Development of GIS methods to assess glaciers response to climatic fluctuations: a Minimal Model approach.

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Abstract

Theoretical work on glacier dynamics led to the construction of mathematical models for estimating glacier response to different climate change scenarios [2]. The aim of this work is to include a simple version of such models (the so-called Minimal Glacier Models [6]) within a GIS framework, to better understand, evaluate and reproduce the glacier response to climate fluctuations. Then, in this work three sections have been included: (I) the formulation of the Minimal Glacier Models, evaluating physical laws and numeric resolution; (II) the description of a GIS algorithm to calibrate and to validate the simulated results; (III) the application of GRASS – GIS module to obtain a spatial representation of glacier retreat.

I. MINIMAL GLACIER MODEL

This type of model tries to reduce the complexity of glacier dynamics to a very simple description based on basic physical laws. The glacier evolution is obtained 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. This starting point is:

$$\frac{dV}{dt} = \frac{d}{dt}\left(WH_m L\right) = W\left(H_m \frac{dL}{dt} + L\frac{dH_m}{dt}\right) = B_S \qquad (1)$$

where V is the ice volume and B_s is the total surface balance rate. The volume is the product of the width W, the mean ice thickness H_m and the glacier length L.

Minimal Glacier Models assume perfect plasticity, an approximation of how the horizontal glacier flow line varies following the glacier thickness variations, and an instantaneous relationship between glacier length and thickness. Starting from these assumptions, H_m is given by [6]:

$$H_m = \frac{\alpha_m}{1+\nu \bar{s}} L^{1/2} \qquad (2)$$

where $\bar{s}$ is the mean bed slope over the glacier length and α_m and ν are constants.

The scheme in Fig. 1 represents the iterative process of Minimal Glacier Model integration. The combination of eq. (1) and (2) describes the variation of glacier terminus along the flow-line direction, dL/dt, shown in Fig. 1 as the core of the algorithm.

Considering a linear balance profile, the surface balance B_S expression includes $\bar{b}$, the mean bed elevation, E, the Equilibrium Line Altitude (*ELA*, the line that divides the accumulation from the ablation areas), and β, the mass balance gradient along the glacier. This gradient is estimated from the annual net mass balance B_n, which is the most important driver of glacier behaviour and describes the amount of mass gained or lost in meters of water equivalent.

In this formulation, the input data are B_n and the ELA, which are 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). Analysing the correlations between climatic variables and snout fluctuations of several glaciers [1] the most significant contributions come from the period November – March for winter precipitation and July – October for summer temperature. Then, we relate climate forcing to the model inputs by using a bivariate fit (Fig. 1, *Climate forcing*):

$$\dot{b}_i = aT_{s,i} + bP_{w,i} + c \qquad (5)$$

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$$E_i = uT_{s,i} + vP_{w,i} + z \tag{6}$$

where i represents the *i-th* year, $T_{s,i}$ is the summer 2m air temperature and $P_{w,i}$ is the winter precipitation.

The glacier length, that is, the output variable, is then obtained by numerically integrating the equations described above [3]. The output length for a given year is an input data for the further cycle, so this is an iterative process.

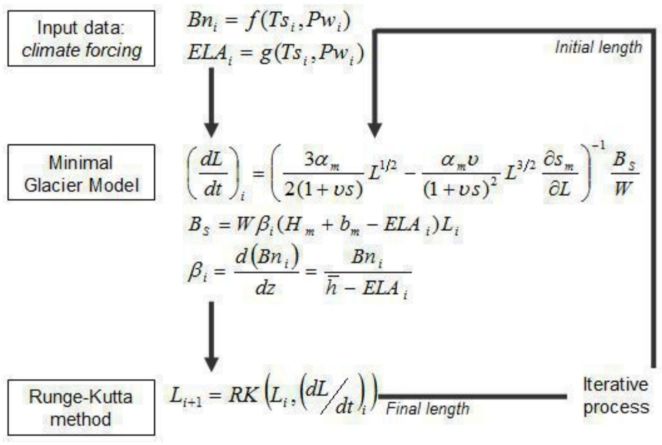


Figure 1. Minimal Glacier Model scheme.

II. USE OF A GIS ALGORITHM TO CALIBRATE THE MINIMAL GLACIER MODEL

A huge quantity of morphometric and morphologic parameters of several glaciers are collected by different remote sensing instruments, such as satellites and UAV, and by in-situ measurements. Such morphometric parameters provide detailed information to calibrate and validate glacier models.

To set the Minimal Model parameters and initial conditions, we determined the glacier geomorphology from a Digital Terrain Model using a GIS. Through DTMs, we reconstructed the evolution of glacier with a multi-temporal analysis and draw the flow lines that follow the accumulation-ablation dynamics, along which the model is applied. The algorithms were developed to extrapolate from DTMs, in a GIS environment, all the features needed to calibrate the Minimal Model (Fig. 2).

This algorithm is developed with QGIS tools, using several libraries and the interoperability of different open source software such as GDAL, GRASS, and SAGA. The procedure requires, as inputs, DTMs, POLYGONs and FLOW LINEs and we obtain all the morphological parameters and initial condition for the Minimal Model, such as maximum and minimum elevation, altitude range along the flow lines, mean slope and its variations, and flow line length.

These parameters are useful to start the iterative process (Fig. 1) and to calibrate the results on real values. Moreover, we validate the simulated results by comparing the numerical outputs with the flow line length values from past measurements.

In this way, the GIS analysis of glacier flow line could increase the accuracy of a Minimal Model (or of more refined glacier models). As shown in Fig. 3 for the Rutor glacier (western Italian Alps, Val d'Aosta), the accuracy of the simulated values obtained from the model calibrated with the DTM analysis (blue line) is much better than the accuracy obtained using bibliographical or standard parameters (red line).

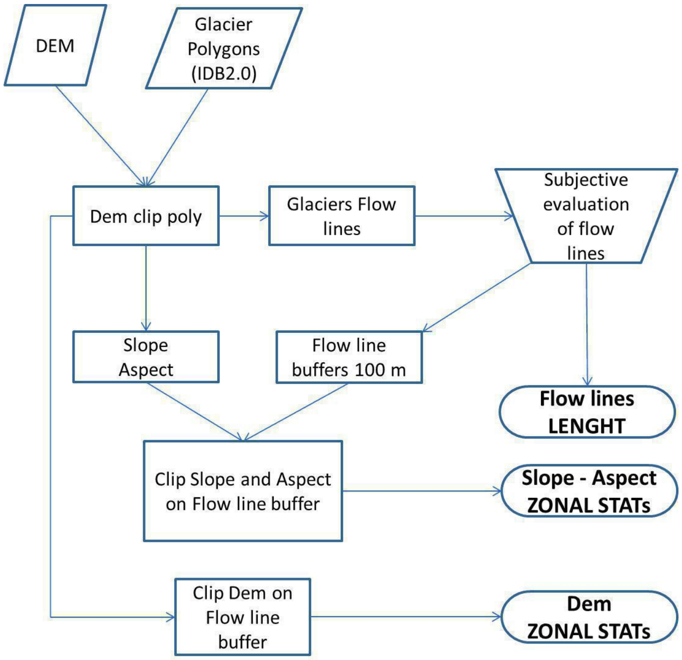


Figure 2. GIS algorithm used to calibrate Minimal Glacier Model boundary and initial condition.

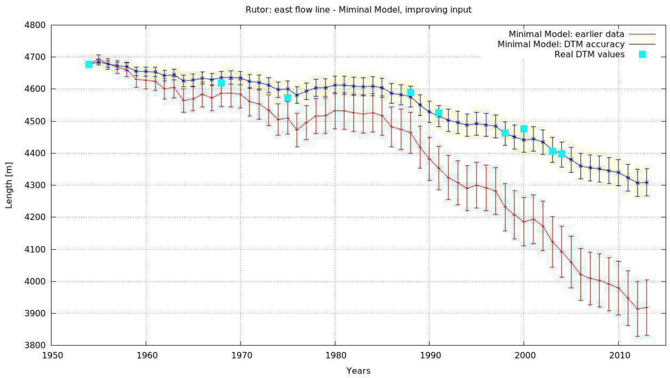


Figure 3. Comparison of model results. Light blue dots represent the flow line lengths measured by polygons on DEM, the blue line represents the simulated results, obtained from a model calibrated using the GIS algorithm, and the red line represents the simulated results with data from the databases of glaciers.

III. APPLICATION OF A GRASS GIS MODULE TO THE MINIMAL GLACIER MODEL: R.GLACIO.MODEL

The final step of this work is the integration of the Minimal Glacier Model with a GIS module, to obtain a spatial representation of the glacier retreat. The different reasons to create this GIS module are:

- the geospatial evaluation of flow line fluctuations;
- the formulation of a useful and simple tool for users;
- the development of an easy way to apply Minimal Models on large scale.

GRASS GIS [5] is an open-source software used for geospatial data management and analysis, image processing, graphics and maps production, spatial modelling and visualization. An easy and powerful development environment was set up, using Python language programming and GRASS GIS tools.

The result was the module r.glacio.model. The last formulation derives from a rigorous validation with different types of glaciers and the module will be released as a GRASS-addon under the GNU General Public License (≥ v.2).

The core of this algorithm is based on the equation in Fig.1, so it requires that some mandatory input data (as in Fig. 2) are included in the module: the glacier maximum altitude, the mean slope around the flow line, the length of flow line, the α_m constant for thickness, the mass balance and the ELA.

The first two parameters are derived from a DTM analysis, the third needs the flow lines and polygons as an input vector layer. The parameter α_m can be set by the user as a constant or it can be calculated from eq. 2, retrieving H_m through [4]:

$$H_m = \frac{\tau}{f \cdot \rho \cdot g \cdot \sin(\gamma)} \tag{7}$$

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 (Paterson, 1994), $\rho = 900$ kg m^{-3} is the mean ice density, $g = 9.81$ m s^{-1} is the gravity acceleration, γ is the glacier surface slope along the flow line and τ is the basal shear stress [4].

The climatic inputs of the Minimal Model are the annual mass balances, which are included in r.glacio.model to start the algorithm. To increase the module's usability and versatility, the ELA data are not included because it is often difficult to retrieve such data. Therefore, the equations are simplified.

We make an illustrative application of the r.glacio.model to the Rutor glacier, for which the algorithm was already calibrated. Fig. 4 shows the glacier retreat along the flow lines from 1954 to 2003.

Fig. 5 shows the initial mask of the module, where the user can insert the input raster, vector layer and the input climatic data.

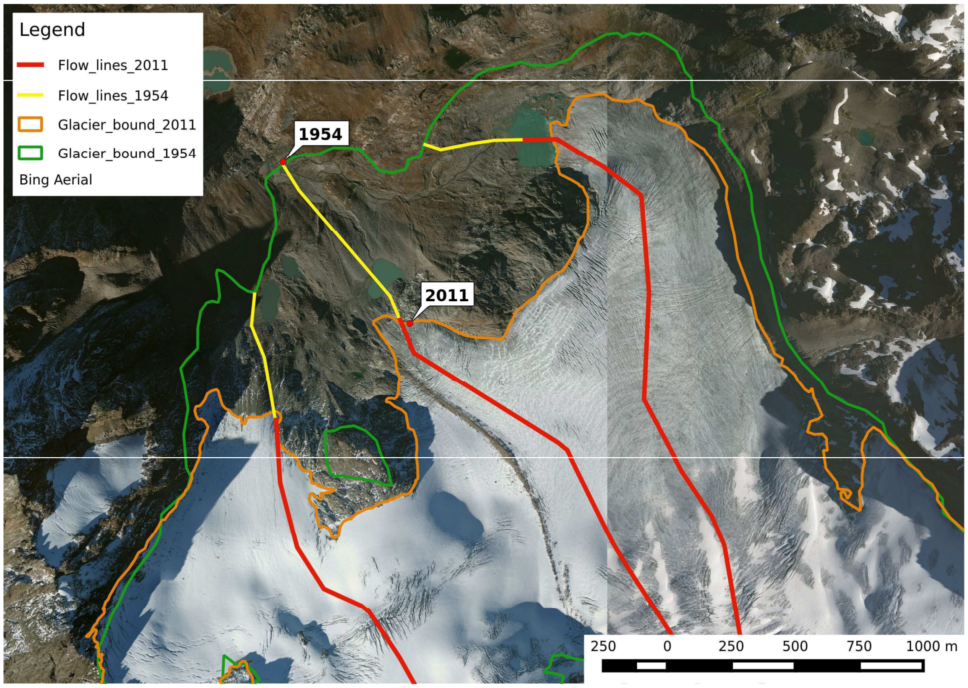
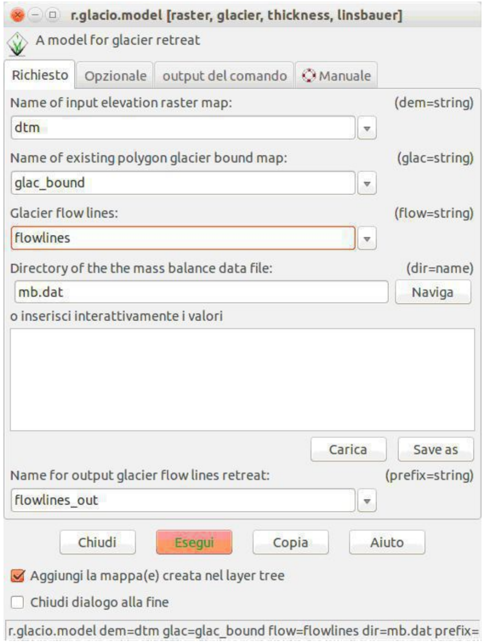


Figure 4. Glacier retreat along Rutor flow lines: results of the r.glacio.model. The yellow lines are the lengths at 1954, then the red lines are the estimated lengths at 2011 applying Minimal Glacier Model.



Name of input elevation raster map: (dem=string)
dtm

Name of existing polygon glacier bound map: (glac=string)
glac_bound

Glacier flow lines: (flow=string)
flowlines

Directory of the the mass balance data file: (dir=name)
mb.dat

o inserisci interattivamente i valori

Name for output glacier flow lines retreat: (prefix=string)
flowlines_out

☑ Aggiungi la mappa(e) creata nel layer tree

☐ Chiudi dialogo alla fine

```
r.glacio.model dem=dtm glac=glac_bound flow=flowlines dir=mb.dat prefix=
```

Figure 5. User mask of r.glacio.model. The inputs are the raster map (DTM), the polygon vector layer, the glacier flow line vector layer created by the user and the data file or the manual insertion of mass balance values for the years under consideration.

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