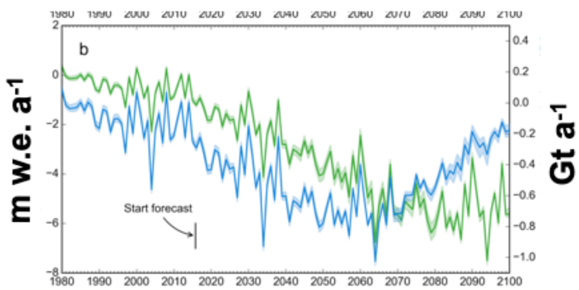
Exercises: Glacier mass balance

1.) HOW DOES MASS BALANCE VARY WITH TIME IN RESPONSE TO A TEMPERATURE INCREASE ? (see separate sheet, page 3)

2) MASS-BALANCE TIME SERIES

The figure shows the annual mass balance that is modeled for Black Rapids Glacier in Alaska until 2100 in two units (specific units and Gt a^{-1}). The projection is based on a climate scenario with air temperature increasing throughout the 21st century. By the end of the century only a small fraction of the glacier remains. Most currently glaciated will be deglaciated. Which curve is in which unit ? Why do they differ?



2.) STAKE MASS-BALANCE MEASUREMENTS

Figure 1 illustrates how the specific mass balance 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 snow.
- In the **ablation area** all winter snow melts and part of the underlying ice/firn disappears.
- The winter and summer mass balances are computed from **stake readings** at the end of the accumulation (winter) season (when glacier mass is at a maximum) and at the end of the melt (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.

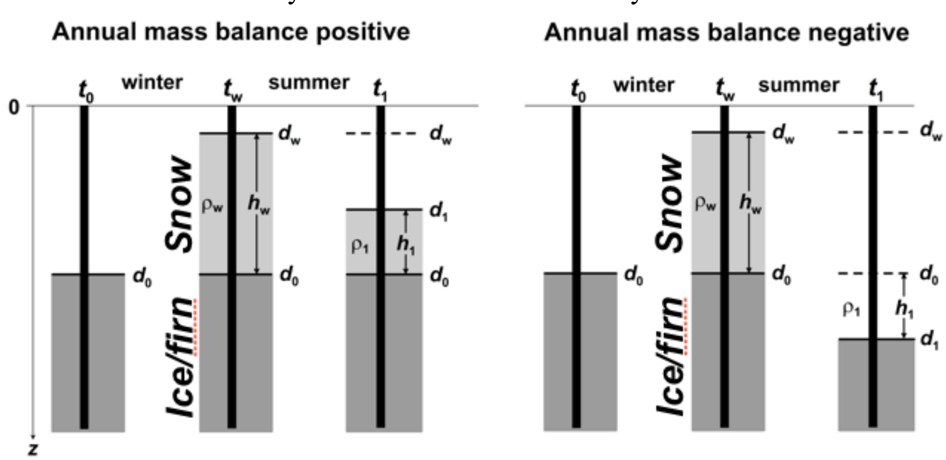


Fig. 1. Stake measurements of seasonal mass balances in a year of positive (left) and a year of negative (right) *surface mass balance*, with no *superimposed ice*. The **stake readings *d*** are made from the origin z = 0 at the top of the stake to the glacier surface. $\boldsymbol{t_0}$ is the start of the *accumulation season*; $\boldsymbol{t_w}$, is the end of the winter and the start of the *ablation season*; and $\boldsymbol{t_1}$ is 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 densities. $\boldsymbol{\rho_1}$ is usually higher than the one in late winter, $\boldsymbol{\rho_w}$. (Cogley et al 2011).

<u>Compute the specific point mass balance (in m w.e.)</u> for the following 2 stakes drilled into the glacier surface. Assume the firn line coincides with the equilibrium line.
It may make it easier if you marked the balances/distances graphically in Figure 1.

Ice **density**, ρ_{ice} = 900 kg/m^3 (0.9 kg/L)
End of **winter snow** $\boldsymbol{\rho_w}$ = 400 kg/m^3
Late **summer snow** $\boldsymbol{\rho_1}$ = 500 kg/m^3 (Note the density increases over summer: compaction, melt)

	Stake 1	**b_w**	**b_s**	**b_a**	**Stake 2**	**b_w**	**b_s**	**b_a**
End winter **snow depth**, h_w	2 m				2 m			
Stake reading at the end of winter, d_w	0.5 m				0.5 m			
Stake reading end of summer, d_1	2 m				3 m			

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

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 annual mass balance B = -0.2 m w.e. and it would change to -0.6 m w.e. if the annual air temperature rose by 1ºC; then the **annual mass-balance sensitivity** to temperature is -0.4 m w.e. K^{-1} (the balance has changed by -0.4 m w.e. K^{-1}).
Instead of looking at annual air temperature changes, one can consider the effect on annual mass balance for a temperature change in each month (Figure 1).

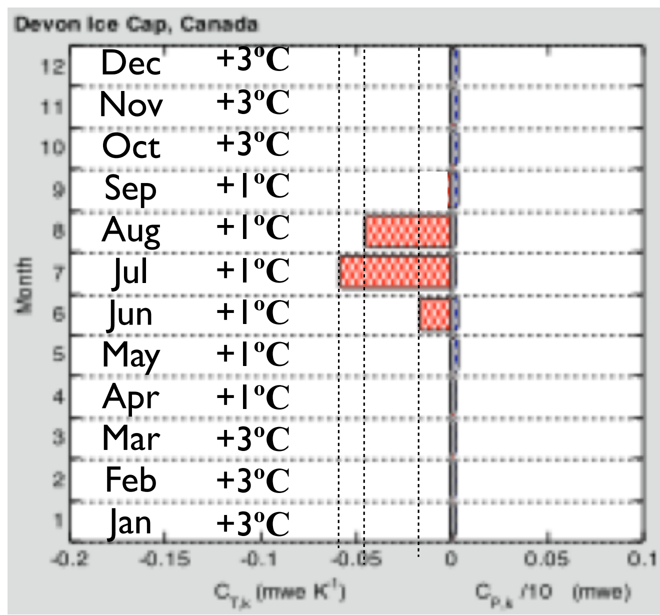


Figure 1. **Seasonal sensitivity characteristic** (SSC) of Devon Ice Cap. The SSC shown here indicates how much the <u>annual</u> specific mass balance of a glacier would change in response to a 1ºC temperature (left) and a 10% precipitation increase (right) for **each month individually**. For example, for a 1ºC temperature rise in August the annual specific mass balance would become almost 0.05 m w.e. more negative. Temperature increases listed for each month refer to projected air temperature increases for each month (see c) below).

a) Compute the **annual mass-balance sensitivity** for Devon Ice Cap from the monthly mass-balance sensitivity characteristic? (Note that the temperature values added to the left of the figure should be ignored here; they are only relevant for question c).

b) Estimate the **specific glacier-wide mass balance** for year 2050 using the annual sensitivity to temperature computed above. Assume a mean annual temperature increase of **2ºC** by 2050. The current specific mass balance rate is -0.5 m yr^{-1}.

Estimate the **specific glacier-wide mass balance be** in 2050 using the **seasonal sensitivity characteristic and seasonally differentiated temperature increase**. 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 (Apr-Sep) 1ºC**. The current specific mass balance rate is -0.5 m yr^{-1}.

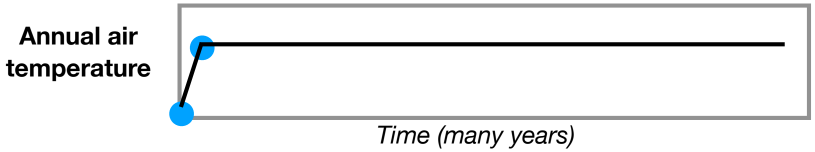
Why do results from b) and c) differ?

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?

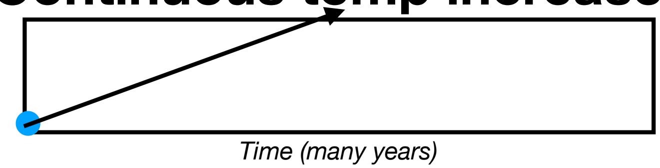
How does annual mass balance vary with time in response to a temperature increase)?

Note that the time series will not only depend on the climate change but also on the dynamic response and associated feedbacks (effects of retreat to higher elevations and glacier thinning)

Step-change in temp

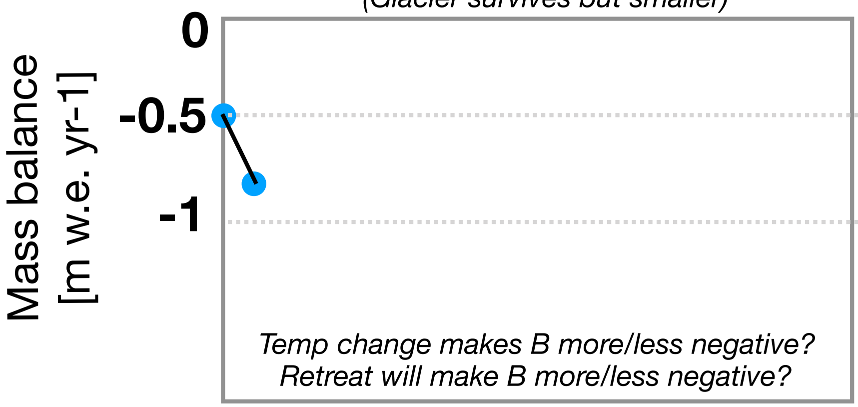


Continuous temp increase



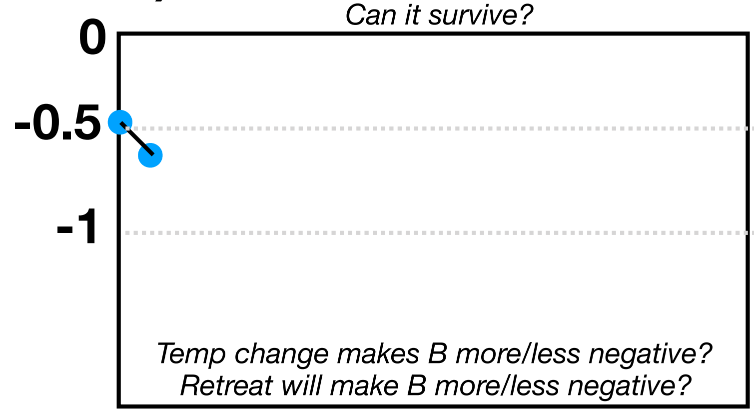
A) Glacier __retreats__ but does **not thin**

(Glacier survives but smaller)



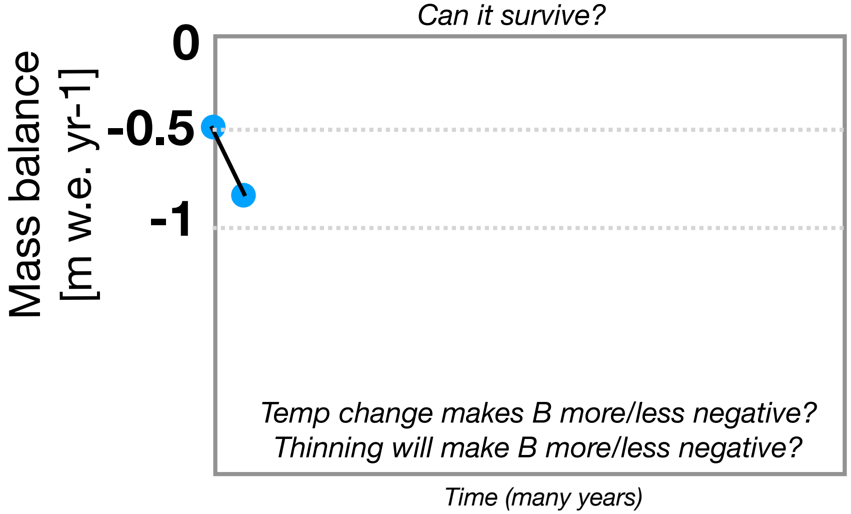
C) Glacier __retreats__ but does **not thin**

Can it survive?



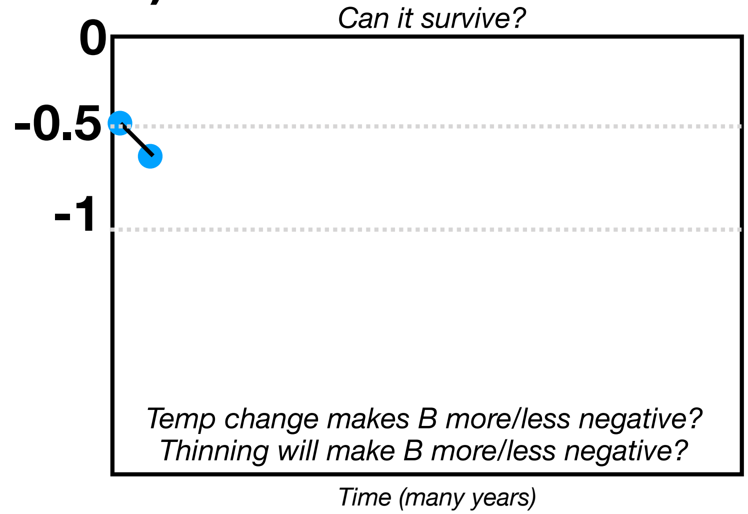
B) Glacier __thins__ but does not **retreat**

Can it survive?



D) Glacier __thins__ but does not **retreat**

Can it survive?



Draw schematic time series for both conventional and reference surface mass balance