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: $T_i^{\max} = T_i \cdot \gamma_{\text{temp}}(z_{\max} - z_{\text{ref}})$, 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 ($T_i^{\text{max}} > T^{\text{liquid}} \Rightarrow f_{\text{solid}} = 0$). For temperatures in between, the fraction of solid precipitation is interpolated linearly as $f_{\text{solid}} = 1 + \frac{T_i^{\text{terminus}} - T^{\text{solid}}}{\gamma_{\text{temp}} \cdot (z_{\text{max}} - z_{\text{min}})}$.

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

$$\tau_L(t) = \frac{V(t)}{P_{\text{clim}}^{\text{solid}}(t^*) \cdot A(t)} \qquad \tau_A(t) = \tau_L(t)\frac{A(t)}{L(t)^2} \tag{2.6}$$

   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 $z_{\text{max}} = \text{const}$.

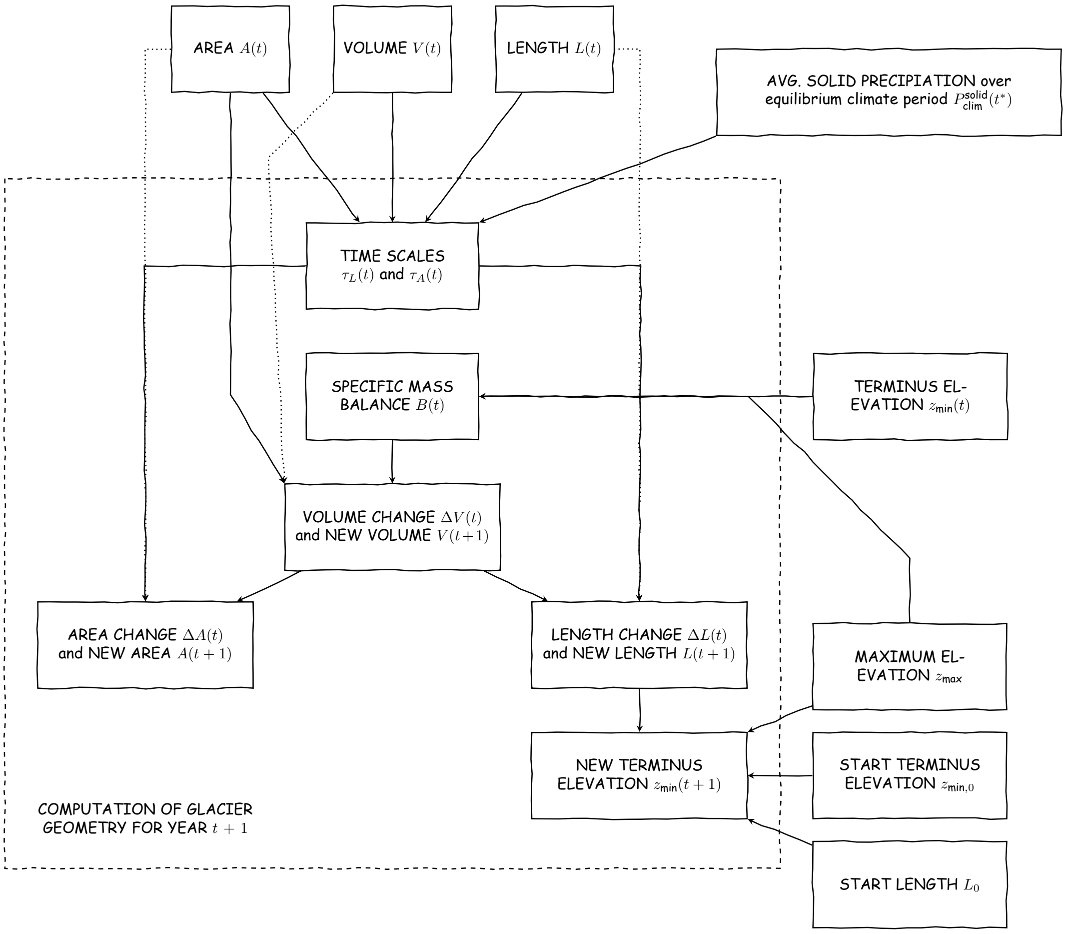


Figure 2.1: Schematic of the glacier evolution model's time stepping.

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 shuffled 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 generator 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 equilibrium 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 runs

As most things in nature, glaciers strive toward an equilibrium condition. Such an equilibrium is reached eventually, by changing the glacier's geometry in reaction to changes in climatic conditions. Analyzing the behavior of a glacier model subjected to a step change in climate can be used to estimate response times and to get insight into the dynamics of the numerical model, among others. The OGGM provides two convenient climate scenarios (or rather mass balance models) 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 (see constant and random climate scenario). The hereafter detailed equilibrium experiments use the HISTALP dataset (Auer and Böhm 2007) as climate input data, with the corresponding hyper parameters (see Mass-balance model calibration for the Alps (Dusch 2018) on the OGGM blog for more information). This obviously limits the suitable glaciers to the ones inside the HISTALP domain, i.e. the Alps. The HISTALP domain corresponds to the region 11-01 of the Randolph Glacier Inventory (RGI) (RGI Consortium 2017; Pfeffer et al. 2014) (version 6.x) and lists 3892 glaciers.

The following paragraph briefly lists the preprocessing tasks needed for the equilibrium runs. For a detailed description of OGGM workflow see Maussion et al. (2019) and the OGGM documentation.

GIS tasks: using the digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM, Jarvis et al. (2008)) and the RGI glacier outlines to compute a local grid, compute a glacier mask, compute centerlines and corresponding catchment areas;

climate tasks: extract the HISTALP time series for the grid point nearest to the glacier and write it in the `climate_historical.nc` file;

mass balance calibration: computing the glacier specific mass balance parameters t^*, μ^* and β^*;

inversion tasks: running the ice thickness inversion to estimate the bed topography (needed only for the flowline model);

The actual model runs are invoked via the `run_constant_climate` and `run_random_climate` tasks (see Section 2.2.1 for implementation details). The used settings depend on the intended experiment and are detailed in the following section.

Hintereisferner test case

A first qualitative look at the volume/area scaling performance uses the Hintereisferner (RGI60-11.00897) as test case. This test case is intended to (a) get a feel for the volume/area scaling model and set the stage for the following experiments (b) compare the two mass balance models suitable for equilibrium experiments. It has to be noted that volume/area scaling applied to single glaciers gives only an order of magnitude estimation. The scaling constant c is a globally averaged value, and the relative error in scaling constant is directly proportional to the error in estimated ice volume (Bahr et al. 2015). However, a qualitative comparison between the volume/area scaling model and the flowline model is more practicable and meaningful for a single glacier.

For this first experiment, both evolution models run with the `ConstantMassBalance` model and the `RandomMassBalance` model, for 1000 years each. Both mass balance models emulate an equilibrium climate to keep the glacier in its initial equilibrium state. Therefore, the mass balance models must be initialized with the climatic period centered around the equilibrium year, i.e., `y0` $= t^*$. As explained above, the mass balance calibration depends, among others, on the chosen t^* (Section 2.1.2, see Calibration of the mass balance parameters). Hence, to run both evolution models with the identical climatic forcing, t^* must be equal 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`, corresponding to the flowline model). Additionally, the mass balance residual must be omitted during the model run

($\beta^* = 0$, as per the definition of μ^*, see Section 2.1.2). For a broader range of comparable data, each mass balance model runs three different climate scenarios defined by the temperature biases of 0 °C, −0.5 °C and +0.5 °C. These runs will be referred to as *equilibrium run*, run with *positive mass balance bias* and run with *negative mass balance bias*, respectively.

Single glaciers under random climate scenario

Volume/area scaling applied to single glaciers gives only an order of magnitude estimation, since the scaling constant c is a globally averaged value (Bahr et al. 2015). However, a qualitative comparison between the volume/area scaling model and the flowline model is more practicable and meaningful for single glaciers. The results of hereafter explained model runs are used for a autocorrelation analysis and a power spectrum density analysis. The main focus hereby lies on the intricate inner workings of the evolution models, much rather than on absolute values or future ice volume projections.

Both evolution models run for 10 000 years with the `RandomMassBalance` model. The mass balance model is initialized around the respective *equilibrium year* for each glacier ($\texttt{y0} = t^*$). Each glacier is subjected to three different climate scenarios, depending on the given temperature bias of 0 °C, −0.5 °C and +0.5 °C. This results in an equilibrium run, a run with positive initial mass balance and a run with negative initial mass balance.

As explained above, the mass balance model calibration depends on the chosen *equilibrium year* t^* (Section 2.1.2, see Calibration of the mass balance parameters). To keep a glacier in its initial equilibrium state, the `RandomMassBalance` model must be initialized with the climatic period centered around $\texttt{y0} = t^*$. Additionally, the mass balance residual must be omitted during the model run ($\beta^* = 0$, as per the definition of μ^*, see Section 2.1.2). Hence, to run both evolution models with the identical climatic forcing, a given glacier must have the same t^* 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` corresponding to the flowline model).

The yearly geometric properties (length, area and volume) of each model glacier are stored to file. In addition to the absolute values, a dataset with normalized values (with respect to the initial value) is produced, allowing better comparability between the evolution models.

Commitment runs

One of the easiest ways of estimating future glacial evolution are so called *commitment runs*. The name stems from the *commitment* to a given climate, which is then held constant for the entire run. For example, applying the current climate to the current glaciers for the next, say, 100 years, gives a (naively optimistic) lower bound of glacial retreat in the Alps. Since both mass balance models allow for a temperature bias, multiple scenarios can be explored.

These scenarios are intended to reflect the reality as good as possible. Hence, the default OGGM mass balance calibration is used (see Section 2.1.2). To be more precise, each evolution model uses its own t^* reference table (which may result in different t^* for the same glacier depending on the evolution model) and the mass balance residual β^* is used for each run.

The first regional simulation is based on an equilibrium climate, similarly to the runs with single glaciers under random climate. The mass balance models are initialized with `y0` $= t^*$ and run with three different temperature biases of 0 °C, −0.5 °C and +0.5 °C. Both evolution models run for 1'000 years with the `ConstantMassBalance` model and with the `RandomMassBalance` model. This experiment allows to investigate the model's sensitivity to random annual fluctuations and serves as *baseline* for the following simulations.

While a climate scenario with yearly fluctuations is more physical than a constant climate, the resulting ice volume changes are comparable (see Section 3.1.1). Which is why, the following experiments can be limited to the `ConstantMassBalance` model without any loss of information. For a more tangible experiment, the mass balance model is initialized with todays climate. Todays climate is assumed to be the average over the most recent 31 years. For the HISTALP dataset this corresponds to the period from 1984 to 2014 with `y0 = 1999`. Since we live in a period of global warming, only positive temperature biases of 0 °C, +0.5 °C and +1.5 °C are used. As before, absolute and normalized values of yearly geometric properties are stored to allow further investigations.

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 experiments, the `ConstantMassBalance` model and the `RandomMassBalance` model (see Section 2.2.1 for implementation details). The experiments are performed on all alpine glaciers using the HISTALP dataset (Auer and Böhm 2007) as climate 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 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 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 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 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.

Hintereisferner test case

This first test case shows preliminary results, explores different possible routes of investigation and sets the stage for the following experiments. For details about the experimental setup see Section 2.3.1. Most (all important/promising) topics are investigated further in the following sections, which is why this section can be skipped by the time crunched reader. It follows the **TL;DR** summary of the key points:

TL;DR: Hintereisferner test case

- Both evolution models produce the same qualitative results, advancing under colder climates and shrinking under warmer climates. The temporal correlation between both models under a random climate is satisfying.
- The volume/area scaling model drastically underestimates changes in glacier geometry compared to the flowline model (up to four times). For example, the relative volume changes for the run with positive mass balance bias amount to +17 % for the volume/area scaling model and +71 % for the flowline model.
- The volume/area scaling does not account for the mass balance-elevation feedback and therefore produces highly symmetrical results between the positive and negative step change in air temperature. This symmetry can also be seen in the e-folding response times.
- The e-folding response times are much shorter for the volume/area scaling model. For example, the volume response times for the run with positive mass balance bias amount to 39 yr for the volume/area scaling model and 139 yr for the flowline model.
- The volume/area scaling model does not show an asymptotic adjustment but behaves more like a damped harmonic oscillator, whereby the model-internal time scale acts as damping factor.

Both evolution models behave as expected and produce the same qualitative results. The model glacier stays in an approximate equilibrium using the climate around t^*, decreases and increases in size for a positive and negative temperature bias of $\pm 0.5\,°\mathrm{C}$. This is true for both mass balance models, whereby the `RandomMassBalance` model produces more short term variability (most obviously).

Glacier advances and retreats correlate nicely between the two evolution models under the same random climatic forcing (with correlation coefficients between 0.44 and 0.72). This is not surprising, given that the implementations of the mass balance models are almost identical. Thereby, the ice volume exhibits the highest year-to-year variability, since volume changes are a function of specific mass balance and happen instantaneously (i.e., over one time step). The changes in surface area and glacier length are smoother, accounting for the glacier's response time. Comparing the evolution models, the flowline model shows stronger long term variations and less short term variability than the volume/area scaling model. This could indicate higher response times for the flowline model. This assumption is backed by the model behavior under the constant climate scenarios. Qualitatively speaking, the flowline model takes longer to reach a new equilibrium (after around 400 years) than the volume/area scaling model (after around 200 years). A quantitative analysis of the response times follows after the evaluation of the equilibrium values.

For the following discussion about the equilibrium values, if not stated otherwise only the constant climate scenarios are considered. It is assumed that the model glacier has reached a new equilibrium after 1000 years of evolution. Hence, the equilibrium values are taken as the final values at year `t = 1000`. This assumption seems valid, given that the values fluctuate only in the order of 0.01 % over the last 200 years of the simulations. The only exception forms the glacier length of the flowline model for a positive mass balance bias. Under this climate scenario, the equilibrium flowline glacier length oscillates between 9.9 km and 10 km. The glacier jumps back and for one grid cell, due to the spatial resolution of 100 m of the flowline model. Hence, the equilibrium length is assumed to be average between both values. Table 3.1 shows all equilibrium values in response to the positive and negative step change in equilibrium climate.

The most apparent result is that the volume/area scaling model underestimates all changes in glacier geometry when compared to the flowline model. While the volume/area scaling model predicts a volume change of around $\pm 16.5\,\%$, the flowline ice volume increases by 71 % and decreases by 42 %, for the positive and negative mass balance bias, respectively. In other words, the flowline glacier grows more than four times larger and shrinks more than two and a half times smaller than the volume/area scaling glacier. The equilibrium surface area is slightly less underestimated, with a change of $\pm 12\,\%$ for the volume/area scaling model versus changes of $+33\,\%$ and $-23\,\%$ for the flowline model. The glacier length of the volume/area scaling model does hardly change at all. The maximum year-to-year variation under any climate scenario shows slightly more than six meters, which is about 1 % of the initial value and therefore hardly physical sensible. This results in an length change of $\pm 7.5\,\%$ for the volume/area scaling model, which is roughly five to six times less than the changes of +44 % and −39 % for the flowline model. The values proof that the volume/area scaling model cannot, self-evidently, resolve all processes as a dedicated ice physics models can.

The changes in glacier geometry produces by the volume/area scaling model are highly symmetrical. Absolute changes ice volume, surface area and glacier length differ by a maximum of 1 % between positive and negative mass balance bias. This can be explained by the scaling mass balance model. For both implementations of the constant mass balance model, the specific equilibrium mass balance can be approximated as a linear function of the temperature bias through the origin ($r^2 > 99.9\,\%$), for small enough temperature biases between −1 °C and +1 °C. Thereby, the linear function for the flowline model has a steeper slope than for the volume/area scaling model. The resulting initial specific mass balances are +306 mm we. yr^{-1} and −322 mm we. yr^{-1} for the flowline model and +210 mm we. yr^{-1} and −218 mm we. yr^{-1} for the volume/area scaling model. As can be seen, the initial mass balance values are symmetrical for both evolution models and can therefore not be the cause of the volume/area scaling model's symmetric equilibrium results. However, the question should not be "What makes the volume/area scaling model results symmetric?" but much rather "What allows the flowline model to produces asymmetric results?". And the answer is the mass balance-elevation feedback. The flowline model continuously adjusts the surface elevation of each grid cell and passes the elevation information onto the mass balance model (implementation note: the mass balance feedback can be adjusted via the `mb_elev_feedback` parameter of the `FlowlineModel` class). Suppressing the mass balance-elevation feedback for the flowline model run results in a volume change of +38 % and −34 %. The results are symmetric and lower than with mass balance-elevation feedback in place. The relative changes in ice volume are reduced to about twice the values produces by the volume/area scaling model.

However, the scaling constant c is a random variable which can vary drastically from glacier to glacier. It is possible that the global mean value of $c = 0.034\,\mathrm{km}^{3-2\gamma}$ is a bad fit for the characteristics of Hintereisferner. A detailed look at the model's sensitivity to the scaling constant is provided in Section **??**.

The responses of the volume/area scaling model and the flowline model to a step change in climate are qualitatively similar but do not compare quantitatively. While the absolute equilibrium values are still in the same order of magnitude, they differ substantially. But what about the time domain? The following paragraphs look at temporal characteristics of the glacier model's response.

The implementation of the volume/area scaling model includes the corresponding response time scaling to estimate temporal changes (see Section 2.1.3). For a proper response time scaling, the length response time scale τ_L and the area response time scale τ_A must be estimated. The length response time scale can be estimated as ratio between ice volume and mass turnover (Jóhannesson et al. 1989), the area response time scale than follows from geometric considerations. The time scales computed for the Hintereisferner under a constant equilibrium climate amount to $\tau_L \approx 52\,\mathrm{yr}$ and $\tau_L \approx 18\,\mathrm{yr}$. Those values are rather low compared to other findings of $\tau_L \approx 100\,\mathrm{yr}$ (Greuell 1992; Schuster 2020). However, it is possible that the used time scales are merely model parameters and do not correspond to the typically used e-folding time scales.

Processes evolving exponentially to an equilibrium can be characterized by their e-folding response time. The assumption that a glacier's geometry changes exponentially is valid for small enough perturbations in climate. The e-folding response time is computed as the time after which the initial difference between a glacier's geometric property (such as ice volume, surface area or glacier length) and its new equilibrium value has decreased by a factor of $1 - \mathrm{e}^{-1} \approx 0.63$. For comparability, e-folding time scales are computed for both evolution models and all geometric properties. The values can be found in Table 3.2. As was to be expected, volume response times τ_V are smallest, followed by τ_A and τ_L. As already qualitatively estimated above, the volume/area scaling model adjust between one and a half times and three and a half times faster to the temperature perturbation of 0.5 °C as the flowline model does. This is especially visible for the growing glacier, where the flowline model takes about 100 yr longer to reach a new equilibrium than the volume/area scaling model does ($\tau_{V,\mathrm{fl}} = 139\,\mathrm{yr}$ vs. $\tau_{V,\mathrm{vas}} = 39\,\mathrm{yr}$).

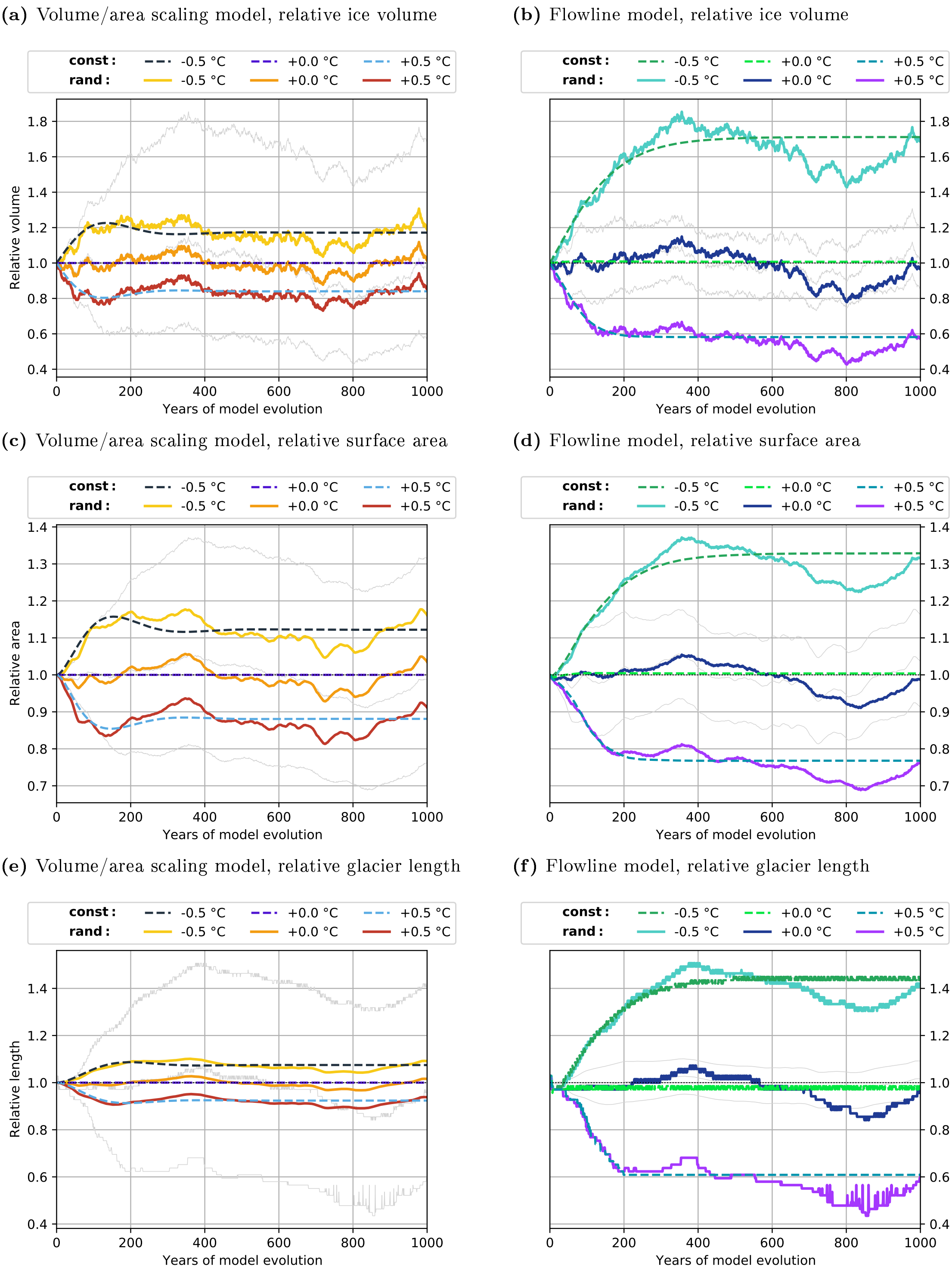
The results of the volume/area scaling model are again very symmetric between the positive and negative temperature perturbation. The volume/area scaling response time scales range within 9 % of each other, while the flowline response time scales vary up to 55 %. Suppressing the mass balance-elevation feedback for the flowline model runs results in symmetric result, whereby the values for the run with negative mass balance bias do only change by a maximum of five years. It has to be noted, that the e-folding length response time for the volume/area scaling model $\tau_{L,\mathrm{vas}} \approx 80\,\mathrm{yr}$ is about thirty years ($\approx$60 %) longer than the model-internal time scale. However, the volume/area scaling model does not show an asymptotic or exponential adjustment. The adjustment of glacier geometries looks like the signal of an underdamped oscillator, with a strongly discernible overshoot. The damping factor seems to be controlled by the model-internal time scale, which could allow for an additional calibration parameter. A closer look at this oscillation behavior is provided in Section **??**

Table 3.1: Hintereisferner (RGI60-11.00897) equilibrium values after 1000 years of model evolution in response to a step change in climate of $\Delta T = \pm 0.5\,^\circ\mathrm{C}$ relative to the average climate between 1912 and 1942. Percentage values in parenthesis indicate normalized changes in respective to their initial values.

	Length [km]		Area [km^2]		Volume [km^3]	
Initial values						
V/A scaling	4.89		8.04		0.60	
Flowline	6.90		8.04		0.80	
$\boldsymbol{\Delta T = -0.5\,^\circ\mathrm{C}}$						
V/A scaling	5.26	(+7 %)	9.02	(+12 %)	0.70	(+17 %)
Flowline	9.95	(+44 %)	10.68	(+33 %)	1.37	(+71 %)
$\boldsymbol{\Delta T = +0.5\,^\circ\mathrm{C}}$						
V/A scaling	4.52	(−8 %)	7.08	(−12 %)	0.50	(−16 %)
Flowline	4.20	(−39 %)	6.17	(−23 %)	0.47	(−42 %)

Table 3.2: e-folding time scales for Hintereisferner (RGI60-11.00897) in response to a step change in climate of $\Delta T = \pm 0.5\,^\circ\mathrm{C}$ relative to the average climate between 1912 and 1942. Time scales are computed for changes in ice volume, surface area and glacier length, denoted as τ_V, τ_A and τ_L, respectively.

	τ_L [yr]	τ_A [yr]	τ_V [yr]
$\boldsymbol{\Delta T = -0.5\,^\circ\mathrm{C}}$			
V/A scaling	85	57	39
Flowline	174	159	139
$\boldsymbol{\Delta T = +0.5\,^\circ\mathrm{C}}$			
V/A scaling	80	52	36
Flowline	123	107	79



(a) Volume/area scaling model, relative ice volume

(b) Flowline model, relative ice volume

(c) Volume/area scaling model, relative surface area

(d) Flowline model, relative surface area

(e) Volume/area scaling model, relative glacier length

(f) Flowline model, relative glacier length

Figure 3.1: Temporal evolution of ice volume in (a) and (b), surface area in (c) and (d) and glacier length in (e) and (f) for Hintereisferner (RGI60-11.00897). The shown values area normalized with their respective initial values. The left panels show the result of the volume/area scaling model, the right panels show the results of the flowline model. Solid lines represent the random climate scenarios, while dashed lines represent the constant climate scenarios. All climate scenarios are based on an equilibrium climate. The applied temperature biases of $-0.5\,^{\circ}$C, $0\,^{\circ}$C and $+0.5\,^{\circ}$C are color coded, see legend for details. The dotted line indicates the initial volume. The light gray lines represent the volume evolutions of the other model, to facilitate comparisons.

Commitment runs

The findings explained hereafter result from runs under (a) equilibrium climate, with `y0` $= t^*$ for each glacier (b) todays climate, with `y0 = 1999`. Both climate scenarios run with different mass balance model and apply different temperature biases. For more details see Section 2.3.1.

Let's first take a more general look at the model behavior under equilibrium climate. Both evolution models run for 1'000 years, once with the `ConstantMassBalance` model and once with the `RandomMassBalance` model. A random climate with its year-to-year fluctuations is obviously more physical than a completely constant climate. However, the changes in glacier ice volume under both climate scenarios are almost identical. Over the last 200 years of the simulations with equilibrium climate, the differences in total ice volume between the constant and random climate scenario average around 0.6 % to 0.7 % for the volume/area scaling model and 0.7 % to 2.3 % for the flowline model, depending on the temperature bias. This makes intuitive sense, considering that glaciers act as natural low-pass filters for climatic variabilities. For simplicity, all following values correspond to the results under a constant climate scenario.

The volume/area scaling model estimates a total ice volume of 139 km^3 (106 %), 115 km^3 (88 %) and 95 km^3 (73 %), for a temperature bias of $-0.5\,°\mathrm{C}$, $0\,°\mathrm{C}$ and $+0.5\,°\mathrm{C}$, respectively. The flowline model estimates a total ice volume of 236 km^3 (145 %), 147 km^3 (90 %) and 86 km^3 (53 %), for a temperature bias of $-0.5\,°\mathrm{C}$, $0\,°\mathrm{C}$ and $+0.5\,°\mathrm{C}$, respectively. Both evolution models adjust their initial ice volume downwards by 12 % (volume/area scaling) and 10 % (flowline) under equilibrium climate. This is due to the mass balance residual β^*. It indicates that the 2003 ge As seen before, the volume/area scaling scaling model underestimates the change in ice volume compared to the flowline model.

3.1.2 Autocorrelation analysis

The autocorrelation function for selected glaciers is shown in Figure 3.3. For details about the experimental setup see Section **??**

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 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

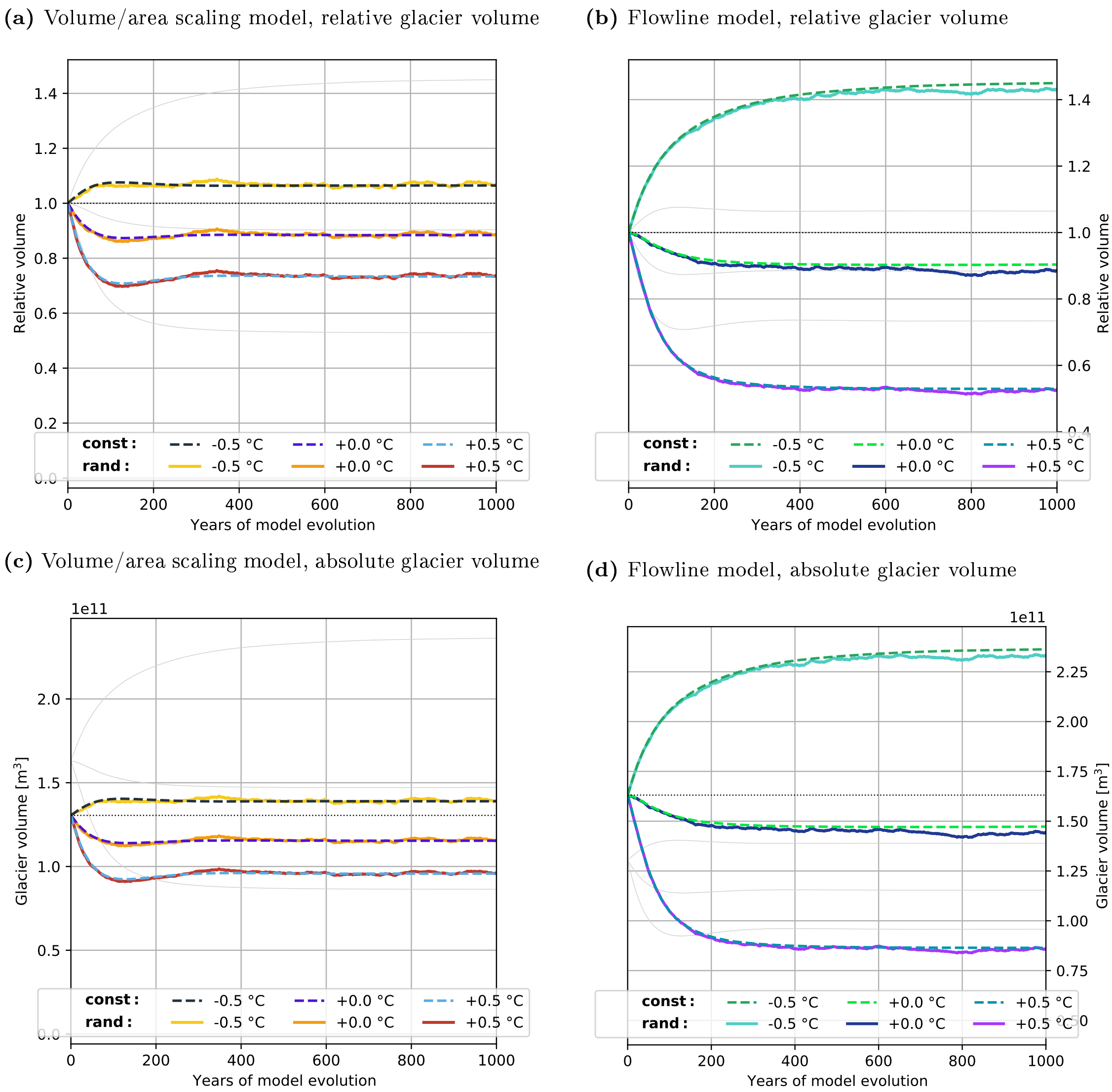


Figure 3.2: Time series of total ice volume for all glaciers in the HISTALP domain. The upper two panels show the relative glacier ice volume, normalized with the initial values, while the lower two panels show the absolute glacier ice volume. The left panels show the result of the volume/area scaling model, the right panels show the results of the flowline model. Solid lines represent the random climate scenarios, while dashed lines represent the constant climate scenarios. All climate scenarios are based on an equilibrium climate, with one of three different temperature biases. Yellow, orange and red solid lines represent the volume/area scaling model, while cyan, blue and purple solid lines represent the flowline model, under a random climate with a temperature bias of $-0.5\,^{\circ}$C, $0\,^{\circ}$C and $+0.5\,^{\circ}$C, respectively. Yellow, orange and red dashed lines represent the volume/area scaling model, while cyan, blue and purple dashed lines represent the flowline model, under a constant climate with a temperature bias of $-0.5\,^{\circ}$C, $0\,^{\circ}$C and $+0.5\,^{\circ}$C, respectively. The dotted line indicate the initial volume. The light gray lines represent the volume evolutions of the other model, to facilitate comparisons.

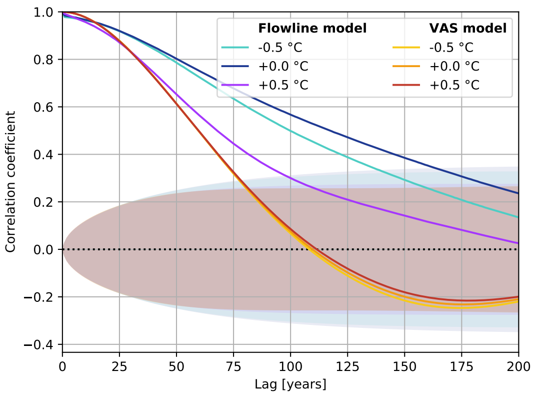
autocorrelation functions. They differ from to glacier, but also for different climate scenarios (temperature biases) on the same glacier. However, there are no discernible patterns, which again confirms the notion that the OGGM flowline model is capable of modeling each glaciers individual response. 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 $\pm$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 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).

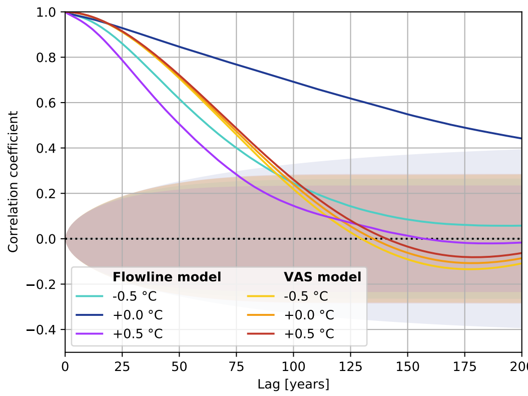
3.2 Sensitivity experiments

3.3 Future projection

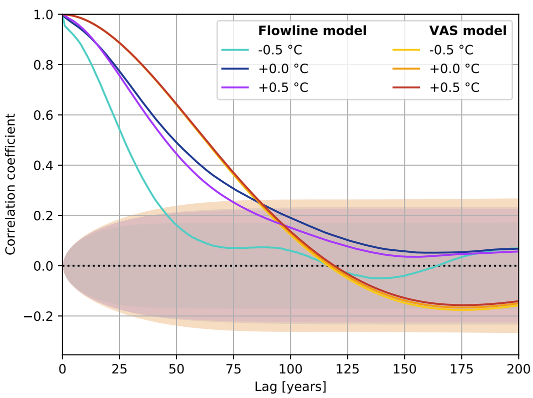
(a) RGI60-11.00897 - Hintereisferner



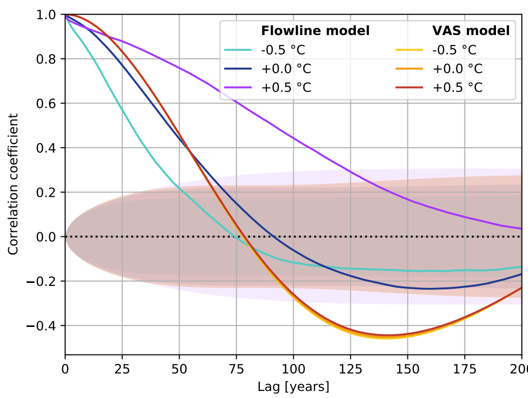
(b) RGI60-11.00106 - Pasterze



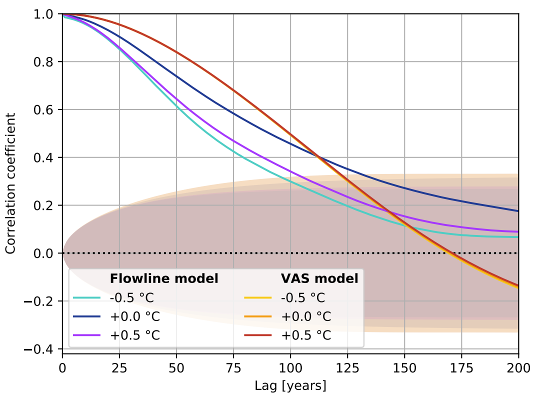
(c) RGI60-11.03643 - Mer de Glace



(d) RGI60-11.03638 - d'Argentière



(e) RGI60-11.01450 - Großer Aletschgletscher



(f) RGI60-11.01238 - Rhonegletscher

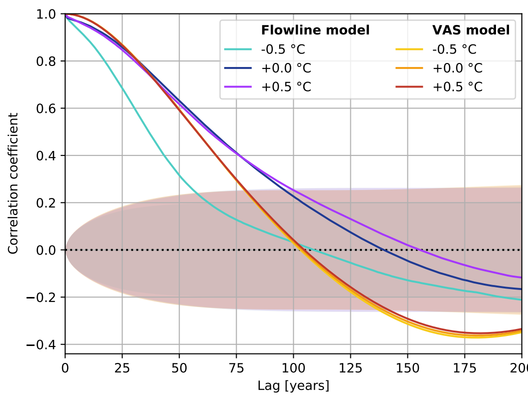


Figure 3.3: Autocorrelation function of modeled length for lag times between zero and 200 years. Different lines represent different combinations of evolution model and climate scenario. The random climate scenario is based on an equilibrium climate, with different temperature biases. Cyan, blue and purple lines represent the flowline model, while yellow, orange and red lines represent the volume/area scaling model, with a temperature bias of $-0.5\,^{\circ}$C, $0\,^{\circ}$C and $+0.5\,^{\circ}$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.

Bibliography

Auer, I. and R. Böhm, 2007: HISTALP – historical instrumental climatological surface time series of the Greater Alpine Region. *INTERNATIONAL JOURNAL OF CLIMATOLOGY*, **27**, doi:10.1002/joc.1377.

Bahr, D. B., W. T. Pfeffer, and G. Kaser, 2015: A review of volume-area scaling of glaciers. *Reviews of Geophysics*, **53 (1)**, 95–140, doi:10.1002/2014RG000470, URL http://doi.org/10.1002/2014RG000470.

Dusch, M., 2018: Mass-balance model calibration for the alps. OGGM Blog, URL "https://oggm.org/2018/08/10/histalp-parameters/", posted on August 10, 2018, URL "https://oggm.org/2018/08/10/histalp-parameters/", posted on August 10, 2018.

Giesen, R. H. and J. Oerlemans, 2012: Calibration of a surface mass balance model for global-scale applications. *Cryosphere*, **6 (6)**, 1463–1481, doi:10.5194/tc-6-1463-2012.

Greuell, W., 1992: Hintereisferner, austria: mass-balance reconstruction and numerical modelling of the historical length variations. *Journal of Glaciology*, **38 (129)**, 233–244, doi:10.3189/S0022143000003646.

Jarvis, A., E. Guevara, H. Reuter, and A. Nelson, 2008: Hole-filled srtm for the globe, version 4. CGIAR Consortium for Spatial Information, University of Twente, published by CGIAR-CSI on 19 August 2008., published by CGIAR-CSI on 19 August 2008.

Jóhannesson, T., C. Rymond, and E. Waddington, 1989: Time-scale for adjustment of glaciers to changes in mass balance. **35 (1)**.

Marzeion, B., A. H. Jarosch, and M. Hofer, 2012: Past and future sea-level change from the surface mass balance of glaciers. *The Cryosphere*, **6 (6)**, 1295–1322, doi:10.5194/tc-6-1295-2012.

Marzeion, B. and A. Nesje, 2012: Spatial patterns of north atlantic oscillation influence on mass balance variability of european glaciers. *The Cryosphere*, **6 (3)**, 661–673, doi:10.5194/tc-6-661-2012, URL https://tc.copernicus.org/articles/6/661/2012/.

Maussion, F., et al., 2019: The Open Global Glacier Model (OGGM) v1.1. *Geoscientific Model Development*, **12 (3)**, 909–931, doi:10.5194/gmd-12-909-2019, URL https://doi.org/10.5194/gmd-12-909-2019.

Pfeffer, W. T., et al., 2014: The randolph glacier inventory: a globally complete inventory of glaciers. *Journal of Glaciology*, **60 (221)**, 537–552, doi:10.3189/2014JoG13J176.

RGI Consortium, 2017: Randolph glacier inventory - a dataset og global glacier outlines: Version 6.0: Technichal report. Global Land Ice Measurements from Space, Colorado, USA, doi:10.7265/N5-RGI-60.

Roe, G. H. and M. B. Baker, 2014: Glacier response to climate perturbations: an accurate linear geometric model. *Journal of Glaciology*, **60 (222)**, 670–684, doi:https://doi.org/10.3189/2014jog14j016.

Schuster, L., 2020: Response time of glaciers using the Open Global Glacier Model : from simple idealized experiments to an estimate for Alpine glaciers. Ph.D. thesis.

World Glacier Monitoring Service, Zürich, Switzerland, 2017: Wgms: Fluctuations of glaciers database. doi:10.5904/wgms-fog-2017-10.

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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.
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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.

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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.