

Motivations

This study aims to **collect the available data on glacier outlines** and to test the potential of those data in **two applications in hydrology**:

A. Analysis of Controls on Glacier Retreat:

→ Empirical Analysis to investigate the potential controls of the glacier retreat of 998 Swiss glaciers for the time period 1850 – 2010

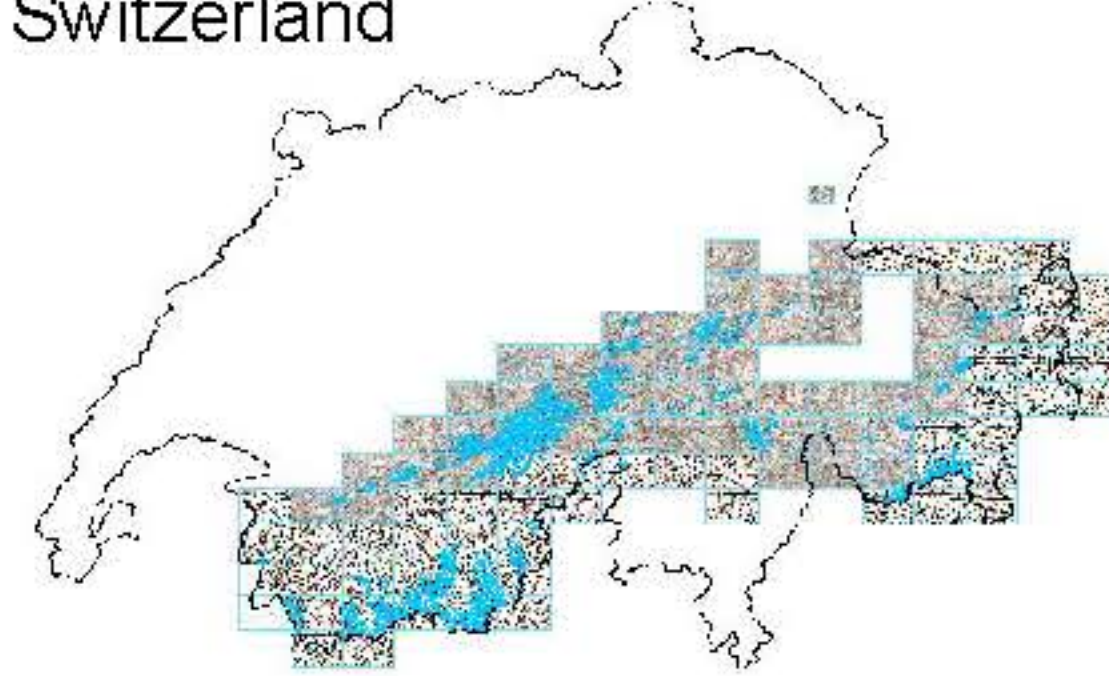
B. Transient Glacier Modeling:

→ Modeling of the transient development of the glacier area for the time period 1901-2006 in the Rhine basin with the HBV-Model.

→ Challenges: to estimate the glacier volume 1900 and to enable the glaciers to advance during the modeling period.

Glacier Outlines Data

1. **Manual digitization** of glacier outlines from historical maps of Switzerland

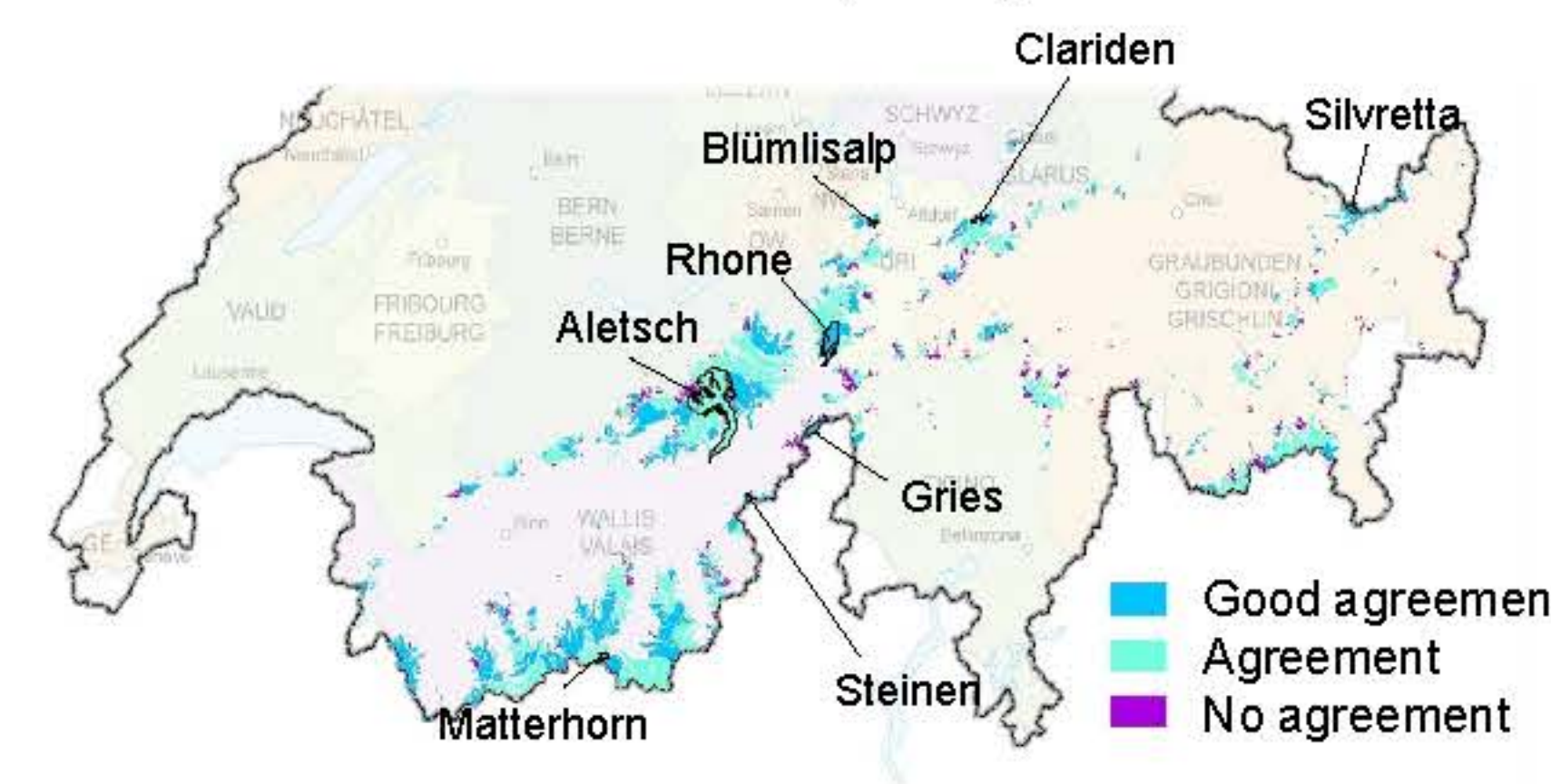


202 Siegfried maps, 1892 – 1944, 1:50'000
Digitization with ArcMAP 10.2.2: >500'000 nodes

2. Comparison of the digitized Siegfried maps with historical photographs



3. Comparison of the digitized Siegfried maps with the other available datasets (table)



Available glacier outlines data:

Year (Appr.)	Data assessed from	References
1850	Aerial photography, from moraine extends of retreated glaciers.	Maisch et al., 2000
1973	Aerial photography data from September 1973	Müller et al., 1976; Maisch et al., 2000
2003	Landsat imagery acquired in Autumn 2003	Paul et al., 2011
2010	Aerial ortho-imagery acquired between 2008 and 2011	Fischer et al., 2014

> 75% of the digitized Siegfried maps in good agreement with the other datasets.

Application
in
Hydrology

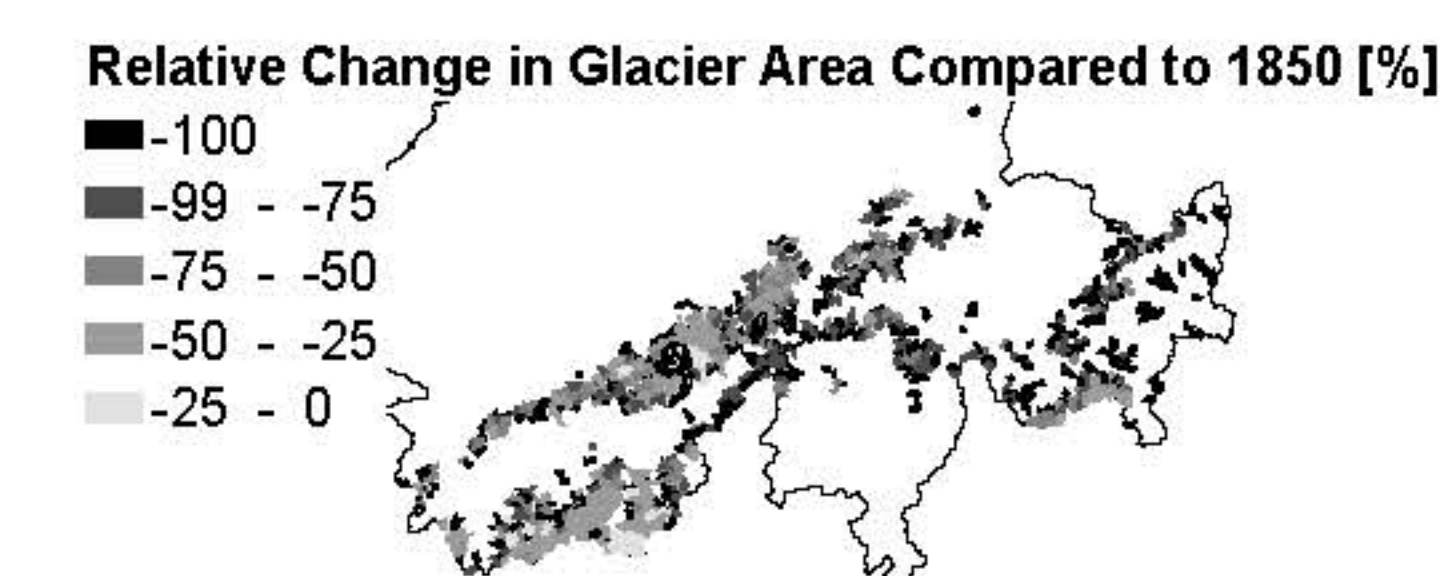
A. Analysis of Controls on Glacier Retreat

Methods

Generalized Linear Model (GLM) on 998 Swiss glaciers to assess the effects of potential controls on glacier retreat.

Model predictors tested for correlation and statistically significance ($p < 0.05$).

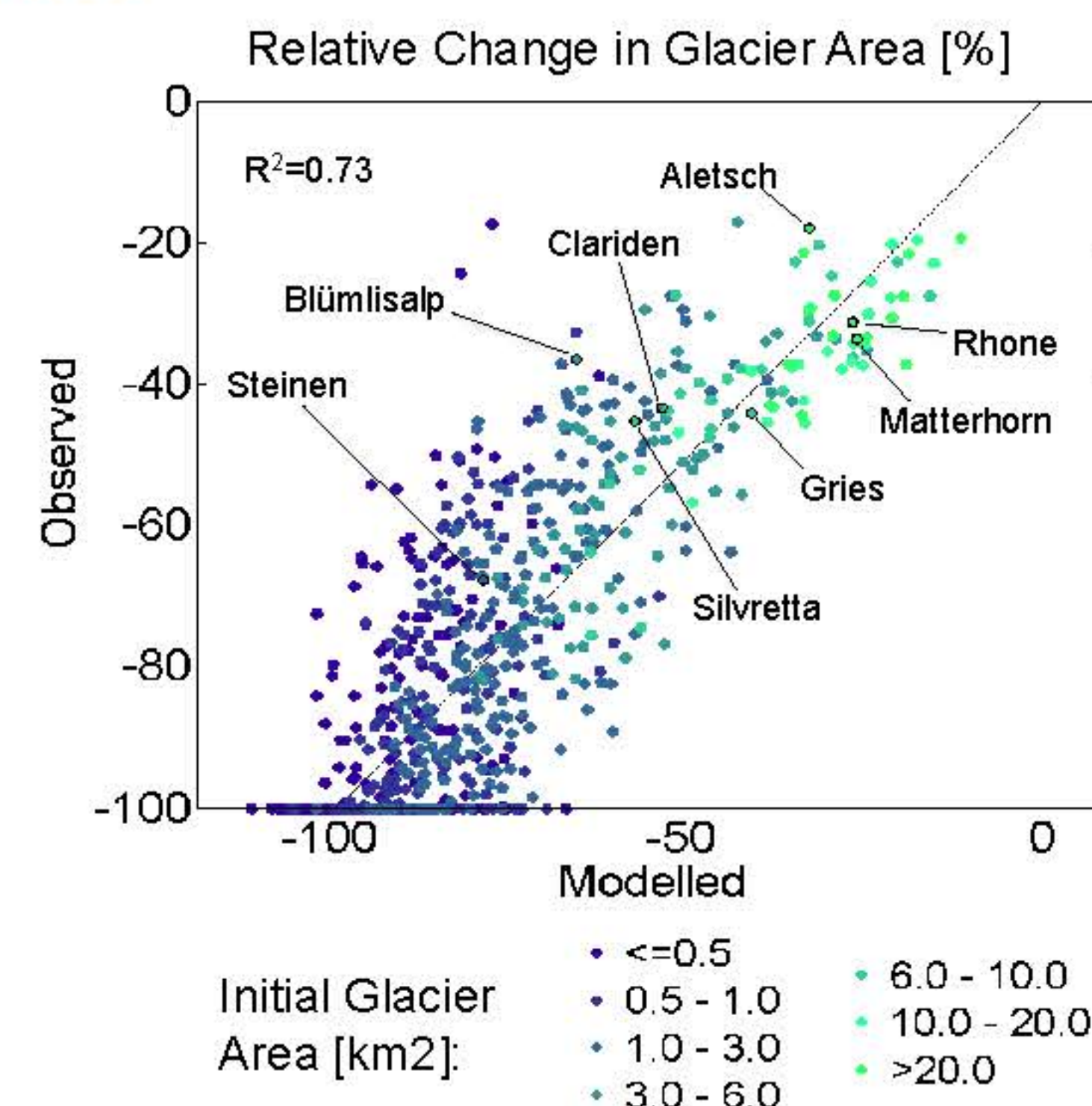
Physiographic Model Predictors: initial glacier area, average slope on and around the glacier area, aspect, mean elevation of the glaciers in 1850 and of the retreated area, elevation range, potential solar radiation derived from the digital elevation model DHM25 of Switzerland.



Climatic Predictors: mean yearly precipitation and temperature calculated from the interpolated gridded datasets TabsD v1.2 and RhiresD v1.0 (MeteoSwiss). Mean snow water equivalent calculated with a Temperature Index Model.

Results

- **73% of the observed variance** of the relative change in glacier area between 1850 and 2010 explained by GLM.
- 6 of 11 model predictors selected by GLM; 5 of the selected predictors statistically significant.
- Higher initial glacier area, yearly precipitation sum, higher slopes around the glacier area led to lower relative changes in glacier areas. Higher slopes on glacier area, higher elevation ranges led to higher relative changes in glacier area.



Conclusions

✓ Relative changes in glacier area of 998 Swiss glaciers were related to several physiographic and climatic controls

✓ Transient modeling of glacier area in HBV was successful thanks to:

- Use of all available data
- Reconstruction of Glacier volume 1900
- Implementation of Type-curves in HBV

✓ Combined dataset of glacier outlines from digitized Siegfried maps and remote sensing data:

- Provides important informations about changes in glacier areas
- Is essential for long-term and accurate hydrological modeling in glacierized basins

B. Transient Glacier Modeling

Methods

1. **Reconstruction of Glacier Volume and Thickness for year 1900:**

Input data:

- Glacier area and thickness 1973 and 2010 (M. Huss, method: Farinotti, 2012; Gl. Inventar: Fischer et al., 2014)
- Glacier outlines 1900: digitized Siegfried maps

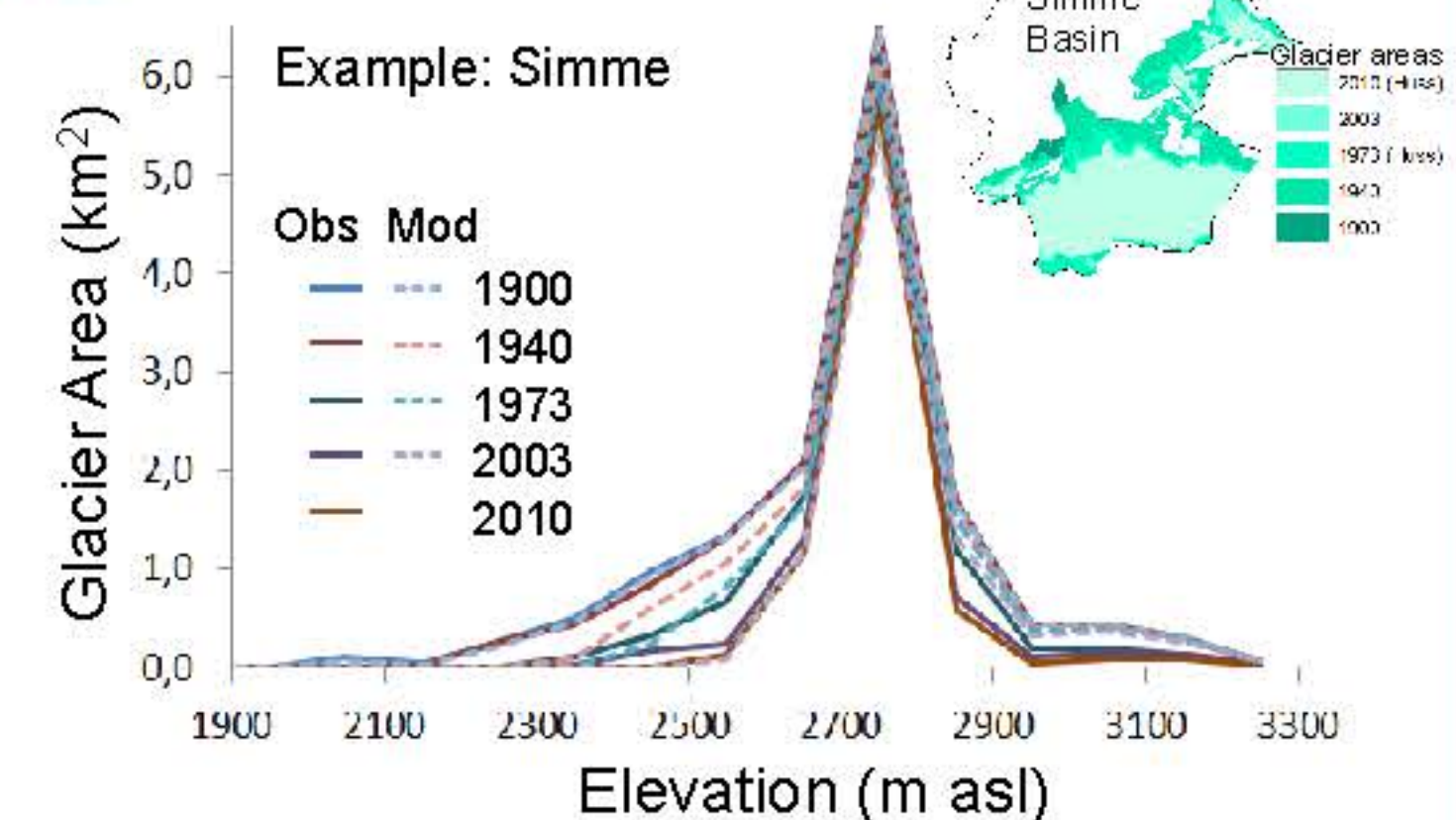
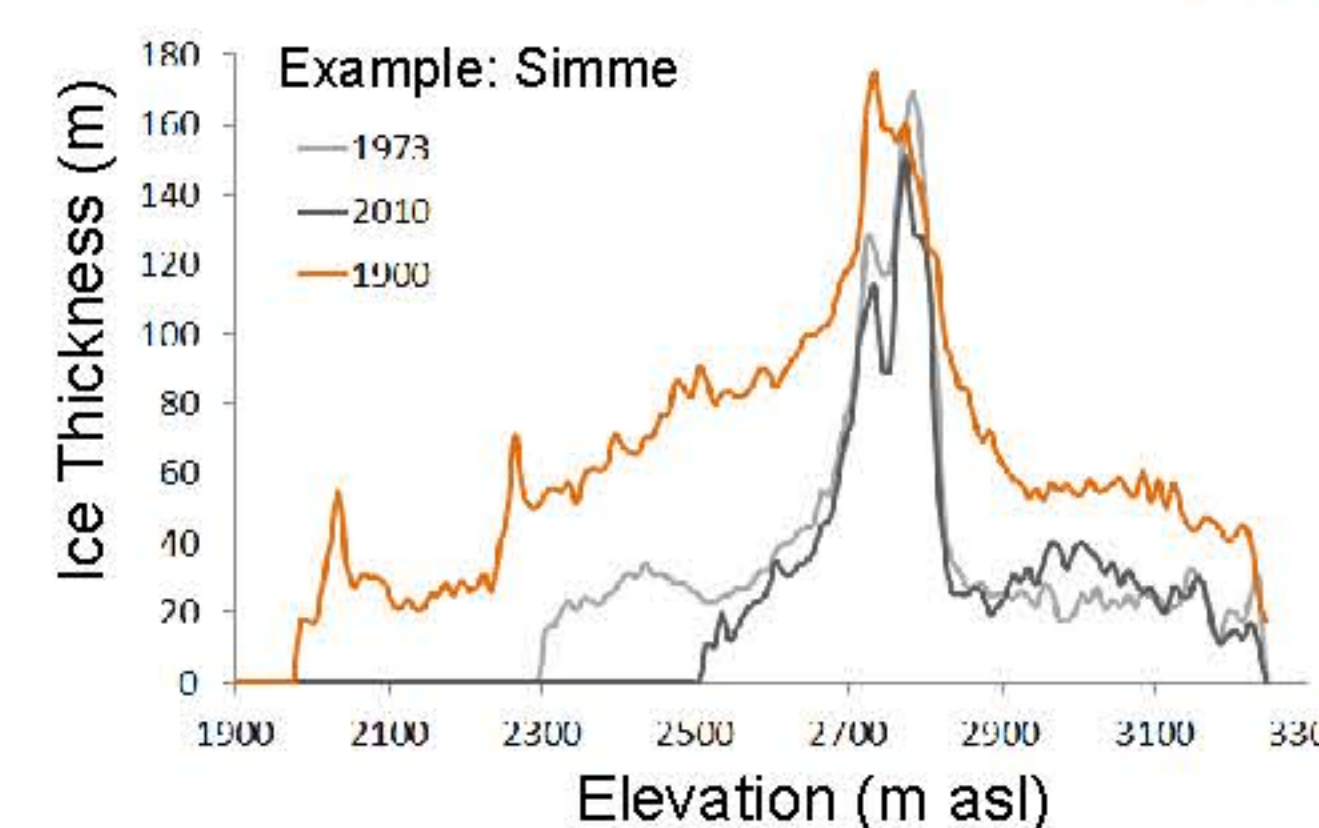
Volume estimation (Bahr et al., 1997):

- a) Volume-Area relationship
- b) Distribution of ice thickness in 10 m elevation bands: $A \propto \sqrt{h}$

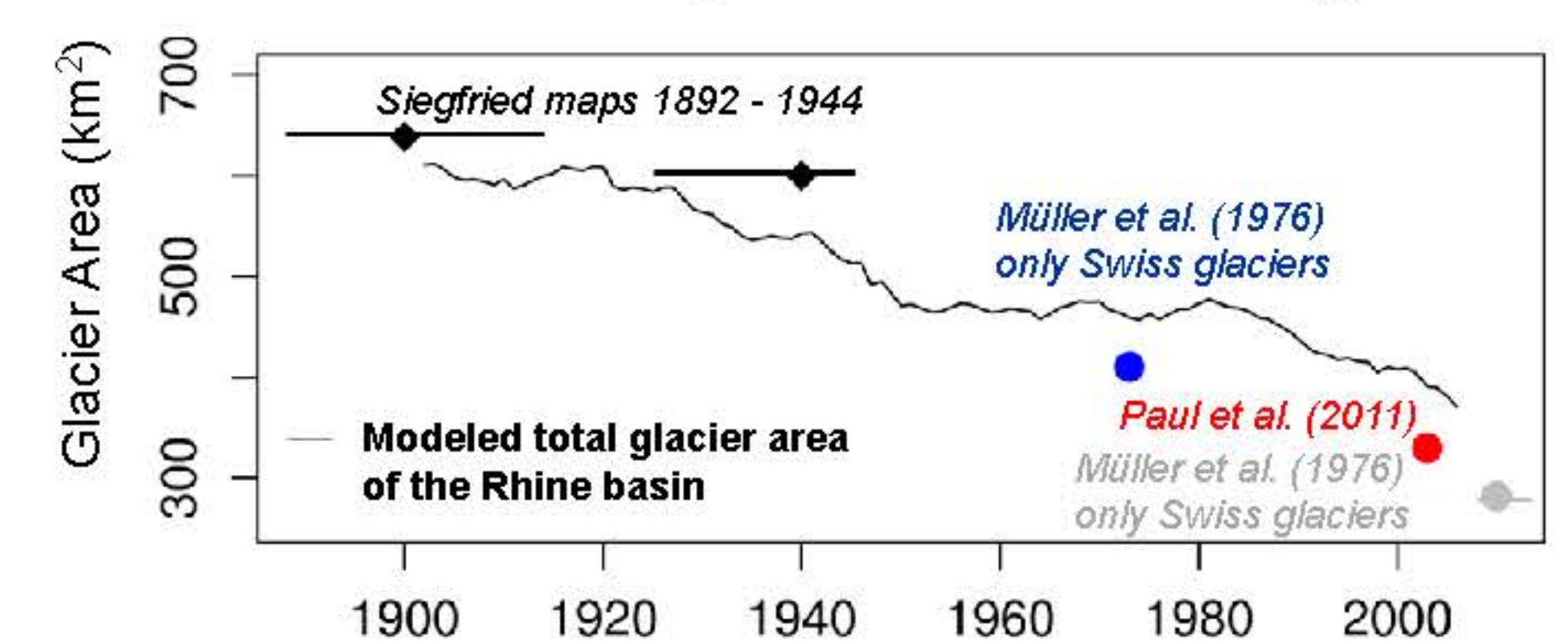
2. **Transient Glacier Modeling:**

- HBV-LightAlpine+
- Use of type-curves depending on glacier area: ice thickness change - elevation range relationship (Huss et al., 2010)
- Area adjustment at the end of each hydrologic year
- HBV: Volume-area lookup tables

Results



- Plausible reconstruction and distribution of the ice thickness for the year 1900
- Successful modeling of the glacier areas for each elevation band and year compared to the observed glacier areas



- Modeled total glacier area of the Rhine basin in good agreement with the observed data, except for underestimation of retreat in the last period
- Note: Observed data also related to certain uncertainty
- Known period of advance and retreat of glaciers well represented for the total glacier area of the Rhine basin and for the mass balance of the Clariden glacier

Clariden Glacier – Comparison Modeled and Observed Mass Balance

