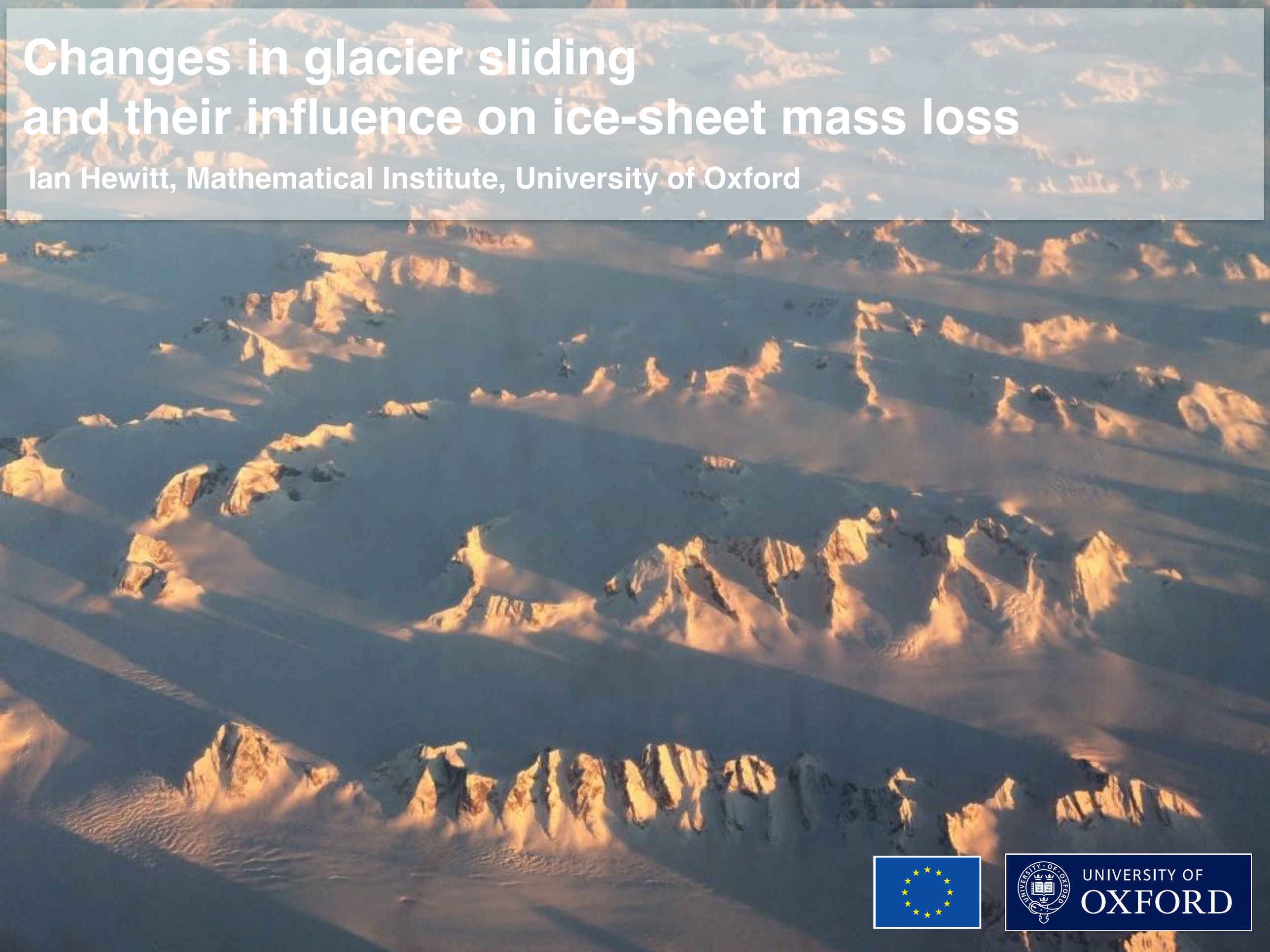
Changes in glacier sliding and their influence on ice-sheet mass loss

Ian Hewitt, Mathematical Institute, University of Oxford



Changes in glacier sliding and their influence on ice-sheet mass loss

Ian Hewitt, Mathematical Institute, University of Oxford

(i) How does meltwater penetrating to the bed of a glacier or ice sheet affect its motion?

(ii) What implications does this have for ice loss / sea level?

UNIVERSITY OF OXFORD

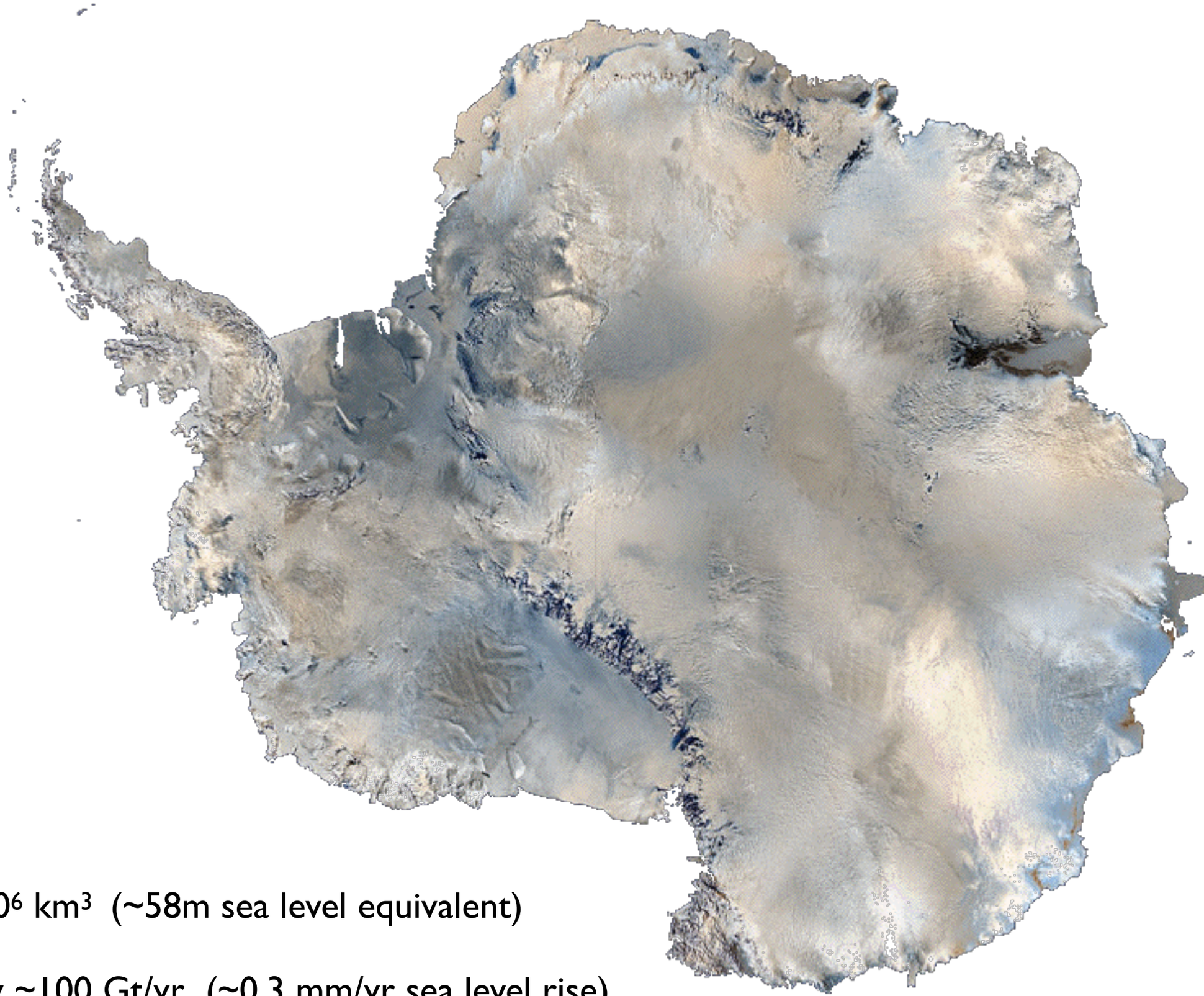
Greenland Ice Sheet

Current volume ~2.9x10^6 km^3 (~7m sea level equivalent)

Net mass loss currently ~200 Gt/yr (~0.6 mm/yr sea level rise)

Timescale ~10,000 years

Antarctic Ice Sheet

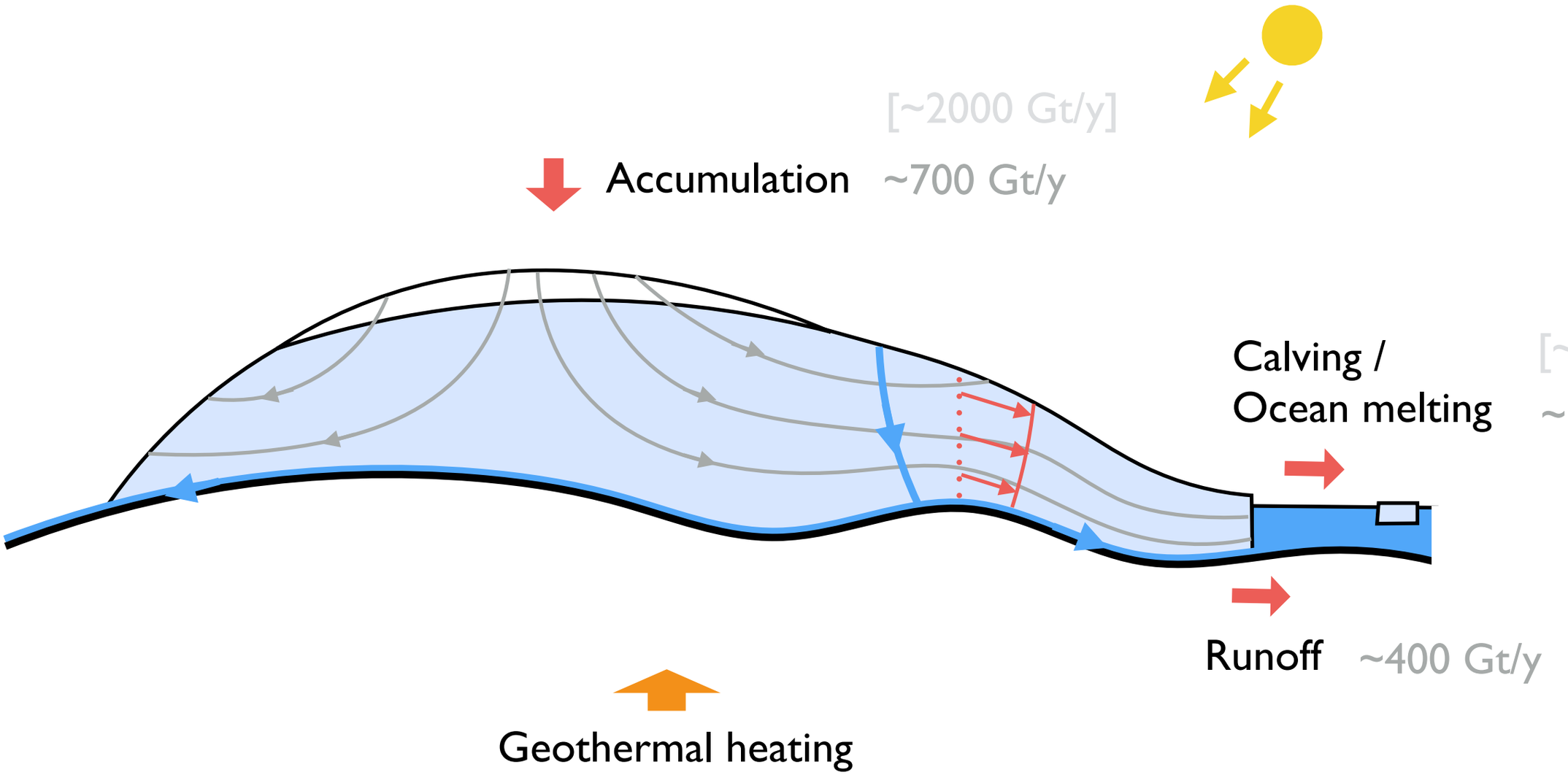


Current volume ~27x10^6 km^3 (~58m sea level equivalent)

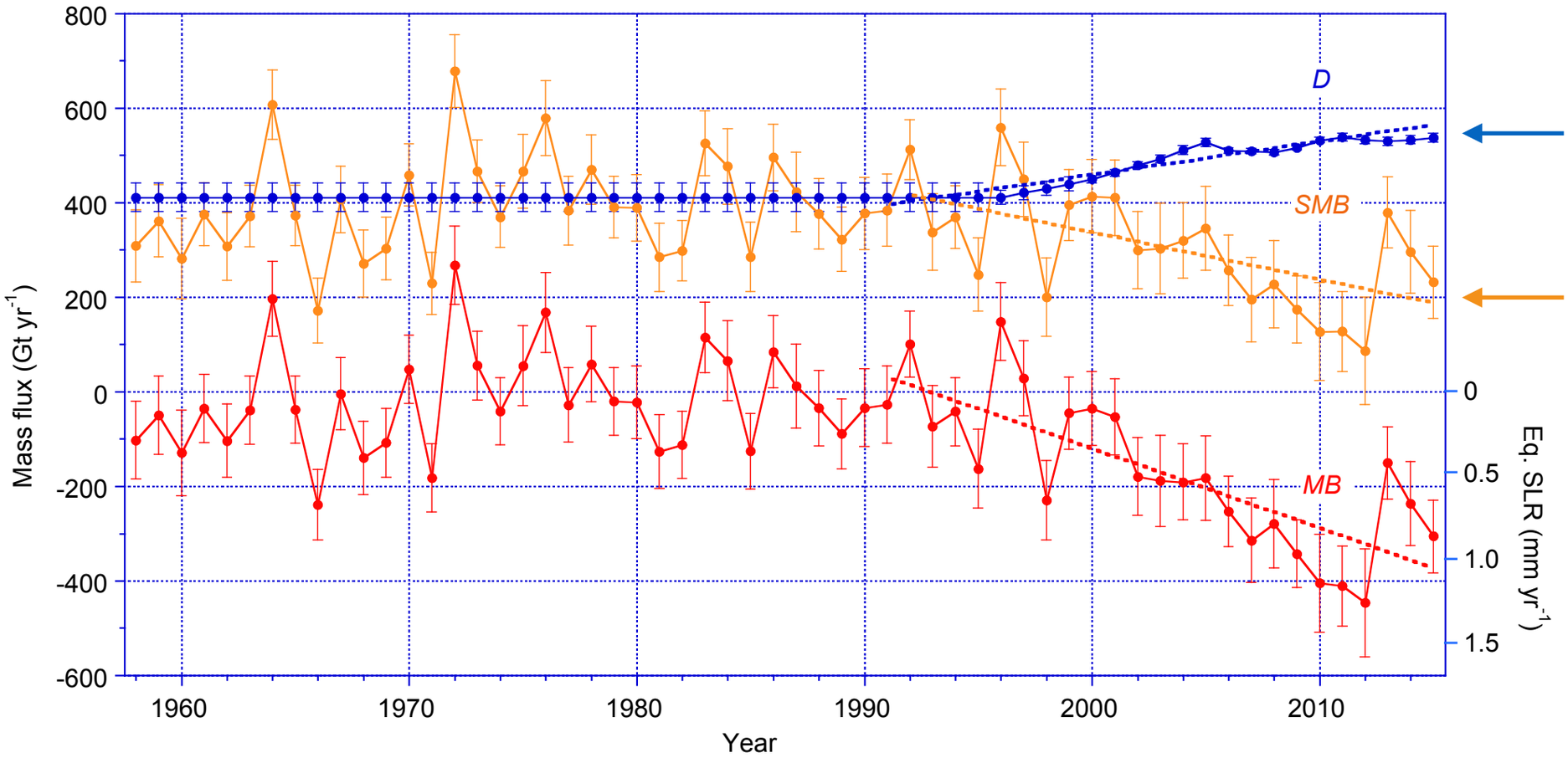
Net mass loss currently ~100 Gt/yr (~0.3 mm/yr sea level rise)

Timescale ~300,000 years

Ice sheet mass balance



Greenland ice sheet mass balance



Discharge
calving

Surface balance (SMB)
accumulation - runoff

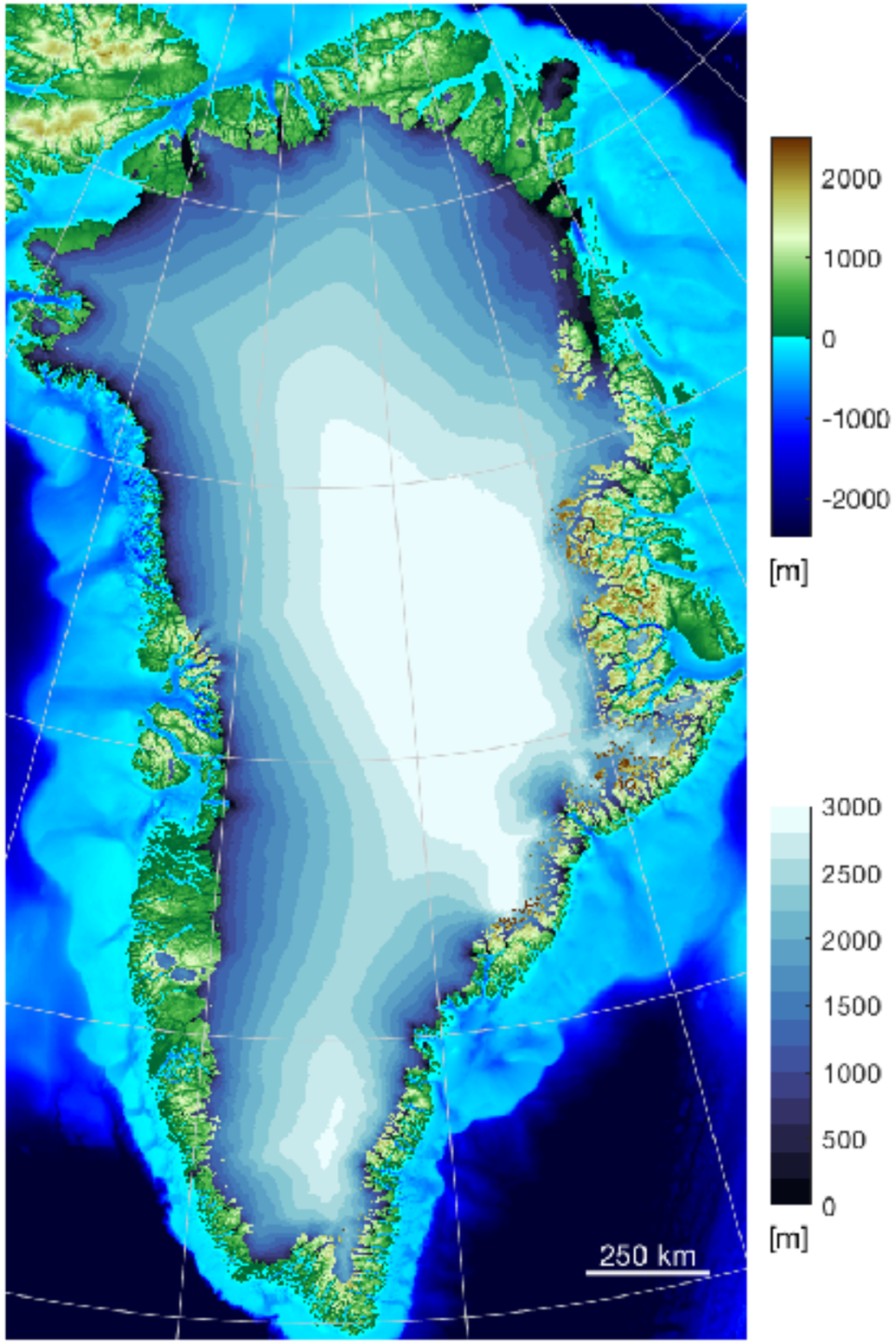
van den Broeke et al 2016

Greenland is losing mass - due to **decreased SMB** and **increased** discharge

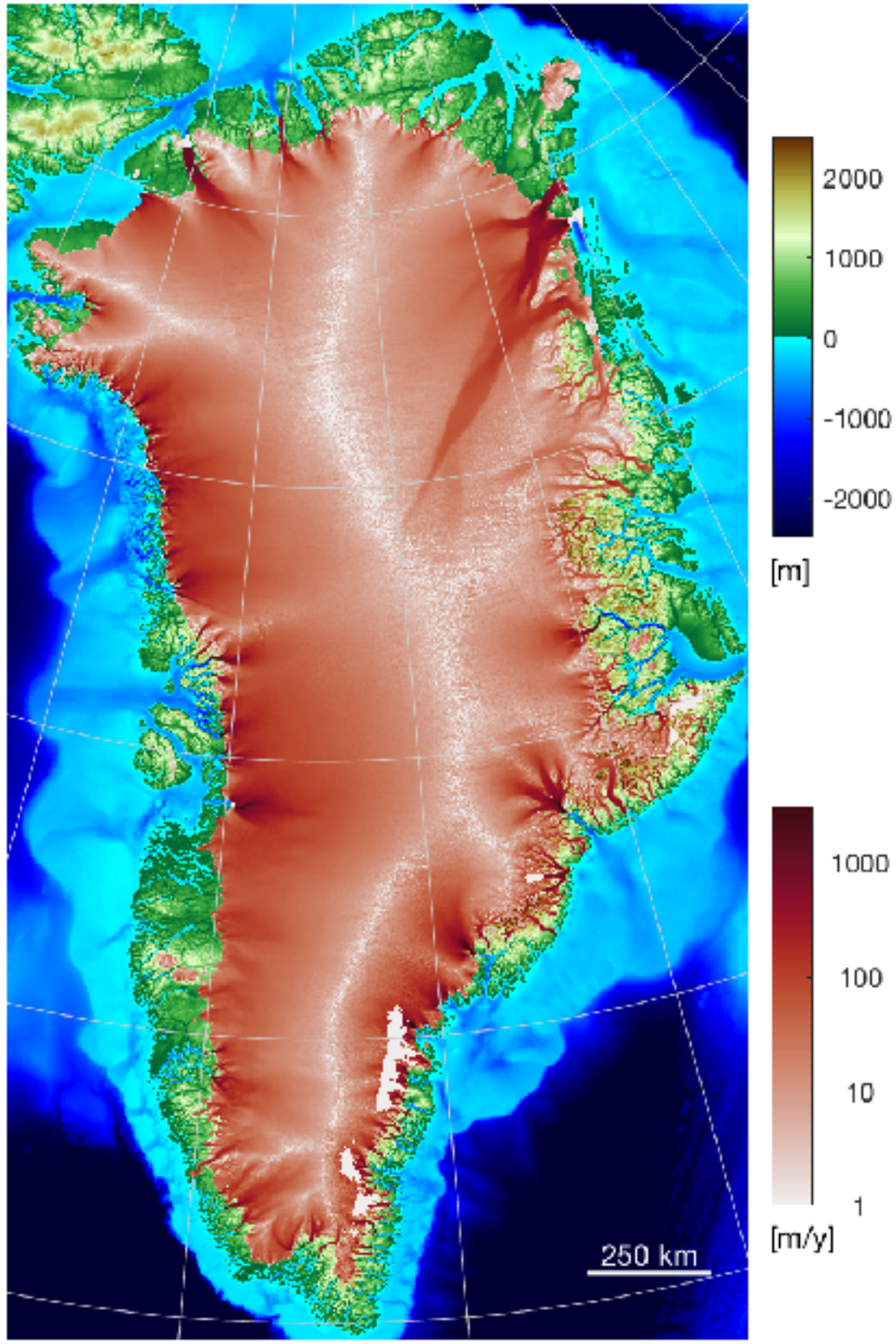
Time-lapse movie

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

Greenland ice sheet

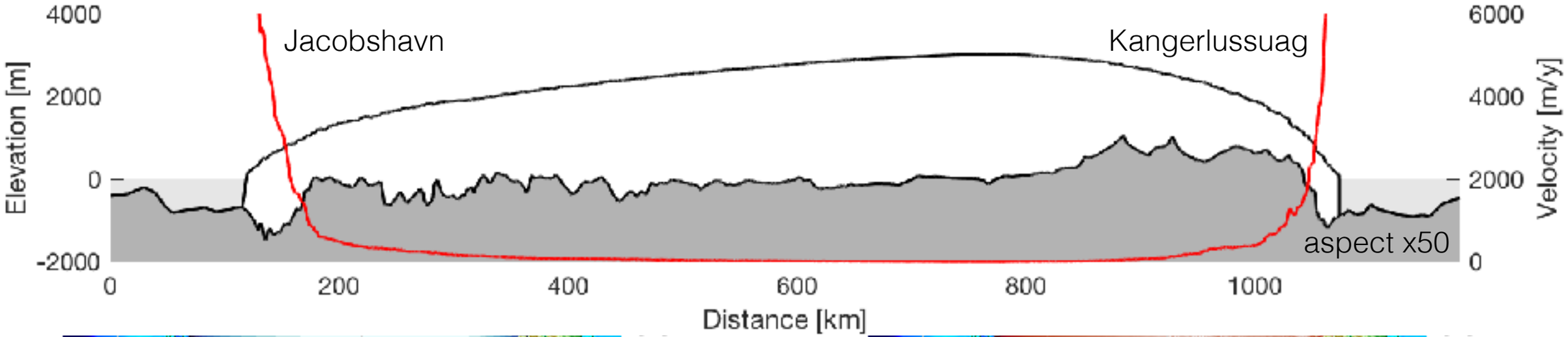


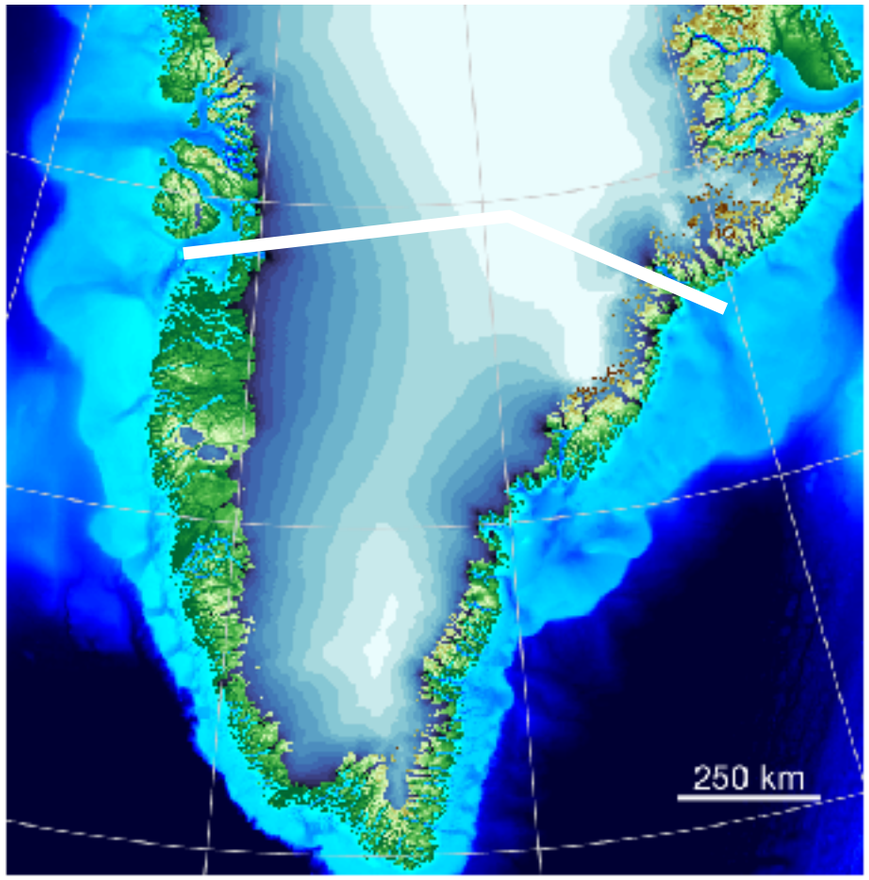
Elevation

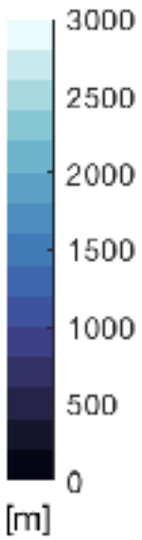


Ice speed (Jan/Feb 2018 from Sentinel 1)

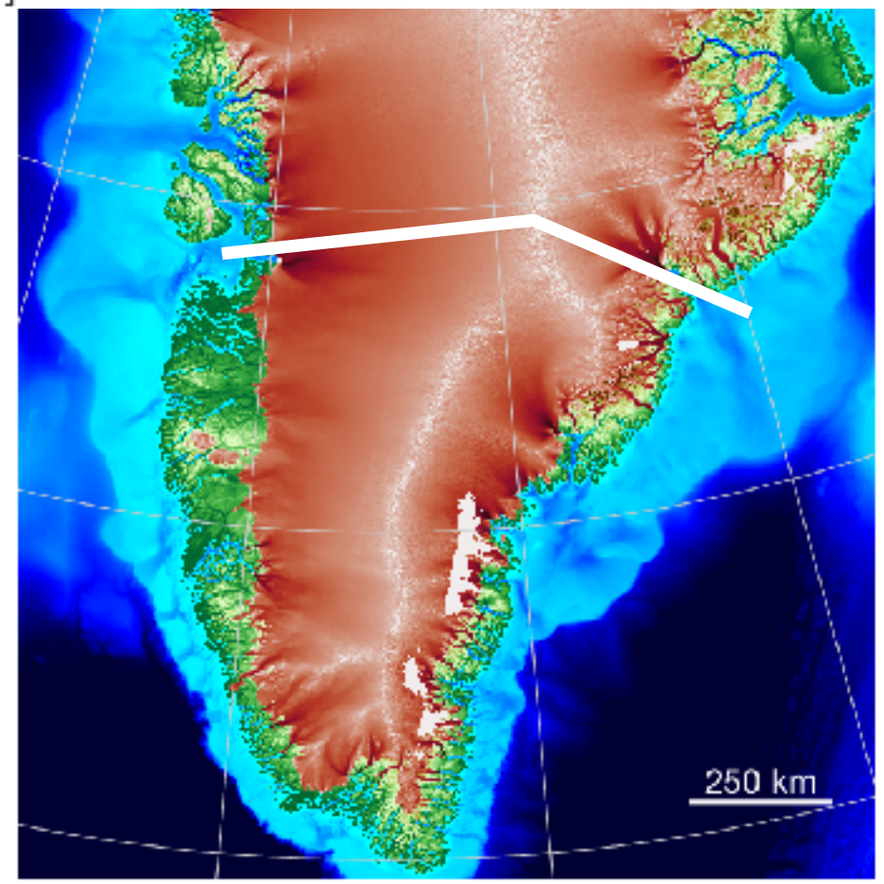
Greenland ice sheet

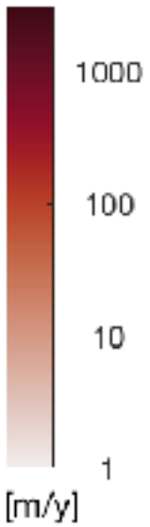






Elevation



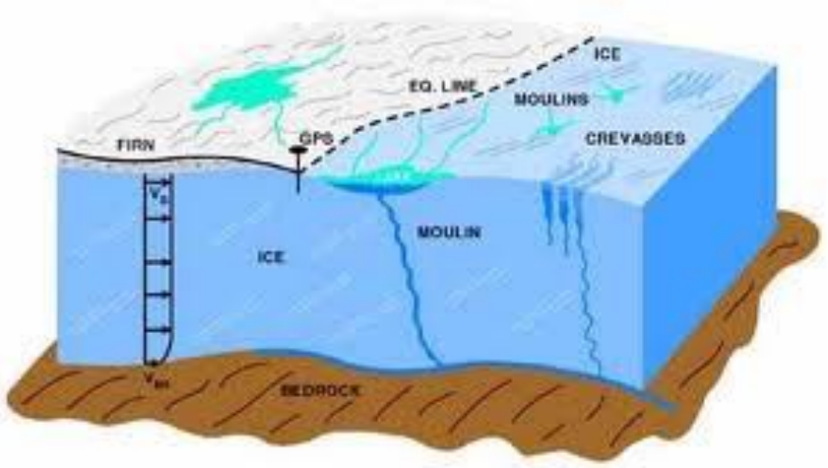


Ice speed (Jan/Feb 2018 from Sentinel 1)

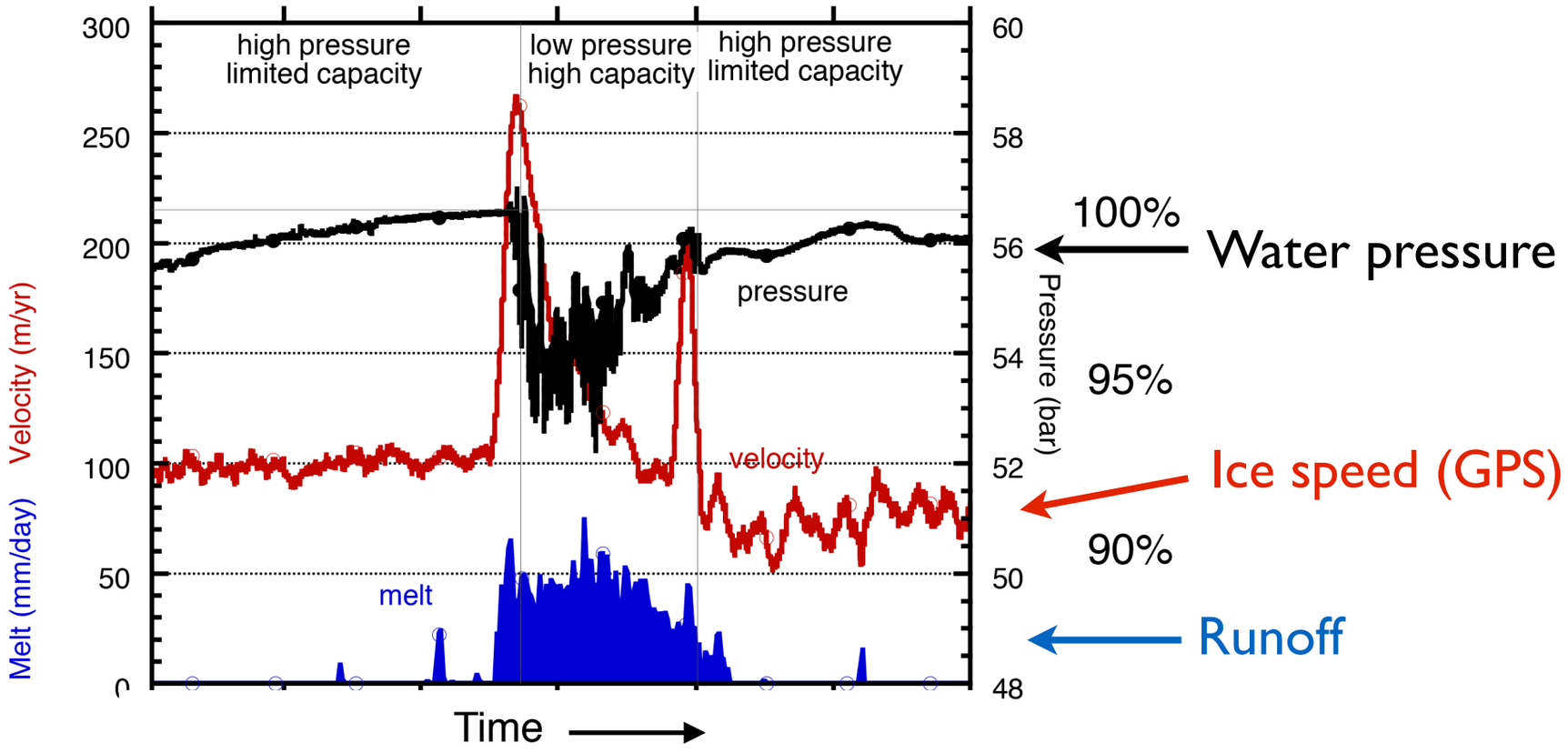
Laura Stevens

Greenland ice sheet velocities

Summer drainage of surface meltwater causes **significant fluctuations** in ice speed including **seasonal**, **diurnal**, and **episodic** acceleration events (measured by GPS)



Zwally et al 2002

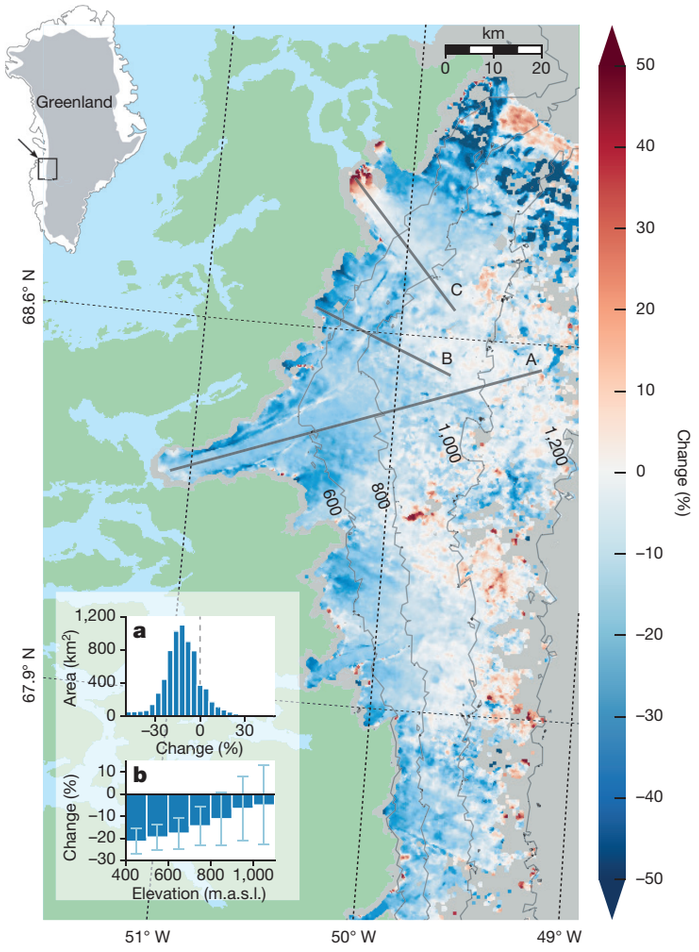


van de Wal et al 2015

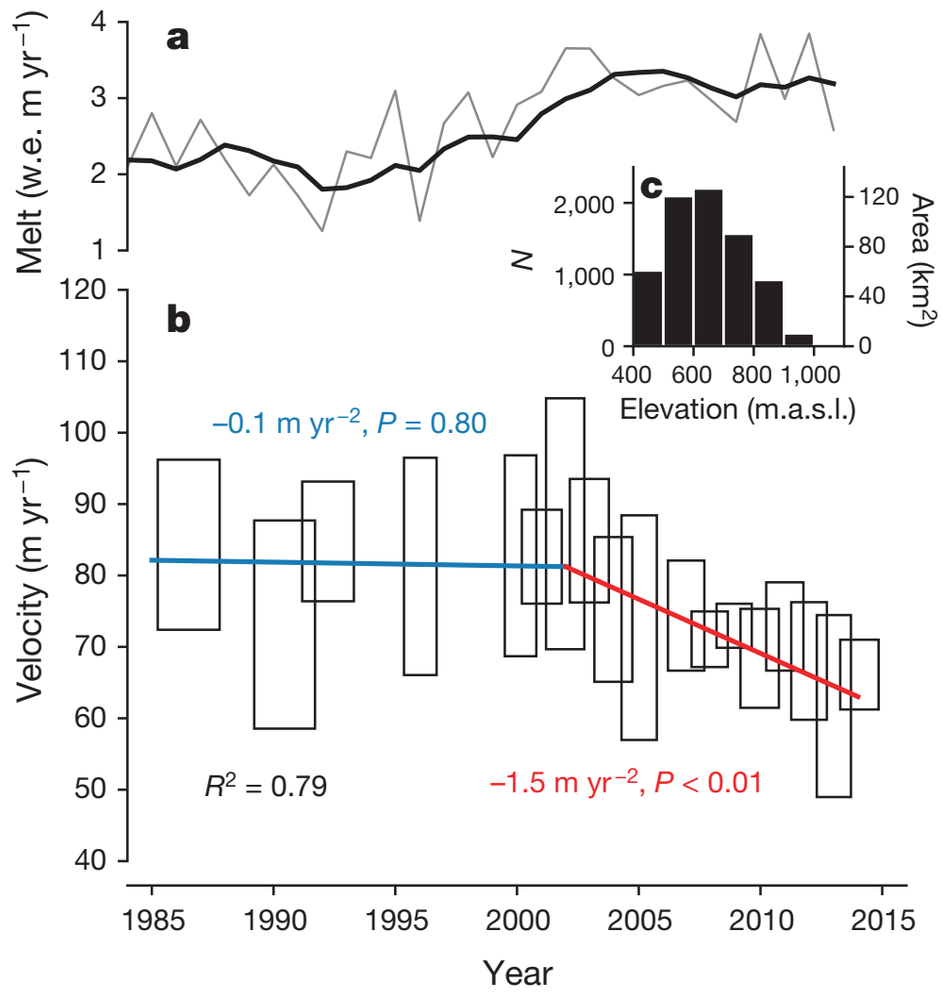
→ positive feedback with increased surface melt?

Greenland ice sheet velocities

Longer term measurements, over a period of increasing surface melt, appear to show a slight **decreasing** trend in **average velocity**. e.g. van de Wal et al 2015, Stevens et al 2016

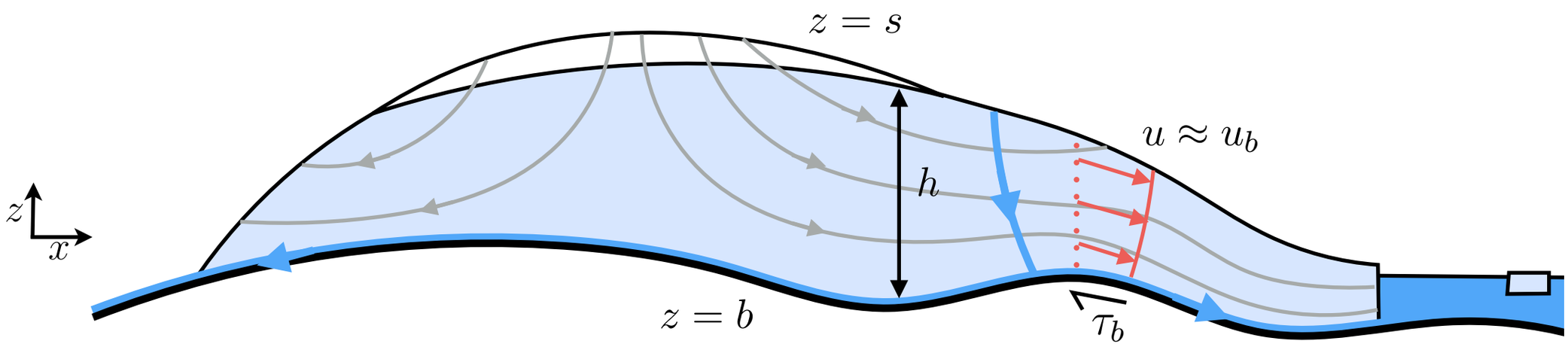


Tedstone et al 2015



→ suggests a **weak, possibly inverse,** relationship between runoff and average velocity

Ice flow



Basal resistance must approximately balance the '**driving stress**' (down-slope component of weight)

$$\tau_d = -\rho_i g h \frac{\partial s}{\partial x}$$

Basal resistance related to ice speed by a **friction law**

$$\tau_b = C(N)\, u_b^{1/m}$$

$N = \rho_i g h - p_w$ effective pressure

Basal **water** flow is driven by the **hydraulic potential** gradient $-\nabla\phi \approx -\rho_i g \nabla s - (\rho_w - \rho_i) g \nabla b$

i.e. both ice and water flow roughly in direction of surface slope.

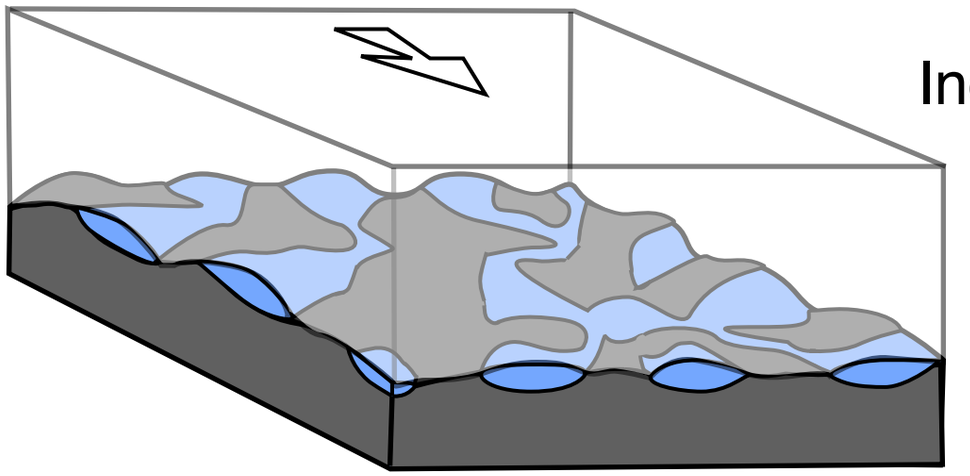
Mount Robson, Canada

Vernagtferner, Austria

1 m

Hochjochferner, Italy

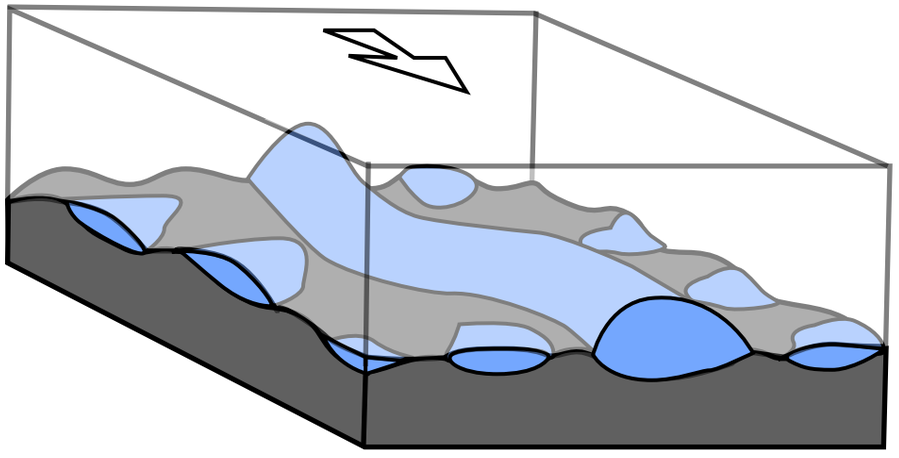
Evolution of the subglacial drainage system



Isolated water **cavities**

Water pressure **increases** (so basal resistance **decreases**) with increasing meltwater flux

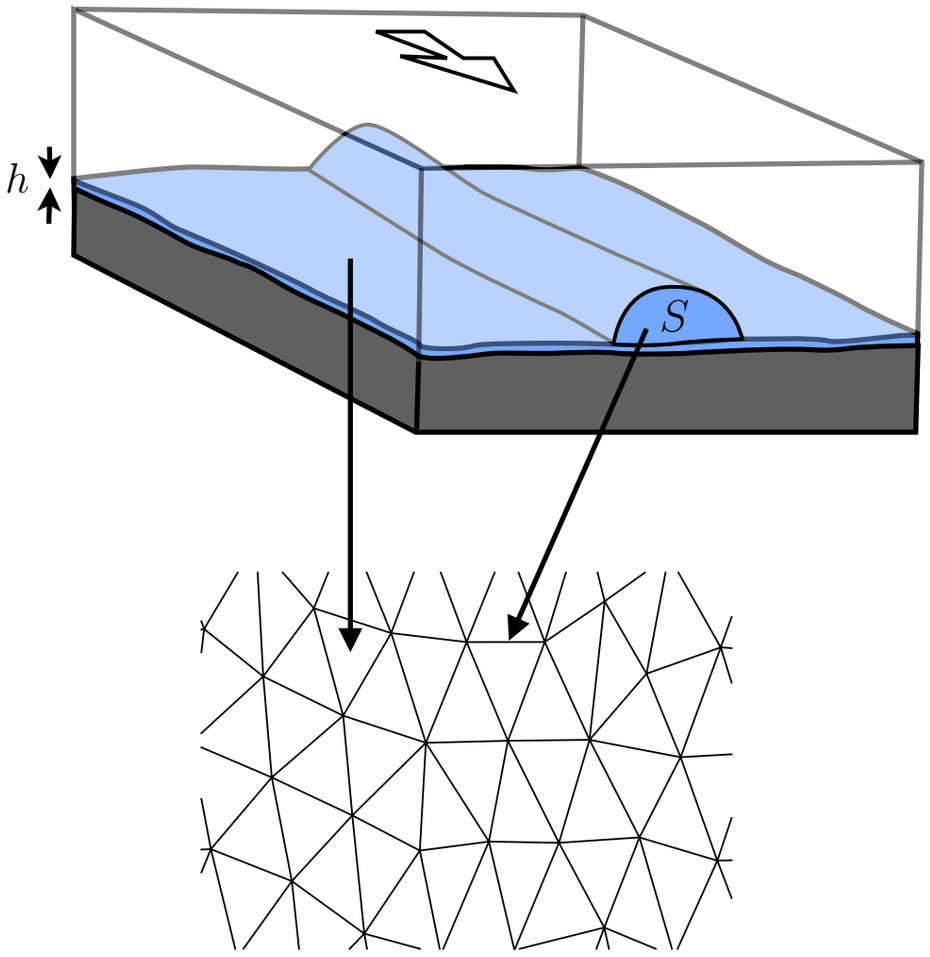
Increased efficiency



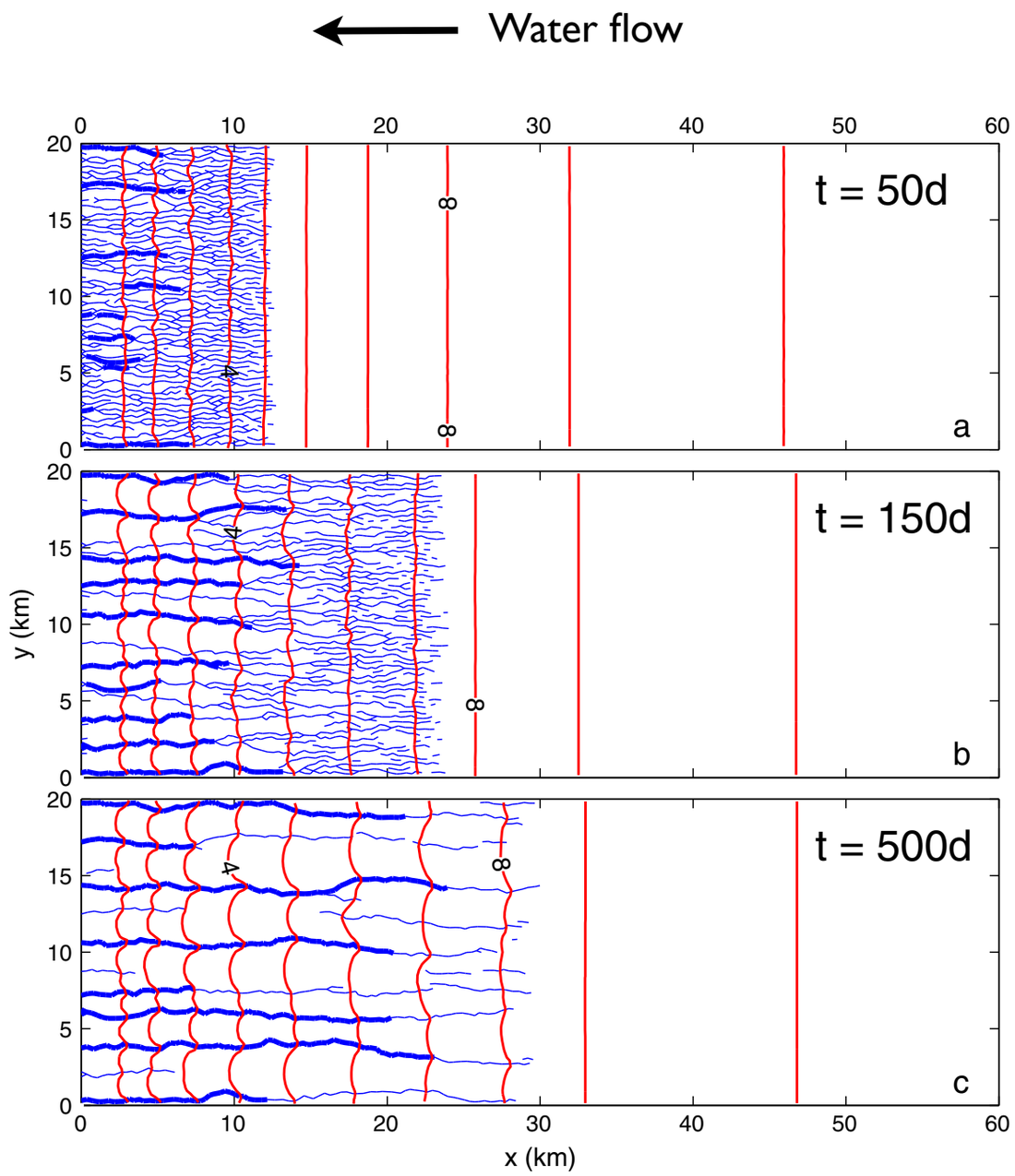
Melt-enlarged **channels**

Water pressure **decreases** (so basal resistance **increases**) with increasing meltwater flux

A model of the evolving drainage system



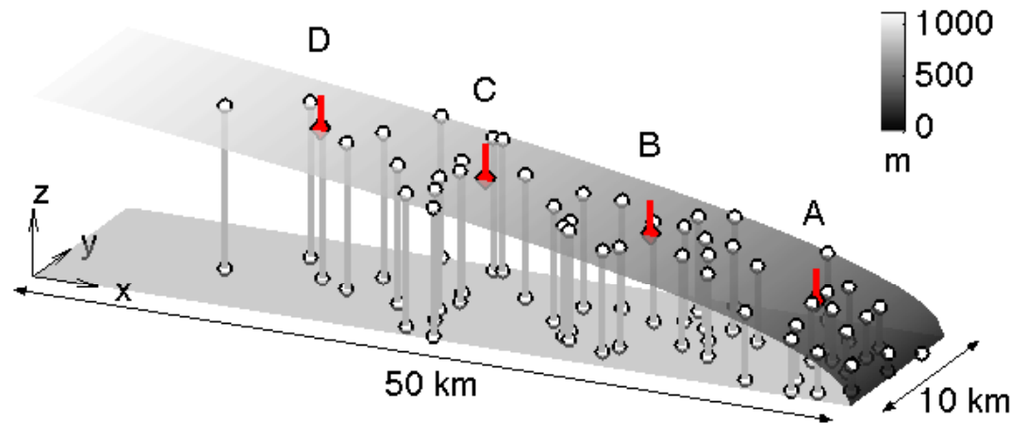
Channel segments connected on a planar graph, coupled to a continuum ‘sheet’.



Werder et al 2013

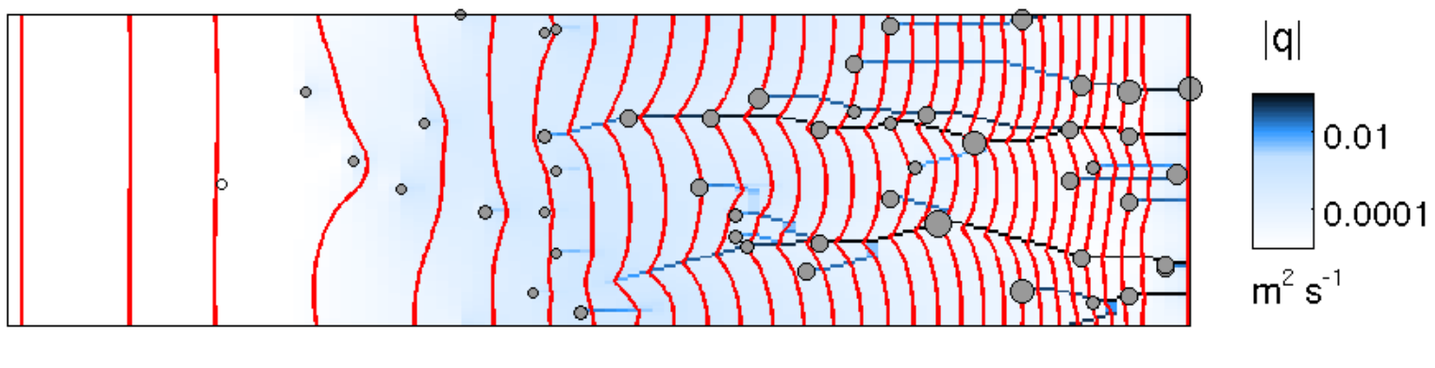
Steady-state driven by surface runoff

+ friction law $\tau_b = cNu_b^{1/m}$

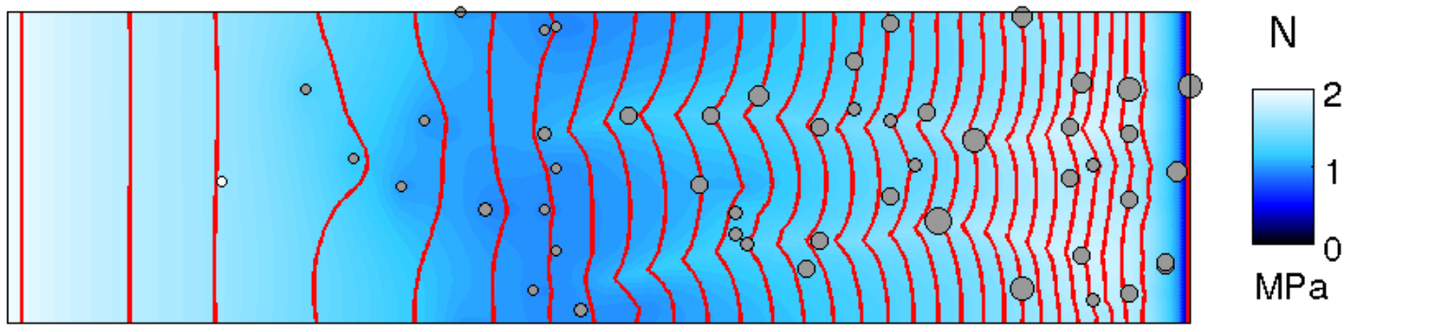


Water flow

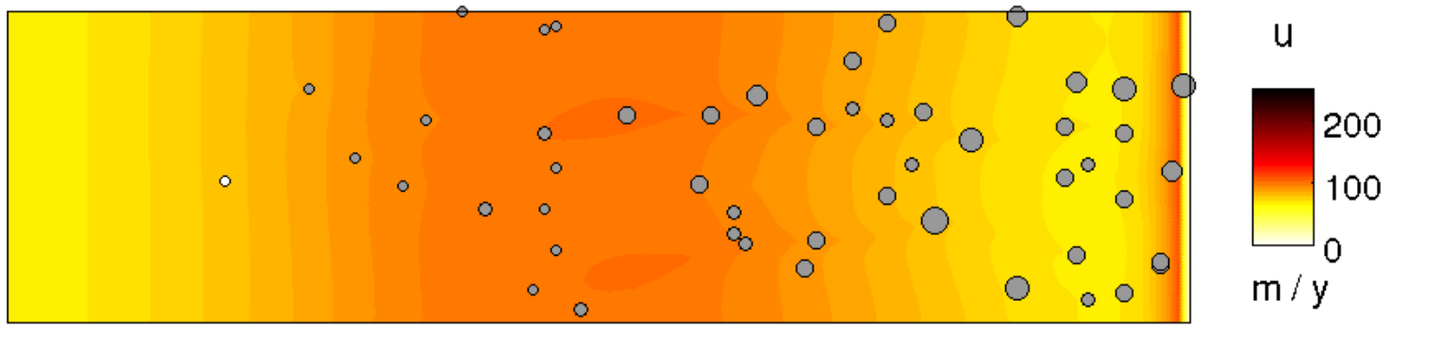
Subglacial discharge



Effective pressure

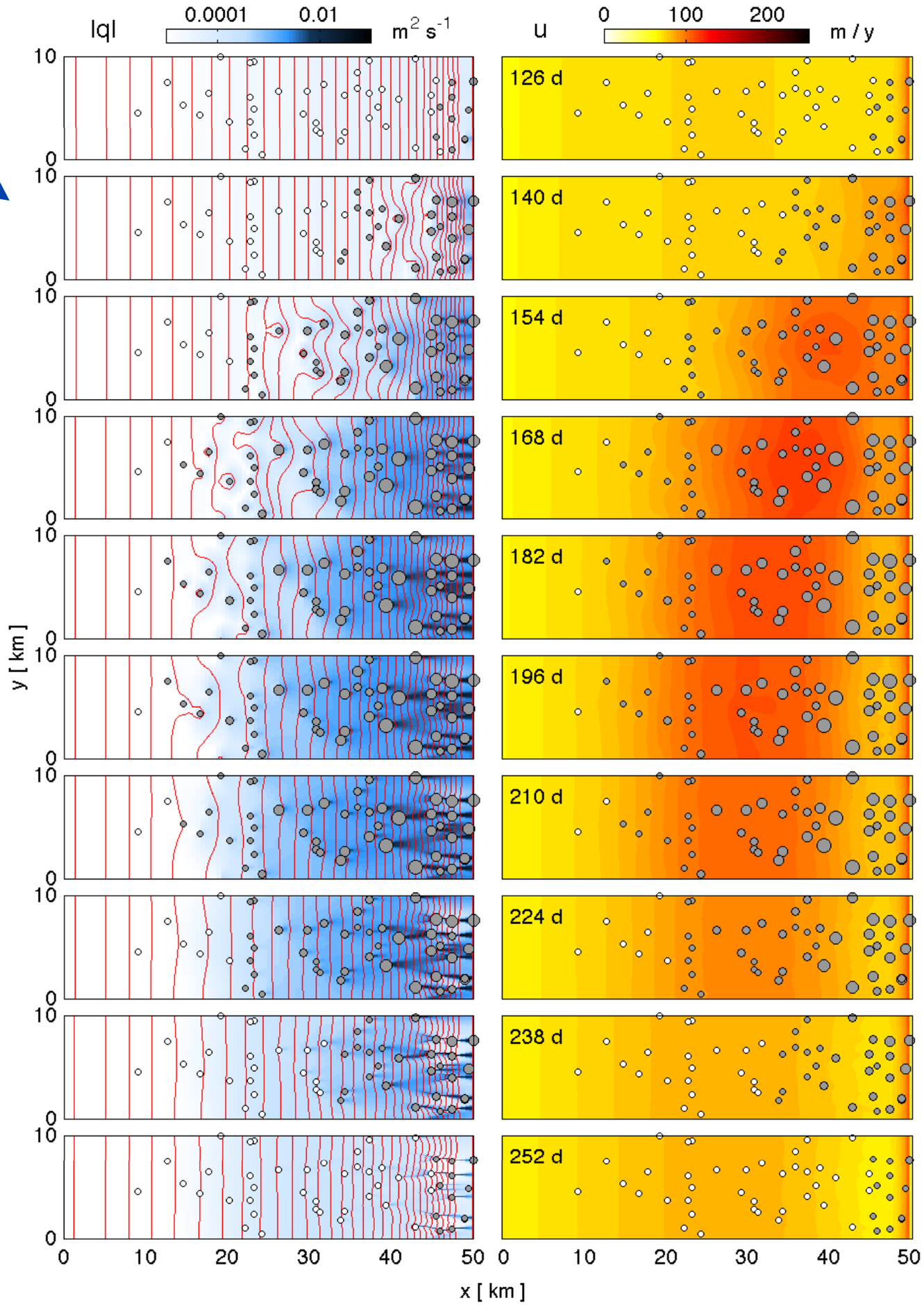


Ice speed



Subglacial discharge (areal m^2/s)

Ice speed



Time

Hewitt 2013, EPSL

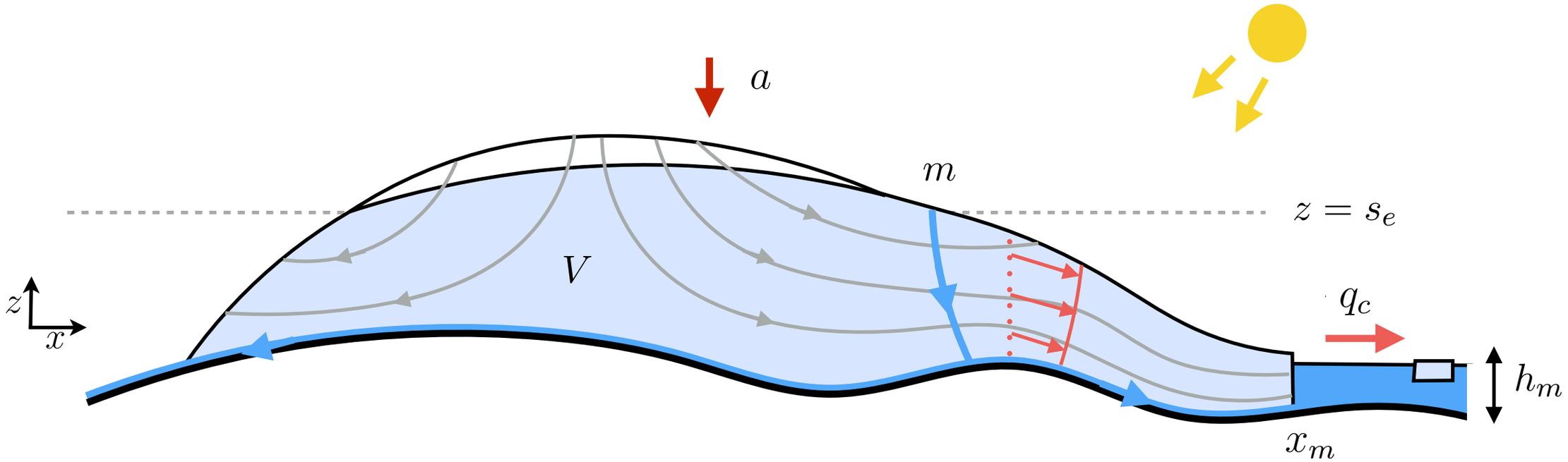
Summary I

Increases in surface melt can both **increase** and **decrease** average ice speeds.

Numerical models are increasingly able to reproduce observed patterns of **seasonal velocity change** (with some tuning) e.g. Bougamont et al 2014, Hoffman et al 2016.

But computations are expensive - these processes are not yet in any continental or decadal-scale models (e.g. CMIP6 models)

Ice-sheet mass balance

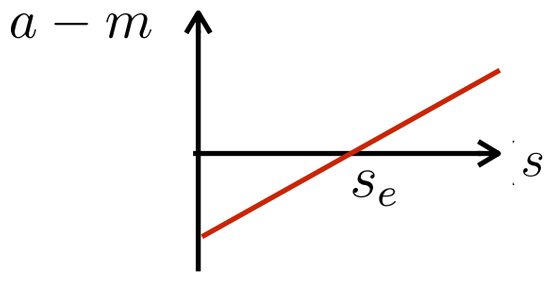


Global **mass conservation**

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \int_A (a - m)\,\mathrm{d}x - q_c$$

- **Surface mass balance** (SMB) depends primarily on surface **elevation**

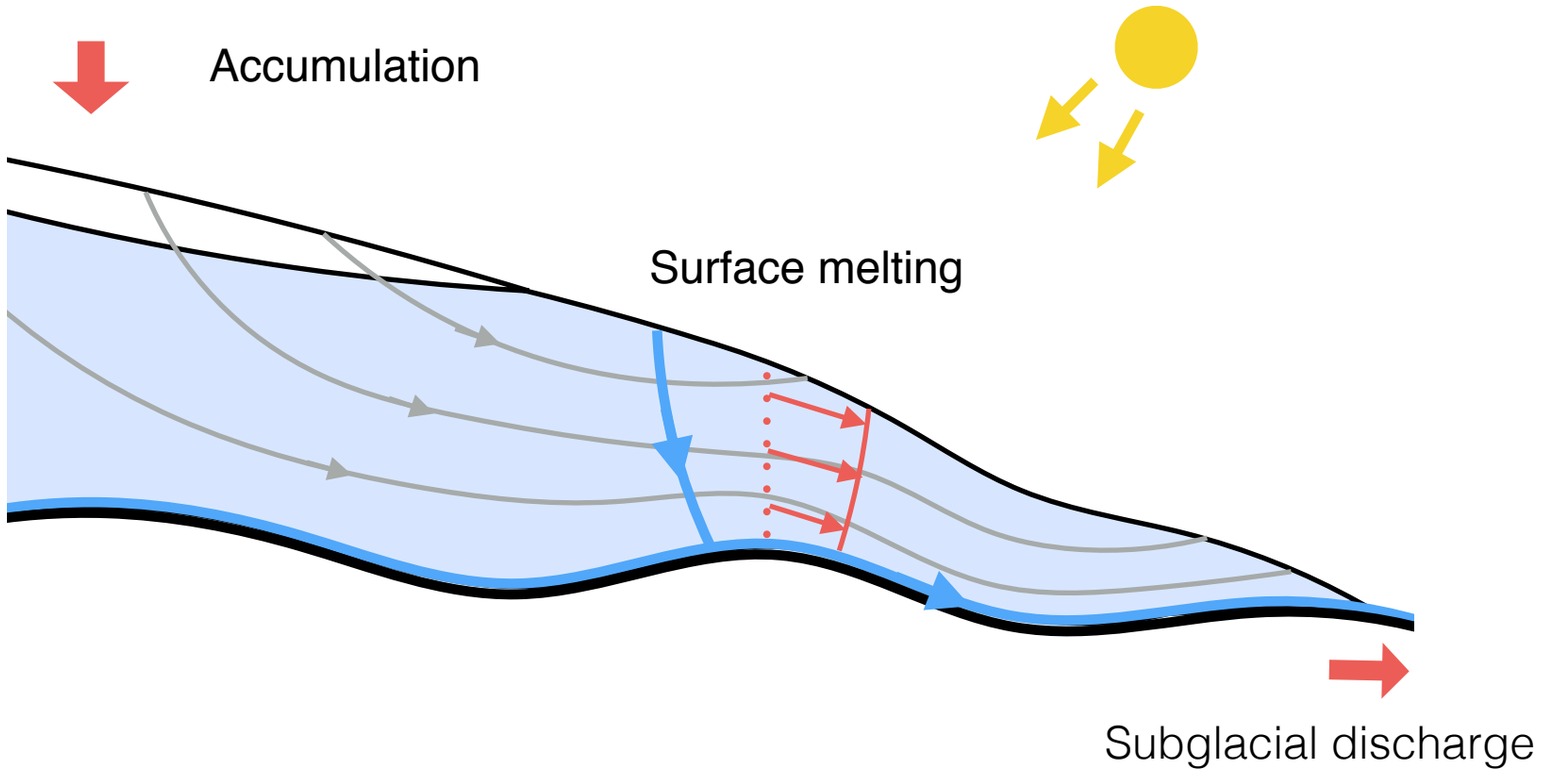
e.g. $a - m = \lambda(s - s_e)$



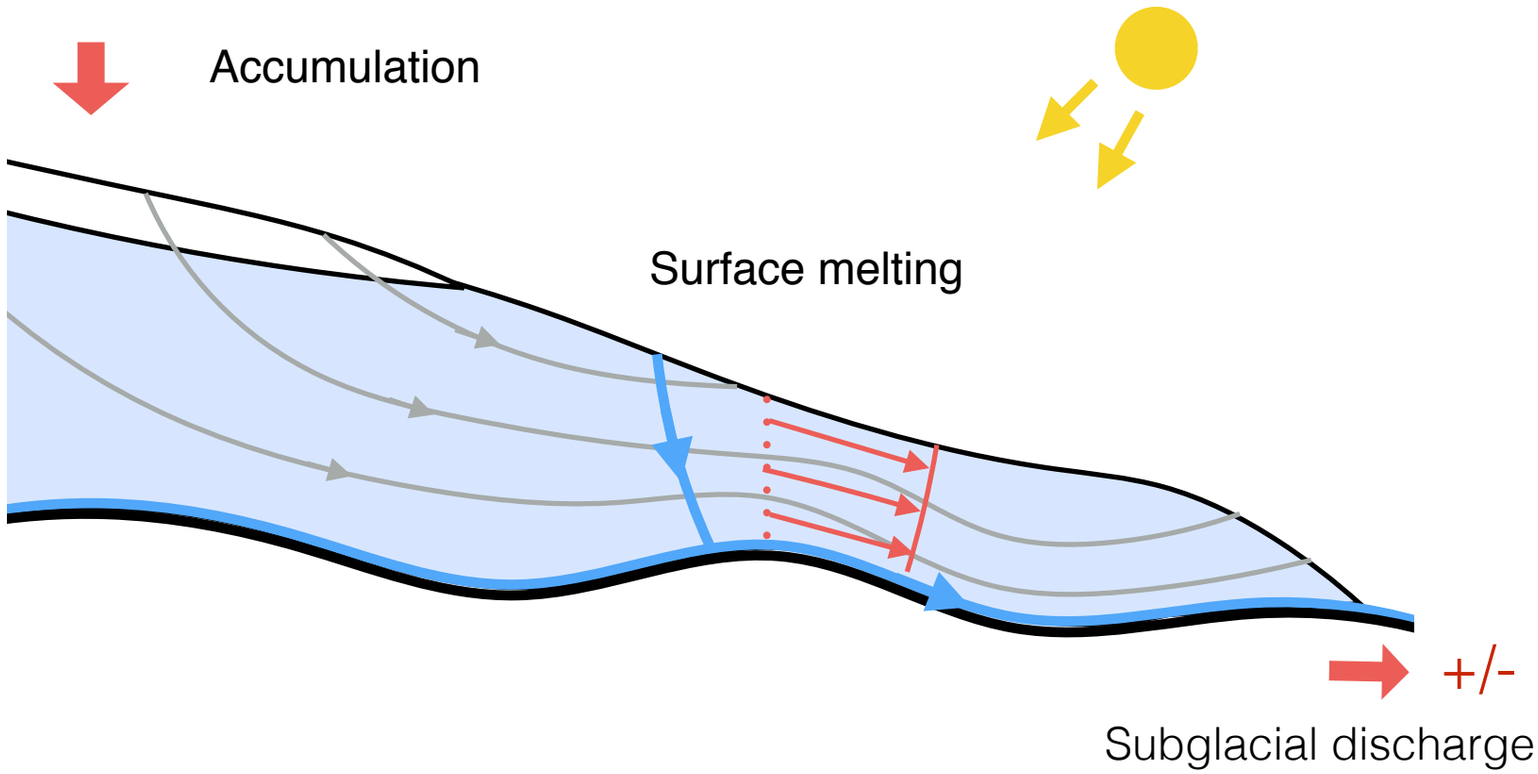
s_e equilibrium line altitude (ELA)

- **Calving flux** is related to ice velocity and margin advance/retreat $q_c = h_m \left(u - \frac{\mathrm{d}x_m}{\mathrm{d}t} \right)$

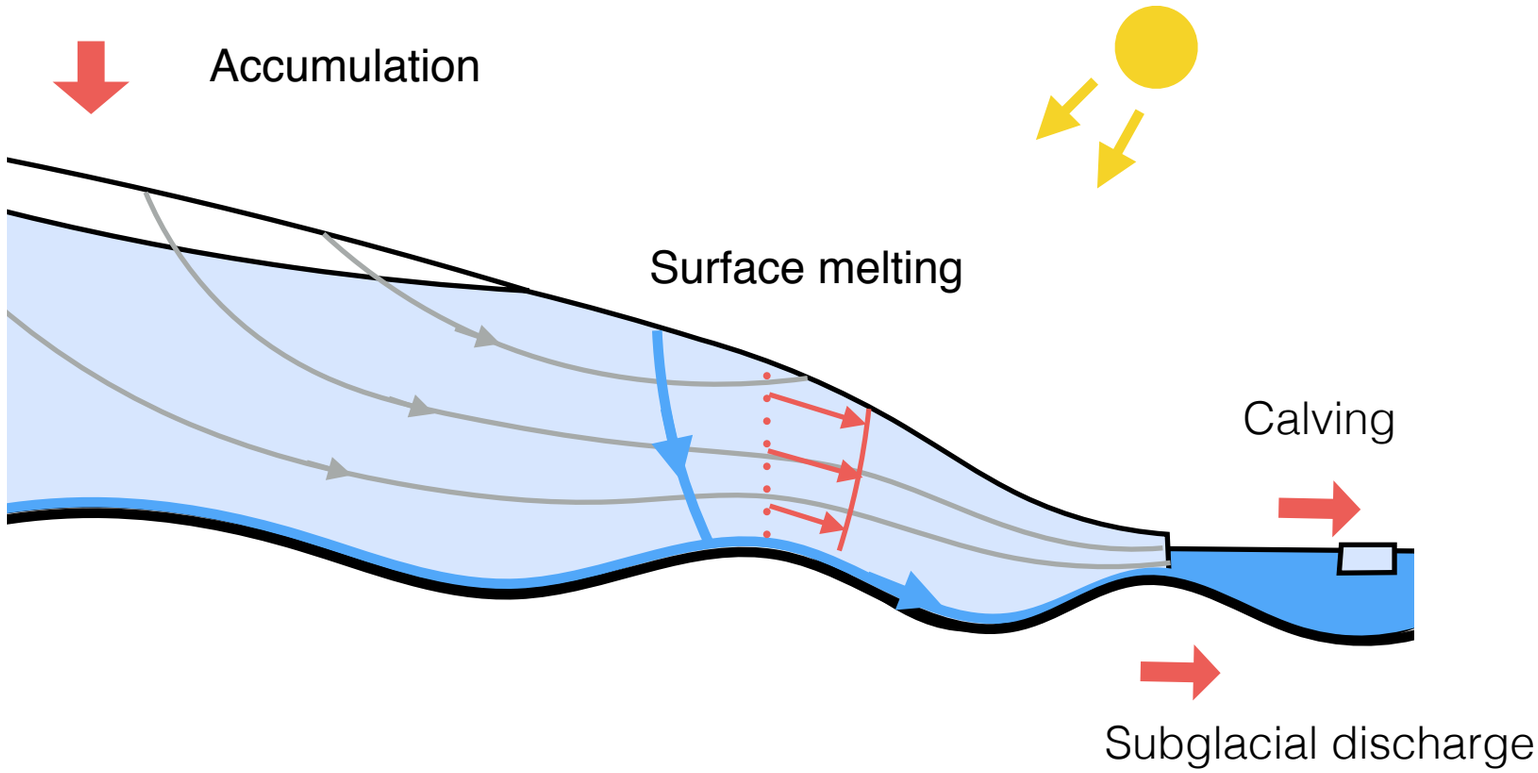
Land terminating glaciers



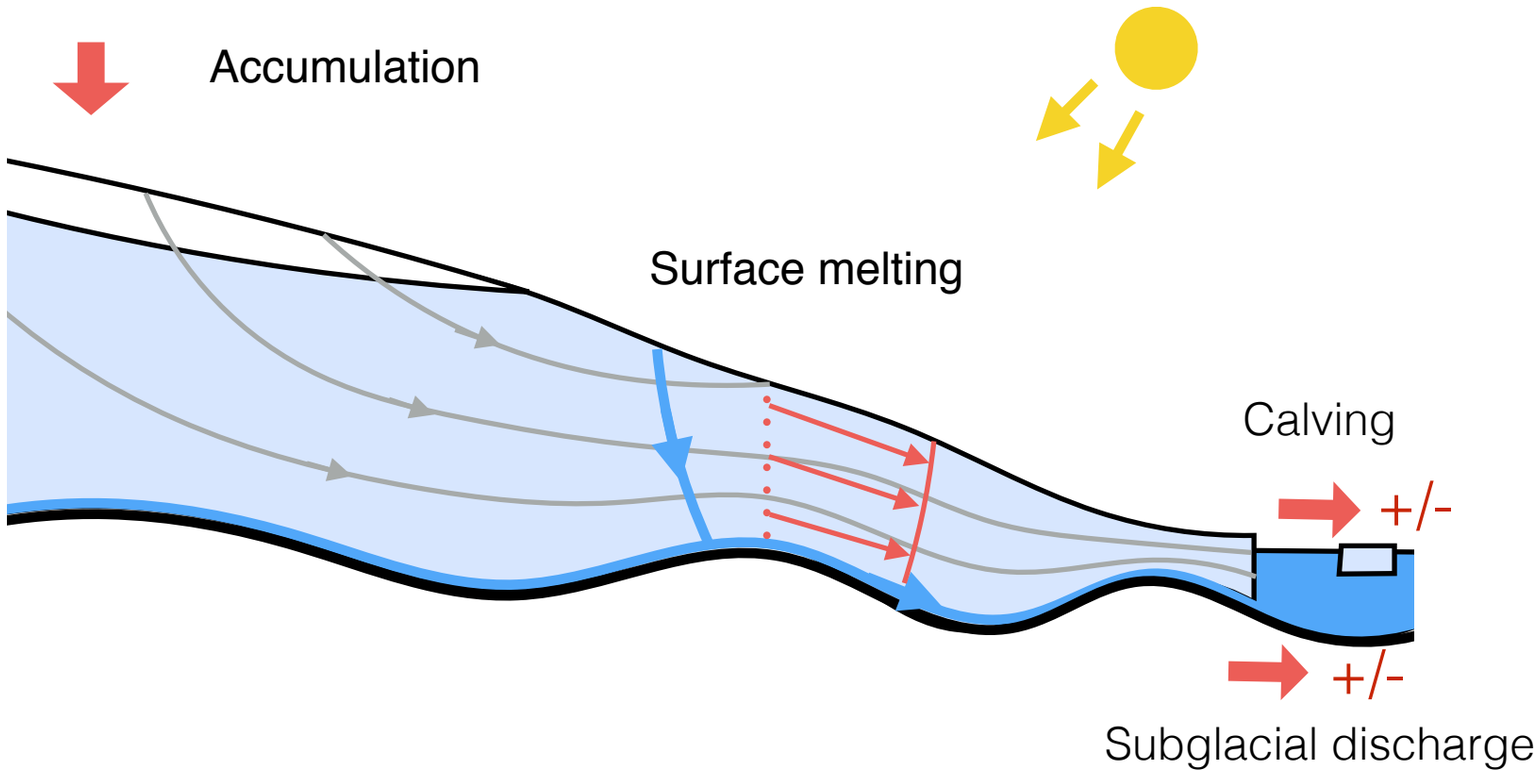
Land terminating glaciers



Marine terminating glaciers



Marine terminating glaciers



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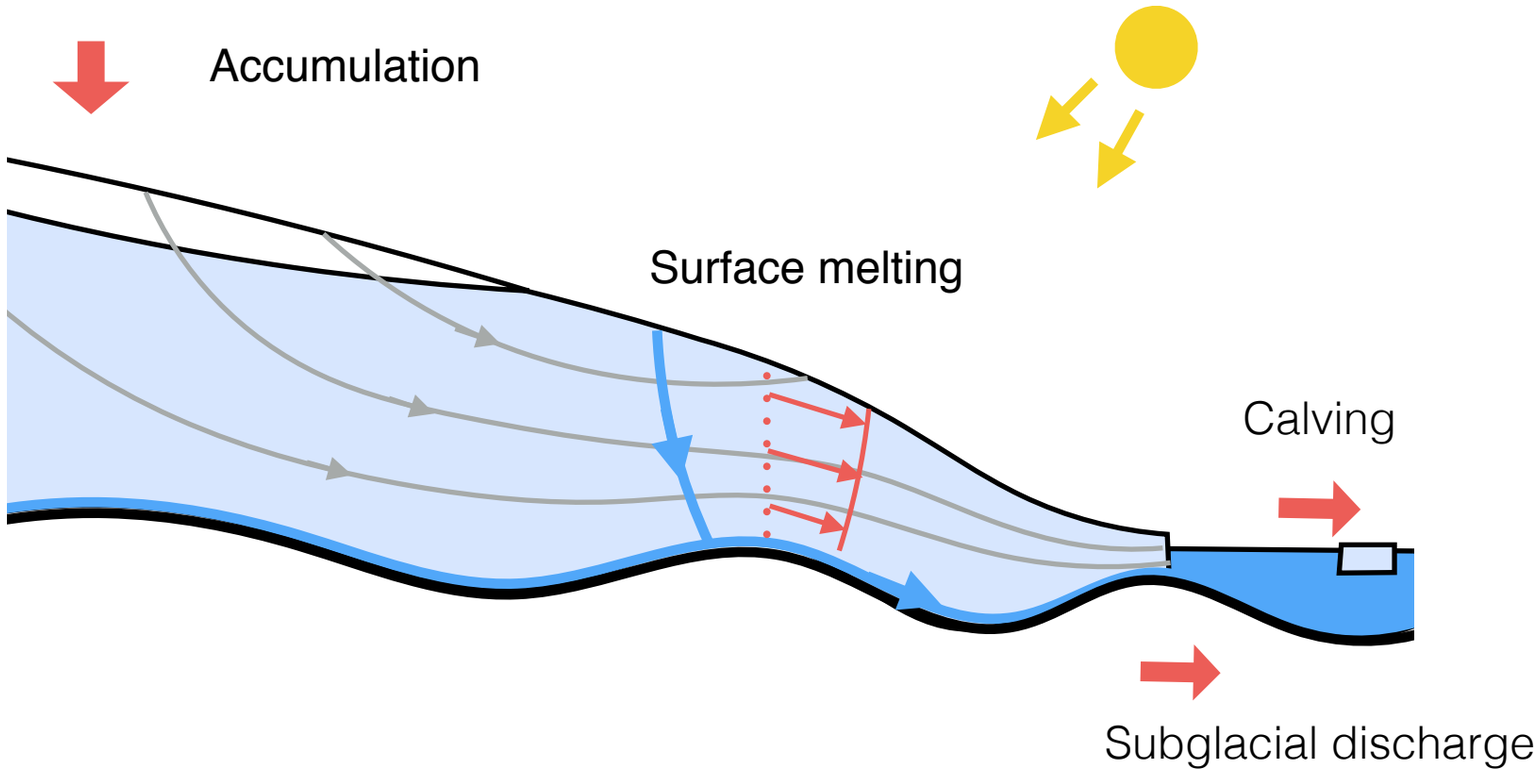

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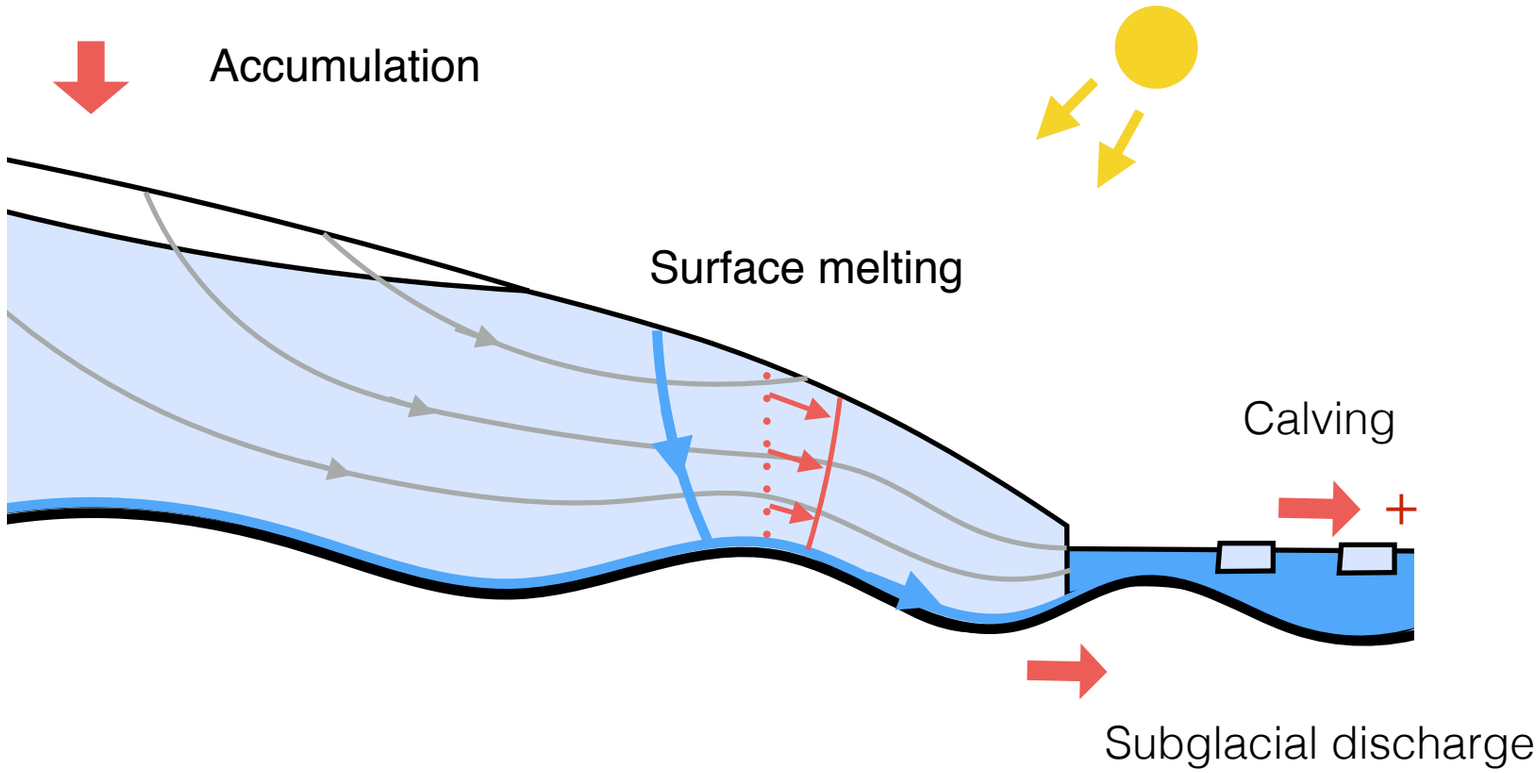

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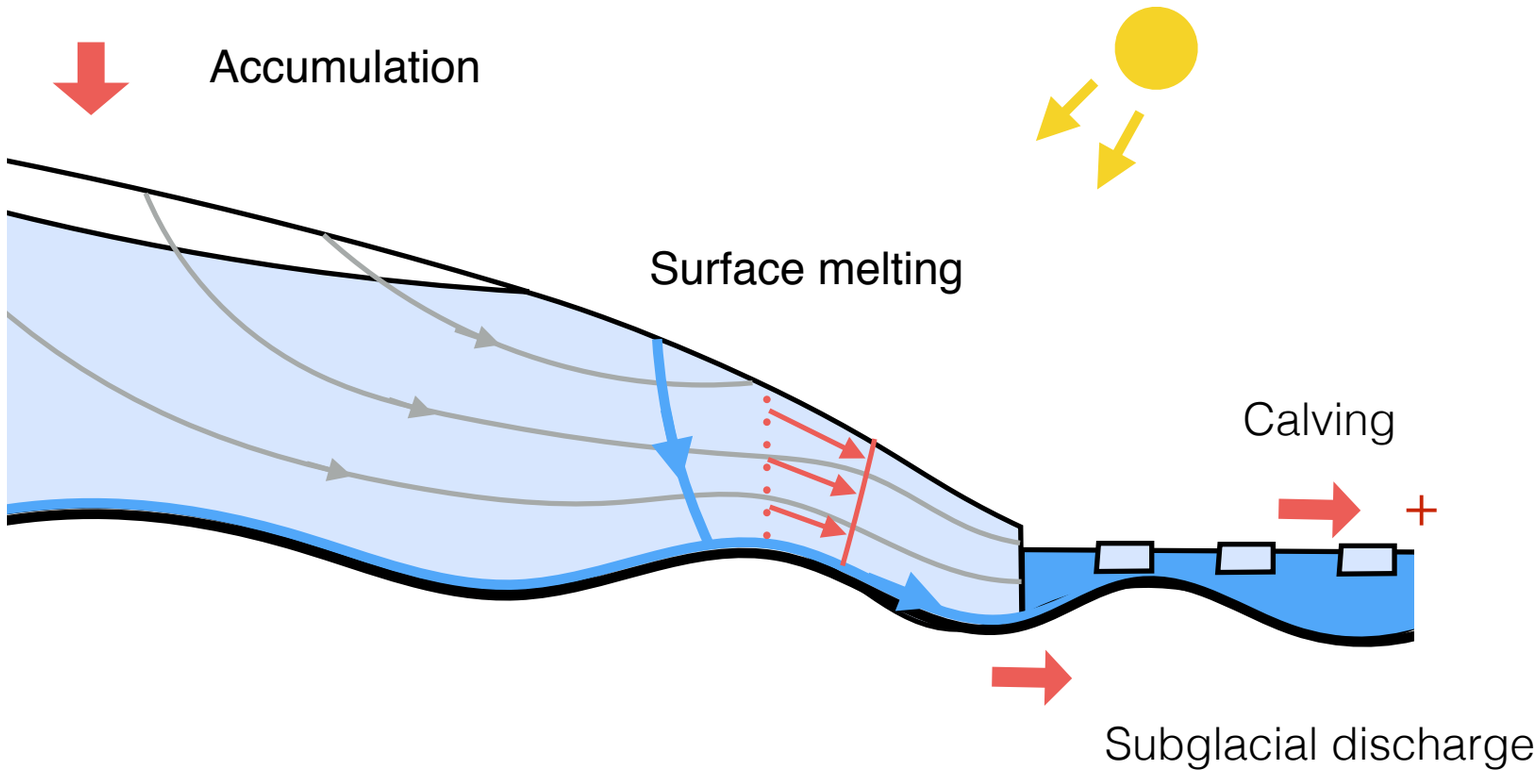
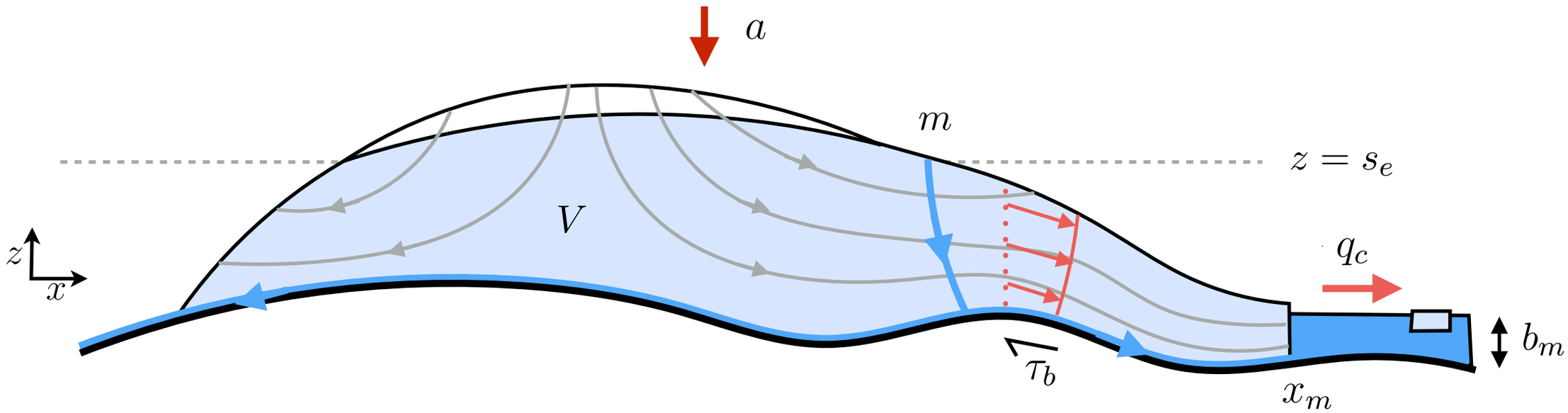


A reduced model



Global **mass conservation**

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \int_A (a - m)\,\mathrm{d}x - q_c \qquad = F(\,V\,;\,N, s_e, f)$$

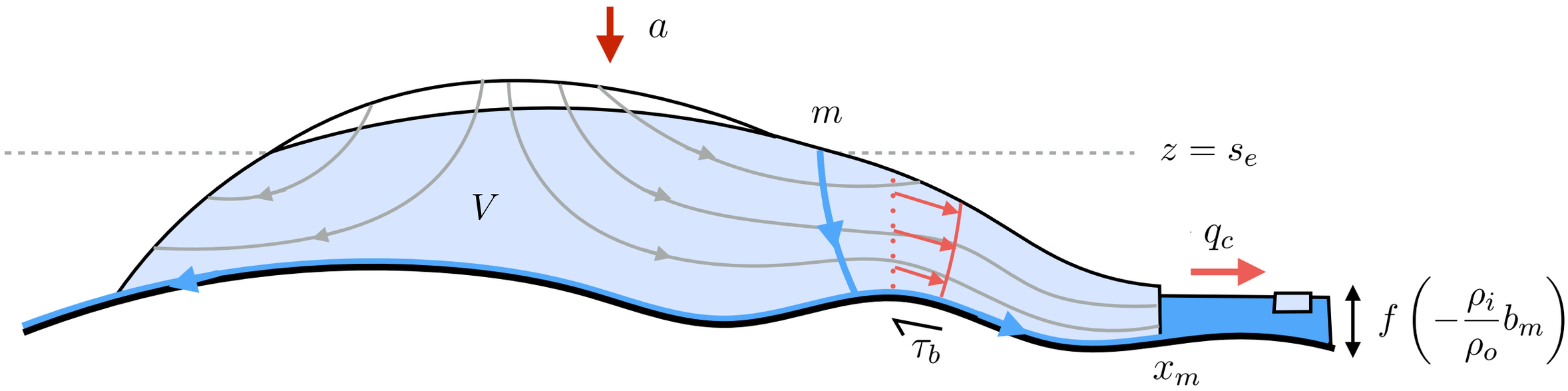
- Assumes a '**plastic**' (rate-independent) friction law $\tau_0 = \mu N \approx -\rho_i g h \dfrac{\partial s}{\partial x}$

  → ice volume / elevation determined purely by margin position and basal friction
  cf. Nye 1951, Weertman 1961

- Uses a boundary-layer analysis to relate **calving flux** to local **water depth** b_m

  → $q_c = \dfrac{A(2\rho_i g)^n}{\mu} \hat{Q}(f) \left(-\dfrac{\rho_i}{\rho_o} b_m\right)^{n+2}$ f flotation factor cf. Schoof 2007, Tsai et al 2015

A reduced model



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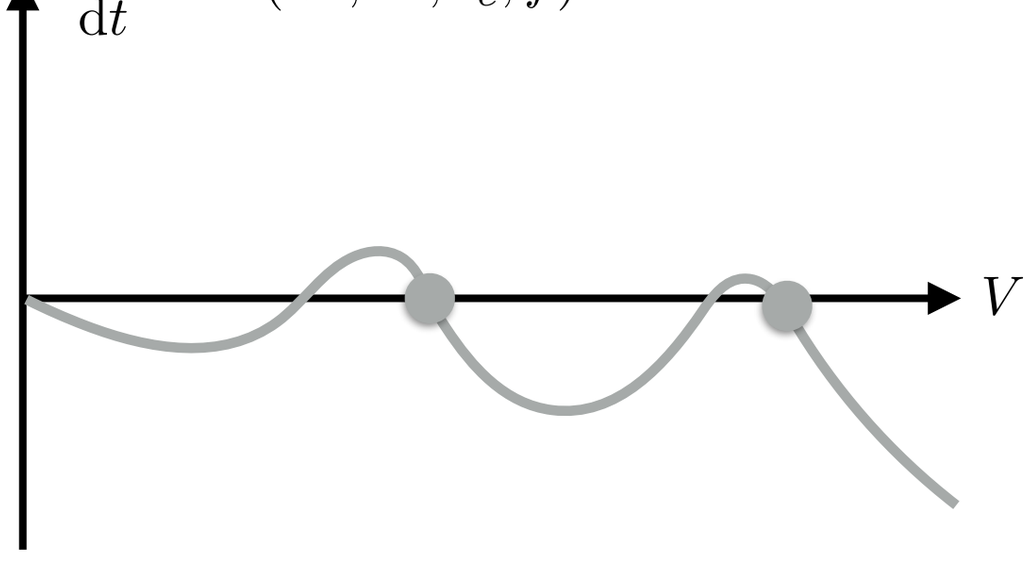

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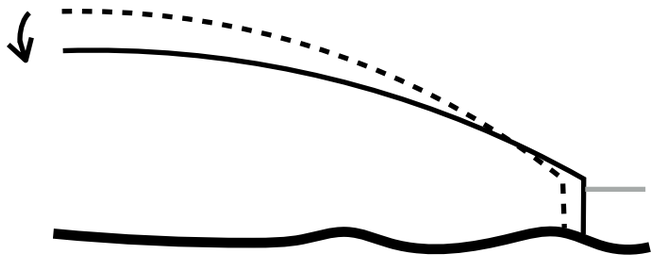
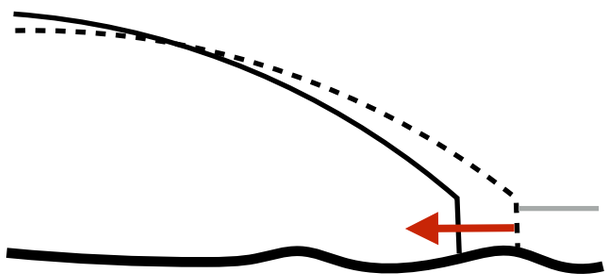
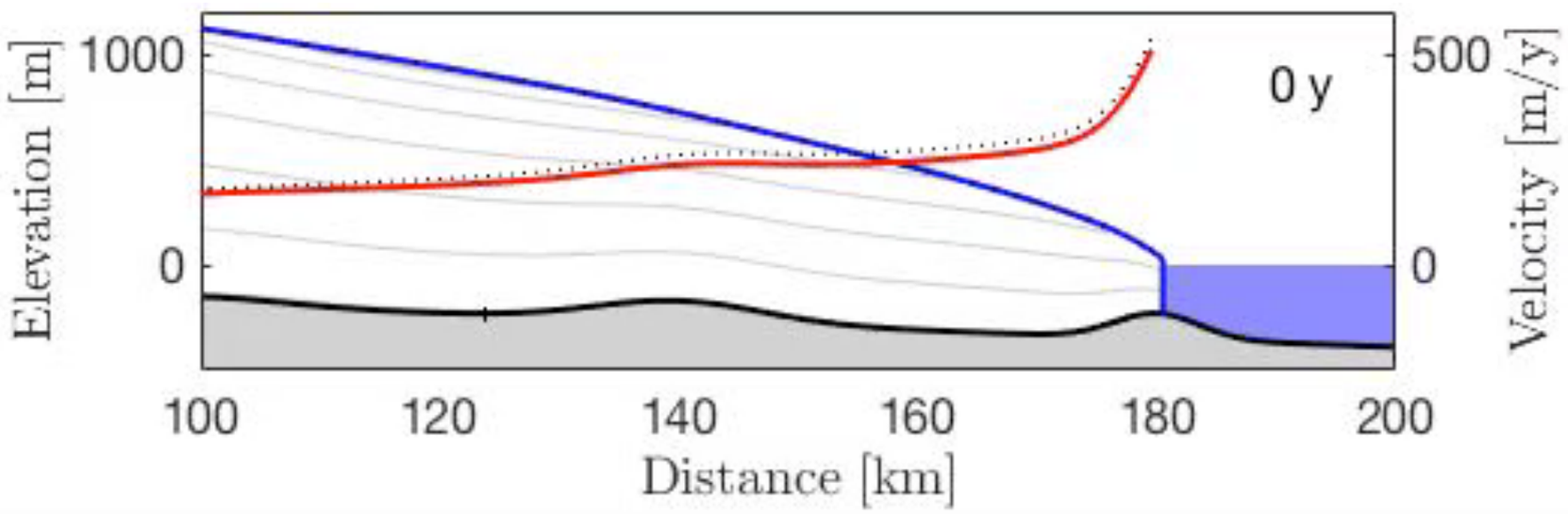


A **decrease** in bed strength results in a lowering of the surface and **increased velocity**

→ increased rate of mass loss



An **increase** in bed strength results in **initially decreased velocities**… but this induces margin retreat, which *may* lead to even larger mass loss (**tidewater-glacier retreat**)



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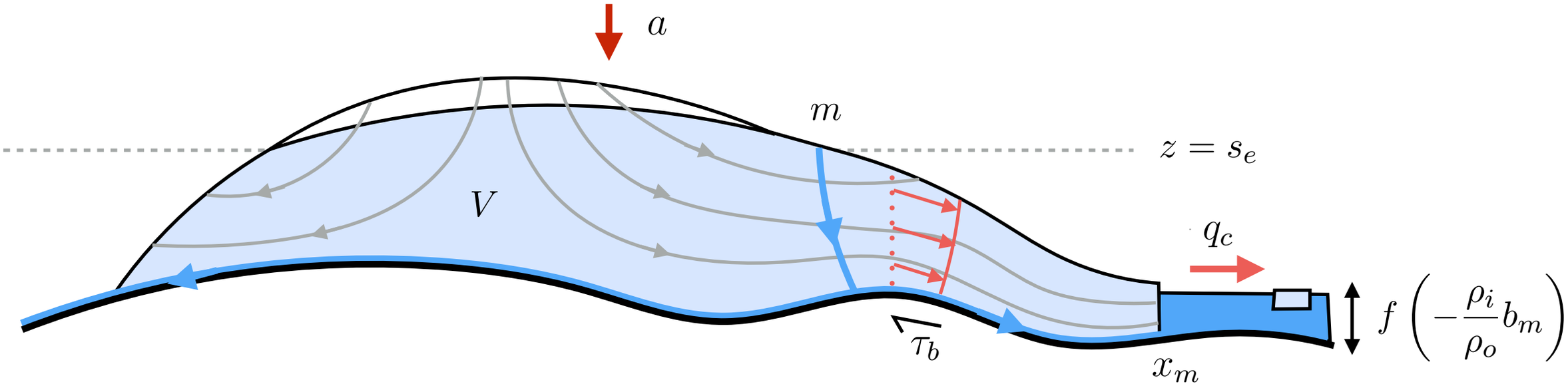
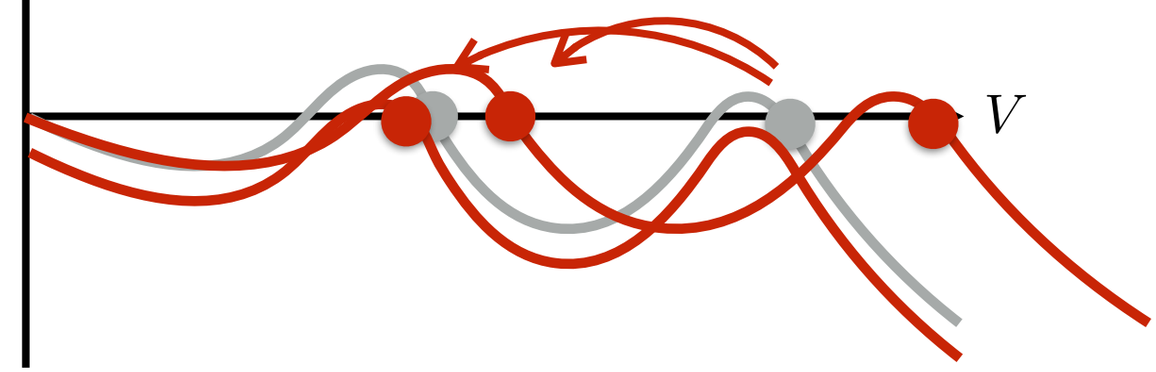


$$\frac{\mathrm{d}V}{\mathrm{d}t} = F(\,V\,;\,N, s_e, f\,)$$



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Numerical models are increasingly able to reproduce observed patterns of **seasonal velocity change** (with some tuning) e.g. Bougamont et al 2014, Hoffman et al 2016.

But computations are expensive - these processes are not yet in any continental or decadal-scale models (e.g. CMIP6 models)

Summary II

Changes in ice speed do not necessarily translate to changes in mass, with potential to influence ice loss in **either direction**.

Inland **slow-down** of the ice-sheet may help induce **tidewater-glacier retreat**, with potential to precipitate more rapid ice loss.