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# A MODEL SIMULATING THE PROCESSES IN RESPONSES OF GLACIER AND RUNOFF TO CLIMATIC CHANGE

## —A Case Study of Glacier No. 1 in the Ürümqi River, China①

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**ABSTRACT:** This paper presents a dynamic glacier model that simulates the processes in response of Glacier No. 1 in headwaters of the Ürümqi River to various future climatic scenarios. The results indicate that the Glacier No. 1 will continue retreating if current climatic conditions prevail, until it reaches an equilibrium state of 1600 m in length after 700 to 800 years. If air temperature raise 1℃, the glacier would become a hanging glacier with a length of 300 m after 700 to 800 years. Due to its retreat, cooling function of the glacier would be weakened, resulting in the air temperature in glaciated area higher than that in ice-free areas. The results also indicate that the current glacier melt runoff is in higher value period in comparison with the runoff in the equilibrium state under the current climatic condition. If the air temperature continues increasing, however, the runoff would still increase to a new peak and then decrease rapidly.
**KEY WORDS:** glacier, runoff, climate change, responses

Mountain glacier is a product of mutually joint action of climate and topography. At this point, climatic change make glacier adapt to its change through adjusting glacier area and length following the glacier inner movement law. In theory, glacier always corresponds to a stable state under a certain climatic condition. Because of limitation of the glacier movement law, the glacier has to gradually adapt to climatic change. Also, climate is always in change. So, it is almost impossible for glacier to reach the theoretical stable state. The purpose of this paper is to simulate the processes as the east branch of the Glacier No. 1 in the headwaters of the Ürümqi River reaches the stable state using a dynamic glacier model as well as the processes in response of the glacier to various climatic conditions.

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## I. THE DYNAMIC GLACIER MODEL

Glacier is always in movement, resulting from its internal deformation caused by gravitation. At the same time, glacier carries on the mass and energy exchange with atmosphere. The horizontal velocity along flow line is much larger than the vertical and perpendicular velocities. The role of the horizontal velocity is mainly considered here by integrating an appropriate equation over vertical coordination, which implies that some processes associated with vertical motion may be included too. As a result, an one-dimensional conservation equation, implicit tow-dimensional equation, for ice volume with independent variable $x$ along flow line can be written:

$$\frac{\partial S}{\partial t} = -\frac{\partial Q}{\partial x} + BW \tag{1}$$

where $S$ is the area of the cross section perpendicular to the main flow line ($x$), $t$ time, $Q$ ice flux, $B$ unit mass balance and $W$ the width of the glacier at the surface.

$Q$ in the equation embodies the information of glacier dynamics and $B$ reflects the effect of climate on glacier. Though climate may affect glacier temperature and therefore alter glacier movement velocity, those changes are so small that they may be ignored due to little fluctuation of air temperature during a long period.

Ice flux $Q$ can be written as:

$$Q = \overline{U} \cdot S \tag{2}$$

where $\overline{U}$ is mean velocity at the cross section.

As mentioned above, the total ice velocity ($U$) consists of a contribution from internal deformation ($U_d$) and base sliding ($U_s$), that is,

$$\begin{aligned} U &= U_d + U_s \\ &= A_1 H \tau_b^3 + A_2 \tau_b^3/(N - P) \end{aligned} \tag{3}$$

where $A_1$ and $A_2$ are flow parameters, respectively, $H$ ice thickness, $\tau_b$ base shear stress, $N$ overburden pressure at the ice base and $P$ surglacial water pressure. The base shear stress is defined as:

$$\tau_b = -\rho g H \sin\alpha \tag{4}$$

where $\rho$ is ice density, g acceleration of gravity, and $\alpha$ slope of glacier surface. As $\alpha$ is small, $\sin\alpha \approx \alpha = \frac{dz}{dx}$, where $z$ is altitude of ice surface.

Because of complex of internal movement, glaciers have different percentages in sliding velocity and deformation velocity. Also, some glaciers may appear to be characterized by the creep on clastic layer at the base. According to observation of the artificial ice cavity of the Glacier No.1 in headwaters of the Ürümqi River (Wang *et al.*, 1965), four movement mechanisms may be identified, i.e., deformation of glacier ice, deformation of ice bed, shear deformation and base sliding deformation, among which the deformation of glacier ice is the most important. For the glacier evolution research, distribution of the internal velocity appears to be trivial. It is only necessary to determine the mean velocity at the cross section. Additionally, the base sliding seems to be ignored for the continental and small glaciers whose end of tongue is in permafrost area. Therefore, the equation (3) can be simplified as:

$$U = A_1 H \tau_b^3 \tag{5}$$

The $\tau_b$ in the equation 4 is suitable for width-infinite glaciers and should be adjusted to fit mountain glaciers by the following way:

$$U = -A_1 f H^4 (\rho g)^3 \left(\frac{\partial z}{\partial x}\right)^3 \tag{6}$$

where $f$ is coefficient of the section morphologic factor(You, 1988).

Substitute equation 6 into equation 2,

$$Q = \overline{U} \cdot S = -f f_u A_1 f H^4 (\rho g)^3 \left(\frac{\partial z}{\partial x}\right)^3 \cdot HW \tag{7}$$

where $f_u$ is a synthetical coefficient from section area and mean velocity. Order $F = f_u \cdot A_1$, and $F$ represents a synthetical parameter determined by parameters of glacier flow, section area and mean velocity.

## II. THE DETERMINATION OF THE BASIC PARAMETERS

To simulate glacier change, the morphologic factors ($H$, $W$, $z$ etc.), mass balance $B$ and the synthetical parameter of glacier flow $F$ have to be determined.

### 1. The Morphologic Parameters

The altitude of ice surface and flow line as well as the width of ice surface can be obtained from glacier topographical map surveyed in 1962 and the map with ice thickness contour surveyed in 1986. To simplify the section shape and mathematical calculation, cross section of glacier is considered as a parabola.

### 2. Mass Balance $B$

Due to difference of ice and snow albedo, ice melt and snow melt volumes are different even under the same climatic condition. Ordering ice melt and snow melt as $M_i$ and $M_s$, respectively, monthly mass balance may be described by:

$$B(z) = P_s(z) - F_t M_s - (1 - F_t) M_i \tag{8}$$

where $P_s$ is snowfall and $F_t$ ratio of monthly snowmelt time ($F_t < 1$). As $F_t = 1$, it is pure snowmelt. As $F_t < 1$, it shows that ice is first melted and then snow. The ratio of monthly snowmelt time may be estimated by snow accumulation $P_{as}$:

$$F_t = P_{as} / M_s \tag{9}$$

Order:

$$M_i = KM_s \tag{10}$$

where $K$ is a constant, approximately 1.56 based on measured data in experiment of runoff in the Glacier No.1 (Ye *et al.*, 1996).

The melt intensity $M_s$ is calculated by monthly ablation of various altitudes and corresponding air temperature (Paterson, 1981). Data of ablation are from Annual Report of Tianshan Glaciological Station (1979 – 1990)①. Air temperature at various altitudes is estimated by air temperature gradient and air temperature jumping (Lai *et al.*, 1990). Their relation may be represented by:

$$M_s = a(T - b)^c \tag{11}$$

$a$, $b$ and $c$ values of each month are shown in Table 1.

Table 1 The coefficients of ablation function on the ice surface

| Month | $a$ | $b$ | $c$ | Coefficient | Samples |
|---|---|---|---|---|---|
| May | 11.19 | −8.5 | 1.267 | 0.50 | 58 |
| June | 0.798 | −7.5 | 3.05 | 0.75 | 63 |
| July | 0.502 | −7.0 | 3.349 | 0:86 | 63 |
| August | 7.94 | −8.0 | 1.945 | 0.56 | 64 |

3. Glacier Runoff

Because the changes of glacier runoff primarily depend on the changes in glacier area and climatic conditions, the contribution of evaporation to glacier runoff is quite small. However, Takahashi Equation (Lai *et al.*, 1990) is still applied in this study to estimate evaporation. Monthly temperature and monthly precipitation are mainly used as input data and sub-zero temperature is also considered. Thus, the glacier runoff is calculated by water balance in glaciated area:

$$R_g = \sum_{j=1}^{n} [F_j M_{sj} + (1 - F_j) M_{ij} + P_{rj} - E_j] \times \triangle F_{gj} \tag{12}$$

where $j$ is the distribution of glacier area along altitude, $F_j$ unit glacier area, $P_r$ precipitation and $E$ evaporation. Precipitation on the ice surface directly produces runoff.

## III. DETERMINATION AND TEST OF PARAMETERS

Major parameter of the glacier dynamic model is $F$. $F$ reflects the speed of glacier ice deformation and affects the results of calculating glacier advance and retreat. For a given section, $F$ is primarily determined by $A_1$ which represents glacier flow. Furthermore, $A_1$ is largely associated with ice temperature, ice crystal size and direction and content of impurity. Since $A_1$

① Annual Report on the Work at Tianshan Glaciological Station, No. 1 – 8.

changes largely in experimental measurements, it is not feasible to be directly determined. Here, $A_1$ is estimated by velocity of the Glacier No. 1 and filtered by the model.

Based on measured surface velocity, surface slope and ice thickness of the Glacier No. 1 during 1980 – 1985(You, 1987), $A_1$ was calculated by the equation 6 and listed in Table 2.

Table 2 suggests that the parameters of glacier flow vary slightly with altitude. Considering both the section area and the synthetical conversion coefficient $f_u$, the sensitive test of the

Table 2 Estimated flow parameter $A_1$ in the eastern branch of the Glacier No. 1

| Altitude (m) | Slope (‰) | Velocity (m/a) | Depth (m) | Width (m) | $f$ | $F$ ($10^{-18}m^6N^{-3}mon^{-1}$) |
|---|---|---|---|---|---|---|
| 4004 | 0.182 | 4.4 | 123 | 600 | 0.666 | 0.568 |
| 3970 | 0.192 | 5.0 | 122 | 615 | 0.696 | 0.556 |
| 3993 | 0.172 | 5.1 | 130 | 765 | 0.752 | 0.583 |
| 3847 | 0.278 | 5.5 | 91 | 575 | 0.764 | 0.593 |

changes in longitudinal thickness and ice length are made under different $F$ values. By comparing those estimated changes with measured ones, it is determined that $F$ is $0.15 \times 10^{-18} m^6 N^{-3} mon^{-1}$.

The model is calibrated and tested through comparison of the processes of glacier change between the simulated results using the model and the measured ones. The mass balance method and the dynamic parameters as mentioned above are selected to simulate the process of length change of the Glacier No. 1 using meteorological data from 1958 to 1988. The simulated and measured results are shown in Fig. 1. The simulated retreating rates and the measured ones are identical. It is demonstrated that the model is able to simulate the process in response of the glacier to climate.

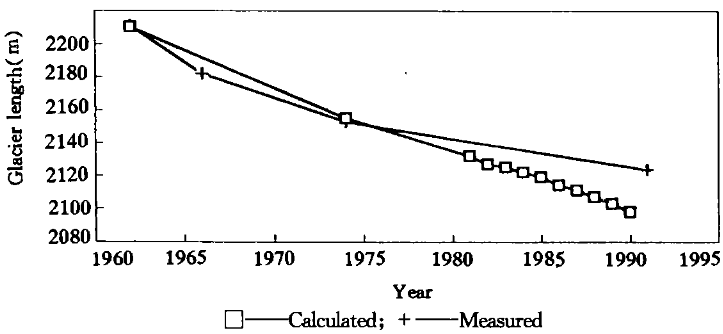
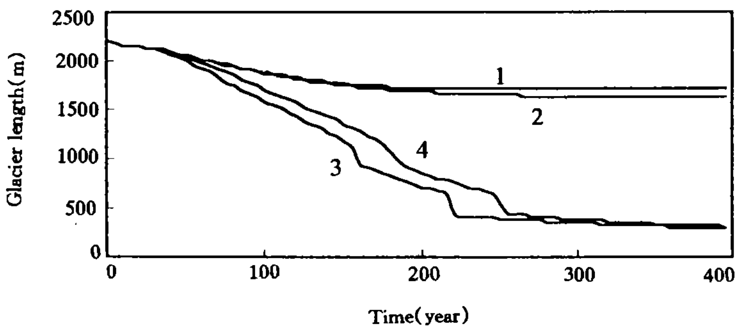



Fig. 1 Time series of glacier length changes at the Glacier No. 1

## IV. RESPONSES OF GLACIER TO CLIMATE

As discussed above, the dynamic glacier model may simulate the processes that determine the responses of glacier length, glacier area and glacier melt runoff to climate.

The Ipcc (Hongton *et al*., 1992) reports that the global temperature would rise by 1.2℃ till 2050 in comparison with 1990. At this rate, it is estimated that the global air temperature would increase about 0.8 – 1.0℃ till 2030. If the base air temperature is taken as the annual average temperature from 1958 to 1988 and the global air temperature would increase about 1.0℃ till 2030, for the purpose of comparison, three climatic scenarios in terms of air temperature can be assumed. Three scenarios are constant temperature, abrupt rising of 1.0℃ and linear rising of 1.0℃ from 1988 to 2030. If the base air temperature keeps constant and the air temperature jumping at glacier is estimated by glacier length in 1962 in consideration of the cooling role of glacier, additionally, another temperature scenario is assumed. Actually, there are four temperature scenarios in total. Changes in the glacier length, area and melt runoff are shown in Fig. 2,3 and 4. The beginning year in the figures is set to 1958.




1——constant temperature as cooling effect of glacier is not considered

2——constant temperature as cooling effect of glacier is considered

3——rising of 1.0℃ in temperature as cooling effect of glacier is not considered

4——rising of 1.0℃ in temperature as cooling effect of glacier is considered

Fig. 2 The change of glacier length under different climatic conditions

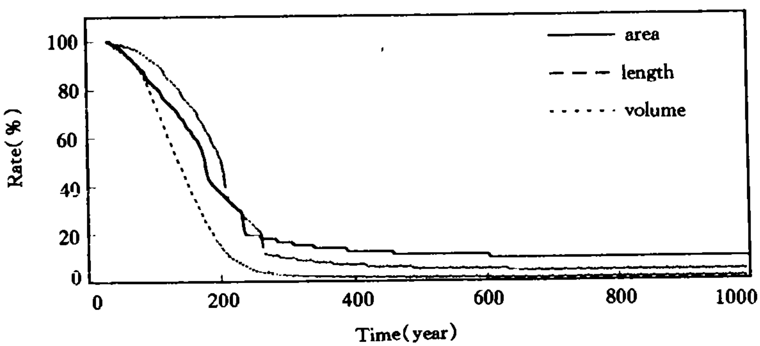
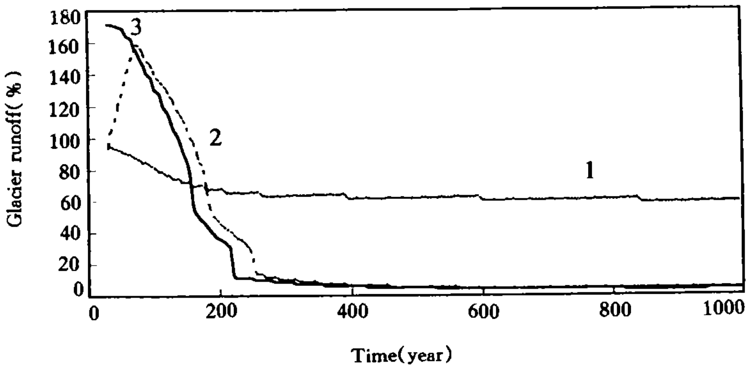



Fig. 3 The change of glacier length, area and volume as air temperature rises by 1℃

It may be seen from the figures that the length of the east branch will be 1600 m as the glacier reaches the stable state if air temperature keeps the level of 1958 – 1988 and cooling effect is not considered (1 in Fig. 2) The result is somewhat different from Cao Meisheng's that the stable length is 1865 m (Cao *et al.*, 1987). The reason is that Cao Meisheng used −81 mm as mass balance but author uses −162 mm through calculation as mass balance. The mass balance used in this study is closer to the measured one.

Fig. 3 shows that the length, area and volume of the glacier will gradually decrease as air temperature rises by 1.0℃ in the coming 40 years. The rate of those decreases will increase with temperature rising, then it will tend to be stable. However, glacier runoff change is diff




1——constant temperature

2——linear rising by 1.0℃ in temperature in 40 years

3——abrupt rising by 1.0℃ in temperature

Fig. 4 The changes of glacier runoff under the different climatic conditions

erent (Fig. 4). It displays the increasing process as temperature rises. As the glacier reaches the stable condition, the decrease of the volume is the most obvious, change of the length is the smallest, and the decrease of the area and runoff are in medium. It needs about 600 years for the Glacier No. 1 to reach the stable condition (weakening is theoretically unlimited). The stable length is about 300 m. The east branch will become a hanging glacier.

Hydrography of glacier runoff (Fig. 4) indicates that runoff of the Glacier No. 1 at present is in higher level than the runoff at equilibrium. In this case, present glacier runoff in the Tianshan Mountains is much higher than the supply of their equilibrium state. The glacier runoff may still continue increasing with rising of temperature in future until it comes up to the maximum. The glacier may keeps its maximum runoff for a short term and then may rapidly reduce with shrinking of the glacier area.

Under the present climatic condition, it would need 800 years for the Glacier No. 1 to reach the stable state at which the stable length would be 1600 m. Based on the size of glacier and time when it reaches stability, the larger the scope of the glacier is, the longer the time when the glacier reaches stability is.

## V. CONCLUSIONS

The study primarily focus on simulations of the processes that control the response of the east branch of the Glacier No. 1 to climatic change using the dynamic glacier model and the glacier runoff model. The results might be obtained as follows.

(1) If the climate is maintained at the level of 1958 – 1988 and cooling effect of glacier is ignored, the stable length of east branch of the Glacier No. 1 would be about 1700 m. If cooling effect of the glacier is considered, however, the stable length would be about 1600 m.

(2) If air temperature rises by 1℃ (because cooling effect reduces, rising of air temperature might be about 2℃ in glaciated area), the east branch of the Glacier No. 1 would become a hanging Glacier with the length of 300 m.

(3) At present, runoff of the Glacier No. 1 appears to be in higher duration and in relative stability.

(4) Rising in air temperature would cause glacier runoff increase in the beginning stage, and then rapidly reduce.

(5) Increment of runoff and occurrence of its peak would be determined by the rate of air temperature rising.

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