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Glaciers as water resources

Abstract

As glaciers retreat worldwide, runoff patterns are shifting to become less predictable and global water resources are strained. Glacier runoff is an important part of many hydrologic regimes because the maximum runoff often coincides with otherwise low flow or drought periods. In this experiment, we use OGGM to model the Columbia Glacier in Washington USA to determine how annual and seasonal glacial runoff changes over the next 300 years under different climate scenarios. We found that in the current 1985-2015 climate the glacier will retreat for 100 years before reaching equilibrium with a reduced length and volume. The climate would need to remain 0.8°C colder than the 1985-2015 average to sustain the 1958 length and volume of the Columbia Glacier. Our results show that the Columbia Glacier contributes the most runoff during the summer months and its peak water discharge has already passed.

Introduction

Global water resources are becoming increasingly unstable as glaciers retreat worldwide and future runoff patterns shift. Nearly one-third of the world's population lives in a drainage basin that is glacierized (Huss & Hock 2018). Glacier runoff oftentimes displays a distinct seasonality with maximum runoff during the melt season and minimum runoff during snow accumulation. With the potential for maximum runoff to occur during seasons of drought or low flow, glacier runoff acts as an important buffer to interannual variability, historically providing a reliable water source to populations in glaciated catchments.

As climate change results in warming temperatures, water discharge from glaciated catchments is expected to initially increase as glaciers start to recede before reaching peak water and then decreasing as glaciers melt away completely. Glacier retreat means changes to water supply, seasonality of supply, and water quality. Here I address how annual and seasonal glacial runoff changes in a changing climate using a model of Columbia Glacier in Washington, USA as a case study (Figure 1).

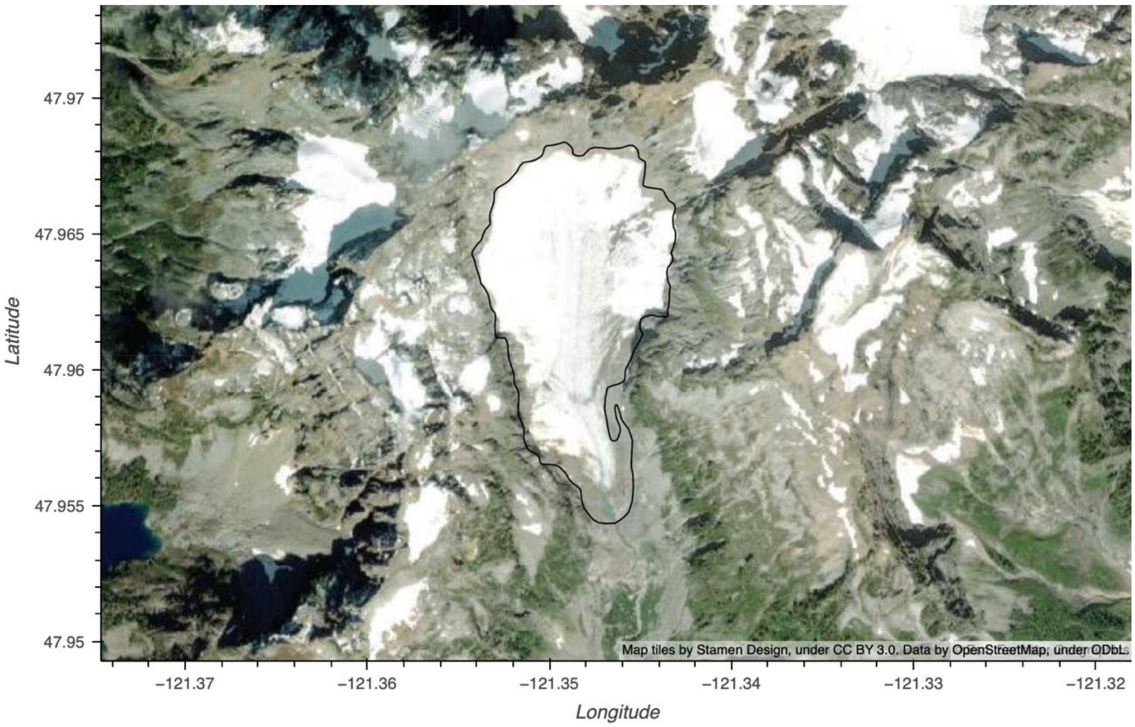

Figure 1. EsriImagery of the Columbia Glacier, Washington USA with the RGI outline of the glacier shown as the black polygon.

Numerical models are a useful approximation of processes that are difficult to directly observe and can help forecast future changes to water resources in the cryosphere. The Open Global Glacier Model (OGGM) is an open-source glacier model run in python. OGGM can model numerous glacier processes such as past and future glacier mass balance, changes in glacier volume and geometry, and different glacier water storage capacities. I employed OGGM to model changes in the water storage capacity of Columbia Glacier over the next 300 years in variable climates.

We used a Jupyter Hub maintained on a cluster at the University of Bremen to access and run OGGM. The Jupyter notebook environment allows GEOL362 students to run a simplified educational version of OGGM and modify parameters within the model code to investigate runoff from real glaciers in the Randolph Glacier Inventory (RGI).

Methods

We first imported the required modules to initialize and run OGGM using real glaciers as opposed to defining a theoretical glacier. To simulate the Columbia Glacier, we define it by its RGI ID: RGI60-02.18415. To visualize the glacier extent and RGI defined polygon we downloaded RGI glacier entity data for the Columbia Glacier, including the glacier outline from 1958. The glacier entity data essentially replaces the parameters we defined in previous labs such as glacier length, elevation range, bed slope (Figure 2).

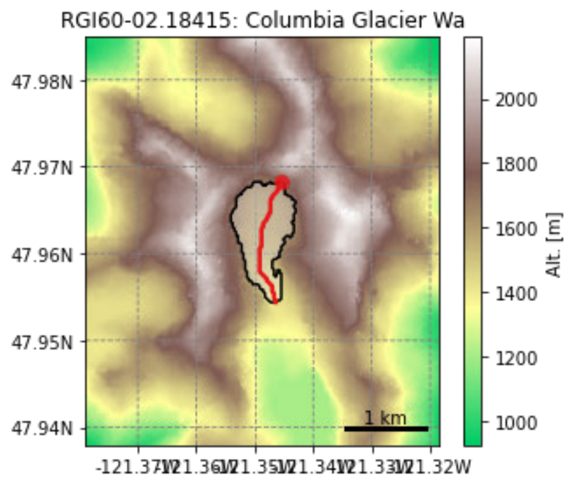

Figure 2. Glacier entity data the OGGM model uses for the Columbia Glacier, Washington USA. The glacier outline is shown as the black polygon with the main flowline displayed in red underlain by a hillshade of the surrounding terrain.

To prepare the model run we initialize glacier regions specific to the Columbia Glacier. Next, we run a random climate for 300 years changing the mass balance yearly, that uses randomly selected years centered around 2000 (1985-2015) and store monthly mass balance elevation feedback data. To explore the climate context for changing water resources we introduce a temperature bias of -0.8 °C. We rerun the model with the temperature bias, shifting each of the 300 years 0.8°C colder.
The model outputs glacier length (m), glacier volume (m^3 ice), and change in water storage (m^3 water) in monthly timesteps for the 300 year runs. To analysis change in water storage, we convert annual sums of change in water storage (m^{-1}).

Results

With random climates from 1985-2015 for the next 300 years, the Columbia Glacier retreats for the next approximately 100 years, losing about 1500 m in length and 4 m^3 of ice volume (Figure 3). As the glacier loses mass and volume, there is also a decreasing trend in the change of amount of water stored per year for slightly over 100 years before the 30-year rolling average sits at 0 m^{-1}, meaning there is no change in water storage (Figure 4). The retreat phase of the glacier is approximately the first 100 years of the model run, before the glacier reaches equilibrium for the remaining 200 years of the model run at a reduced length and volume.

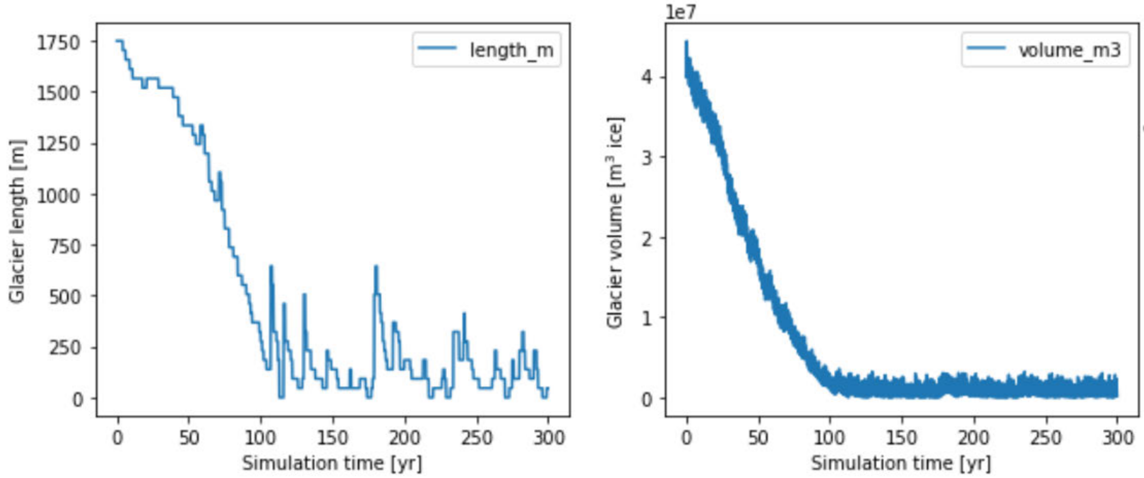

Figure 3. Change in the length (m) and volume (m^3) of the Columbia Glacier, USA over the next 300 years with random climates each year from 1985-2015.

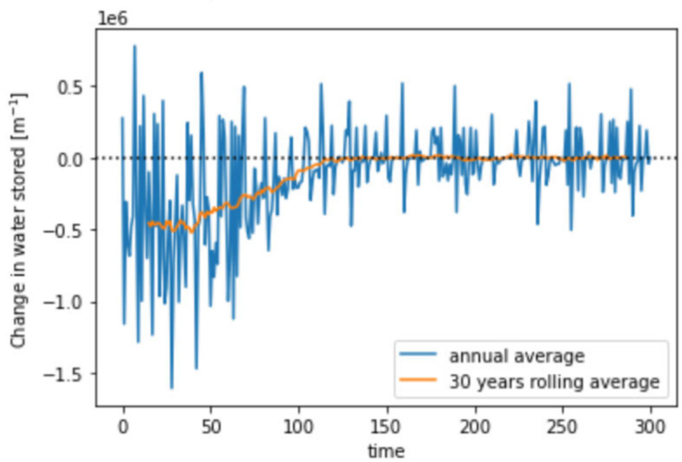

Figure 4. Change in water stored per year (m^{-1}) for the Columbia Glacier, USA over the next 300 years with random climates each year from 1985-2015.

On a yearly timescale, the Columbia Glacier gains water storage capacity during the accumulation period in the winter months and loses water storage capacity during the ablation period in the summer. While in the retreat phase, the change in water storage capacity during the summer is larger in magnitude than the change in water storage capacity magnitude during the winter. While in equilibrium, the net change in water storage capacity over the year is 0 m^3 (Figure 5). The most water lost from the glacier corresponds with the highest yearly temperatures, meaning the glacier is a source of water during the summer. Additionally, Columbia Glacier receives most precipitation during the winter months (Figure 6).

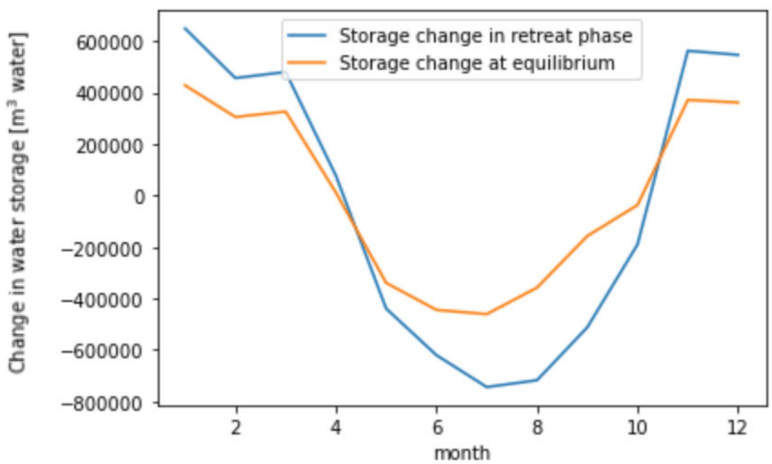

Figure 5. Change in water storage (m^3) over a year for the Columbia Glacier in a retreat phase and in equilibrium.

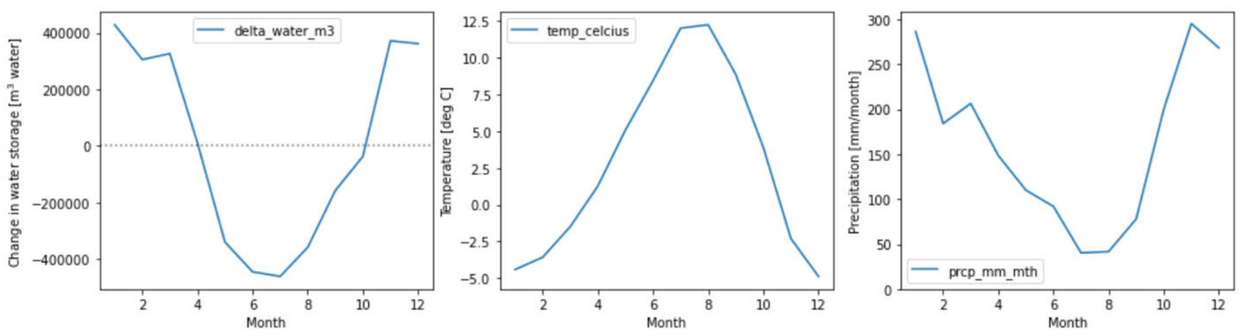

Figure 6. Change in water (m^3) over a year for the Columbia Glacier compared to monthly temperature (°C) and precipitation (mm) for the region.

For the Columbia Glacier to remain in equilibrium given the 1958 input conditions of the glacier the climate needs to be 0.8°C colder per year. If the climate were 0.8°C colder per year, the Columbia Glacier would maintain a length of approximately 1750 m and a volume of 4 m^3 of ice (Figure 7). Compared to the baseline 1985-2015 climate, the colder climate results in a larger change in water storage capacity from the winter to summer (Figure 8).

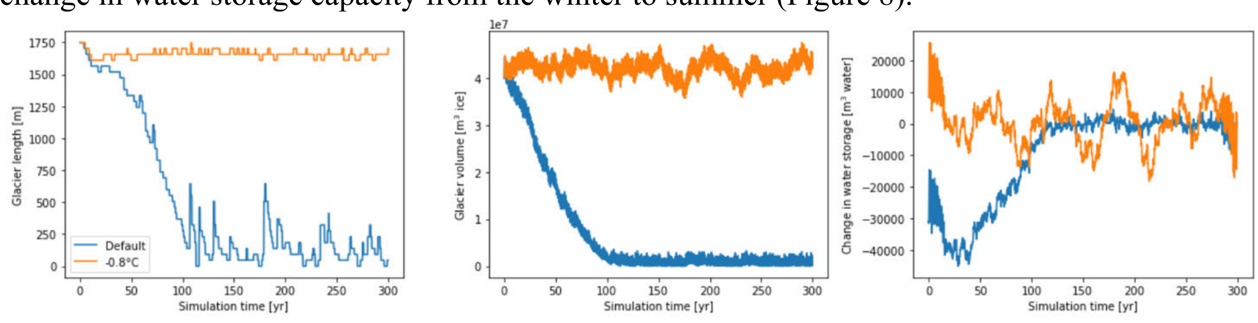

Figure 7. Columbia Glacier length (m), volume (m^3 ice), and change in water storage (m^3 water), in the current 1985-2015 climate (blue lines) compared to in a climate 0.8°C colder.

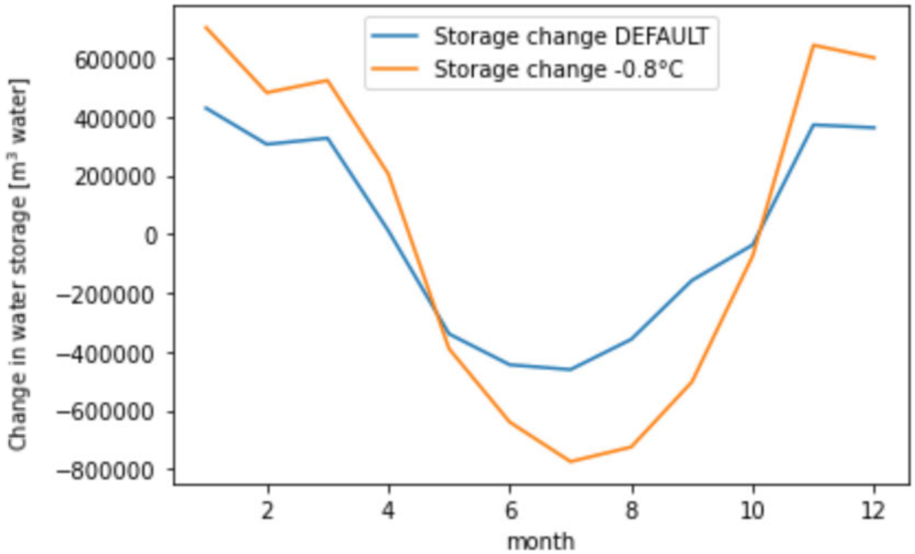

Figure 8. Change in water storage (m^3) over a year for the Columbia Glacier in the 1985-2015 climate and in a climate 0.8°C colder.

Discussion

The decreasing and then stagnant change in water stored over the 300-year model run indicates that the Columbia Glacier is already past peak water runoff. This has potentially significant implications for downstream populations that rely in some part on the meltwater from the glaciated catchment. Most of the precipitation the region receives comes during the late fall and winter, meaning that glacier runoff comprises a relatively higher percentage of runoff and stream flow than in a region where precipitation is high while glacial melt is high.

In this modeled scenario, we consider temperatures remaining at the same for the next 300-year period. However, given anthropogenic climate change, temperatures are expected to increase for over this timespan. Given this reality, the runoff and potential water storage capacity from the Columbia Glacier is likely to drop to 0 when the glacier becomes extinct with warming temperatures.

The accuracy of the OGGM mass balance model for Columbia Glacier can be compared against a field program that has measured annual glacier mass balance in situ since the early 1980s (Figure 9). OGGM is able to consistently replicate interannual trends in mass balance, but the magnitude of the mass balance is consistently lower than the physical measurements. In particular, two outlying extremely negative mass balance years, 2005 and 2015, are not captured in the model even after cross validation with the measured data. The outliers contribute to a worse performance of the model. If there was additional data available, such as water discharge, it would be useful to test the change in storage calculations against in situ data.

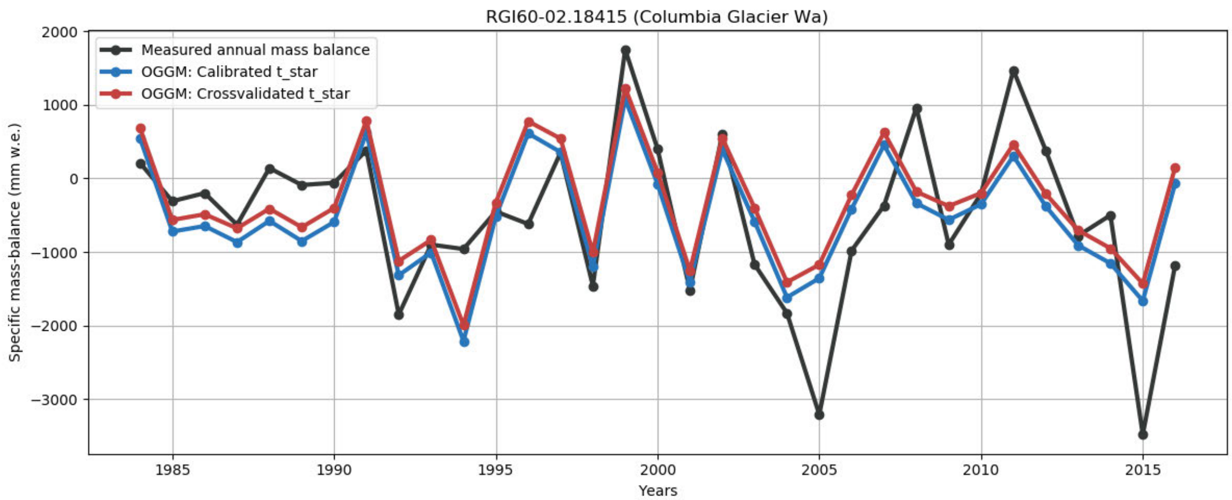

Figure 9. Specific mass balance (mm w.e.) over time for Columbia Glacier, Washington measured in situ and modeled using OGGM.

Conclusion

The OGGM model of the Columbia Glacier in Washington USA demonstrated in the current 1985-2015 climate the glacier will retreat for 100 years before reaching equilibrium with a reduced length and volume. The climate would need to remain 0.8°C colder than the 1985-2015 average to sustain the 1958 length and volume of the Columbia Glacier. The Columbia Glacier contributes the most runoff during the summer months, but its peak water has already passed. Overall, the OGGM model is in good agreement with in situ mass balance measurements, but does not capture outlying years with extremely negative mass balances.

References

Huss, Matthias, and Regine Hock. "Global-Scale Hydrological Response to Future Glacier Mass Loss." *Nature Climate Change* 8, no. 2 (February 1, 2018): 135–40. https://doi.org/10.1038/s41558-017-0049-x.