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GEOL 362Z
Nov. 13, 2021

Lab Number 4: Modeling Glacier Water Resources with OGGM

Abstract

This lab differs from previous ones as we set out model runs to simulate a real glacier under multiple climate scenarios. The goal of this lab is to investigate how annual and seasonal glacial runoff changes in changing climates. To achieve this, we used Open Global Glacier Model to simulate random climate model runs for 300 years and provided the model run with different temperature bias. We compared the change of volume, length, and water storage of the simulated glacier over time among different scenarios. To achieve balance with the climate, the glacier experiences increase or decrease in its length and volume as it gains or loses mass over time. The change in water storage overlaps after the glacier reaches equilibrium whether the glacier increases or loses mass under the climate scenario or not. This means that glaciers under colder climate experience more pronounced seasonal changes as they produce more runoff during wet season. These results correspond with what we know about glacial mass balance. Glaciers in colder climate are longer and thicker so more glacier mass resides in the ablation zone, resulting in more glacial runoff. Our results provide useful information for understanding glacial runoff under different climates.

Introduction

In previous labs, we worked with idealized glaciers with simply shaped flowline model and linear mass balance model to explore theoretical questions about glaciers. In this lab, we conducted experiments on a real-life glacier to investigate how annual and seasonal glacial runoff changes in a changing climate.

We used Open Global Glacier Model (OGGM), the same open-sourced model developed in Python used in previous labs. It is beneficial to use OGGM for the purpose of this lab because OGGM has built-in pipeline to access historical glacier outline data in model runs. OGGM also provides the function to run a random mass balance model for a given number of years with options to provide a temperature bias.

We chose the Hintereisferner Glacier which is from northern hemisphere at mid-latitude region. Hintereisferner glacier is a clean-ice valley glacier located in Central Eastern Alps, Austria (Fig 1). It is a reference glacier classified by World Glacier Monitoring Service, meaning that it has a long history of measurements and observations, and glacier fluctuation is mainly driven by climate factors instead of other influences such as calving, surge dynamics or heavy debris coverage (WGMS, 2018). This makes Hintereisferner suitable for studying the effect of changing climate on glacier runoff change. Hintereisferner is also a reference glacier with OGGM and is often used as the sample glacier in OGGM tutorials. This is helpful for us because we know its digital outlines and climate output data are available. The climate of Hintereisferner is characterized by dry inner alpine climate with low precipitation during winter and high precipitation in summer (Wijngaard et al., 2019).

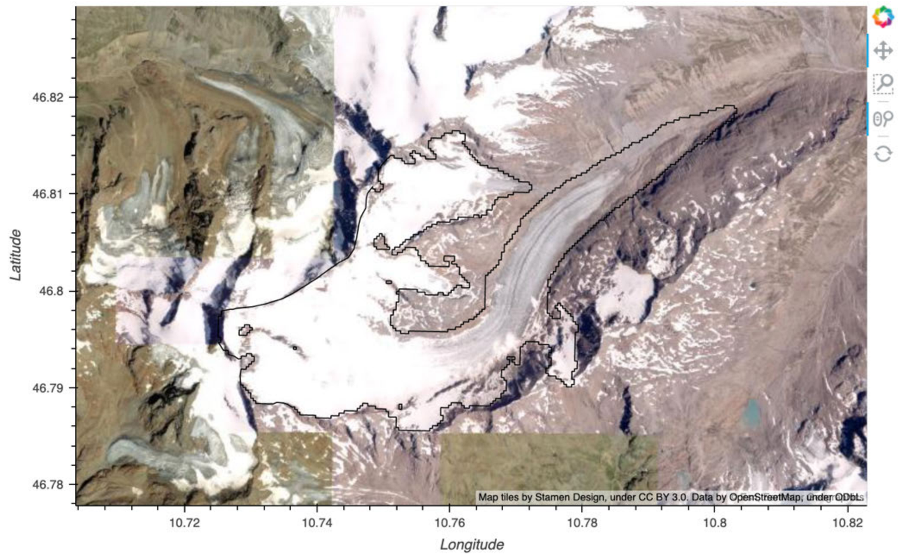

Figure 1: Map view of Hintereisferner Glacier, Central Eastern Alps, Austria

Methods

We start the lab with preprocessing process that initiates a new list of glacier directories, which we reference using variable *gdir*, for this model run using OGGM's *workflow.init_glacier_regions* function which downloaded the digital outlines into *gdir*. We then invoked *tasks.init_present_time_glacier* function to create a stand-alone numerical glacier ready to run using data in *gdir*. Checking the RGI date of glacier outlines tells us that the "present"/initial date of the glacier is from 2003. This means all future projected change of the glacier will be developed based on the initial glacier state from 2003. To get a better sense of the glacier flowlines, we plotted the centerlines of the glacier (Fig 2). This setup is different from a that of a theoretical simulation. Instead of supplying a theoretical flowline model such as Rectangular Flowline model and a theoretical Linear Mass Balance model, we supplied neither to the real glacier. Instead, the flowline and mass balance would be derived from historical data accessible through the RGI id.

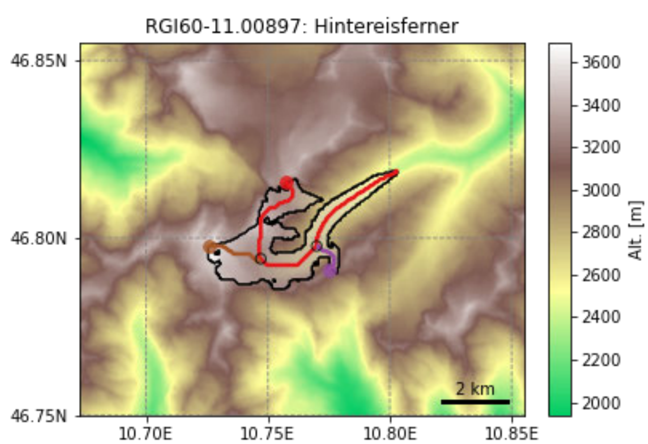

Figure 2: Centerline of Hintereisferner Glacier

With the glacier directories set up, we ran a simulation for 300 years using the function *tasks.run_random_climate*. This function runs the random mass-balance model for a given number of years by initializing *oggm.core.massbalance.MultipleFlowlineMassBalance* model. This means that based on the parameters we provided, the model ran for 300 years, each year randomly picking a mass balance model from the 30-year period 1985-2015, while storing model output monthly. The Multiple Flowline Mass Balance Model wraps a list of mass-balance models, one for each flowline from the 30-year mass-balance years. After the model run finished, we used *read_run_results* function to store simulation outputs into a temporary variable for analysis. We plotted glacier volume, length and change in water storage over time (Fig 3).

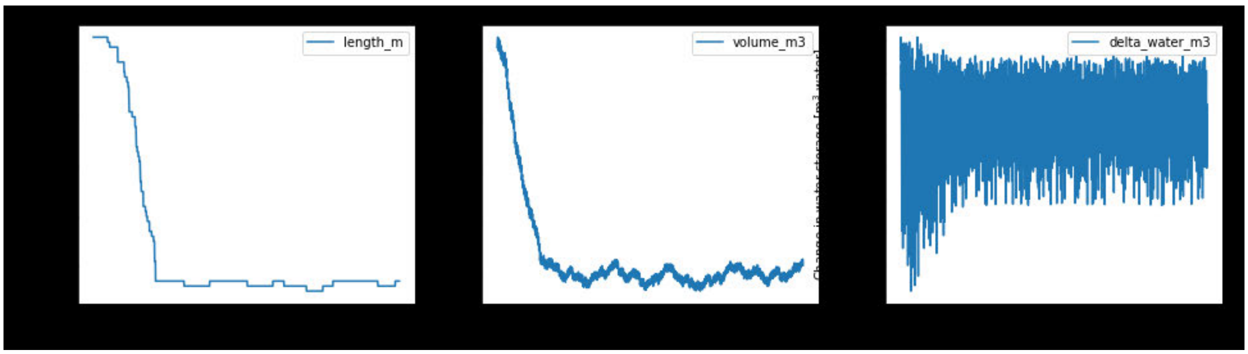

Figure 3: Glacier length, volume and change in water storage over time for a 300-year random mass balance simulation

To facilitate understanding of change in water storage over time, we calculated its annual sum and 30-year rolling average and overlayed the plot over top of one another (Fig 4).

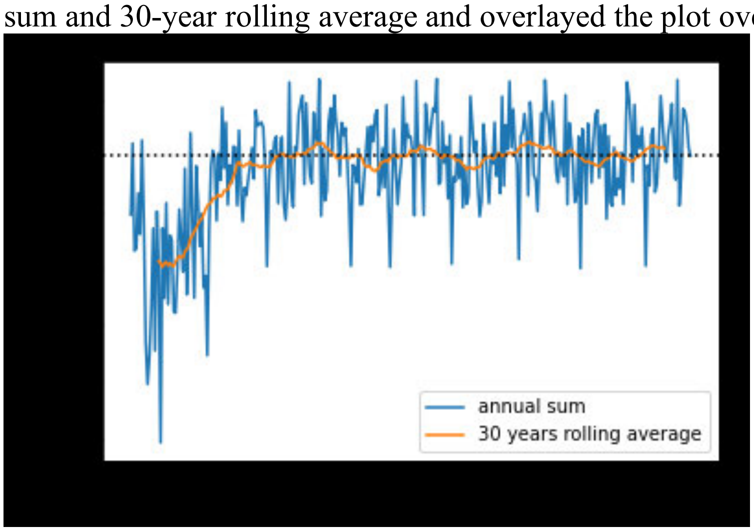

Figure 4: Change in water storage over time with annual sum and 30 years rolling average

Additionally, we plotted the annual cycle of water storage during retreat phase and at equilibrium, by obtaining the mean of each month of the year for the first 30 years and last 30 years of the 300-year simulation respectively.

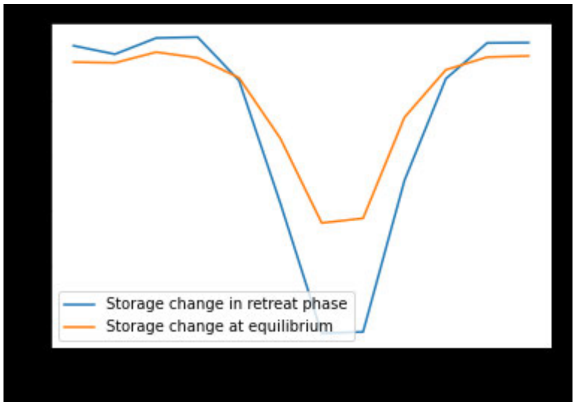

Figure 5: Annual cycle of water storage in retreat phase and at equilibrium

Using function *read_climate_statistics*, we read the annual cycle of climate for 1985-2015 at the glacier terminus elevation and plotted out three panels of water storage, temperature and precipitation over time.

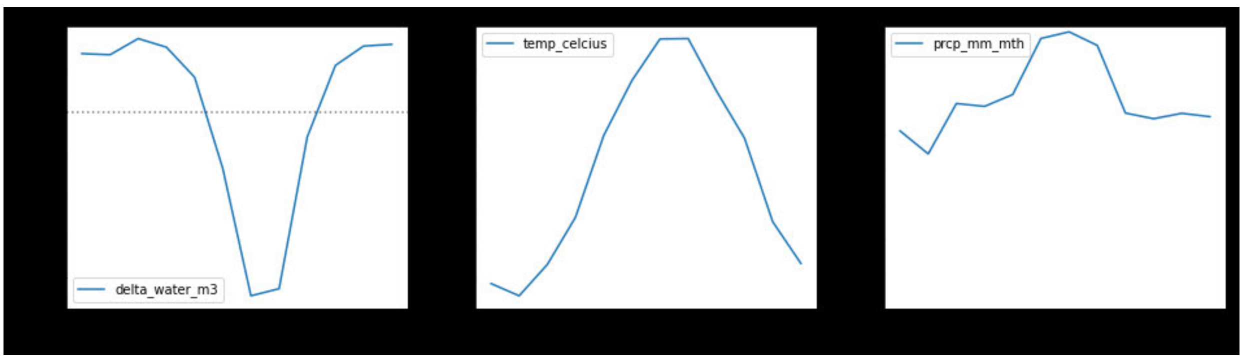

Figure 6: Climate context: change in water storage, temperature and precipitation across a year

After exploring the first simulation, we ran another simulation supplied with temperature bias. We again used the function *tasks.run_random_climate* with the same set of values for parameters that we used in the previous simulation, but we added a temperature bias of -0.8 °C timeseries (Fig 7).

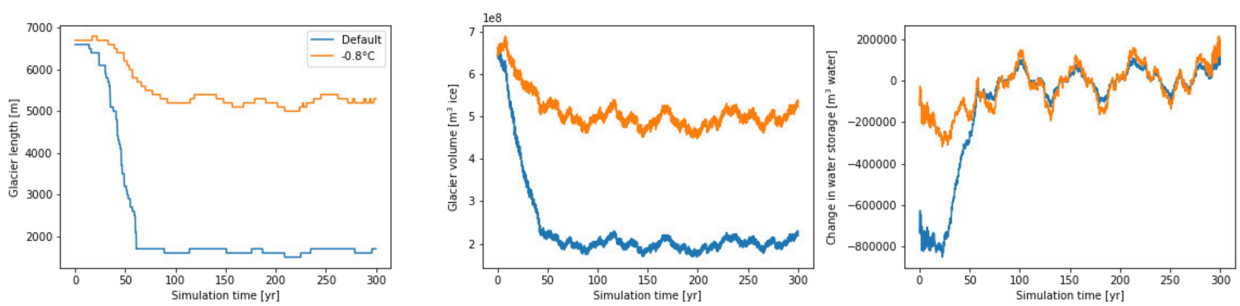

Figure 7: Comparison of glacier length, volume and change in water storage over time for a 300-year random simulation with default glacier and temperature-biased glacier

Interestingly, the glacier in colder climate is a lot longer but with similar change in annual water storage as the default glacier. To understand this, we overlaid the annual cycles of water storage change of default glacier and biased glacier on top of one another (Fig 8).

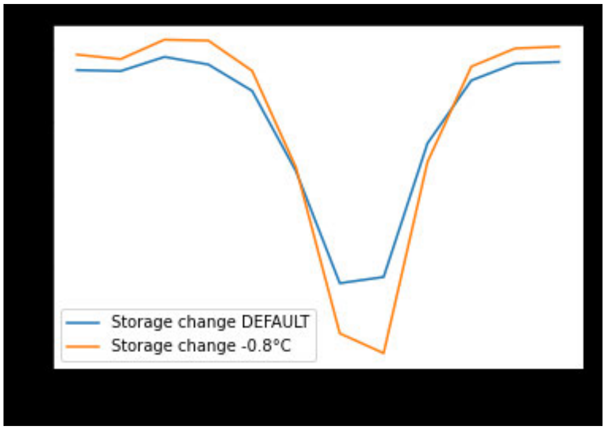

Figure 8: Annual cycle of water storage of default glacier and temperature-biased glacier

Results

During 300 years of simulation of Hintereisferner Glacier under default climate, the glacier experienced continued and sharp decrease in length and volume for the first 80 years roughly, and both length and volume reaches a level of equilibrium when they fluctuate in a relatively fixed interval (Fig 3). It takes longer, for about 100 years, for change in water storage to reach equilibrium. The change in water storage is negative at first, and then it experiences continuous increase until equilibrium (Fig 4).

The annual cycles exhibited by change in water storage, temperature and precipitation fit our expectation of northern hemisphere, mid-latitude climate, where glacier loss in water storage increases until August, and decreases until around May (Fig 6). Glacier melt is largest in summer months, when precipitation level and temperature are highest, smallest in winter months, when precipitation level and temperature are lowest.

By supplying a negative temperature bias to the simulations, we obtained glacier information under a colder climate in a period of 300 years. Under such a climate, the length and volume of glacier stabilizes sooner, and their values in the glacier under equilibrium are much higher than the glacier in default climate (Fig 7). In terms of change in water storage, the glacier in colder climate experiences much smaller change (decrease) in water storage in the first few decades of the simulation. The equilibrium level of change in water storage, however, overlaps greatly with the glacier in default climate. As a result, as the climate gets colder, its length and volume reach equilibrium at larger values, but its change in water storage eventually overlap with the projection of default glacier over time.

Discussion

To better understand the annual cycle of change in water storage, we plotted in figure 5 the comparison of water storage of the default glacier in retreat phase and equilibrium phase. The glacier loses a lot more water during retreat phase than during equilibrium phase during summer and gains more water in winter. During the retreat phase, the glacier loses more water than it gains as the glacier loses volume and length, and during equilibrium phase, the glacier gains as much water as it loses. Therefore, a glacier in equilibrium is not a net producer of water. This tells us that glaciers in retreat have different seasonal variations in runoff from glaciers in equilibrium. Retreating glaciers have more runoff during the wet season. This could mean that water supply increases downstream while a glacier retreats.

After analyzing figure 7, we were puzzled over the fact that change in water storage does not follow the same trends seen in length and volume change over time with temperature-biased glacier. To solve this puzzle, we plotted figure 8 to better understand the relationship between annual water storage of default glacier and colder glacier. The figure shows that colder glacier loses more water during the summer season and gains more water during the winter season, by which it maintains equilibrium water storage level as the default glacier. We analyze that the colder glacier is larger, thicker, and taller (given by its length and volume), and this means that more glacier ice resides in the accumulation zone during the winter season and amasses more accumulation. Similarly, more glacier ice resides in the ablation zone during summer season and produces more ablation. As a result, this produces small net difference between default glacier and temperature-biased glacier but divergence in their seasonality.

To further investigate the seasonality influence from climate, we used the same method of producing temperature-biased random climate simulation of 300 years with a bias of -1.6°C. We produced figure 9 to compare the behavior of default glacier, and two temperature-biased glaciers. The resulting plot confirms the trend we have witnessed, that change in volume and length tend to follow similar trends but change in water storage eventually converge with glaciers under different climate scenarios. With a -1.6°C bias, the glacier in imbalance with the climate conversely experiences increase in length and volume over time. In the first few decades, the glacier experiences decrease in water storage as the glacier's length and volume increase. At around the same time when the -0.8°C biased glacier's water storage projection overlaps with the default glacier, the -1.6°C biased glacier overlaps with the other glaciers. Figure 10 tells us that our rationale for such behaviors is still valid, when the -1.6°C biased glacier produces more runoff in summer and gains more mass in winter.

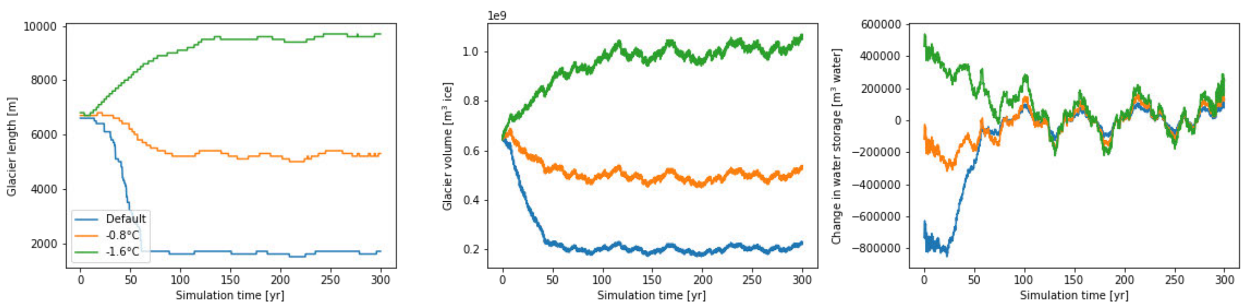

Figure 9: Comparison of glacier length, volume and change in water storage over time for a 300-year random simulation with default glacier and temperature-biased glacier of -0.8°C and -1.6°C

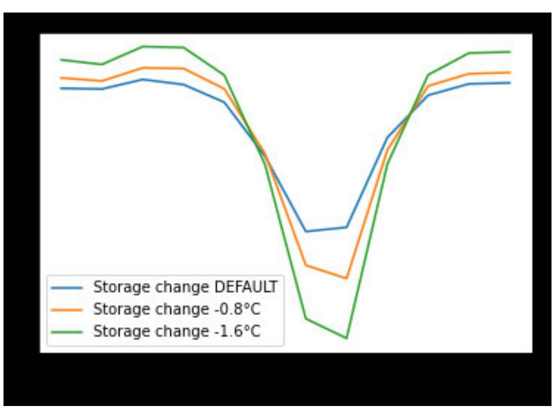

Figure 10: Annual cycle of water storage of default glacier and temperature-biased glaciers

Glaciers attempt to maintain equilibrium with the climate through gaining or losing mass. Glaciers under different climate scenarios have different seasonality. As the temperature gets colder, the glacier produces more runoff during wet season and gains more mass during dry season. This could mean that glaciers are able to produce more water supply downstream in colder climates.

By comparing observational data, measured annual mass balance, with annual mass balance produced from OGGM's mass balance model, we are able to assess model performance. Since Hintereisferner Glacier is one of the global reference glaciers classified by OGGM, OGGM provides a figure that compares OGGM's *Calibrated t_star* mass balance plot with measured annual mass balance plot from 1955 to 2015. The figure shows that the OGGM's mass balance model is fitting for the Hintereisferner Glacier, as the mass balance output from OGGM closely follows the measured specific mass balance over the years. The quality of performance of mass balance model depends on model physics that determines the type of glacier and climate that the model is best suited for and the mass balance data that the model is calibrated with. For example, OGGM's mass balance model is most likely to be best suited for Alpine glaciers under cold and dry climate, while being less fitting with Andean glaciers. To test this hypothesis, we can test OGGM's mass balance model on glaciers of different types, such as debris covered glaciers or marine terminating glaciers, in different climate, such as the tropics.

Reference:

Wijngaard, R. R., Steiner, J. F., Kraaijenbrink, P. D. A., Klug, C., Adhikari, S., Banerjee, A., Pellicciotti, F., van Beek, L. P. H., Bierkens, M. F. P., Lutz, A. F., & Immerzeel, W. W. (2019). Modeling the Response of the Langtang Glacier and the Hintereisferner to a Changing Climate Since the Little Ice Age. *Frontiers in Earth Science*, *7*, 143. https://doi.org/10.3389/feart.2019.00143

WGMS (2018). *Reference Glaciers for Mass Balance*. Available online at: https://wgms.ch/products_ref_glaciers/ (accessed November 14, 2021).