Glaciology lab: Bed inclination and surface mass balance with OGGM

Lab report 2

[redacted]

Introduction

"All models are wrong, but some are useful" (Box and Draper, 1987).

Numerical models in glaciology are either diagnostic, to understand glaciological changes and processes that impact the systems that the glaciers are in, such as hydrology, climate and ocean, or prognostic, to generate historical profiles or future projections to facilitate better understanding of glacier processes across time scale for decision making. A question that a diagnostic model could ask is: how does slope impact annual mass balance of maritime glaciers? A question that a prognostic model could ask is: what is the pattern of advancement and retreat of Echaurren Norte glacier in the Andes in the next century?

In this lab, we are going to use numerical models to investigate bed slope, equilibrium line altitude and mass balance gradient impact glacier changes over time. A theoretical relationship exists between the length (L) of the glacier, its equilibrium line altitude (E) and the slope of the glacier bed (s).

$$\frac{\partial L}{\partial E} = \frac{2}{s}$$

Equilibrium line altitude (ELA) is a line or an area on a glacier where accumulation balances ablation and annual mass balance is zero. It is often used as a single-number stand-in for the local climate. Theoretically, if ELA remains constant, the length of the glacier decreases as its slope increases, and vice versa. This could imply that glacier volume decreases along with its length as the slope increases. Alternatively, if the slope remains constant, glacier length and volume decrease as ELA increases, and vice versa. Increase of ELA results in smaller region of accumulation and greater region of ablation. Glacier retreats. Decrease of ELA results in smaller region of ablation and larger region of accumulation. Glacier advances. The relationship between mass balance gradient and the glacier processes over time is still unknown.

Open Global Glacier Model (OGGM) is an open course modeling framework that can be run locally or on remote servers. It is used to simulate past and future glacier mass-balance with different volume and geometry, and glacier metrics such as hydrological output. OGGM allows us to simulate the advancement and retreat of a theoretical glaciers with predetermined metrics such as bed slope, bed geometry, height and equilibrium line altitude. In this lab, we ran OGGM models with Jupyter notebooks on the JupyterLab that is maintained on a cluster at the University of Bremen to access. The Jupyter notebook environment allows us to run code, create visualizations and include markdown notes in one contained notebook. This facilitates model execution for educational purposes.

Methods

Experiment 1 – Simulating Ice on Different Inclines

1. How did you define the geometry of the bed?
2. What were the initial settings for bed shape and glacier width? What new settings did you try?
3. How did you define the mass balance?
4. What method must we use to study the glacier change over time?

Experiment 1 investigates the relationship between bed slope and glacier change over time. We set up the experiment by first defining the geometry of the bed. We defined the resolution of our idealized glacier with 200 grid points with 100 meters of grid spacing (map_dx). We used Rectangular Bed Flowline model from oggm.core.flowline to define a linear bedrock profile from top to bottom in a rectangular shape (fig 1). We supplied the model with four parameters – surface_h, bed_h, widths and map_dx. Both surface_h and bed_h are arrays of 200 equally spaced grid points from elevation peak (3400m) to the bottom (1400m) of the idealized glacier of slope 0.1. Variables surface_h and bed_h of our idealized glacier has the same values because ice thickness is zero initially. Widths is an array of widths of 200 grid points. We defined our glacier width to be 300 meters. Map_dx is the grid point spacing that we defined, which is 100 in meters.

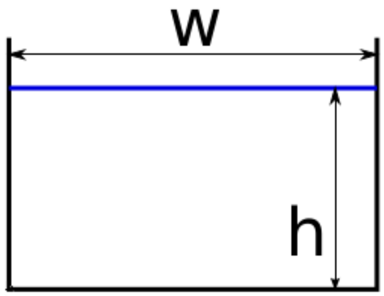

Figure 1: Rectangular bed cross-sectional illustration from OGGM documentation

We then defined the mass balance with Linear Mass Balance model from oggm.core.massbalance. We supply two parameters to the model, equilibrium line altitude which we defined as 3000 meters, and mass balance gradient which we defined as 4 millimeters per meter. This defined model gives us mass balance on the glacier at any given altitude (fig 2).

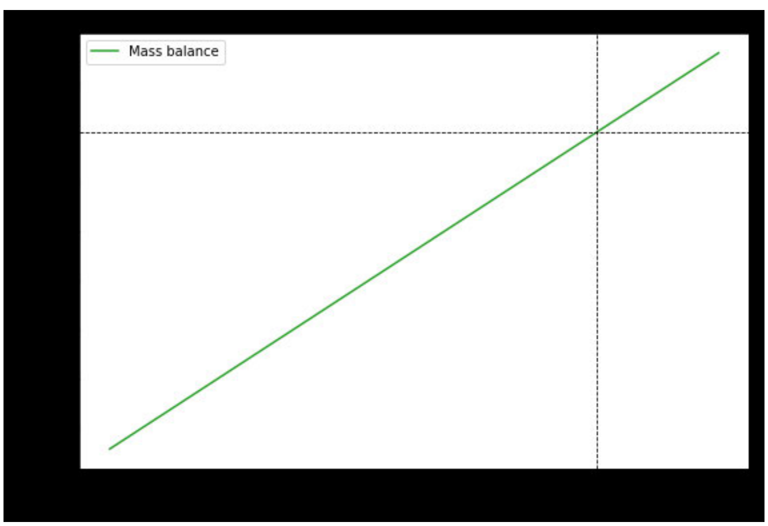

Figure 2: Annual mass balance at any given altitude in the linear mass balance model

With Rectangular Bed Flowline and Linear Mass Balance models defined, we were ready to simulate the advancement of our idealized glacier. We supplied our existing models to Flux Based Model with some default options from oggm.core.flowline. Now we can provide our model with different runtimes to find advancement of the idealized glacier over time.

To investigate the relationship between length of glacier and bed slope, we created two more Rectangular Bed Flowline models defined on bed slopes of 0.2 and 0.3 (instead of 0.1) with all other parameters remained the same. In order to compare the three idealized glaciers with different bed slopes over time, we ran all models from year 0 to year 600 with equal spacing of 5 years (using a for loop). We stored the length and volume of the idealized glaciers with different bed slopes at each time stamp and visualized the change of length and volume over time.

Experiment 2 – Mass Balance

1. What mass balance parameters did you vary, and what is their physical meaning?
2. How did you vary the parameters in the model?

As described in experiment 1, two parameters determine the Linear Mass Balance model, equilibrium line altitude and mass balance gradient. Experiment 2 investigates the relationships between these two variables and glacier change over time. We first set up glacier bed using the Rectangular Bed Flow model in the same way with the same parameters as in experiment 1 (slope is chosen at 0.1).

We first investigated how changes in equilibrium line altitude (ELA) impact glacier change. As described in the introduction, ELA is often used as the single number substitute for the local climate. Glacier region above the ELA is the accumulation zone, the region below it is the ablation zone, while accumulation balances ablation on equilibrium line altitude (fig 3). ELA changes indicate a change in the local climate. If ELA increases, it can be expected that warmer climate or decrease in precipitation creates a more favorable environment for ablation, as glacier loses more mass from processes such as melting, frontal ablation and sublimation than before. If ELA decreases, it can be expected that colder climate or increase in precipitation creates a more favorable environment for accumulation, when glacier gains more mass from processes such as solid precipitation, basal freeze-on and avalanching than before.

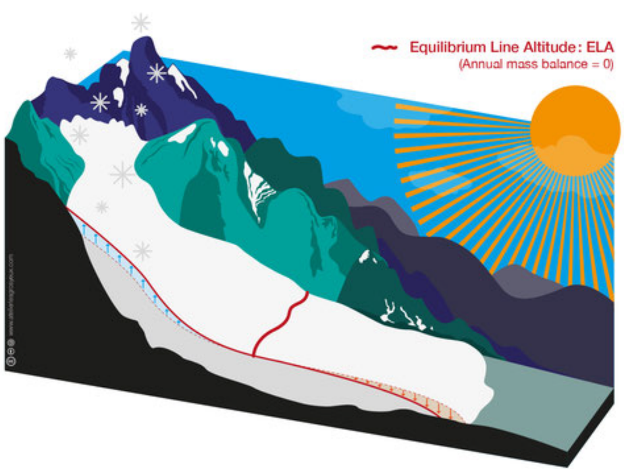

Figure 3: ELA diagram, Anne Maussion

We created three mass balance models with different ELAs at 2700 meters, 3000 meters and 3200 meters with the same mass balance gradient at 4 millimeters per meter. Three different Flux Based Models are created based on these mass balance models, and we ran all of them for 600 years.
Similarly, we selected different mass balance gradients (MBGs) to investigate its impact on glacier change. Mass balance gradient is the change in mass balance of the glacier with altitude. Greater mass balance gradient indicates greater accumulation and ablation of a glacier, while smaller mass balance gradient suggests less accumulation and ablation (fig 4). Continental glaciers tend to have smaller mass balance gradients than maritime glaciers. Orographic lift occurs when warm air from the ocean encountering a

mountainous terrain is forced to rise. The air quickly cools down at the higher elevation to form heavier water droplets. The humidity in the air greatly increases likelihood of precipitation. As a result, maritime glaciers are situated in a relatively warm climate with higher precipitation, allowing for greater ablation and greater accumulation, thus larger mass balance gradient. In contrast, cold and dry regions implicate continental glaciers with smaller ablation and accumulation, thus smaller mass balance gradient.

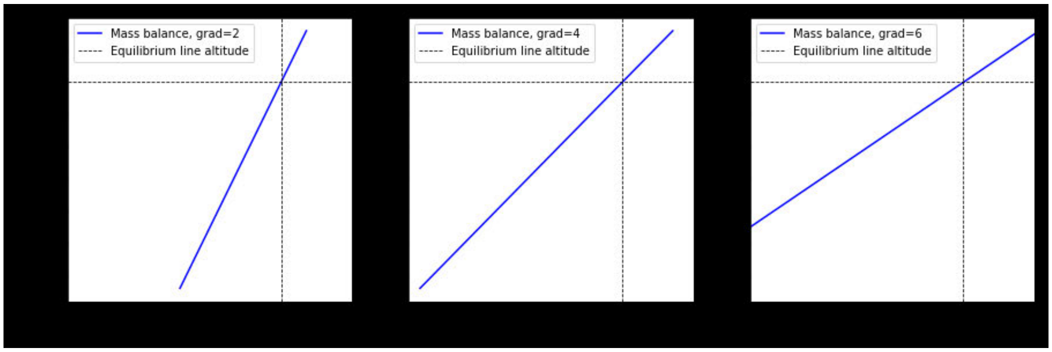

Figure 4: Altitude over annual mass balance for MBG of 2, 4 and 6

We created three Linear Mass Balance Models with different mass balance gradients at 0.3 mm/m, 4 mm/m and 5 mm/m, with the same ELA at 3000 meters. Again, three different Flux Based Models are created based on these mass balance models, and we ran them for 300 years.

For both scenarios, investigating ELAs and MBGs, we created figures of altitude over annual mass balance and figures of altitude over distance along glaciers (glacier side profiles) to compare glacier changes over time with different ELAs and MBGs.

Results

Experiment 1

1. How does the final length of the glacier depend on bed slope?
2. How does the pattern of glacier growth over time depend on bed slope?

Before the glacier reaches the equilibrium line altitude, accumulation accounts for all of mass balance, so we can see a drastic increase of glacier length in the first few years in the simulation (fig 5). Afterwards, the length of the glacier remains constant for a few decades, as the glacier is very thin and the portion of the glacier beneath ELA melts off and is replenished from the accumulation zone constantly. After the glacier accumulates enough depth, it starts to a steady increase in length (fig 5). Unlike length, glacier volume increases in a smooth curve. Both length and volume change in idealized glaciers stops after a certain amount of time.

The three idealized glaciers with different slopes follow similar patterns of glacier growth over time. As slope increases, final length and volume of the glacier decreases. The glacier with smaller slope has greater length increase in the first few years, longer periods of length stagnancy afterwards and greater slope of length increase over time. Similarly, glacier with smaller slope has greater slope of volume increase over time.

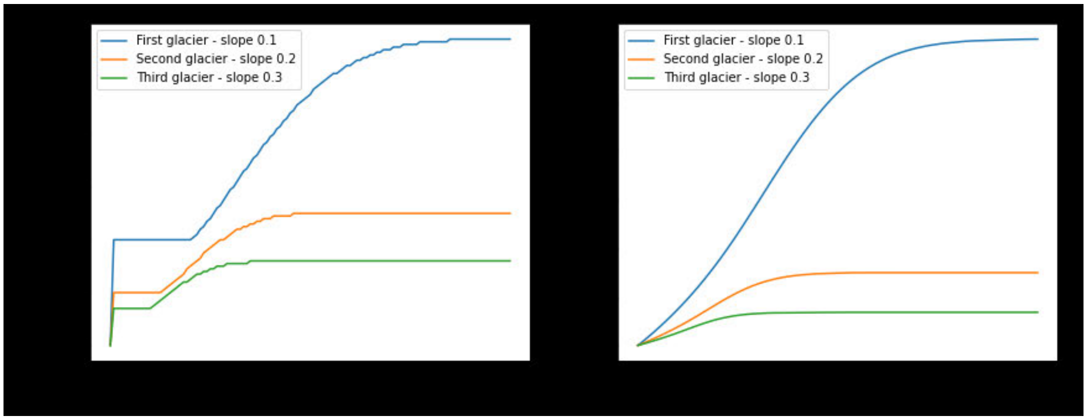

Figure 5: Idealized glacier length and volume change over time with slope 0.1, 0.2 and 0.3

It is worth noting that glacier of slope 0.1 has a much greater increase of length and volume from glacier of slope 0.2, than increase of glacier of slope 0.2 from glacier of slope 0.1. 0.2 is two times the amount of 0.1, while 0.3 is only 1.5 times the amount of 0.2. There is a greater effective change from 0.1 to 0.2.

Experiment 2

1. How does the shape of the glacier depend on the equilibrium line altitude?
2. Let's consider two glaciers with the same ELA, but one with a large mass balance gradient and one with a smaller mass balance gradient. Which one should we expect to store more water?

There exists an inverse correlation between equilibrium line altitude and glacier change. Greater ELA renders smaller glacier growth and smaller ELA correlates with larger glacier growth. The glacier has higher ratio of positive annual mass balance over negative annual mass balance with smaller ELA, so it has larger zone of accumulation (fig 6). From side profiles of idealized glaciers, glaciers with different ELAs have similar shape but at different scales. Glaciers with larger ELAs are thicker and longer, and vice versa.

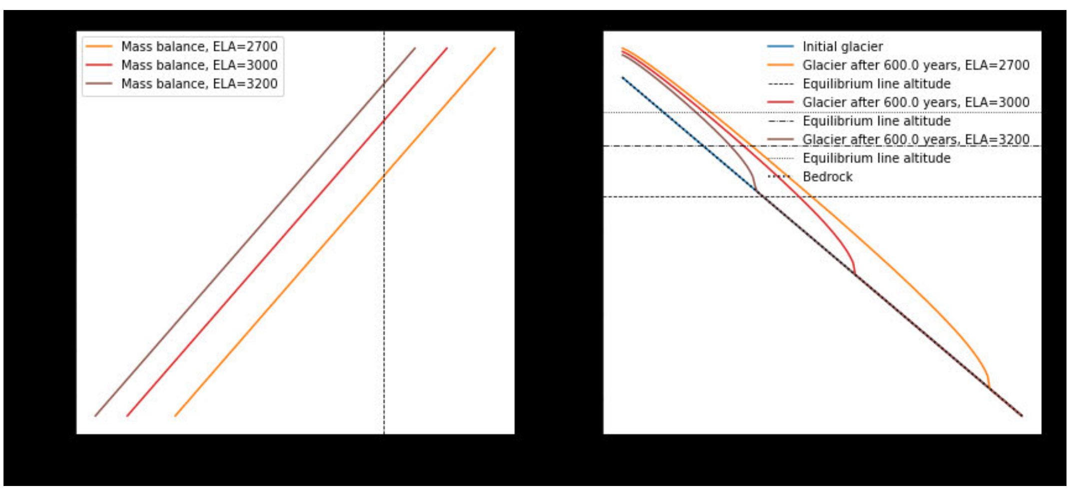

Figure 6: Glacier changes over time with respect to equilibrium line altitude

Glaciers with the same ELAs but different mass balance gradients have the same ratio between the area of accumulation and area of ablation, but different scale of annual mass balance. With larger mass balance gradient, glaciers have higher rate of accumulation and rate of ablation (left panel of fig 7). As a result, glaciers with higher mass balance gradient are thicker and longer, with more volume (right panel of fig 7).

Resultingly, it can be anticipated that such a glacier would have more water storage capacity than one with lower mass balance gradient and smaller length and volume (table 1).

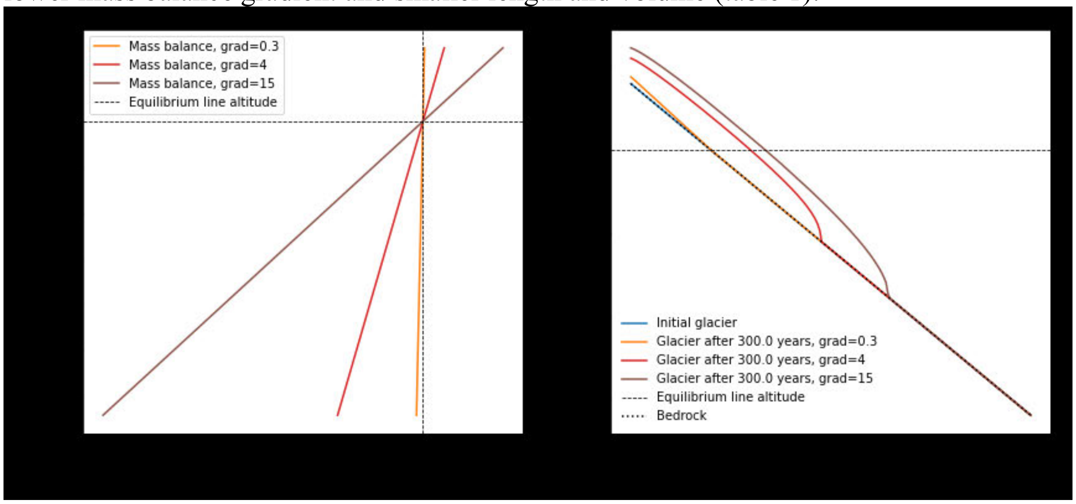

Figure 7: Glacier changes over time with respect to mass balance gradient

	MBGs	length	volume	equivalent water
0	0.3	4000.0	0.025744	2.316948e+10
1	4.0	9500.0	0.521354	4.692187e+11
2	15.0	12900.0	0.941441	8.472969e+11

Table 1: Water storage of idealized glaciers with different mass balance gradients

Discussion

1. Compare and contrast the numerical glacier in OGGM with the goo glacier you observed in the lab.
2. What is simulated in OGGM that was not included in the goo glacier?
3. How might a real glacier differ from what you have simulated in this experiment?
4. What insight can you gain by combining these OGGM experiments with your goo glacier experiments?

In a previous experiment, we used goo glacier on PVC pipe to model glacier flow on an incline. Goo glacier and OGGM are different types of modeling. The experimental procedures of this numerical lab are similar to those of the goo glacier. In both experiments, glacier beds are set up, and then we supply “ice” by either dropping glacier goo or starting model run (ice addition is incorporated in the model). Experimental results are recorded either by noting down the time passage and taking pictures and videos, or by storing values of key variables in Python arrays at regular time stamps. In both experiments, different experimental glacier bed slopes were used, either with different inclines of the PVC pipe or by supplying different slope to the model.

However, the glacier goo experiment and numerical modeling are fundamentally different types of modeling. Glacier goo creates the experience of simulating glacier movements with real-life objects, facilitating the development of physical intuitions about glacier flow. In contrast, numerical modeling provides the benefit of visualizations of abstract concepts and procedures. It is proven that numerical modeling has a lot of benefits over real-life object simulation. The glacier goo is fundamentally a different material from the glacier ice. The flow of glacier goo happens in the order of minutes, while actual glacier changes in the order of hundreds of years. In our lab, though our model only ran a few seconds on our laptops, it is representative of hundreds of years of glacial changes with the volume and length of the glacier accounted for at each year. Contribution of ablation and accumulation to annual mass balance is also incorporated in numerical simulations but not in the glacier goo experiment (by which the annual mass balance of the glacier is assumed constant). The Linear Mass Balance model defined by equilibrium line altitude and mass balance gradient allows local climate of the glacier be quantified and incorporated into the model.

However, the idealized glaciers simulated in this experiment still differ from real-life glaciers. The simulation leaves out multiple variables such as local climate variations, debris coverage, particular ablation processes such as avalanching and local variations on the glacier. Real glaciers are a lot more complicated with a lot more factors to consider. The rectangular bed geometry that we defined is not realistic and cannot be reasonably applied to all glaciers. Despite the limitations of glacier goo model and numerical simulations, their combination allows experimenters to be able to develop physical intuitions about glacier flow as well as numerical understanding of fundamental variables governing glacier bed geometry and local climate. It is identified that all models lack the complexity of real-world systems, and different models are suitable for experiments of different purposes. A combination of different models serves best at explaining a complex system.

Conclusions

Numerical modeling assists in understanding of glacier processes and future projections. Glacier flow processes is fundamentally influenced by glacier bed geometry and local climate. Three major variables, slope, equilibrium line altitude and mass balance gradient, are investigated in this lab. Glaciers with larger slope haver shorter final length and volume. With smaller equilibrium line altitude, glaciers can grow longer and thicker because there is more accumulation and less ablation. With smaller mass balance gradients, glaciers tend to be shorter and thinner, with less water storage capacity, since there is less contribution of both accumulation and ablation to its mass balance.