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Research paper

A GRASS GIS module to obtain an estimation of glacier behavior under climate change: A pilot study on Italian glacier

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ABSTRACT

The aim of this work is to integrate the Minimal Glacier Model in a Geographic Information System Python module in order to obtain spatial simulations of glacier retreat and to assess the future scenarios with a spatial representation. The Minimal Glacier Models are a simple yet effective way of estimating glacier response to climate fluctuations. This module can be useful for the scientific and glaciological community in order to evaluate glacier behavior, driven by climate forcing. The module, called *r.glacio.model*, is developed in a GRASS GIS (GRASS Development Team, 2016) environment using Python programming language combined with different libraries as GDAL, OGR, CSV, math, etc. The module is applied and validated on the Rutor glacier, a glacier in the south-western region of the Italian Alps. This glacier is very large in size and features rather regular and lively dynamics. The simulation is calibrated by reconstructing the 3-dimensional dynamics flow line and analyzing the difference between the simulated flow line length variations and the observed glacier fronts coming from ortophotos and DEMs. These simulations are driven by the past mass balance record. Afterwards, the future assessment is estimated by using climatic drivers provided by a set of General Circulation Models participating in the Climate Model Inter-comparison Project 5 effort. The approach devised in *r.glacio.model* can be applied to most alpine glaciers to obtain a first-order spatial representation of glacier behavior under climate change.

1. Introduction

Mountains are sentinels of climate change due to their rapid response to environmental modifications (UN A/Res/62/196). An important effect on high-altitude environments is the rapid retreat of the mountain glaciers in most of the world (Nesje and Dahl, 2000) with localized exceptions such as the Karakoram (Gardelle et al., 2012). To obtain assessment of future glacier conditions, quantitative descriptions of glacier dynamics are developed. The first choice concerning the theoretical description of glacier dynamics is between complex and simple models. The more complex models provide a detailed description of glacier dynamics, but also require a larger amount of input data and surrounding conditions. This information is not available for most mountain glaciers and the best way is to simplify the glacier description to use the existing data. In this work is developed a Python GRASS GIS module, called *r.glacio.model*, to adopt a description based on the minimal glacier model approach and to show the geospatial retreat of glacier terminus. This approximation is useful also to overcome the lack of data, such as bedrock analysis or drift velocity or other detailed parameters. The approach of this module is to validate by investigating the dynamics of the Rutor glacier in Aosta Valley,in the western Italian Alps. This process is divided into two different steps: 1) the calibration of module results on historical data; 2) the future assessments of glacier behavior, driven by climate variables that influence the mass balance of the glacier. This paper is structured as follows: the second section describes the Minimal Glacier Model and its implementation into *r.glacio.model*; the third section briefly introduces the study area and the input dataset about Rutor glacier; the fourth section introduces and reports the results of *r.glacio.model* about calibration and future behavior of the Rutor glacier and the fifth section gives the conclusions of this work.

2. Methods

2.1. Model basics – minimal glacier model

The Minimal Glacier Model falls into a class of models that normally have a simplified description about several variables like

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ice thickness, basal water pressure, sliding velocity, etc. (Oerlemans, 2008). This type of model is developed in order to reduce the complexity of glacier dynamics to a very simple description based on basic physical laws. In this model, the glacier evolution derives from an integrated continuity equation over the entire volume, assuming that the glacier has a constant width and accepting a crude representation of the real glacier geometry. For alpine glaciers, the equation for the total ice volume V is:

$$\frac{dV}{dt} = B_s \tag{1}$$

where B_s (m^3 w.eq.) is the total surface mass balance rate. The glacier volume V (m^3) is given by the product of the mean width W (m), the mean ice thickness H_m (m) and the glacier length L (m). Minimal Glacier Model is based on numerical experimentation with a Shallow Ice Approximation model (Oerlemans, 2008). Starting from these assumptions, the mean thickness H_m is given by (Oerlemans, 2008):

$$H_m = \frac{\alpha_m}{1 + \nu\bar{s}} L^{\frac{1}{2}} \tag{2}$$

where $\bar{s}$ (°) is the mean bed slope over the glacier length and α_m and ν are constants. To build the model, the parameter ν is fixed from the literature for valley glaciers (Oerlemans, 2008), as $\nu = 10$. The α_m is a parameter that regulates the glacier thickness. It is often set to $\alpha_m = 3m^{\frac{1}{2}}$ for valley glaciers and ice sheets, but to retrieve a better simulation different methods are presented (see Section 2.2). The scheme in Fig. 1 represents the iterative process of Minimal Glacier Model integration. The combination of Eqs. (1) and (2) describes the variation of glacier terminus along the flow-line direction $\frac{dL}{dt}$, shown in Fig. 1, as the core of the algorithm.

Considering a linear balance profile, the surface balance B_s expression includes the annual net mass balance $\dot{b}$, the most important driver of glacier behavior. It describes the amount of mass gained or lost in meters of water equivalent.

$\dot{b}$ is an input data; it is determined by the climatic forcing: mainly, winter precipitation and summer air temperature (although in principle there is a contribution also from the net incoming solar radiation).

The glacier length, that is the output variable, is finally obtained by numerically integrating the equations above (Hamming, 2012). MGM is an iterative process: the flow line variations are used as input of following cycle of MGM. So, the output length for the given year is an input data for the further cycle.

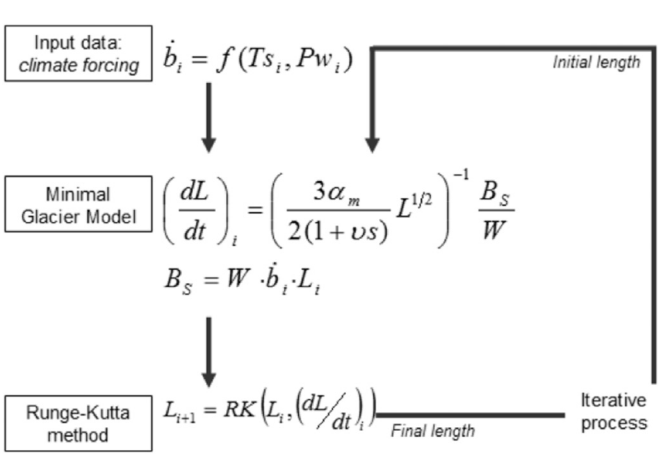

Fig. 1. Minimal Glacier Model algorithm scheme.

2.2. A method to estimate the thickness parameter α_m

The α_m is a key parameter in the development of this study because most of the input data is available from a geomorphological analysis or from other sources making it the only way to manage the model behavior. Two methods are presented to set this value:

- by a calibration process (see Section 4.2);
- by estimating the glacier thickness.

Focusing on the second method, the equation in Fig. 1 requires that some mandatory input data are included in the module: the glacier maximum altitude, the mean slope and the length of the flow line, the α_m constant for thickness and the mass balance. The first two parameters derive from DTM analysis, the third needs the flow lines and the glacier bound polygons as the input vector layer.

Eq. (2) requires the knowledge of the ice thickness H_m. We obtained these values with an approach that considers a constant basal shear stress along the flow line of the glacier and estimates the ice thickness along the central flow line (Linsbauer et al., 2012):

$$H_m = \frac{\tau}{f^{*} \rho_{*} g_{*} \ \sin(\gamma)} \tag{3}$$

where f=0.8 is the shape factor, related to the lateral drag on the glacier through friction at the valley walls and to the general form of the glacier cross section (Cuffey and Paterson, 2010), $\rho = 900\frac{Kg}{m^3}$ is the mean ice density, $g = 9.81\frac{m}{s^2}$ is the gravity acceleration, γ is the glacier surface slope along the flow line and τ is the basal shear stress (Linsbauer et al., 2012).

The basis for this parameterization scheme is the estimation of maximum and minimum altitude (h_{max}, h_{min}), defining the mean altitude as $\bar{h} = \frac{h_{max} + h_{min}}{2}$ and the elevation range as $\triangle h = h_{max} - h_{min}$. The value of τ is then obtained from an empirical relationship between τ and $\triangle h$, according to a polynomial regression (Haeberli and Hoelzle,):

$$\begin{cases} \tau = 0.005 + 1.598\triangle h - 0.435\triangle h^2 & \triangle h \leq 1600 \text{ m} \\ \tau = 150 \text{ kPa} & \triangle h > 1600 \text{ m} \end{cases} \tag{4}$$

Finally, we can combine the results of Eq. (4) with the mean ice thickness and the flow line length of Eq. (2) and we can estimate the average value α_m for some studied glaciers.

2.3. Implementation into GRASS GIS

2.3.1. Flow line

The general pattern of the ice flow is determined by the net budget between accumulation and ablation of the ice mass driven by the morphology of bed rock and the gravity force. The balance velocity is a parameter that describes this behavior (Waddington, 1998) and can be calculated from directions of ice flow using ice thickness and slope map (Huybrechts et al., 2000).

The flow line reconstruction is usually used in addition to a basic topographic analysis, in particular to model the erosion and the deposition in complex terrain. In this context, the flow line can be estimated by various algorithms that are based on morphological factors from which the flow depends. Some of these parameters are: slope angle, slope length, aspect and the upslope contributing area. Downhill flow lines merge in valley and can be used also for the extraction of the channels (Mitasova et al., 1996).

The flow lines were calculated starting from the results of r. flow algorithm (Mitasova et al., 1996) and to adjust the path of the principal flow line, after a subjective evaluation based on morphological parameters, the most important glaciers flow lines