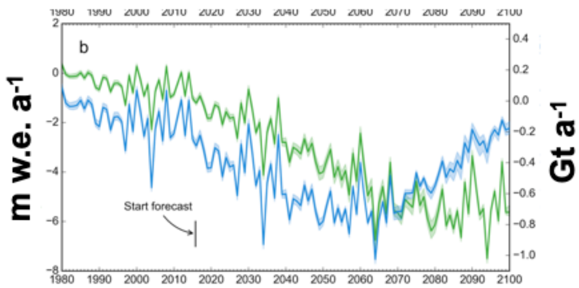
Exercises: Glacier mass balance

1.) HOW DOES MASS BALANCE VARY WITH TIME IN RESPONSE TO A TEMPERATURE INCREASE? (see separate sheet, page 5)

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?



Blue (curve towards less negative balances in the last decades) is Gt/a since the total mass loss reaches a maximum and declines as the glacier becomes smaller and smaller (mass loss is product of thinning and area)

3.) 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 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.

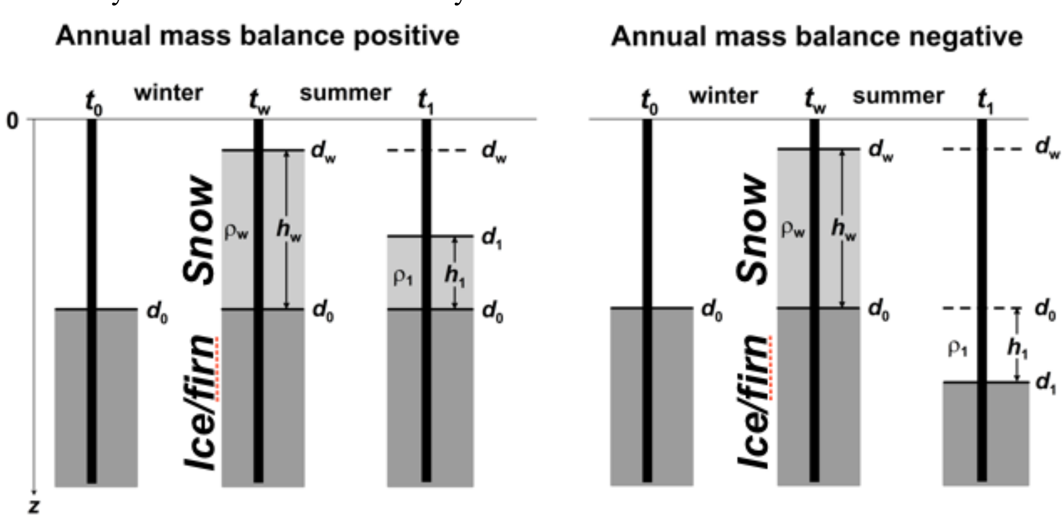


Fig. 1. Stake measurements of seasonal mass balances in a year of positive (left) and a year of negative (right) *surface mass balance*, with no *superimposed ice*. The **stake readings *d*** are made from the origin $z = 0$ at the top of the stake to the glacier surface. t_0 is the start of the *accumulation season*; t_w, is the end of the winter and the start of the *ablation season*; and 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. ρ_w and ρ_1 are the mean snow densities. ρ_1 is usually higher than the one in late winter, ρ_w. (Cogley et al 2011).

Compute the specific point mass balance (in m w.e.) 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** ρ_w = 400 kg/m^3
Late **summer snow** ρ_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	2x0.4=0.8	-0.25	0.55	2 m	0.8	-1.25	-0.45
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**. (because the density of water is 1000 kg/m^3).

*a) Stake 1: The **winter balance** b_w is 2 x 400 /1000 (density of water) = 0.8 m w.e.*
The stake is in the accumulation area because the drop in relative elevation is (2-0.5 m) 1.5 m, i.e. there is still snow left at the end of the summer.
*The **annual balance** b_a is what is left after summer (half a meter of snow): 0.5 x 500/1000 = +0.25 m w.e.*
*The **summer balance** b_s is the annual balance (=0.25 m w.e.) minus the winter balance (0.8 m w.e.) → B_s=(0.25 – 0.8) =-0.25 m w.e.*

*b) Stake 2: The **winter balance** is 2 x 400 /1000 (density of water) = 0.8 m w.e.*

The stake is in the ablation area because the drop in relative elevation is 2.5 m, i.e. more than the winter snow depth.
Thickness of ice melt = 0.5 m (0.5+2-3 m).

All winter snow is gone, so the ***annual balance*** *b_a is the ice melt of 0.5 m, i.e. b_a = -0.5 x 900/1000 = -0.45 m w.e. (Note, mass loss is negative)*

The ***summer balance*** *includes all melt, i.e. all snow that was there (i.e. the winter balance and the ice melt). Total summer balance is -(0.8 + 0.45) = -1.25 m w.e.*

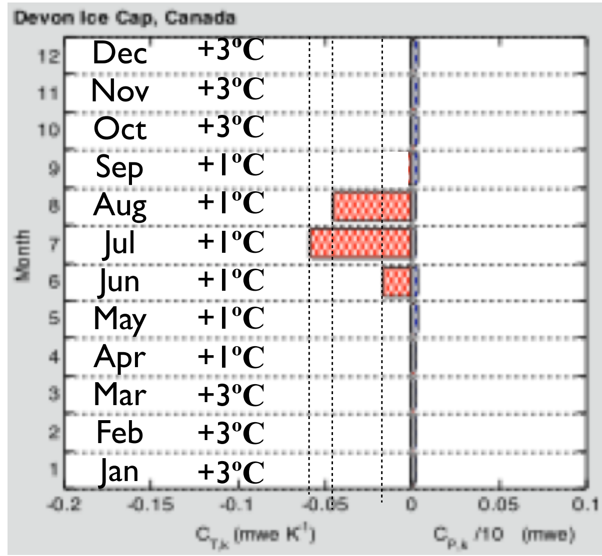


Figure 1. **Seasonal sensitivity characteristic** (SSC) of Devon Ice Cap. The SSC shown here indicates how much the annual specific mass balance of a glacier would change in response to a 1ºC temperature (left) and a 10% precipitation increase (right) for **each month individually**. For example, for 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).

4.) 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).

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).

   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 annual mass balance will change by -0.13 m w.e..*

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}.

   Answer: Temp increase is 2ºC. 2x(-0.13) = -0.26 m w.e. /yr. The balance was already negative before, i.e. the annual balance in 2050 is = -0.26 +(-0.5) m w.e. /yr = -0.76 m w.e. /yr.

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}.

*Answer: Multiply each months sensitivity with each months temperature increase and then sum up the numbers: (1ºC *-0.02 m w.e. /yr) + (1ºC *-0.06) +(1ºC*0.05) m w.e. /yr=* ***-0.13 m w.e./yr****; add previous imbalance of -0.5 m w.e. /yr yields* ***-0.63 m w.e. /yr***

c) Why do results from b) and c) 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.

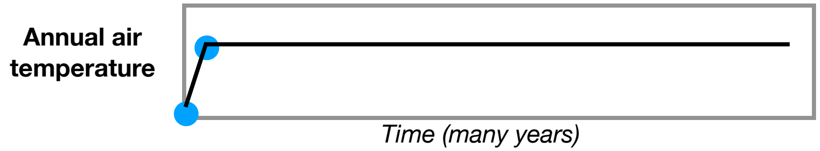
In reality the specific mass balance will probably be different because there are a number of assumption. Will the specific mass balance be over- or underestimated by your approach? Why?

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

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)

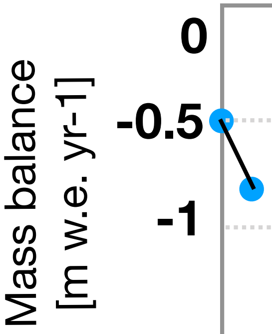
Step-change in temp



Continuous temp increase

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

(Glacier survives but smaller)



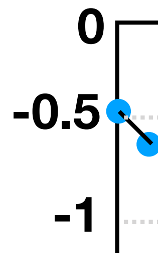
Answer: The ***conventional mass balance*** *(integrated over the shrinking surface area) becomes less and less negative although the climate does not change, because low lying high ablation area are progressively lost and the glacier 'moves' to higher colder regions where there is less melt. The glacier reaches a new equilibrium and the specific mass balance will be zero. The retreat of the glacier to higher altitudes will stabilize the glacier (less melt higher up) as long as thinning is not dominant (which destabilizes the glacier).* ***Although the climate does not change the conventional balance changes with time due to dynamic adjustments (retreat to higher elevations).***

Temp change makes B more/less negative?

Retreat will make B more/less negative?

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

Can it survive?



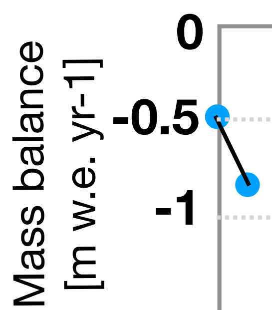
Answer: It depends, the temp change will make it more and more negative, but the retreat will make it less negative, i.e. 2 opposing effects and it depends which process is dominant (can change over time). I

Temp change makes B more/less negative?

Retreat will make B more/less negative?

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

Can it survive?



Answer: Specific balance will become more and more negative because with the thinning the glacier surface will be at lower and lower elevations where it is warmer and therefore there will be more melt, which lowers the surface even more (positive feedback). This thinning effect is often dominant with low-lying ice caps where the glaciers can not retreat to higher elevations.

In reality there is always both retreat AND thinning. The response will depend on which effect is dominant,

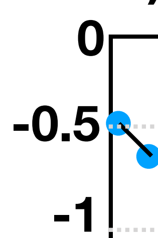
Temp change makes B more/less negative?

Thinning will make B more/less negative?

Time (many years)

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

Can it survive?



Answer: Temp change will make it more and more negative, and so does the thinning which makes the glacier surface air temperature even warmer. Both processes go in the same direction. The balance will become more and more negative until the glacier is gone. There is no stabilizing effect.

Temp change makes B more/less negative?

Thinning will make B more/less negative?

Time (many years)

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