Feedbacks between subglacial hydrology and glacier dynamics

Matthew Hoffman
Stephen Price
Climate, Ocean & Sea Ice Modeling Group,
Los Alamos National Laboratory

1. Introduction

On most glaciers and ice sheet outlets the majority of motion is due to basal sliding. The importance of water at the bed in controlling basal sliding is well established, with increased sliding generally related to high basal water pressure, but the details of the interactions between the ice and water systems has not received much study when there is two-way coupling between the systems.

We explore feedbacks between subglacial hydrology and ice dynamics using a coupled model of two-dimensional subglacial hydrology and three-dimensional, higher-order ice dynamics within the Community Ice Sheet Model.

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References

This material is described in:

M.J. Hoffman and S. Price. 2014. Feedbacks between subglacial hydrology and glacier dynamics. Journal of Geophysical Research – Earth Surface, 119, doi:10.1002/2013JF002943.

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Hewitt, I. J. (2011), Modelling distributed and channelized subglacial drainage: the spacing of channels, Journal of Glaciology, 57(202), 302–314.

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2. Model Formulation

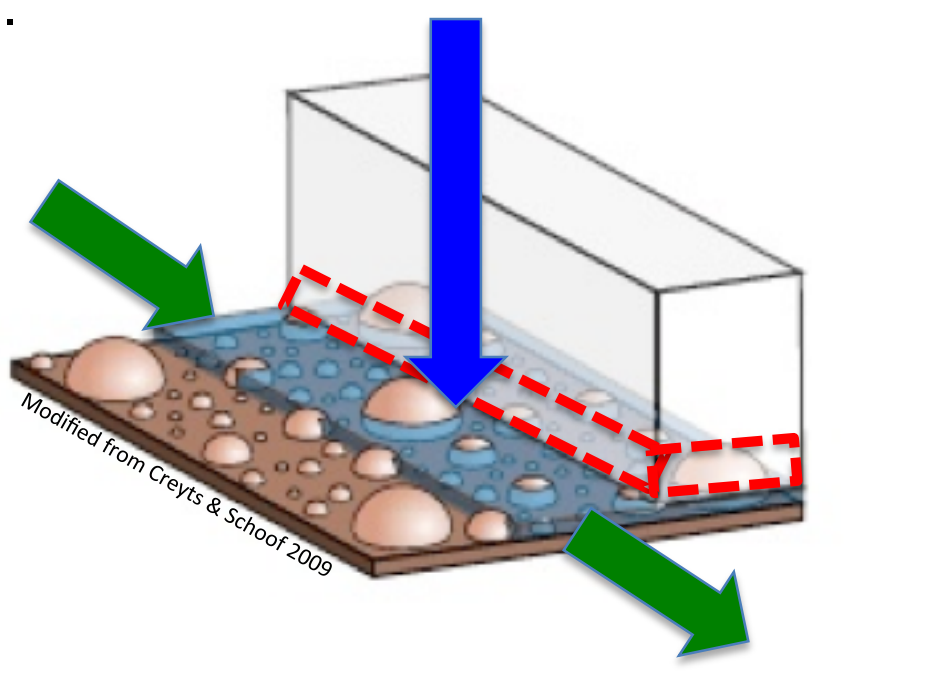
The model couples models for distributed drainage, channelized drainage, and ice dynamics.

a) Distributed Drainage

Describes water in a macroporous film (e.g. linked cavities).
Based largely on formulation of Hewitt (2011).

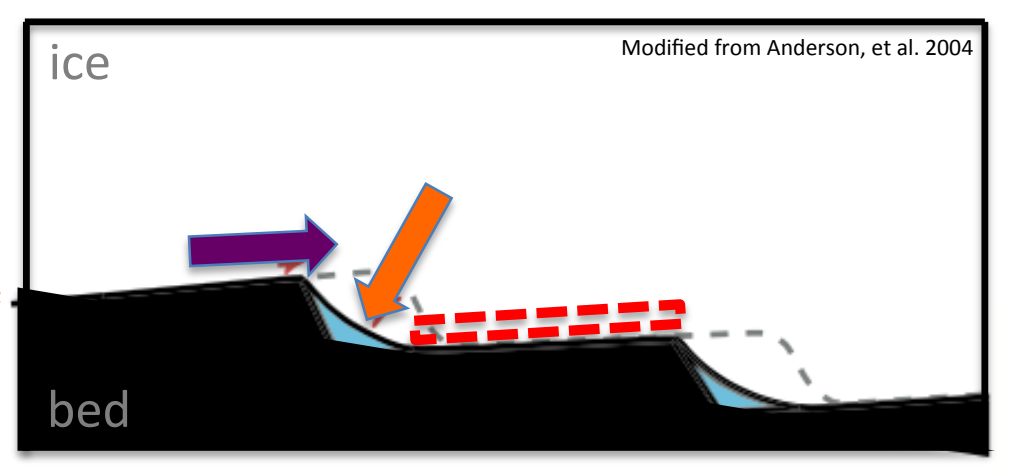
1) Mass conservation of water

$$\frac{\partial h}{\partial t} + \underbrace{\nabla \cdot \mathbf{q}}_{\text{Flux divergence}} = \underbrace{\frac{m}{\rho_w}}_{\text{Basal melt}} + \underbrace{\omega}_{\text{Water input from surface}}$$



2) Evolution of subglacial cavities

$$\frac{\partial h}{\partial t} = V_O - V_C = \left(\underbrace{\cancel{\frac{m}{\rho_i}}}_{\text{Melt opening}} + \underbrace{|\mathbf{u_b}|\frac{h_r - h}{l_r}}_{\text{Sliding over bumps}}\right) - \underbrace{\left(\frac{hN}{\eta_i}\right)}_{\text{Creep closure of ice}}$$



3) A Darcy style flow law

$$\mathbf{q} = -\frac{k_0 h^3}{\eta_w}\nabla\phi$$

4) Heat from passive sources
(heat from water flow neglected)

$$mL = \underbrace{G}_{\text{Geothermal}} + \underbrace{\mathbf{u_b}\cdot\boldsymbol{\tau_b}}_{\text{Basal friction}} - \cancel{\mathbf{q}\cdot\nabla\phi}$$

○ **Variables from ice dynamics**
○ **Uncertain parameters**

b) Channelized drainage

Describes a single R-channel.

A channel forms when melting from dissipation becomes larger than passive opening of cavities ($D_f > 1.0$):

$$D_f = \frac{\frac{\mathbf{q}\cdot\nabla\phi_s}{\rho_i L}}{|\mathbf{u_b}|\frac{h_r - h}{l_r}}$$

1) Mass conservation of water

$$\frac{\partial S}{\partial t} + \frac{\partial Q}{\partial x} = \frac{M}{\rho_w} + \gamma\Delta x$$

2) Evolution of channel area

$$\frac{\partial S}{\partial t} = \frac{M}{\rho_i} - \frac{SN_c}{\eta_i}$$

3) Manning flow law

$$FQ^2 = S^{8/3}\frac{\partial\phi_c}{\partial x}$$

4) Energy balance

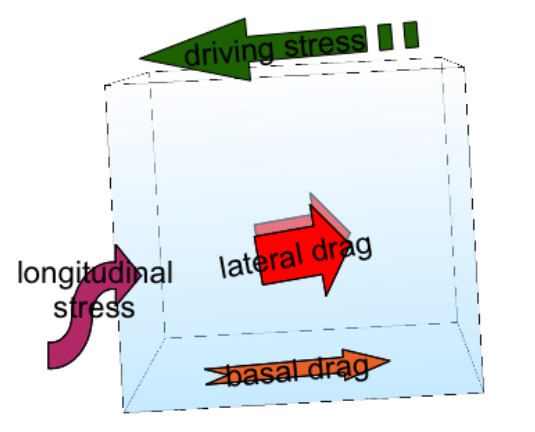
$$ML = Q\frac{\partial\phi_c}{\partial x}$$

An exchange term couples the channel to the surrounding sheet:

$$\gamma = -\frac{k_0 h^3}{\eta_w}\frac{\phi_c - \phi_s}{\frac{1}{2}\Delta y}$$

c) Ice Dynamics

- Community Ice Sheet Model (CISM)
- Higher-order stress balance

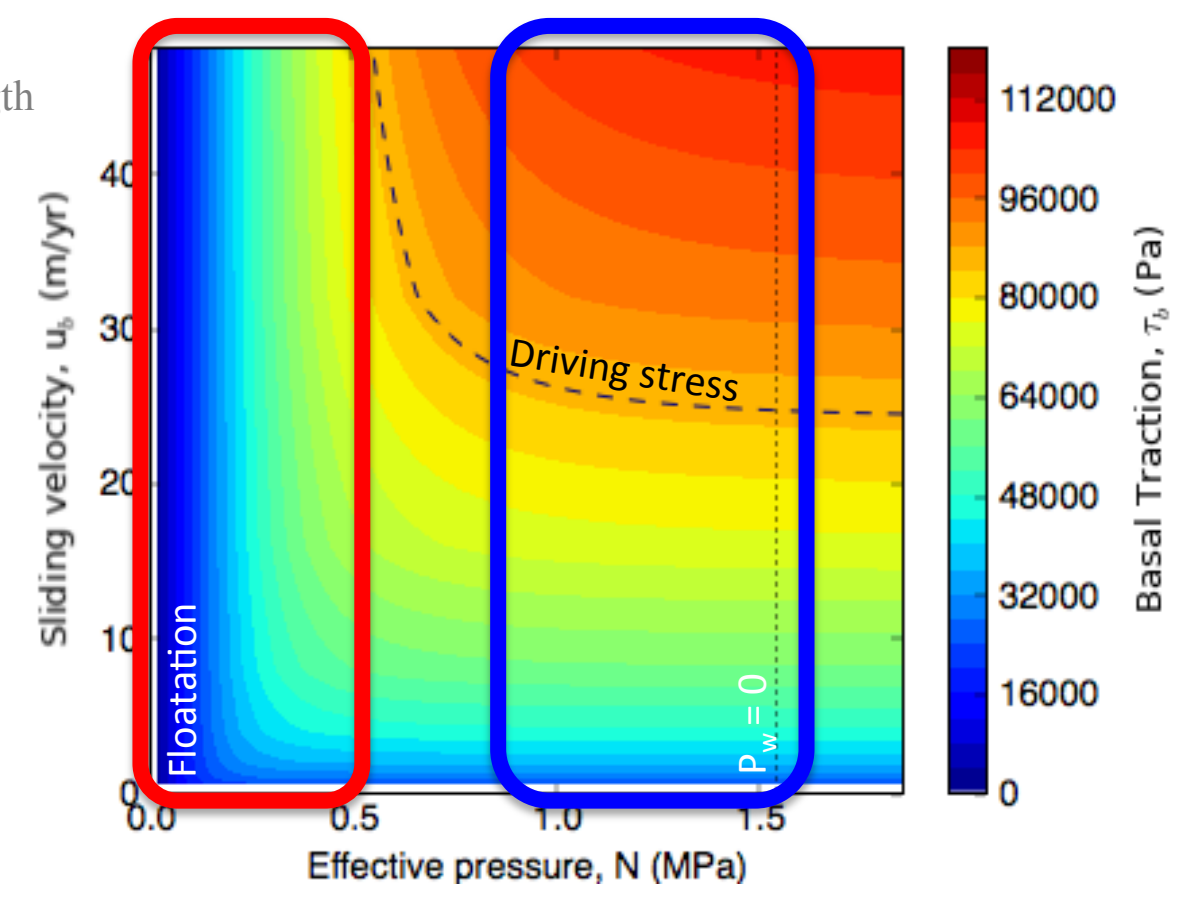


○ **Variable from hydrology**
○ **Uncertain parameters**

Sliding law: Couples hydrology (N) to dynamics (τ_b, u_b)

- Coulomb friction sliding law *(Schoof 2005, Proc. R. Soc. A)*
- bounded basal drag, cavitation

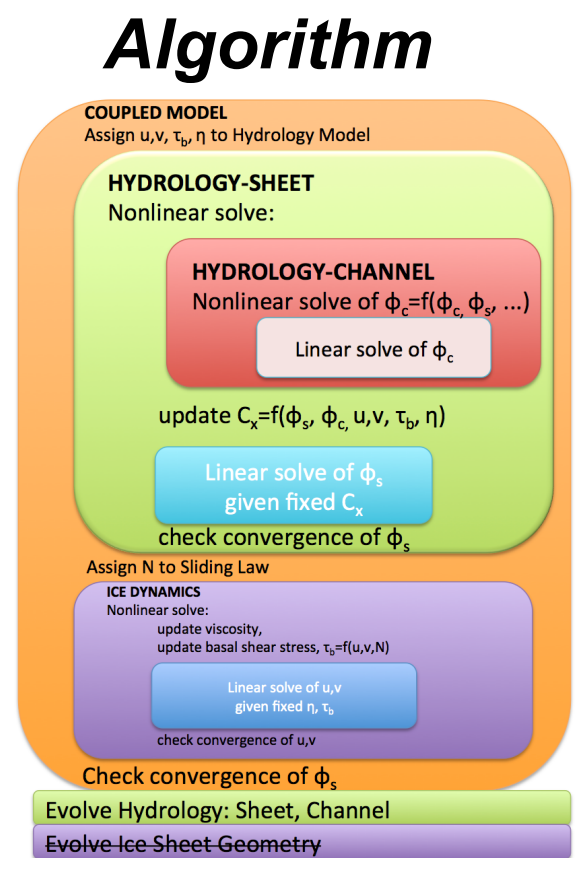
$$\tau_b = \underbrace{C}_{\text{Coulomb friction coefficient}}\left(\frac{u_b}{u_b + N^n\Lambda}\right)^{1/n} N, \qquad \Lambda = \frac{\overset{\text{Bedrock bump wavelength}}{\lambda_{max}} A}{\underset{\text{Bedrock bump slope}}{m_{max}}}$$



At high N, basal traction is independent of N.
$\tau_b \propto u_b^{1/n}$

At low N (near floatation), basal traction is independent of u_b (Coulomb friction).
$\tau_b \propto N$

Solution Algorithm



COUPLED MODEL
Assign u,v, τ_b, η to Hydrology Model

HYDROLOGY-SHEET
Nonlinear solve:

HYDROLOGY-CHANNEL
Nonlinear solve of $\phi_c = f(\phi_c, \phi_s, \ldots)$
Linear solve of ϕ_c

update $C_x = f(\phi_s, \phi_c, u, v, \tau_b, \eta)$
Linear solve of ϕ_s given fixed C_x
check convergence of ϕ_s

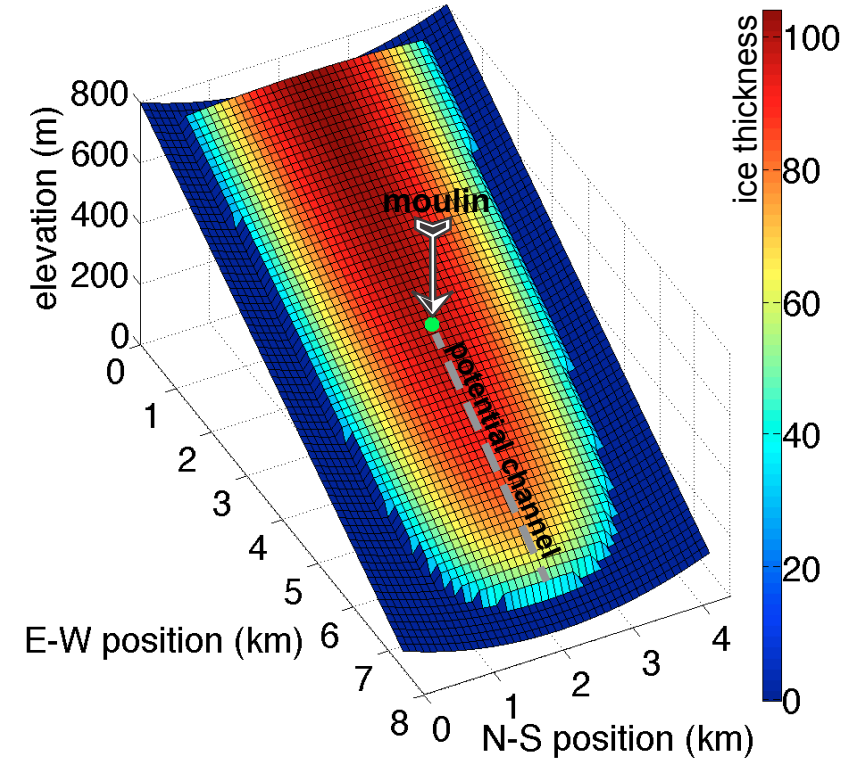
Assign N to Sliding Law

ICE DYNAMICS
Nonlinear solve:
update viscosity,
update basal shear stress, $\tau_b = f(u,v,N)$
Linear solve of u,v given fixed η, τ_b
check convergence of u,v

Check convergence of ϕ_s
Evolve Hydrology: Sheet, Channel
~~Evolve Ice Sheet Geometry~~

3. Test Case & Experiment Setup

We use an idealized mountain glacier test case.

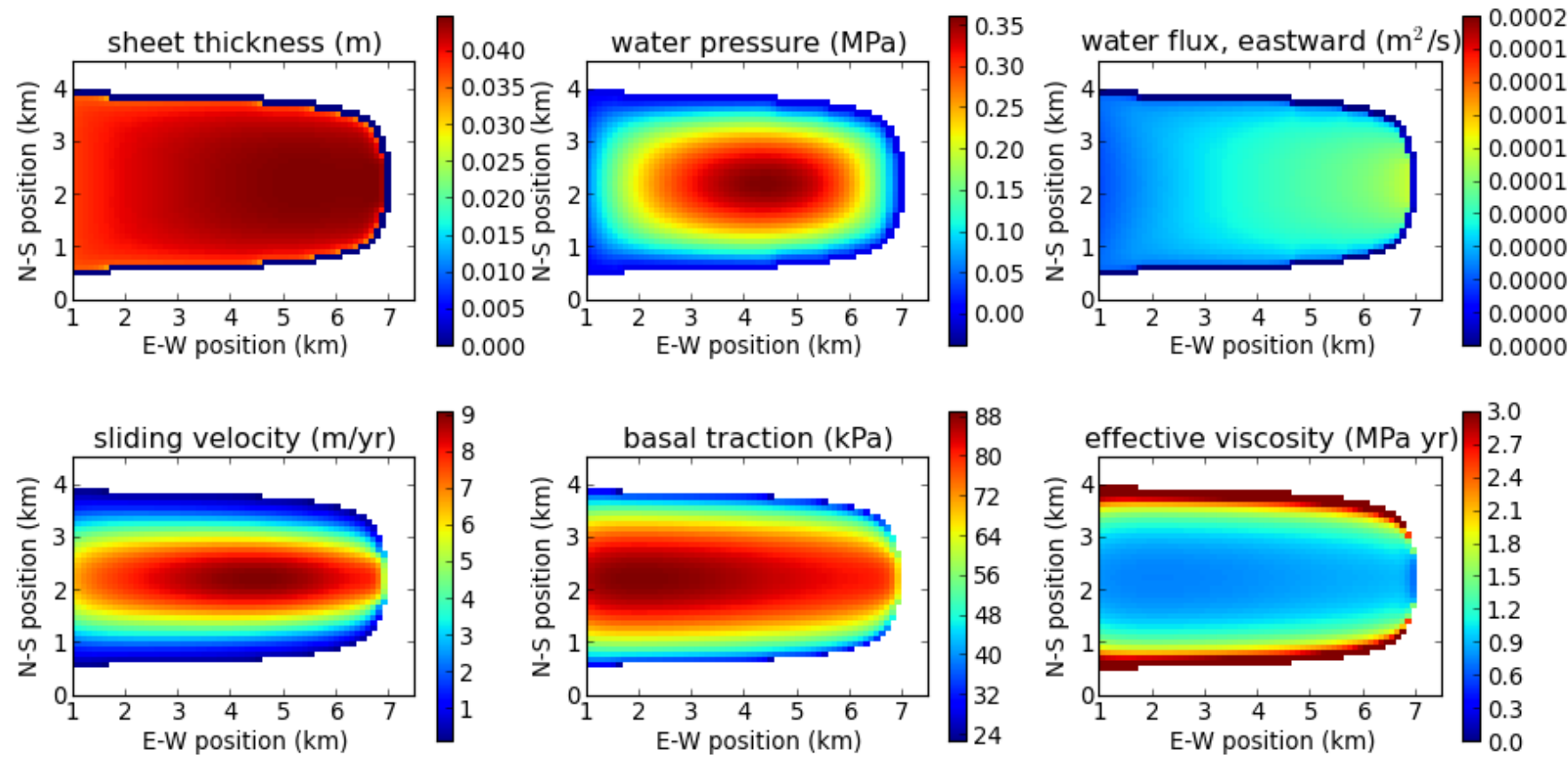


"Snout" of alpine glacier in an inclined trough:
"Plastic glacier" shape ($\tau_c = 10^5$ Pa)
7 km long, 3 km wide
100 m grid resolution, 10 vertical levels

Model parameters are set to reasonable values for a mountain glacier.

Physical Constants		
ρ_w	density of water	1000 kg m^{-3}
ρ_i	density of ice	900 kg m^{-3}
g	gravitational acceleration	9.81 m s^{-2}
L	latent heat of fusion of water	3×10^5 J kg^{-1}
η_w	viscosity of water	10^{-3} Pa s
Hydrology Parameters		
h_r	height of bedrock bumps	[0.05 m]
l_r	wavelength of bedrock bumps	[2 m]
G	geothermal heat flux	0.06 W m^{-2}
k_0	dimensionless transmissivity coefficient	10^{-6}
Ice Dynamics Parameters		
A	flow law parameter	1.0×10^{-16} Pa^{-3} yr^{-1}
C	Coulomb friction coefficient	[0.25]
λ_{max}/m_{max}	ratio of controlling bedrock bump wavelength to maximum slope	[1.5 m]

The coupled model is spun-up to steady-state with no external forcing (no moulin) and a fixed geometry. This represents "winter" conditions.

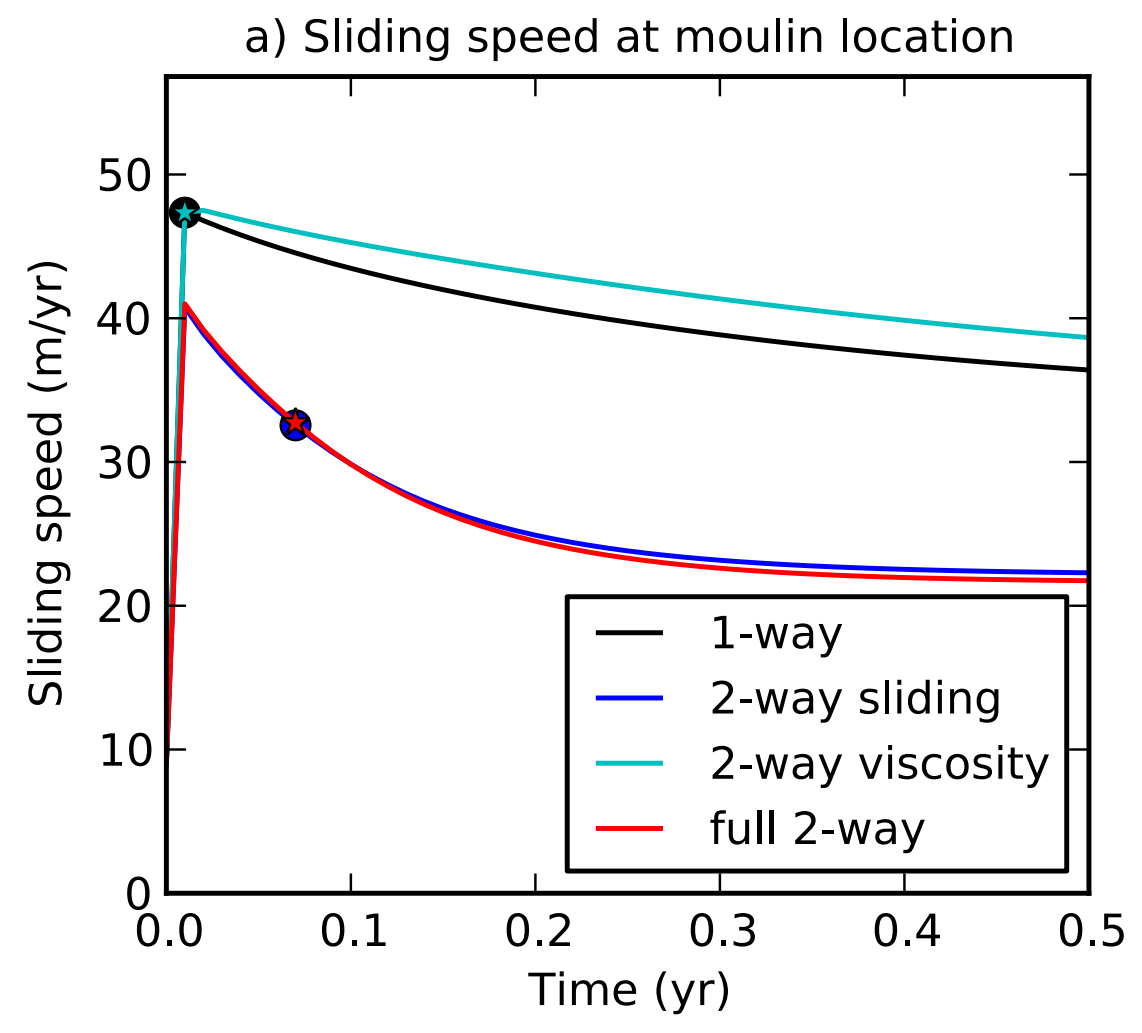


Then a series of "spring-speedup" experiments are performed by turning the single moulin on. The degree of coupling between hydrology and ice dynamics gets successively more sophisticated:

Coupling	Ice dynamics sees water pressure	Hydrology sees sliding velocity	Hydrology sees ice effective viscosity
1-way	✔		
2-way velocity	✔	✔	
2-way viscosity	✔		✔
2-way both	✔	✔	✔

4. Results - Distributed Drainage only

We first assess the strength of feedbacks between hydrology and ice dynamics without allowing a channel to form.


a) Sliding speed at moulin location

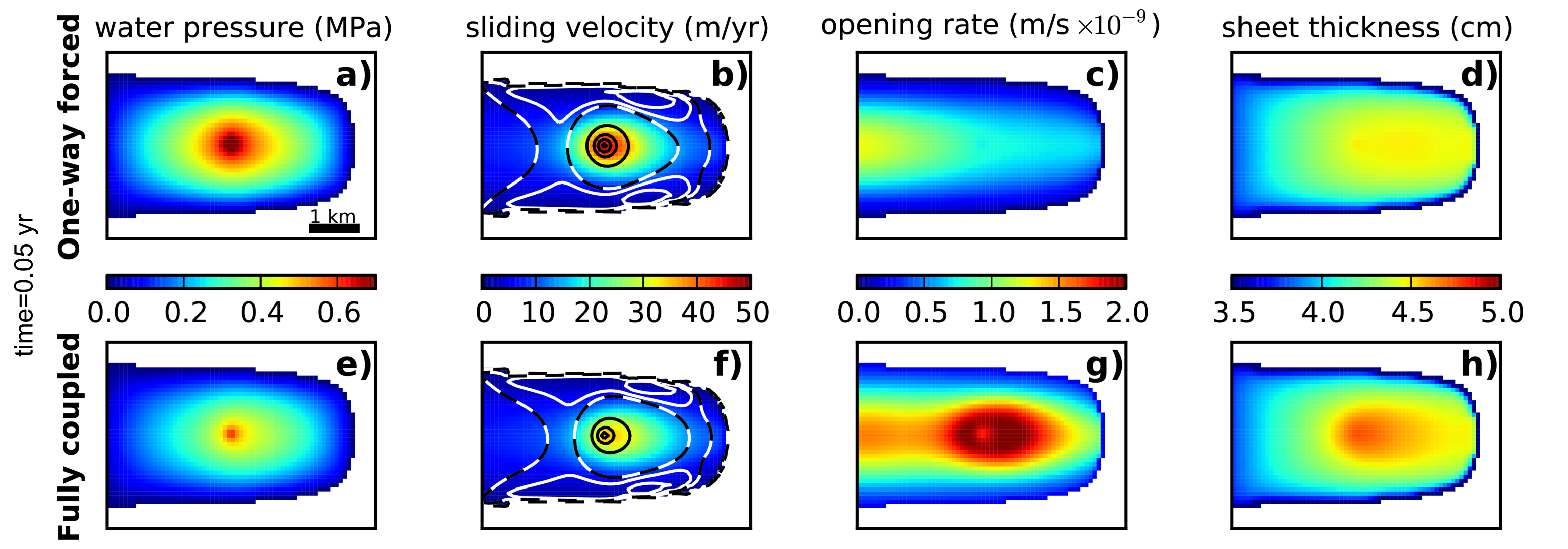
1-way: Hydrologic system adjusts to new input but slowly: new steady state water pressure and sliding velocity are lower than transient.

2-way velocity: Increased sliding opens subglacial cavities, lowering water pressure and sliding. (negative feedback)

2-way viscosity: Increased strain rates softens ice, enhancing creep closure, water pressure, and sliding. (positive feedback)

2-way both: Velocity effects dominate over viscosity effects. (net negative feedback)

In the **1-way** model, cavities enlarge only from reduced creep closure rates when the system is pressurized. Sheet capacity evolves slowly and water pressure and sliding are maintained.



In the **fully coupled** model, sliding leads to increased cavity opening and a much larger capacity sheet. The increase in cavity size rapidly lowers water pressure and reduces sliding.

5. Parameter Sensitivity

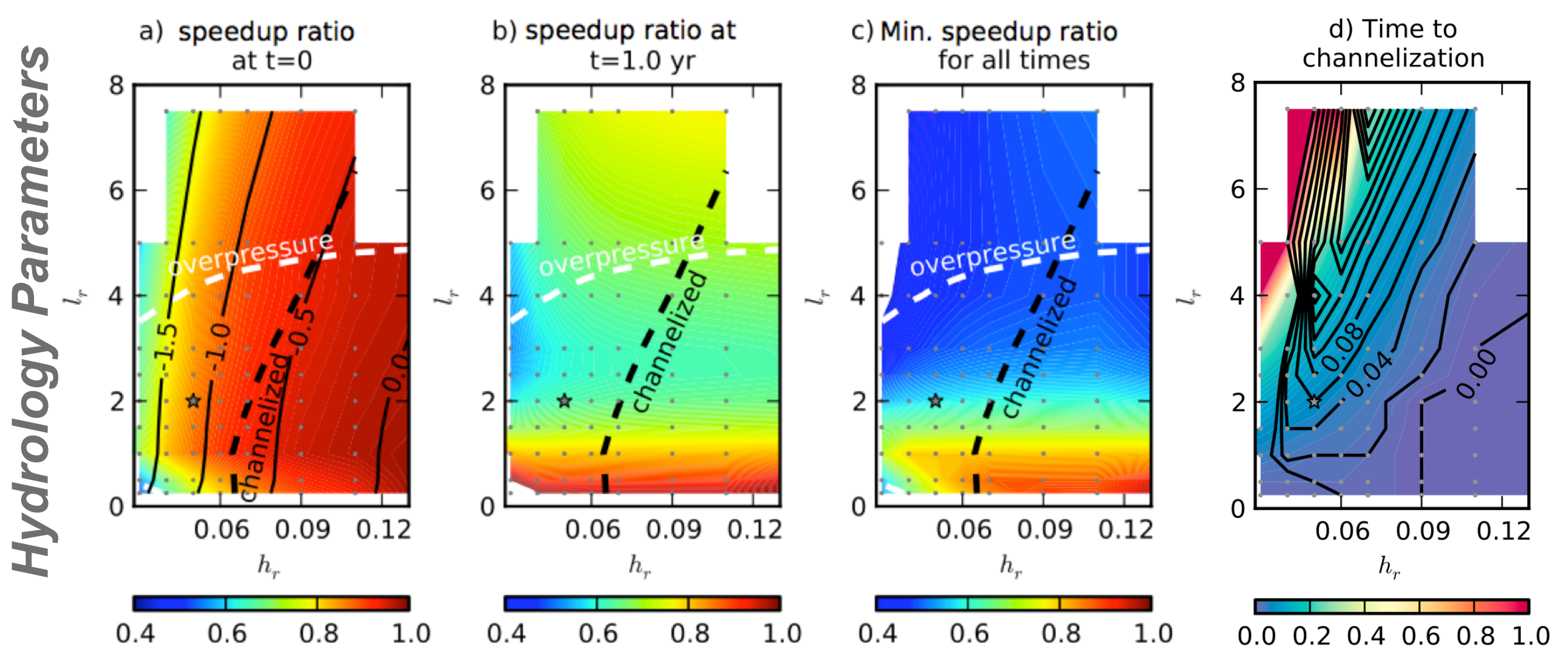
We assess the strength of feedbacks for a range of parameter values.

1. Find moulin input needed to achieve 4.55x speedup for fully-coupled model (to match speedup of the base case).

2. Run both fully-coupled model and one-way forced model for 1 year.

3. Calculate speedup ratio at the moulin location for all time steps:

$$\frac{\text{fully coupled sliding speed}}{\text{one-way forced sliding speed}}$$

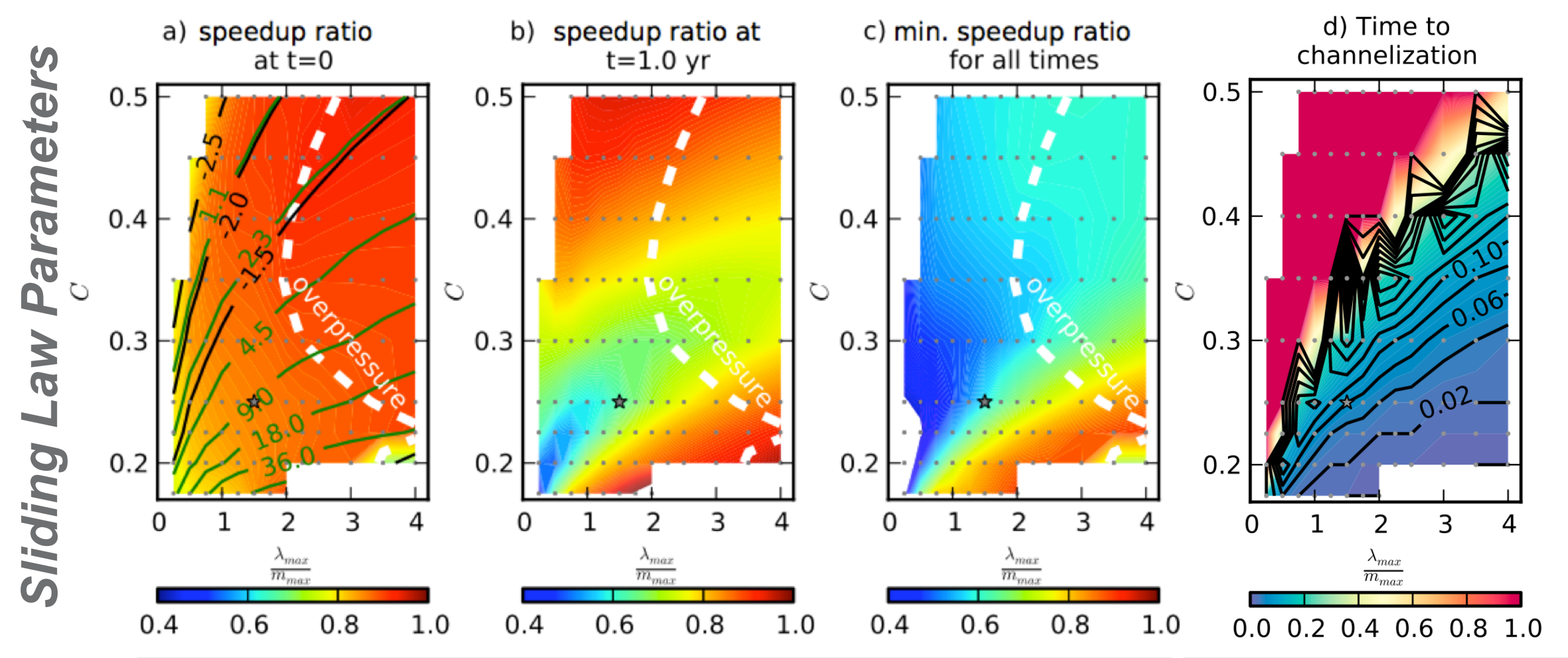


Only some parameters show substantial feedback strength at initial time.

Most parameters show moderate feedback strength at new SS.

Most parameters show large feedback strength at some point.

Most parameters show much longer time to channelization with the fully coupled model.

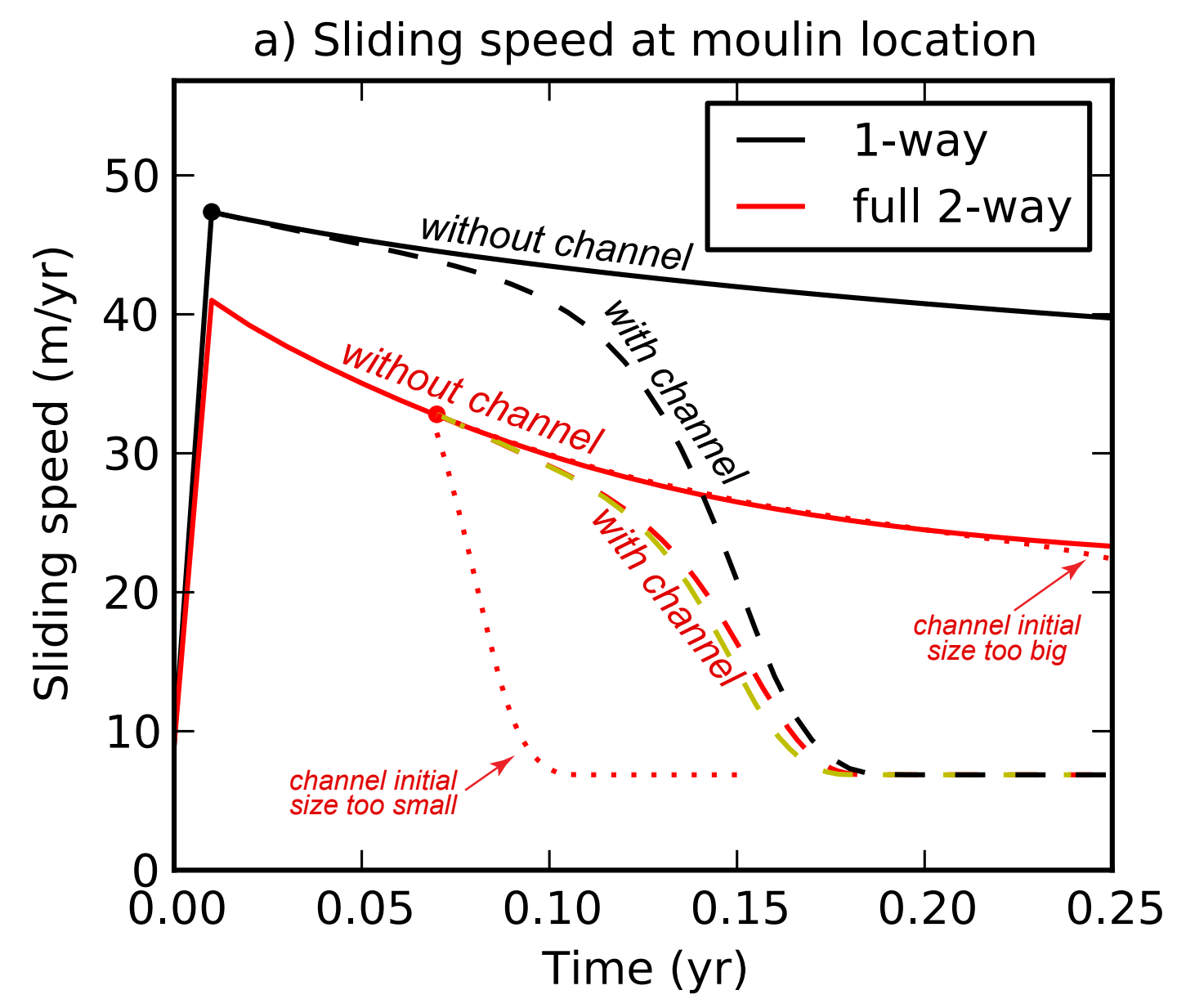


Star is base case shown in section 4.
Black lines are contours of the log of meltwater input (m³ s⁻¹) required to achieve 4.55x speedup.
Green lines are selected contours of initial sliding speed at moulin location (m yr⁻¹)

Time past moulin activation at which channelization threshold is surpassed for the coupled model (colors). The black lines show contours of additional time to channelization for the coupled model relative to the uncoupled model.

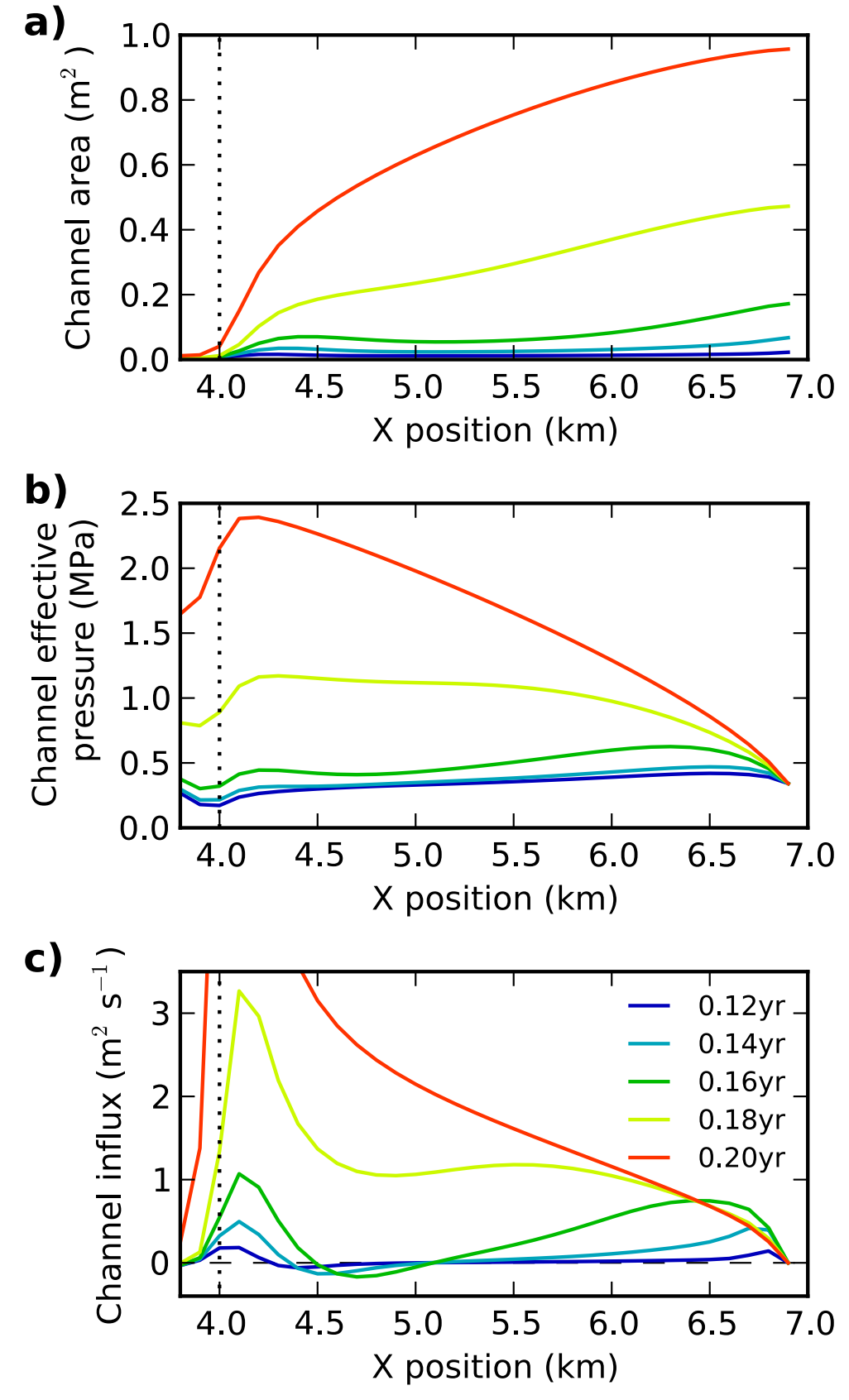
6. Effects of Channelization

Finally, we repeat the experiments in section 4 but allow a single channel to form if the channelization threshold is reached.


a) Sliding speed at moulin location

- * Channelization causes much faster cessation of speedup
- * Feedbacks not important when channelization occurs.
- * But, channel takes some time to develop to efficiency.
- * Fully coupled model takes longer to reach channelization threshold.

Channel Profiles with full 2-way model



Channel growth is initially slow but accelerates after a constriction between the moulin and the terminus is eliminated.

Effective pressure in the channel initially matches the surrounding sheet. It grows as the channel increases in size.

* The channel is introduced with no exchange with the sheet.
* By 0.12 yr there is small inflow to the channel near the moulin, outflow back to the sheet around 5 km and inflow to the channel again near the terminus.
* As the channel grows it captures a substantial volume of the water from the moulin, as well as water from the sheet downstream.

7. Conclusions & Implications

* Sliding-opening is a persistent negative feedback to sliding in the coupled system.
* However, channelization terminates speedup more quickly.
* **Even so, the sliding-opening feedback is important prior to channelization and delays channelization.**
Recent observations indicate subglacial drainage below the Greenland Ice Sheet remains distributed, therefore:
* Coupled modeling of subglacial drainage and ice dynamics may be necessary to accurately predict meltwater-induced speedup.
* The sliding-opening feedback may limit the magnitude of meltwater-induced speedup.