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

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by

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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 (i.e., gained mass by snowfall, avalanches, snow drift, ...) and ablation (i.e., lossed mass via ice melt, sublimation,) over the course of a year. Accumulation refers to mass gain by snowfall, avalanches, snow drift, etc. 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 at the climate file reference elevation z_{ref} to the glacier's terminus elevation z_{terminus} using the temperature lapse rate γ_{temp}.

$$T_i^{\text{termiuns}} = T_i \cdot + \gamma_{\text{temp}}(z_{\text{mean}} - z_{\text{ref}}) \tag{2.2}$$

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 glaciers temperature sensitivity μ^* relates the positive melting temperature to the actual ice loss. μ^*needs to be calibrated for each glacier, as well as a potential mass balance residual β^*). The calibration process of these mass balance parameters is described below. The temperature at the maximal glacier elevation $T_i^{\max}$ is computed analogously to the terminus elevation. $T_i^{\max} = T_i \cdot + \gamma_{\text{temp}}(z_{\max} - z_{\text{ref}})$, whereby $z_{\max}$ represent the maximum glacier surface elevation.

The area average monthly solid precipitation onto the glacier surface P_i^{solid} is computed from the total precipitation P_i (from 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, the temperature at the maximum glacier surface elevation 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 ($f_{\text{solid}} = 1$). For temperatures at the maximum glacier surface elevation above the threshold for liquid precipitation, all precipitation is liquid ($f_{\text{solid}} = 0$). For temperatures in between, the fraction of solid precipitation is interpolated linearly as $f_{\text{solid}} = 1 + \frac{T_i^{\text{terminus}} - T^{\text{solid}}}{\gamma_{\text{temp}} \cdot (z_{\max} - z_{\text{terminus}})}$. ***Note:*** (historical) climate models generally underestimate the precipitation in alpine regions, hence the 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 compenent of the mass balance equation and hence omitted 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 $a \approx 2.5$. On the other hand, the variability of the modeled mass-balance is quite low for values of $a \leq 2.5$, which is the OGGM default.

Calibration of the mass balance parameters

A complete and thourough description of the mass balance calibration for this particular temperature index model can be found in Marzeion et al. (2012, Section 2.1.9 and 2.1.10) and Maussion et al. (2019, Section 3.3). The following section serves as a summary, describing the most relevant steps

The first step is to estimate the so called candidates $\mu(t)$ for all galciers with available mass balance records (254 glaciers globally, see World Glacier Monitoring Service, Zürich, Switzerland (2017)). This is done by requierung the mass balance

$\bar{B}(t)$ over a 31-year period centered around year t to be zero and solving for $\mu(t)$.

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

whereby $P^{\text{solid}}_{\text{clim. avg}}$ and $T_{\text{clim. avg}}$ are the average yearly solid precipitation amount and average yearly air temperature during the climatological period centered on 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 observation. The computed difference $\beta(t)$ is a measure of how good the temperature sensitivity candidate $\mu(t)$ approximates the *real* value μ^*. Hence, μ^* is chosen as the candidate $\mu(t^*)$ for which the absolute bias is minimal, which in the best case is zero $\beta(t^*) =: \beta^* \approx 0$. The *equilibrium year* t^* represents the center of a 31-year climatic period where the given glacier geometry would stay in equilibirum. However, this is more of a model parameter than an real live value. The same is true for the corresponding tempreature senistivity μ^* and mass balance residual β^*.

Implementation note: The computed t^* and β^* for each glacier are store in a `ref_tstars.csv` file. 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 and the precipitation scaling factor). 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 RGI v5 and v6 and CRU4 and HISTALP.

For all glaciers without mass balance records, t^*—as well as β^*—is interpolated from the ten closest glaciers, inversly weighted with distance. The temperature senisitivity is computed by requiring the mass balance to be zero $\bar{B}(t^*) = 0$ 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 neighbouring glaciers. On the other hand, it is intuitively more likely for a glacier to be in equilibrium if its surrounding glaciers are 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 (Marzeion et al. 2012; Maussion et al. 2019, cf.).

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 every 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 and response time scaling are both well-known glaciological relationships, but one cannot be considered separately from the other. Instead, a real glacier is characterized and modeled by both relationships simultaneously, and there is no need to artificially assign time dependence to the volume-area exponent. [...]

Volume-area scaling does not explicitly include a variable for time, but volume-area scaling can still be applied to transient and nonsteady state conditions—the temporal component is included via the separate but equally relevant response time scaling. [...]

[...] the nonsteady state temporal behavior of volume-area scaling is encapsulated in the separate response time scaling" (Bahr et al. 2015)

The volume/area scaling model is initialized with an initial glacier surface area A_0. The initial glacier volume V_0 and the initial glacier length L_0 are computed using the volume/area scaling realtion and the 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 and maximal glacier surface elevation are needed.

The volume/area scaling model runs with yearly time steps $\Delta t = 1\,\text{yr}$. 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

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

As introduced during the calibration process, $P(t^*)_{\text{clim}}^{\text{solid}}$ is the average solid precipitation during the 31-year period cetered 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, in contrast to the volume, and propper 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 length change and updated glacier length 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_{terminus}, assumig linear change with changing glacier length.

$$z_{\text{terminus}}(t+1) = z_{\max} + \frac{L(t)}{L_0} (z_{\text{terminus},0} - z_{\max}) \tag{2.9}$$

   The maximum glacier elevation stays constant during the entire model run $z_{\max} = \text{const}$.

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

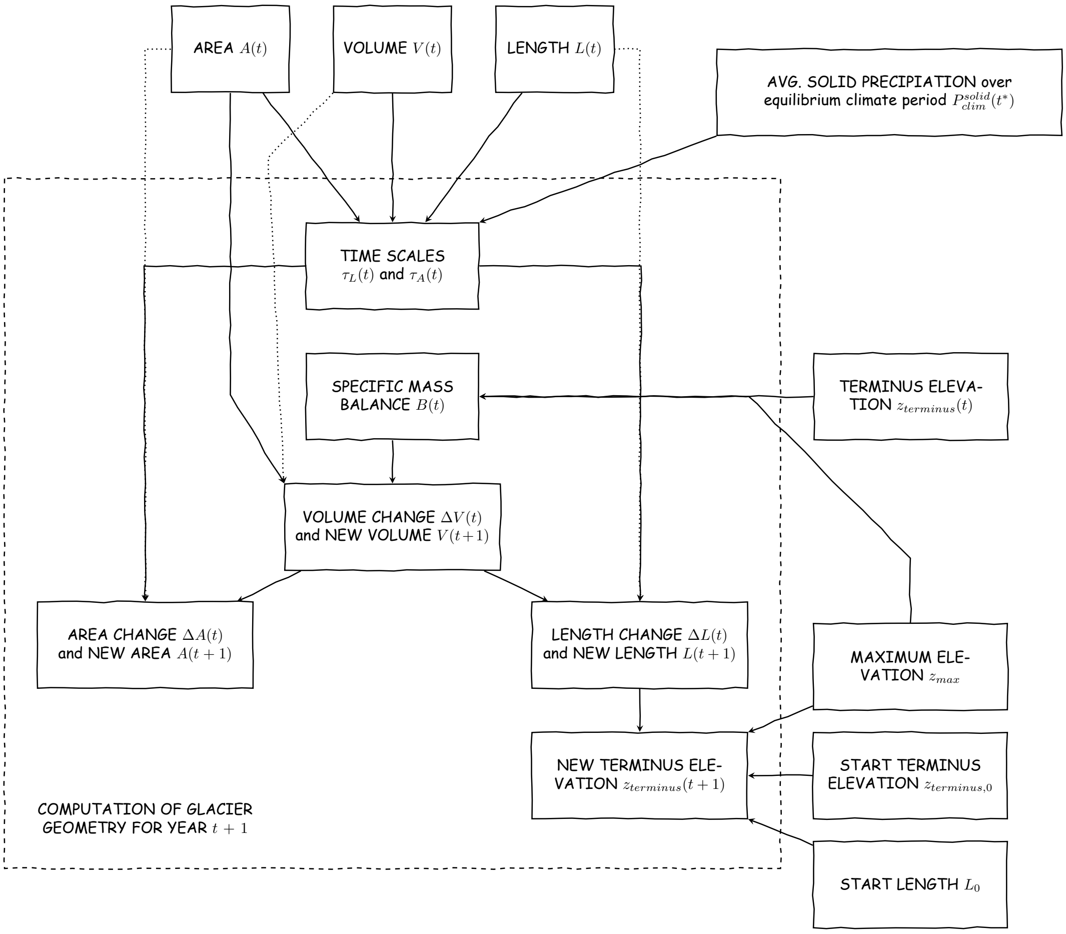

Figure 2.1: TODO

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_historica`. 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

2.3 Problems

2.4 Experimental setup

2.4.1 Equilibrium experiments

As most things in nature, glaciers strive toward an equilibrium condition by reacting to changes in climate with a change 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. Analysing 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 Subsection 2.2.1 and Subsection 2.2.1, respectively.

The equilibrium experiments are performed on all alpine glaciers 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 Shuttel 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 model are supposed to run under the same climatic conditions (i.e., using the same temperature and precipitation records from the same 31-year period), t^* must be equal for both evolution models. This is done for single glaciers, in order to compare the models under equal forcings. Hereby, the temperature sensitivity μ^* is computed using the t^* reference table for the flowline model (which is different from the reference table for the volume/area scaling model, see 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 $0\,°\mathrm{C}$, $-0.5\,°\mathrm{C}$ and $+0.5\,°\mathrm{C}$ 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.

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 2.4.1

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 voulume. 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 geometrie 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 eigth 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

3.2 Sensitivity experiments

3.3 Future projection

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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EDUCATION AND PROFESSIONAL TRAINING:

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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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.