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GEOL 362Z
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Lab week 7: Glacier Surge Simulation

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Abstract

To better understand mechanisms that contribute to surging glaciers, we conducted literature review and experiments to simulate glacier surge cycles using Open Global Glacier Model. By modifying the values of Glen's creep parameter and sliding parameter, we learned how to use model parameters to influence model behaviors over an extended period. We identified basal sliding as the dominant factor behind surging glaciers, and by adjusting sliding parameter periodically, we are able to simulate surging cycles. We found that both length and volume of the glacier vary periodically but their cycles vary. We also found that adjusting Glen's creep parameter also produces surging glacier cycles, but this is unlikely the cause for glacier surge. This means that sometimes, experiments can produce expected results for the wrong reason.

Introduction

A small percentage of glaciers undergoes glacier surging, which is a type of short-lived events when a glacier advances significantly. A glacier surge period can happen every 1 to 15 years, and when the glacier surges, it can move at 10 – 1000 times its normal velocity. Despite the small percentage of surging glaciers, they are important for understanding of glacier processes and flow instabilities, thus suitable for the purpose of this lab.

The motion of glaciers is mainly determined by two flow mechanisms, internal deformation of ice due to gravity and basal sliding. In previous labs, we ignored basal sliding and assumed that the glaciers are frozen to the bed. In this lab, we conducted experiments to investigate the effect of both processes on glaciers through simulations of glacier surge cycles in order to understand how each mechanism contributes to the surging phenomenon.

Glacial processes of internal deformation and basal sliding can be described by two parameters, Glen's creep parameter A and the sliding parameter. Glen's creep parameter is a constant rate factor, denoted by A, that is defined in Nye's generalization of Glen's flow law (fig 1). It is widely accepted that A is an exponential function of temperature. The value of A also depends on ice temperature, crystal orientation, debris content and other factors (Van der Veen et al., 1990). Based on the constitutive relationship between strain rate and stress, a larger flow factor A corresponds to a larger strain rate, indicating greater extent of glacial deformation, while smaller flow factor in turn contributes to less strain rate and smaller degree of glacial deformation. Thus, simplistically, small flow factor indicates stiffer glacier and large flow factor indicates softer glacier.

$$\dot{\varepsilon}_{ij} = A\tau_e^{n-1}\tau_{ij}$$

Figure 1: Nye's generalization of Glen's law that defines the proportional relationship between strain rate and deviatoric stress. A is the flow parameter.

Sliding parameter is an idealized, representational parameter for basal sliding. Basal sliding becomes important when basal temperature (temperature at the base of the glacier) reaches pressure melting and basal water is produced, thus contributing to glacier flow. Many variables contribute to basal sliding, for example, basal drag, bed roughness and water pressure. A high value of sliding parameter indicates higher sliding velocity, while lower value indicates smaller sliding velocity. However, the mechanism of basal sliding is poorly understood because of the paucity of data and dynamism of basal conditions. The sliding parameter utilized in this lab is only one way representing basal conditions, and it is more important to investigate the relative difference of glacier flow with different sliding parameter, than the accuracy of glacial outputs.

It is widely agreed that basal condition is one of the main factors controlling glacier processes (Sevestre and Douglas, 2015). In the case of surging glacier Svalbard, the large contrast between calculated creep velocity and measured velocities suggests that basal motion, either sliding or sediment deformation, is the dominating factor for glacier flow during an active surging period (Murray et al., 2003). Therefore, in this lab, we focused on investigating the effect of sliding glacier on glacier surge cycle, in comparison with the effect of Glen's creep parameter.

We conducted the experiment using Open Global Glacier Model (OGGM), the same open-sourced model in Python used in the previous lab. In OGGM, both creep and sliding parameter have default values that do not need to be specified while defining a flowline model. In this lab, we changed the value of each parameter separately on an otherwise identical model run.

Methods

The process of setting up the model is similar to what we did in the previous lab. The glacier bed is defined by the Rectangular Bed Flowline model assuming a linear bed profile from top to bottom. The mass balance is defined by Linear Mass Balance model with equilibrium line altitude of 3000 meters and mass balance gradient of 4 millimeters per meter. After the initial setup, we learned how to modify each parameter by changing the values of creep and sliding parameters separately.

OGGM sets default Glen's creep parameter to be 2.4e-24. We used the default creep parameter value, initialized the Flowline model, and ran the model for 1500 years. We then stored the outline of the glacier as an array into a variable. To target the effect of creep parameter A, we created two new creep values by increasing or decreasing A by a degree of 10, 2.4e-23 and 2.4e-25. We used the new creep values and developed two new Flowline models for 1500 years (fig 2).

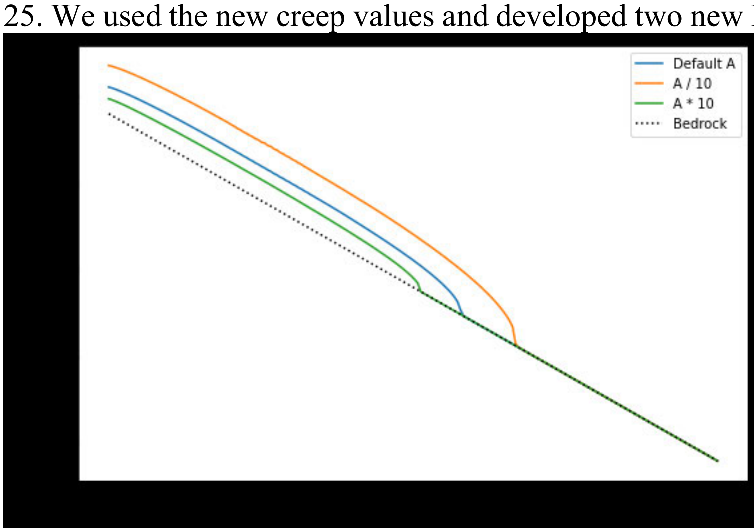

Figure 2: Glacier profile with different Glen's creep parameter values (2.4e-24, 2.4e-23, 2.4e-25)

Following the same procedure but changing the value of sliding parameter instead, we created figures to compare glaciers of different sliding parameter values (default at 0 and new value at 5.7e-20).

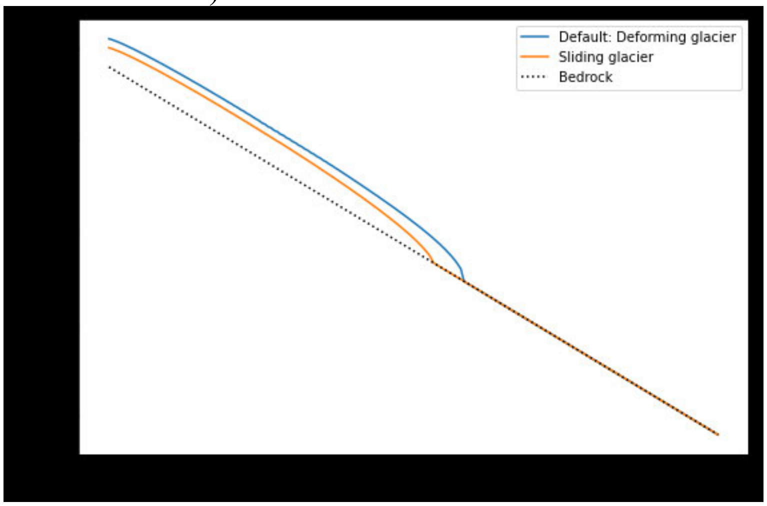

Figure 3: Glacier profile with different sliding parameter values (0, 5.7e-20)

After investigating both parameters, we were ready to simulate glacier surge cycle. A new model is reinitialized with the same Rectangular Bed Flowline model and Linear Mass Balance model with the same parameters above. We also provided original values of both parameters, Glen's creep parameter at OGGM's default and the sliding parameter at 5.7e-20, to the new model. We set surge-multiplier at 10, meaning that the original parameter values are increased 10 times during surging period. Next, we set the surging period to be 10 years, time span between surging periods to be 100 years and 10 number of surges. Based on these criteria, time steps that the model will be run on are generated from year 0, starting with 100 years of normal non-surge period divided into 10 periods of 10 years, followed by 10 years of surge period divided into 10 periods of 1 year, followed by non-surge and surging periods periodically until year 1200.

With the model initialized and time steps set up, it is time to set up the procedures of surging experiment. We allocated three empty arrays, length_surge, volume_surge, surging_glacier_h, to store the length, volume, and surface height of the glacier at every time step. Since we know the basal sliding is the dominating factor for glacier surge, we need to modify sliding parameter during surging period. This means that the model needs to be re-initiated with different sliding parameter during surging period, while preserving the information about glacier outlines from previous years' model run. We achieve this by running a for loop over all the time steps. For each year, we run the model until the specified year and save the length, volume, and surface height of the current state. Then we check the conditions to re-initialize different models with different parameters. If the current year is the year before a surge period, we re-initialize the model with the sliding parameter during surge. If the current year is the year before the non-surge period, we re-initialize the model with the original sliding parameter. All models reinitialized are fed with an instance of Rectangular Bed Flowline model from the previous time step, thus preserving the information from previous model runs.

We then conducted the above experiment with surge-multiplier at 20.

Results

The investigation in previous labs shows continuously increasing length and volume over time for a glacier. However, by changing the sliding parameter during the surging period, glacier's length and volume change becomes cyclical after a certain number of years (fig 4 and 5).

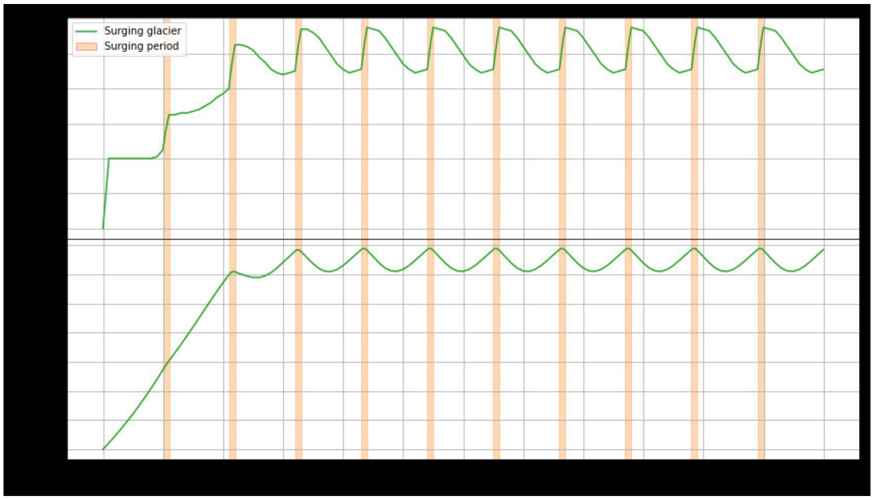

Figure 4: Fluctuation of length and volume of the idealized surging glacier, rendered by adjusting the sliding parameter with surging multiplier as 10. The yellow vertical bars denote surging periods.

For the initial 100 years, the length and volume change of the glacier resembles that of a normal glacier (described in previous lab). The idealized glacier hits its first surging period at year 100 and experiences increased rate of change in length and unnoticeable rate of change in volume. The glacier length and volume continue to increase until year 210, when the glacier experiences its second surging period, after which the glacier reaches its maximum length and volume during non-surging periods. Periodically, the glacier experiences drastic increase in length during the surging periods and slow decrease in length until its value resumes its previous value before surge. In contrast, glacier volume over time gradually increases and decreases, forming a shape of inverse parabola in between surging periods.

By applying larger surge-multiplier of value 20, the glacier experiences more pronounced fluctuations in both length and volume over time (fig 5). Interestingly, glacier length experiences decrease between year 100 and 200.

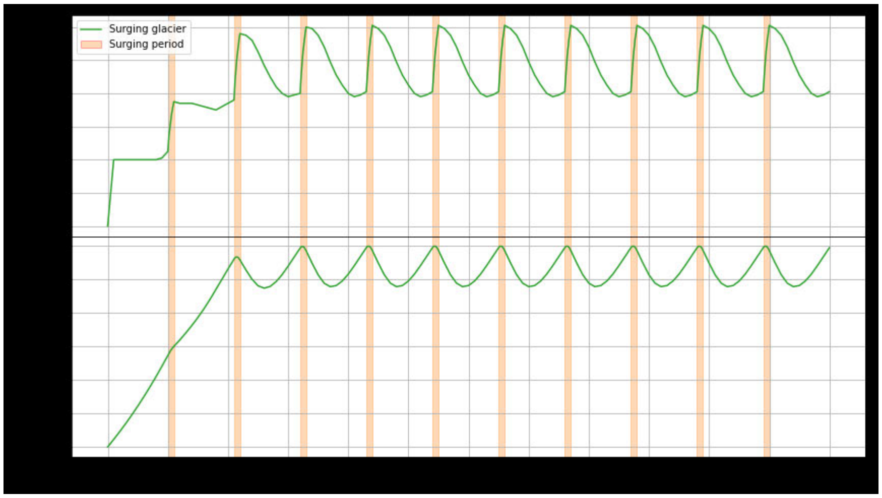

Figure 5: Fluctuation of length and volume of the idealized surging glacier, rendered by adjusting the sliding parameter with surging multiplier as 20. The yellow vertical bars denote surging periods.

The profile of a surging glacier does not resemble a non-surging one (fig 6). The deforming glacier with default parameters has greatest thickness, volume, and final length. The sliding glacier has medium thickness and volume but shortest final length. The surging glacier has smallest thickness and volume, but medium final length.

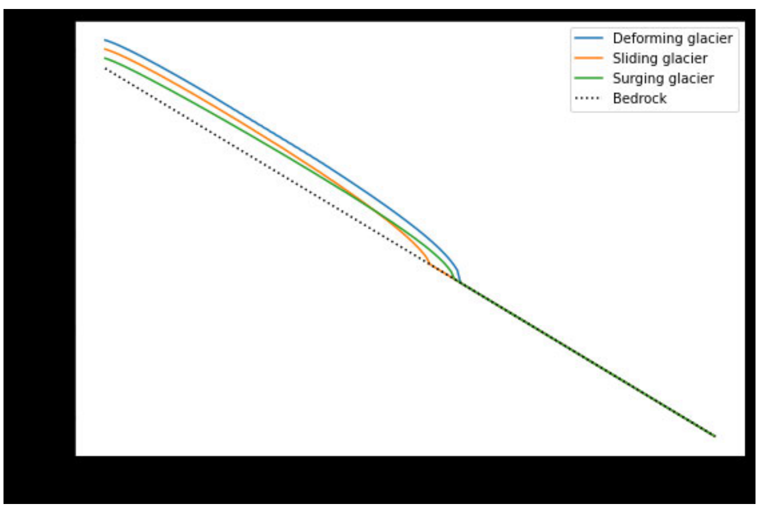

Figure 6: Glacier profiles at the end of model run. Deforming glacier is the one with default values; sliding glacier is the one with sliding parameter at 5.7e-20; surging glacier is the one changing sliding parameter when surge-multiplier is at 10.

The length and volume over time figure exhibits similar periodical trend when Glen's creep parameter is adjusted during the surging period instead of the sliding parameter (fig 6). The fluctuations in length and volume are less pronounced than those in previous experiment.

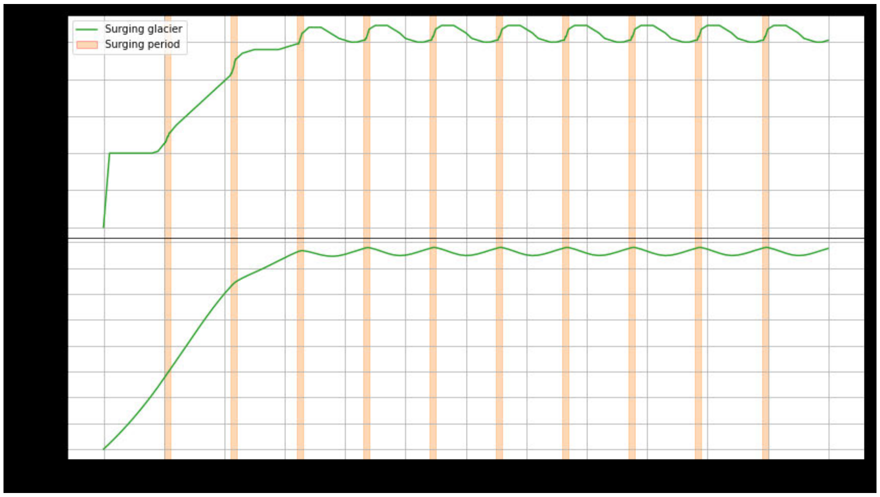

Figure 7: Fluctuation of length and volume of the idealized glacier, rendered by adjusting the Glen's creep parameter with surging multiplier as 10. The yellow vertical bars denote surging periods.

Discussion

Surging glaciers flow differently from normal glaciers. We needed to have smaller step size during the surging period to both distinguish between surging period and non-surging period, and to generate more granular data during the surging period. Doing so, our experiment exhibits the periodical cycle in length and volume change as expected, but they do not vary in the same way. Change in length over time experiences drastic increase during surging period and slow decrease during non-surging period. Change in volume over time denotes similar amount of time for increase and decrease. During the surging period, as the length of the glacier drastically increases, its volume plateaus; during the first half of the non-surging period, both the length and volume of the glacier decrease; during the second half of the non-surging period, the volume of the glacier increases while its length continues to decrease.

Such variation can be interpreted as a delayed response between volume and length change. In learning to modify sliding parameter, we discovered that a larger sliding parameter produces a flatter glacier with smaller length and volume (fig 3). During surging period, there is more basal sliding so glacier length increases. This means that more glacier volume is concentrated in the ablation zone, so glacier volume decreases. However, change in volume is slower than change in length so it continues to decrease even after sliding parameter value is re-initialized. In correspondence with volume, glacier length also decreases. After the volume decreases sufficiently in response to basal sliding, its proportion in the accumulation zone is enough to generate volume increase. However, glacier length is still decreasing since it takes time for glacier ice to move from the accumulation zone to the ablation zone. After glacier ice accumulates enough, its length starts to increase until the next surging period.

The figure generated from adjusting Glen's creep parameter exhibits similar periodical cycle and similar length and volume change, but with less pronounced variation. In learning to change Glen's creep parameter, we discovered that a larger value generates flatter glaciers with smaller length and volume (fig 2). As a result, it is physically reasonable that adjusting Glen's creep parameter during surging period generates similar trend. However, we also know that Glen's creep parameter is a constant regarding ice temperature, crystal orientation, debris content, factors about the physical structure and condition of the glacier that are unlikely to change in a cyclical way. Therefore, the similar trend exhibited is an instance when the expected result is produced for the wrong reason.

Conclusion

By increasing the value of sliding parameter during the surging period, we are able to simulate a cyclical surging glacier. Even though adjusting Glen's creep parameter during the surging period also generates cyclical glacial change, we do not think this is the cause of surging periods. We have analyzed the relationship between length and volume change over time as effects of glacier accumulation and ablation.

Reference:

Murray, Tavi, Tazio Strozzi, Adrian Luckman, Hester Jiskoot, and Panos Christakos. "Is there a single surge mechanism? Contrasts in dynamics between glacier surges in Svalbard and other regions." *Journal of Geophysical Research: Solid Earth* 108, no. B5 (2003).

Sevestre, Heïdi, and Douglas I. Benn. "Climatic and geometric controls on the global distribution of surge-type glaciers: implications for a unifying model of surging." *Journal of Glaciology* 61, no. 228 (2015): 646-662.

Van Der Veen, Cornelis J., and I. M. Whillans. "Flow laws for glacier ice: comparison of numerical predictions and field measurements." *Journal of Glaciology* 36, no. 124 (1990): 324-339.