ESTIMATION OF ACCUMULATION FROM SNOW AVALANCHES ON THE MOUNTAIN GLACIERS

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ABSTRACT: Snow avalanches redistribute snow from the top of the mountain ridges down to the valley bottoms, which can be occupied by glaciers. The contribution of snow avalanches, coming outside the glacier limits, into the seasonal snow accumulation on a glacier is the least studied component of the glaciers' mass balance. We present a new approach for the numerical estimation of snow avalanches contribution into accumulation on glaciers, allowing not to carry out detailed terrestrial snow surveys, based on DEM and meteorological data analysis using GIS and numerical modeling of snow avalanches. The approach was tested on the Batysh Sook Glacier located in the Kyrgyz Tien Shan. A case study was realized for the 2015/2016 balance year based on the high-resolution DEM obtained from a drone in July 2016 and the data of meteorological observations at the distance nearest to the glacier weather station. The snow avalanches accumulation on the Batysh Sook Glacier during the winter season 2015/2016 turned out to be 13±4% of the total accumulation. The results of numerical assessment of snow avalanches contribution into glacier accumulation possess a high scientific significance due to high sensitivity of all components of glacial mass balance to climate change. The developed approach is applicable in the long term not only for glaciers but avalanche's contribution to river runoff that adds even more practical significance to the research.

KEYWORDS: avalanche, accumulation, mountain glacier, numerical modeling, GIS, RAMMS

1. INTRODUCTION

Snow avalanches are considered to be among the main sources, composing the income part of a glacier mass balance (Popovnin & Pylayeva, 2015). However, there are still almost no commonly accepted methods for the numerical evaluation of avalanches accumulation on the glaciers. This is related to the poor avalanche data availability and lack of possibilities to obtain these data on most of high-altitude mountain glaciers.

The evaluation of snow avalanches' contribution into mountain glacier accumulation with a lack of direct observational data on the amount of avalanche-drifted snow deposited on glaciers implies a highly relevant task delivering the important knowledge of one of the least studied components of the glaciers mass balance and it is affected by changing climate.

We present a new approach for the numerical estimation of snow avalanches contribution into accumulation on mountain glaciers without carrying out detailed terrestrial snow surveys based on GIS analysis as well as numerical modeling of snow avalanches using avalanche dynamics program RAMMS (Christen et al., 2010; Bartelt et al., 2017).

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Glaciers located in high mountain areas such as the Kyrgyz Tien Shan are indispensable water reservoirs (Kaser et al., 2010; Kenzhebaev et al., 2017). Changes in glacier mass are a key focus of glacier monitoring. The developed approach for the numerical estimation of snow avalanches contribution into accumulation has been tested on the Batysh Sook Glacier located in Kyrgyzstan. A case study was realized for the 2015/2016 balance year.

2. STUDY AREA AND DATA

Batysh Sook Glacier (in earlier studies also known as Suyok (Suek), Zapadniy Glacier, or Glacier No. 419) is located 41°46.668′N, 77°45.071′E, within the Sook range in the Inner Tien Shan, Central Asia (Kenzhebaev et al., 2017). The Sook range consists of 44 glaciers with a total area of 30.9 km^2 and volume of 1.2 km^3, as estimated in 2007 (Hagg et al., 2013). From 1956 to 2007, these glaciers lost over 12% of their volume (Hagg et al., 2013).

The Batysh Sook Glacier spans an altitudinal range of 3950 to 4450 m a.s.l and in 2016 covered an area of around 1.08 km^2 (Kenzhebaev et al., 2017).

Field measurements taken place in 2016 showed that snow avalanches bring additional snow, coming outside the glacier limits, to the Batysh Sook Glacier. Avalanche debris were widely spread on the glacier surface in July 2016. There is no available direct data on snow avalanches in

the research region as well as avalanche-drifted snow deposited on the Batysh Sook Glacier.

The research was based on the application of the high-resolution (1 m) digital elevation model (DEM) of the glacier that was received from the eBee drone in July 2016 by S. Gindraux and C. Hergarden. Unfortunately, this DEM doesn't cover all the surrounding the research glacier avalanche active slopes, therefore SRTM (1 arc-second) digital elevation data was used for the uncovered area.

The nearest to the Batysh Sook Glacier is the Tien Shan Kumtor automatic weather station (AWS) situated 32 km from it in the Akshiirak massive at an elevation of 3660 m a.s.l. The Tien Shan Kumtor AWS (records data every hour) started to operate in August 1996, replacing the former Tien Shan station located nearby.

The mean annual temperature measured at the Tien Shan Kumtor AWS is −5.8°C (2003–2014). Mean annual precipitation is 360 mm (2003–2014), and on a long-term perspective (1930–1996) up to 76% of the annual precipitation was recorded during the summer months (May–September) (Kutuzov & Shahgedanova, 2009).

3. APPROACH

The developed approach for the numerical estimation of snow avalanches contribution into accumulation on glaciers consists of the following steps: relief analysis; meteorological data analysis; snow avalanches volumes assessment during the analyzed winter period; numerical simulation of snow avalanches using RAMMS; evaluation of snow avalanches contribution into glacier accumulation.

3.1. Relief analysis

Using GIS technologies in combination with DEM, the potential avalanche release zones have been indicated and analyzed with respect to topographic characteristics.

Topographic characteristics were derived from the DEM for the semi-automatic defining (using ArcGIS 10.3) of avalanches release return period (see Figure 1) in the potential release zones using regional dependency of Haritonov (1979) based on the analysis of 4972 avalanches recorded in different parts of Central Asia. Avalanches release return period was estimated depending on the slope and aspect (see Figure 1).

3.2. Snow data analysis

Available snow data from the Tien Shan Kumtor AWS has been analyzed. The maximum snow height during the investigated winter season 2015–2016 turned out to be 28 cm on the AWS corresponding to the 2-year return period value.

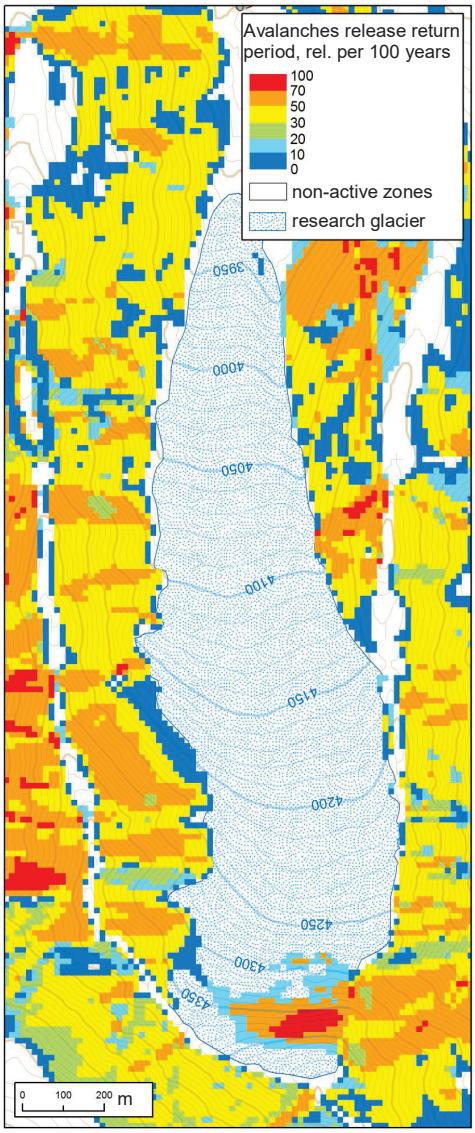

Figure 1: Avalanches release return period estimated depending on the slope and aspect.

The analyzed AWS is located too far away to be representative for the research area. As in most of the other mountain regions, there is a lack of high elevation meteorological records in Tien Shan. Moreover, existing records are relatively short. Therefore, we have been forced to operate by only this available data.

Snow height has been re-calculated for the research area using regional dependencies from (Kotlyakov, 1997; Severskiy et al., 2000). Maximum snow height on the mean altitude of the Batysh Sook Glacier during the analyzed winter period 2015–2016 turned out to be 62 cm.

3.3. Snow avalanches volumes assessment

To evaluate the contribution of snow avalanches, coming from outside the glacier limits, into the seasonal accumulation on the Batysh Sook Glacier, we estimated release zones (see Figure 2) that were most probably active during the winter season 2015/2016 based on the regional dependency of the avalanche activity on relief (Haritonov, 1979) and the snow height return period. An assumption has been made that 2-year return period release zones and more frequent ones to be active during the analyzed winter period.

As only a part of the total snow cover as usual participates in the avalanche formation we computed two different scenarios of avalanches volumes: (1) with the total maximum snow height in the release zones and (2) its part calculated according to (Blagoveshchenskiy, 1991). We assumed that the only one avalanche released during the analyzed winter season from each release zone.

3.4. Numerical simulation of snow avalanches

We performed the numerical simulations of snow avalanches that were most probably released during the winter period 2015/2016 using avalanche dynamics program RAMMS (Christen at al., 2010; Bartelt et al., 2017) and estimated avalanches run out distances and deposition heights (see Figure 2). We simulated avalanches with the automatically generated variable friction coefficients (μ and ξ) as recommended by RAMMS User Manual (Bartelt et al., 2017) with no modification.

Two different scenarios of avalanche fracture snow heights in the same release zones were simulated: (1) with the total value of maximum snow height in the release zone; (2) with the avalanche fracture height calculated according to (Blagoveshchenskiy, 1991).

RAMMS simulation results (run out distances and deposition heights) were compared with field measurements and orthophoto image received from the drone (July 2016). The outlines of avalanches deposits were realistically reproduced by both RAMMS modeling scenarios using predicted input model parameters considering the time difference with field measurements and corresponding to that uncertainties.

RAMMS was calibrated for large avalanches in the Swiss Alps and was never tested for simulating of small volume avalanches in Tian Shan. Therefore, we have decided to operate by both scenarios and provide the final result of the avalanche-drifted snow volume as an interval of values.

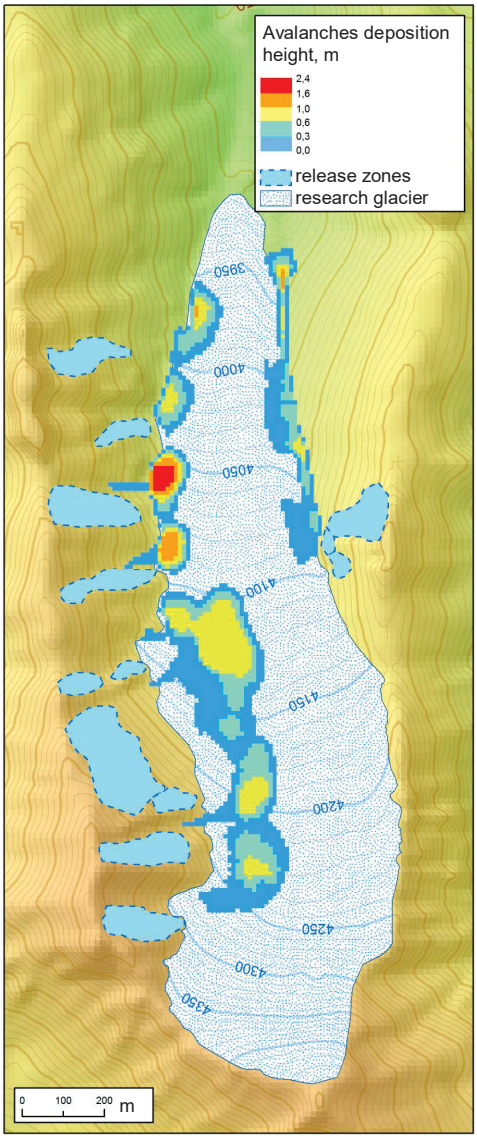

Figure 2: Most probably active avalanche release zones during the analyzed winter period and avalanches deposition height calculated using RAMMS from them.

3.5. Evaluation of snow avalanches contribution into glacier accumulation

The estimated total volume of avalanche drifted snow deposited on the Batysh Sook Glacier during the winter season 2015/2016 turned out to be approximately 75 000 m^3 (from 50 000 up to 100 000 m^3). The total winter accumulation on the Batysh Sook glacier was received from Kenzhebaev et al. (2017). Snow avalanche accumulation on the Batysh Sook Glacier during the winter season 2015/2016 turned out to be 13±4% of total accumulation.

5. RESULTS

A new approach for the numerical estimation of accumulation from snow avalanches on mountain glaciers was developed and tested on the Batysh Sook Glacier located in Central Asia.

The approach includes following steps:

1) Relief analysis:
- DEM analysis; definition of potential avalanche release zones that can provide avalanche drifted snow on the glacier;
- definition the avalanches release return period from the potential avalanche release zones using regional dependences on local topography.

2) Meteorological data analysis:
- definition of the maximum snow height and its return period in the avalanche release zones during the analyzed winter season.

3) Snow avalanches volumes assessment:
- indication of the active avalanche release zones and the corresponding snow fracture height during the analyzed winter season;
- avalanches volumes assessment during the analyzed winter season.

4) Numerical simulations of avalanches in three-dimensional terrain:
- evaluation of snow avalanches characteristics (run out distances and deposition heights) using avalanche dynamics program RAMMS;
- comparison of numerical simulation results with field observations or remote sensing data.

5) Evaluation of snow avalanches contribution into glacier accumulation.

6. CONCLUSIONS

GIS analysis together with numerical modeling of snow avalanches using RAMMS in combination with regional dependencies were applied for the first time for the estimation of snow avalanches accumulation on a high-altitude mountain glacier located in the region with no avalanche as well as snow data.

This research is a first numerical estimation of accumulation from snow avalanches on the mountain glacier based on all the available remote data. A lot of questions still remain open. At the same time joint application of different cross methods shows the prospects of the presented approach implementation into the practice.

The proposed approach based on the data and regional dependences from the Inner Tien Shan can be tested in other mountainous regions in the future. It is possible to apply it in the regions where DEMs, regular meteorological observations are available as well as general data on the regional avalanche formation factors.

The results of numerical assessment of snow avalanches contribution into glacier accumulation possess a high scientific significance due to high sensitivity of all components of glacial mass balance to climate change.

The developed approach is applicable in the long term not only for glaciers but avalanche's contribution to river runoff that adds even more practical significance to the research.

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