Testing the importance of explicit glacier dynamics for future glacier evolution in the Alps

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To Psycho

And all others who try to move their toes individually

Abstract

The abstract is a short summary of the thesis. It announces in a brief and concise way the scientific goals, methods, and most important results. The chapter "conclusions" is not equivalent to the abstract! Nevertheless, the abstract may contain concluding remarks. The abstract should not be discursive. Hence, it cannot summarize all aspects of the thesis in very detail. Nothing should appear in an abstract that is not also covered in the body of the thesis itself. Hence, the abstract should be the last part of the thesis to be compiled by the author.

A good abstract has the following properties: *Comprehensive:* All major parts of the main text must also appear in the abstract. *Precise:* Results, interpretations, and opinions must not differ from the ones in the main text. Avoid even subtle shifts in emphasis. *Objective:* It may contain evaluative components, but it must not seem judgemental, even if the thesis topic raises controversial issues. *Concise:* It should only contain the most important results. It should not exceed 300–500 words or about one page. *Intelligible:* It should only contain widely-used terms. It should not contain equations and citations. Try to avoid symbols and acronyms (or at least explain them). *Informative:* The reader should be able to quickly evaluate, whether or not the thesis is relevant for his/her work.

An Example: The objective was to determine whether … (*question/goal*). For this purpose, … was … (*methodology*). It was found that … (*results*). The results demonstrate that … (*answer*).

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In a nutshell, a glaciers annual specific surface mass balance B is the difference between accumulation and over the course of a year. Hereby, accumulation refers to mass gain by snowfall, avalanches, snow drift, etc., while ablation refers to mass loss via ice melt, sublimation, calving, etc. The temperature index mass balance model used by the volume/area scaling model relies solely on the area average monthly solid precipitation onto the glacier surface P_i^{solid} and the monthly mean air temperature at the glacier's terminus elevation T_i^{terminus} as input. Hereby, the index i denotes the month of the year. The mass balance equation described by Marzeion et al. (2012) reads

$$B = \left[\sum_{i=1}^{12} \left[P_i^{\text{solid}} - \mu^* \cdot \max\left(T_i^{\text{terminus}} - T_{\text{melt}},\ 0\right)\right]\right] - \beta^*. \tag{2.1}$$

The terminus temperature T_i^{terminus} is computed by scaling the monthly average air temperature T_i from the climate file reference elevation z_{ref} to the glacier's terminus elevation z_{min} using the temperature lapse rate γ_{temp}.

$$T_i^{\text{terminus}} = T_i \cdot \gamma_{\text{temp}}(z_{\text{min}} - z_{\text{ref}}) \tag{2.2}$$

The temperature at the maximum glacier elevation T_i^{max} is computed analogously to terminus temperature: $T_i^{\text{max}} = T_i \cdot \gamma_{\text{temp}}(z_{\text{max}} - z_{\text{ref}})$, whereby z_{max} represent the maximum glacier surface elevation. The positive melting temperature is computed as the difference between terminus temperature and temperature threshold for ice melt T_{melt}, with an obvious lower bound of 0 °C. The glacier's temperature sensitivity

μ^* relates the positive melting temperature to the actual ice loss and needs to be calibrated for each glacier (as does the potential mass balance residual β^*). The calibration process of these mass balance parameters is described below.

The area average monthly solid precipitation onto the glacier surface P_i^{solid} is computed from the total precipitation P_i (given by the climate file) as

$$P_i^{\text{solid}} = P_i \cdot f_{\text{solid}} \cdot (1 + \gamma_{\text{precip}} \cdot (z_{\text{mean}} - z_{\text{ref}})). \tag{2.3}$$

The total climatic precipitation P_i is scaled from the reference elevation of the climate file z_{ref} to the average glacier surface elevation z_{mean} using the precipitation lapse rate γ_{precip}. The precipitation lapse rate γ_{precip} is given in percentage of precipitation per meters of elevation change [$\%\,\text{m}^{-1}$]. The fraction of solid precipitation f_{solid} depends on the terminus temperature T_i^{terminus}, the temperature at the maximum glacier surface elevation $T_i^{\max}$ and the temperature thresholds for solid and liquid precipitation, T^{solid} and T^{liquid}, respectively. For terminus temperatures below the threshold for solid precipitation, all precipitation is solid ($T_i^{\text{terminus}} < T^{\text{solid}} \Rightarrow f_{\text{solid}} = 1$). For temperatures at the maximum glacier surface elevation above the threshold for liquid precipitation, all precipitation is liquid ($T_i^{\max} > T^{\text{liquid}} \Rightarrow f_{\text{solid}} = 0$). For temperatures in between, the fraction of solid precipitation is interpolated linearly as $f_{\text{solid}} = 1 + \frac{T_i^{\text{terminus}} - T^{\text{solid}}}{\gamma_{\text{temp}} \cdot (z_{\max} - z_{\min})}$.

Climate models generally tend to underestimate the precipitation in mountainous regions, hence the monthly precipitation amount is additionally scaled by a factor a. While this scaling factor is implemented in the mass balance models (as `prcp_scaling_factor`), it is not a physical component of the mass balance equation and hence omitted in the Equation 2.3 above. A global mean of $a = 2.5$ is found by Giesen and Oerlemans (2012), whereas Marzeion and Nesje (2012) found a mean of 2.1 for Central Europe and Scandinavia. The sensitivity study by Marzeion et al. (2012) shows the strongest correlation between observed and modeled mass balance for $a \approx 1.3$ and the highest skill score for $a \approx 2.5$. The variability of the modeled mass-balance is quite low for values of $a \leq 2.5$.

The values of the above mentioned hyper parameters (temperature thresholds, lapse rates, scaling factors, ...) can be calibrated, depending on the region and the used baseline climate. For Alpine model runs with the HISTALP baseline climate the following values are recommended (set as default in OGGM) and used this work (Dusch 2018): $\gamma_{\text{temp}} = -6.5\,\text{K}\,\text{km}^{-1}$, $T^{\text{melt}} = -1.75\,°\text{C}$, $\gamma_{\text{precip}} = 0$, $T^{\text{solid}} = 0.0\,°\text{C}$, $T^{\text{liquid}} = 2.0\,°\text{C}$, $a = 1.75$;

Calibration of the mass balance parameters

A complete and thorough description of the mass balance calibration process for this particular temperature index model can be found in Marzeion et al. (2012, Section

2.1.9, 2.1.10) and Maussion et al. (2019, Section 3.3). The following section serves as a summary.

The first step is to estimate the so called *candidates* $\mu(t)$ for all glaciers with available mass balance records (254 glaciers globally, see World Glacier Monitoring Service, Zürich, Switzerland (2017)). This is done by requiring the average mass balance $\overline{B}(t)$ over the 31-year period centered around the year t to be zero and solving for $\mu(t)$.

$$\mu(t) = \frac{P_{\text{clim}}^{\text{solid}}(t)}{\max(T_{\text{clim}}^{\text{terminus(t)}} - T_{\text{melt}}\, 0)}, \tag{2.4}$$

whereby $P_{\text{clim}}^{\text{solid}}(t)$ and $T_{\text{clim}}^{\text{terminus}}(t)$ are the average yearly solid precipitation amount and average yearly air temperature at the glaciers terminus during the climatological period centered around the year t, respectively. The next step is to solve the mass balance equation (Eq. 2.1) for each candidate $\mu(t)$ and compare it to the mass balance observations. The computed difference $\beta(t)$ is a measure of how good the temperature sensitivity candidate $\mu(t)$ approximates the *real* value of μ^*. Hence, μ^* is chosen as the candidate $\mu(t = t^*)$ for which the absolute bias is minimal $\beta^* := \beta(t = t^*) \approx 0$, which in the best case is around zero. Hereby, the *equilibrium year* t^* represents the center of a 31-year climatic period where the given glacier geometry would stay in equilibrium. However, this is more of a model parameter and should not be overinterpreted as a real live value. The same is true for the corresponding temperature sensitivity μ^* and mass balance residual β^*.

For all glaciers without mass balance records, t^* and β^* are interpolated from the ten closest glaciers, inversely weighted with distance. The temperature sensitivity is computed by requiring the mass balance to be zero $\overline{B}(t^*) = 0$ and solving for μ^*. The temperature sensitivity μ^* depends highly on glacier specific factors, such as avalanches from surrounding terrain, topographical shading, etc. Therefore, μ^* can vary drastically from one glacier to another, even between neighboring glaciers. On the other hand, it is intuitively more likely for a glacier to be in equilibrium if its surrounding glaciers are in equilibrium as well. This is one major factor, why the interpolation of t^* instead of μ^* reduces the mass balance error in a leave–one–out cross–validation (cf. Marzeion et al. 2012; Maussion et al. 2019).

Implementation note

The results of the steps above depend on the glacier outlines, the climate data and the mass balance hyper parameters (i.e., the temperature thresholds, lapse rates and the precipitation scaling factor). The equilibrium year t^* and mass balance residual β^* computed for each reference glacier is stored in the `ref_tstars.csv` file. Hence, for a given combination of RGI version, climate data and hyper parameters the calibration for the reference glaciers has to be done only once. Afterwards, it can be read directly from the corresponding file. OGGM comes with reference tables for combinations of RGI v5 and v6 and CRU4 and HISTALP.

Differences between the flowline mass balance model and the volume/area scaling mass balance model

The volume/area scaling mass balance model computes an average mass balance value for the entire glacier. The mass balance model requires only the minimal and maximal glacier elevation as additional input parameters (z_{min}, z_{max}), to compute the monthly terminus temperature T_i^{termiuns} and the area averaged monthly amount of solid precipitation P_i^{solid}. The flowline model, on the other hand, requires a mass balance value for each grid point of the flowline (i.e., for each elevation band). Therefore, the mass balance is a function of elevation $B(z)$ and the elevation of the grid points must be supplied. Solid precipitation and air temperature are then computed for the given points of elevation, resulting in a point mass balance.

2.1.3 Glacier evolution model

Volume/area scaling is derived from the full set of continuum equations with no assumptions of plane strain, shallow ice, perfect plasticity, or steady state conditions. This derivation from the fully time dependent equation of motion allows the volume V, area A and scaling constant c_A to change with time. Especially the scaling constant c_A can incorporate transient behavior, since it depends on closing conditions which show an explicit time dependency. However, to explicitly include a temporal component, volume/area scaling has to be used in conjuncture with proper response time scaling. Response time scaling is a separate but equally valid scaling relation, derived during the same dimensionless analysis. Hence, these two scaling relations cannot be separated and have to be applied together to successfully model glacier evolution (Bahr et al. 2015).

The volume/area scaling model starts with an initial glacier surface area A_0 as input. The initial glacier volume V_0 and the initial glacier length L_0 are computed using the volume/area scaling relation and the inverted volume/length scaling relation, respectively (cf. Section 2.1.1).

$$V_0 = c_A \cdot A_0^{\gamma} \qquad\qquad L_0 = \left(\frac{V_0}{c_L}\right)^{\frac{1}{q}} \tag{2.5}$$

Additionally, only a mass balance model and the initial terminus elevation $z_{\mathrm{min},0}$ and maximal glacier surface elevation z_{max} are needed.

The volume/area scaling model runs with yearly time steps $\Delta t = 1\,\mathrm{yr}$. Each time step from year t to year $t+1$ includes the following steps:

1. Compute the time scale of the glacier's length change response to volume change τ_L and the time scale of the glacier's surface area change response to volume change τ_A as
$$\tau_L(t) = \frac{V(t)}{P_{\text{clim}}^{\text{solid}}(t^*) \cdot A(t)} \qquad\qquad \tau_A(t) = \tau_L(t)\frac{A(t)}{L(t)^2} \tag{2.6}$$
As introduced during the calibration process, $P_{\text{clim}}^{\text{solid}}(t^*)$ is the average solid precipitation during the 31-year period centered around t^*. For more details see Marzeion et al. (2012). The implementation includes lower bounds for both time scales as well as the climatological turnover, for details see Section 2.2.2.

2. Get the specific mass balance $B(t)$ from mass balance model, by solving Equation 2.1. For implementation details see Section 2.2.1

3. Compute the volume change $\Delta V(t) = \frac{1}{\rho_{\text{ice}}}A(t) \cdot B(t)$ as product of specific mass balance and glacier surface area. The volume change happens instantaneously, i.e., over one time step, hence the updated volume equals the sum of current volume and volume change $V(t+1) = V(t) + \Delta V(t)$.

4. The (hypothetical) equilibrium surface area can be computed by inverting the volume/area scaling relation $(V(t+1)/c_A)^{1/\gamma}$. However, the surface area does not change instantaneously, and proper response time scaling must be applied. Hence, the area change is computed as
$$\Delta A(t) = \frac{1}{\tau_A}\left(\left(\frac{V(t+1)}{c_A}\right)^{\frac{1}{\gamma}} - A(t)\right). \tag{2.7}$$
The updated area then equals the sum of current area and area change $A(t+1) = A(t) + \Delta A(t)$.

5. The updated glacier length and length change are computed analogously to the glacier surface elevation. $L(t+1) = L(t) + \Delta L(t)$, with
$$\Delta L(t) = \frac{1}{\tau_L}\left(\left(\frac{V(t+1)}{c_L}\right)^{\frac{1}{q}} - L(t)\right). \tag{2.8}$$

6. Adjust terminus elevation z_{min}, assuming a linear elevation change with changing glacier length (i.e., constant slope):
$$z_{\text{min}}(t+1) = z_{\text{max}} + \frac{L(t)}{L_0}(z_{\text{min},0} - z_{\text{max}}) \tag{2.9}$$
The maximum glacier elevation stays constant during the entire model run $z_{\text{max}} = \text{const}$.

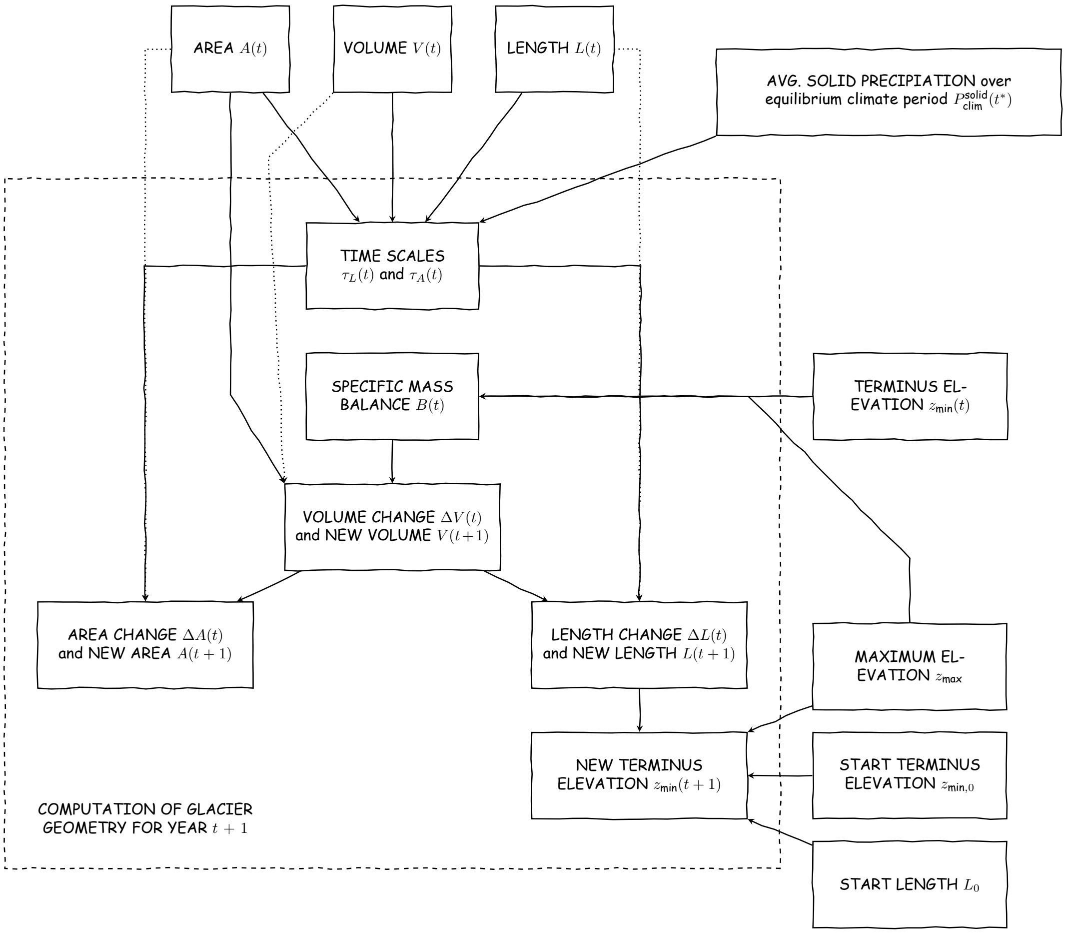


Figure 2.1: Schematic of the glacier evolution model's time stepping.

2.2 Implementation

2.2.1 Mass balance models

Volume/area scaling mass balance model

The `VAScalingMassBalance` model is the implementation of the *original* mass balance model by Marzeion et al. (2012). The model computes the mass balance of a glacier during the climate data period. The general concept is fairly similar to the `oggm.core.massbalance.PastMassBalance` model. The main difference is, that the volume/area scaling mass balance model returns only one glacier wide average mass balance value, instead of point mass balance values for the different elevation bands.

The mass balance model is initialized for a single glacier, denoted by the OGGM specific glacier directory `gdir`. Per default, the model will use the calibrated mass balance parameters μ^* and β^* and read temperature and precipitation records from the preprocessed climate file `climate_historical`. An alternative climate file can be used, by supplying either the filename and/or it's suffix via the parameters `filename` and `input_filesuffix`, repecitvely. It is possible to specify the start year and end year of the climate period (`ys` and `ye`), if not all available data should be used. The parameter `repeat` controlls whether the climate period given by `[ys, ye]` should be repeated indefinitely in a circular way.

The volume/area scaling mass balance model inherits the following methods from the `oggm.core.massbalance.MassBalanceModel` super class:

- `get_annual_climate()` and `get_monthly_climate()` compute and return the mass balance relevant climate information, i.e. positive air temperature at the terminus elevation in °C and solid precipitation amount in $\mathrm{kg\,m^{-2}}$, for the given year and month/year combination, respectively.

- `get_annual_mb()` and `get_monthly_mb()` compute and return the glacier wide average mass balance in $\mathrm{m\,s^{-1}}$, for the given year and month/year combination, respectively. The possible mass balance residual β^* is applied.

- `get_specific_mb()` and `get_monthly_specific_mb()` compute and return the glacier wide average specific mass balance in mmw e /yr, for the given year and month/year combination, respectively. The possible mass balance residual β^* is applied.

All methods need the glacier terminus elevation `min_hgt` and the maximal glacier surface elevation `max_hgt` as parameters. The date is supplied via the `year` parameter, using the hydrological float year convention. Given that the scaling mass balance model computes the glacier wide average mass balance, it is not possible to estimate the equilibrium line altitude. Hence, the the method `get_ela()` is not implemented, in contrast to the `PastMassBalance` model.

Constant climate scenario

The `ConstantMassBalance` model simulates a constant climate based on the observations averaged over a 31-year period centered on a given year `y0`. Hence, the specific mass balance does not change from year to year. The task `run_constant_climate(gdir, ...)` initializes a `ConstantMassBalance` for the given glacier `gdir` and runs for a given number of years `nyears`. The task takes an additional temperature bias as parameters `temp_bias`, to alter the observed climate records.

The same idea of a constant climate is used during the mass balance calibration, solving the mass balance equation (Equation 2.1) for the temperature sensitivity μ^*. So per definition, μ^* is the temperature sensitivity to keep the glacier in equilibrium over the 31-year climate period centered around the *equilibrium year* t^* while neglecting a potential mass balance residual β^*. Consequentially, a `ConstantMassBalance` model with `y0` $= t^*$ keeps the glacier in equilibrium.

Random climate scenario

Similar to the `ConstantMassBalance` model, the `RandomMassBalance` model is based on a 31-year period centered on a given year 'y0'. However, the mass balance years are randomly shuffeled within that period. More precise, for each simulated year the model computes the specific mass balance using temperature and precipitation records from a randomly selected year within the given period. Hence, the model runs on a synthetic random climate scenario based on actual observations. A seed `seed`' for the random generatore can be supplied as parameter, to allow for reproducibility. Additionally, it is possible to choose between draws with and without replacement via the `unique_sample` parameter.

The task `run_random_climate(gdir, ...)` works analogously to the task `run_constant_climate(gdir, ...)`, using an instance of `RandomMassBalance` model instead of the `ConstantMassBalance` model. Hence, using the climatological period centered around `y0` $= t^*$, the model glacier should stay in an equilibrium state while underlying minor fluctuations. Supplying a positive or negative temperature bias will result in a retreating or advancing model glacier, respectively, reaching a new equilibrium after some years.

2.2.2 Glacier evolution model

The `oggm−vas.VAScalingModel` is the implementation of the above describe glacier evolution model (see Section 2.1.3, Marzeion et al. (2012, cf.)) into the OGGM framework. The full source code is publicly available on GitHub.

An instance of the `oggm−vas.VAScalingModel` class is initialized with the initial area `area_m2_0`, the initial glacier terminus elevation `min_hgt` and maximum glacier surface elevation `max_hgt` and an instance of a `oggm−vas.VAScalingMassBalance` model. Additionally, the start year of the simulation `year_0` must be defined. Those initial values are stored as instance variables, since they are needed for later computations. Other than that, the `oggm−vas.VAScalingModel` object stores all model parameters as instance variables for the current year it is in. This includes glacier geometries (V, A, L, z_{min}, z_{max}) and their changes (ΔV, ΔA, ΔL), time scales (τ_A, τ_L), the mass balance model and the specific mass balance B, but also constants like the scaling parameters (c_A, γ, c_L, q) and ice density ρ_{ice}.

To advance the glacier model, there are three different methods. The `step()`

method advances the model by one year, following the above described steps (see Section 2.1.3). The method `run_until(year_end)` runs the model until the specified year and returns the geometric glacier parameters at the end of the model evolution (year, length, area, volume, terminus elevation and specific mass balance). Thereby, the model starts from whatever year it currently is in. It is possible to start the model run from `year_0` with the flag `reset`. The method `run_until_and_store()` works analagous to the previous one, with the difference that all parameters are stored for each time step (i.e., for each year). The resulting data set is returned and possible stored to file, if a file path is give. The method `run_until_equilibrium()` tries to run the glacier model until an equilibirum state is reached. The model runs for a fixed number of iteratrions `max_ite`, the total elapsed time changes with the chosen time step `ystep`. The iteration breaks, either if the glacier volume is below $1\,\mathrm{m}^3$ or an equilibirum is reached. An equilibrium state is reached, if the volume change rate $|V(t) - V(t + \Delta t)|/V(t)$ falls below a given value `rate`. Therefore, the method can only be used with a constant climate scenario (see Section 2.2.1).

2.3 Experimental setup

2.3.1 Equilibrium experiments

As most things in nature, glaciers strive toward an equilibrium condition by reacting to changes in climate with changes in geometry. Subjecting a glacier model to a constant climate (or a step change in climate) is a useful tool to asses the behavior of glacier models. Analyzing the behavior of glacier models subjected to a step change in climatic conditions is a widely used practice to estimate response times and get an insight into the dynamics of a numerical model. The OGGM provides two convenient mass balance models (or rather climate scenarios) for such equilibrium experiment: the `ConstantMassBalance` model and the `RandomMassBalance` model. The implementation and workings of both mass balance models are described in Section 2.2.1 and Section 2.2.1, respectively.

The equilibrium experiments are performed on all alpine glaciers and using the HISTALP dataset (Auer and Böhm 2007) as climate input data, with the corresponding hyper parameters (see Mass-balance model calibration for the Alps on the OGGM blog for more information).

The needed preprocessing includes GIS tasks (computing a local grid using the Shuttle Radar Topography Mission (SRTM, Jarvis et al. (2008)) digital elevation model (DEM) and the outline from the Randolph Glacier Inventory (RGI Consortium 2017; Pfeffer et al. 2014); computing centerlines), climate tasks (preparing the HISTALP data), mass balance calibration (computing the temperature sensitivity

μ^*) as well as the inversion tasks (estimating a bed topography) for the flowline model. For more details about the OGGM workflow see (Maussion et al. 2019) and the OGGM documentation.

As explained above, the mass balance model calibration depends on the chosen *equilibrium year* t^*. Hence, if both evolution models are supposed to run under the exact same climatic conditions (i.e., using the same temperature and precipitation records from the same 31-year period), t^* must be same for both evolution models. This is done by computing the temperature sensitivity μ^* for both models using the same t^* reference table `oggm_ref_tstars_rgi6_histalp.csv`. (cf. Section 2.1.2) and no mass balance residual ($\beta^* = 0$). For the regional run, however, each glacier uses it's own "best fitting" t^* and therefore μ^*. The calibration of the μ^* parameter is based on Marzeion et al. (2012), ensuring a minimal mass balance error due to the spatial interpolation of t^* rather than μ^* (for more details see Maussion et al. 2019, Sec. 3.3).

Both evolution models run for 1'000 years with the `ConstantMassBalance` model and for 10'000 years with the `RandomMassBalance` model. Both mass balance models are initialized around the respective *equilibrium year* for each glacier, `y0` $= t^*$. Furthermore, each climate scenario runs with three different temperature biases of $0\,°C$, $-0.5\,°C$ and $+0.5\,°C$ resulting in an equilibrium run, a run with positive and negative mass balance bias, respectively. The yearly geometric properties (length, area and volume) of the model glacier are stored to allow further investigations. In addition to the absolute values, a dataset with normalized values (with respect to the initial value) is produced, allowing better comparability.

Autocorrelation analysis

Chapter 3

Results

3.1 Equilibrium experiments

Equilibrium experiment are a useful tool to asses the behavior of glacier models. The OGGM provides two climate scenarios for such equilibrium experiment, the `ConstantMassBalance` model and the `RandomMassBalance` model. The implementation and workings of both mass balance models are described in Subsection 2.2.1.

The experiments are performed on all alpine glaciers using the HISTALP dataset (Auer and Böhm 2007) as climatic input data. The baseline climate for each glacier comes from a 31-year period centered around the *equilibrium year* t^*. An additional temperature bias of $0\,°\mathrm{C}$, $-0.5\,°\mathrm{C}$ and $+0.5\,°\mathrm{C}$ results in a neutral, positive and negative step change in mass balance, respectively. The detailed experimental setup can be found in Section 2.3.1

The first qualitative conclusions are drawn from the temporal evolution of glacier length, surface area and ice volume. We are looking at selected single glaciers as well as at the regional scale, i.e. at the sum over all glaciers in the HISTALP domain. Scaling methods applied to a single glacier give only an order of magnitude estimation (section 8.5 Bahr et al. 2015, cf.), which is accounted for in the following analysis. More quantitative results are drawn from an autocorrelation analysis and a power spectral density analysis, inspired by Roe and Baker (2014).

3.1.1 Time series

The following section tries to explain the model behavior using the temporal evolution of the glacier length, surface area and ice volume. The plots show a comparison between the volume/area scaling model and the flowline model time series, both for the constant and random climate scenario. Since the volume/area scaling model derives the initial glacier geometry from the surface area, absolute values of initial length and volume differ between the volume/area scaling model and the flowline model. The results are therefore normalized with respect to their initial values for better comparability.

Overall findings

- Both evolution models behave as expected and produce the same qualitative results. The model glaciers stay in an approximate equilibrium state using the climate around $t^*$and decreases/increases in size (length, area, volume) for a positive/negative temperature bias. Plots with absolute values can be found in the appendix

- The glacier size (length, area, volume) changes drastically less (i.e., between two to eight times less) with the volume/area scaling model than with the flowline model. However, volume estimations from volume/area scaling of a single glaciers must be considered as order of magnitude result. The scaling constant c is a random variable which can vary drastically from glacier to glacier. Apparently, the global mean value of $c = 0.034\ \mathrm{km}^{3-2\gamma}$ is a bad fit for the characteristics of Hintereisferner.

1.

2. The glacier size changes (dramatically) less under the VAS model than under the flowline model (true for length, area, and volume).

Note: However, volume estimations from volume/area scaling of a single glaciers must be considered as order of magnitude result. The scaling constant c is a random variable which varies (drastically) from glacier to glacier. Apparently, the global mean value of $c = 0.034\ \mathrm{km}^{3-2\gamma}$ is a bad fit for the characteristics of Hintereisferner.

Second Note: Changing the scaling constants changes the absolute values of ice volume (as well as surface area and glacier length). A higher volume/area scaling constant results in a larger initial ice volume. Subjected to the same climate perturbation (temperature step change), an initially larger glacier will gain/loose more ice and reach a higher equilibrium ice volume than a smaller one. However, when normalized with initial ice volume there are no more discernible differences in the magnitude of ice volume change. The temporal evolution, i.e., the oscillation behavior, is comparable, even if smaller glaciers react faster than larger ones (which is to be expected).

TL;DR; Turns out, the scaling constant does not change the magnitude of the normalized volume change.

3. The glacier length of the VAS model has to be seen more as a model parameter, rather than as an actual glacier property. The VAS glacier length decreases/increases only by about 8 percent compared to its initial value, for a positive/negative

temperature bias of 0.5 °C. This correspond to an absolute length change of less than 400 m, which is very little compared to the 3 to 4 km in length change (40

4. The result of VAS model under a constant climate scenario with a non-zero temperature bias reminds of a damped oscillating signal. The modeled length reaches its maximum after 200 years, overshooting the equilibrium result by more than 1

3.1.2 Constant climate scenario

3.1.3 Random climate scenario

3.1.4 Autocorrelation analysis

The autocorrelation function for selected glaciers is shown in Figure 3.1. For details about the experimental setup see Section 2.3.1

The autocorrelation function of the volume/area scaling length shows little to no variability between runs under different climate conditions. The autocorrelation function of the volume/area scaling length is comparable even between different glaciers. It has the same behavior of a dampened oscillator as described above. Their are differences in amplitude and frequency–most likely affected by glacier size–the general behavior is almost identical.

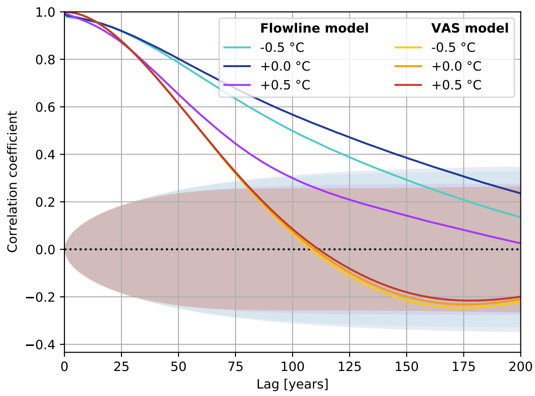
The flowline model is able to represent different glacial geometries and grasp individual responses to climatic forcings, which can be seen in the vastly different autocorrelation functions. They differ from glacier to glacier, but also for different climate scenarios (temperature biases) on the same glacier. However, there are no discernible patterns, which again confirms the notion that the OGGM flowline model is capable of modeling each glaciers individual response. Here are some examples: for Hintereisferner the autocorrelation of the flowline model is stronger than that of the volume/area scaling model, while for Mer de Glace and Großer Aletschgletscher it is lower (for all tested climate scenarios); the flowline model of the Pasterze shows a strong autocorrelation under the equilibrium climate, i.e., 0 °C temperature bias, (>0.7 for lags times between 0 and 95 years, still >0.43 for 200 years lag time, statistically significant up until a lag time of 232 years), while with a positive and negative temperature bias of ±0.5 °C the autocorrelation is less than for the volume/area scaling model. The volume/area scaling model has a stronger autocorrelation for short lag time (i.e., less than about 20 years) than the flowline model; similarly, the flowline model of the Glacier d'Argentière shows a strong autocorrelation under the climate with +0.5 °C temperature bias, and lower autocorrelation than the volume/area scaling model for the other two climate scenarios; The only observation made for all glaciers, it that the volume/area scaling model has a stronger autocorrelation for short lag time (i.e., less than about 20 years) than the flowline model. This is true even for glaciers, where the autocorrelation of the flowline mode is generally stronger (e.g., Hintereisferner).

It is not the intent of this work to investigate the relation between a glacier's geometry and its autocorrelation function, therefore we leave it at this qualitative first look. However, it is notable that the OGGM flowline model behaves differently for different glaciers and/or different climatic forcings. How far these results are comparable to real world glaciers is anyones guess. The *one size fits all* approach of the volume/area scaling model produces comparable results, mostly independent the glaciers geometry and the climate forcing (which was to be expected).

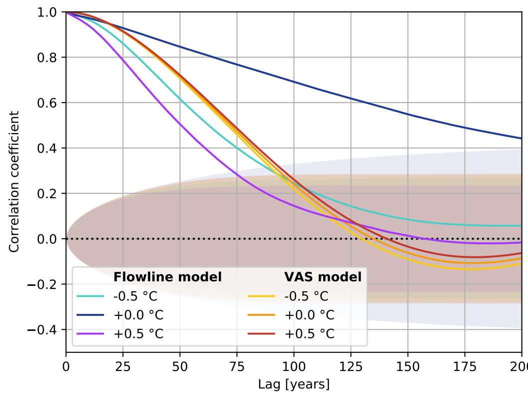
3.2 Sensitivity experiments

3.3 Future projection

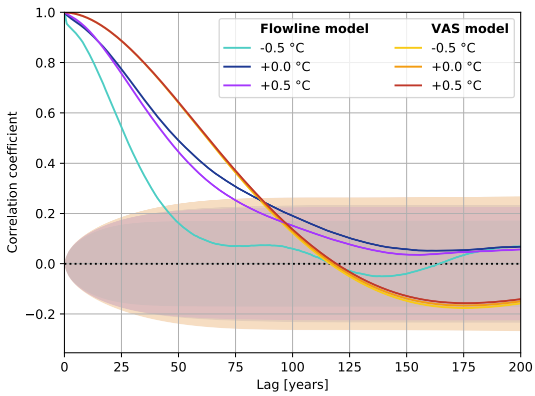
(a) RGI60-11.00897 - Hintereisferner



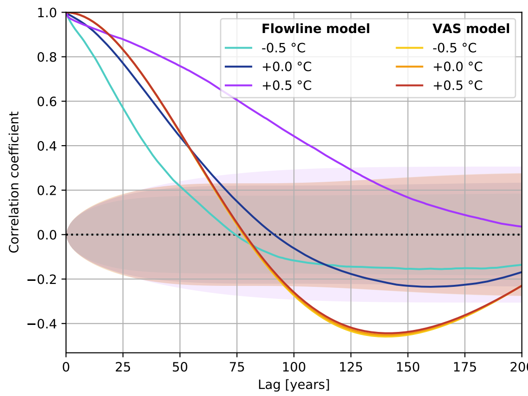
(b) RGI60-11.00106 - Pasterze



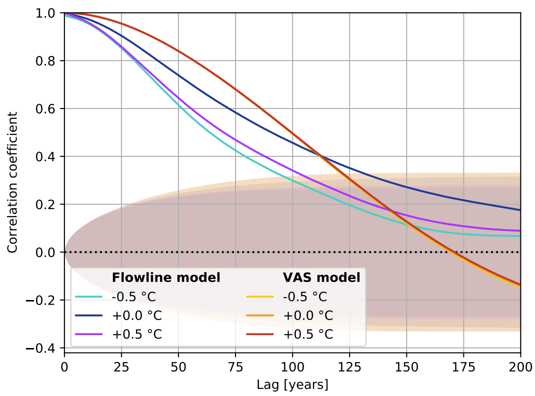
(c) RGI60-11.03643 - Mer de Glace



(d) RGI60-11.03638 - Glacier d'Argentière



(e) RGI60-11.01450 - Großer Aletschgletscher



(f) RGI60-11.01238 - Rhonegletscher

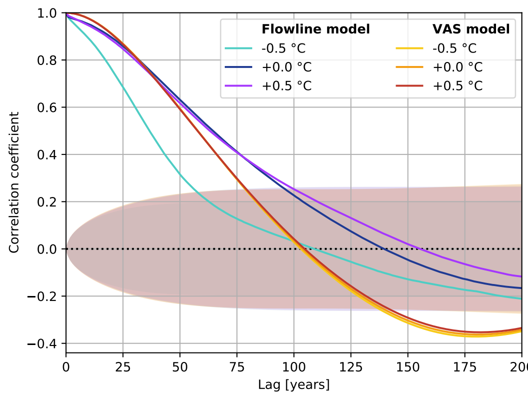


Figure 3.1: Autocorrelation function of modeled glacier length for lag times between zero and 200 years. Different lines represent different combinations of evolution model and climate scenario. The random climate scenario is based on an equilibrium climate, with different temperature biases. Cyan, blue and purple lines represent the flowline model, while yellow, orange and red lines represent the volume/area scaling model, with a temperature bias of $-0.5\,^{\circ}\mathrm{C}$, $0\,^{\circ}\mathrm{C}$ and $+0.5\,^{\circ}\mathrm{C}$, respectively. The 99 % confidence intervals are shaded in the corresponding colors.

Chapter 4

Discussion

Chapter 5

Conclusions

Appendix A

Large Quantities of Data

Large quantities of data should be placed in an appendix. They should only be "summarized" in the chapter Results. Another way is to present some representative cases together with some extreme cases in the chapter Results. In any case, there should always appear a reference to the appendix in the main part of the thesis.

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Curriculum Vitae

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1999–2003	Research assistant and Ph.D. student in the group of Dr. LastName at the Institute of Meteorology and Geophysics, University of Innsbruck.
1998–1999	Diploma thesis under the guidance of Dr. LastName, Institute of Meteorology and Geophysics, University of Innsbruck: *"Title of your diploma thesis"*.
1993–1998	Diploma study at the University of Innsbruck. *Master of Natural Science (Magister rerum naturalium)* in Meteorology.
1989–1993	Highschool, Town. *Matura*.

Meteorological training courses: "Numerical methods and adiabatic formulation of models", ECMWF, 1998; "Data assimilation and use of satellite data", ECMWF, 1998.

Participation in field experiments: Gap flow study (MAP), Austria, 1999.

Epilogue

Here is the place where you may want to tell a little story or a fairy tale which has some relevance for your thesis, such as "Once upon a time, ...". The Epilogue is optional.