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Model-based calculations of surface mass balance of mountain glaciers for the purpose of water consumption planning: focus on Djankuat Glacier (Central Caucasus)

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Abstract. Mountain glaciers act as regulators of run-off in the summer period, which is very crucial for economy especially in dynamically developing regions with rapidly growing population, such as Central Asia or the Northern Caucasus in Russia. In overall, glaciers stabilize water consumption in comparatively arid areas and provide conditions for sustainable development of the economy in mountainous regions and in the surrounding territories. A proper prediction of the glacial run-off is required to elaborate strategies of the regional development. This goal can be achieved by implementation of mathematical modeling methods into planning methodologies. In the paper, we consider one of the first steps in glacier dynamical modeling – surface mass balance simulation. We focus on the Djankuat Glacier in the Central Caucasus, where regular observations have been conducted during the last fifty years providing an exceptional opportunity to calibrate and to validate a mathematical model.

1. Introduction

Mountain glaciers play an exceptionally substantial role in functioning of the regional economies and in the everyday life of the local communities in mountain and piedmont areas. Indeed, they act as main regulators of water run-off. Fresh water accumulated by glaciers is gradually released during the melting season. For example, in summer season melting glaciers contribute up to 70-80% to the total river run-off [1]. Obviously, growing economy and population increase demand higher water consumption. That is why accurate prediction of future available water resources is a challenging problem for the scientific community.

Consequences caused by degradation of mountain glaciation under condition of changing climate [2, 3] are rather acute especially in developing countries, first of all in the countries experiencing sharp deficiency of fresh water. In some regions situation is aggravated by very uneven distribution of water resources, for instance, in Central Asia. Here, main rivers originate in the mountains of Kyrgyzstan and Tajikistan, but the main consumer is Uzbekistan with rapidly growing population and developing

economy. This situation provokes tensions between the countries, which may anytime in future evolve in a full-scale armed conflict.

Current changes of regional climate do not necessarily follow global warming trend [4]. This will probably also be the case in future. Nevertheless, elaboration of strategies of development of local economies and maintaining social infrastructure require scientifically based possible scenarios of availability of water resources. Therefore, accurate prediction of future glacial run-off is a key problem of sustainable development in the region where hydrological regime is highly dependent on glacial run-off. In turn, evaluation of future run-off requires dynamical modeling of mountain glaciers.

Prognostic estimates of the glacial run-off can be obtained in several steps, which can be schematically represented as follows:

1. Choice of a desired climatic scenario (either schematic or based on modeling).

2. Choice of a type of a mathematical model of a mountain glacier.

3. Determining so-called reference glaciers in the region with the maximum available information and direct measurements (on topography, flow velocity, mass balance etc).

4. Determining the way of extrapolation of model results on the rest of the glaciers in the study region

5. Model calibration – defining values of the key tuned model parameters [5, 6].

6. In case desired climatic scenario is based of prognostic modeling on a GCM, it is necessary to choose an optimum downscaling methodology [7]. Another approach is implementation of a kind of simplified scenario(s) by setting schematically evolving climatic forcing [8].

7. Model validation – reconstruction in numerical experiments past observations on the glacier (flow velocity, mass balance) by forcing the model with a set of the past climatic records.

8. Carrying out a series of prognostic numerical experiments and further interpretation of their results [9].

The main obstacle for accurate prognostic calculations is the lack of observations. It is explained, first of all, by bad accessibility of the mountain glaciers and by unfavorable working conditions. Of course, growing amount of data obtained with remote sensing partially solves the problem. Nevertheless, remote methods cannot totally replace direct instrumental measurements at the glaciers. Monitoring of all or even of only biggest glaciers is quite demanding in terms of regular financial investments. That is why it is expedient to perform regular observations on certain typical (reference) glaciers. Djankuat Glacier is such reference glacier for Central Caucasus. Djankuat is a valley glacier with morphometric characteristics typical for the glaciers in the region. In the years 2012-2013 its area and volume were equal to 2.45 km^2 and 0.077 km^3 respectfully [10]. Regular observations have been conducted here for a half of the century. This is the reason to choose Djankuat for calibration and validation of a mathematical model of mountain glacier dynamics. In the current paper we consider on of the necessary steps in prediction methodology - surface mass-balance modeling of Djankuat glacier and collate results with observations.

2. Methods and data

2.1. Model formulation
We employ an energy-balance model to calculate amount of energy E coming on the surface of a skin layer on the surface of a glacier (figure 1):

$$E = SW(1 - \alpha) - E_{eff} + SHF + LHF, \tag{1}$$

where SW is incoming short-wave radiation, α - surface albedo, E_{eff} – effective radiation (balance of long-wave radiation), SHF and LHF – sensible and latent turbulent heat fluxes. Using skin-layer approach supposes that heat exchange between the surface of snow/ice and rest of the glacier is neglected. Normally, ablation areas of the glaciers are covered with debris. Debris cover transforms essentially processes of heat exchange [11], therefore we take into account presence of this layer where necessary.

Annual mass balance on the surface of the glacier, *SMB*, is expressed as a difference between accumulation, *AC,* and run-off, *RO*:

$$SMB = \sum_{1}^{365}[ACC - RO],\tag{2}$$

Accumulation is calculated as the sum of solid and liquid precipitation *ACC=PS+PL,* from which we subtract evaporation (only in the zone of ablation), *SU*. The latetter is proportional to *LE*. We avoid explicit description of post-depositional redistribution of snow because it is rather individual quantity for the particular glacier. Instead, the latter is regarded as a tuned parameter. Ratio of *PS* and *PL* depends on daily average air temperature $\bar{T}_A$. Hourly values (daily cycle) are expressed as follows:

$$T_A = \bar{T}_A - \tilde{T}_A \cos\left(2\pi\frac{t}{24}\right),\tag{3}$$

where $\tilde{T}_A$ – is the daily amplitude; $t = 0, \dots, 23$ – time (hours). $\tilde{T}_A$ is a key tuned parameter determining the area of surface melting. It has to be defined from available observations on particular glaciers. Actually, $\tilde{T}_A$ acts as a switcher between melting and no-melting conditions:

$$\begin{aligned} M &= \max(E, 0)/L_m & T_A \geq T_0 \\ M &= 0 & T_A < T_0 \end{aligned}.\tag{4}$$

Run-off is evaluated as a sum of melted water and liquid precipitation reduced by refrozen and retained water.

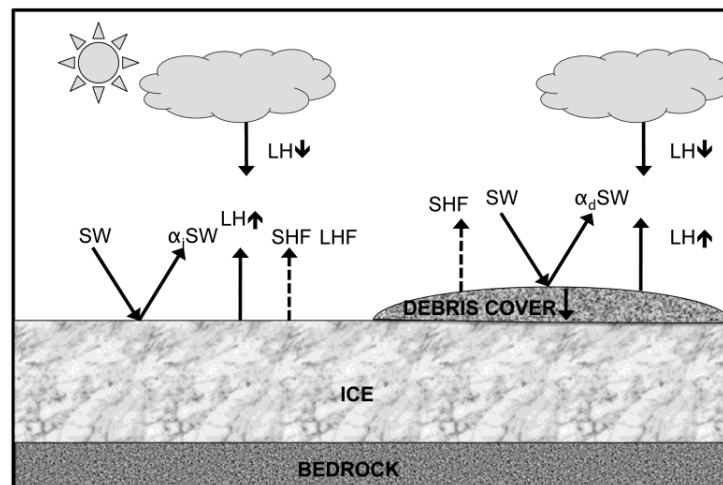More details of the model formulation are given in [2, 12].

Figure 1. Heat fluxes on the surface of the mountain glacier taken into account in the mathematical model.

2.2. Input data and set up of a numerical experiment

To validate the model, in the current study we utilized data from two weather stations located close to the Djankuat Glacier – Terskol and Mestia. Both stations are located within several tens of kilometers to the glacier. Another reason of choice was completeness of data. Surface air temperature measured at Terskol (2144 m above sea level, a.s.l.) on the Northern macroslope of the Main Caucasus Chain can be easily

remapped to the area of the Djankuat Glacier. We carried out comparison of parallel observations at Terskol and at the automatic weather station (AWS) located directly on the glacier at the elevation of about 3100 m a.s.l. during several summer seasons (data obtained in summer of the year 2011 is shown in figure 2a) and derived a simple linear transformation expression $T_{Djankuat} = -2.91 + 0.48 T_{Terskol}$ to recalculate air surface temperature observed at Terskol to the elevation of AWS Djankuat (figure 2b). Unfortunately, available precipitation record at Terskol is corrupted. This was the reason to utilize daily precipitation data from Mestia, located at the Southern macro-slope of Caucasus at the elevation of 1434 m a.s.l. Preliminary analysis of climatic averages proved that monthly and annual precipitation averages at both sites are quite similar. Unfortunately, precipitation was not measured directly on the glacier, therefore direct comparison could not be carried out. For model validation we have chosen a 10-year time segment with minimum gaps in the records: from October, 1, 1999 to September, 30, 2009 (ten conventional hydrological years).

Absorbed solar radiation, effective radiation and available melting energy are calculated every hour. Precipitation, refrozen/retained water run-off and mass balance are evaluated once a day.

We limit climatic forcing to only two records – daily temperature and precipitation rate. In view of using our modeling approach for evaluation of the future glacier dynamics, we find it reasonable to restrict prognostic forcing variables to only those chosen and to parameterize the others – cloudiness, absorbed radiation etc. For instance, cloudiness in our approach is set to 0.2 when daily precipitation is zero and to 1.0 when precipitation is not zero.
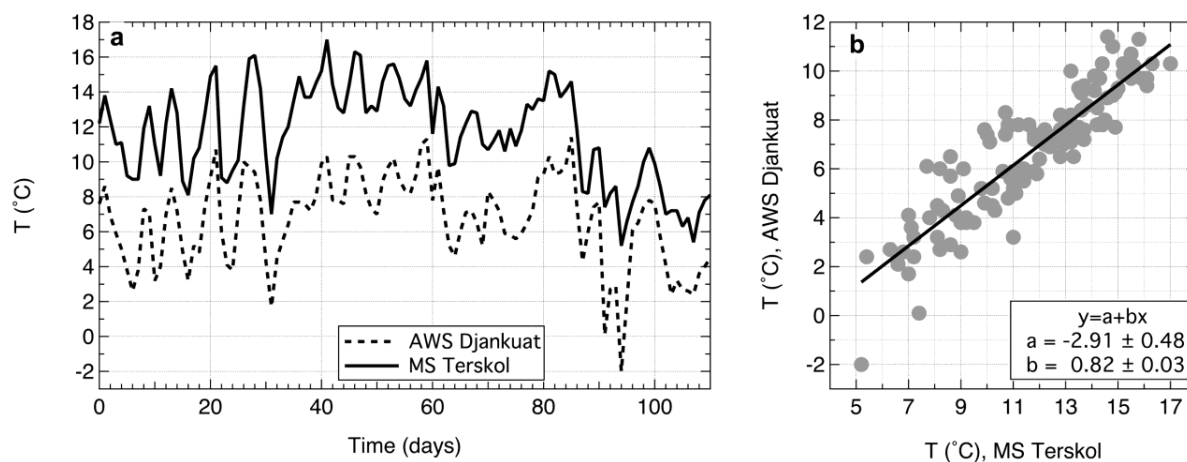

Figure 2. Parallel observations of air surface temperature at Terskol weather station and Djankuat weather station in summer of the year 2011 (a), linear relation between both records (b).

3. Results and discussion

Specific mass balance obtained during ten model years was compared to the similar characteristic evaluated from direct accumulation and ablation measurements (V V Popovnin, personal communication) (figure 3). Two solid curves indicating annual mass balances are quite similar. Model failed to reproduce positive mass balance in the year 2004. That is why cumulative mass balance in the end of the decade is 300 mm more negative in the modeled case. We established several crucial model parameterizations and assumptions affecting final results most of all. Among those are parameterization of albedo, ratio between direct and diffuse radiation, daily amplitude of surface air temperature. Comparison with fields of surface

mass balance and ablating rate based on observations (V G Pastukhov, personal communication) with simulated results indicate that model fails to reproduce small details of observations. This mostly happens because albedo parameterization is rather simple and cannot describe its spatial and temporal distribution exactly. This is perhaps not necessary for predictions of glacial run-off since the overall result is reasonable. Therefore, we find it expedient to follow a rather simplified approach described in [12]. Another source of deviations between the model and reconstructions is possible not exact masks of debris covered areas.

We find that obtained results are promising, because we managed to elaborate a comparatively simple mathematical model, which can reproduce processes of heat exchange of a mountain glacier using only two input variables - surface air temperature and precipitation rate. In future, we plan to couple surface mass balance calculations and ice flow simulation using a model previously applied to one of the alpine glaciers [11]. This will enable to carry out prognostic calculations basing on the results of global climate modeling downscaled to a particular mountain glacier as discussed in [7].
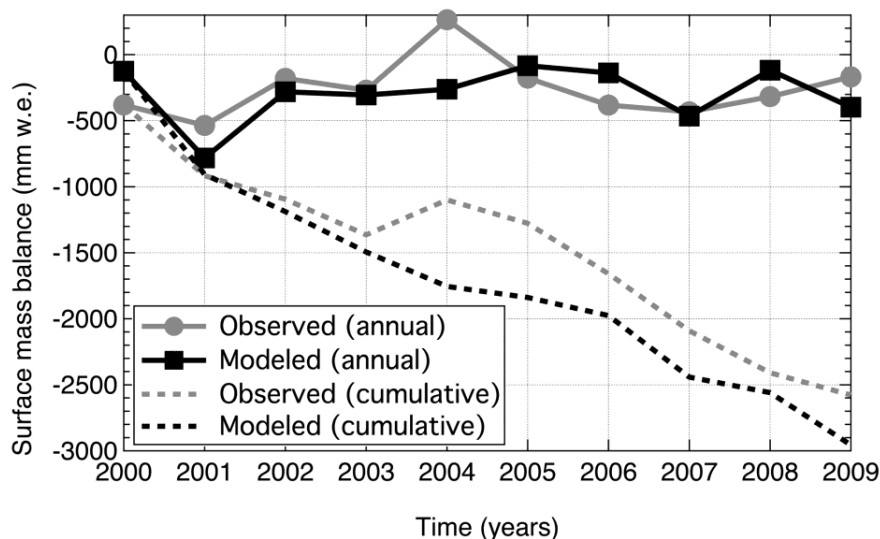

Figire 3. Observed and modeled specific surface mass balances (mm of water equivalent) of the Djankuat Glacier, annual 2000-2009 and cumulative.

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