# Hydrologically-induced slow-down as a mechanism for tidewater glacier retreat

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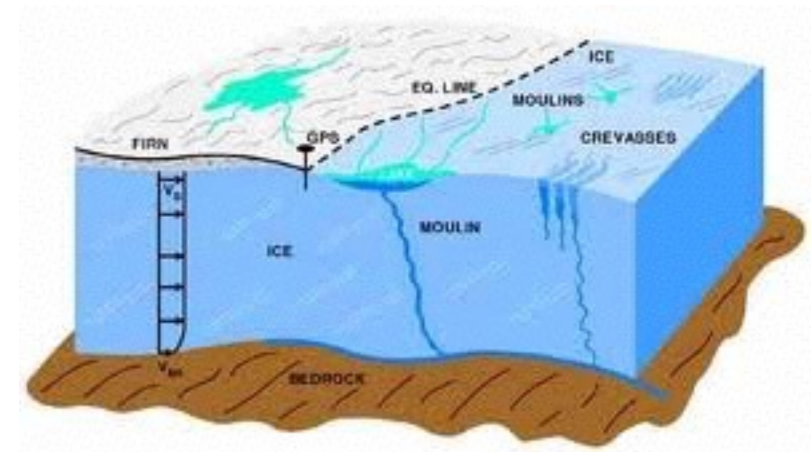
# Subglacial hydrology and ice flow

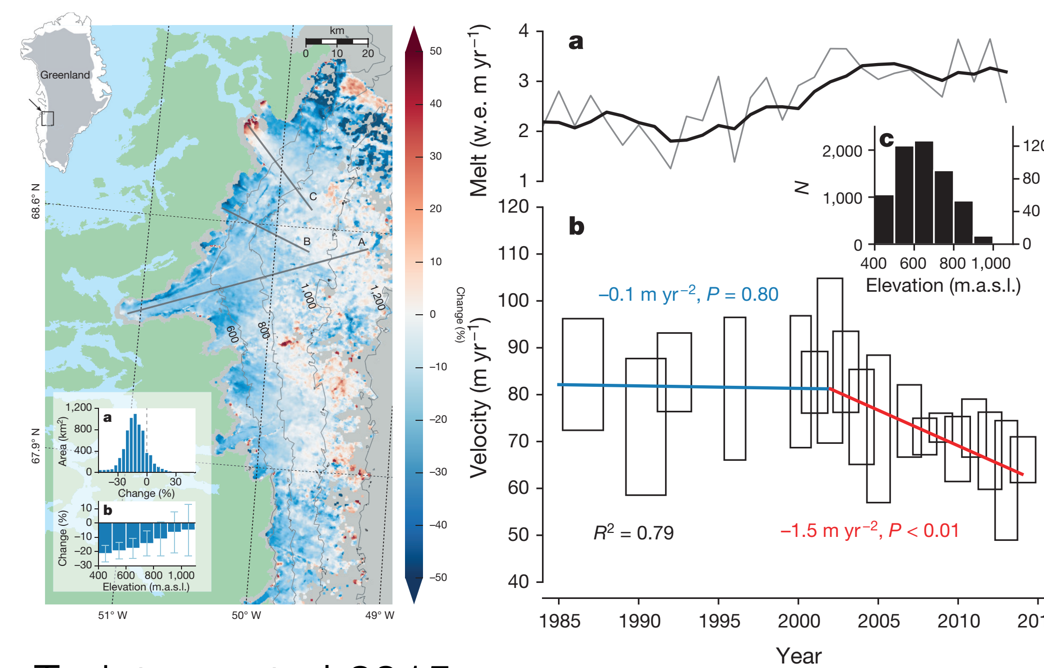
Drainage of surface meltwater to the bed affects ice speed (due to influence on water pressure).

Possibility of positive feedback? Increased surface melting ⟶ increased ice speeds ⟶ larger ablation area / increased discharge.




Zwally et al 2002

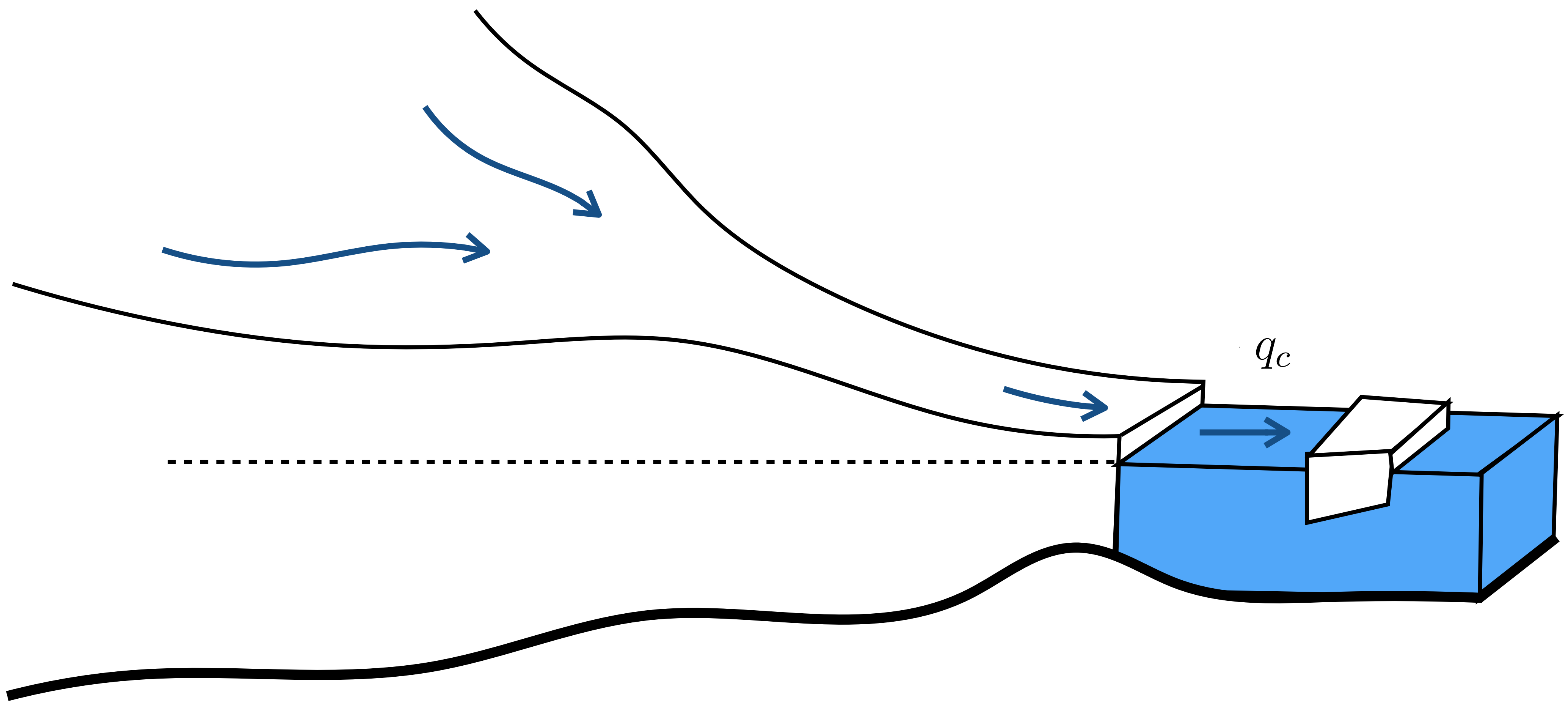
Longer term observations suggest No. Increased melting ⟶ **decreased** average ice speeds (due to more efficient subglacial drainage).




Tedstone et al 2015

But… decreased ice speeds may be **more** significant for ice loss.

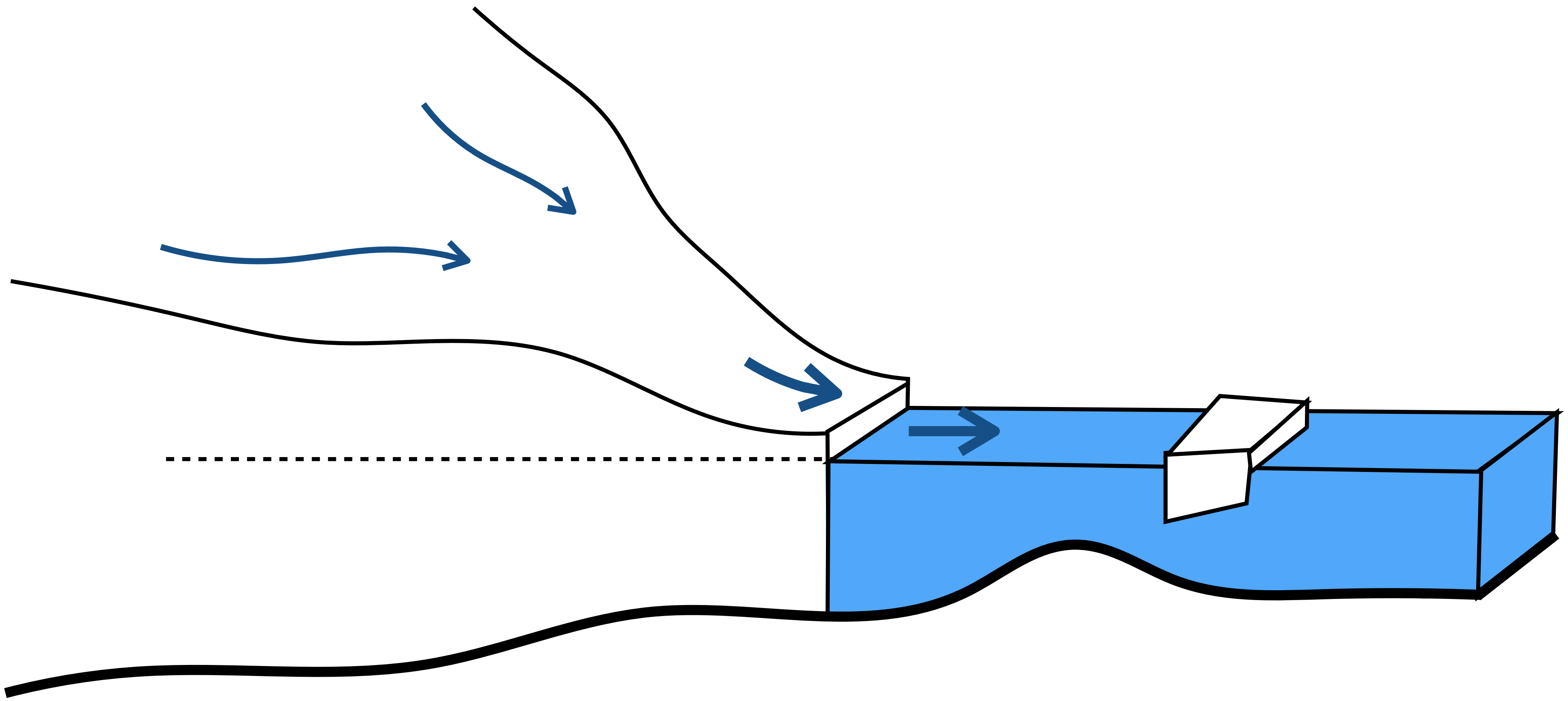
# Tidewater glaciers




Ice discharge (calving + frontal melting) controls dynamic mass loss.

Primary control on discharge is ice depth at margin.

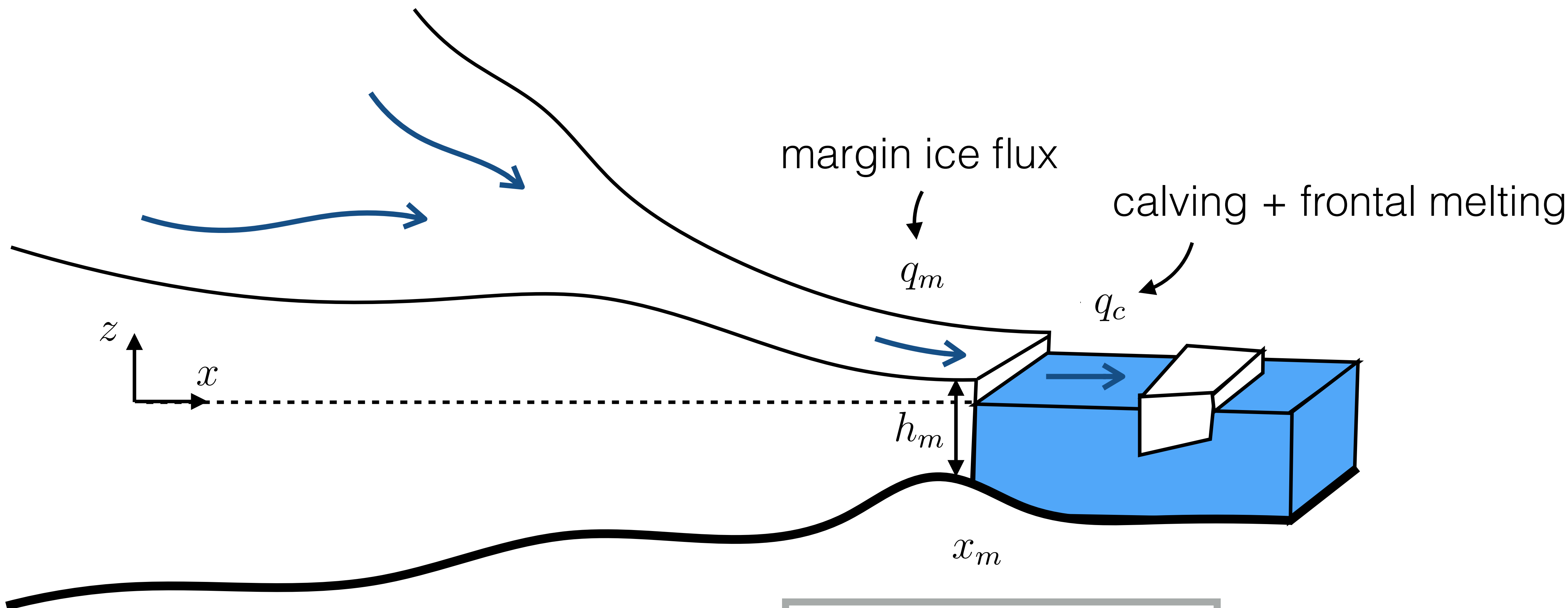
# Tidewater glaciers



Most rapid mass loss caused by retreat into over-deepening.

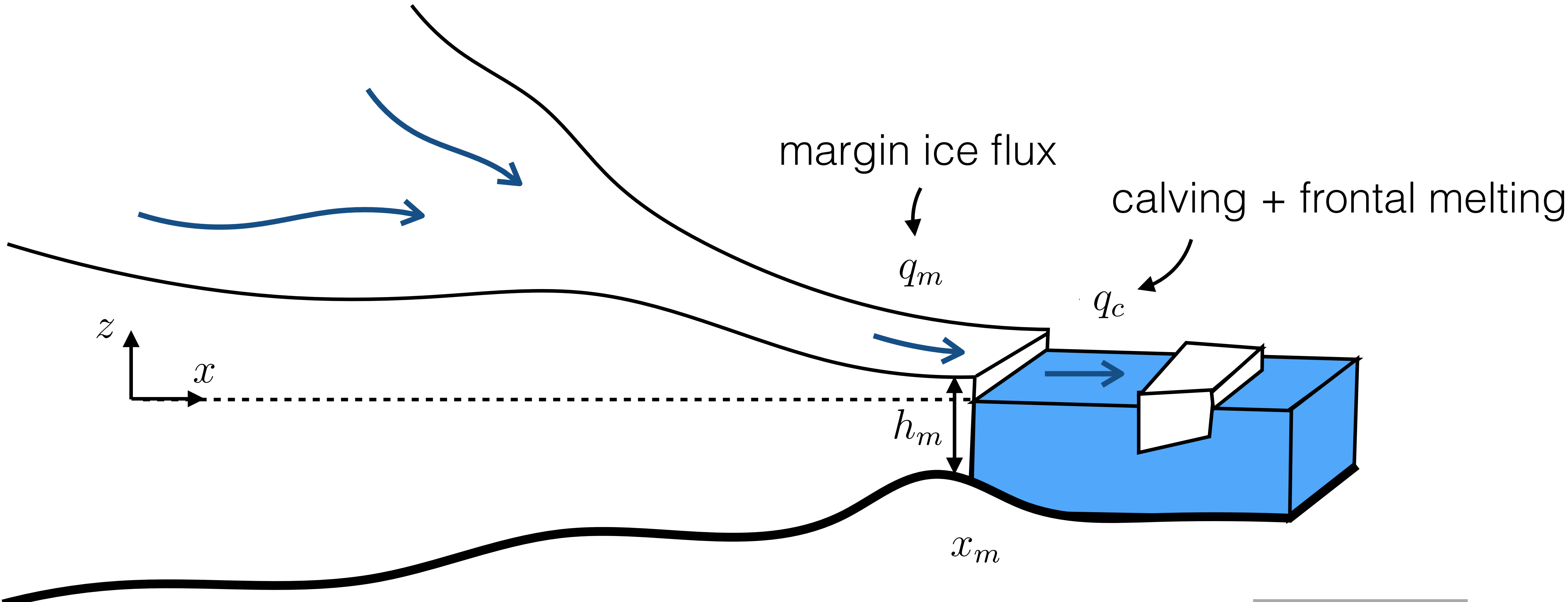
Such retreat is induced by a **decrease** in supply from upstream.

# Ice margin evolution




$$h_m \frac{\mathrm{d}x_m}{\mathrm{d}t} = q_m - q_c$$

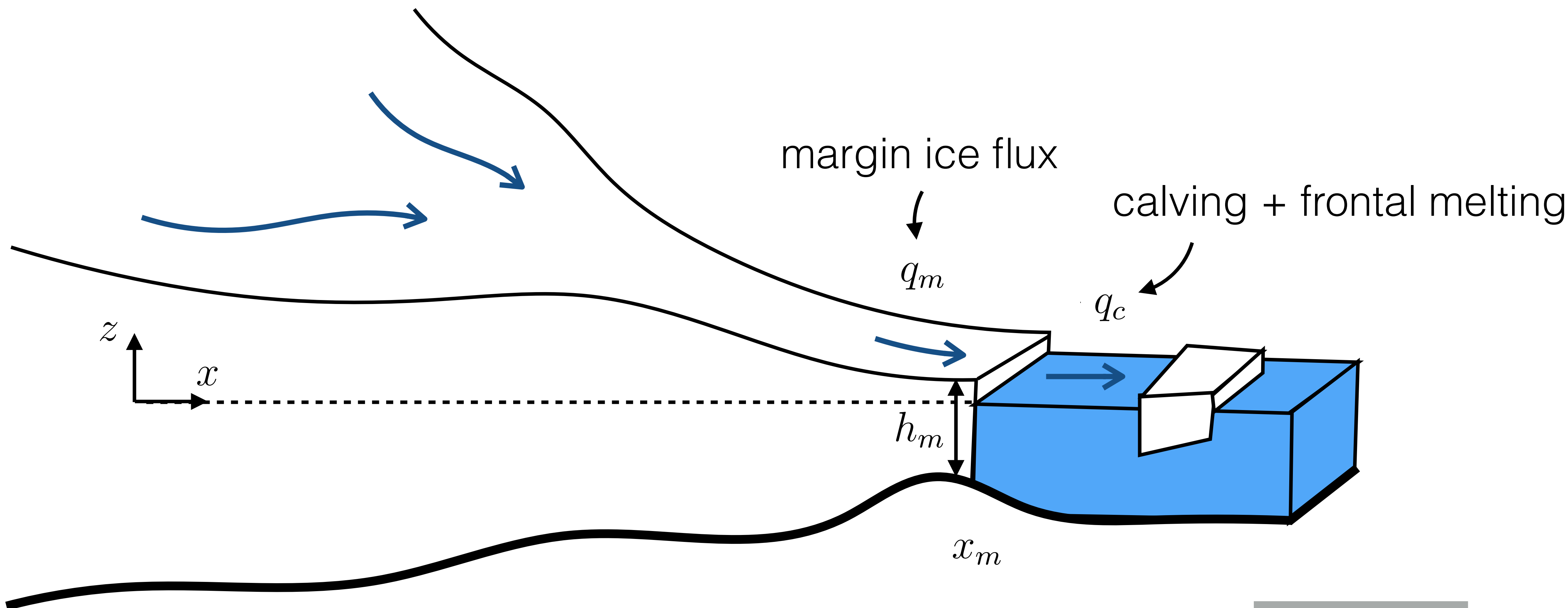
# Ice margin evolution




$$h_m \frac{\mathrm{d}x_m}{\mathrm{d}t} = q_m - q_c$$

$$q_c \approx q_m$$

# Ice margin evolution

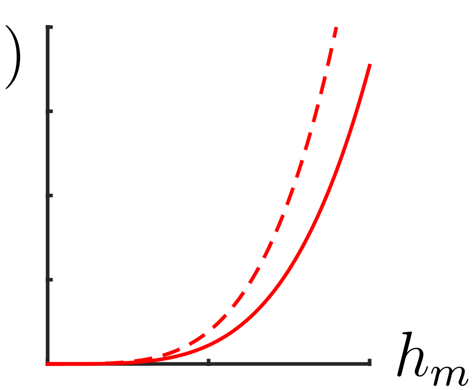



$$\require{cancel}\cancel{h_m \frac{\mathrm{d}x_m}{\mathrm{d}t} = q_m - q_c}$$

$$\boxed{q_c \approx q_m}$$

Discharge primarily determined by ice dynamics (near-margin force balance)

$$q_m = \mathcal{Q}(h_m)$$




+ calving criterion

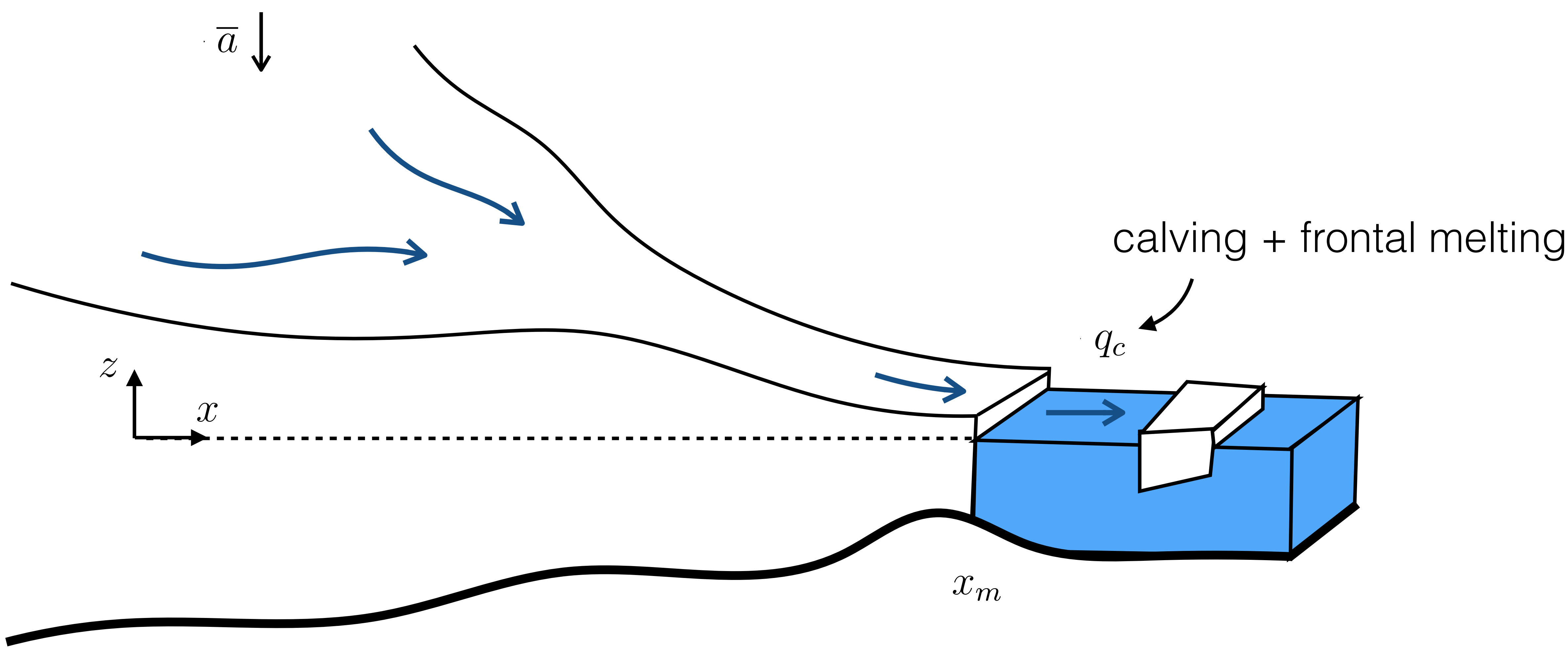
$$h_m = h_f$$

cf. Schoof 2007, Hindmarsh 2012

# Time-lapse movie


Extreme Ice Survey - Time-lapse camera
Columbia Glacier, Alaska

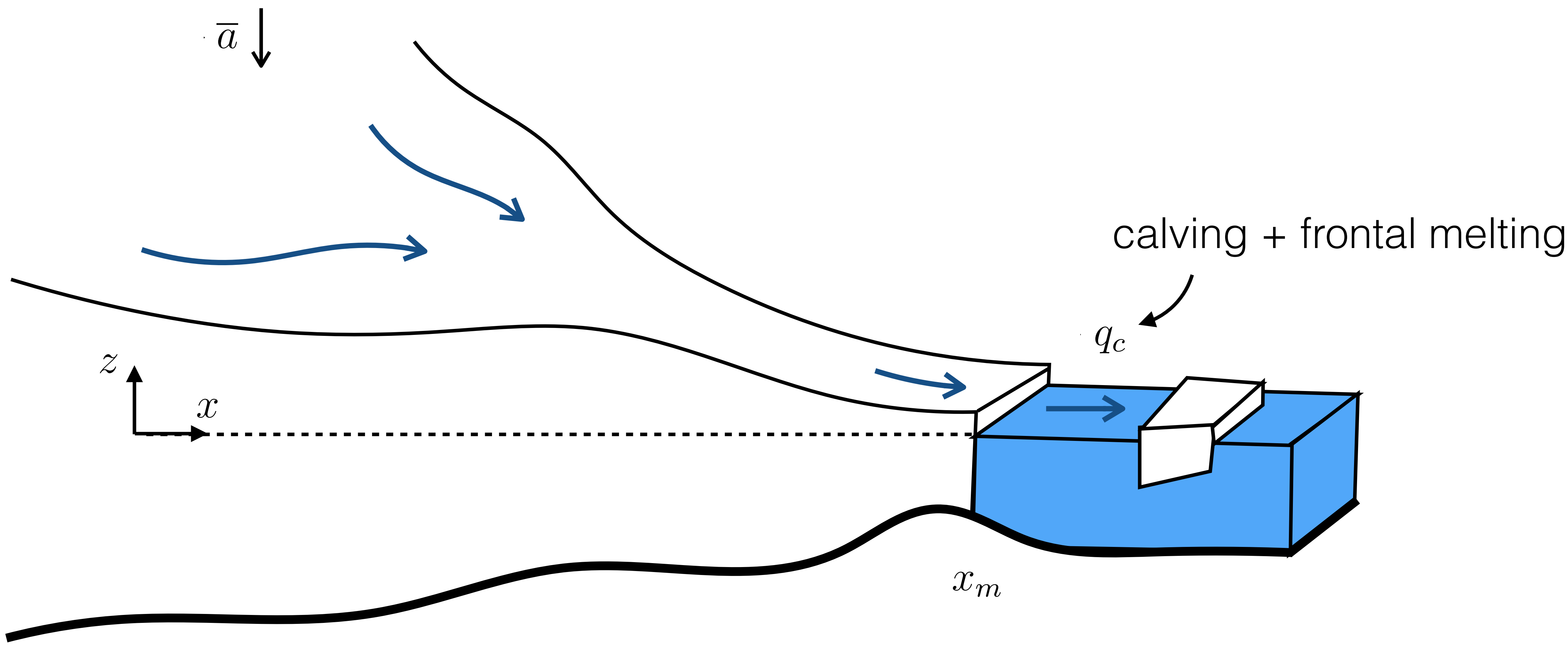
# Global mass conservation




Ice volume $V = \int_0^{x_m} h \, \mathrm{d}x$ →

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \int_0^{x_m} \overline{a} \, \mathrm{d}x - q_c$$

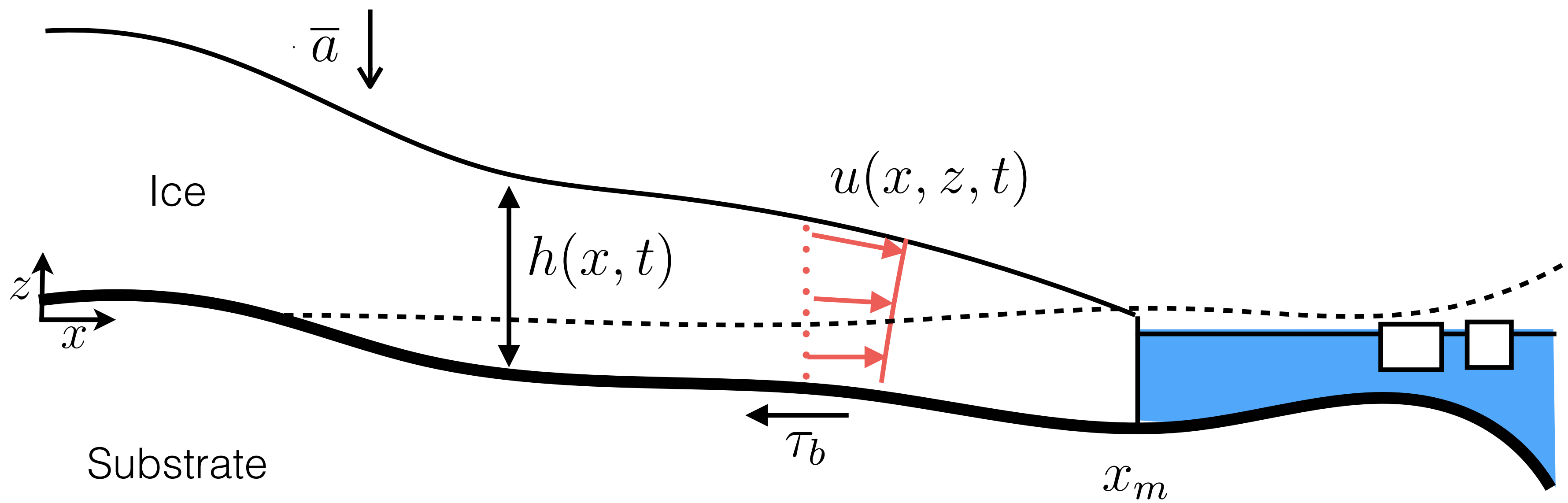
# Global mass conservation




Ice volume $V = \int_0^{x_m} h \, \mathrm{d}x$ → $$\frac{\mathrm{d}V}{\mathrm{d}t} = \int_0^{x_m} \overline{a} \; \mathrm{d}x - q_c$$

$$\frac{\partial V}{\partial x_m} \frac{\mathrm{d}x_m}{\mathrm{d}t}$$

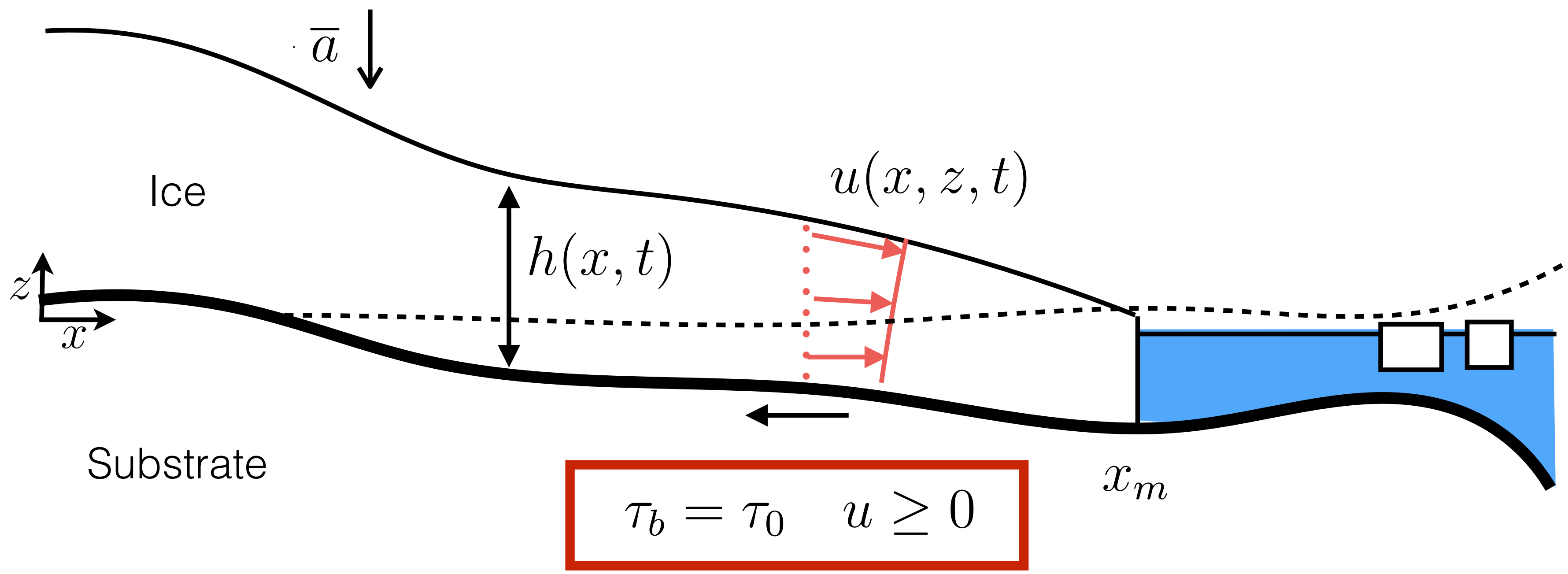
# Conventional ice-sheet model




**Force balance** (Stokes flow + sliding law) ⟶ ice velocity / flux $q = \int_b^s u \, \mathrm{d}z$

**Mass conservation** ⟶ ice thickness $\dfrac{\partial h}{\partial t} + \dfrac{\partial q}{\partial x} = \overline{a}$

# Plastic bed ice-sheet model



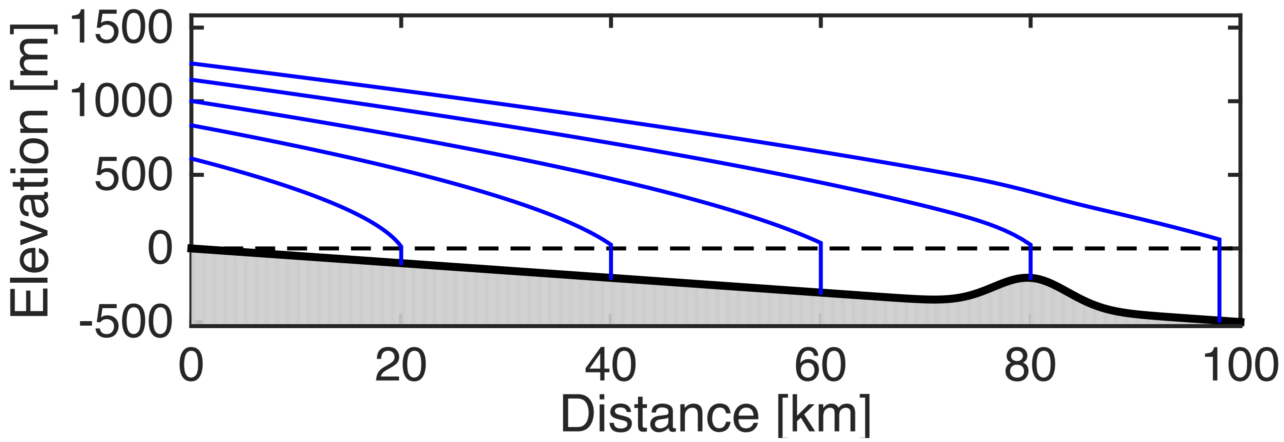

**Force balance** ⟶ ice thickness e.g. flat bed $h = \sqrt{\frac{2\tau_0}{\rho_i g}}(x_m - x)^{1/2}$

**Mass conservation** ⟶ ice velocity / flux $q = \int_0^x \left( \overline{a} - \frac{\partial h}{\partial t} \right) \mathrm{d}x$

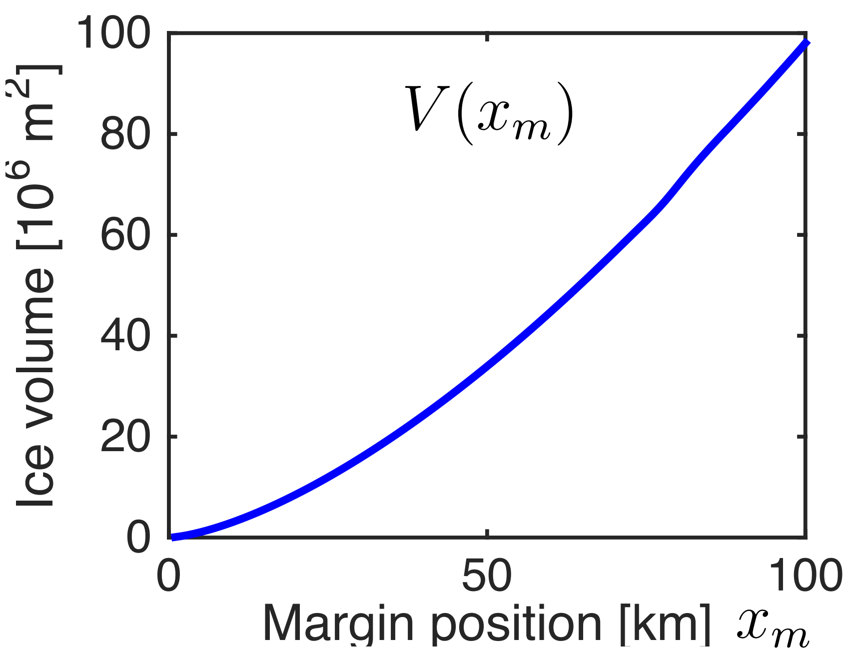
cf. plastic ice models (Nye 1951, Weertman 1961, 1976, Ultee & Bassis 2016)

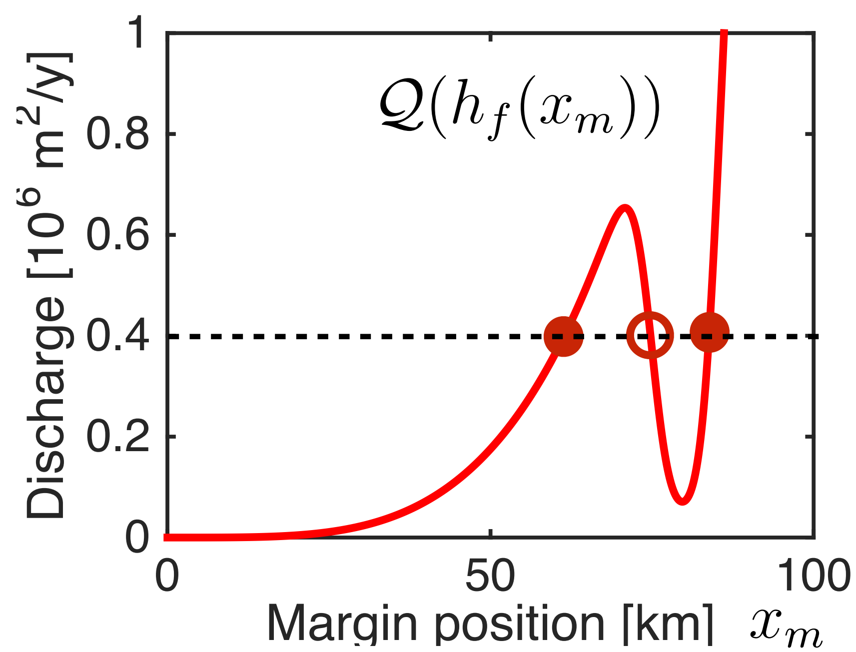
# Example

One dimensional glacier with an over-deepened bed




Ice volume and ice flux at margin depend on margin position:



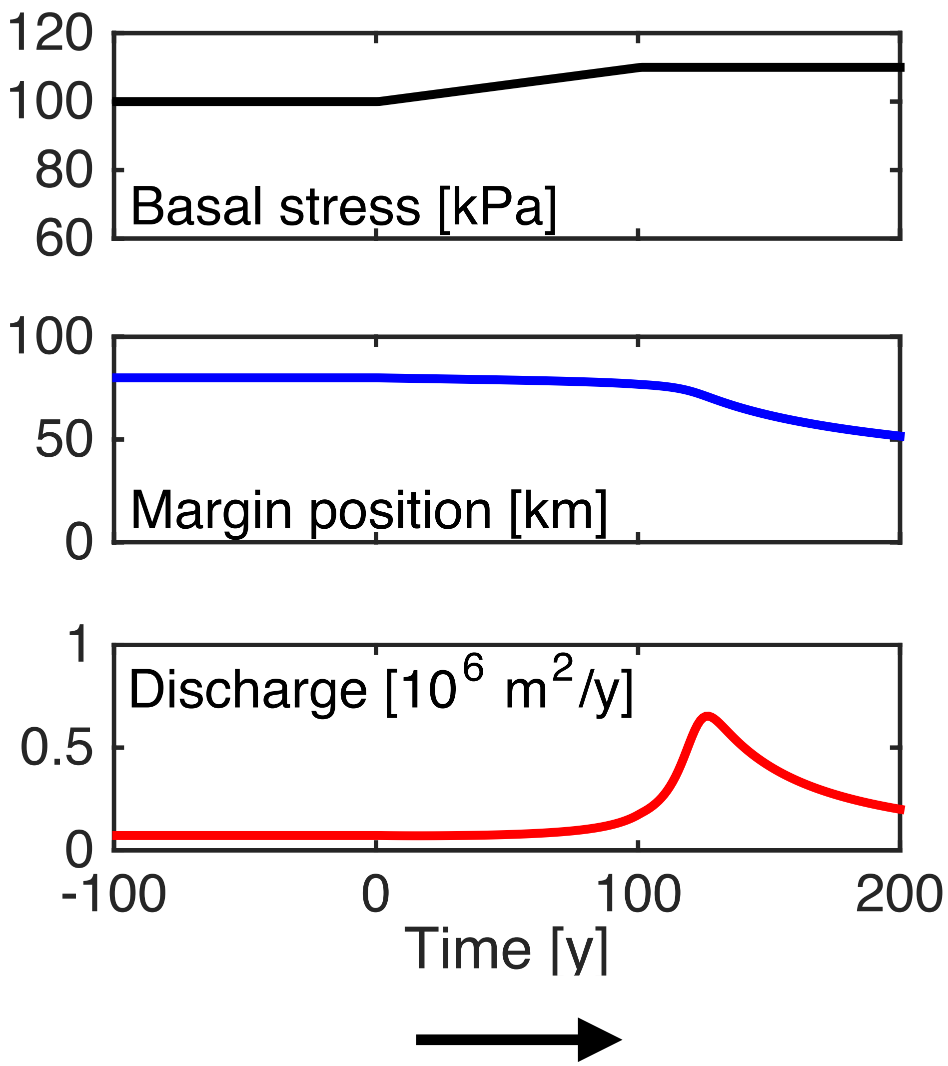



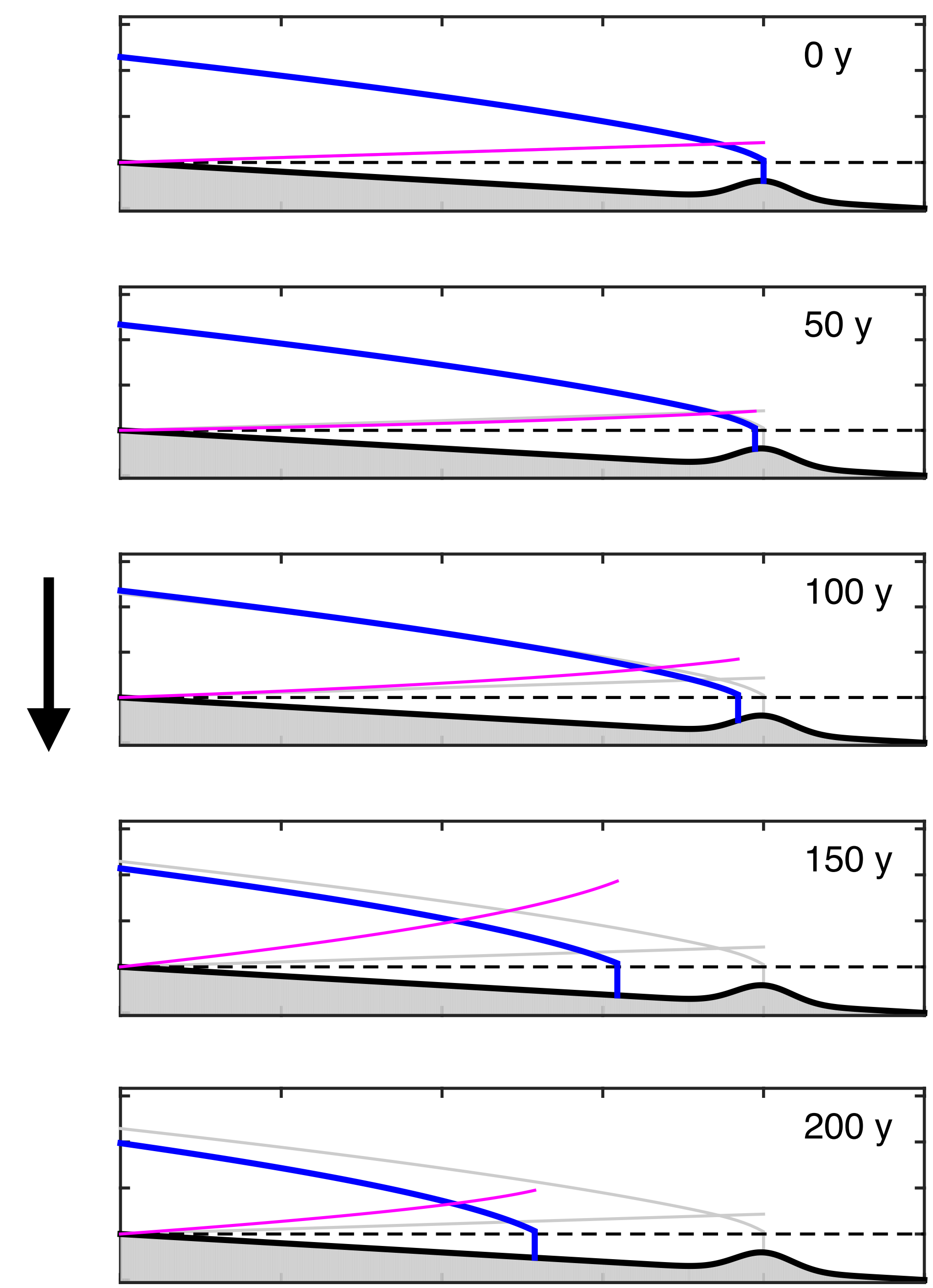

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \int_0^{x_m} \overline{a}\,\mathrm{d}x - \mathcal{Q}(h_f(x_m))$$

# Strengthening bed

Impose a gradual increase of basal stress (hydrology-induced) → induces retreat

$$\frac{\partial V}{\partial x_m}\frac{\mathrm{d}x_m}{\mathrm{d}t} = \int_0^{x_m} \overline{a}\,\mathrm{d}x - \mathcal{Q}(h_f(x_m)) - \frac{\partial V}{\partial \tau_0}\frac{\mathrm{d}\tau_0}{\mathrm{d}t}$$

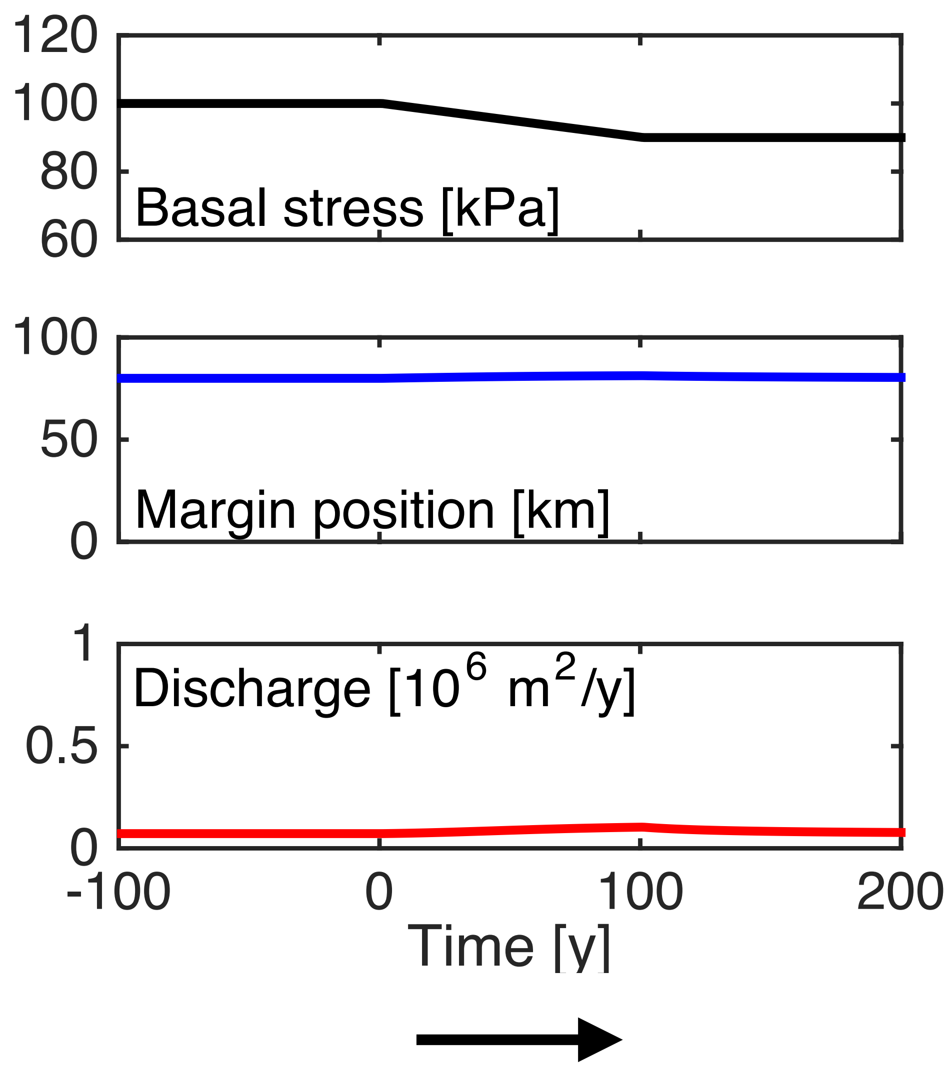


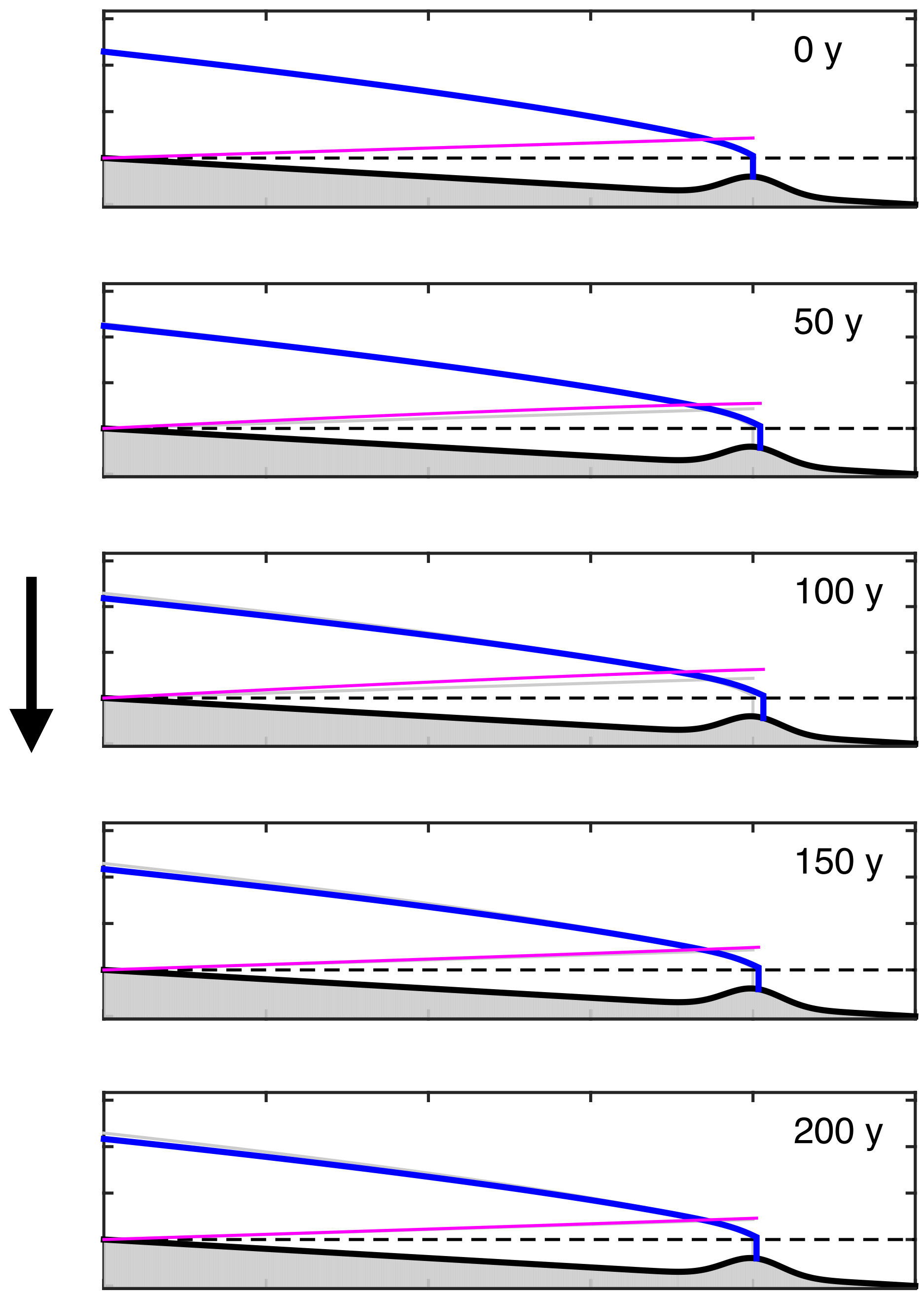



# Weakening bed

In contrast, a **weakening** bed results in initial advance, then retreat - much lower cumulative discharge

$$\frac{\partial V}{\partial x_m}\frac{\mathrm{d}x_m}{\mathrm{d}t} = \int_0^{x_m} \overline{a}\,\mathrm{d}x - \mathcal{Q}(h_f(x_m)) - \frac{\partial V}{\partial \tau_0}\frac{\mathrm{d}\tau_0}{\mathrm{d}t}$$

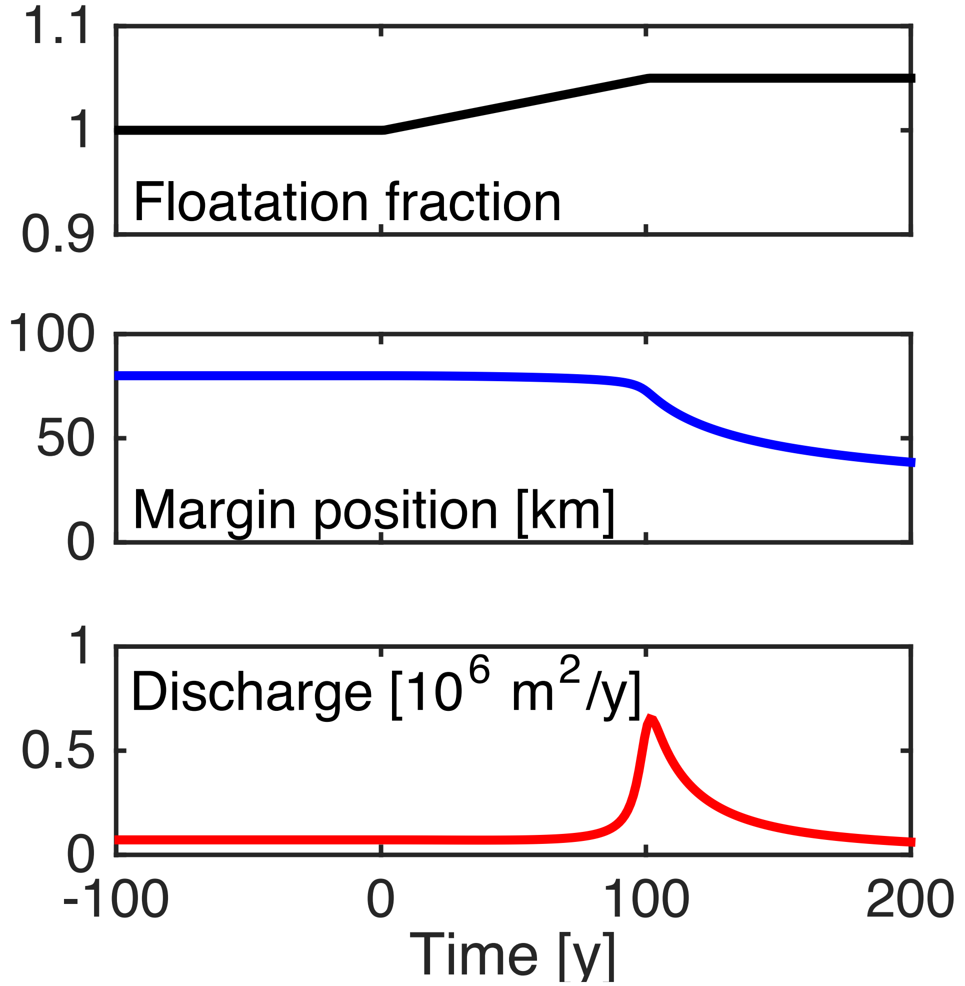


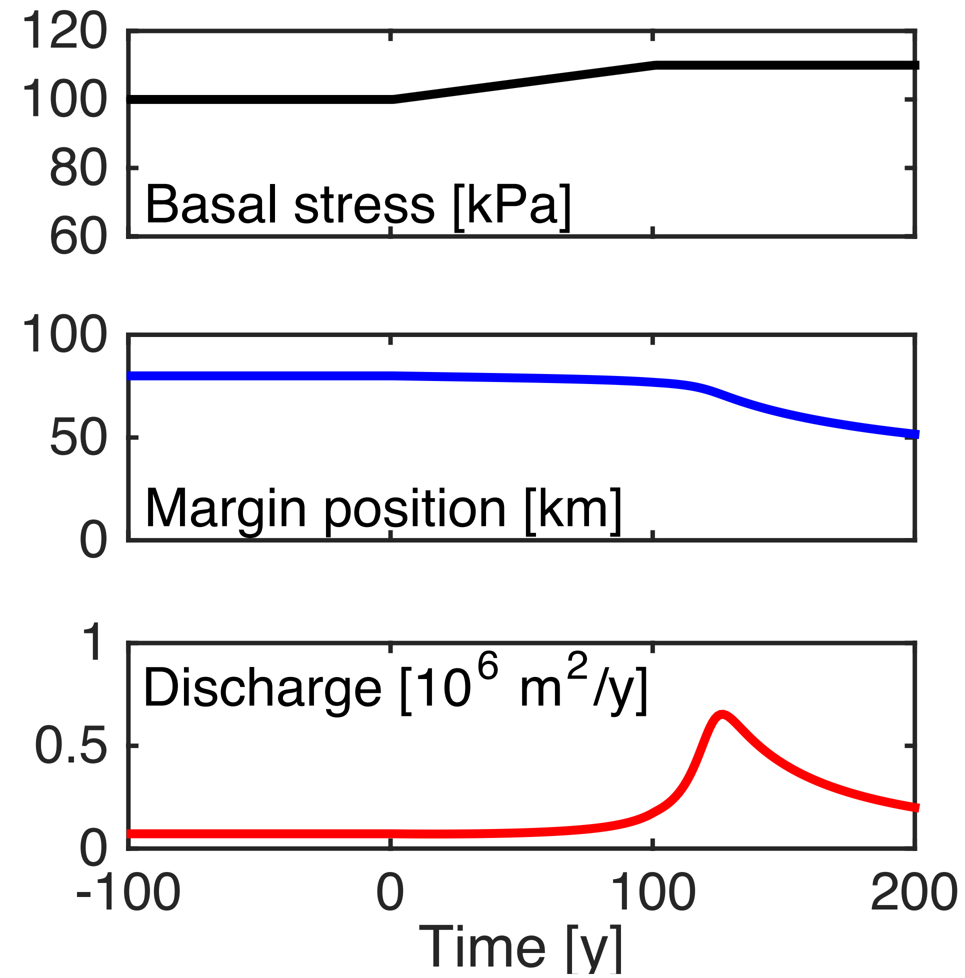
# Ocean forcing

Impose an increase in the floatation fraction required for calving $h_m = f h_f$

$$\frac{\partial V}{\partial x_m}\frac{\mathrm{d}x_m}{\mathrm{d}t} = \int_0^{x_m} \overline{a}\,\mathrm{d}x - \mathcal{Q}(h_f(x_m), f)$$




Compare with strengthening bed:




very similar response

# Summary

Subglacial meltwater can both increase and decrease ice speeds.  The *decrease* may be the more significant for ice loss.

Conventional ice-sheet models are not yet equipped to investigate this.

Plastic-bed ice-sheet models provide a useful means to examine margin retreat - limited by re-distribution of ice mass rather than by ice rheology / sliding law.

Both an ocean-induced **increase in calving rate** and a hydrologically-induced **decrease in upstream supply** can precipitate rapid retreat.