change of glacier volume in a given year i is:

$$\Sigma V_{di} = \Sigma |b_{ni}|S_i/900\,000. \quad (18)$$

The rate of the variation of volume for a glacier is:

$$\frac{\Sigma V_{di}}{V_0} = \frac{\Sigma |b_{ni}|S_i}{900\,000 V_0}, \quad (19)$$

where V_0 is the total volume of a glacier system under steady state conditions.

Runoff variation of glacier systems. If evaporation is disregarded, annual glacier ablation is equal to its runoff, and the total runoff for a glacier system W_i in a given year i is:

$$W_i = a_i S_i / 1\,000\,000. \quad (20)$$

Three signal years have been identified to depict the variation characteristics of glacier systems in response to climate warming. The year when the runoff of a glacier system reaches its maximum is denoted as T_1 . The year when the runoff of a glacier system reestablishes its original runoff is T_2 , and the year when the runoff of a glacier system is close to zero ($S_i \rightarrow 0$), is denoted as T_3 .

ELA₀ variation of glacier systems. When glaciers retreat, the area of the glaciers is reduced. However, the ELA₀ of a glacier will spontaneously rise to maintain the stability of the accumulation area ratio (AAR) of the glacier. To determine the increase in value of ELA₀ for glacier systems exposed to climate warming, ΔELA_0 , the altitude structure of the glacier system is used to compute the AAR. The accumulation area

Table 1. Main parameters of the glacier system functional model

Item	Description	Unit	Note
S_0	Glacier area	km ²	Obtained from glacier inventories of China
V_0	Glacier volume		
S_{med}	Median size of glacier system		
ΔH_0	Difference of elevation between mean highest altitude and the mean lowest altitude of the glaciers distribution	m	Calculated using section 2(3) above
\overline{ELA}_0	Mean equilibrium line altitude		
t_{s0}	Mean summer temperature at \overline{ELA}_0	K	Calculated using formula (6)
a_0	Depth of annual ablation at \overline{ELA}_0	mm	Calculated using formula (5)
w_0	Glacier runoff	km ³	Calculated using formula (20)
ELA_0	Rising value of ELA_0	m	Calculated using formula (21)
Δt_s	Changes in value of mean summer temperature at \overline{ELA}_0	K	Calculated using formula (23)

ratio is the indicator of climate and immediate surroundings in a glaciated region, and it is minimally affected by climatic fluctuation. When glacier retreat begins at the terminus, ELA_0 will rise simultaneously. Statistical analysis shows that polynomial relationships exist between ΔELA_0 and $\Delta S/S_0$:

$$\Delta ELA = C_1(\Delta S_i/S_0)^3 + C_2(\Delta S_i/S_0)^2 + C_3(\Delta S_i/S_0), \quad (21)$$

where $\Delta S_i/S_0$ is the rate of retreat of the area of the glacier system; ΔS_i is the value of variation of glacier area in a given year i ; S_0 is the glacier area in the original year, and C_1 , C_2 and C_3 are empirical coefficients dependent on the variation of the relationship between glacier area and height.

Secondary to an increase in altitude of ELA_0 , the mean summer temperature at the ELA_0 will inevitably fall, and can be calculated by:

$$\Delta t'_{si} = \gamma \Delta ELA, \quad (22)$$

where $\Delta t'_{si}$ is the decrease of summer temperature as a result of the ELA rising, and γ is the local vertical lapse rate of summer temperature.

To compute the glacier variation for the following year, the summer temperature at the ELA in a given year i , should be modified as:

$$t_{si+1} = t_{si} - \Delta t'_{si}, \quad (23)$$

where t_{si+1} is the mean summer temperature in the following year; t_{si} is the mean summer temperature in a given year i .

Running the glacier system models

Original year of modeling. We make the assumption that glaciers remain in a steady state in the initial year of modeling. When temperature rises, the ablation of the glaciers accelerates, a negative mass

balance occurs, and the steady state of the glacier system no longer exists. The time when aerial photos were taken was set as the initial year of modeling because the aerial photography topographic maps were also used for the Chinese Glacier Inventory. Although individual aerial photos may have been modified before the topographic maps were officially published, the boundaries and area of the glaciers would not have changed significantly. The aerial survey time for glacier systems differed, and time gaps would have caused errors in glacier area. However, most of the aerial surveys were carried out between the 1950s and 1970s, and glaciers in China changed little during those years [35]. Therefore, 1980 was selected as the initial year when modeling the variations of glacier systems across China.

Parameters for modeling. Glaciers in China were cataloged according to the size of associated watersheds, and we also divided and subdivided glacier systems in terms of watersheds. For large watersheds such as the Yangtze River, the Yarlung Zangbo River, and the Yellow River, we further subdivided glacier systems according to upper, middle and lower reaches because different climates exist along these rivers. Glacier systems in large mountain ranges, including the Himalayas, the Tian Shan Mountains, and the Kunlun Mountains, were subdivided on the basis of directional aspect, because different climates exist on different sides of mountain ranges. The main parameters of the glacier system functional model are summarized in Table 1. The initial parameters are labeled with the subscript 0.

Scenarios of climate variation. The Intergovernmental Panel on Climate Change (IPCC) and Chinese scientists have made predictions on the magnitude of climate change in China by 2050, but much

Table 2. Modeled changes in features of glacier systems supplying the Yarlung Zangbo River (Y), Ganges River (G), and Indus River (I) for the three signal years T_1 , T_2 , and T_3

Glacier system (code)	a_0 , m	S_{med} , km ²	ΔH , m	Climatic scenario, K/a	T_1			T_2			T_3		
					a , year	W/W_0	S/S_0	a , year	W/W_0	S/S_0	a , year	ΔELA , m	Δt , °C
Y(502)	1.855	5.15	5400	0.01	29	1.027	0.986	72	1	0.939	928	1335	-8.00
				0.03	29	1.083	0.955	74	1	0.805	358	1337	-8.00
				0.05	30	1.141	0.923	73	1	0.680	237	1336	-8.00
G(501)	0.851	7.15	5400	0.01	58	1.064	0.973	181	1	0.848	1322	1797	-11.67
				0.03	78	1.220	0.867	170	1	0.474	497	1797	-11.67
				0.05	80	1.414	0.760	142	1	0.404	324	1798	-11.66
I(5Q)	0.479	2.25	2900	0.01	85	1.118	0.938	227	1	0.697	776	858	-5.99
				0.03	93	1.408	0.779	174	1	0.392	328	857	-5.98
				0.05	80	1.707	0.710	142	1	0.286	225	854	-5.95

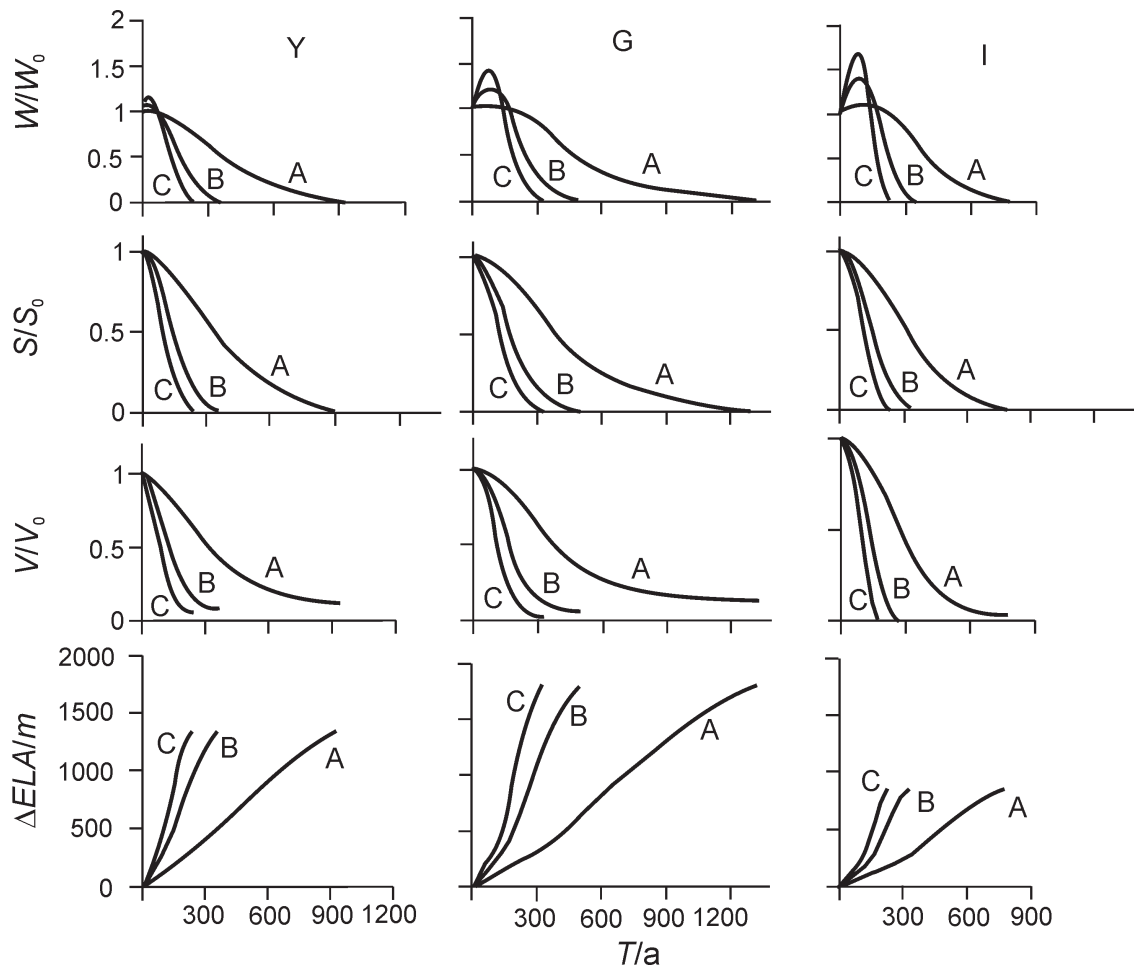


Fig. 2. Changes in glacier runoff W/W_0 , glacier area S/S_0 , glacier volume V/V_0 , and equilibrium line altitude ΔELA for the Yarlung Zangbo River (Y), the Ganges River (G), and the Indus River (I) glacier systems.

A, B, and C indicate climate warming rates of 0.01, 0.03 and 0.05 K/a respectively

Рис. 2. Изменения ледникового стока W/W_0 , площади ледников S/S_0 , объёма ледников V/V_0 и высоты границы питания ΔELA для ледниковых систем бассейнов рек Ярлунг Зангбо (Y), Ганг (G), и Инд (I).

A, B и C – тренд потепления соответственно 0,01, 0,03 и 0,05 К/год

uncertainty exists. Based on currently available data, three possible climate change scenarios have been proposed, that global temperature will rise by 0.01, 0.03, or 0.05 K/a, assuming that the rate of change in the global annual mean temperature is consistent with that of the summer mean temperature. The effect of precipitation was also considered, as shown in formula (8), with a 10% increase in precipitation predicted for every 1 °C increase in temperature [18]. For the purpose of our model we consider the impact of the increase in precipitation levels in solid form supplying glacier systems.

Results of model predictions. The parameters shown in Table 1 and Table 2 were used in the functional model for the response of glacier systems to climate warming. The modeled changes in glacier runoff, area, volume, and *ELA* are shown in Fig. 2. Predicted rates of retreating glacier area, increasing altitude of *ELA*, and changes in the rate of runoff for the three signal years (T_1 , T_2 , T_3) are listed in Table 2 for southern Tibet watersheds.

Functional models for glacier systems have been widely used to predict the response of glacier systems to climate warming in China [15, 24, 26, 28, 34, 36]. The modeled trends for the response of glaciers in China to the three possible climate warming scenarios are shown in Fig. 3.

Discussion and conclusion

If the global mean surface air temperature rises this century, and so will the temperature in Northwest China. The prediction of climatic warming is accompanied by many uncertainties, and therefore we made some assumptions about climate change scenarios. The three possible scenarios selected were temperature increases of 0.01, 0.03, and 0.05 K a⁻¹ in this century. We selected 1980 as the initial year and modeled the changes of glacier systems in response to the three possible climatic scenarios. The increasing availability of survey data on glacier variation, and alpine meteorological data, makes it possible to verify the functional model results as shown in Table 3. Survey data were obtained from satellite or aerial images. Changes predicted using the glacier system model were in close agreement with results based on physical monitoring. For example, the area of 16 ice cap glaciers on the Chang Tang Plateau, in the northwest of the Qinghai–Xizang Plateau, totaled 2075 km². The area of these glaciers declined by 90 km² from 1970 to 2000, and the average annual retreat rate was $-0.0145\% \text{ a}^{-1}$.

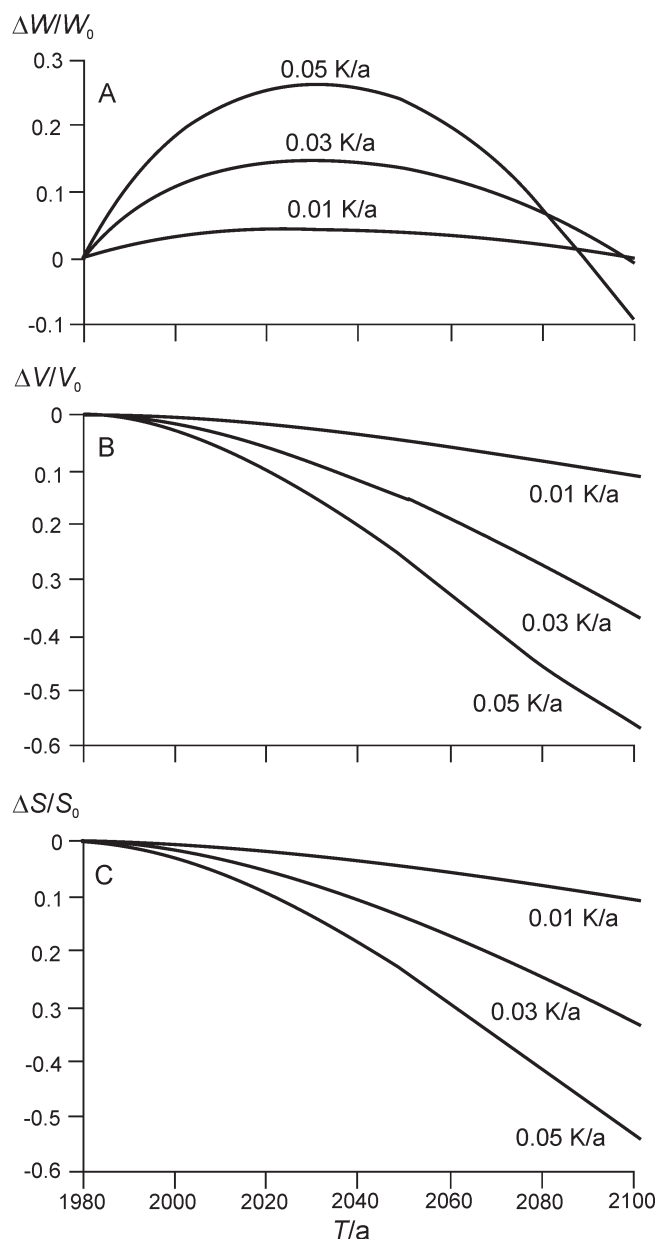


Fig. 3. Modeled variation rates for glacier systems in China in response to three possible climate warming scenarios to the end of this century.

A – glacier runoff W/W_0 ; B – glacier volume V/V_0 ; C – glacier area S/S_0

Рис. 3. Результаты моделирования изменений ледниковых систем Китая к концу XXI в. в соответствии с тремя возможными сценариями потепления климата.

A – ледниковый сток W/W_0 ; B – объём ледников V/V_0 ; C – площадь ледников S/S_0

According to the glacier system model results, under the scenario of a 0.03 K a⁻¹ warming rate, the average annual retreat rate was $-0.0147\% \text{ a}^{-1}$ over 30 years [24]. The actual average temperature increase on Tibet Plateau between 1971 and 2000

Table 3. Verification of model results using survey data on changes in the area of glacier systems for Western China over recent decades

Glacier systems	Survey data				Model results		
	area, km ²	<i>a</i> , period	area retreating rate, %	reference	temperature rising rate, K/a	<i>a</i> , period	area retreating rate, %
Urumqi River Basin	48.04	1964–1992	–13.8	[8]	0.03	28	–13.7
Gangrigabu	3031.25	1915–1980	–47.9	[22]	0.05	65	–54.2
Pengqu-boqu Basin	1642	1970–2001	–9.0	[11]	0.03	31	–11.3
Altay Mountains	804.9	1952–1998	–7.1	[24]	0.02	46	–8.2
Kashen River Basin	133.85	1962–1990	–3.5	[18]	0.02	27	–3.5
SiKesu River Basin	102.22	1962–1990	–2.6	[18]	0.02	27	–3.1
West of Qilian Mountains	162.8	1956–1990	–4.8	[20]	0.03	34	–4.6
Animaqing Mountains	125.5	1966–2000	–17	[21]	0.05	60	–16.4
East Pamir	1067.24	1962–1999	–7.9	[29]	0.05	37	–7.2
Geladandong	889	1969–2002	–4.8	[47]	0.03	33	–3.5
Naimaona	84.41	1976–2003	–3.8	[48]	0.03	27	–3.0
Yulongkashi	1776.96	1989–2001	–0.5	[30]	0.03	12	–0.3
Changtang Plateau	2075.24	1970–2000	–0.15	[33]	0.03	30	–0.15

was 0.024 K a⁻¹ [29]. In conclusion, as shown in Table 3, the survey results for rates of change were largely supported by modeled results based on temperature increases of 0.02–0.05 K a⁻¹. The temperature change scenarios used for the model agree well with the observed temperature increases of 0.02–0.05 K a⁻¹ [23, 39] over the last 30–40 years in the glaciated regions of China. The Animaqing Mountains glacier system was an exception, with survey results indicating that 17% of the glacial area was lost over the last 35 years. However, the functional model indicated that the area of the Animaqing glacier system would have declined by only 16% over 60 years, even with a temperature increase of 0.05 K a⁻¹. Despite this discrepancy we can assume that the functional model simulates changes in glacier systems reliably in most cases.

It should be noted that glacier systems with diverse glacier types respond to climate change in a complex manner. For example, glacier systems with large debris-covered glaciers, as seen in the central Tien Shan Mountains and the Himalayan region, show a lag in the time of response to climate changes. Therefore, some model parameters will need to be modified when applying the model to glacier systems in these regions. Furthermore, it is possible that, with extreme changes in climate, features of the structure of glacier systems will change greatly. Climate does not usually change in a linear fashion, so while glacier system models

can estimate the trends of changes in glacier systems in general, further research is needed to fine tune models for application to individual glacier systems.

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Моделирование трендов изменений ледниковых систем

В результате современных изменений климата многие ледники на Земле продолжают отступать, что приводит к серьёзным последствиям для окружающей среды. В связи с этим исследования колебаний ледников и прогноз трендов этих изменений, включая моделирование реакции ледников на климатические изменения, динамические и гидрологические модели, представляют собой одну из актуальных задач современной гляциологии. Мировой каталог ледников служит источником глобальных данных о ледниках, а современные космические технологии позволяют проводить широкомасштабные исследования изменений ледников. В последнее время предложены модели, описывающие изменения ледников. Так, Paul et al. [20] основывают прогноз изменений ледников в нескольких областях Швейцарии на данных о площади области аккумуляции на ледниках. Г. Глазырин и Ю. Кодама [9], используя три каталога ледников для четырёх бассейнов Памира, разработали метод моделирования изменений площади ледников. В.А. Кузьмиченок [13] предложил статистический метод моделирования стока и оценки процессов для ледников Кыргызстана.

В настоящей статье рассматриваются основные принципы и характеристики функциональной модели ледниковой системы Северо-Западного Китая, разработанной на базе теории о ледниковых системах [4, 32]. При использовании модели предполагается, что в начальный год ледниковая система находится в стационарном состоянии. За характерную площадь ледника в системе принята его медианная площадь. Кривая распределения площади ледников в зависимости от высоты применяется для расчётов повышения высоты границы питания, а величина годовой абляции на леднике рассчитывается по формуле $a = 1,33(9,66 + t_s)^{2,85}$ [4, с. 96]. За исходный баланс массы всей системы принимаются балансовые характеристики ледника на высоте границы питания при стационарных условиях. Изменение ледникового стока рассчитывается через величину абляции на высоте границы питания, а изменение объёмов — через абсолютный баланс массы. Прогнозы, сделанные на основе моделирования, подтвердились результатами полевых наблюдений на опорных ледниках за последние десятилетия. Таким образом, модель предлагает реальный метод прогноза изменений ледниковой системы в связи с климатическими изменениями.