Towards the demise of French alpine glaciers: Parameterized modelling and perspectives on glacier evolution for the 1984-2100 period

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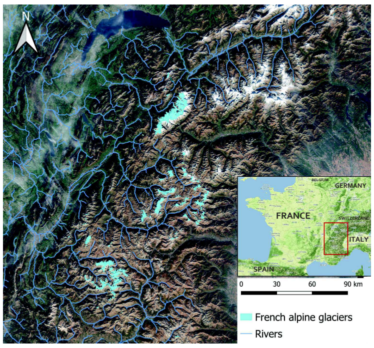


Study region: the French Alps

Introduction

The **Rhône** river basin is a highly populated area in **southeastern France,** with a high concentration of alpine glaciers which have been rapidly retreating in the last decades as the climate warms. In order to anticipate **potential issues and conflicts concerning water resources** in the high alpine valleys, there is a **strong need for local-to-regional projections** of glacier and snow hydrological contributions.

In this study, we present **ALPGM** (**AL**pine **P**arameterized **G**lacier **M**odel), a **fully parameterized glacier model,** which makes use of the most recent available data and reanalysis to simulate the evolution of all the ~660 glaciers in the French Alps for the **1984-2100 period**. It computes glacier-wide yearly surface mass balances (**SMB**) using **machine learning,** and it updates the glacier geometry by redistributing the glacier-wide SMB values along the glacier elevations according to a **glacier-specific parameterized function**.

Model and Data - ALPGM

SMB simulation

In contrast to most glacier models, here we have considered a **fully parameterized approach** using **machine learning**:

Training dataset (24 parameters)

- **Meteorological data**

(SAFRAN + ADAMONT reanalyses)
(Durant et al., 1993) (Verfaillie et al., 2017)

+

- **Topographical data**

(GLIMS glacier database)
(GLIMS, 2003, updated 2018)

+

- **All possible combinations**

Validation dataset (920 values)

SMB

- **Yearly glacier-wide SMB**

Values estimated from the snow line using remote sensing (Rabatel et al., 2016)

920 x 24 matrix

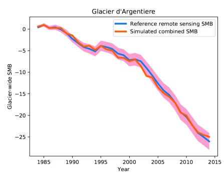
Machine Learning Algorithm

Multi-linear model based on the combination of the best models:

$0{,}62 \leq \mathbf{R^2} \leq 0{,}65$ | **VIF** $< 1{,}2$ | **p-value** $< 0{,}01$

(CPDD*, winter snow, summer snow)$_{anomalies}$, Z_{mean}, Z_{max}

Yearly glacier-wide SMB simulations



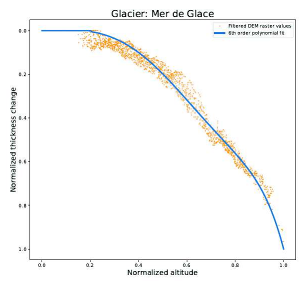
SMB simulation results from ALPGM

* future changes in ablation season length are taken into account computing a dynamic yearly CPDD value.

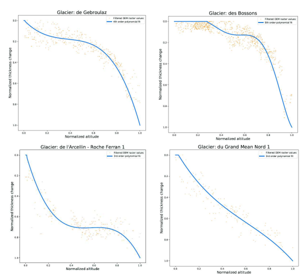
Glacier geometry change

The glacier **ice volume** (Huss and Farinotti, 2012), **area** and **surface elevation** are updated with an annual time step, using the mass-conserving **Δh function parameterization** (Huss et al., 2010).

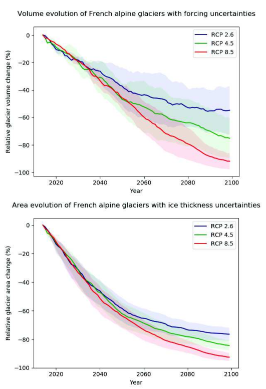
For every glacier ≥ 0.5 km² we compute a **glacier-specific normalized Δh function** which redistributes the yearly glacier-wide mass change along all the glacier altitudes. For very small glaciers (< 0.5 km²) we use a simplified flat function. As opposed to previous studies (Vincent et al., 2014; Huss and Fischer, 2016), it is computed by directly **processing** the **DEM raster files** (1979 – photogrammetric, 2011 – SPOT5) instead of using elevation bands.

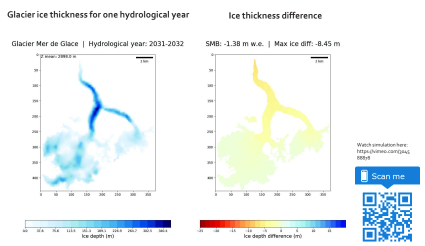


Normalized Δh function for the Mer de Glace glacier



Examples of normalized Δh functions for different glaciers





Example of simulations output using ALPGM

Glacier surface area and volume projections for the 21st century (2 GCM/RCM combinations for 3 different RCPs)

- CSC-REMO2009_MPI-M-MPI-ESM-LR
- SMHI-RCA4_ICHEC-EC-EARTH

Discussion and Results

Extensive simulations considering different RCPs and GCM/RCM combinations from the EURO-CORDEX-based **ADAMONT** dataset still need to be run, but the first simulations show a **severe retreat of alpine glaciers** in the French Alps, with **more than 90%** of the current **ice volume lost** in the **worst scenario (RCP 8.5)** and **around 55%** for the **most conservative one** (RCP 2.6). The **negative trend** seems to **only stabilize** for **the RCP 2.6** in the last decades of the century.

ALPGM, being fully parameterized and with roots on **Data Science,** is an easily **extendable model,** whose performance grows as new data become available. The validation and training datasets will soon be enlarged, and new algorithms and types of variables will be tested. To our knowledge, this effort represents the **first foray** into **machine learning** applied to **glacier modelling**.

Conclusions and Perspectives

- Fully parameterized models using machine learning represent an interesting and logical step in glaciology in an era of ever-expanding data. Here we present the first effort known to date towards Data Science-based glacier models.
- More advanced algorithms, such as LASSO, Ridge or Random Forest will be explored, besides complex multiple linear regressions, in order to improve and adapt the model. The validation and training datasets will also be expanded
- Alpine glaciers in the French Alps are likely to disappear by the end of the 21st century, where only the largest glaciers in the Mont Blanc massif might remain
- ALPGM's results will be compared to the generic Δh parameterization approach (Huss et al., 2010), as well as previous regional and global studies (Huss, 2011; Huss and Hock, 2015; Huss and Hock, 2018) which included the western Alps
- The ALPGM glacier model will be coupled to the J2K-Rhone (Fink et al., 2007; Krause, 2002) semi-distributed hydrological model in order to study the impact of glacier retreat in the Rhône river catchment

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