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Article

Evaluation of glacierized area of mountainous river basin in transition

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Abstract

Glaciers continuously change in response to varying climate and they are always in transition. This study presents a method to estimate long-term change, with annual resolution, of the equilibrium line altitude (ELA) and area of transient glacierization (the covering of large land area by glaciers) of river basins. In this analysis, a glacierized area rather than area of individual glaciers, was examined. Two ELAs were introduced: adjusted ELA (AELA) and calculated zero balance altitude (CZBA). The AELA of an inventory year was obtained as the converged value of individual glaciers' ELA when the ELAs were plotted against the area of individual glaciers. The CZBA was calculated as an altitude of zero annual specific mass balance, combining the empirical formulae for precipitation and ablation. The rate of change in adjusted ELA (AELA) of glacierization was assumed to be proportional to the difference between the AELA and the calculated zero balance altitude (CZBA). The series of AELA and area of glacierization were obtained using three years of glacier inventory data of three years and the series of annual precipitation and summer (JJA) mean air temperature at a near by station by minimizing the mean squared error sum for the three glacier inventory years. The AELA of an inventory year is obtained as the converged value of individual glaciers' ELA when the ELAs are plotted against the area of individual glaciers. The CZBA was calculated as an altitude of zero mass balance, combining the empirical formulae for precipitation and ablation. The glacierized area was calculated using an empirical formula, which relates the glacierized area with the area of river basin above the AELA. The method was applied to four river basins in the Pamirs for the period from 1954 to 1980.The change of AELA was much smoother than CZBA. Our method can be used to predict future change of the equilibrium line altitude of a glaciation and the glacierized area from at least three glacier inventories taken over time and projected meteorological data. to estimate glacier mass balance.

1. Introduction

Glaciers continuously change in response to varying climate and they are always in transition. The response of a glacier to climate change is different among glaciers within a climate region due to the differences in local conditions such as glacier size, local climate, glacier bottom topography *etc.* Many simulation models have been developed for individual glaciers to evaluate the glacier response to climate change. In order to run the model, detailed information on the glacier and climate are required. Therefore, the simulations can be applied to a few, well-investigated glaciers only. However, climatologists and hydrologists are usually interested in the changes in glacierization in a river basin, not individual glaciers, because they are concerned with basin scales or larger.

The word "glacierization" is frequently used as a process of glacier formation and growth, but it also has a meaning of "the covering of large land area by glaciers or ice sheets" (Bates and Jackson, 1980). It is synonymous to "glaciation." Here, we use "glacierization" with the latter meaning.

Glazirin (1981; 1996) has developed a technique to estimate the final state of the glacierized area after a climate change. It consists of two parts. First is the evaluation of the mean equilibrium line altitude shift (ΔZf) for a river basin. Summer (June-August) mean air temperature (Ts) and annual precipitation are assumed to be the main climate factors influencing ΔZf. The following formula is based upon the fact that annual specific accumulation (c) is equal to annual specific ablation (a) at the equilibrium line:

$$\Delta Zf = -[p \cdot c(Ts(Zf)) - a(Ts(Zf) + \Delta Ts)]/E, \quad (1)$$

where p is the coefficient of annual change of precipitation, *e.g.* p equals to 1.5 when the precipitation increases by 50%(precipitation changes as much as p times), Zf the mean equilibrium line altitude, ΔTs the change of summer mean air temperature and E the vertical gradient of mass balance at Zf ("energy of glaciation" (Shumsky, 1997)). A similar technique was developed by Kuhn (1981). Second is the estimate of the glacierized area within a river basin as a function of Zf. The formula has a form:

$$Fg(Zf) = aFb(Zf)^{\beta}, \qquad (2)$$

where $Fg(Zf)$ is the area of glacierization with a given Zf, $Fb(Zf)$ the area of a part of the basin above Zf, α and β the parameters. Using Eq. 2, one can calculate the glacierized area after climate change knowing new Zf using Eq. 1.

Glazirin's method (Glazirin, 1981; 1996) described above estimates the mean equilibrium line altitude and the final, steady state area of glacierization after climate change. However, glacierization never actually reaches a steady-state because it continuously changes, and is always in transition adapting to a varying climate.

The aim of this paper is to develop a method of evaluation of glacierized area in transition. For this purpose, the equilibrium line altitude (ELA) and area of glacierization are used to express the condition of glacierization.

In this paper, a method to estimate the ELA of glacierization is introduced in Section 2, followed by the introduction of the ELA estimate by meteorological parameters in Section 3. These two estimates are combined in order to obtain the long-term variation of ELA in Section 4, and the ELA is discussed with a relation to the glacierized area in Section 5. The data set used in this analysis is introduced in Section 6, followed by the results of ELA and glacierized area variation in Section 7 and they are summarized in Section 8.

2. Equilibrium line altitude of glacierization

ELA is the best parameter linking the glacier and the surrounding climate (*e.g.* Ahlmann, 1948; Tronov and Lupina, 1977). Generally an alpine glacierized area consists of many glaciers with different ELAs, although they exist within the same climate zone. Especially small glaciers can exist far below or above the ELA of the larger ones (Fig. 1). Therefore, the mean ELA calculated from the values of locally influenced glaciers is different from the representative ELA of the glacierization.

The averaging scale to estimate ELA without local orographic influence is still being debated, however, several techniques to estimate representative ELA of the glacierization have been proposed using snow cover duration (Tronov and Lupina, 1977), meteorological data (Glazirin, 1991) and ELAs of glaciers (Severski, 1997). In this paper, we will use two completely different ELAs. One is the altitude of zero mass balance (CZBA) calculated only from meteorological parameters. The CZBA will be introduced in Section 3. Another is an, so called, "adjusted ELA" (AELA), which was first introduced by Seversky (1997). The ELAs of individual glaciers (zf) are plotted against the individual glacier area (fg) in Fig. 1. The data in Fig. 1 is obtained from the dataset of glacier inventory of Obihingow river basin in the Pamirs in 1980. The deviations of ELA from some mean value decrease with increasing glacier area. The envelope can be drawn around the field of points, revealing an asymptotic convergence to a smaller range of ELA as the glacier area increases. The converged value of ELA is called the "Adjusted Equilibrium Line Altitude", AELA. The AELA can be interpreted as the ELA of virtual ice field, which cover the whole glacierized area. The form of these envelopes is universal for many mountain regions (Seversky, 1997). For the reliable calculation of AELA, it is necessary to have a large dataset of ELAs and glacier areas including several big glaciers. We must emphasize that the AELA is obtained only from the ELAs and area of glaciers, and no climate data are used. Therefore, AELA is a parameter suitable to indicate the glacierization condition at the moment of the glacier inventory.

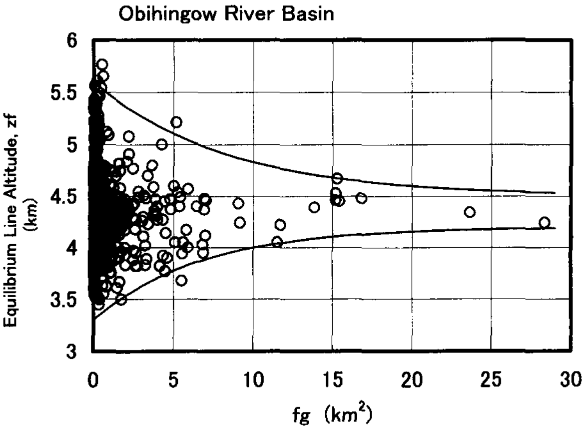

Fig. 1. Equilibrium line altitude (zf) as a function of the area of glaciers (fg) in Obihingow River basin (Data of inventory in 1980). (Shchetinnikov, 2000)

3. Calculated zero balance altitude

Calculated zero balance altitude, CZBA, is the elevation where the calculated annual specific ablation equals the calculated annual specific accumulation. The CZBA varies strongly from year to year depending on the weather conditions. From the long term experience on many glacier researches in the world, the specific annual ablation a (Z) (mm a^{-1}) at an elevation of Z (km) can be expressed by Krenke-Khodakov formula (Krenke, 1982) as follows:

$$a(Z)=(Ts(Z)+9.5)^3, \tag{3}$$

where $Ts(Z)$ (>-9.5°C) is summer (JJA) mean air temperature at the elevation of Z and calculated by the following formula:

$$Ts(Z)=Ts(Zst)\ +\gamma(Z-Zst), \tag{4}$$

where Zst is the elevation of the nearby meteorological station and γ the lapse rate of air temperature. We assumed that γ is equal to -6.5 ℃ km^{-1} (*e.g.* Glazirin, 1991; Shchetinnikov, 1998). Similarly, the annual precipitation $X(Z)$ at a height of Z is estimated as follows (Borovikova *et al.*, 1972) :

$$X(Z)=X(Zst)(1+k_0(Z-Zst)), \tag{5}$$

where $X(Zst)$ is the annual precipitation at the nearby meteorological station at the elevation of Zst, and k_0 the parameter indicating the rate of change of precipitation with elevation. $X(Z)$ equals the annual accumulation because there is no liquid precipitation at these high altitudes (>4 km a.s.l.) in the Central Asia. In other cases, the amount of only solid precipitation out of annual precipitation should be considered. Since the ablation equals the accumulation at the CZBA (Zc), we can have the following formula combining Eqs. 3, 4 and 5:

$$X(Zst)(1+k_0(Zc-Zst))=(Ts(Zst)+\gamma(Zc-Zst)+9.5)^3. \tag{6}$$

Eq.6 is a non-linear equation for Zc and k_0.

4. Change in AELA in response to change in CZBA

CZBA, which is defined only by meteorological parameters, is related to climate and the AELA, which is calculated only from glacier inventory data, expresses more closely the condition of glacierization. The AELA as well as the CZBA responds immediately to climate change, but they respond with different manner. The CZBA varies largely from year to year, whereas the AELA changes gradually.

It is necessary to apply some smoothing operator to relate the CZBA (Zc) fluctuations with the change of AELA (Za) reflecting glacierization changes. For the first approximation it is appropriate to use the simplest linear operator:

$$\tau\frac{dZa}{dt}=(Za-Zc), \tag{7}$$

where τ is a parameter. Eq. 7 can be expressed by a simple difference form and the time step of one year as:

$$Za_{i+1}=Za_i+C(Za_i-Zc_i), \tag{8}$$

where i expresses the number of year and $C=-1/\tau$.

Using Eqs. 6 and 8 we can solve for k_0, C and the series of Za_i making the mean squared error sum between the calculated AELA (Za_i) and the observed AELA (Zao) (obtained from glacier inventory data) of the three inventory years minimal. The values of k_0 and C are assumed to be constant. It is necessary to have at least three observed values of Zao in order to obtain a series of Za_i by applying Eqs. 6 and 8. It means that inventory of glaciers should be repeated three times in various years.

5. Total area of glacierization

The area of glacierization (Fg) is related to the river basin area (Fb) via Eq. 1. Substituting Zf with Za in Eq. 1, it becomes:

$$Fg(Za)=\alpha Fb(Za)^\beta. \tag{9}$$

Mean values of parameters α and β were found using the data on glacierization for 42 river basins in Central Asia to be $\alpha=6.52$ and $\beta=0.59$ (Glazirin, 1991). In this analysis, α is adjusted for each river basin by inversely solving Eq. 9 for α knowing Zao, $Fg(Zao)$ and $Fb(Zao)$ of the first inventory year and assumed to be constant after that year. The β is kept constant (0.59), and $Fb(Zao)$ is obtained from the altitudinal distribution of river basin area.

Summarizing above, the method to obtain the AELA and glacierized area is:

1) A set of data on the annual precipitation for a hydrological year, $X(Zst)$, and the summer mean air temperature ($Ts(Zst)$) at the nearest meteorological station located at an altitude of Zst are collected.

2) Data on the ELA (zf) and area of individual glaciers (fg) in the basin are collected from three glacier inventories.

3) The values of AELA (Zao) in the three glacier inventory years are calculated.

4) The values of k_0, C and the series of AELA(Za) are evaluated using Eqs. 6 and 8 by an optimization, which makes the mean squared error sum between the Zao and Za of the three inventory years minimal.

5) Annual glacierized areas (Fg) are calculated as the function of Za using Eq. 9.

If a plausible forecast of air temperature and precipitation are available, future values of Za and Fg could be calculated using Eqs. 6-9.

6. Data set

One of the main obstacles to apply the method is scarcity of data, as it requires at least three years of repeated glacier inventory to obtain Za_i, k_0, and C using Eqs. 6 and 8. The Catalogue of Glaciers of the USSR (more than 50 volumes) is a useful dataset, but repeated inventories have been made only for a few mountainous regions. Unfortunately, some inventories were repeated with different techniques. And most were not repeated more than twice, which is insufficient for the application of the proposed method.

For our analysis, we have used the data provided by Shchetinnikov (2000) for glaciers in the Pamirs. He has repeated cataloguing glaciers of several river basins for three times (Table 1). In the table, the glacierized area (*Fg*) and the mean ELA (*Zf*) of the three glacier inventories are shown for the Yazgulem, Obihingow, Shahdara and Vanch River basins (Fig. 2).

Some numbers in the table are difficult to understand. For example, the area of glaciers of Yazgulem River Basin shrank from 326 km^2 in 1956 to 311 km^2 in 1972, but the mean *Zf* decreased during the period, opposite to that expected. Similarly, the area of glaciers in the Shahdara River Basin reduced 20% from 1954 to 1973, but the *Zf* was not much changed. The left figure in Fig. 3 shows the changes in the *Zf* between the years of inventories plotted against the changes in *Fg* of the same period for the four river basins in Table 1. There are other similar inconsistencies in the table. Nonetheless, it is very valuable to have this data set of glacier area and ELA in three different years over more than 20 years.

In order to circumvent the inconsistencies in the data set, *Zao* for second and third inventory is adjusted, and it is shown as *Zac* in Table 1. For the *Zac* in the first inventory year the *Zao* is taken as it is and the α is calculated by Eq. 9 knowing *Zao*, *Fg*(*Zao*), *Fb* (*Zao*) and β. For the second and third inventory year the *Zac* is calculated inversely solving Eq. 9 knowing the *Zao*, *Fg*(*Zao*), *Fb*(*Zao*), α and β. The right figure in Fig. 3 shows the changes in *Zac* between the years of inventories plotted against the changes in *Fg* of the same period for the four river basins in Table 1. We can see the inconsistencies are corrected by the adjustment when compared with the left figure in Fig. 3. It should be noted that, in a glacier inventory, total area

Fig. 2. Map of Amudarya tributaries in Pamirs.

Table 1 Characteristics of glacierization of four river basins ion the Pamirs. Glaciers with the area of not less than 0.1 km^2 were taken into account. *Fg* is the glacierized area, *Zf* is the simple mean value for all glaciers in a river basin, *Zao* is the adjusted equilibrium line altitude obtained from glacier inventory data, the parameter α in Eq. 9, *Zac* and τ are explained in the text.

River Basin	Years	*Fg* km^2	*Zf* km	*Zao* km	α	*Zac* km	τ years
Yazgulem	1956	326	4.54	4.89	14.12	4.890	187
	1972	311	4.48	4.93		4.909	
	1980	258	4.55	4.97		4.975	
Obihingow	1956	587	4.31	4.70	16.97	4.700	303
	1970	549	4.24	4.62		4.736	
	1980	537	4.33	4.59		4.747	
Shahdara	1954	213	4.91	5.22	17.65	5.220	145
	1973	164	4.91	4.84		5.300	
	1980	160	4.96	5.19		5.308	
Vanch	1956	344	4.40	4.53	9.99	4.530	227
	1972	354	4.41	4.59		4.504	
	1980	292	4.41	4.51		4.642	

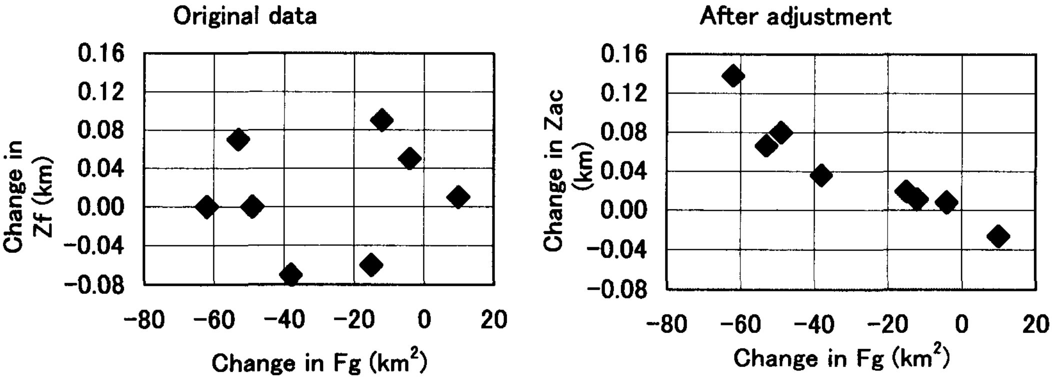

Fig. 3. Change in the mean equilibrium line altitude (*Zf*) (left) and the adjusted equilibrium line altitude (*Zac*) (right) plotted against the change in the glacierized area (*Fg*) in the period between the glacier inventories (See also Table 1).

of glacierization (*Fg*) is usually obtained much more accurately than ELA of individual glaciers (*zf*), which are the source data for *Za* calculation. Therefore, it is appropriate to adjust *Zao* using *Fg* in Eq. 9. The values of *a* and *Zac* are used in the calculation for Za_i (see Section 5).

7. Results

Long term changes of the annual precipitation for hydrological year and mean summer air temperature in Yazgulem River basin are shown in Fig. 4. The meteorological data was obtained at the meteorological station "Lednik Fedchenko" (*Zst*=4.17 km). Note that air temperature has no appreciable positive trend from 1938 to 1990 (0.0051 °Ca^{-1}), whereas precipitation increases in the same period (7.1 mm a^{-1}). In this period the glacierized area decreased (Table 1).

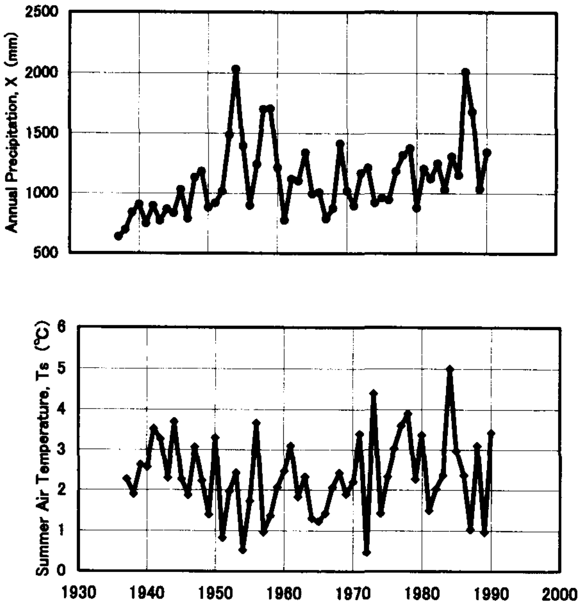

Fig. 4. Long-term change of annual precipitation and mean summer (June-August) mean air temperature at the station "Lednik Fedchenko".

The calculated long-term changes of *Za* and *Zc* in Yazgulem River basin from 1957 to 1980 are shown as an example in Fig. 5. The change of *Za* is much smoother than the fluctuation of *Zc*. The parameter *C* in Eq. 6 for the Yazgulem River Basin was −0.0053. The values of *C* for other three river basins varies between −0.0033 and −0.0069. The value of response time, τ ($=-1/C$), varies between 145 and 303 years (Table 1).

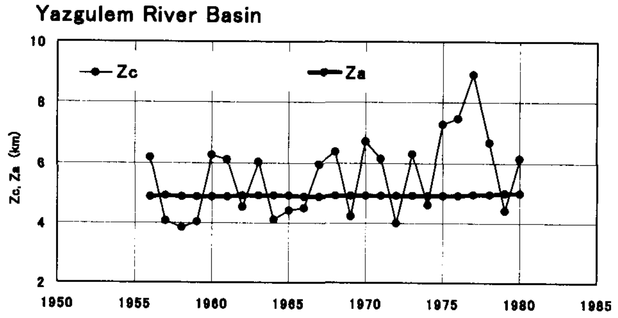

Fig. 5. Calculated zero balance altitude (*Zc*) (thin line) and adjusted equilibrium line altitude (*Za*) (thick line) in Yazgulem River basin.

The long-term change of glacierized area of the four river basins calculated using Eq. 9 is shown in Fig. 6. The best conformity of real and calculated glacierized areas was found in Yazgulem River basin. The poorest performance of the model occurred in the Vanch River basin. We can suggest that the result of second inventory of this basin in 1972 is wrong as no increase of glacierization is found for other river basin of the whole Central Asia.

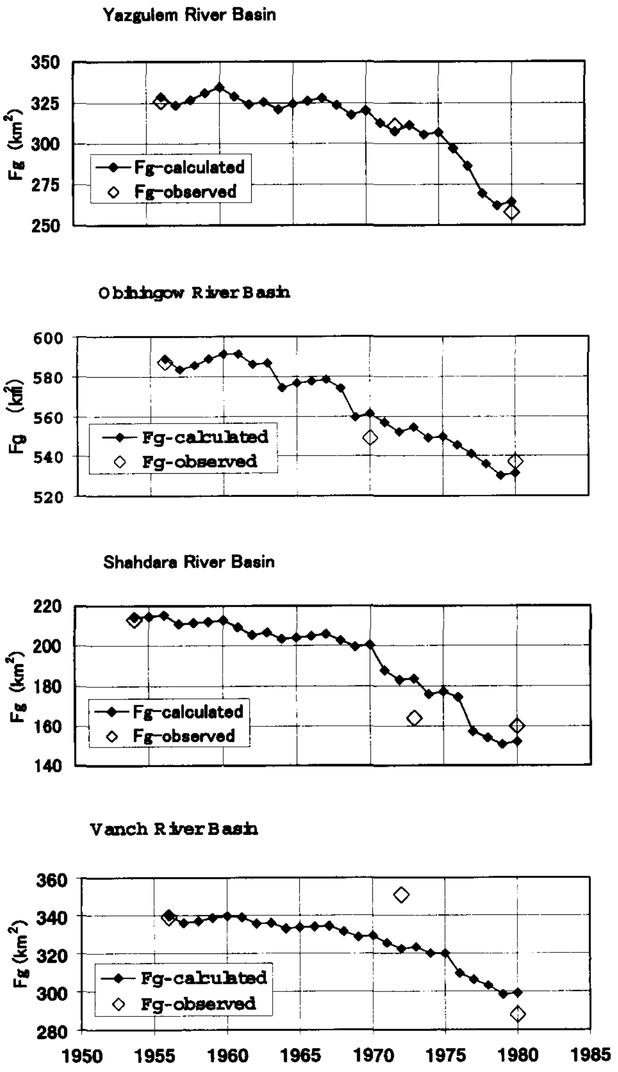

Fig. 6. Calculated long-term change of the glacierized area (*Fg*) in four river basins (solid lines with solid diamond) and the glacierized area determined as a result of glacier inventories (hollow diamond) in the Pamirs.

8. Summary

The method to estimate a long-term change of the adjusted equilibrium line altitude (*Za*) and glacierized area (*Fg*) of river basins with one-year resolution was proposed. In this study, a glacierization, not an individual glacier, in a river basin was examined. The change in *Za* was assumed to be proportional to the difference between *Za* and the calculated zero balance altitude (*Zc*), and the series of annual *Za* were obtained. The adjusted equilibrium line altitude in the glacier inventory year (*Zao*) was obtained as the converged value of equilibrium line altitude (*zf*) of individual glacier when the area of individual glaciers (*fg*) would become infinity. The *Zc* was calculated as an altitude of zero mass balance combining the empirical formulae for precipitation and ablation. This method requires three different years of glacier inventory data of three different years and the series of annual precipitation and summer (JJA) air temperature at a station near by. The method was applied for the four river basins in Pamirs. The change of *Za* was much smoother than the fluctuation of *Zc*. The method makes it possible to predict future change of the equilibrium line altitude and glacierized area if there are inventories of the glacierization of three years were three years of and the future annual precipitation and summer mean air temperature could be predicted.

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