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The Future of the Glacier

From the past to the next 100 years

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Development of theoretical minimal model on glacier flow line with GIS tool, to assess glacier response in climate change scenarios

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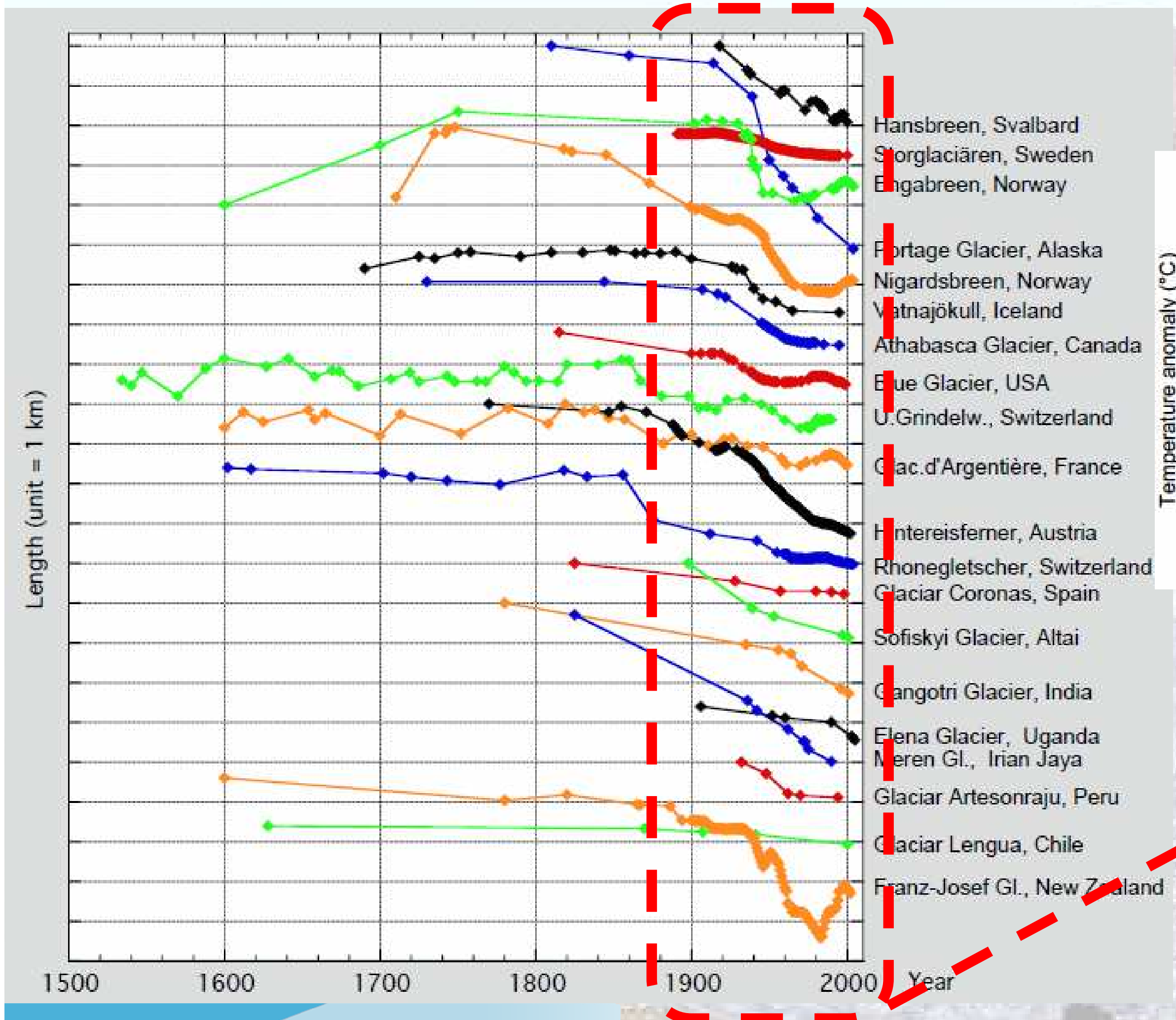
UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

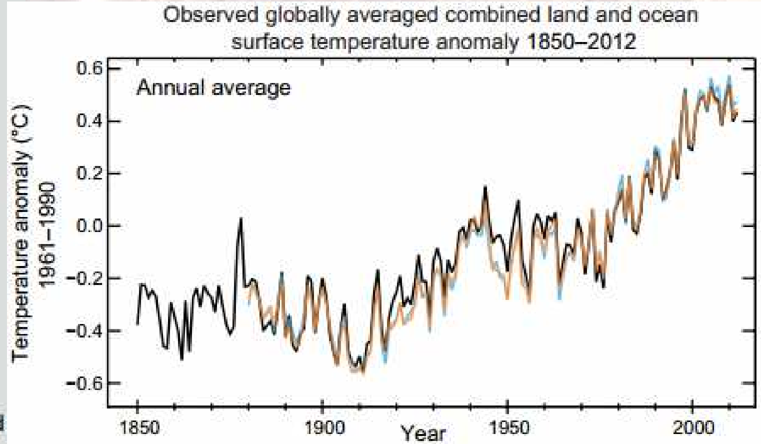
NextData

Introduction

"Recognizes that mountains provide indications of global climate change through phenomena such as […] the retreat of mountain glaciers […]"

UN A/Res/62/196, 2008





IPCC report 2013

Comitato Glaciologico Italiano

How to study glacier response to CC?

CLIMATE FORCING

- Temperature 2m
- Precipitation
- Snow deposition
- Humidity
- Radiation balance Lw, Sw
- Wind speed & direction
- Atmospheric pressure
- Cloud height
- …

MATHEMATICAL MODELS

They reduce a complex situation to a simple description, using laws of physics.

GLACIER RESPONSE

- Glacier terminus variation
- Area fluctuation
- Lose or gain volume
- Increase or decrease of thickness
- …

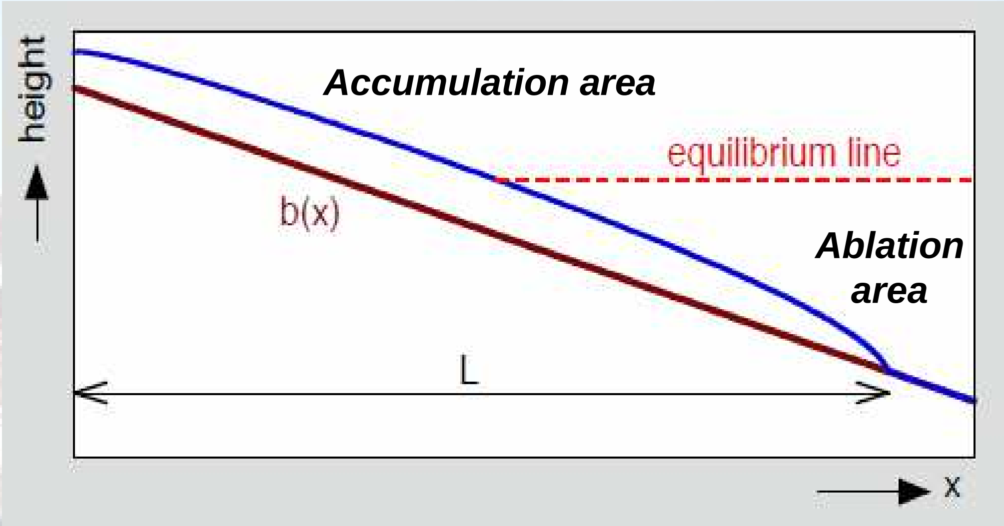
Minimal Glacier Model

(Oerelemans 2008, 2011)

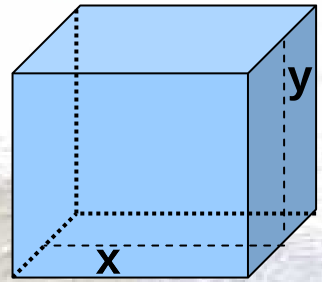
CONTINUITY EQUATION: describes the transport or variation of a conserved quantity.

$$V = H_m \cdot W_m \cdot L$$

$$\frac{dV}{dt} = H_m W_m \frac{dL}{dt} + H_m L \frac{dW_m}{dt} + W_m L \frac{dH_m}{dt} = B_S$$



PERFECT PLASTICITY PRINCIPLE: first-order estimate of how the thickness of a glacier varies with its horizontal dimension.



The elaboration is based on reconstruction of historical time series, after have obtained ***meteoreological***, ***physical*** and ***morphological data*** to start the model it is possible compare the **flow line length variation** ,the model results, with real measured variations.

Minimal Glacier Model - 2

Length variation of glacier terminus on flow line direction

$$\boxed{\frac{dL}{dt}} = \left(\frac{3\alpha_m}{2(1+\upsilon s)} L^{1/2} - \frac{\alpha_m \upsilon}{(1+\upsilon s)^2} L^{3/2} \frac{\partial s_m}{\partial L} \right)^{-1} \frac{B_S}{W}$$

Surface balance

$$B_S = W\beta(H_m + b_m - E)L$$

Mass Balance gradient

$$\beta = \frac{d\dot{b}}{dz} = \frac{\dot{b}}{\bar{h} - E}$$

$$\bar{h} = H_m + b_0 - \frac{L \cdot s}{2}$$

Boundary Condition:

- **B0 = highest elevation [m] (β)**
- **Hm = mean thickness [m] (ΔH)**
- **bm = mean bed elevation [m]**
- **L = length of the flow line [m]**
- **s = mean slope**

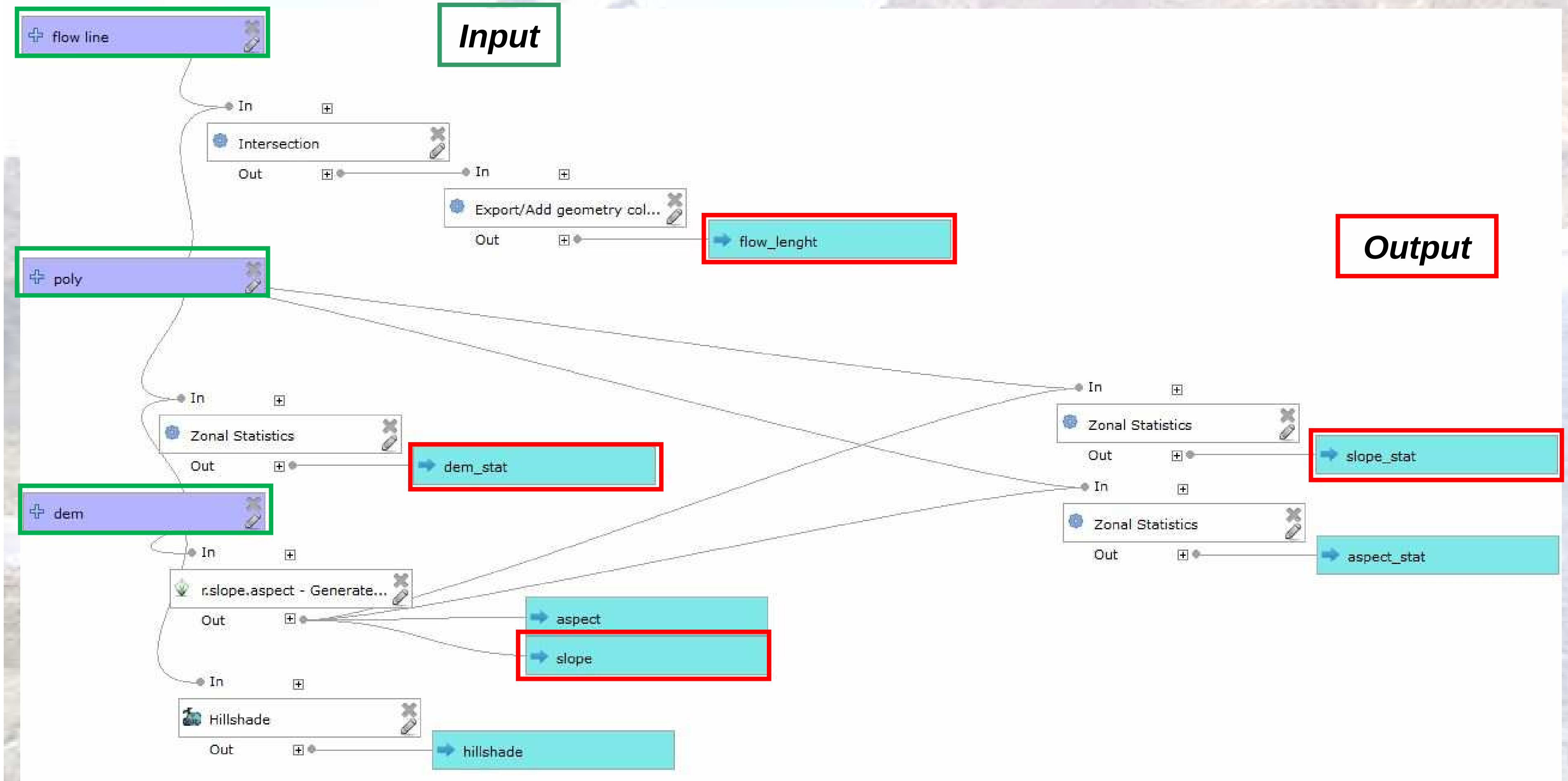
GIS

Equilibrium Line Altitude [*m*]
Net Mass Balance [*m w.e.*]

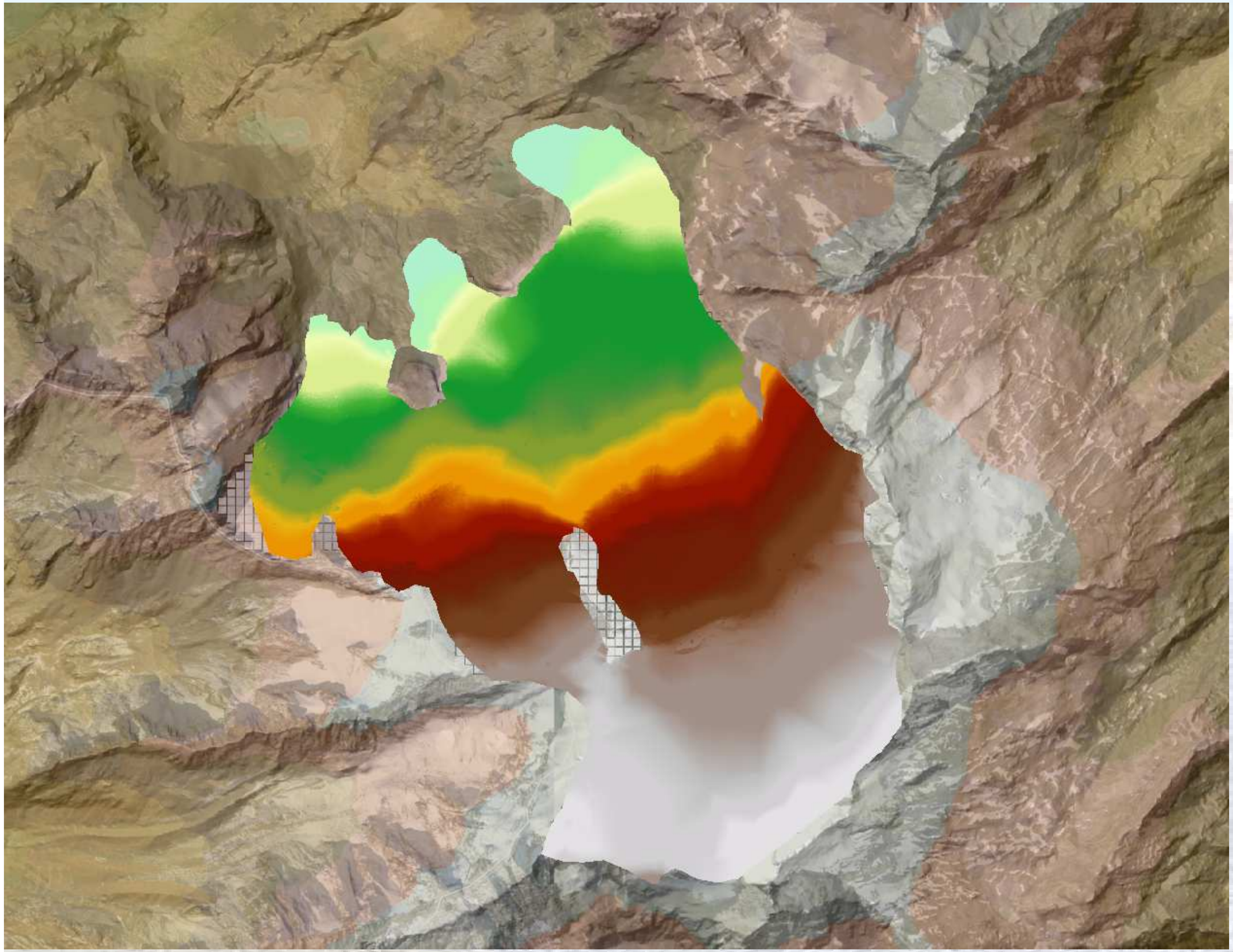
Climate forcing

Minimal Model: GISmodule for boundary conditions

Algorithm to calculate and to iterate the GIS operations to obtain Minimal Model input, using QGIS and other instruments: GRASS module and GDAL/OGR-libraries.



Minimal Model: GISmodule - 2

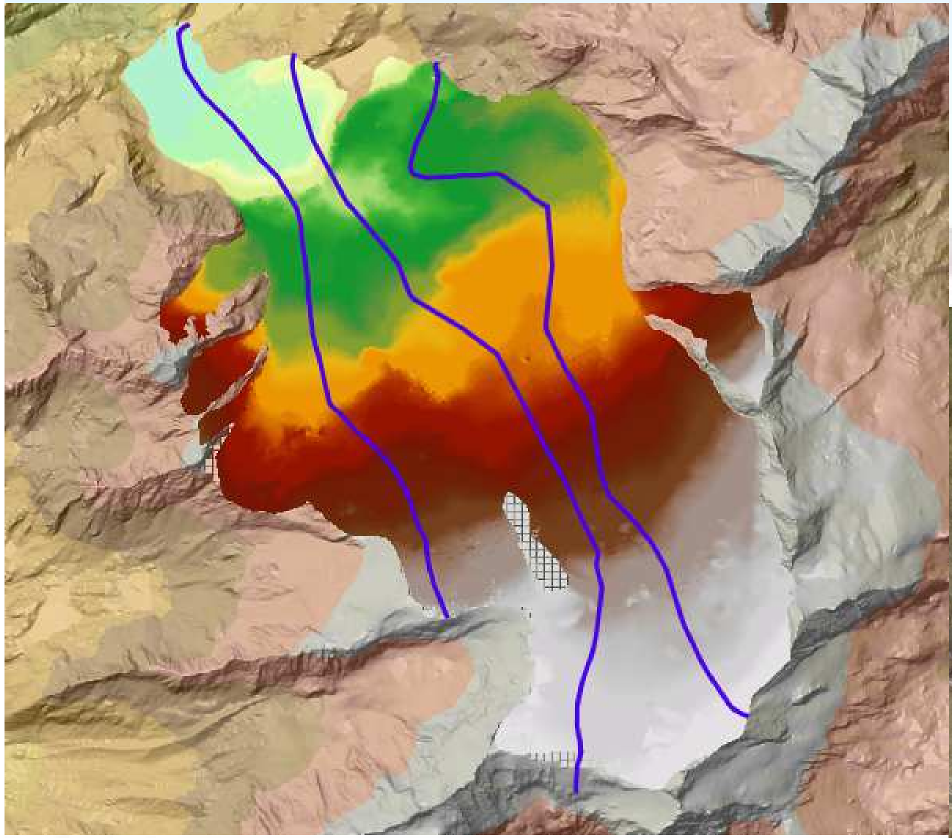


GIS process allows to apply spatial approach on deterministic one, that is Minimal Mole equations.

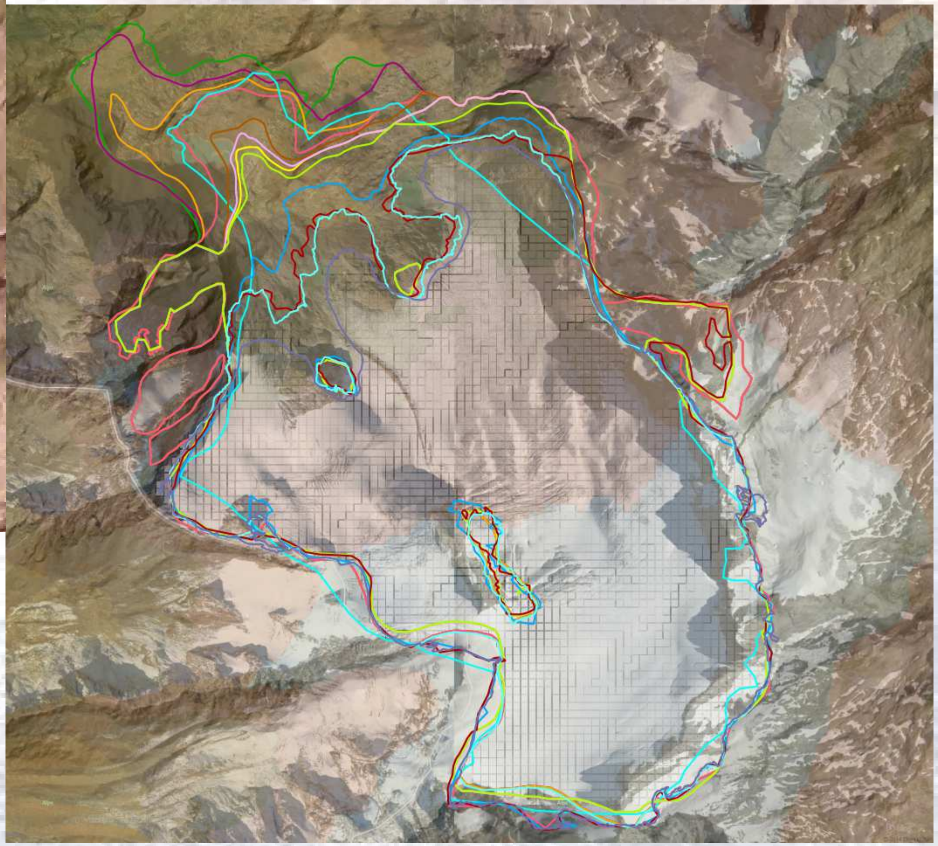
DTMs are the basis of GIS analysis, on which we can study the flow line and the polygons to obtain the morphological data set.

All the module results are rely on DTM resolution.

Minimal Model: GISmodule - 3



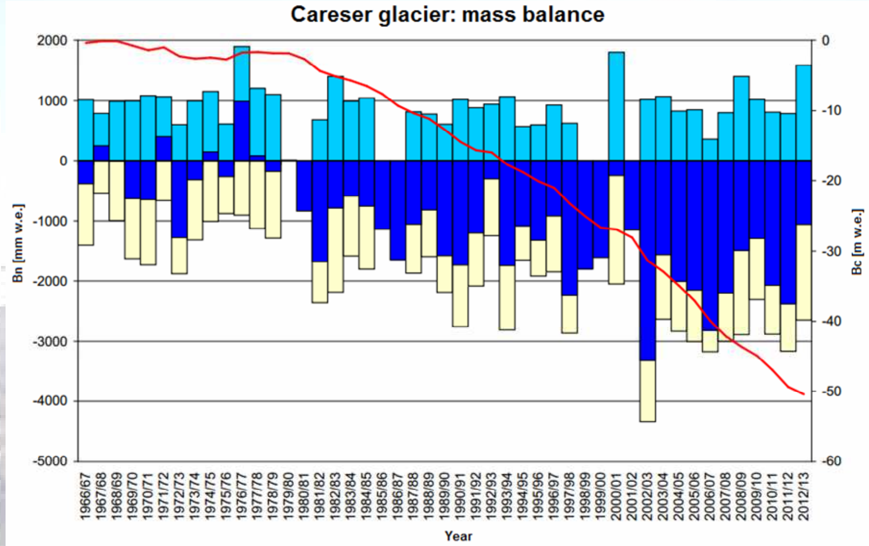
Polygons are used to evaluate the length of the flow line and to obtain the DTM statistics for a single year.

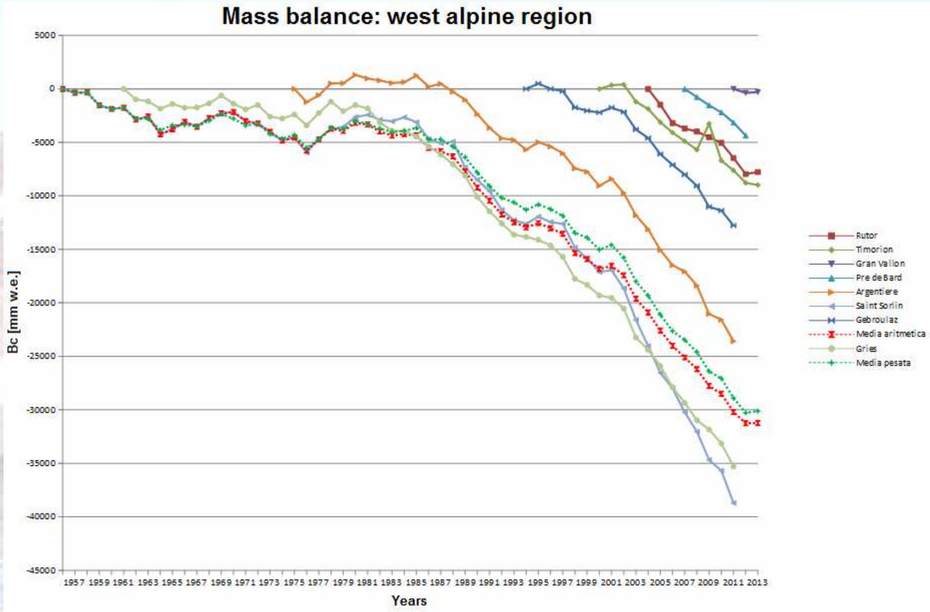


Flow lines are calculated with Grass **r.flow** and they are drawn with morphological analysis to choose the most plausible.

Minimal Model: input data

In minimal glacier model, the input data set are given by **b** and **ELA**.





Climate forcing on glacier

Mass balance and ELA are very closely related to the climate forcing and oscillations. We use a bi-variate fit to describe mass balance and ELA as a functions of summer temperature and winter precipitation, year on year.

$$\dot{b}_i = aT_{s,i} + bP_{w,i} + c \qquad E_i = uT_{s,i} + vP_{w,i} + z$$

Weather values comes from climate model, used to validate the algorithm through comparison with real measures and to assess future glacier response.

Minimal Model flow chart

Climate forcing with transfer function.

$$y_i = f(Ts_i, Pw_i)$$

Input data and **boundary condition.**

$$in = (Bn_i ; ELA_i)$$

$$L_{i+1} = L_i + \left(dL/dt\right)_i$$

Algorithm: explicit formulation of Model and Runge-Kutta solutions

$$\left(dL/dt\right)_i$$

Output data: length variation of glacier terminus on flow line direction.

Model calibration: validation of simulated results with real measurements.

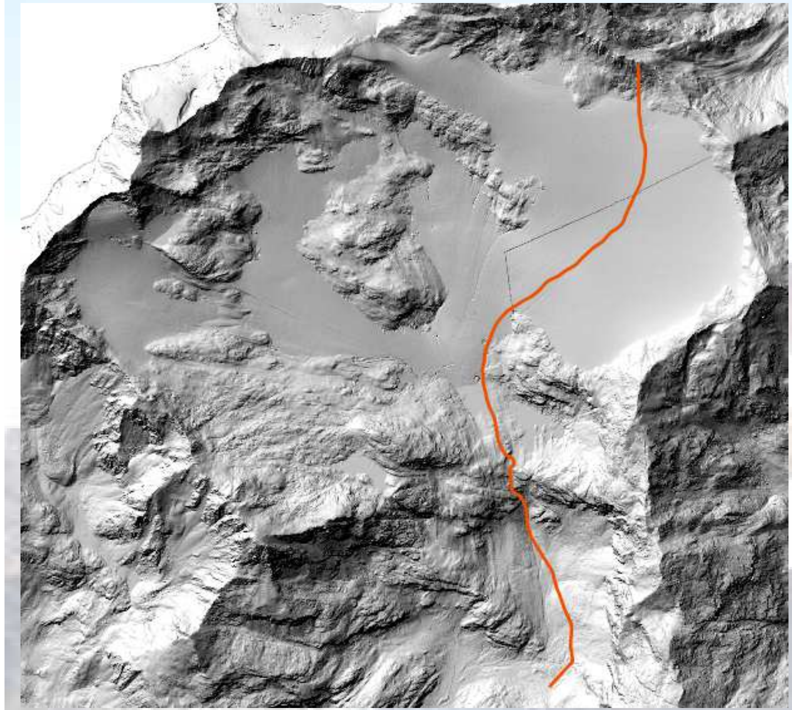
Future evaluation: assess glacier response in climate change scenarios.

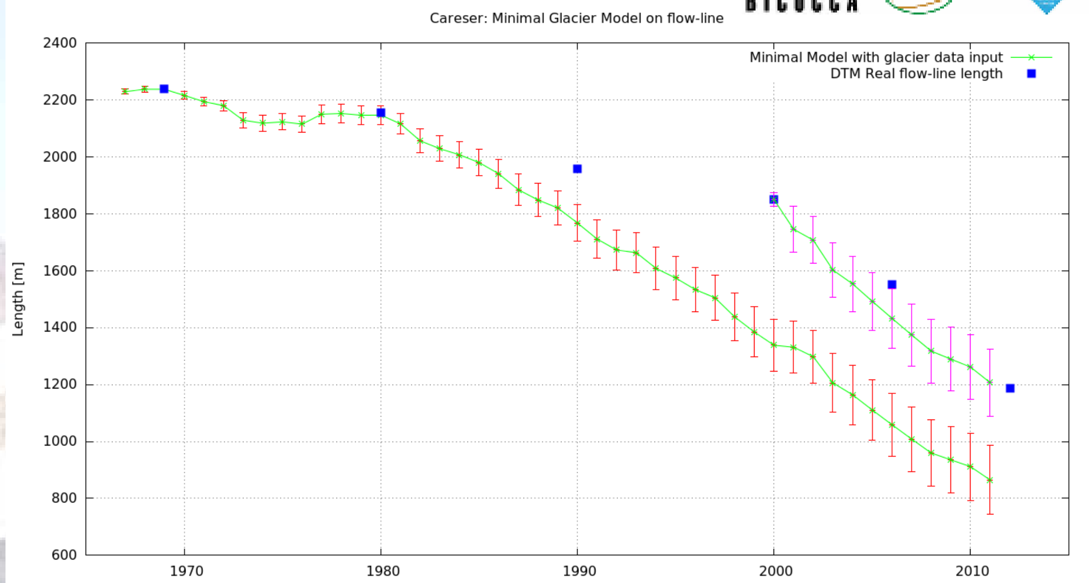
Minimal Model on Careser glacier

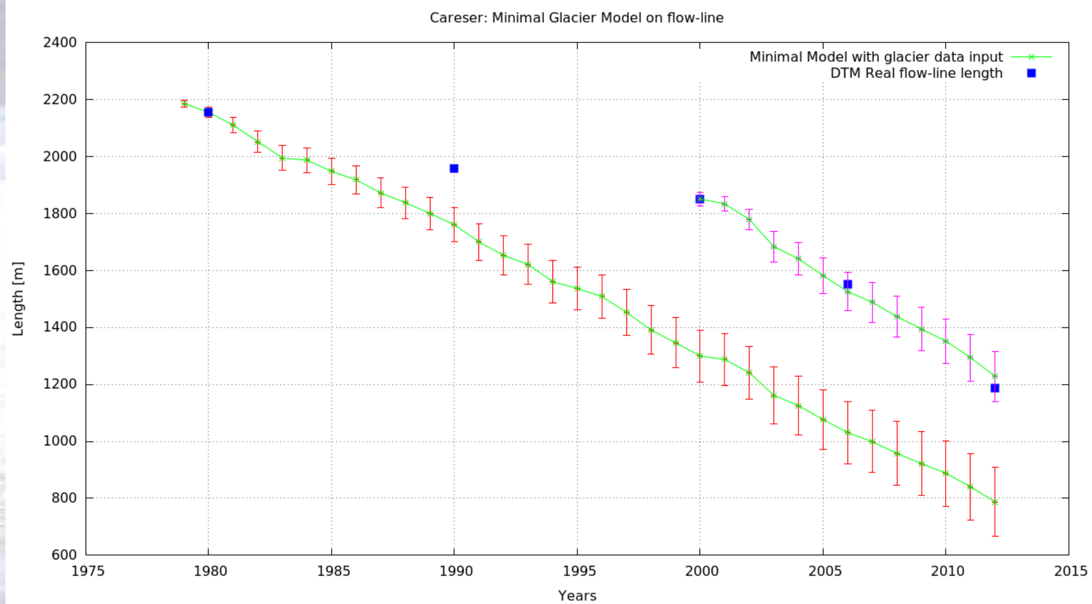
Careser glacier *(3279–2870 m a.s.l.) - Ortles-Cevedale group*

Glacier features:
- flat bedrock (slope ≈ 16%);
- mainly exposed to the south;
- no accumulation area;
- exhibits rapid mass loss and fragmentation;
- mass-balance and ELA measurements have been carried out since 1967.

Minimal Model on Careser glacier - 2



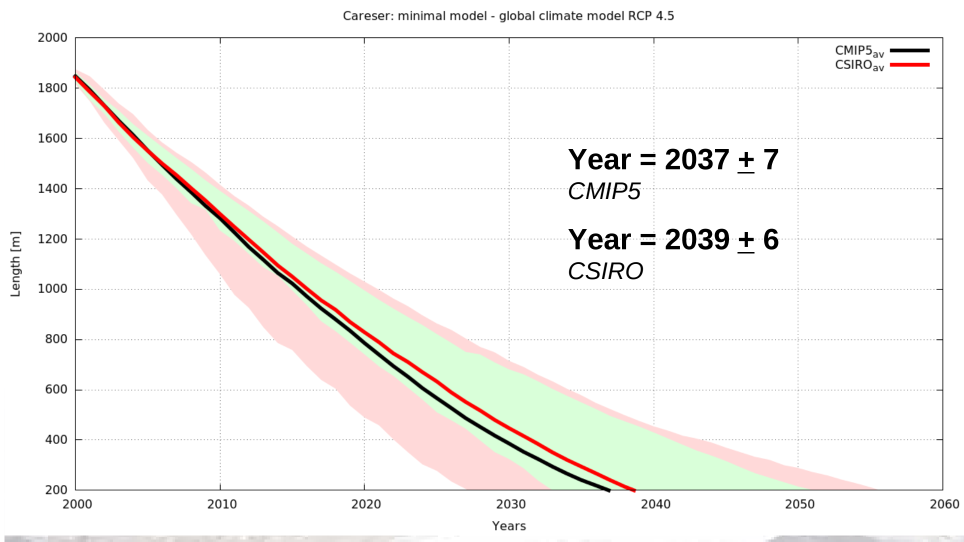


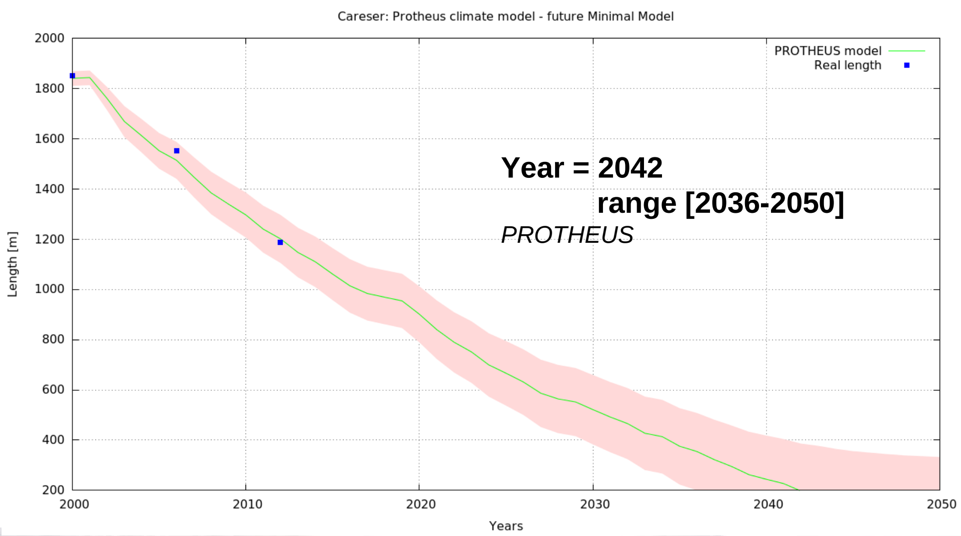


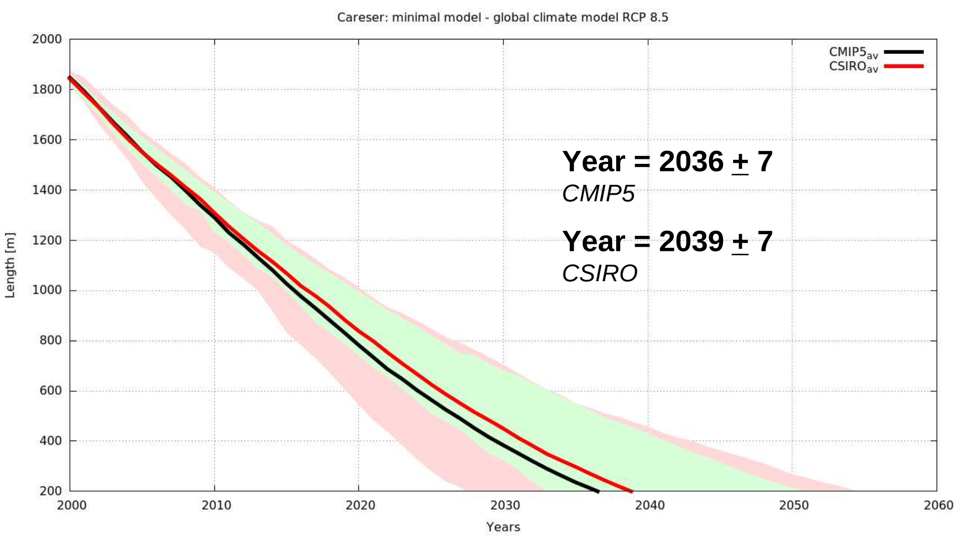
We identify in the east section: the 90% of the whole area of the glacier.

The elaborations show the slow down of the front retreat since 1980. Around 2000 the tendency changes slope and the real values becomes parallel to simulated ones.

Minimal Model on Careser glacier - 3







Future projection on Careser glacier.
L = *200m* is the statistic threshold for the disappearance of the studied flow line.

GCM [2005 – 2100]
CMIP5 ensemble and CSIRO runs in two different Emission scenarios:
RCP 4.5 & RCP 8.5.

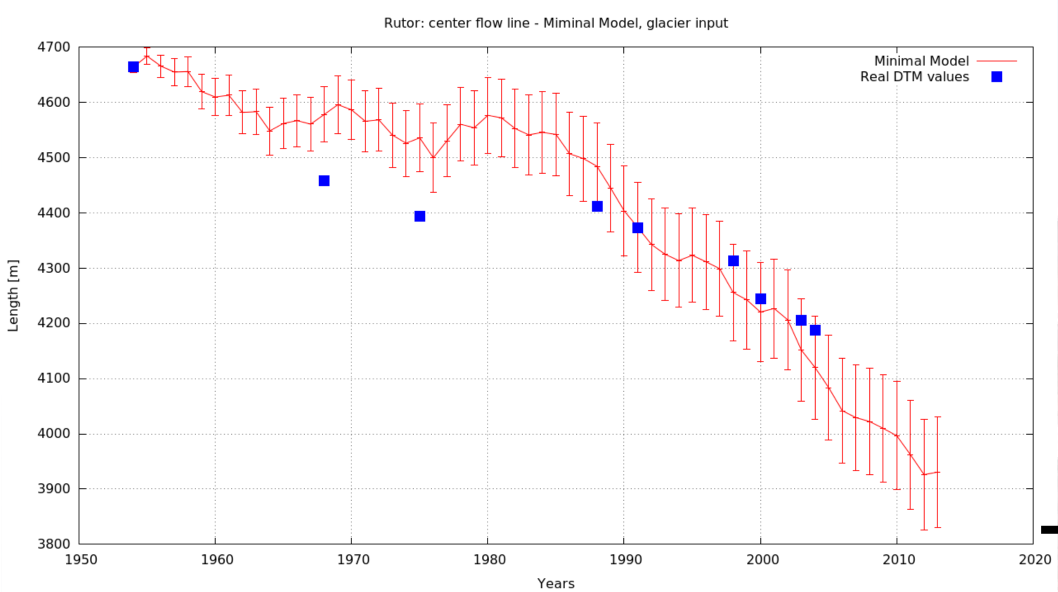
RCM [2005 – 2050]
Regional climate model PROTHEUS.

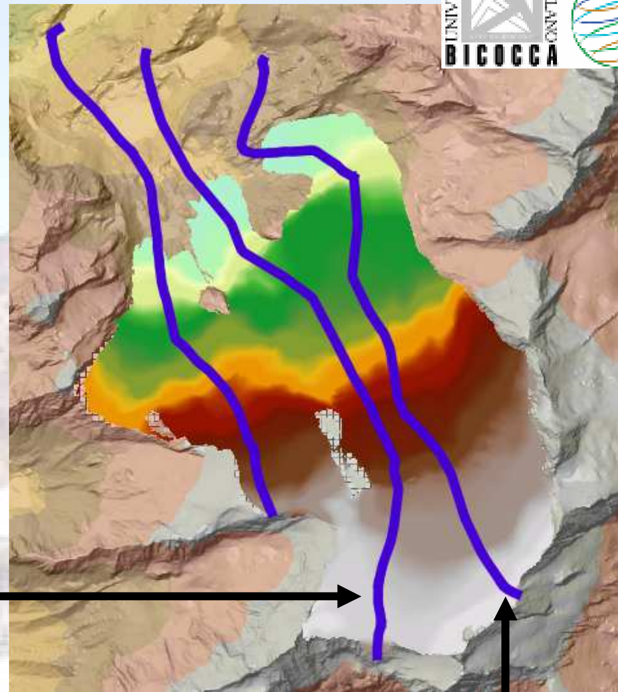
Minimal Model on Rutor glacier

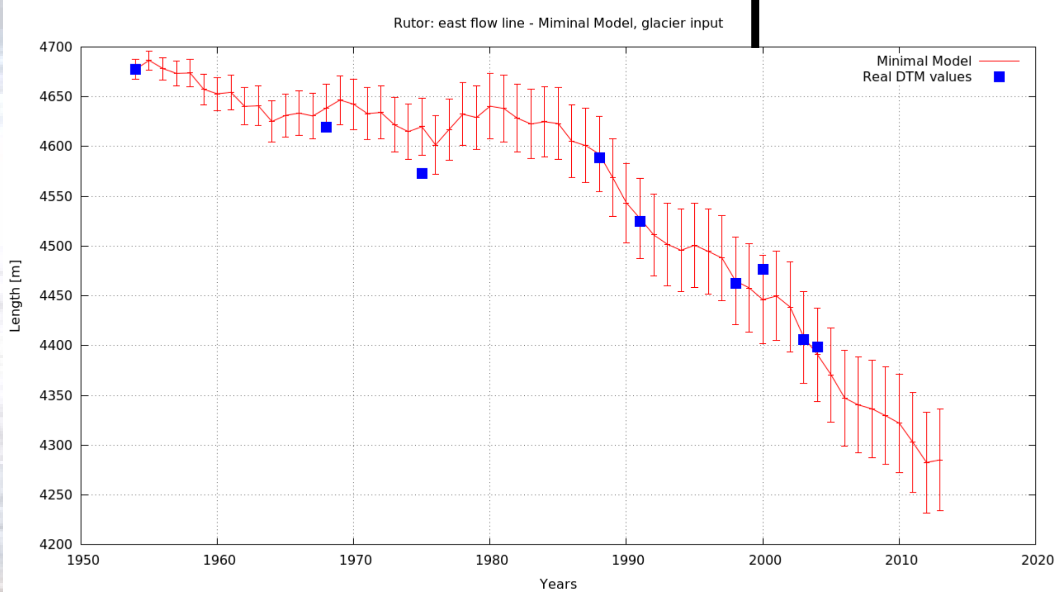
Rutor glacier *(3480–2640 m a.s.l.) – Vallone di La Thuile (AO)*

Glacier features:
- surface slope ≈ 22%;
- mainly exposed to the north;
- currently there are three main flow line;
- L ≈ 4000m.

Minimal Model on Rutor glacier - 2



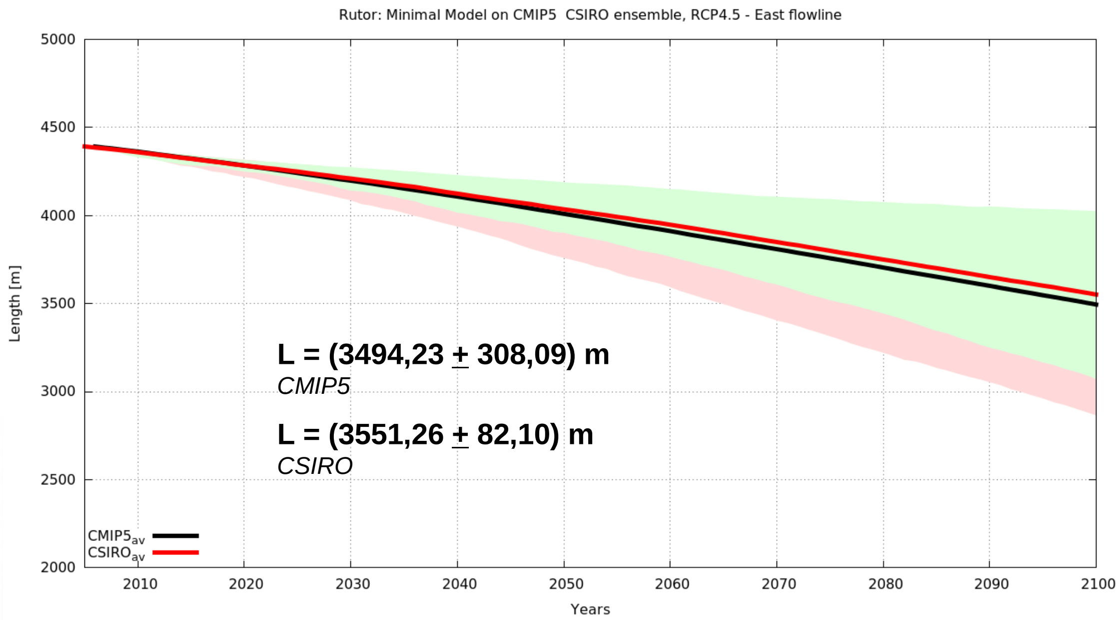




We identify three different flow line, but only east and center region have a good dataset that allow the application of Minimal Glacier Model coupling with Climate Model input.

The real values are the validation points come from GIS analysis by intersection between polygons and flow lines.

Minimal Model on Rutor glacier - 3

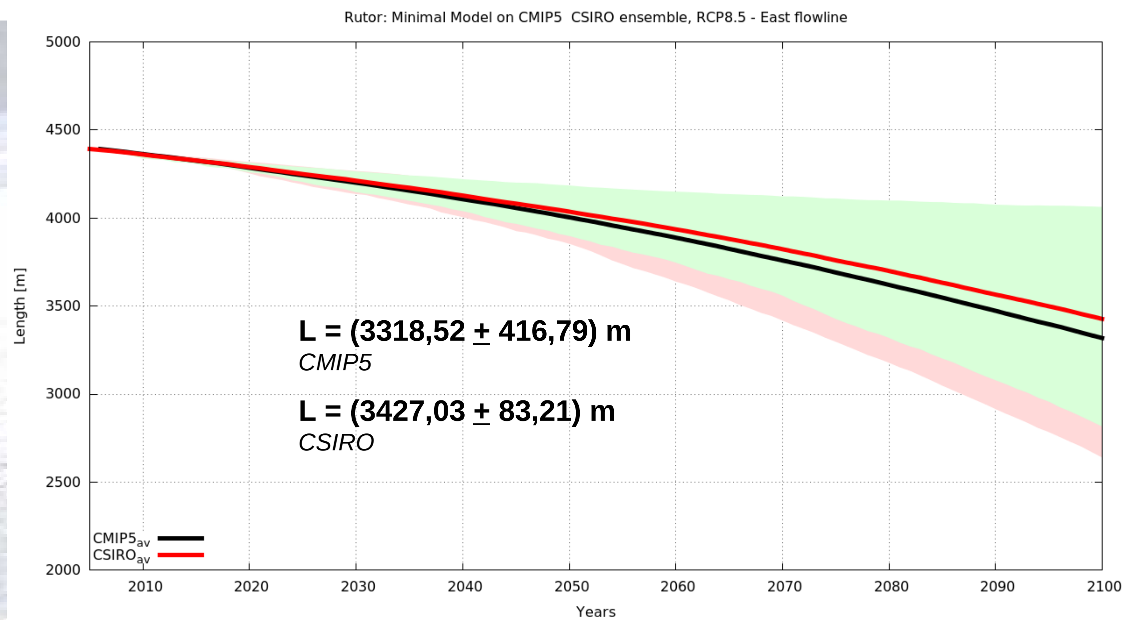


Initial length (2004)
Li = 4398,32 m

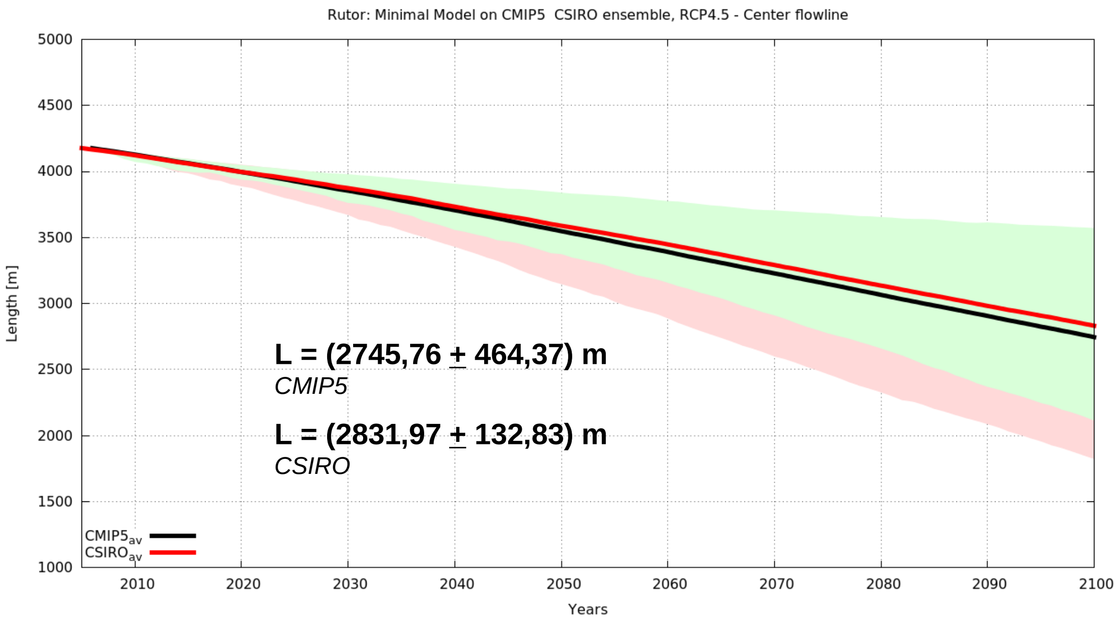
Future projection on east flow line of Rutor glacier.
The different RCP scenarios show a gap of length retreat at about 600m.

GCM [2005 – 2100]

CMIP5 ensemble and CSIRO runs in two different Emission scenarios: RCP 4.5 & RCP 8.5.



Minimal Model on Rutor glacier - 4

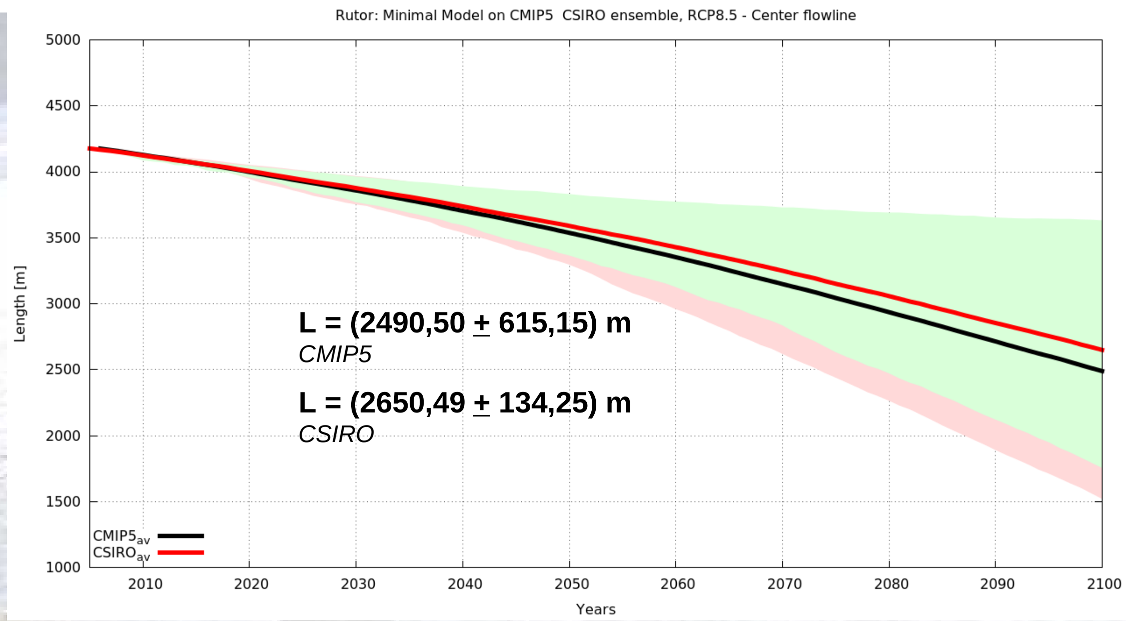


Initial length (2004)
Li = 4187,53 m

Future projection on center flow line of Rutor glacier.
The different RCP scenarios show a gap of length retreat at about 300m.

GCM [2005 – 2100]

CMIP5 ensemble and CSIRO runs in two different Emission scenarios: RCP 4.5 & RCP 8.5.



Conclusions and future developments

CONCLUSIONS

- Development of **Minimal Model** algorithm to simulate glacier behavior into the past following **climate forcing** on Bn and ELA.
- Link with **GIS analysis** to apply spatial approach for the best evaluation of boundary condition and morphological data set.
- After validation, we proceed to evaluate **future fluctuation** of glacier terminus, following climate data by GCM or RCM.

FUTURE DEVELOPMENTS

- Improve the error spreading.
- Apply Minimal Model on historical series of other glaciers to validate equations.
- Apply Minimal Model coupling with Global Climate Model ensembles on meaningful survey of glaciers, to evaluate a retreat trends of entire GAR or specific areas.
- Study the difference of response between the use of GCM and RCM on Minimal Model.

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Minimal Model: solution method

$$\frac{dL}{dt} = f\left\{L, P_j\right\}$$

$$t_{n+1} = t_n + \Delta t$$

The estimation of solution is obtained by discretization of continuous problem, to approximate the real results with numerical method.

Runge-Kutta method: one of the most refined methods of integrating ordinary differential equations.

We use this method to solve Minimal Model equations, considering final length as input of new cycle.

$$y_{n+1} = y_n + \frac{h}{6}(k_1 + 2k_2 + 2k_3 + k_4) \tag{2}$$

$$k_1 = f\left(x_n, y_n\right) \tag{3}$$

$$k_2 = f\left(x_n + \frac{h}{2}, y_n + \frac{h}{2}k_1\right) \tag{4}$$

$$k_3 = f\left(x_n + \frac{h}{2}, y_n + \frac{h}{2}k_2\right) \tag{5}$$

$$k_4 = f\left(x_n + h, y_n + hk_3\right) \tag{6}$$