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Exercises: Glacier mass balance

1.) STAKE MASS-BALANCE MEASUREMENTS

Figure 1 illustrates how the specific mass balance (i.e. mass per area) is computed from ablation stakes drilled into the ice/firn of a glacier.
In the **accumulation area** snow remains at the end of the summer, hence, all melt is due to snow.
In the **ablation area** all snow melts and part of the underlying ice/firn disappears.
The winter and summer mass balance is computed from stake readings at the end of the accumulation season (when glacier mass is at a maximum) and at the end of the summer season (or mass-balance year) when glacier mass attains the annual mass minimum (Fig. 1). Also end winter snow density and end summer firn density need to be known.

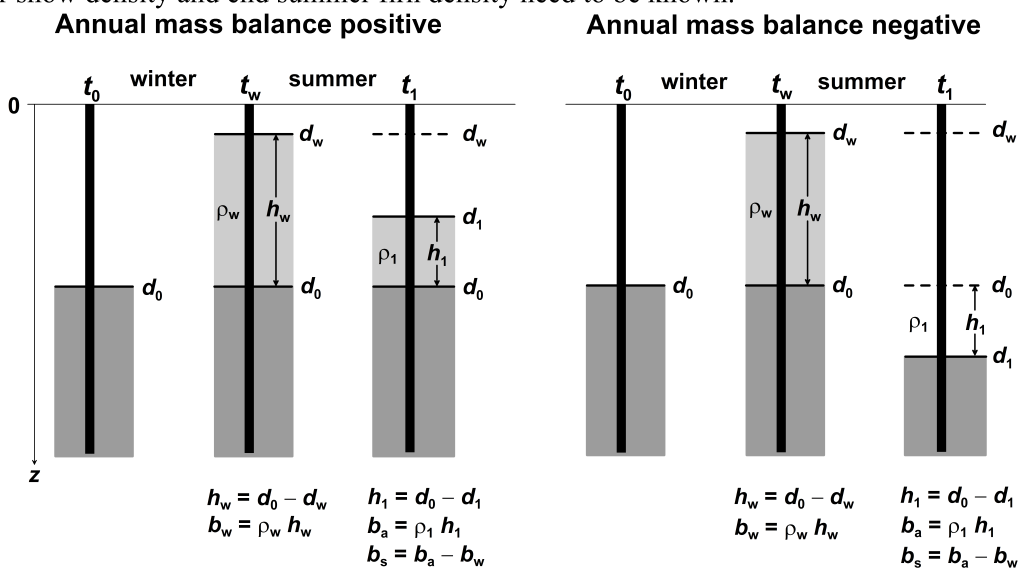


Fig. 1. Stake measurements of seasonal mass balances in a year of positive (left) and a year of negative (right) *surface mass balance*, with no *superimposed ice*. The vertical coordinate is positive downwards, and all distances are measured from the origin $z = 0$ at the top of the stake. Light shading represents *snow*; dark shading represents *firn* or *glacier ice*. Measurements are made at t_0, the start of the *accumulation season*; at t_w, the start of the *ablation season*; and at t_1, the end of the mass-balance year. The *winter balance* b_w is the change of mass between t_0 and t_w. The *summer balance* b_s is the change of mass between t_w and t_1. $\boldsymbol{\rho_w}$ and $\boldsymbol{\rho_1}$ are the mean snow densitites. $\boldsymbol{\rho_1}$ is usually higher than the one in late winter, $\boldsymbol{\rho_w}$. Ice density, $\boldsymbol{\rho_i}$ is often assumed to be 900 kg/m^3 (0.9 kg/L) (Cogley et al 2011).

Assume the firn line coincides with the equilibrium line and **compute the specific mass balance for the following 2 stakes drilled into the glacier surface**.

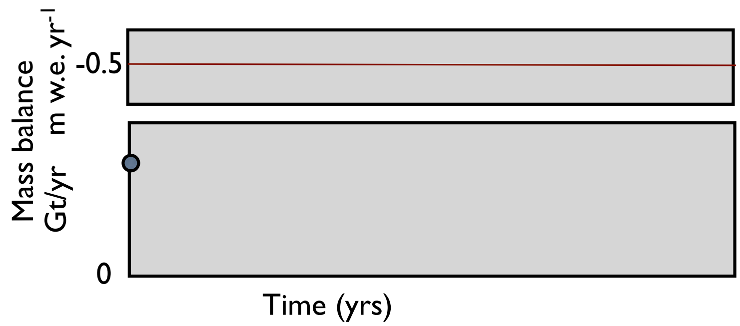
	Stake 1	b_w	b_s	b_a	**Stake 2**	b_w	b_s	b_a
End winter snow depth, h_w	**2 m**	0.8 m w.e.	-0.55 m	-0.25	**2 m**	0.8	-1.25	-0.45
Stake reading (top of stake to snow/ice surface) at the end of winter, d_w	**0.5 m**				**0.5 m**			
Stake reading end of summer, d_1	**2 m**				**3 m**			
End winter mean snow density ρ_w	**400** kg/m3				**400** kg/m3			
Late summer snow density ρ_1	**500** kg/m3				N/A			
Ice density	N/A				**900** kg/m3			

Note: **1 kg/m^2 = 1 mm w.e.** (because the density of water is 1000 kg/m^3).

2.) MASS-BALANCE VARIATIONS WITH TIME

→ *Using different mass balance units*

2.1 Case 1: The **specific mass balance rate** (i.e. mass per area, in kg/m^2 or m w.e.) of a 10 km long valley glacier is B= -0.5 m yr^{-1}, and the climate is such that the specific mass balance rate is constant for 100 years. The glacier retreats several km and disappears in year 100. How does the **mass balance rate in Gt/yr** vary with time? The specific rate is constant (see upper panel). Sketch the course of the **mass balance rate in Gt/yr** in the lower panel.



Answer: The specific mass is constant, i.e. the amount of average thinning per year, however, as the glacier retreats it becomes smaller and there is less area over which the glacier things half a meter per year. Therefore the mass balance in Gigaton becomes less and less with time until it is zero. Mass balance in Gigatons is important for hydrological purposes, because it shows how much water is released from the glacier. The exact shape of the curve depends on glacier geometry and other factors.

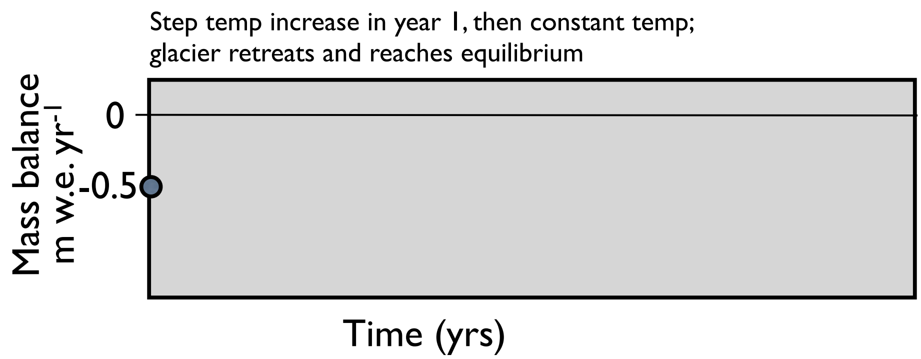
2.2 Case 2: Assume a sudden step-like temperature increase by 1ºC (i.e. constant teperature thereafter) which leads to increased melt of the glacier resulting in a specific glacier-wide mass balance rate of B= -0.5 m a^{-1} for the first year of the temperature increase. The glacier retreats by 2 km until it has reached a new equilibrium after 50 years. How does the specific mass balance (m w.e. yr^{-1}) vary with time?

a) **conventional** mass balance

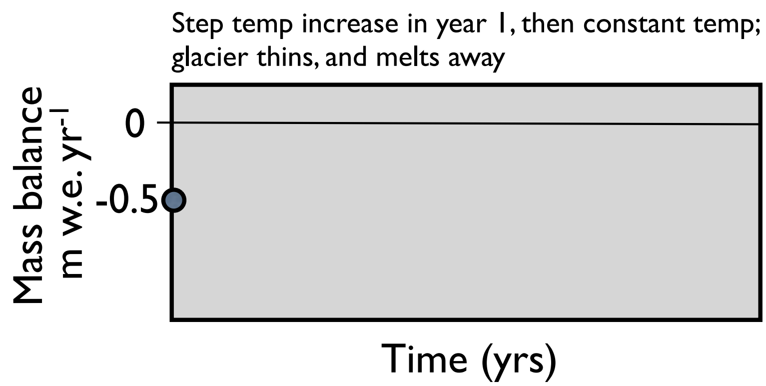
b) **surface-reference** mass balance

Answer: The conventional mass balance (integrated over the shrinking surface area) becomes less and less negative for the same specific balance rate, because low lying high ablation area are progressively lost and the glacier 'moves' to higher colder regions where there is less melt. The glacier reaches a new equilibrium and the specific mass balance will be zero. Although the climate does not change the conventional balance changes with time. Requires caution when interpreting long-term mass-balance series, which are usually reported over the actual area.

The reference surface balance does not change and therefore is a better indicator for climate. The climate does not change, and the ref-surface balance does not change.



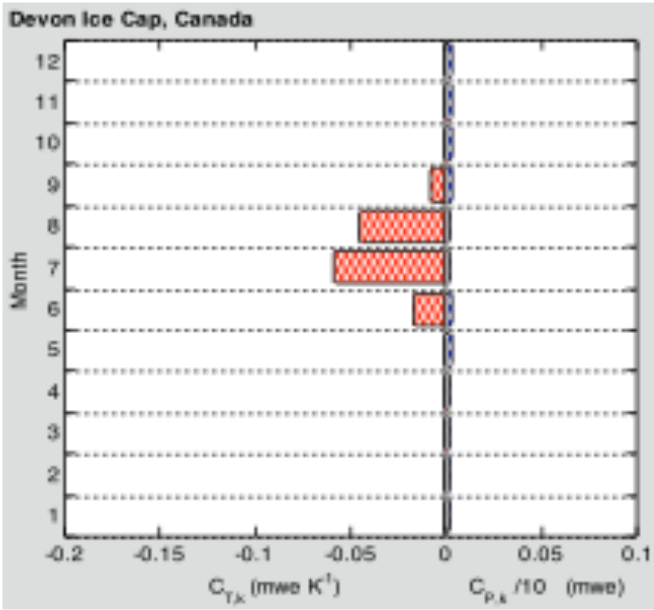
2.3 Case 3: As case 2 but the glacier does not retreat much but it **thins** considerably; it does not reach a new equilibrium but eventually melts away. How does the specific conventional specific mass balance vary with time?



Answer: There is 2 opposing effects: The retreat of the glacier to higher altitudes will stabilize the glacier (less melt higher up). However, the thinning of the glacier will destabilized the glacier (more area at lower elevations). It depends on which process is dominant whether or not the specific balance will approach zero or become more and more negative. The latter will happen here, because there is a steady temperature increase and considerable thinning. The specific mass balance will be become more and more negative.

3.) MASS-BALANCE SENSITIVITY – PROJECTING FUTURE MASS BALANCES

Background: Mass balance sensitivities give the change in mass balance in response to a step-change in climate, for example, a temperature or precipitation increase. A temperature increase will make the mass balance less positive or more negative; the opposite is true for an increase in precipitation (more snow). For example, assume the specific annual mass balance is -0.2 m w.e.; if the temperature increased by 1ºC the mass balance would be -0.6 m w.e.; then the annual mass-balance sensitivity to temperature is -0.4 m w.e. K^{-1}.



The figure shows the seasonal sensitivity characteristics of Devon Ice Cap, i.e. how the mass balance would change in response to a 1ºC temperature index and a 10% precipitation increase.

Exercise: A climate model projects an increase in annual air temperature by 2050 by 2ºC. The temperature increase is not uniform throughout the year but warming is more pronounced in winter: The increase in winter (Oct-March) is 3ºC and in summer 1ºC. The current specific mass balance rate is -0.5 m yr^{-1}.

a) Compute annual **mass-balance sensitivity** for Devon Ice Cap?

b) Estimate the **specific glacier-wide mass balance be** in 2050. Use the sensitivity approach based on annual sensitivities and annual mean temperature increase?

Answer: The sensitivities are zero except for 3 months. During June, July and August they are roughly -0.02, -0.06 and -0.05 m w.e. K-1, respectively. During the remaining months the mass balance does not change if the temperature is increased by 1 K. The annual sensitivity is the sum of the monthly values, i.e. -0.13 m w.e. /yr. This means that if the temperature rises by 1 K, the mass balance will change by -0.13 m w.e. per year.

c) What is the specific mass balance in 2050 using the seasonal sensitivity characteristic and the seasonally variable temperature increase?

Answer: Temp increase is 2 C. 2x(-0.13) = -0.26 m w.e. /yr

d) Why do results differ?

Answer: The specific mass balance is less negative compared to computing the balance using annual sensitivities. This is because the temperature increase is less than the annual mean during the 3 months where it matters.

e) In reality the specific mass balance will probably be different because there are a number of assumption. Will the specific mass balance be over- or underestimated by your approach? Why?

Answer: It will probably be underestimated (i.e. to negative) because the glacier retreats and the specific mass balance becomes less negative (assuming that the retreat effect dominates the thinning effect).