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ESTIMATION OF DISPERSED GLACIATION SHRINKAGE UNDER CLIMATE CHANGE

ABSTRACT. We propose a new method of estimating the shrinkage of glaciers over a wide area under conditions of changed climate. The method can be also used to quantitatively estimate the presence of glaciers under past climatic conditions, in mountainous areas where they are currently absent. The method is based on the use of statistical parameters of the distribution of glaciers by altitude zones, according to vertical distance from the climatic equilibrium line altitude (CELA). The method was used for the Pskem River basin (tributary of the Chirchik River, Western Tien-Shan) where glaciation has been extensively studied. Data are available for several glacier inventories for the basin for different time periods from 1957 to 2010. The number of glaciers for the part of the basin considered in the studies decreased by 16 percent during that period. Mean summer air temperature and annual precipitation were used as climate indicators characterizing ablation and accumulation on glaciers. Data of several meteorological stations located in the Pskem River basin were used to document these climatic characteristics. We estimated shrinkage of glaciers over the area for increases of summer air temperature of 0.5 - 2°C.

KEY WORDS: glaciers distribution, glaciation shrinkage, climate change

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INTRODUCTION

Estimation of the change in characteristics of mountain glaciation under climate change is an important scientific and practical problem that has been solved for different mountainous regions around the world. In those past studies, however, the estimation of change was made either for individual large glaciers or for the total area of glaciation, in the respective regions.

The objective of our present work is to estimate the change in dispersed glaciation, using a different approach based on the use of statistical characteristics of glaciers (Glazirin 1991). By the term *glaciation* we denote an area of mountainous territory occupied by glaciers. *Dispersed* type of glaciation was identified by Khodakov (1978) and used to name a set of small glaciers that do not form a single massif but rather form a distributed or scattered array of glaciers, with possible concentrations or groups in sub-areas of the territory. Such glaciation is widespread in the peripheries of mountainous regions and is the only type of glaciation in some regions (for example, the Northern Ural, Kuznetsk Alatau). A method similar to the one we propose in the present paper has been used to assess the potential presence and viability of glaciers in some regions where they are currently absent or where they are critically endangered (Glazirin et al. 2000; Glazirin, Escher-Vetter 1998).

STUDY AREA

We show here how the proposed method can be applied to the example of glaciation of the left side of the Pskem River valley (Fig. 1). This area is located on the western periphery of the Tien-Shan. Currently it has about one hundred small glaciers having one accumulation area in most cases. According to the Catalogue of Glaciers (1968), their total area in 1957 was 63.6 km2. The climatic and orographic conditions for the existence of glaciation in the basin have been studied quite well (Schetinnikov 1976). In addition, real changes in glaciation have been identified in recent decades through several repeated glacier inventories (Narama et al. 2010; Semakova et al. 2016; Semakova and Semakov 2017; etc.), the last one done in 2010.

Typical glaciers of the region are shown in Fig. 2.

INPUT DATA

As mentioned, the proposed method is based on the use of statistical characteristics of glacier distribution. Thus, the inventories containing data suitable for our purposes were those containing information on the elevation and the area of each glacier. This criterion is satisfied, firstly, by the Catalogue of Glaciers (1968), prepared by Schetinnikov and reflecting the state of glaciers in 1957; secondly, by the inventory carried out by Schetinnikov based on the materials of the spatial survey from 1978 (unpublished data of Schetinnikov); and, thirdly, for the inventory carried out by Semakova et al. (2016).

In our work we only consider glaciers with an area more than or equal to 0.1 km2. This was done for two reasons. Firstly, this is the size limit used in the Catalogue of Glaciers of USSR (1968). Secondly, the possibility of errors in identifying and determining the size of smaller glaciers increases dramatically (Catalogue 1968; Semakova et al. 2016).

There are several meteorological stations in the Pskem River basin, but the longest and most reliable data series, starting with 1937, is available from Pskem station, located at an altitude of 1,260 m in the middle part of the valley. This station serves as a base for all hydrological and glaciological calculations in the Pskem River basin. The relationships between its data and expeditionary observation data in the glacial zone of the basin verify its representativeness for the basin (Borovikova et al. 1972; Schetinnikov 1976; etc.).

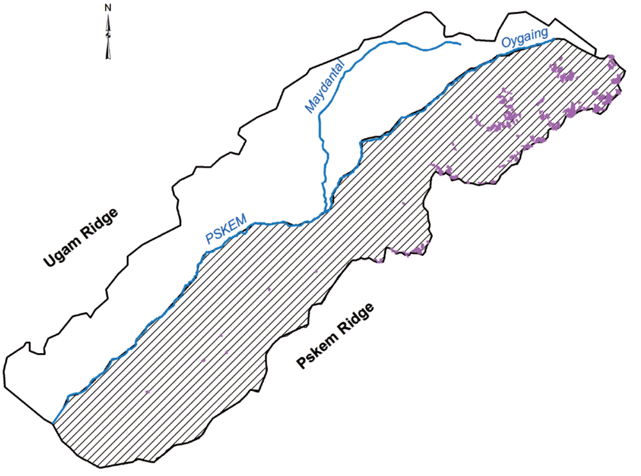
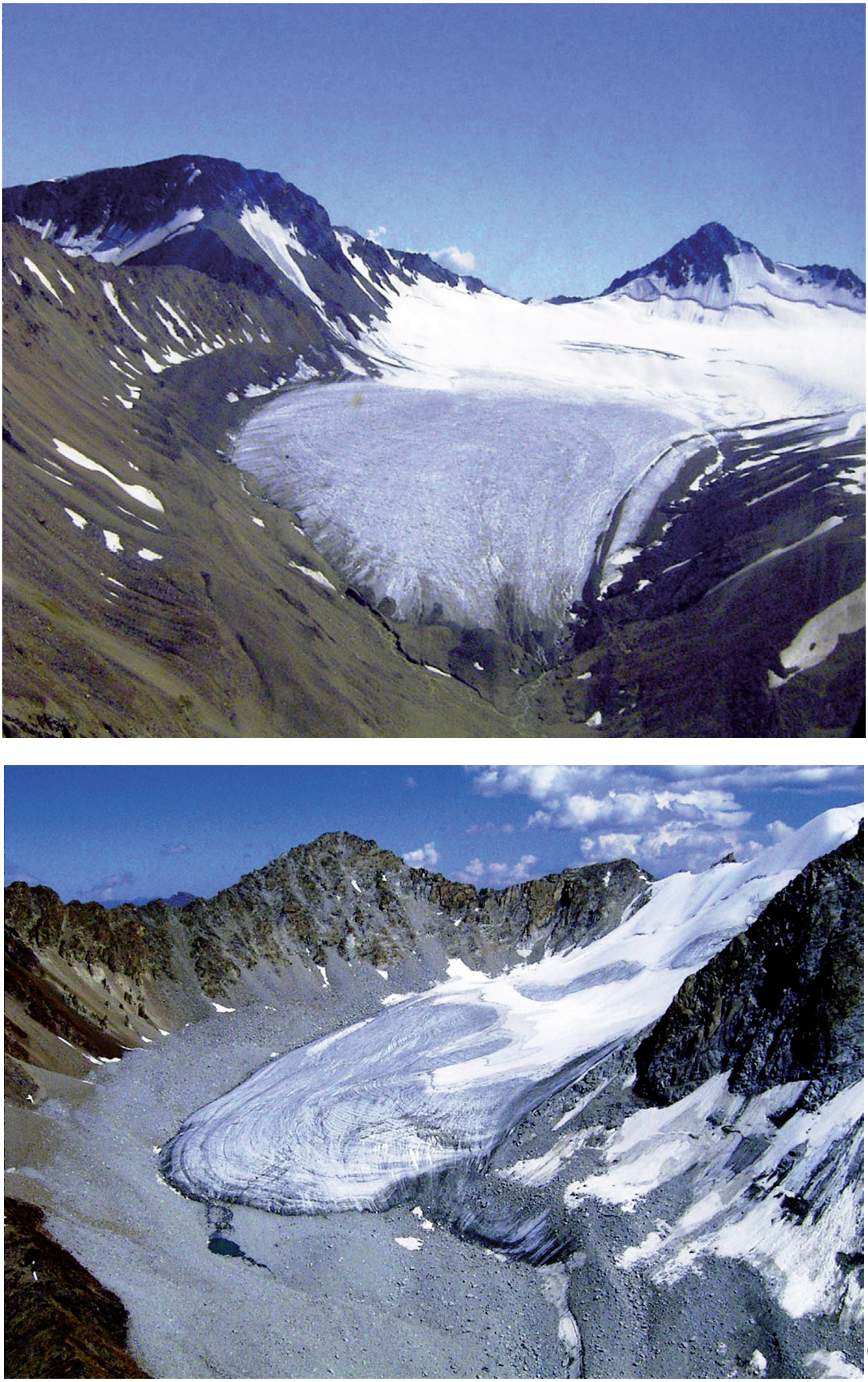


Fig. 1. Filled is the study area in the Pskem River basin

The main climatic parameters that affect the size and regime of glaciers are known to be solid atmospheric precipitation and air temperature. In the study area the main amount of precipitation falls in the winter-spring season (according to Pskem



(a)

(b)

Fig. 2. Typical glaciers in the Pskem River basin

station observations about 90.5% of precipitation falls during the period from October to May), so it can be assumed that the annual solid precipitation at glaciation altitudes is equal to the total annual precipitation.

METHODOLOGY

The main idea of the method is as follows: the possible number of glaciers is estimated under given climatic conditions and the climatic equilibrium line altitude (*CELA*) is considered to be an integral indicator of these climatic conditions.

In regions with developed mountain glaciation *CELA* can be found from the relation of *CELA* and the area of glaciers present (Severskiy 1978). Successful application of the method requires, however, a large set of glaciers, including big ones. There are no big glaciers in the basin, so application of the method is unacceptable for our task solution. *CELA* was calculated by Glazirin (1991) on the basis of glaciation data from 1957, yielding a value for *CELA* of 3.93 km for the selected part of the basin. To characterize the climatic conditions of the basin for the time period the values of annual precipitation and the mean summer air temperature at Pskem station were taken for the preceding eleven years (1947-1957).

The next step is to calculate a possible number of glaciers under given climatic conditions (evaluated *CELA*). Glazirin (1991) proposes a formula for calculating a probability of the existence of glaciers in an altitude zone with an average Z elevation, depending on how far Z is from *CELA*. We estimated this dependence directly for the studied area (Fig. 3). The input data were the areas of the altitude zones evaluated from SRTM v.4 (Farr et al., 2007) and the number of glaciers in each altitude zone in 1957. The total number of glaciers is equal to the sum of the numbers of glaciers in each of the altitude zones.

Now it is necessary to determine the change in *CELA* under possible climate changes.

Let us assume that *Xa(CELA)*, which is the mean long-term annual precipitation on *CELA* position, is equal to *ab(CELA)*, which is the mean long-term annual ablation. We are able to calculate *ab(CELA)* using the Krenke-Khodakov formula (1982):

$$ab(CELA) = 1.33 \cdot (9.66 + Ts(CELA))^{2.85} \qquad (1)$$

Here, *Ts(CELA)* is the mean summer air temperature at *CELA* altitude. This temperature can be calculated using a simple formula,

$$Ts(CELA) = Ts(Zst) + y(CELA - Zst) \qquad (2)$$

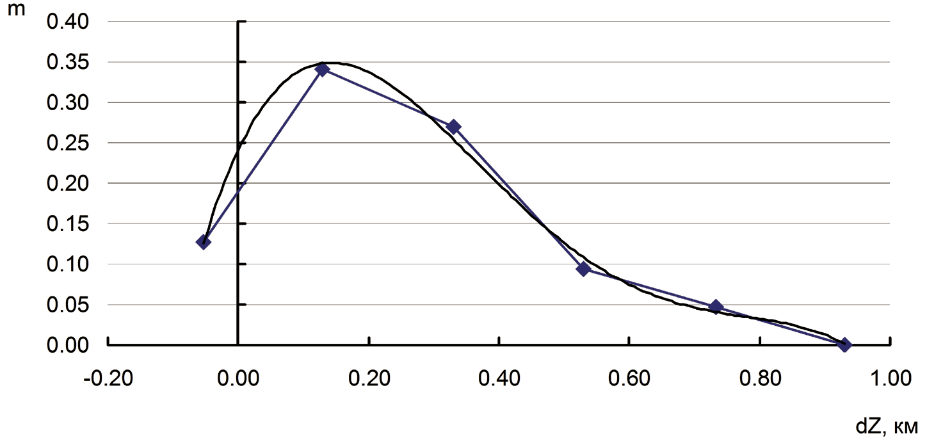


Fig. 3. Dependence of *m* (the number of glaciers per 1 km² of the altitude zone) on the difference between *CELA* and the average altitude of the corresponding zone (*dZ = CELA - Z*)

where γ is the vertical gradient of the mean summer air temperature. It was determined from the data of meteorological stations located in this basin and adjacent ones and turned out to be equal to -7.3^{0}C per 1 km. We used data from four weather stations (Chimgan, Oygaing, Maydantal, and Pskem, located at altitudes ranging from 1.26 to 2.16 km), as well as data gathered during several summer expeditions to glaciers in the basin. Thus, it is assumed that the change in air temperature is the same at all altitudes.

We will assume that the change in the annual precipitation *(Xa)* according to altitude, including ridges, is also linear (Getker 1987), and is determined by the following formula developed by Borovikova et al. (1972):

$$Xa(CELA) = Xa(Zst) \cdot (1 + k(CELA - Zst)) \quad (3)$$

The coefficient k can be calculated if we know the mean long-term precipitation at Pskem station *Xa(Zst)* and the precipitation sum at *CELA*, taken as equal to the mean long-term annual ablation. The coefficient k calculated for the period of 1947-1957 is equal to 0.09. So, the precipitation varies identically at all altitudes in a percentage ratio. The vertical temperature gradient γ and the coefficient k are assumed constant for subsequent periods.

We can find a new value of *CELA* by the equality of the calculated ab and Xa using formulas (1 - 3) if we specify a change in temperature at Pskem station. Further, it is possible to calculate a new number of glaciers in the altitude zones and in the study area overall using the new *CELA* and Fig 3.

Calculations were performed under the assumption that the annual precipitation was constant (this assumption is acceptable since according to observations at Pskem station for the period from 1937 to 2014 the mean change in annual precipitation is only 0.35 mm per year, the mean precipitation being 861 mm per year) while the mean summer air temperature increased.

We are also interested in finding the total area of glaciers. This area can be calculated in the following way. Let us assume that, under conditions of shrinkage of glaciation, the size distribution of glaciers remains the same (Glazirin 1991). The integral distribution of glaciers according to the inventory of 2010 (Semakova et al. 2016) is shown in Fig. 4. Taking into consideration the shrinkage of total glacial area and decrease in number of glaciers, the upper part of this distribution is cut off, so the remaining maximum value of the distribution is its new area.

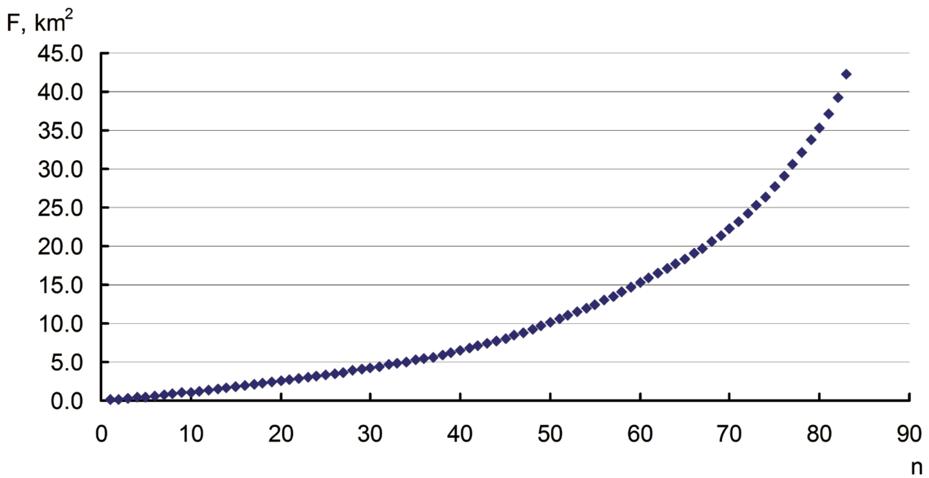


Fig. 4. Integral distribution of the glaciers in the study area according to the inventory data from 2010; n - numbers of glaciers, ranked by the increase of their area

We tried to estimate the reliability of the method by comparing the actual and calculated number of glaciers obtained in the result of the second and third inventories (1978 and 2010) using *k* and *m(dZ)* parameters found from the first catalogue of data (1957).

The calculated number of glaciers (95) at the time of the second inventory almost coincided with the actual number (94 glaciers with a total area of 52.6 km^2). For the third inventory, the calculated number of glaciers (91) slightly exceeded its actual number (83, with a total area of 42.2 km^2). This information allows us to judge the reliability of the methodology. Unfortunately, it is not possible to assess this reliability more generally because for the period between the first, second, and third inventories the climate has not changed significantly. The mean summer air temperature at Pskem station for the period of 1947-1957 was equal to 20.5°C, for the period of 1968-1978 it was 20.7°C, and for the period of 2000-2010 it was 20.9°C. The mean annual precipitation sums for the respective periods were 868, 885 and 892 mm per year. Given that the method is based on reliable and proven regularities we hope that the accuracy will be quite satisfactory, at least in the case of an insignificant deviation from modern climatic conditions.

RESULTS

The estimation was done on the assumption that the mean summer air temperature (ΔT) would rise by 0.5, 1.0, 1.5, and 2.0°C, which are appropriate values according to long-term climate change forecasts (Nikulina, Spectorman 1998). The change in the parameters of glaciation was determined according to the latest glacier inventory (2010). The table shows the values of *CELA*, the number of glaciers (N), and their total area (F) under possible air temperature increases.

As we see, with a temperature increase of 0.5°C *CELA* increases by 60-70 m. The number of glaciers decreases on average by 11 glaciers and glaciation area decreases significantly. We should note that glaciation persists in the study area even under such a significant air temperature increase.

It should be mentioned that the calculation allows us only to estimate stationary glaciation, i. e., when it has fully adapted to new climatic conditions. The period of adaptation is not expected to be a long one, given the small size of the glaciers. We assume that it should be equal to 11 years.

DISCUSSION AND CONCLUSION

We propose a method for estimating the change in the parameters of dispersed glaciation under conditions of climate change. It should be noted that the method can be used even when no direct data are available on the relationship between the climate and the area of glaciation of a certain region, i.e., when only meteorological data from the nearest meteorological stations and a single glacier inventory are available.

The relationship presented in Fig. 3 will apparently differ in other mountainous regions, because the specifics of orography, and various vertical gradients of air temperature and precipitation, are different. It is desirable to find an individual relation for each region, and also the relation be-

Table 1. Characteristics of the study area glaciation under given changes in the mean summer air temperature

	ΔT, ^{0}C				
	0	0,5	1	1,5	2
CELA, km	3.98	4.05	4.11	4.18	4.24
N	83	79	64	51	40
F, km^2	42.2	33.7	17.7	10.6	6.5

tween the calculated number of glaciers and their total area. In the interest of improving accuracy the proposed method, namely, that of using integral distribution of glaciers, has to be improved in the future. It should be noted that the method can even be used for areas where there are only single glaciers, or where only their traces are preserved (Glazirin and Escher-Vetter 1998; Glazirin et al. 2000).

We emphasize that this method is only suitable for calculating the reduction of glaciation in situations and terrains where the style of glaciation may properly be described as dispersed. And, it may not be suitable for calculating the increase in glaciation when new, small glaciers are forming, and existing glaciers are growing in size, or when glaciers are merging so as to lead to formation of large, complex glaciers: it can happen that the area of glaciation increases but the number of glaciers decreases. It is obvious that statistical regularities in the numbers of glaciers, as they are distributed by altitude zones, may change, and the relationships of the type shown in Fig. 3 may change as well.

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