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

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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2.1 General concepts

2.1.1 Glacier volume/area scaling

2.1.2 Temperature index model

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 monthly solid precipitation onto the glacier surface P_i^{solid} and the monthly mean air temperature T_i as input. Hereby, the index i denotes the month of the year. The details and differences between the volume/area scaling and flowline implementation will be explained later.

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

Hereby, μ^* is the glacier specific temperature sensitivity, β^* is the mass balance residual (compared to observations) and T_{melt} the mean air temperature above which ice melt occurs. 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^*.

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

The flowline model requires a point 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 and the elevation of the grid points must be supplied. Solid precipitation and air temperature are then computed for the given elevation.

The volume/area scaling mass balance model, on the other hand, 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, to compute the terminus temperature and the area averaged amount of solid precipitation.

2.2 Implementation

2.2.1 Mass balance models

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` takes an additional temperature bias (and a possible precipitation bias, for that matter) as parameters, to alter the observed *climatic* conditions.

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^*. The temperature sensitivity μ^* is calibrated, in order to keep the model glacier in equilibrium under a constant climate centered on t^*.

$$\mu^* = \frac{P^{\text{solid}}_{\text{clim. avg}}}{\max(T_{\text{clim. avg}} - T_{\text{melt,}}\ 0)}, \tag{2.2}$$

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. Consequentially, a `ConstantMassBalance` model with `y0` $= t^*$ keeps the glacier in equilibrium.

Random climate scenario

The `RandomMassBalance` model takes the climate information from a randomly chosen year within a 31-year period centered on a given year 'y0' to compute the specific mass balance. Hence, the model runs on a synthetic (pseudo random) climate scenario based on actual observations.

Similar to the `ConstantMassBalance` model, the `RandomMassBalance` model is based on a 31-year period centered on a given year 'y0'. However, the model uses the temperature and precipitation records from a randomly selected year out of that period. The specific mass balance is then computed using temperature and precipitation records. Hence, the model runs on a synthetic (pseudo random) climate scenario based on actual observations.

Using the climatological period around the *equilibrium year* t^*, the model glacier should stay in an equilibrium state, while underlying minor fluctuations. In analogy to the `ConstantMassBalance` model, the `run_random_climate` task takes a temperature bias as parameter. Increasing/decreasing the temperature of the equilibrium period will result in a retreating/advancing model glacier, reaching a new equilibrium after some years.

2.3 Problems

2.4 Experimental setup

2.4.1 Equilibrium experiments

The equilibrium experiments are performed on all alpine glaciers using the HISTALP dataset (Auer and Böhm 2007) as climatic 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 SRTM DEM and the RGI outline, 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.

As explained above, the mass balance model calibration depends on the chosen *equilibrium year* t^*.

Hence, t^* must be equal for both evolution models since we want to use the same climatic period. Rather than relying on the reference tables, which are different for the different evolution models, the temperature sensitivity μ^* is computed using $t^* = 1927$ as equilibrium year and no mass balance residual ($\beta^* = 0$). This corresponds to the reference year for the flowline model and is not too far off from the reference year for the VAS model (which is 1905).

Both evolution models run for 3'000 years with the 'ConstantMassBalance' model and for 10'000 years with the 'RandomMassBalance' model, both initialized around 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 negative and a positive mass balance run, 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 runs are a useful tool to asses the behavior of glacier models. The OGGM provides two convenient mass balance models (or rather climate scenarios) for equilibrium experiment, the `ConstantMassBalance` model and the `RandomMassBalance` model. The implementation and workings of both mass balance models are described in Section 2.2.

The experiments are performed on all alpine glaciers using the HISTALP dataset (Auer and Böhm 2007) as climatic input data. Thereby, each mass balance model runs three times. One run is under equilibrium conditions, i.e., using the climatic conditions around the *equilibrium year* t^* for each glacier. The other two runs are under a positve and negative mass balance perturbation, accomplished by a temperature bias of $-0.5\,°\mathrm{C}$ and $+0.5\,°\mathrm{C}$, respectively.

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. 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 Constant climate scenario

3.1.2 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.

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.

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.

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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.
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.
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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.

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.