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Article

The response of glacier ELA to climate fluctuations on High-Asia

ZHANG Yinsheng[1], **Koji FUJITA**[2],
Yutaka AGETA[2], **Masayoshi NAKAWO**[2], **YAO Tandong**[1] **and PU Jianchen**[1]
1 Lanzhou Institute of Glaciology and Geocryology, CAS, Lanzhou, 730000 China
2 Institute for Hydrospheric-Atmospheric Sciences, Nagoya University, Nagoya 464-01, Japan

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Abstract

An algorithm for quantitatively estimating the fluctuation of equilibrium line altitude (ELA) in response to climate changes, coupling the effects of evaporation and formation of superimposed ice to the energy exchange process on the glacier surface, was developed and examined. The correlation of accumulation to air temperature variation on the glacier surface was introduced. The application with the algorithm to Dongkemadi Glacier in Tanggula Mts, Glacier No.1 in Tianshan Mts, "July 1" Glacier in Qilian Mts and Glacier AX010 in the Nepal Himalayas suggested the quite different response of glaciers to the same climatic change scenario. It was found that the ELA fluctuation ranged from 52 to 152 m in response to a summer mean air temperature change of 1°C, about 9 to 85 m to an annual precipitation change of 100 mm, and 37 to 63 m to the net radiation change of 1MJ/m^2 for the studied glaciers. The sensitivity examination revealed that the higher the mean air temperature in melting season at ELA was, the larger the ELA fluctuated in response to temperature variations, in contrast, the higher the annual precipitation at ELA was, the smaller the ELA fluctuated in response to precipitation change in the region. The simulated results of ELA fluctuations to climate change on Glacier No.1 by the algorithm are fairly consistent with those observed from 1959 to 1993.

1. Introduction

Equilibrium line altitude (ELA), glacier length as well as mean specific mass balance, are important parameters in characterizing the state of a glacier. The inter-annual variations or deviations from a long-term mean value of the parameters can be interpreted as the response of glaciers to the changing climate. Among these parameters the ELA is considered as the most sensitive one to the climatic fluctuations. The pioneer work in relevant studies has been conducted by Kuhn (1980), with an algorithm developed by coupling the mass-, energy- exchange on the glacier surface with glacial-meteorological approach. The algorithm was applied for estimation of ELA shift on glaciers of Andes and Greenland Ice Cap (Kuhn, 1989; Ambach and Kuhn, 1985; Ambach, 1985; Ambach and Kuhn, 1989) for the given climatic conditions.

On the basis of models mentioned above, an algorithm for estimating the glacier response to climate change in High-Asia was developed with the following modifications. 1) Evaporation on the glacier surface was coupled in the algorithm owing to its significant contribution to mass and energy exchange budget in the mass-energy regimes for the glaciers in arid or semi-arid regions (Zhang *et al.*, 1996). 2) The effect of superimposed ice formation to retention of water on the glaciers under conditions of low temperature (Fujita *et al.*, 1996) was taken into account in the model. 3) The snowfall in the total precipitation was partitioned by using a empirical formulae instead of accumulation on the glaciers. The following glaciers are selected for the present study: Dongkemadi Glacier in Tanggula Mts., Glacier No.1 in Tianshan Mts. and "July 1" Glacier in Qilian Mts. in China, and Glacier AX010 in the Nepal Himalayas. The geo-

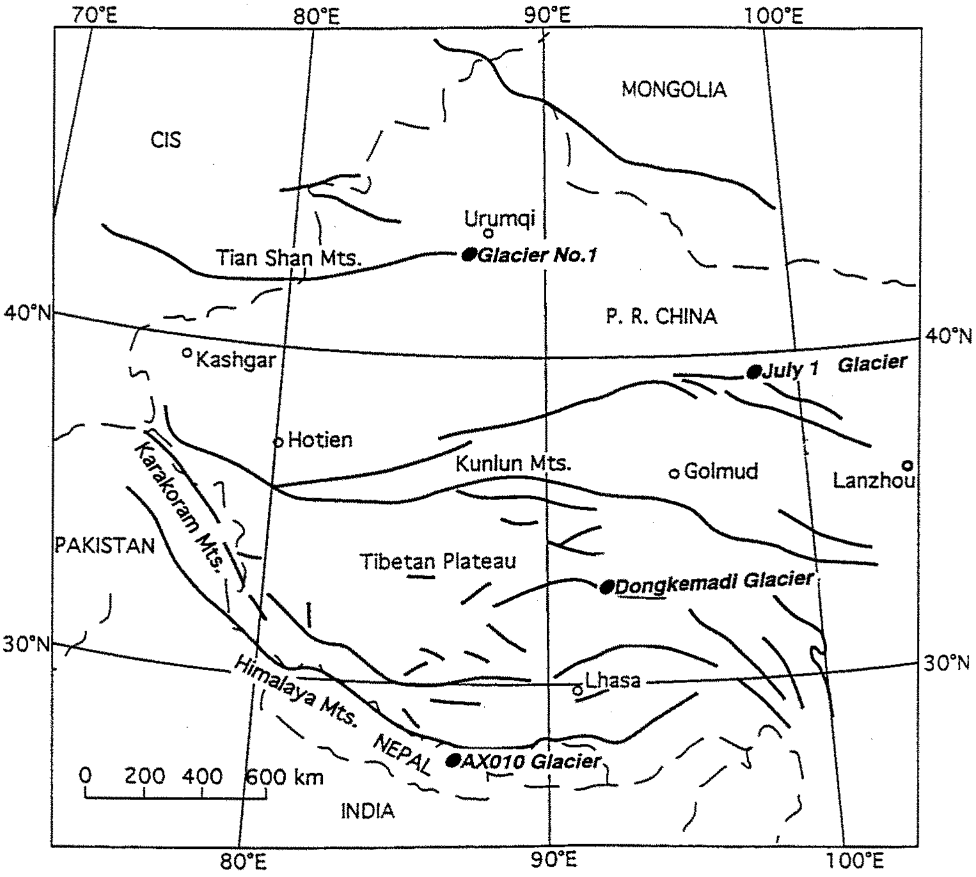

Fig. 1. Geographic location map of the studied glaciers

graphical locations of these glaciers are shown in Fig. 1. The long-term mass- and energy- balance measurements and glacio-meteorological observations have been carried out on these glaciers.

2. Principal method

2.1. Mass and energy balance at ELA

At the equilibrium line altitude H, the annual accumulation C equals annual ablation A within a mass balance year. Ablation A can be calculated from the surface energy budget of glaciers. The energy budget equation with the unit of MJ/m²d can be written as :

$$Q_m + Q_l = Q_r + Q_s + Q_c, \tag{1}$$

in which right side of equation are energy income terms, and the left side are outgoing energy terms. We definite the flux as positive when it comes to the glacier, and as negative when flux leaves from the surface. Q_r, Q_s, Q_l, Q_m and Q_c are average flux of net radiation, sensible heat, latent heat, melting heat, and conductive heat for a whole melting season respectively. At ELA, annual cumulative accumulation and ablation are equal at the end of the balance year. Melting amount M and evaporating amount E for a whole melting period are response to the heat flux Q_m and Q_l respectively (Ambach and Kuhn, 1989) :

$$\tau Q_m = LKM, \tag{2}$$

$$\tau Q_l = L_v E, \tag{3}$$

where, τ is the number of days in melting season with daily mean air temperature over 0℃. Note that an air temperature of 0℃ is not necessarily the threshold of ablation, but it is a practical approximation (Ambach and Kuhn, 1989). τ is assumed to be a constant on a given glacier. L is the specific latent heat of melting

(0.334 MJ/kg), while L_v denotes the specific latent heat of vaporization (2.5 MJ/kg). K is the proportional factor when taking the contribution of the superimposed ice formation into account. In case of superimposed ice formation, the heat necessary for melting one annual layer (Q^l_m) is higher by a factor of K than it is in case of melting annual layer without any formation of superimposed ice (Q_m) :

$$\mathrm{K} = Q^l_m / Q_m \tag{4}$$

At the ELA, the mass balance equation can be expressed as :

$$C = A = M + E \tag{5}$$

Synthesizing the equations (1) to (5), the energy-mass balance equation at ELA can be deduced to the expression like this :

$$C = \frac{\tau}{LK} Q + \left(\frac{\tau}{LK} + \frac{\tau}{L_v}\right) Q_l. \tag{6}$$

Where $Q = Q_r + Q_s + Q_c$. A climatic fluctuation of either one, δC, δQ_r and δT, will lead to a shift of the equilibrium line altitude by δH to a position where the variables have changed according to their respective vertical gradient, $\partial C / \partial z$, $\partial T / \partial z$, and $\partial Q / \partial z$.

At the new ELA, where the elements have varied with $\delta + \delta H(\partial / \partial z)$, the mass-energy balance can be written as :

$$\frac{\partial C}{\partial z} \delta H + \delta C = \frac{\tau}{LK} \left(Q + \frac{\partial Q}{\partial z} \delta H + \delta Q\right) + \left(\frac{\tau}{LK} + \frac{\tau}{L_v}\right) \left(Q_l + \frac{\partial Q}{\partial z} \delta H + \delta Q_l\right). \tag{7}$$

From equation (5) and (6), it is easy to deduce that:

$$\delta H = \frac{\frac{\tau}{LK} \delta Q - \delta C + \left(\frac{\tau}{LK} + \frac{\tau}{L_v}\right) \delta Q_l}{\frac{\partial C}{\partial z} - \frac{\tau}{LK} \frac{\partial Q}{\partial z} - \left(\frac{\tau}{LK} + \frac{\tau}{L_v}\right) \frac{\partial Q_l}{\partial z}} \tag{8}$$

δH is ELA shift value under a climatic fluctuation of δ.

2.2. *Parameterization*

For the application, the model has to be parameterized. Some variables have to be fixed as constant values following the previous assumptions in modeling work on glaciers. Some factors will be simplified considering the accuracy and the present condition of glaciological measurements.

a) The effect of temperature on accumulation

Due to the influence of monsoon climate, both accumulation and ablation processes on the studied glaciers simultaneously take place in warm season. Amount of accumulation is not only determined by the total precipitation, but also depends on the proportion of solid precipitation in the total precipitation due to the air temperature variations. Therefore, it is necessary to introduce the relation between solid precipitation and air temperature to the algorithm. If drift snow and avalanches are disregarded, accumulation could be thought to be equal to the amount of solid precipitation. Previous studies, which carried out on the glaciers of the Tianshans, China and the Nepal Himalayas (Ageta, 1980 ; Ageta, 1983a ; Ageta, 1983b ; Ageta, 1983c), show that solid precipitation in the melting season can be written as :

$$C_s = SP_a (a_1 + b_1 T) \tag{9}$$

in which a_1 and b_1 are coefficients, C_s denote the accumulation from solid precipitation in melting season, P_a is annual precipitation, S is the ratio of precipitation in melting season to annual one. T is mean air temperature in melting season. So, the annual accumulation from precipitation C can be expressed as :

$$C = P_a S (a_1 + b_1 T) + P_a (1 - S),$$

$$\text{or} \quad \delta C = \delta [P_a S (a_1 + b_1 T) + (1 - S) P_a]. \tag{10}$$

Furthermore, for the accumulation gradient, we have :

$$\frac{\partial C}{\partial z} = \frac{\delta (P_a S (a_1 + b_1 T) + P_a (1 - S))}{\partial z}.$$

It is wildly accepted that S is independent of altitude :

$$\frac{\partial C}{\partial z} = (1 + a_1 S - S + b_1 ST) \frac{\partial P_a}{\partial z} + b_1 SP_a \frac{\partial T}{\partial z} \tag{11}$$

The calculated results which in form of equation (9) for the selected glaciers are shown in Table 1.

b) The formation of superimposed ice

The contribution of superimposed ice formation on energy budget regime of the glaciers has been studied on Greenland ice sheet and glaciers of Alps (Ambach and Kuh, 1985). For the calculation of K, the water equivalent of initial snow-pack before melting (W_0), superimposed ice (W_1) formed from the melted part of W_0, and superimposed ice layer (W_2) are introduced. The mean density of snow layer and superimposed ice are fixed to be 300 kg/m³ and 900 kg/m³ respectively. The water equivalent of the above mentioned parameters can be calculated as :

$$W_0 = h_0 \ 300, \tag{12}$$

$$W_1 = (h_0 - h_2) \ 300, \tag{13}$$

Table 1. The descriptive formulas for an amount of solid precipitation correlated to the summer air temperature and precipitation

	Formula	suitable range of T (℃)	Reference
Dongkemadi Glacier	$C_s=P_aS\ (0.92-0.14T)$	$-0.6<T<0.6$	Ueno *et al.*, 1994
Glacier No. 1	$C_s=P_aS\ (0.89-0.13T)$	$-0.9<T<6.8$	This work
"July1" Glacier	$C_s=P_aS\ (0.85-0.10T)$	$-1.5<T<8.5$	This work
Glacier AX010	$C_s=P_aS\ (0.80-0.23T)$	$-0.8<T<3.4$	Ageta, 1983

C_s: amount of solid precipitation in melting season.
P_a: amount of annual precipitation.
S : fraction of precipitation in melting season to annual precipitation.
T : mean air temperature in melting season, the formula for Dongkemadi Glacier is simulated to the mean temperature for precipitation period. To consider the similarity of the formula for the mean temperature in whole melting season and for the precipitation period (Ageta, 1983), the formula is quoted directly here.

$$W_2=h_2\ 900. \tag{14}$$

In which h_0 is the initial snow depth and h_2 is the thickness of the superimposed ice layer.

In the case of superimposed ice formation at the equilibrium line, the melting amount is W_1+W_2, whereas in case of no superimposed ice formed the melting amount is W_0. By means of expression (4) and (12-14), the fraction K can be deduced as :

$$K=1+\frac{2}{3}k_2 \tag{15}$$

Note, $k_2=W_2/W_0$, which denotes the fraction of superimposed ice to annual snow accumulation in w.e.

From equation (15), one can easily deduce that $K=5/3$ when melted snow layer has been completely transited into superimposed ice ($W_2=W_0$), while $K=1$ corresponds to none superimposed ice formed ($W_2=0$).

c) Radiation

When ELA changes to a new position, the difference of net radiation at new ELA and former one consists of two parts. One is temporal variation (δQ_r), and another is spatial variation caused by ELA shift ($\delta H(\partial Q_r/\partial z)$). The first one is naturally caused and will be taken as an element for sensitivity examination, hence, only spatial variation has to be parameterized

When a negative flux is defined as it leaves the glacier surface, net radiation can be expressed as:

$$Q_r=Q_g(1-\alpha)+\varepsilon\sigma T^4-\sigma T_s^4, \tag{16}$$

thus its altitude gradient can be written as:

$$\frac{\partial Q_r}{\partial z}=(1-\alpha)\frac{\partial Q_g}{\partial z}-Q_g\frac{\partial \alpha}{\partial z}+4\varepsilon\sigma T^3\frac{\partial T}{\partial z}-4\sigma T_s^3\frac{\partial T_s}{\partial z}, \tag{17}$$

in which Q_g is global radiation. α albedo. σ Stefan-Boltzmann constant. ε the relative emissivity which is fixed at 0.91 according to Group of Tibetan Plateau Meteorological research (1979).

In the right-hand of equation (17), the fourth term, as an upward long-wave radiation gradient, can be considered as zero for the melting surface. The gradient of albedo also can be neglected considering the less difference of surface condition between former ELA and shifted ELA.

Previous works of heat balance study on glaciers in High-Asia show that the global radiation gradient is small at the altitude over 3500 m a.s.l. (Bai, 1988). It is only about 17 % of mean value in the free atmosphere. Actually, Kuhn (1980) has point out that, in variation of net radiation along altitude, only the change of the long-wave downward radiation with the air temperature needs to be taken into account. Combining discussion made previously, the gradient of net radiation can be written as :

$$\partial Q_r/\partial z=4\varepsilon\sigma T^3\partial T/\partial z \tag{18}$$

d) Turbulent fluxes of sensible heat and latent heat

Turbulent flux can be computed by :

$$Q_s=\alpha_h(T-T_s), \tag{19}$$

$$Q_l=0.622\,L_v\alpha_L((e-e_s)/P). \tag{20}$$

Where α_h and α_L are bulk heat and vapor transfer coefficient respectively, T and T_s are air temperature above and on the surface of glaciers, e and e_s are vapor pressure above and on surface of glaciers, P is air pressure.

In the melting seasons, the T_s and e_s are assumed to be at 0 ℃ and 0.611 hPa respectively. Such assumption is necessary for the calculation and has been frequently used in the modeling work on the glacier surfaces (Kuhn, 1989; Oerlemans, 1992). Another assumption is performed on relative humidity (RH), which is considered to be independent of altitude on the glacier surface.

The bulk transfer coefficient, α_h and α_L are considered to be independent of altitude. These values have taken to be a constant for modeling studies (Oerlemans, 1992). α_h and α_L, therefore, are calculated according to previous energy balance results on each glaciers in the present study.

On the basis of analyses made previously, one can parameterize the sensible heat in the following forms:

$$\delta Q_s=\alpha_h\delta T \quad \text{or} \quad \frac{\partial Q_s}{\partial z}=\alpha_h\frac{\partial T}{\partial z}, \tag{21}$$

as for latent heat, the spatial variation can be parameterized by :

$$\frac{\partial Q_l}{\partial z}=0.622\frac{L_v}{c_p}\alpha_L\frac{PH}{P}\frac{\partial F(T)}{\partial z} \tag{22}$$

Where $F(T)$ is a function of air temperature. Considering that there is no suitable method to parameterize δRH up to now, it is necessary to introduce Bowen ratio β to parameterize δQ_l by relation of $\delta O_l=\delta O_s/\beta$. Here, β is fixed to the average value that can be calculated from previous heat balance equations.

Previous work has shown that the conductive heat Q_c on the given glaciers is very small compared to other energy terms (Kang *et al.*, 1992, Ohata *et al.*, 1980, Zhang *et al.*, 1996). Furthermore, the heat transfer which caused by refreezing has been taken into account by introducing factor K , therefore, δQ_c and $\partial Qc/\partial z$ are negligible in the present algorithm.

3. Numerical results

3.1. Previous results on the given glaciers

The typical values of some parameters used for the present calculation are shown in Table 2. These values are quoted from previous studies on the related glaciers (Ageta, *et al.*, 1980 ; Bai *et al.*, 1988 ; Kang *et al.*, 1992). The data were obtained partly from energy balance observations carried out on elevations higher than mean ELA, partly from lower elevations. These results will be extended to the whole elevation ranges of the glaciers in the calculations by means of equations (18)-(22).

It should be pointed out that the k_2 values used in present work was quoted from the observed results on glacier accumulation zone. It is calculated as the ratio of superimposed ice to the annual snow accumulation

Table 2. Some characteristic values on the studied glaciers of High-Asia

	Dongkemadi Glacier	Glacier No. 1	"July 1" Glacier	Glacier AX010*
Location	33°04N 92°05E	43°06N 86°49E	39°14N 99°45E	27°42N 86°34E
Mean ELA (m a.s.l.)	5600	4049	4670	5200
area (km²)	1.77	1.83	2.98	0.57
Length (km)	2.80	2.20	3.80	1.70
τ (days)	61	71	42	90
k_2	0.26	0.10	0.90	0.00
Q_s (MJ/m²d)	0.52	1.49～1.00	0.34	3.26～0.34
Q_l (MJ/m²d)	−0.33	−0.34～−0.96	−0.30	−0.04～0.33
$\partial P_a/\partial z$(mm/m)	0.47	0.22	0.15	0.00
$\partial T/\partial z$(K/m)	0.0086	0.0088	0.0066	0.0060
*Pa*** (mm)	845	650	413	1600
S (%)	72.5	65.8	69.7	80.0
T** (℃)	−1.4	−0.5	0.0	1.1
*RH*** (%)	77	65	67	82

* : The data after Ageta, (1983), Ohata *et al.*, (1980) and Kayastha, (1994).

** : Average value for melting season.

with unit of w.e. The value of k_2 on "July 1" is abnormally high, the results were obtained by the investigation in summer of 1995. It has been reported that the snow layers was almost completely transited to superimposed ice on "July 1" Glacier (Xie, 1988).

On the given glaciers, the mean air temperature at ELA in melting seasons are equal or lower than 0 ℃ except on Glacier AX010. It is attributed to the effect of the regional climatic regime that is controlled by monsoon climate. As mentioned previously, much of the precipitation on the glaciers occur in melting seasons. The air temperature would decrease to much lower level than 0 ℃ since one weather system passes, then the temperature will go up to high and sustained to another weather system comes. Therefore, the ablation occurs in melting season even the mean air temperature is below 0 ℃.

3.2. The sensitivity of ELA in response to climatic fluctuations

According to the parameterizations described, equation (7) can be solved for individual climatic fluctuation scenarios. The calculated ELA shifts under the different climate fluctuation scenarios on given glaciers are presented in Table 3.

The shifts of ELA on the selected glaciers behave quite differently for individual scenarios. The maximum $\delta H/\delta T$ occurs on Glacier AX010 with the value of 152.9 m/K, but its $\delta H/\delta P_a$ is the least among the glaciers with the value of 9.0 m/100 mm. The minimum $\delta H/\delta T$ can be seen on the "July 1" Glacier, which is just 1/3 of that on Glacier AX010, but its $\delta H/\delta P_a$ is maximum among the studied glaciers. The maximum value of $\delta H/\delta Q_r$ is calculated on "July 1" Glacier located on the most exterior region of the Tibetan Plateau.

The relevant studies have been conducted on Hintereis Glacier in the Alps by Kuhn (1989), and on the Greenland Ice Cap by Ambach (1985). Results from Hintereis Glacier revealed that 65 m shift of the ELA corresponds to 1 K change in an annual mean air temperature, and -35 m shift of the ELA to 100 mm change of annual accumulation, and 130 m shift to a net radiation changes of 1 $\mathrm{MJm^{-1}d^{-1}}$. On the Greenland Ice Cap, the $\delta H/\delta T$ and $\delta H/\delta P_a$ were calculated to be 87.5 m/K and -48.6 m/100 mm respectively. The value of $\delta H/\delta Q_r$ on Hintereis Glacier is about two or three times larger than those from glaciers in High Asia. This is probably attributed to the seasonal difference in precipitation distribution between these two types of glaciers. Higher albedo resulted from large amount of precipitation in melting seasons is undoubtedly responsible for the decrease of $\delta H/\delta Q_r$ values in High Asia-glaciers.

3.3. The sensitivity of mass balance in response to climatic fluctuations

Mean specific mass balance was found roughly correlated with the ELA in a linear relationship by the expression as below :

$$B=a_2+b_2H \text{ or in another form } \delta B=b_2\delta H. \quad (17)$$

Here, a_2 and b_2 are coefficient. Equation (17) makes it possible to compute the sensitivity of mass balance to climatic fluctuation. The computed results are listed on Table 4, which based on the reported mass balance

Table 3. The calculating results of shift of ELA response to climatic fluctuation on glaciers of High-Asia

	Dongkemadi Glacier	Glacier No. 1	"July 1" Glacier	Glacier AX010*
$\delta H/\delta T$ (m/K)	58.2	85.8	52.1	152.9
$\delta H/\delta P_a$ (m/100mm)	−38	−29	−85	−9
$\delta H/\delta Q_r$ ($\mathrm{m/MJm^{-2}d^{-1}}$)	55.6	44.5	62.9	37.3

* : The data source same as Table 2.

Table 4. Sensitivity of glacier mass balance in response to climatic fluctuation on High-Asia

	Dongkemadi Glacier	Glacier No. 1	"July 1" Glacier
$\delta B/\delta T$ (mm/K)	−181.9	−571.7	−130.5
$\delta B/\delta P_a$ (mm/100mm)	130	126	213
$\delta B/\delta Q_r$ ($\mathrm{mm/MJm^{-2}d^{-1}}$)	−173.8	−297.0	−167.2

observation on the glaciers (Liu *et al.*, 1992 ; Pu 1994 ; UNESCO, 1996).

It was calculated that value of $\delta B/\delta T$ on Glacier No.1 is 4.6, and 3.3 times higher than those obtained on "July 1" Glacier and Donkemadi Glacier correspondingly. The value of $\delta B/\delta Q_r$ on Glacier No.1 is also high compared with those obtained on other glaciers. It is about 1.9 and 1.7 times higher than those obtained from "July 1"Glacier and Dongkemadi Glacier respectively. This result may be helpful to explain the reason why there is such a difference in tendency of mass balance variations between Glacier No.1 and "July 1" Glacier since 1958 as shown in Fig. 2. On Glacier No. 1, with relative a large $\delta B/\delta T$ but small $\delta B/\delta P_a$ values, the cumulative mean specific mass balance reaches -4700 mm w.e. from 1958 to 1993. Conversely, the mass balance on "July 1" Glacier of small $\delta B/\delta T$ but large $\delta B/\delta P_a$ values, varied more steadily and the cumulative mean specific mass balance reached about 2000 mm w.e. during 1956 and 1988.

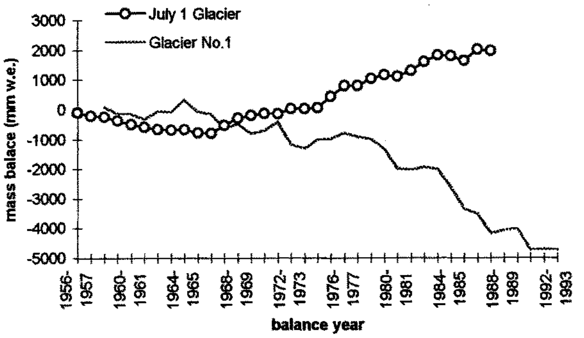

Fig. 2. Cumulative specific mass balance for whole glacier area on Glacier No.1 and on "July 1" Glacier

The different response of the glaciers to climatic fluctuation might be partially resulted from their characteristic energy exchange processes. An evidence is the bulk heat transfer coefficient (α_h). Value of α_h on Glacier No.1 is as 4 times higher as that on "July 1" Glacier. That means with same temperature condition, the surface of Glacier No.1 can receive more heat for melting from turbulent transfer than that of "July 1" Glacier.

It is worthwhile to mention that the calculated $\delta B/\delta P_a$ values for the studied glaciers are higher than 100 mm/100 mm as whole, especially on "July 1" Glacier it reaches to 213 mm/100 mm. It is probably caused by two reasons. One is that the superimposed ice is formed by a process in which it involves not only the formation but also the re-melting of the superimposed ice. Such process will consume more energy, and probably result in the increase of $\delta B/\delta P_a$. Another is attributed to the effect of the albedo on accumulation and ablation process of the glaciers in melting seasons.

4. Simulation on Glacier No. 1

4.1. Simulation on historical ELA shift

The changes in the radiation balance (δQ_r) play a significant role for the ELA shift in response to climatic fluctuations. Unfortunately, there are few long-term net radiation or related observations that has been carried out in the High Asia glaciers. Therefore, in the practical simulation of ELA shifts in response to climatic fluctuations on glaciers, δQ_r was usually disregarded and the model was simplified when it was used for simulation on historical ELA variations (Kerschner, 1996).

In consideration of data availability, the Glacier No.1 at the Headwater of Urumuqi River, Tianshan Mts., China was selected as an example for simulation by using the proposed algorithm. The mass balance measurement as well as meteorological observations at the nearby Meteorological Station of Daxigou on 3549 m a.s.l. have been carried out from 1958 up to now. Furthermore, short-term intensive glacial-meteorology investigations in the melting seasons were carried out near the ELA in 1958, 1982, and 1985-1988 respectively. The parameters required in the model, therefore, can be calculated reasonably.

The mean summer air temperatures on the glacier were taken from data on Daxigou Station and extended it to the position of ELA with constant gradient which is calculated as 0.88 K/100 m with the long term data. Similarly, annual precipitation at ELA was obtained by taking its gradient with altitude (22 mm/100 m) and catch ratio of the precipitation gauges into accounts. As for the ratio of precipitation in melting season to the annual amount (S), the temporary values were used in the model regarding to its sensitiveness to the climatic changes, and was calculated for each mass balance years separately.

To achieve optimal results, summer air temperature deviation δT^l and annual precipitation deviation δP_a^l at ELA of Glacier No.1 can be calculated as :

$$\delta T^l = (T - \bar{T}) * 0.958,$$

$$\delta P_a' = (P_a - \bar{P}_a)*0.961.$$

The coefficient of 0.958 and 0.961 were obtained from computation technique. The differential adjustment of δT and δP_a will help to improve the correlation between observed and modeled ELAs.

Figure 3 illustrates the simulated results of ELA variations in response to climate fluctuations on Glacier No.1 from 1958 to 1993 (observation was interrupted from 1968 to 1978). Calculated curve is fairly consistent with the observed one. The correlation coefficient between the observed and simulated ELA is 0.90, which means over 80 % of the variance has been explained.

4.2. The contribution of climatic elements to ELA shift

The fluctuation of climatic parameters, such as air temperature, precipitation and radiation, is bound to lead the varying state of the glaciers. This varying state of the glaciers will be manifested in the variation of ELA and mass balance. In another words, the glaciers always adjust its state in response to climatic fluctuations through its energy, mass and dynamic processes. For glaciological studies, it is essential to understand how the ELA varies to respond to the changing climatic conditions.

The probability analyses on occurrence of such fluctuations can be made through comparing their magnitude to the long-term variance of seasonal means. Such values can be conveniently estimated from air temperature (T) in the melting period and from annual precipitation (P_a). The following examples, for Glacier No.1, are taken from the data of 1958-1993 on Daxigou Meteorological Station at Headwater of Urumuqi River Tianshan Mts., China.

According to results represented on Table 3, changes needed to cause a 100m shift of the ELA on the Glacier No.1 are calculated as :

$$\delta T = 1.2\ ℃,\ \delta P_a = 334\ \text{mm}.$$

The mean summer air temperature $\bar{T}$ and its standard deviation σT at ELA from 1959-1993, which are calculated by extension of data on Daxigou Station as :

$$\bar{T} = -0.5\ ℃, \text{ and } \sigma T = 0.57\ ℃.$$

The mean annual precipitation $\bar{P}_a$ and its standard deviation σP_a at ELA from 1959-1993, which are calculated by extension of data on Daxigou Station as :

$$\bar{P}_a = 624.0\ \text{mm and } \sigma P_a = 52.3\ \text{mm or } 8.4\ \%.$$

Comparing the δ values that are required for a 100 m shift of the ELA to the respective deviations, we have :

$$\delta T / \delta T = 2.1 \quad \text{and} \quad \delta P_a / \sigma P_a = 6.4.$$

Since $\delta T / \sigma T$ is lower than $\delta P_a / \sigma P_a$, as we expected the change is more likely to occur in temperature than in precipitation. On Hintereis Glacier in the Alps, it was deduced that the corresponding fluctuation is more likely in the accumulation than that in the summer air temperature (Kuhn, 1980).

There are no data for the other glaciers. Previous

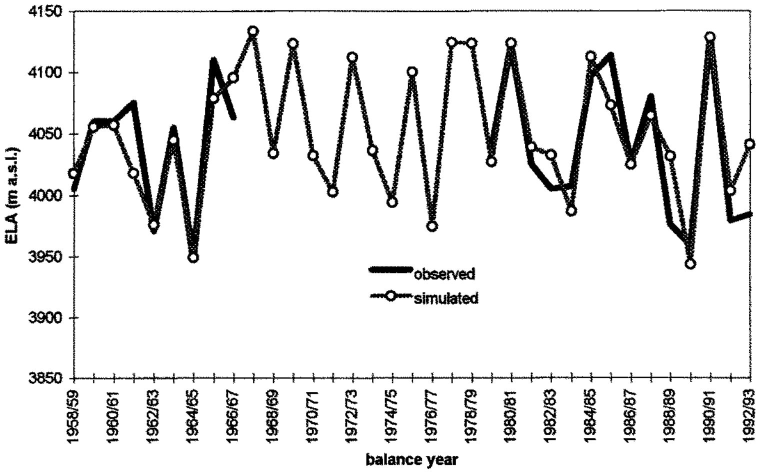

Fig. 3. Simulation results of ELA on Glacier No.1, Tianshan Mts.

study showed that precipitation contributed much to ELA shift on continental-type glacier (Ren, 1988). Actually, there exists quite complex relation among air temperature, precipitation and glacier fluctuation. The study in the Nepal Himalayas shows that the glaciers are likely more sensitive to air temperature fluctuations (Ageta, 1983a).

5. Discussion

5.1. The effect of formation of superimposed ice on ELA shift

It has been reported that the superimposed ice plays a significant role in the glacier fluctuation on Tibetan Plateau. Therefore, it is important to know how the superimposed ice influences the ELA shift in response to the climatic fluctuation. However, due to the limitation of the present algorithm, we can not discuss it with a physical equation. Here, the sensitivity of ELA to the climatic elements was recalculated disregarding the formation of superimposed ice and compared it to real results. The comparison between them is given in Table 5.

From this study, it is clear that the formation of superimposed ice plays a significant role on ELA shift in response to the climatic fluctuation, except for AX010 Glacier on which the superimposed ice formation is small formed (Ageta *et al.*, 1980). The formation of superimposed ice reduces the $\delta H/\delta T$ values about 6-31 %, and $\delta H/\delta Q_r$ values of about 2-28 %. Conversely it raises $\delta H/\delta P_a$ values by 12-34 %. Consequently, the formation of superimposed ice reduces the sensitivity of ELA to the climatic change on the glaciers in High Asia under the global warming. But its influence is different depending on glaciers.

5.2. The effect of evaporation on ELA

Table 5 shows the ELA shift in response to the climatic fluctuation when the effect of evaporation on the mass-, energy- exchange regimes of the glaciers was neglected.

The effect of evaporation on ELA shift is more complex than the formation of superimposed ice does. It reduces the $\delta H/\delta T$ values about 3-25 % and raise the $\delta H/\delta P_a$ value with 4-10 % on the glaciers. Meanwhile, $\delta H/\delta Q_r$ is increased 3-5 %.

5.3. The correlation of ELA shift to the ambient atmospheric conditions

The behaviors of ELA shift in response to the climatic fluctuations would be influenced by its ambient atmosphere conditions. Figure 4 shows relation of $\delta H/\delta T$ versus the mean summer air temperature at ELA (a) and $\delta H/\delta P_a$ versus the mean annul precipitation at ELA (b). On the given glaciers, the $\delta H/\delta T$ values increase with the mean summer air temperature at ELA. Moreover, the absolute values of $\delta H/\delta P_a$ regularly decrease with the mean annul precipitation at ELA.

In Table 6, the calculated results of $\delta H/\delta T$ and $\delta H/\delta P_a$, which were obtained on the glaciers in Greenland, Europe Alps and High-Asia, are compared. The values of $\delta H/\delta P_a$ are converted to the unit of m/% instead of m/mm for considering the regional differ-

Table 5. The effects of formation of superimposed ice (FSI) and evaporation (Eva) on ELA shift values of glaciers on High Asia

		Dongkemadi Glacier	Glacier No. 1	"July 1" Glacier
$\delta H/\delta T$ (m/K)	Result	58.2	85.8	52.1
	Disregard FSI	69.5	90.8	68.2
	difference	−11.3 (−19 %)	−5.0 (−6 %)	−16.1 (−31 %)
	Disregard Eva	59.7	91.8	65.1
	difference	−1.5 (−3 %)	−6.0 (−7 %)	13 (−25 %)
$\delta H/\delta P_a$ (m/mm)	Result	−42	−29	−85
	Disregard FSI	−37	−19	−64
	difference	5 (12)	10 (34 %)	21 (24)
	Disregard Eva	−40	26	−32
	difference	2 (5 %)	3 (10 %)	3 (4 %)
$\delta H/\delta Q_r$ (m/MJm²d)	Result	55.6	44.5	62.9
	Disregard FSI	62.1	45.4	80.3
	difference	−6.5 (−12 %)	−0.9 (−2 %)	−17.4 (−28 %)
	Disregard Eva	54.1	42.3	60.8
	difference	1.5 (3 %)	2.2 (5 %)	2.1 (3 %)

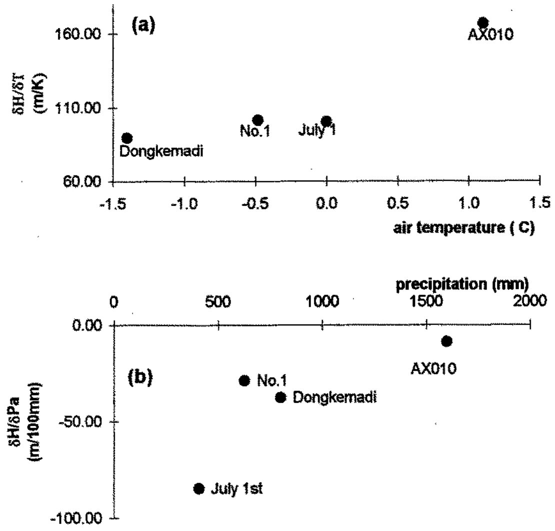

Fig. 4. The correlation of $\delta H/\delta T$ value to the summer mean air temperature at ELA (a) and $\delta H/\delta P_a$ to the mean annual precipitation at ELA (b).

ence of climatic fluctuation. The shift of ELA behaves very different in response to the climatic fluctuations. The value of $\delta H/\delta T$ on Glacier AX010 is as 2 times higher as that on Greenland ice cap. It is worthwhile to mention that large difference of $\delta H/\delta T$ occurs on High-Asia glaciers. The largest value of $\delta H/\delta Pa$ occurs on Greenland Ice Cap, on which the annual accumulation was estimated to be 450mm (Ambach and Kuhn, 1989).

Under global warming, it is thought that air temperature rising is generally accompanied with precipitation increasing. Such climatic fluctuations will result in two types of contrary effects on glaciers' fluctuations. The 5th column in Table 6 gives the estimation of the ELA shift corresponding to air temperature increase of 1 K and precipitation increase of 20 %. It can be seen that the ELA fluctuates differently for the respective glaciers in the world under the same climatic change scenario. On the High-Asia glaciers, the difference in ELA shift reaches 136 m, while, the difference in ELA shifts in response to the climatic fluctuation on the glaciers in Europe reaches 69 m. The results delineate regional diversity of glacier fluctuation. Annual precipitation has undergone short term fluctuation about 8.4 % in Tianshan Mts. since 1958, but about 38 % in Austria Alps from 1969-1978 (Kuhn, 1980). The net accumulation has fluctuated about 10 % on Greenland Ice Cap since 550AD (Ambach and Kuhn, 1985).

6. Concluding remarks

On the basis of the present study, some preliminary conclusion about ELA fluctuation in response to climatic change on glaciers of High-Asia can be drawn :

(1) The algorithm developed for simulating the ELA shift in response to climatic fluctuation is applicable to the glaciers of High-Asia, and it is demonstrated by a convincing example that performed on the Glacier No.1 at the Headwater of Urumuqi River, Tianshan. The fluctuation of the ELA is predictable from precipitation and air temperature information.

(2) In the presented model, that the ELA shifts in response to climatic fluctuation can be simulated by the algorithm coupling the energy and mass budget regimes on the glaciers. On the studied glaciers in High-Asia, the ELA shift can be

Table 6. Comparison of sensitivity of ELA with respect to changes in temperature and precipitation on different types of glaciers, 5th column implying that the ELA shift as air temperature rises of 1 K and precipitation increase of 20 %.

Glacier	Location	$\delta H/\delta T$ (m/K)	$\delta H/\delta P_a$ (m/%)	$\delta H\|^{\delta T=1K}_{\delta P_a=20\%}$	Reference
Dongkemadi	Asia	58.2	−3.5	−12	This work
"July 1"	Asia	52.1	−3.5	−8	This work
Glacier No.1	Asia	85.8	−1.8	49	This work
AX010	Asia	152.9	−1.4	124	This work
Hellstugubreen	Europe	108	−6.7	−26	Oerlemans, 1992
Alfotbreen	Europe	135	−6.8	−1	Oerlemans, 1992
Nigarsbreen	Europe	110	−5.2	6	Oerlemans, 1992
Hinteris	Europe	125	−4.1*	43	Kuhn, 1980
Greenland	Greenland	87.5	−9.9*	−121	Ambach, 1989

* : The number are implying the annual accumulation.

caused individually by climatic elements fluctuating with the following ranges : 52-152 m for air temperature change of 1 ℃ in melting season ; 9-85 m for annual precipitation change of 100 mm ; and 37-63 m for mean net radiation change of MJ/m^{2}d.

(3) The shift of glacier ELA in response to temperature fluctuation is intensive in the region where the ambient mean air temperature is high in melting season at ELA, while the shift due to precipitation change is less intensive in the region where the annual precipitation is high at ELA.

(4) Both evaporation and formation of superimposed ice play a significant role in the insensitivity of ELA shift in response to climatic fluctuations.

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