Glacial hydrology
and consequences for ice-sheet dynamics

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Outline

Hydrological balance of ice sheets

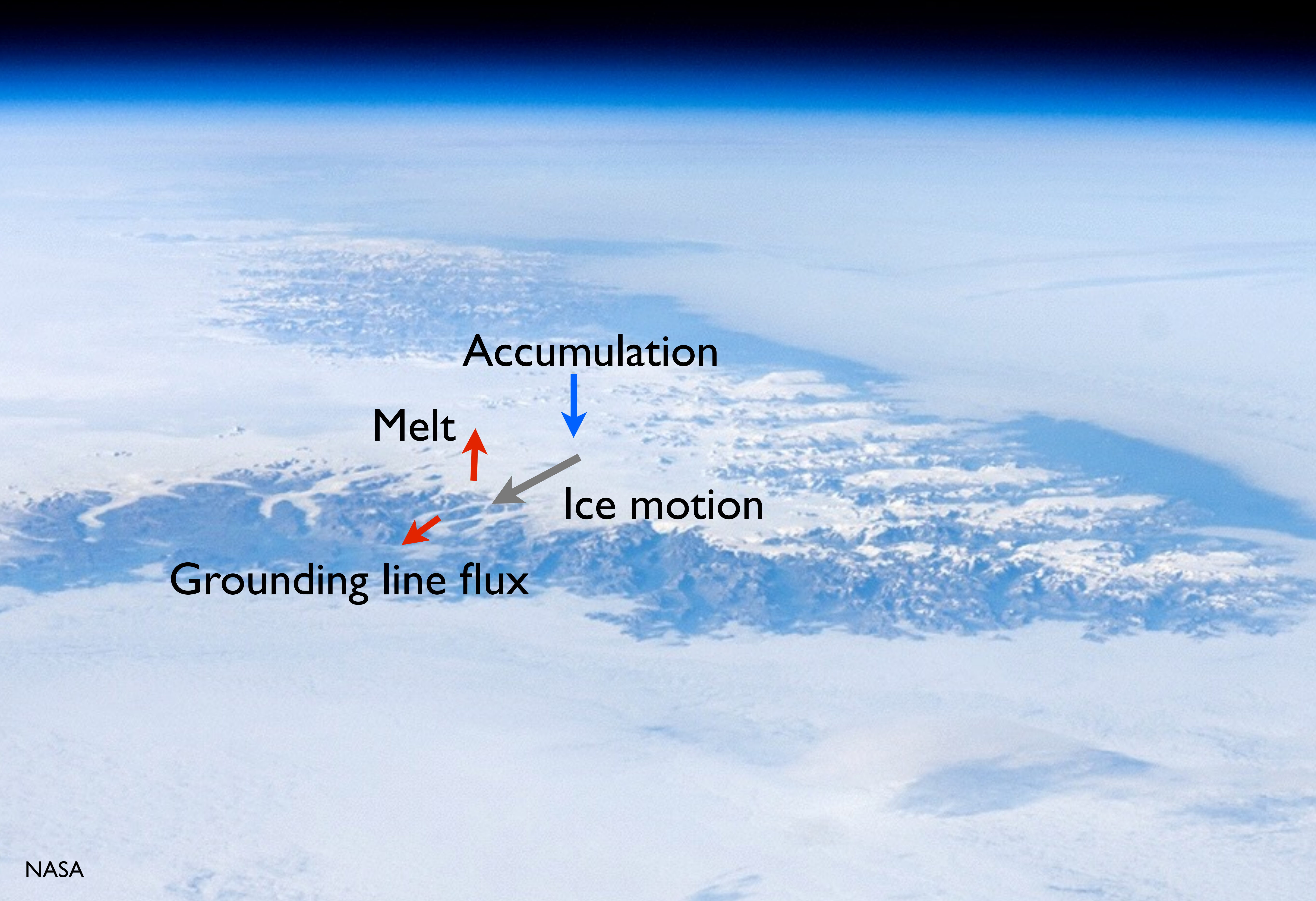
Subglacial hydrology

Effect of subglacial hydrology on ice dynamics

Effect of subglacial hydrology on ice-ocean interactions

Hydrological balance of ice sheets

Ice sheet mass balance



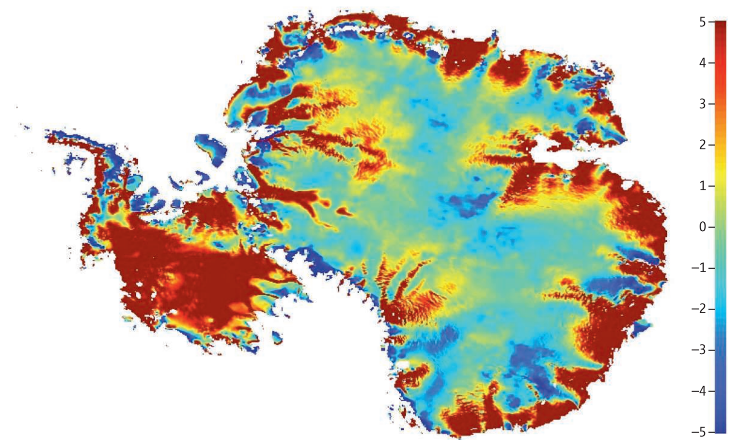
NASA

Sources of water

Antarctica

Basal melting ~ 5 mm/y

Surface melting ~ 0 mm/y

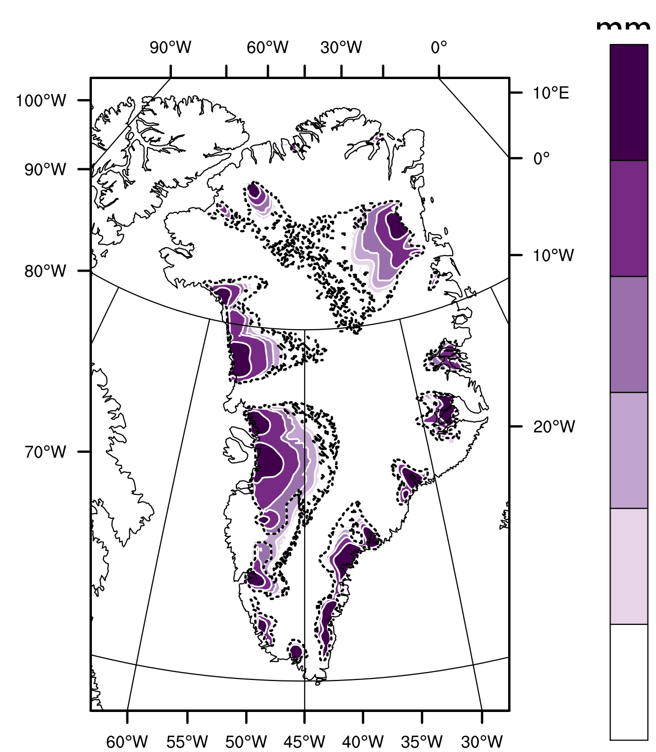


Tulaczyk & Hossainzadeh 2011

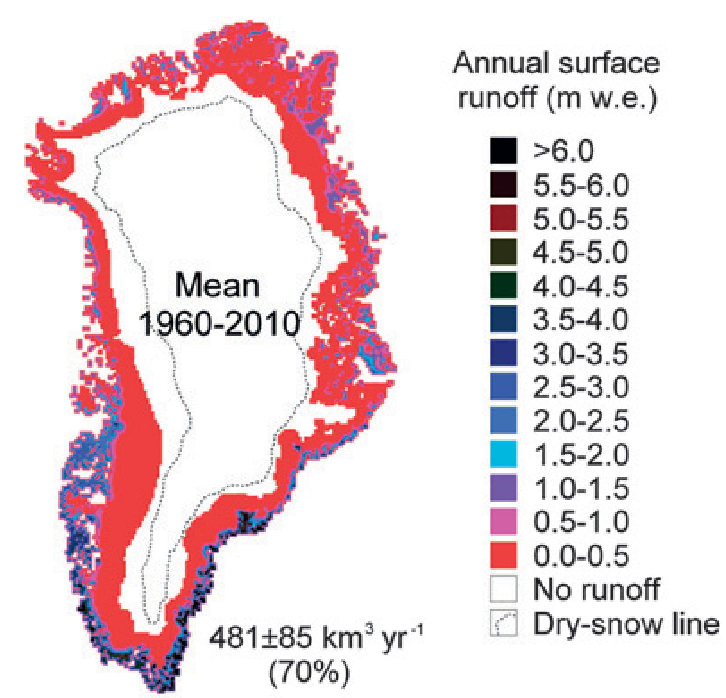
Greenland

Basal melting ~ 5 mm/y

Surface melting ~ 1000 mm/y



Aschwanden et al 2012



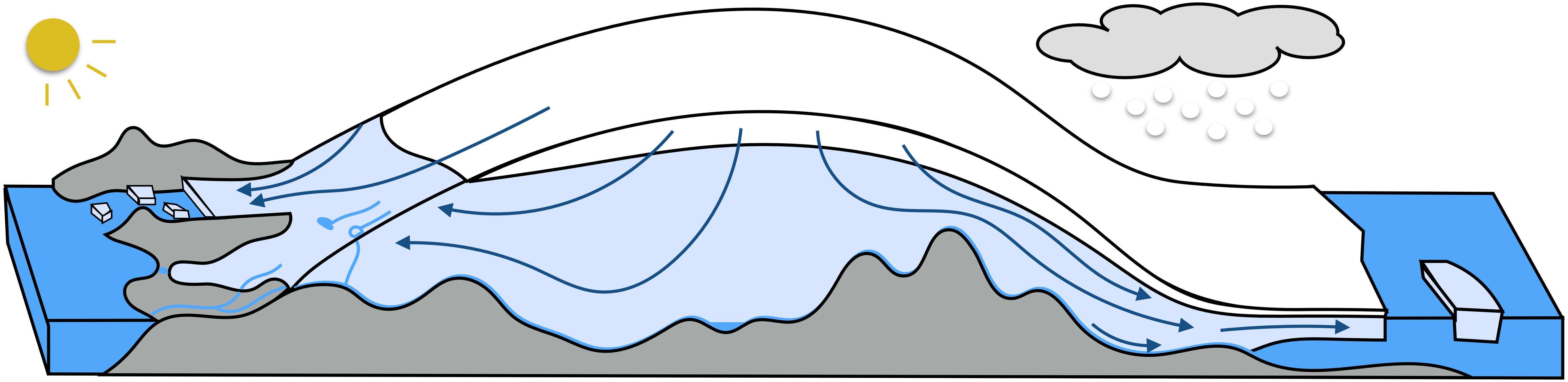
Mernild & Liston 2012

The fate of melt water I

Some **surface** melt water refreezes in snowpack (up to ~50%), some stored temporarily in supraglacial lakes

Remaining water runs off into moulins or crevasses and most reaches the subglacial drainage system

Greenland surface runoff ~ 300 Gt/y (0.01 Sv)

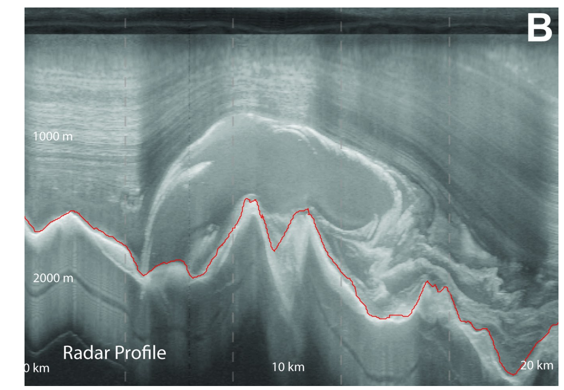


The fate of melt water II

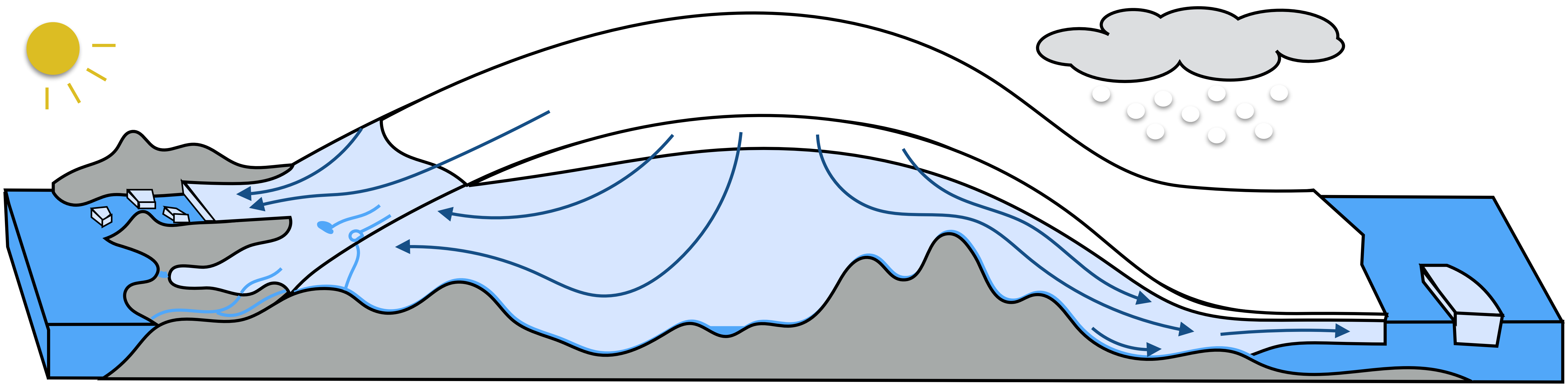
Basal melt water (from surface + geothermal, frictional) flows at the ice-bed interface - driven by potential gradients

Some water refreezes (depressurisation, conductive cooling), some stored temporarily in subglacial lakes

Majority of surface-derived water flows out from margin



Bell et al 2011

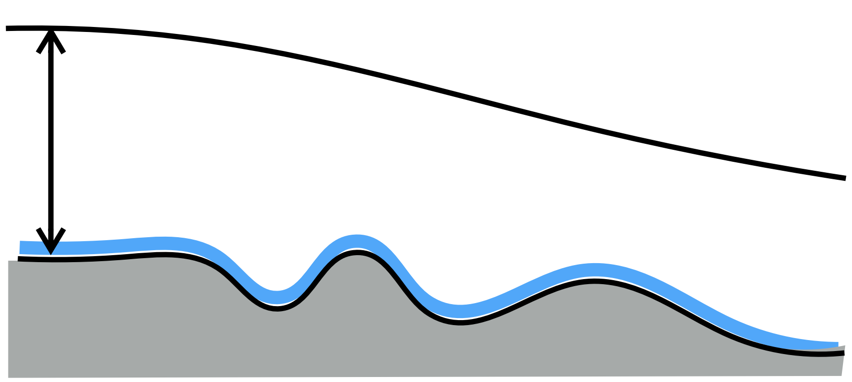


Subglacial hydrology

Two key concepts

Hydraulic potential $\phi = \rho_w g Z_b + p_w$

Water pressure $p_w \approx \rho_i g (Z_s - Z_b)$

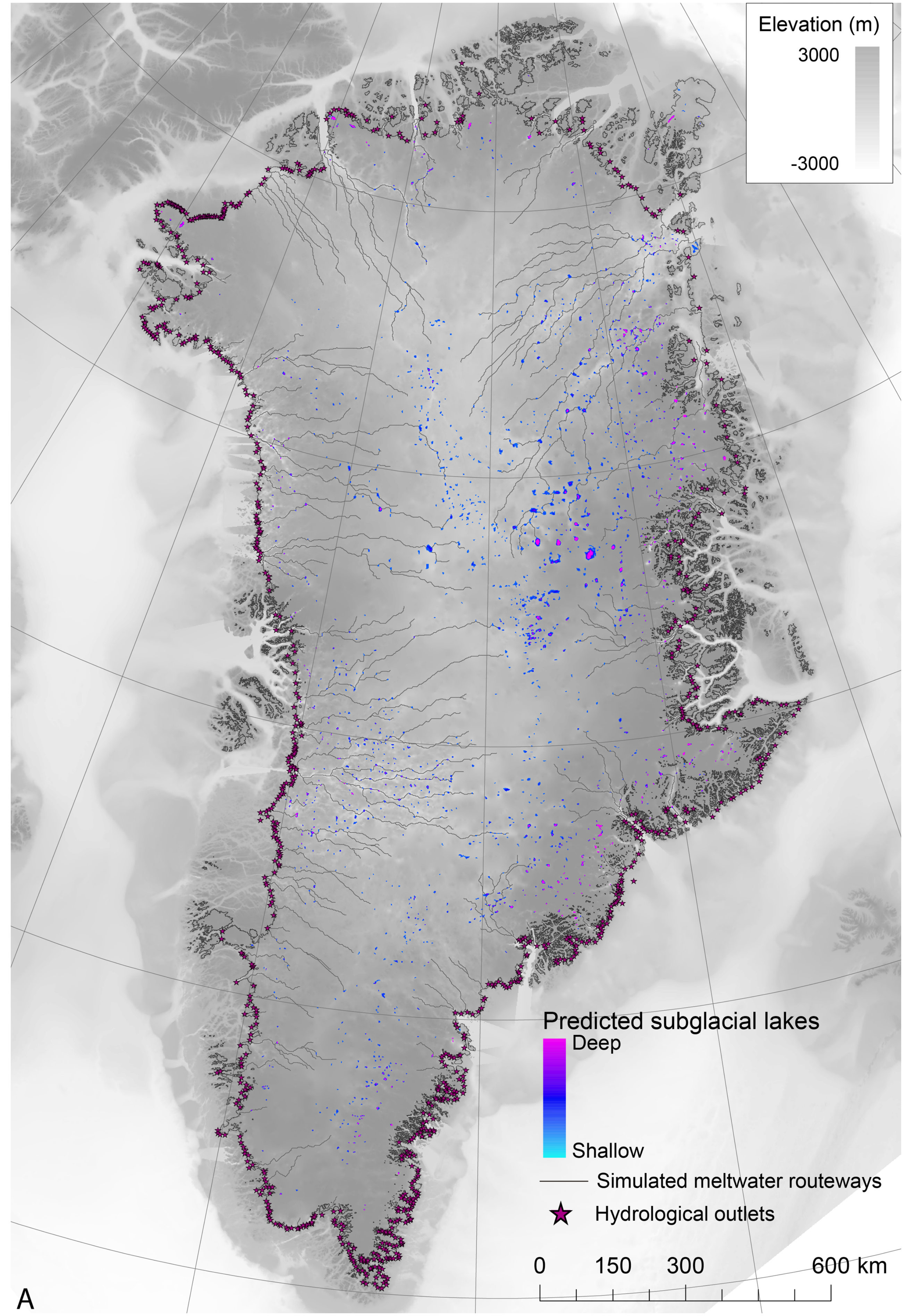


Direction of water flow controlled primarily by surface slope

… but to a significant extent by basal topography too

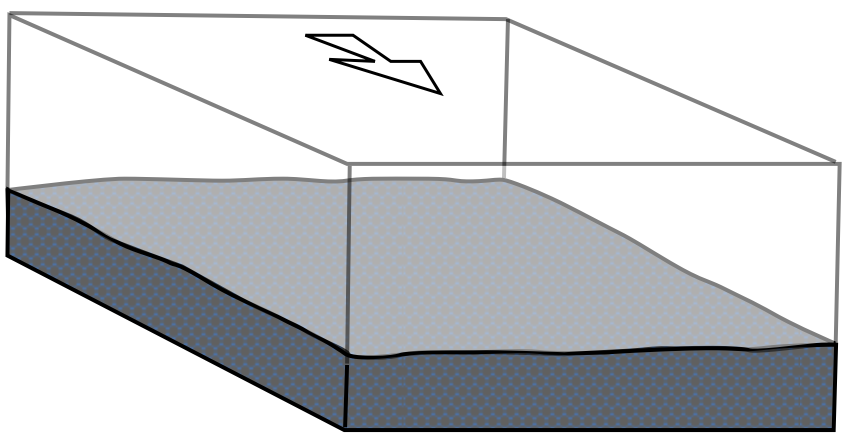
In fact, $p_w = \rho_i g (Z_s - Z_b) - N$

Effective pressure $N = p_i - p_w$

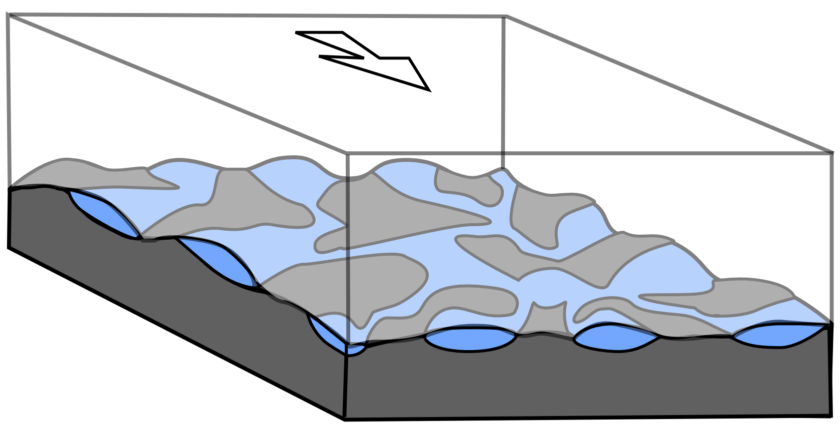


Livingstone et al 2013

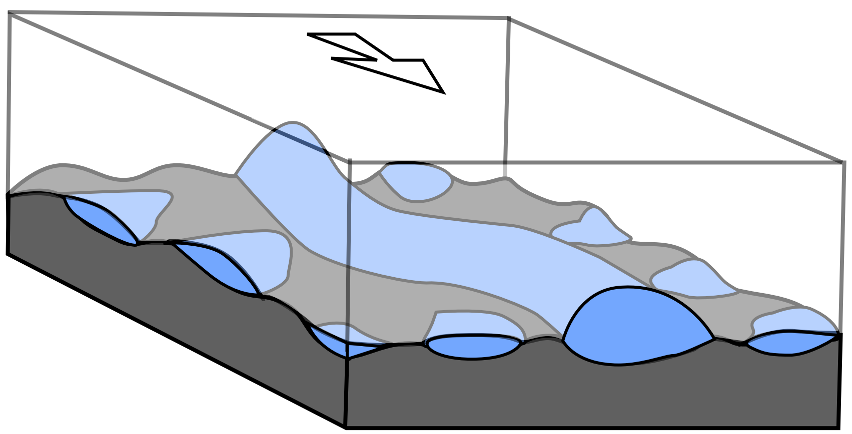
Drainage system structure



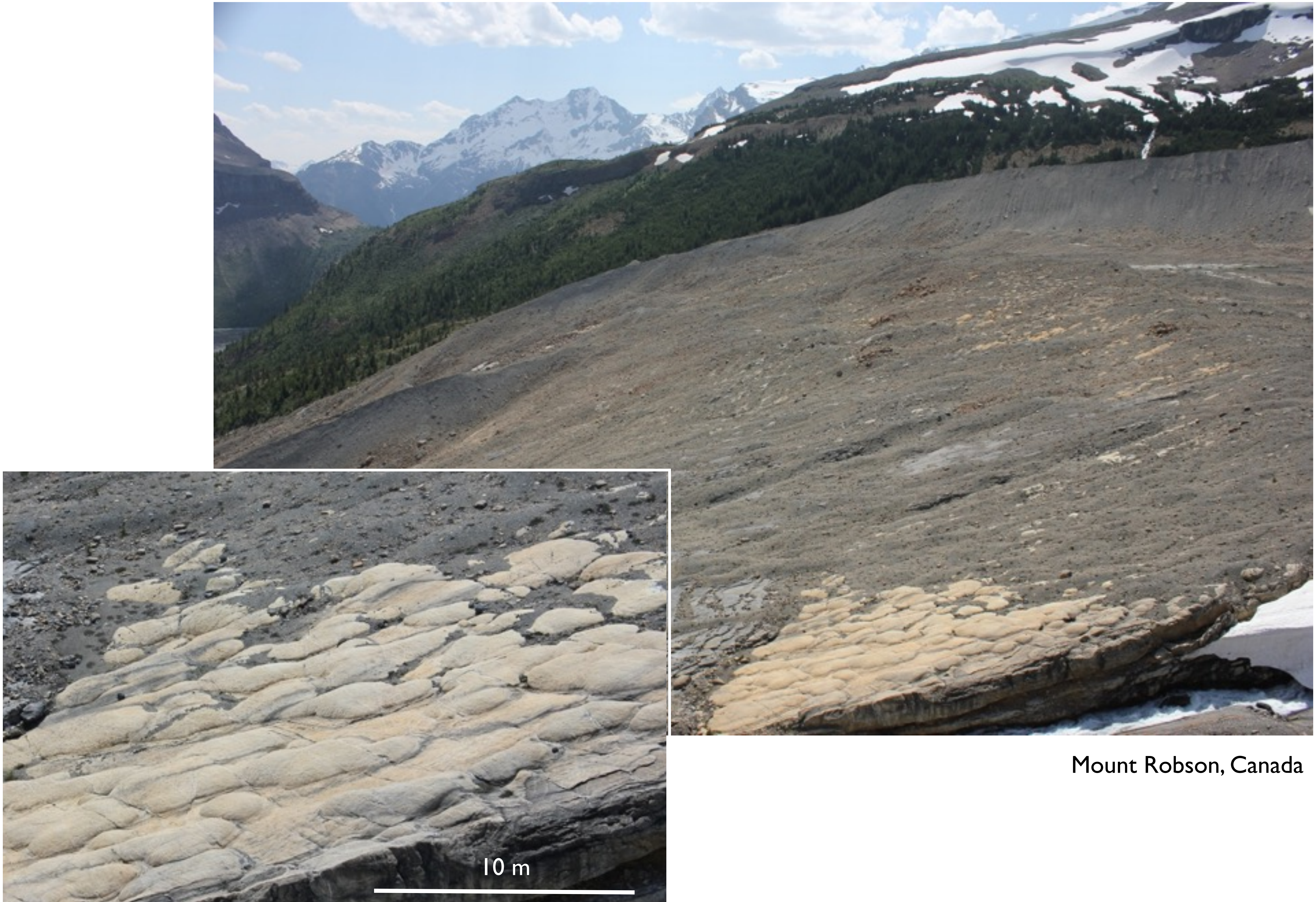
Saturated sediments



'Cavity' systems

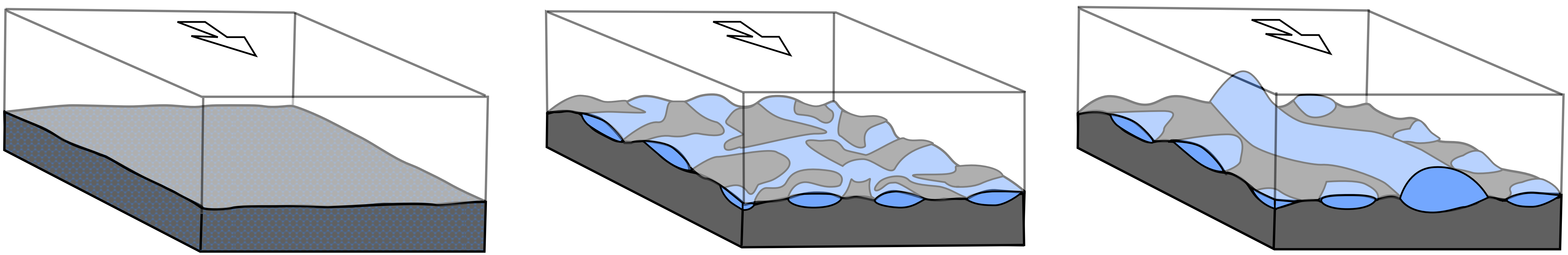


'Channel' systems



Mount Robson, Canada

Drainage system structure



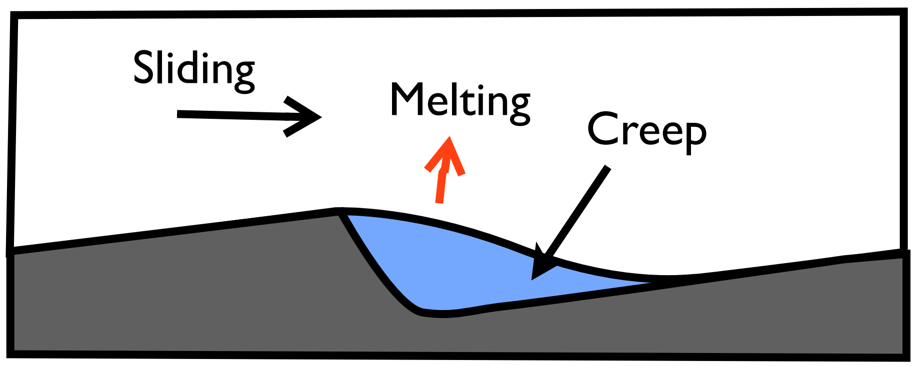
Saturated sediments

'Cavity' systems

'Channel' systems

Drainage theories - steady states

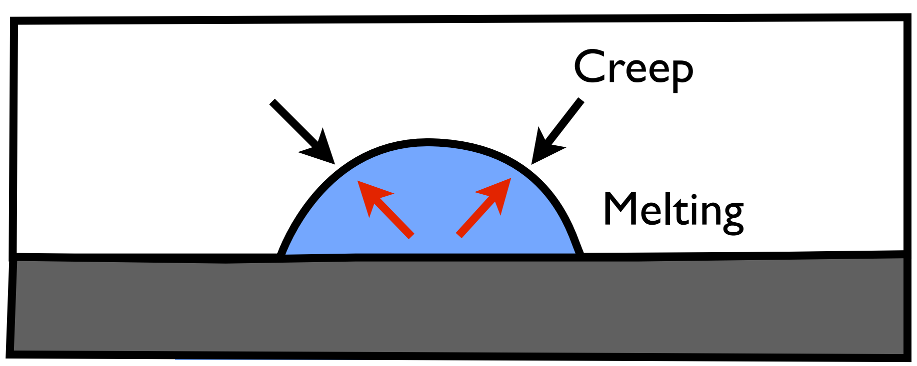
Cavities



(Walder 1986, Kamb 1987)

$$N \propto \frac{U_b^{1/3}\Psi^{1/9}}{Q^{1/9}} \qquad t \propto \frac{Q^{1/3}}{U_b \Psi^{1/3}}$$

Channels



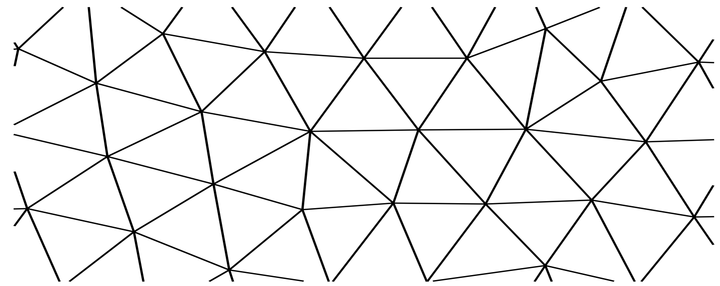
(Rothlisberger 1972, Nye 1976)

$$N \propto \Psi^{11/24} Q^{1/12} \qquad t \propto \frac{1}{Q^{1/4}\Psi^{11/8}}$$

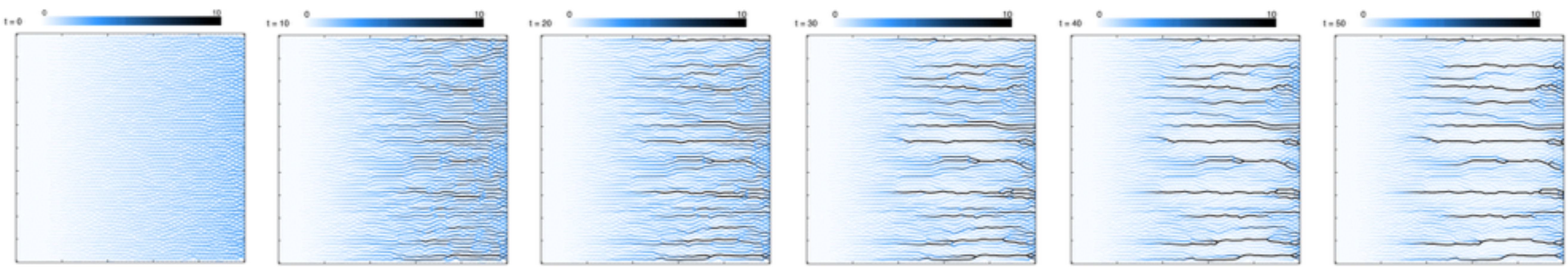
More efficient drainage networks have lower water pressure

Numerical models

$$\frac{\partial S}{\partial t} = \frac{Q\Psi}{\rho_i L} - \tilde{A}SN^n$$



Mesh of conduits (plan view)

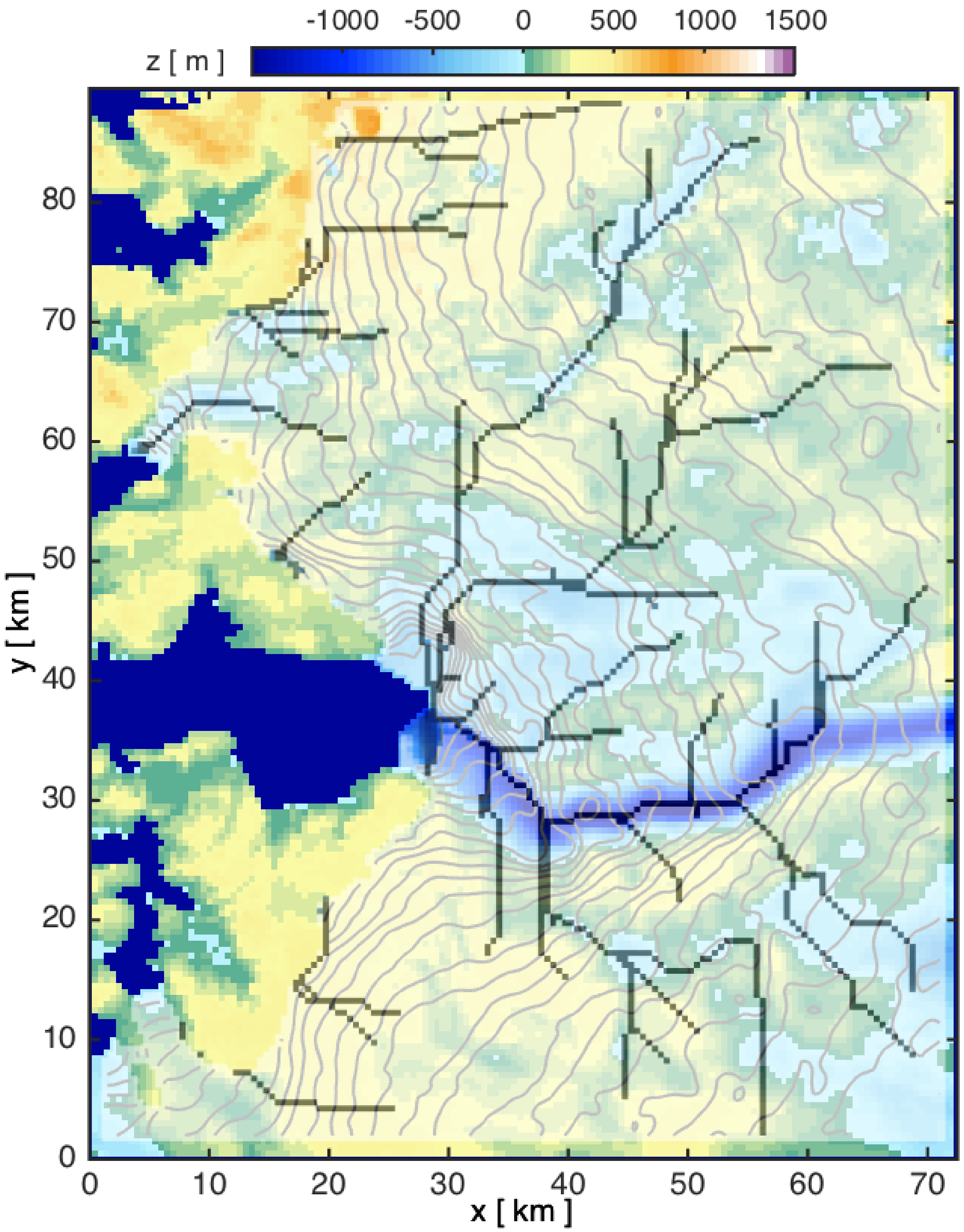


Time

Channel networks grow over time with sustained water input

Numerical models

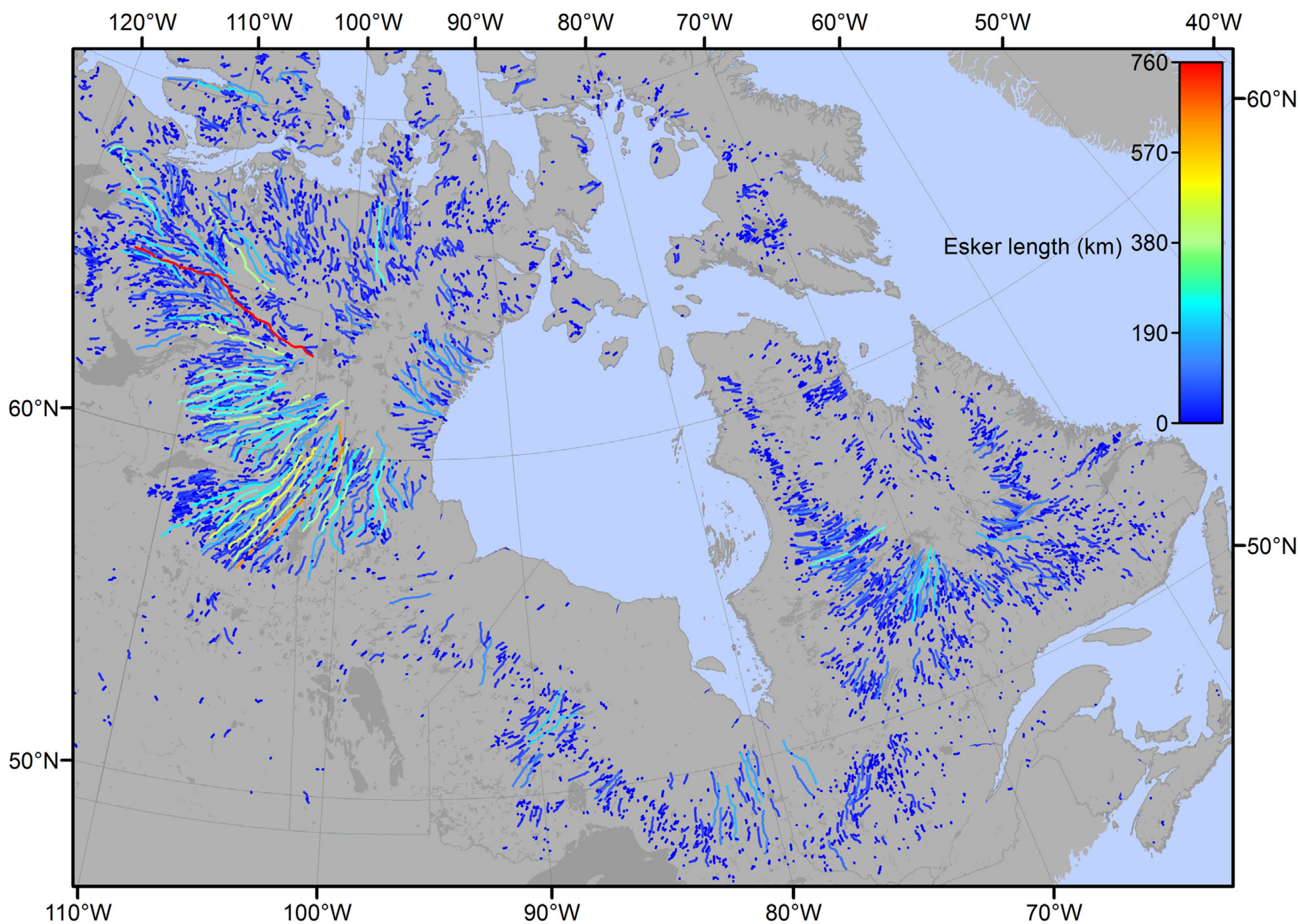
Jacobshavn Isbrae (West Greenland)



Subglacial water routing sensitive to supraglacial inputs (and bed topography)

Large and spatially-localised water pressure variations

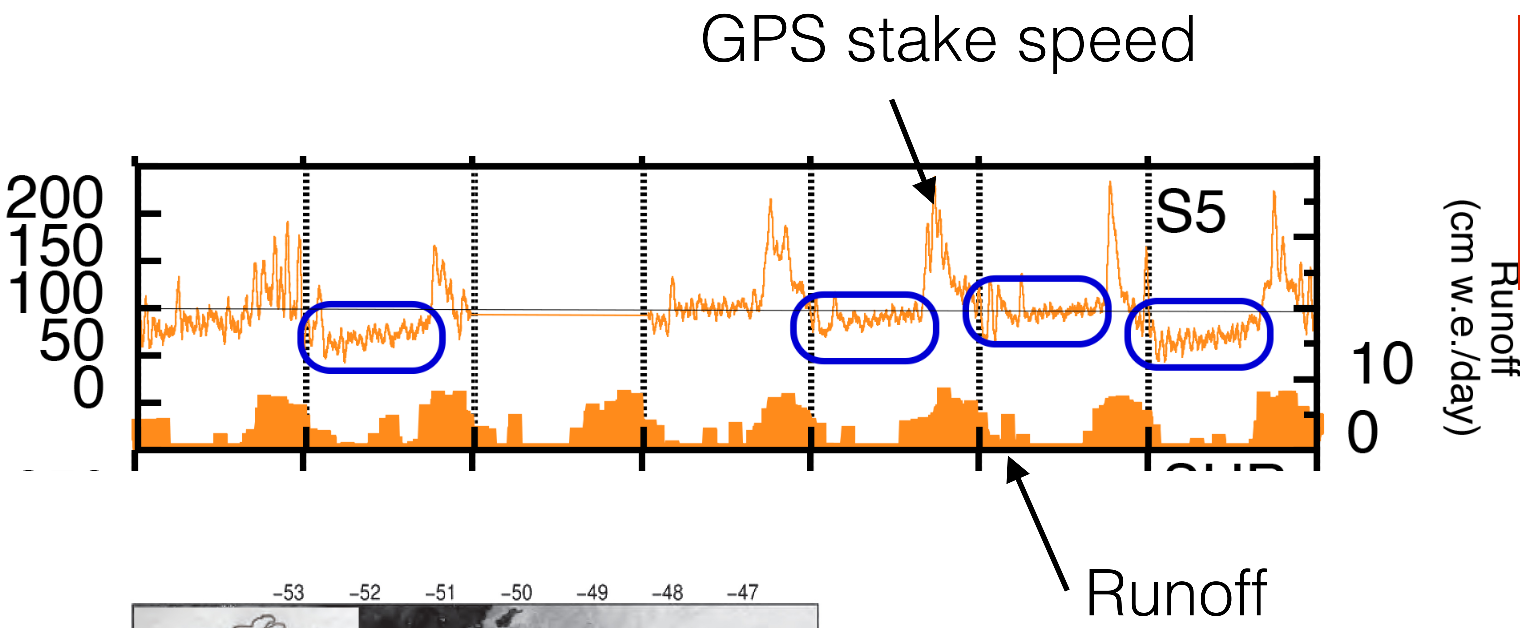
Eskers beneath Laurentide ice sheet

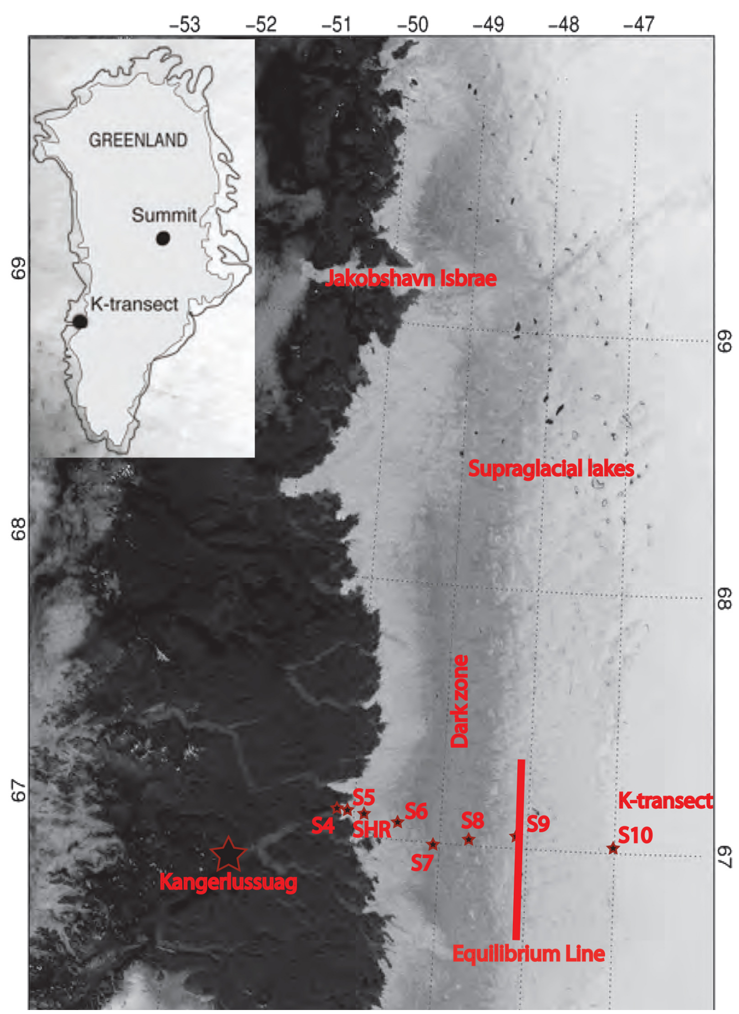


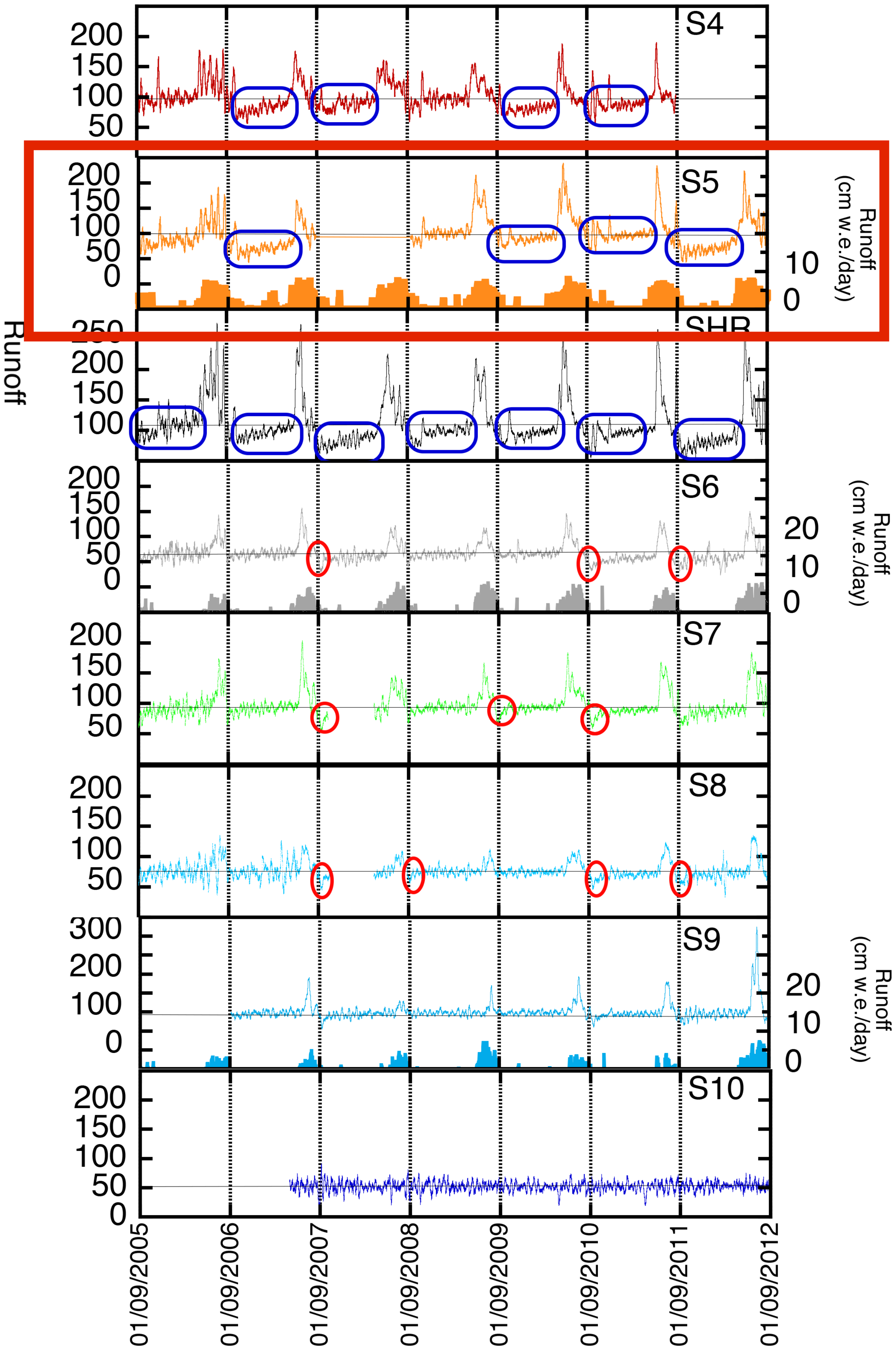
Storrar et al 2014

Effect of subglacial hydrology on ice dynamics

Greenland ice speeds

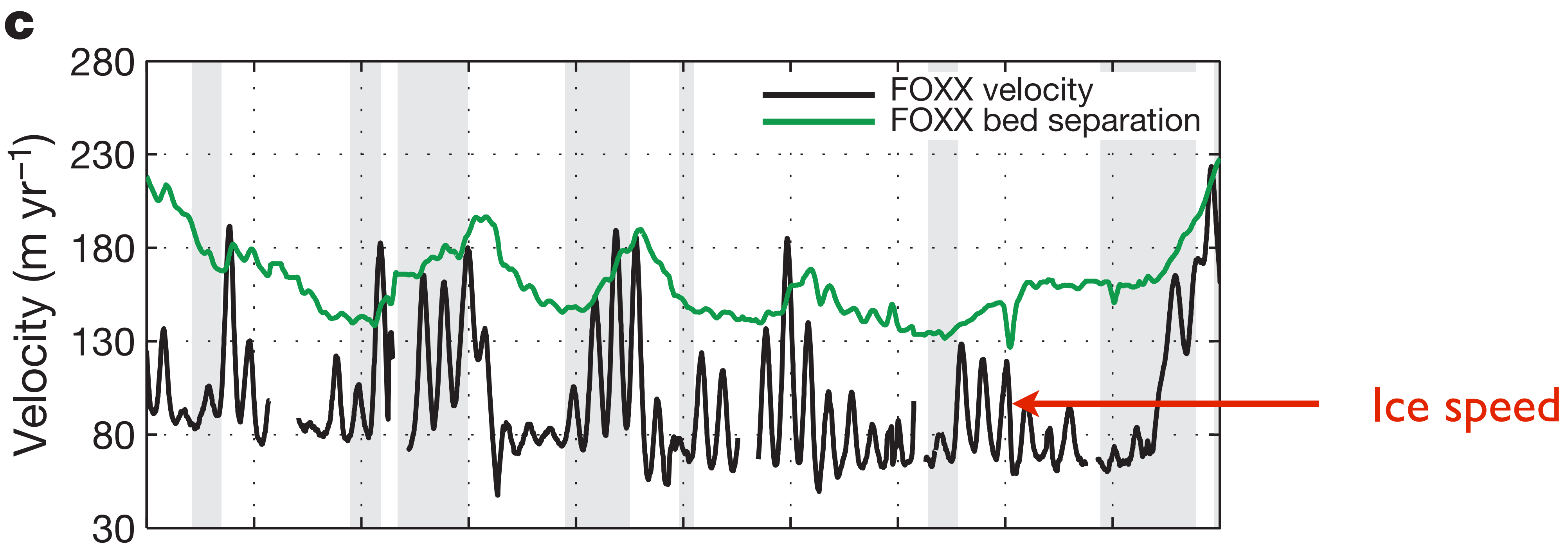






van de Wal et al 2015

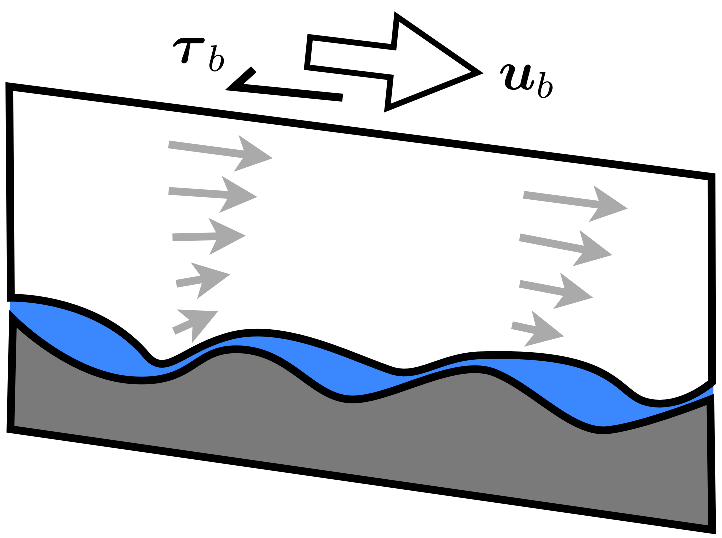
Ice speed varies diurnally



Andrews et al 2014

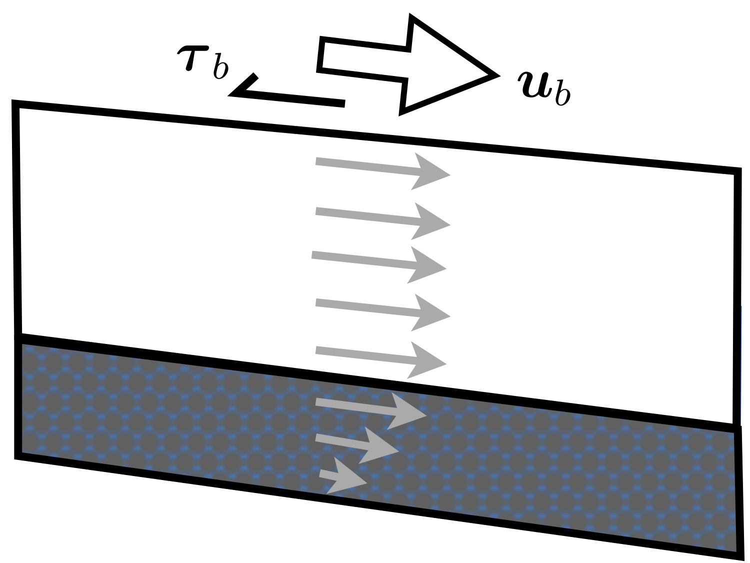
How does basal water affect ice sliding?

Conventional wisdom: effective pressure controls basal shear stress τ_b



Lower effective pressure
> larger cavities

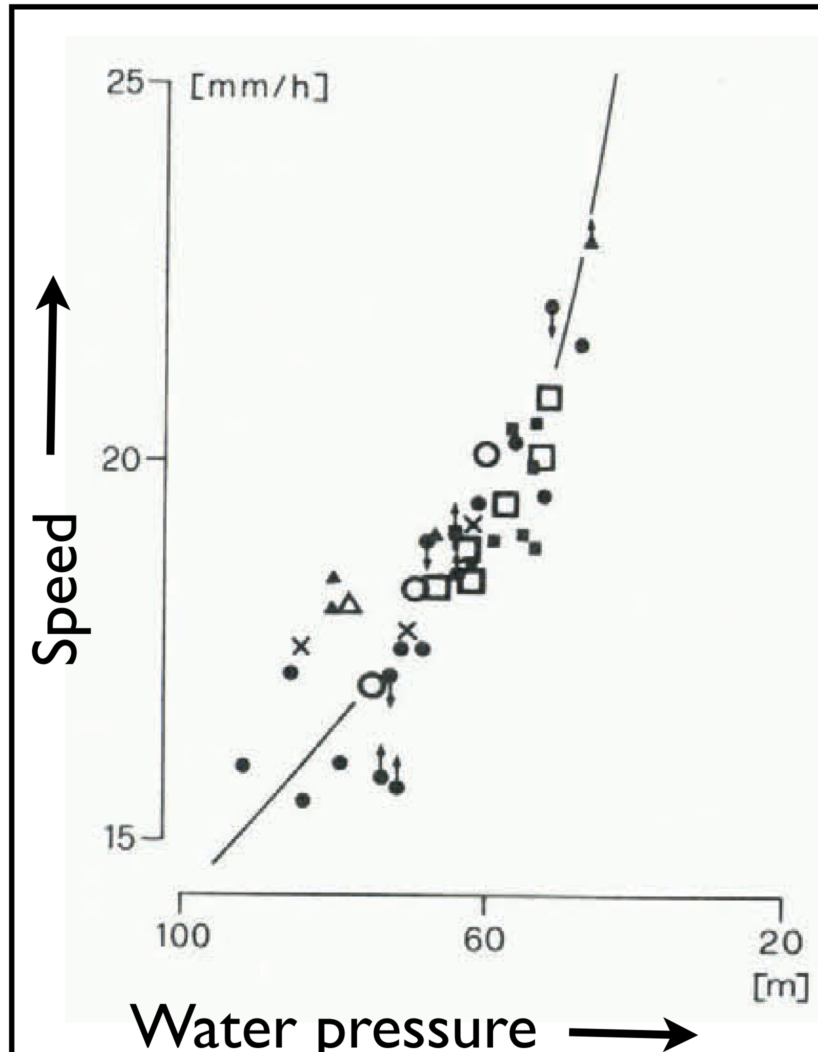
$$\tau_b = C U_b^p N^q$$



Lower effective pressure
> lower yield stress

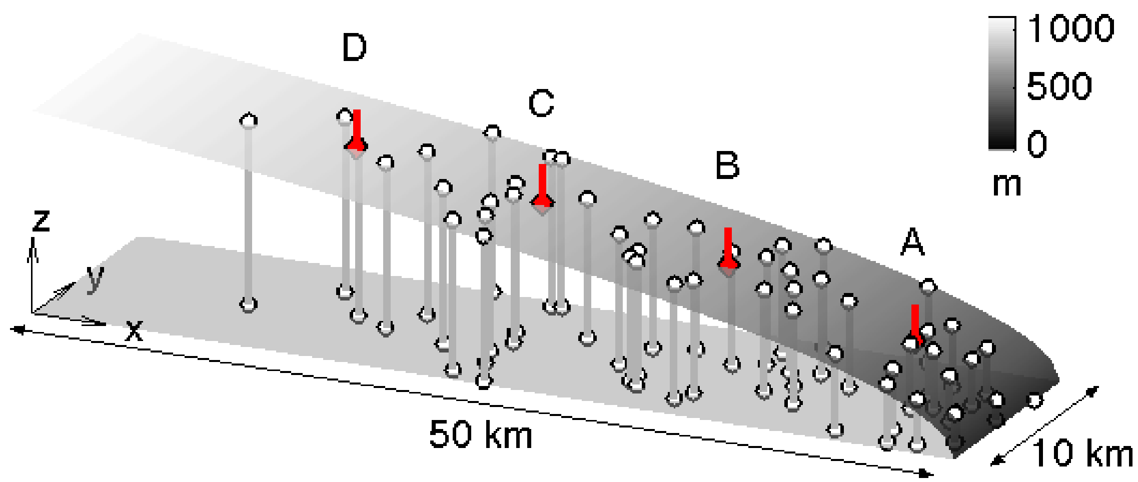
$$\tau_b = \mu N$$

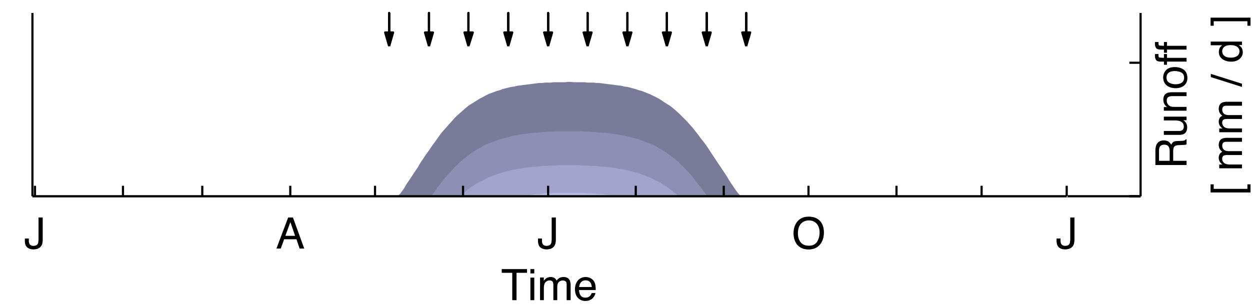
Observed correlations between ice speed and borehole water pressure



Iken & Bindschadler 1986

Model results - coupling subglacial water to ice sliding

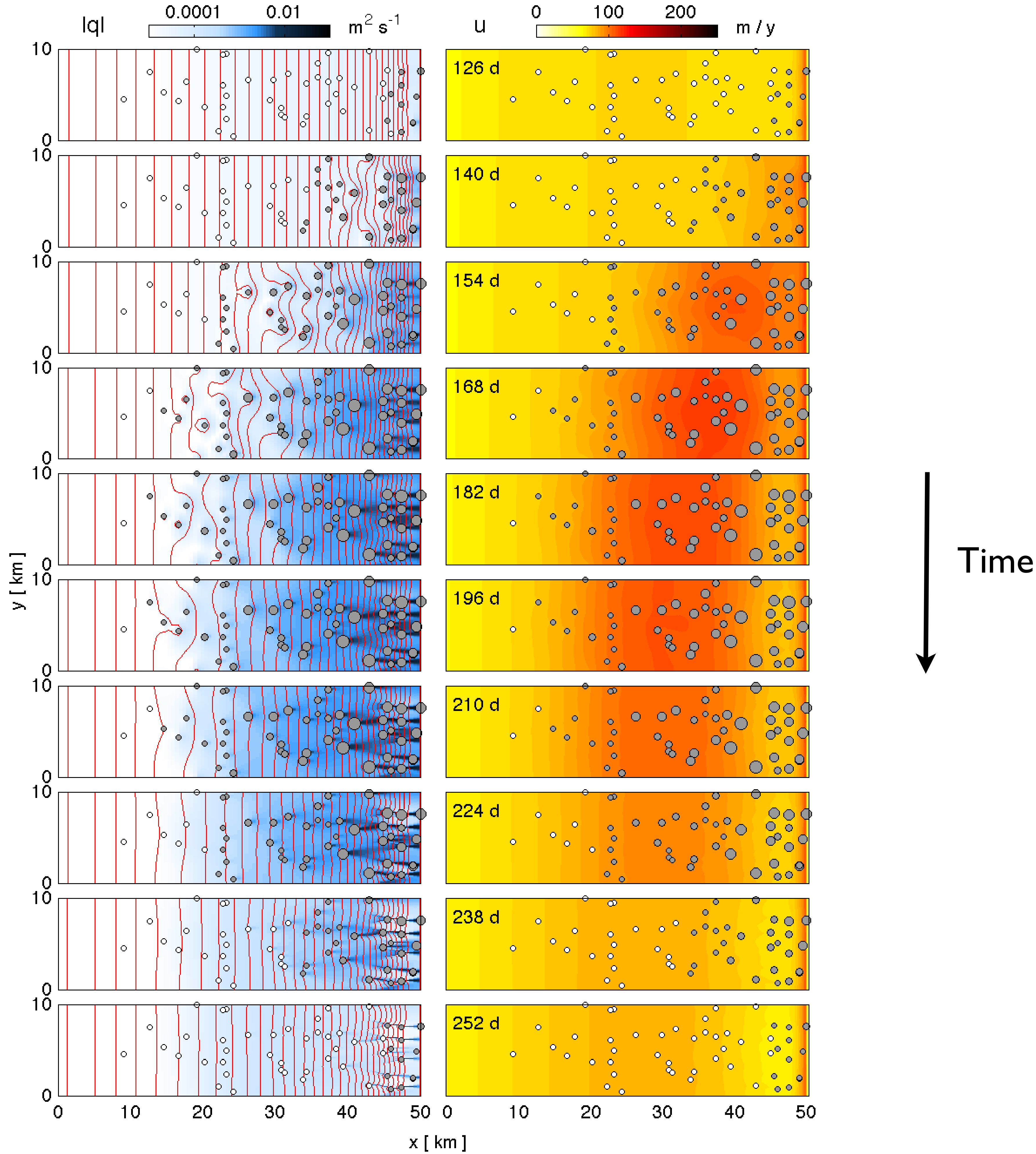




Surface runoff varies with seasonal pattern - input to subglacial system through moulins

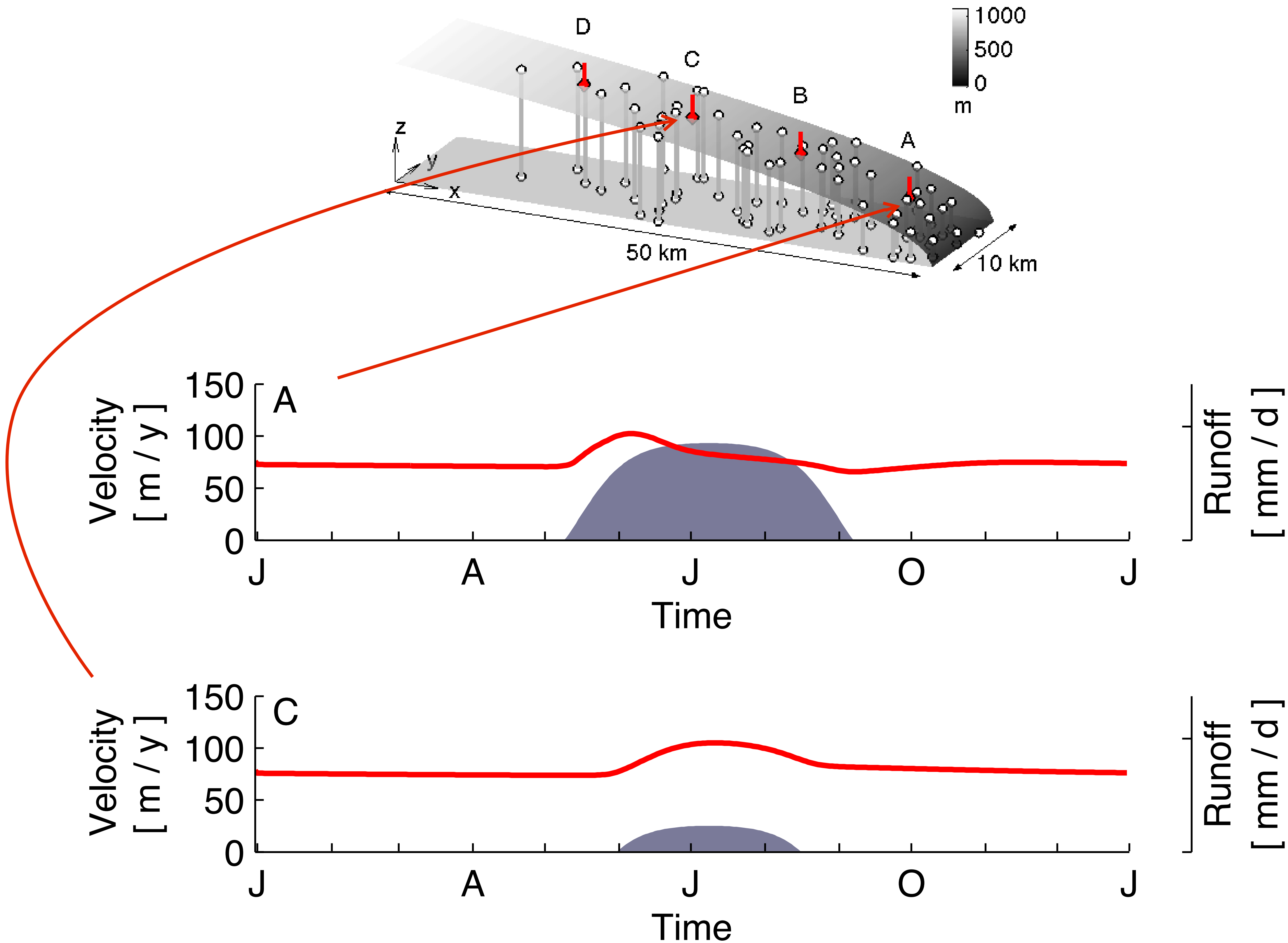
Friction law for ice flow model (viscous fluid) $\tau_b = \mu U_b N$

Hewitt 2013, EPSL

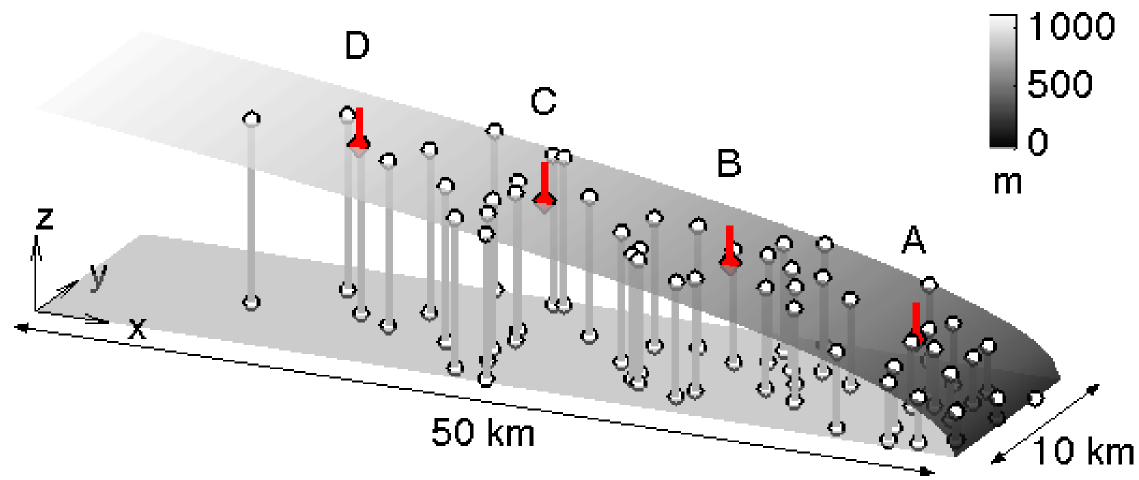


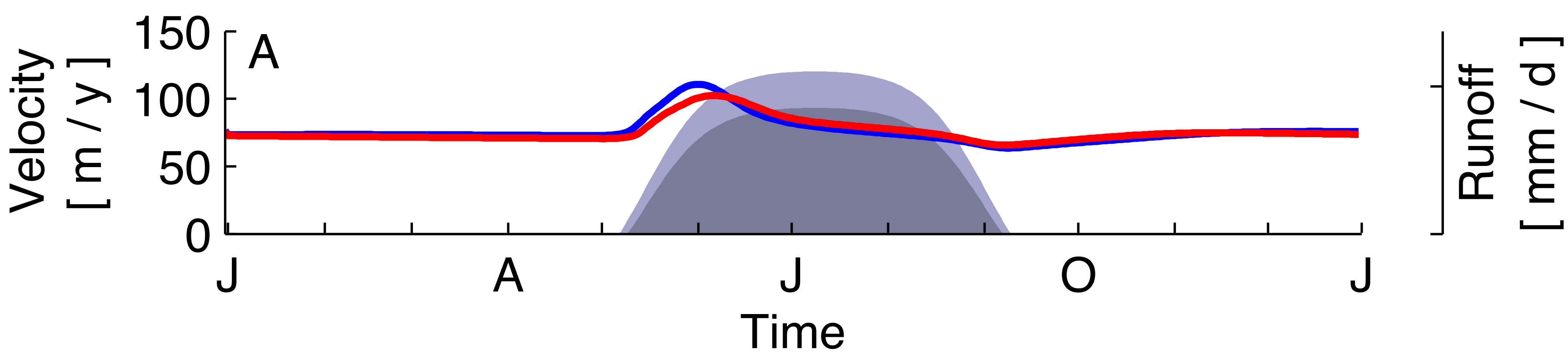
|q|
0.0001
0.01
m² s⁻¹
u
0
100
200
m / y
126 d
140 d
154 d
168 d
182 d
196 d
210 d
224 d
238 d
252 d
y [km]
x [km]
Time

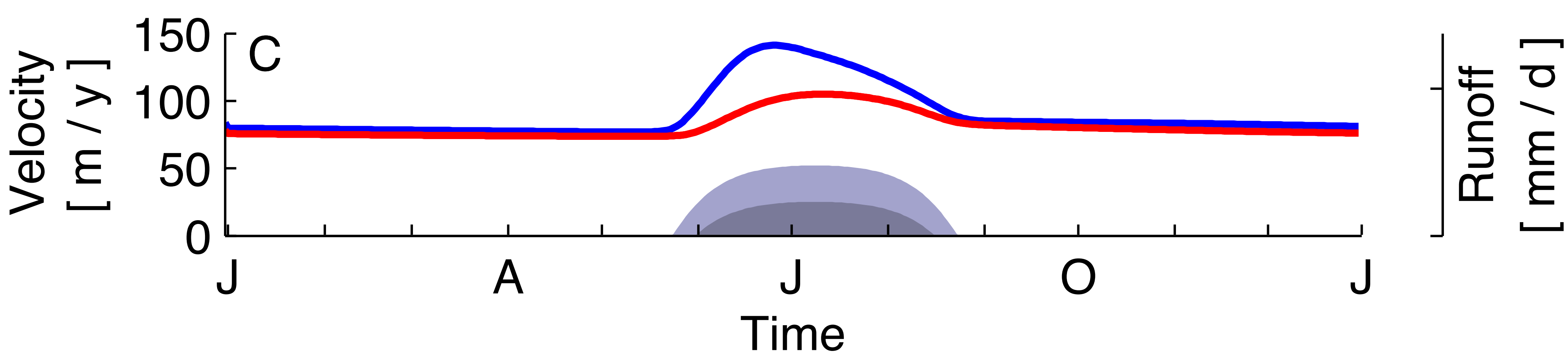
Model results



Model results - increased surface melt

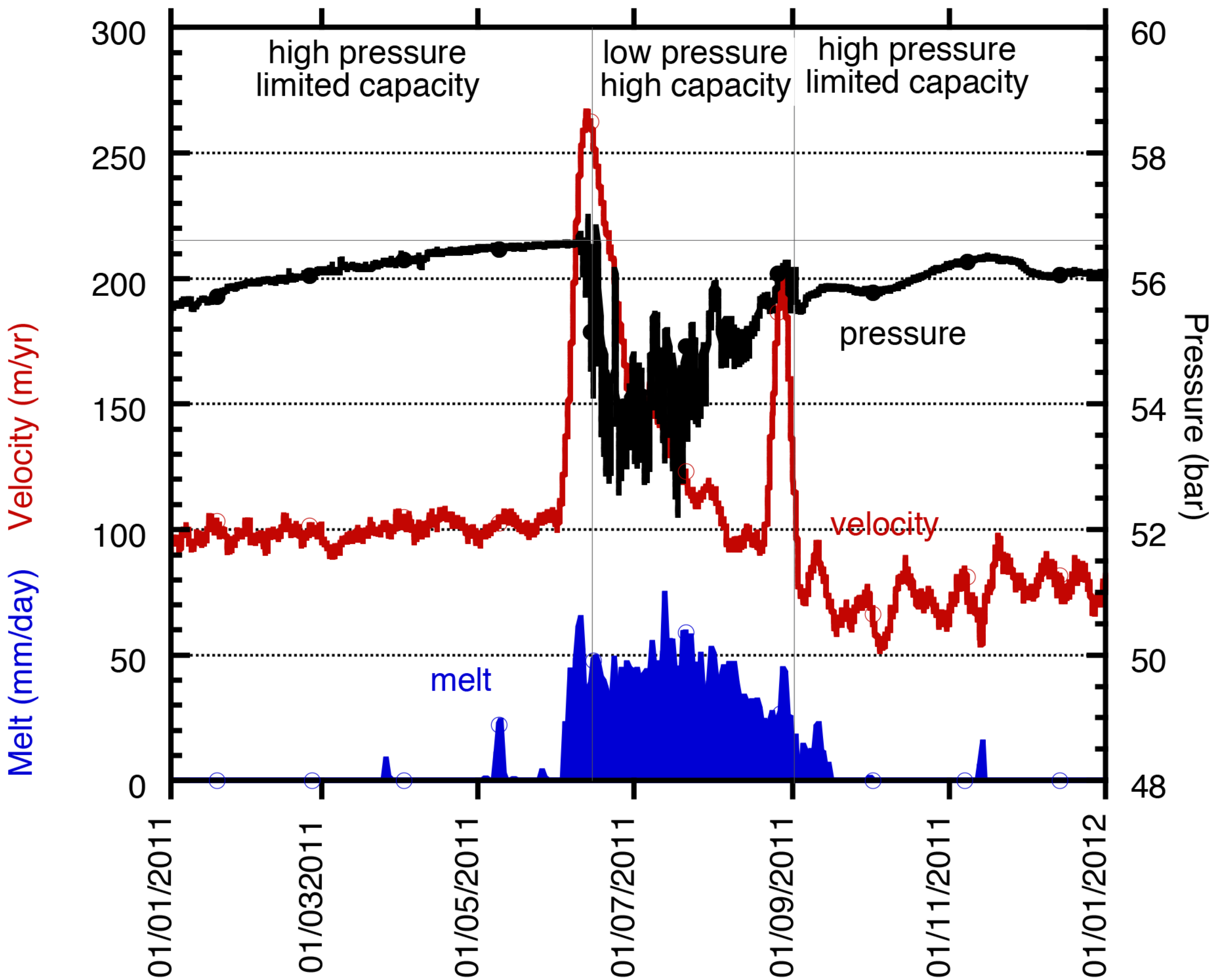






Results broadly agree with observations

Is subglacial water pressure really what's important?



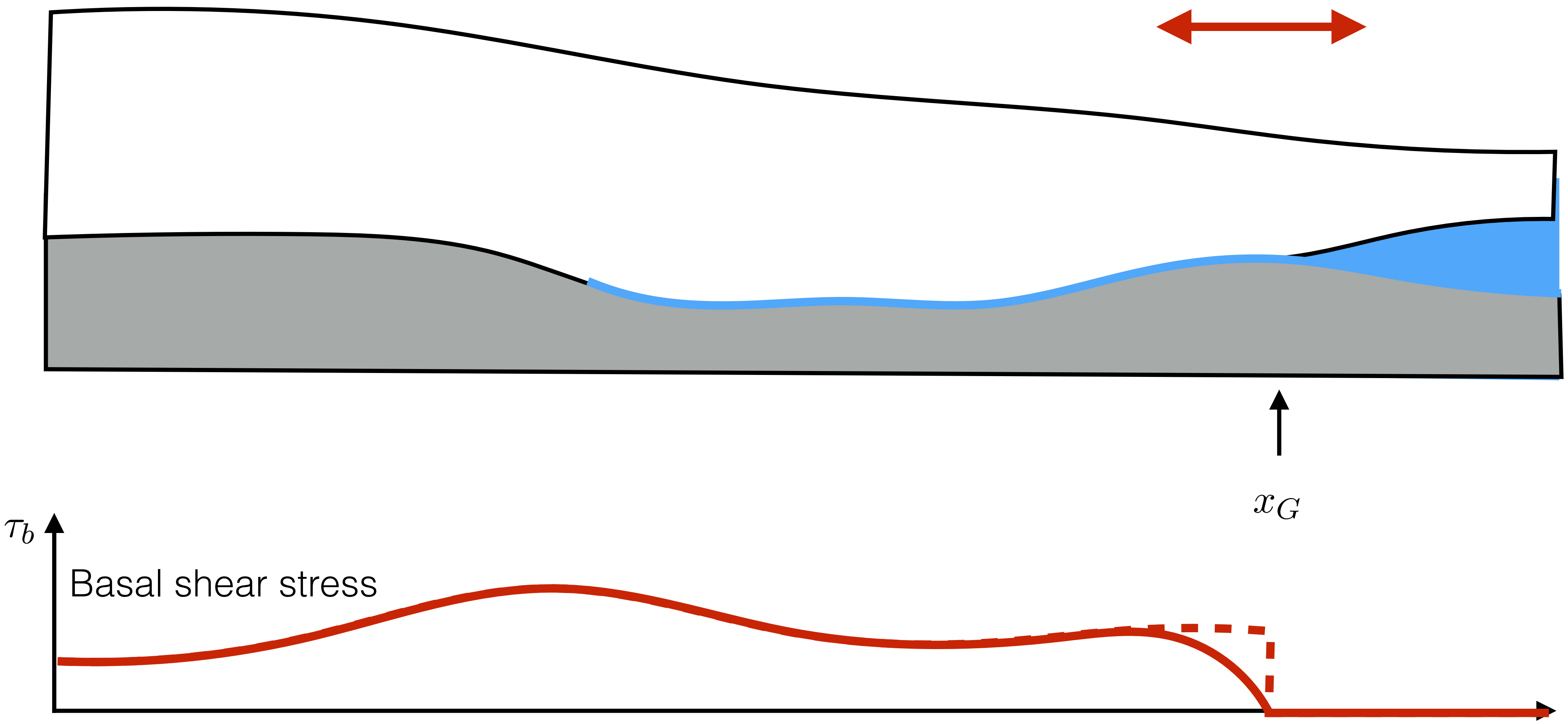
100%

95%

90%

van de Wal et al 2015

Subglacial water at grounding lines



Shear stress at grounding lines controlled by subglacial water (since effective pressure low)

> affects location of grounding line, and speed of advance / retreat Tsai et al 2015

Inclusion of water makes numerical computations easier! > ongoing work

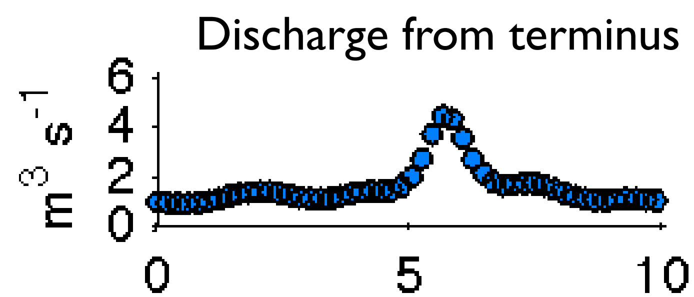
Effect of subglacial hydrology on ice-ocean interactions

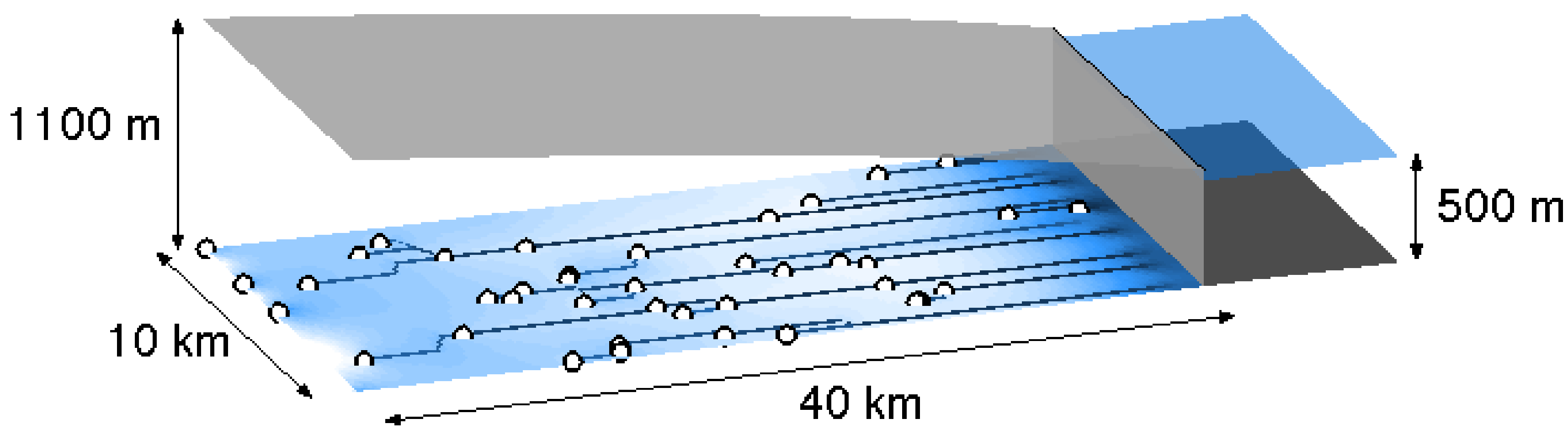
Subglacial discharge to ocean

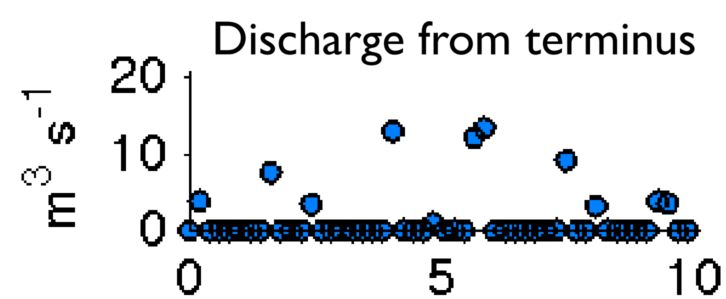
Distributed subglacial discharge enhances ocean-driven melting   Jenkins 2011

Models > Distribution depends quite delicately on effective pressure near grounding line

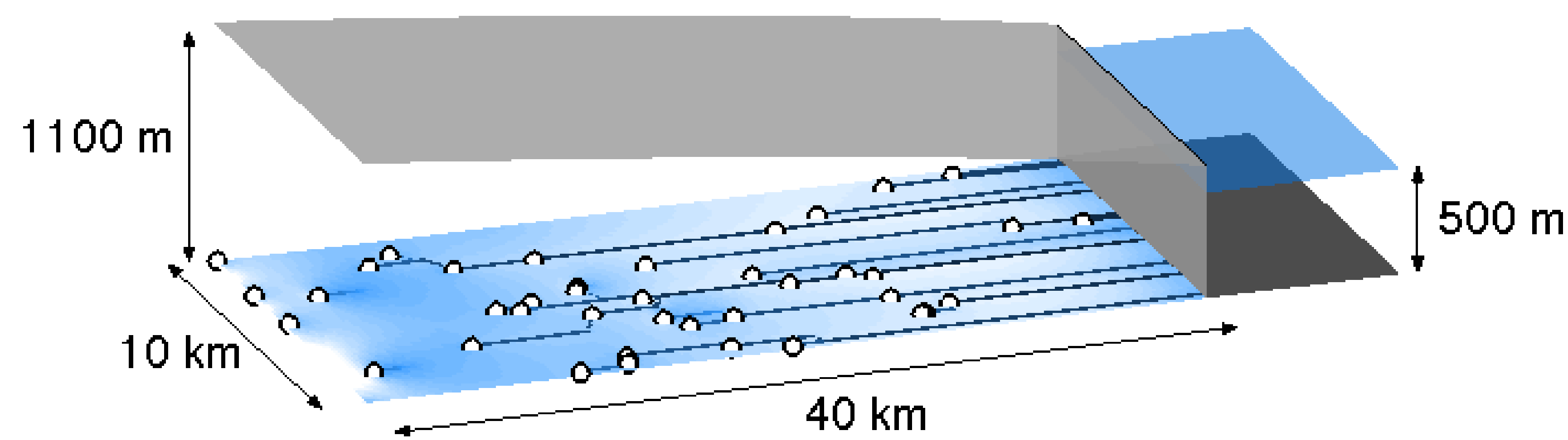
Terminus at flotation



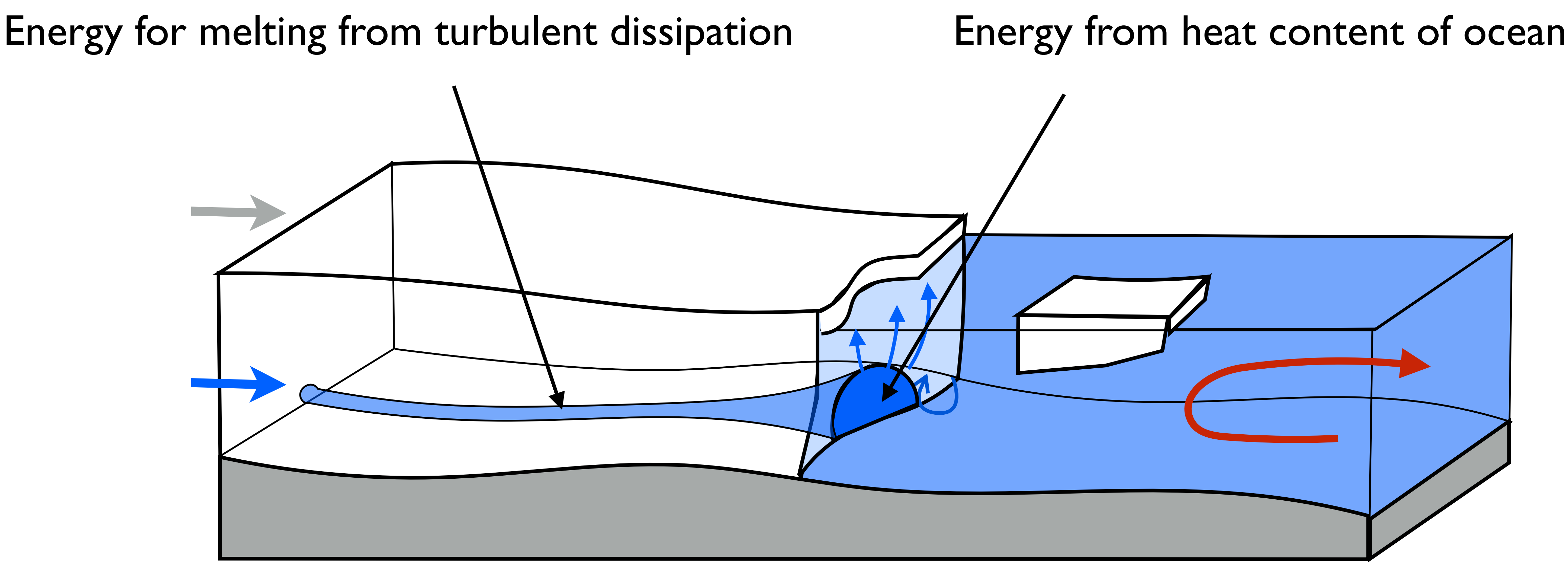




Terminus above flotation



Trumpeting shape of conduits approaching the margin



Cross-sectional area at margin: $S_0 \approx \mathcal{C} u^{-3/14} \Psi_0^{-3/14} Q^{6/7}$ $C \approx 3 \ \mathrm{m}^{1/4} \ \mathrm{s}^{-27/44}$

… but intrusion of ocean water into mouth of conduit causes additional melting, so area likely bigger than this > ongoing work

Effects on ice shelves

Subglacial conduits ‘seed’ sub-shelf channels for focussed melting of ice shelves

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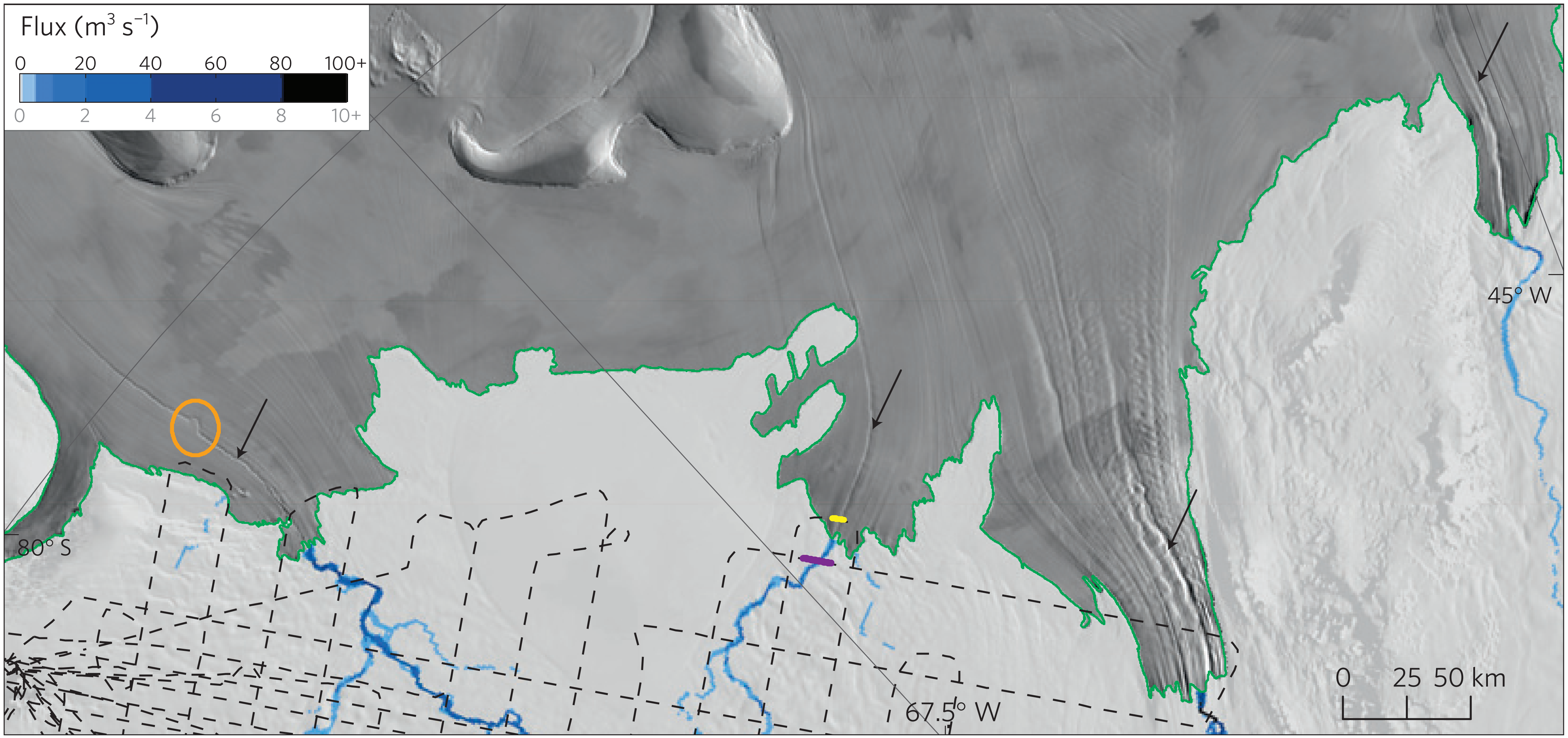

Le Brocq et al 2013 (also Alley et al 2016)

Summary

Glacial hydrology plays many roles in ice-sheet dynamics:

Lubrication - complex, but no clear evidence for positive feedback

Thermal evolution - likely a small / long-term effect (‘cryo-hydrologic warming’)

Hydrofracturing of ice shelves - may become increasingly important

Surges & streaming - certainly a big role, still mechanistically uncertain

Understanding of ice-sheet scale hydrology significantly advanced with recent Greenland campaigns

… but understanding why individual outlet glaciers behave as they do still a challenge

Antarctic subglacial hydrology still very unknown - role of subglacial water in ice streams likely to be crucial