

Impact of the choice of surface mass balance models and their calibration on large-scale glacier change projections

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Hi everyone! I am a first-year PhD student working on implementing a new mass balance calibration scheme and several mass balance models into OGGM with an assessment of their uncertainties. We present our method ideas and first outcomes (for Alpine glaciers) and are happy about any feedback or ideas related to the topic of glacier model uncertainty, specifically related to SMB glacier models and calibration. Just contact us via the EGU chat or via e-mail lilian.schuster@student.uibk.ac.at 

click on these icons  to get more information!

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Motivation and project goal

The "Glacier Model Intercomparison Project" (GlacierMIP2, Marzeion et al., 2020¹) found that the dominant uncertainty in the first half of the century comes from differences between glacier models:

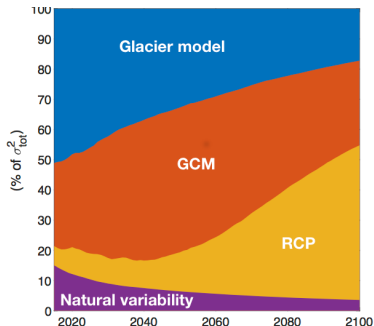


Figure 1: Relative contributions of four sources of uncertainty (%) to the total uncertainty in 21st century global mass change projections. Modified after Marzeion et al. (2020)¹

PROBLEM: each glacier model has their own unique set of process representations
→ makes it impossible to determine model components that contribute most to uncertainties

PROJECT GOAL: Better understand sources of model uncertainty by comparing directly different modules under controlled boundary conditions using the OGGM  framework

In my PhD project we will focus on:

- improving model parameter calibration
- implementing different surface mass balance (SMB) models
- and on assessing and reducing their uncertainties

¹Marzeion et al.: Partitioning the Uncertainty of Ensemble Projections of Global Glacier Mass Change, <https://doi.org/10.1029/2019EF001470>, 2020

Used surface mass balance (SMB) models

at the moment only very simple temperature-index models used:

	constant temperature lapse rate (6.5 K km^{-1})	seasonally and spatially variable lapse rate (from ERA5)
monthly temperature and precipitation	monthly_cte (same as default OGGM SMB model ↗ but residual=0)	monthly_var_an_cycle
+ daily temperature standard deviation	pseudo_daily_cte	pseudo_daily_var_an_cycle (similar to Huss & Hock, 2015 ↗) ¹
daily temperature and precipitation	real_daily_cte	real_daily_var_an_cycle

for the SMB models, we calibrate only two parameters²: the melt factor (degree day factor) and the multiplicative precipitation factor (pf). Hence, the models are overparametrised, i.e., various parameter combinations result in the same outcome, also called equifinality (e.g. Rounce et al., 2020) [↗](#)

plans for the future: include other SMB options, such as

- surface type distinction and refreezing (e.g. as in, Huss & Hock, 2015 [↗](#); Zekollari et al., 2019 [↗](#); Rounce et al., 2020 [↗](#))
- incoming shortwave radiation or simplified energy balance (e.g. as in: Hock, 1999 [↗](#); Oerlemans, 2001 [↗](#); Pellicciotti et al., 2005 [↗](#); Reveillet et al., 2017 [↗](#); Landmann et al., 2020, in discussion [↗](#))

¹ but without surface type differentiation and refreezing

² we add a temperature bias if the climate data does not allow for melting or accumulation at all, see [↗](#)



Data used with OGGM



- global inventory of glacier outlines: Randolph Glacier Inventory (RGI 6.0 )
- topography data (automatically chosen , for Alpine glaciers it is NASADEM )
- for each glacier, the ice thickness consensus estimate from Farinotti (2019) 
- for each glacier, individual geodetic SMB of 2000–2010 and 2010–2020 with uncertainties (Hugonnet et al., 2021)¹
- standard deviation of SMB from glaciers with direct glaciological observations (World Glacier Monitoring Service, WGMS )
- climate data for calibration: WFDE5², monthly and daily resolution (we will switch to ISIMIP3a³ when available for 2000–2019), ERA5  for temperature lapse rates (both used at 0.5° spatial resolution)
- ISIMIP3b³ General Circulation Model for projections, at the moment, we use only one GCM ensemble (*mri-esm2-0-r1i1p1f1*) and only the *ssp126* scenario (interpolated from 1° to 0.5° spatial resolution)

After the Bayesian mass balance calibration of the two mass balance parameters (melt and precipitation factor, see slide 5–7), we get a posterior distribution of fitting calibration parameters and select 200 random draws. We apply a bias-correction between WFDE5 and historic GCM climate data (similar as in ) . The OGGM's inversion procedure  is repeated and the ice dynamics parameter (*glen_a*) is tuned for each draw to match Farinotti (2019)  . For the random 200 draws, we compute volume projections and assume that they represent the SMB calibration uncertainties.

other implementation details are same as in the default OGGM framework. They can be found on the OGGM documentation website  and in Maussion et al. (2019)⁴. Otherwise just contact us via lilian.schuster@student.uibk.ac.at  !

¹Hugonnet et al.: Accelerated global glacier mass loss in the early twenty-first century, will be published on 29th of April in *Nature*, 2021

²Cucchi et al.: WFDE5: bias-adjusted ERA5 reanalysis data for impact studies, <https://doi.org/10.5194/essd-12-2097-2020>, 2020

³Stefan Lange, Matthias Büchner: ISIMIP3b bias-adjusted atmospheric climate input data (1.0). ISIMIP Repository <https://doi.org/10.48364/ISIMIP.842396>, 2020, (some inconsistencies were found in the ISIMIP3b data , we will repeat the projections when the new data is available)

⁴Maussion et al.: The Open Global Glacier Model (OGGM) v1.1, <https://doi.org/10.5194/gmd-12-909-2019> , 2019

Use Bayesian inverse model¹ to calibrate the mass balance model

1. Pre-calibration of "priors" (assumed parameter distributions before calibration)

Repeat for each Alpine reference glacier with at least two direct glaciological observations during calibration time period 1979-2018 (n=59 glaciers):

we try to match the two geodetic observations and the standard deviation (std) of the direct glaciological observations, by tuning melt factor and precipitation factor (pf)

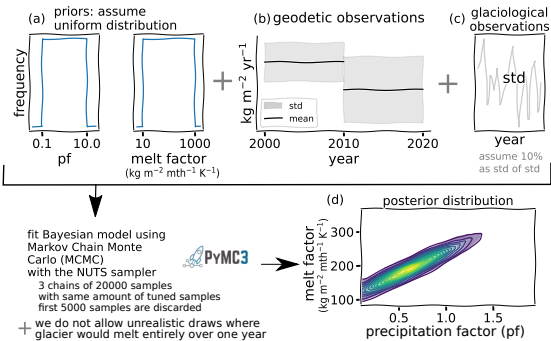


Figure 2: (a) assume first uniform prior distributions of the two free model parameters pf and melt factor ($\text{kg m}^{-2} \text{ mth}^{-1} \text{ K}^{-1}$), (b) use geodetic mass balance data from Hugonnet et al. (2021)¹ for each individual glacier for time periods 2000–2010 and 2010–2020 with given std and (c) use std of direct glaciological observation to fit a Bayesian model using PyMC3².
→ (d) get a posterior distribution of the parameters for each reference glacier which is used as priors for step 2 (Fig. 3,4)!

¹ Adapted method of Rounce et al.: Quantifying parameter uncertainty in a large-scale glacier evolution model using Bayesian inference: application to High Mountain Asia, <https://doi.org/10.1017/jog.2019.91>, 2020

² Salvatier et al.: Probabilistic programming in Python using PyMC3. PeerJ Computer Science 2:e55 DOI: 10.7717/peerj-cs.55, 2016

Use calibrated mass balance parameters of the reference glaciers as priors for Alpine glaciers

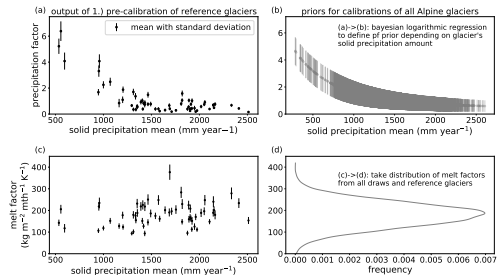


Figure 3: (a, c) Output of reference glacier calibration (aggregated posterior distributions of step 1, Fig. 2d) used to generate (b, d) input (priors) for Alpine glacier calibration (here for monthly_cte)

How can we constrain the precipitation factor (pf) for non-reference glaciers?

- no clear relation found for glaciers of similar location, volume, elevation, mass balance, ...
- BUT: precipitation factor is rather large and accompanied with more uncertainty for glaciers with smaller solid precipitation amounts (area-weighted temporal mean and before multiplying it with pf, Fig. 3a)

→ use this relation to get individual priors for pf (Fig. 3b)

plans for the future

- we only analysed the solid precipitation - pf relation for the Alps. What is the influence of less constrained pf priors and do we need to constrain the melt factor in a different way?
- use seasonal geodetic SMB estimates from e.g. Jakob et al. (2021)  to better constrain pf

Use Bayesian inverse model¹ to calibrate the mass balance model

2. Mass balance calibration repeated for each Alpine glacier with geodetic observations

for each glacier, we try to match the two geodetic observations under priors from pre-calibration step 1

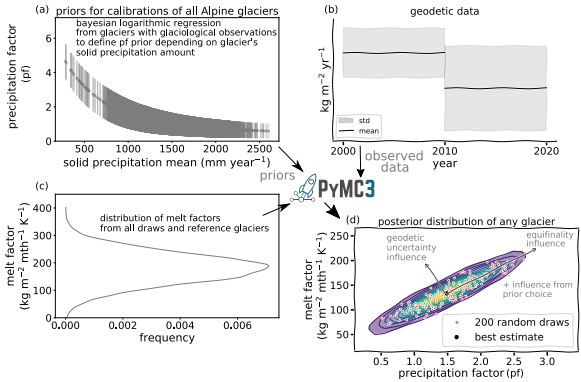


Figure 4: fit Bayesian model using PyMC3 → take 200 combinations (draws) from each glacier (Fig. 4d) that equally fit to the observed geodetic data given their uncertainties (Fig. 4b) and prior assumptions (Fig. 4a, c, step 1) to assess future volume projections and uncertainties.

- plans for the future
- there are glaciers without geodetic measurements. We need to find a way to incorporate them. For Alpine glaciers, however, they are negligible: ~ 0.1% of total volume
 - assess individual influence of geodetic uncertainty, equifinality and prior choice on calibration

mass balance parameter distributions for different SMB models

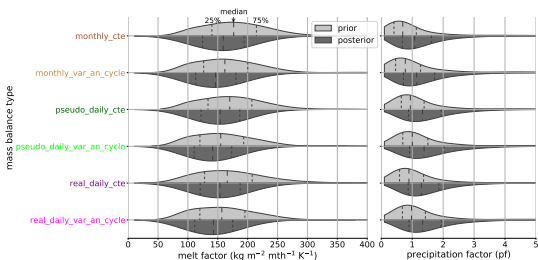


Figure 5: Pre-calibrated priors (see Fig. 4a,c) from reference glaciers versus posterior Alpine mass balance parameter distributions after calibration for each mass balance type

plans for the future

specifically for the melt factor, the prior and posterior distributions are quite similar, i.e. the priors drive our calibration due to equifinality.
→ further analysis & repeat calibration with other prior assumptions

calibrated **melt factor** is ↘ when:

- using temperature lapse rates that vary spatially and over the months (var_an_cycle) compared to a constant lapse rate (cte)
→ lapse rates are in summer stronger than in winter, which might explain the smaller melt factor sensitivity of var_an_cycle
- using pseudo_daily (via daily temperature std) or real_daily climate data compared to monthly data
→ with daily temperature values, melt occurs also if mean temperature is below 0°C, which could explain the smaller melt factor sensitivity.

calibrated **precipitation factor (pf)** ↗ for:

- pseudo_daily or real_daily
(true for priors and posterior)

Projections for an example glacier: Hintereisferner, Ötztal Alps

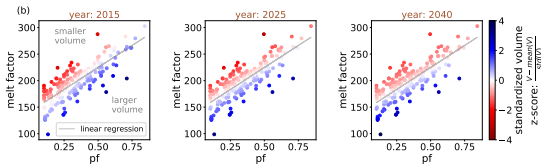
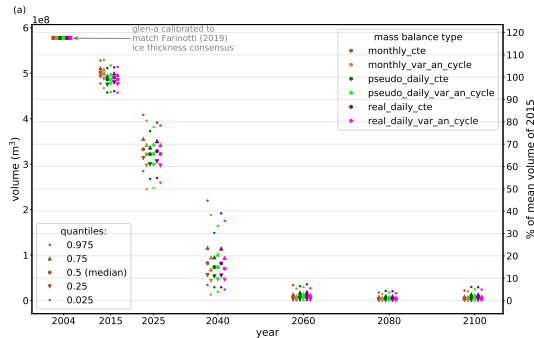


Figure 6: (a) Volume projections of Hintereisferner using ISIMIP3b data (only GCM *mri-esm2-0_r11p1f1* for the ssp126 scenario). The 200 draws are taken from individual posterior distributions (see Fig. 4d) and are summarised by the quantiles. OGGM's inversion procedure  is repeated and the ice dynamics parameter (*glen_a*) is tuned for each draw to match the Farinotti (2019)  ice thickness. (b) Standardized volume distribution is shown in dependence of the mass balance parameters for the 200 draws for *monthly_cte*.

- (a) for Hintereisferner, most uncertainties from the calibration are in 2030–2050
- (b) draws with rather lower melt factors and higher pf, have a larger volume. The draws with larger volume in 2015 are also those draws with larger volume in 2040

Alpine glacier projections¹ with uncertainties (only GCM *mri-esm2-0_r1i1p1f1* for ssp126 scenario)

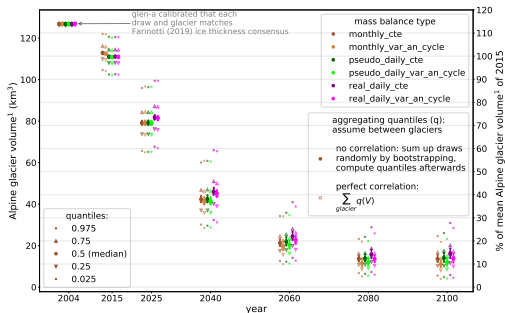


Figure 7: Volume projections of Alpine glaciers¹. The 200 draws are taken from individual posterior distributions (see Fig. 4d) and are summarised by the quantiles. OGGM's inversion procedure is repeated and the ice dynamics parameter (*glen_a*) is tuned individually for each draw to match the Farinotti (2019) ice thickness.

Volume in 21st century:

$$V_{\text{real_daily_cte}} > V_{\text{monthly_var_an_cycle}}$$

- assuming **perfect correlation** by summing up quantiles of each glacier results in **uncertainty overestimation**:
→ SMB calibration uncertainties $\gg$ SMB model choice
- assuming **perfect independence** by randomly summing up draws (with bootstrapping) and computing then the quantiles, results in **uncertainty underestimation**
→ SMB calibration uncertainties $<$ SMB model choice

→ errors correlated only over limited spatial scale: need to compute autocorrelation via (semi)variograms as in Shean et al. (2020) or in Hugonnet et al. (2021)

¹only Alpine glaciers with geodetic observations (n=3412); only qualitative estimate because of a single GCM

Individual Alpine glacier volume projections depending on calibrated mass balance parameters

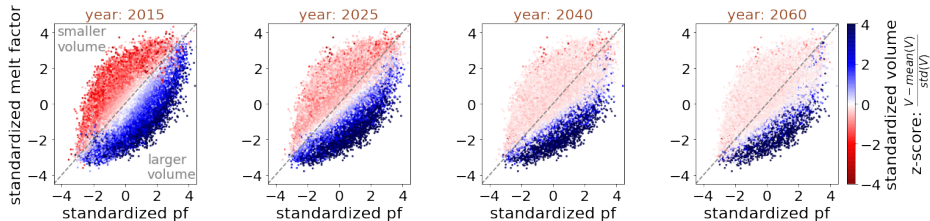


Figure 8: Standardized (z-score computed via $\frac{X - \text{mean}(X)}{\text{std}(X)}$) volume of all Alpine glaciers depending on the standardized melt factor and precipitation factor (pf) for *monthly_cte*. Each dot represents one draw of one glacier, i.e., amount of dots are 200 draws $\times$ amount of glaciers. For year 2040 and 2060 many glaciers have a volume mean near to zero, which results in many not so negative volume z-scores.

Generally, we find the same qualitative relation for all Alpine glaciers as already described for the example glacier in Fig. 6b:

- the individual glacier volume is larger for a draw with a smaller than usual melt factor and a larger than usual precipitation factor
- draws with larger than usual volumes in 2015 are also draws with rather large volumes in 2060



Preliminary conclusions:

working on a surface mass balance (SMB) model calibration scheme using geodetic observations of individual glaciers for OGGM and on assessing their uncertainties

- individual glacier uncertainties from SMB parameter calibration (melt factor and precipitation factor) can be large due to geodetic uncertainties, equifinality and prior choice
- a draw with an unusual large volume in the 21st century has an unusual high precipitation factor and unusual low melt factor. We believe that this is a result from the geodetic uncertainties (but we will further analyse this). Combining other datasets could improve solid precipitation estimates and help to constrain better the precipitation factor prior.

working on implementing more enhanced SMB models in OGGM

analysed differences between monthly, pseudo_daily (use daily temperature standard deviation) and real_daily (daily precipitation and temperature) climate input for the SMB model and influence of seasonally and spatially changing temperature lapse rates on calibration and volume projections

- using pseudo_daily or real_daily instead of monthly data results in smaller calibrated melt factors (degree day factors) and higher precipitation factors. Using variable lapse rates, results also in smaller melt factors.
- Over the 21st century, real_daily with constant lapse rates results in the largest Alpine glacier volume, while monthly with variable lapse rates has the lowest Alpine glacier volume. Whether these differences are significant compared to SMB calibration uncertainties depends on the spatially correlated strength of uncertainties, which we will analyse in future.



Discussion points for the EGU chat!

- 1 What additional data could we use to constrain the precipitation factor?
→ IDEA: use seasonal geodetic estimates from (Jakob et al., 2021)
- 2 Quantitative description of calibration and volume projection uncertainties resulting from geodetic uncertainties versus those from equifinality or from prior choice! What is the influence of using instead of two geodetic observations the bulk estimate (2000-2020)?
→ IDEA: Repeat calibration with different strategies
- 3 How can we aggregate individual glacier volume projection uncertainties to regional uncertainties? → IDEA: compute autocorrelation via (semi)variograms as in Shean et al. (2020) or Hugonnet et al. (2021)
- 4 How can we include the influence of ice dynamic, ice thickness (glen_a calibration) and ice density uncertainties on glacier projections? For Alpine glaciers, the ice thickness standard deviation is substantial with 23% of the regional volume estimate.
- 5 Which SMB model would you like to have implemented in OGGM? ;-)

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