Greenland subglacial drainage evolution regulated by weakly-connected regions of the bed

Matthew Hoffman
Stephen Price

Lauren Andrews
Ginny Catania

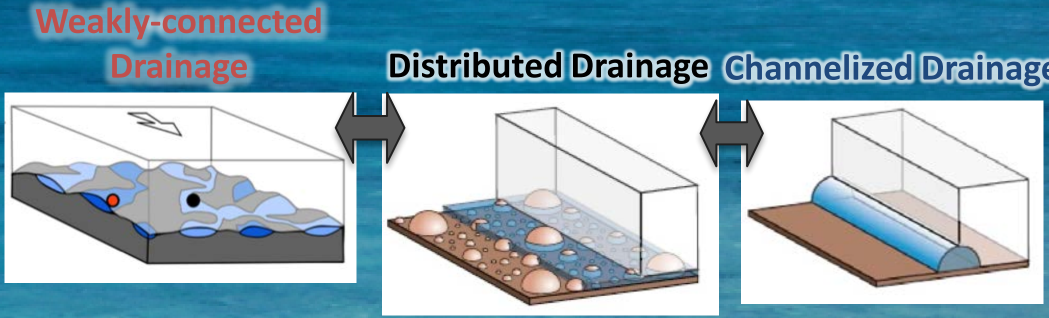
Jason Gulley

Martin Lüthi

Claudia Ryser

Robert Hawley

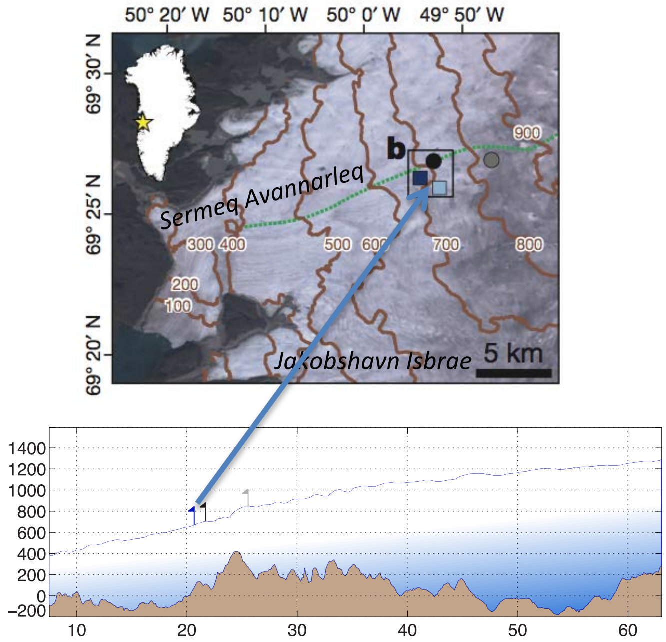
Thomas Neumann



Field campaign and modeling supported by:

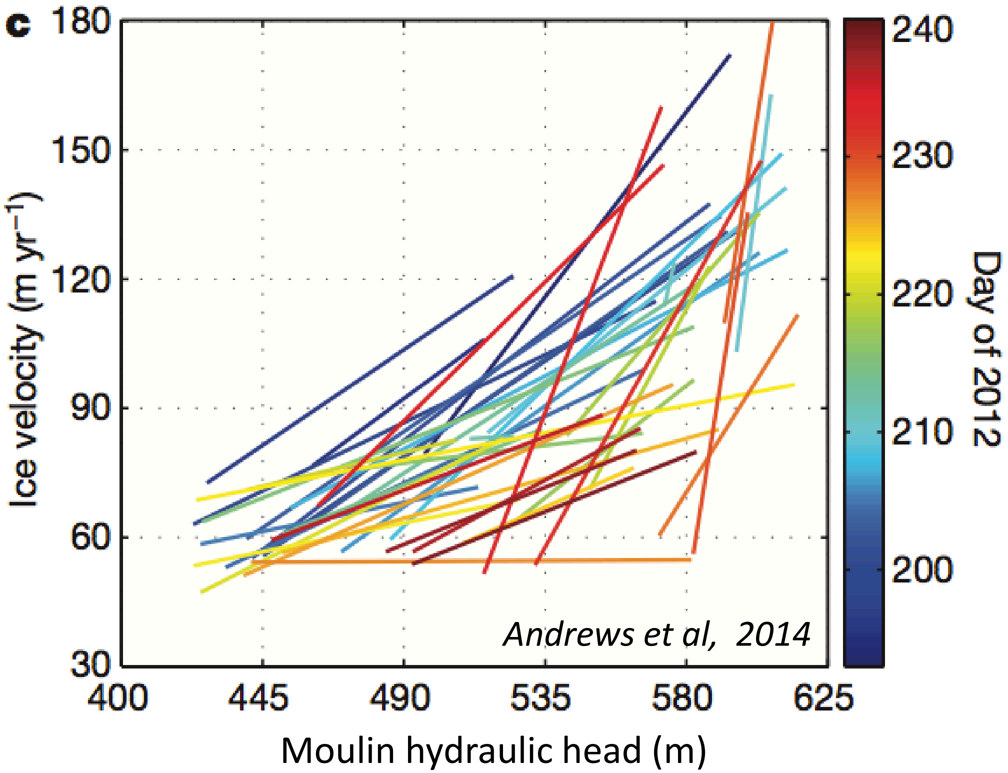
Field campaign, 2012

- moulin water pressure
- borehole water pressure
- ice velocity



Moulin water pressure indicates equilibrated subglacial **channels**.

However, ice speed continues to drop.

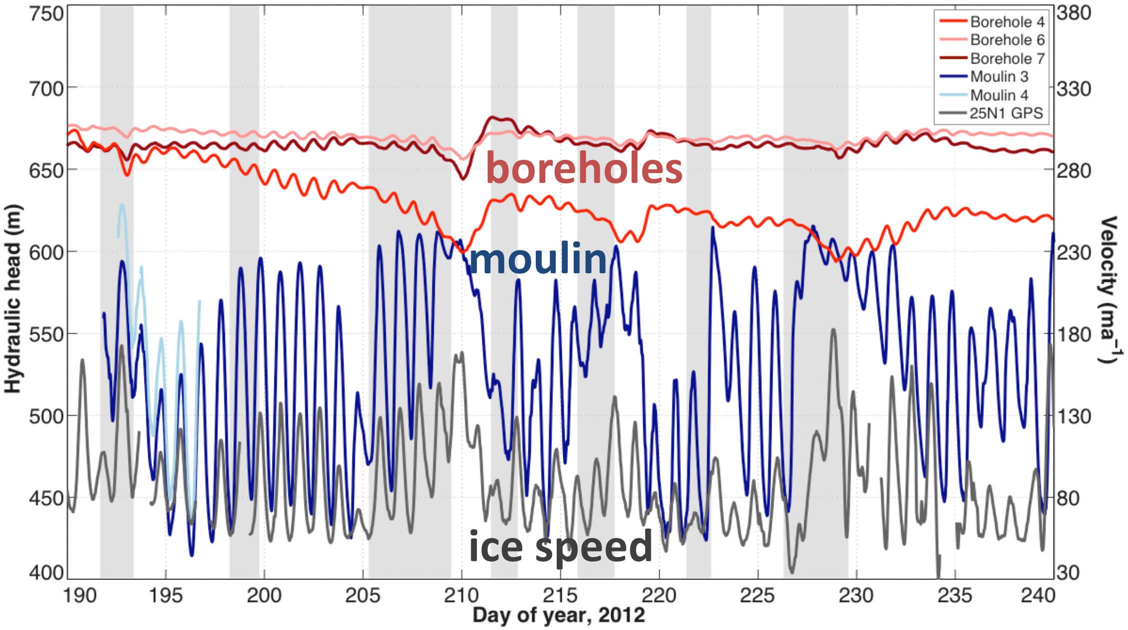


Andrews et al, 2014

...continued evolution elsewhere in the drainage system?

Subglacial changes outside the channelized regions

- Low amplitude diurnal changes in boreholes
- Borehole head out of phase with velocity
  - Sampled 'disconnected' or 'isolated' distributed system
- Seasonal trends in some boreholes match seasonal trends in ice velocity.



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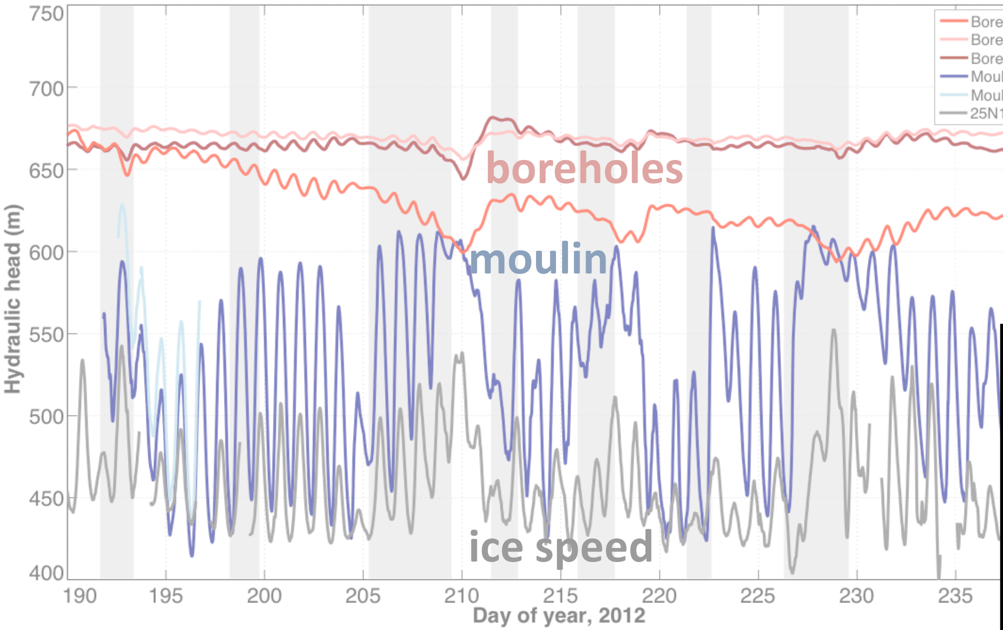
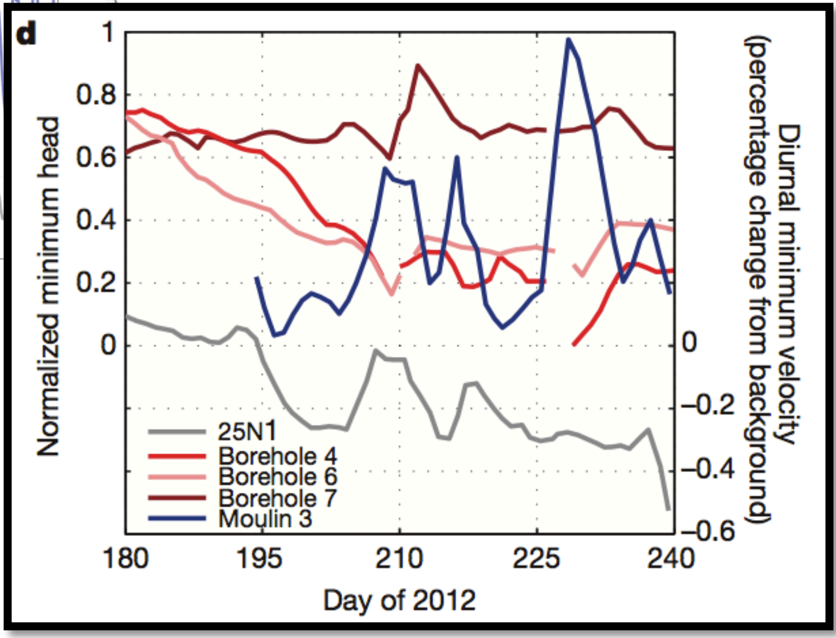


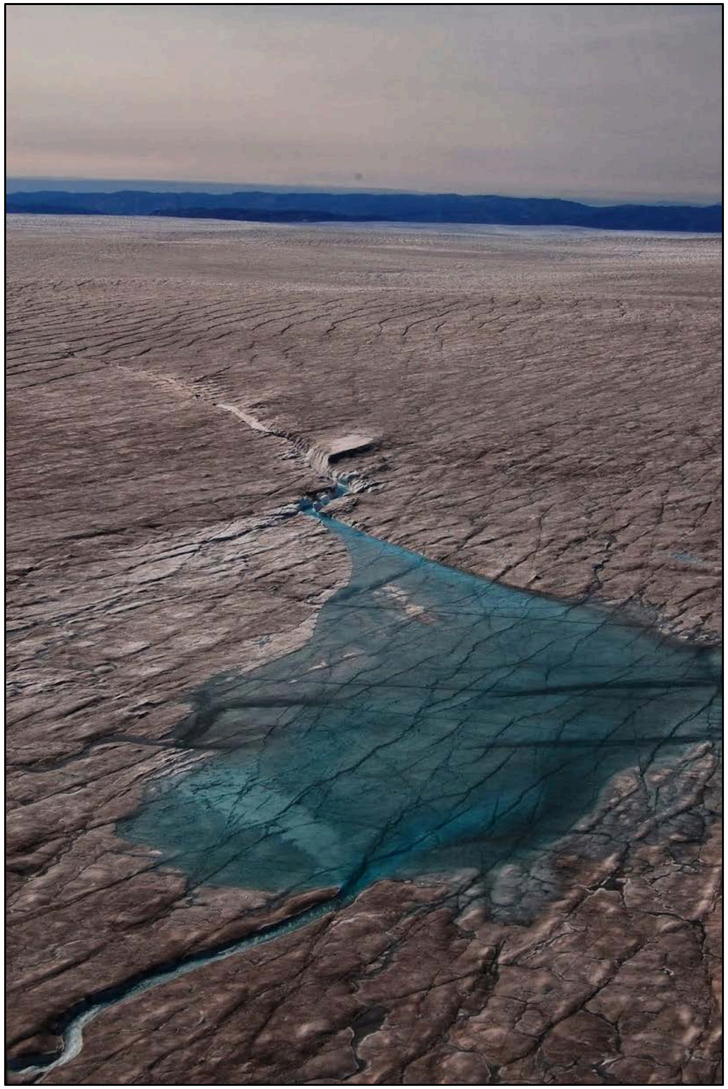
Seasonal Variation

(smoothed, normalized)



Observational Summary

- Channels control short-term variations in velocity but *not* late-summer evolution.
- Late-summer evolution may be affected by changes in **"isolated regions"** of the bed.



Importance of Isolated Drainage?

Ice dynamics respond to the integrated basal traction over both connected and **disconnected (isolated)** regions (Iken & Truffer 1997).

If water pressure lowers in the disconnected region, that should increase the overall basal traction, causing less sliding.

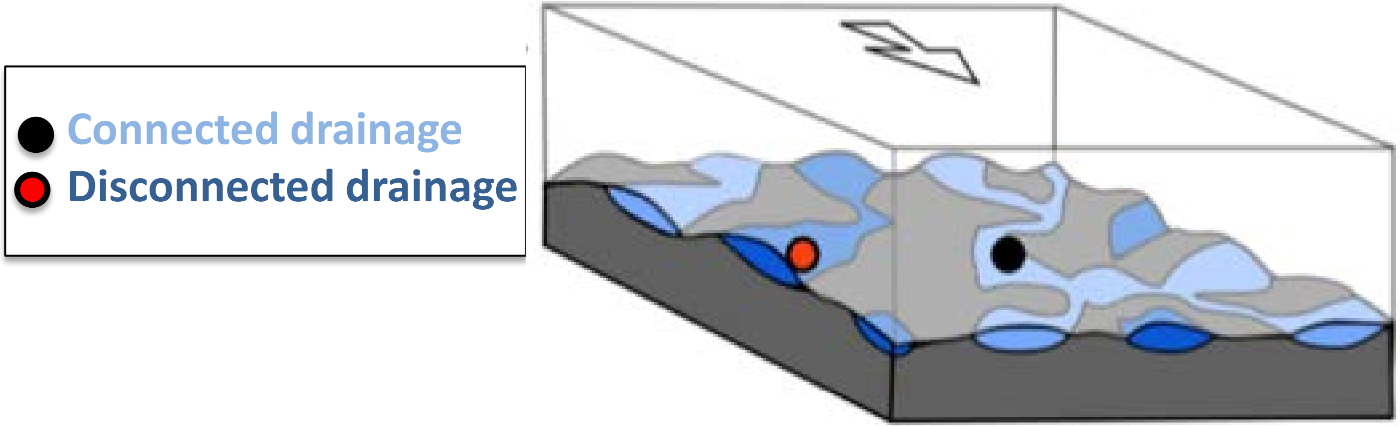


Figure modified from Ian Hewitt

Ample evidence for **extensive** and **dynamic** isolated system from mountain glaciers, e.g.:

- Hodge (1979): 22/24 boreholes drilled in South Cascade Glacier intercept 'inactive' regions:
  *"Most of the bed, **possibly as much as 90%**, appears to be hydraulically inactive and isolated from a few active subglacial conduits"*
- Murray & Clarke (1995), Gordon et al. (1998): Inactive regions can **change in pressure** or switch to active as water pressure in the active system rises.
- Iken & Truffer (1997): isolated cavities moderate active drainage regions

Subglacial Hydrology Model

(Modified version of Hoffman & Price, 2014, JGR)

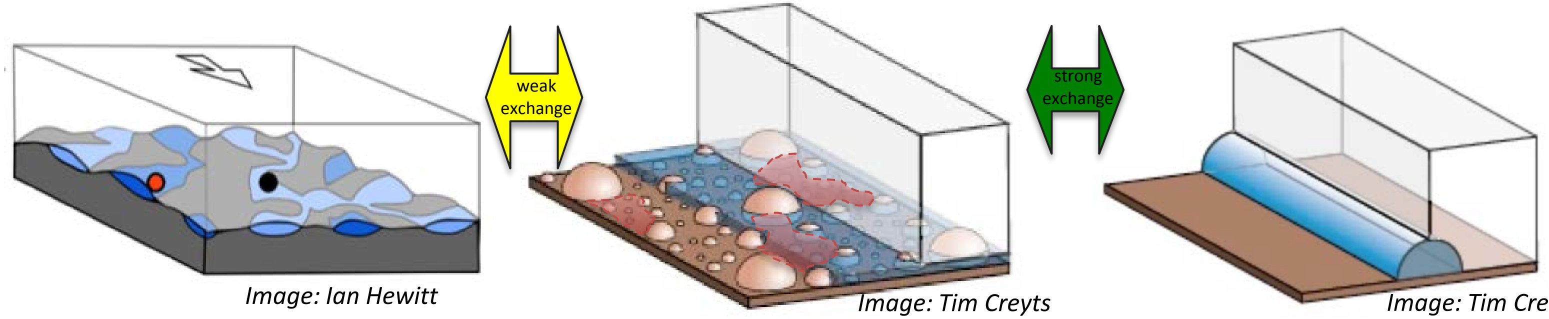


Image: Ian Hewitt

Image: Tim Creyts

Image: Tim Creyts

Weakly-connected Drainage

new component

(0-d subgrid representation)

Distributed Drainage

e.g. Hewitt 2011, J.Glac.

(Macroporous sheet)

Channelized Drainage

e.g. Hewitt 2011, J.Glac.

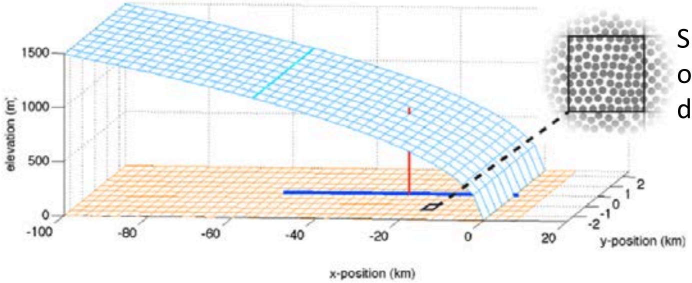
Cavities open by sliding, close by creep.

Cavities open by sliding, close by creep.

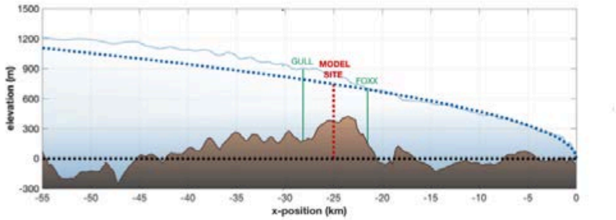
Channels open by melting, close by creep.

Idealized "ROGUE" Experiment

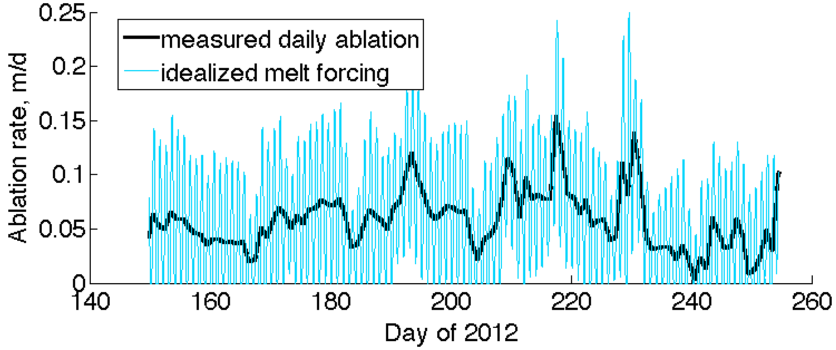
- 100km long domain
- "Plastic" glacier shape
  (constant $\text{Tau}_d=10^5$ Pa)
- 5 km wide "catchment-scale" domain with laterally periodic boundaries & potential channel along centerline
- Study site:
  25km inland, H=~750m, ds/dx = ~0.01

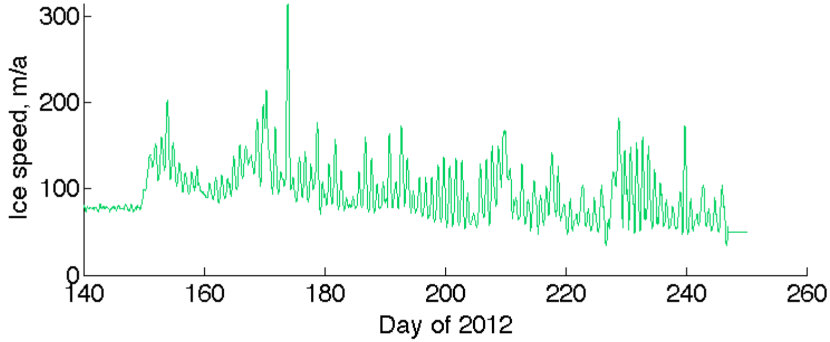


Sub-grid representation of weakly-connected drainage



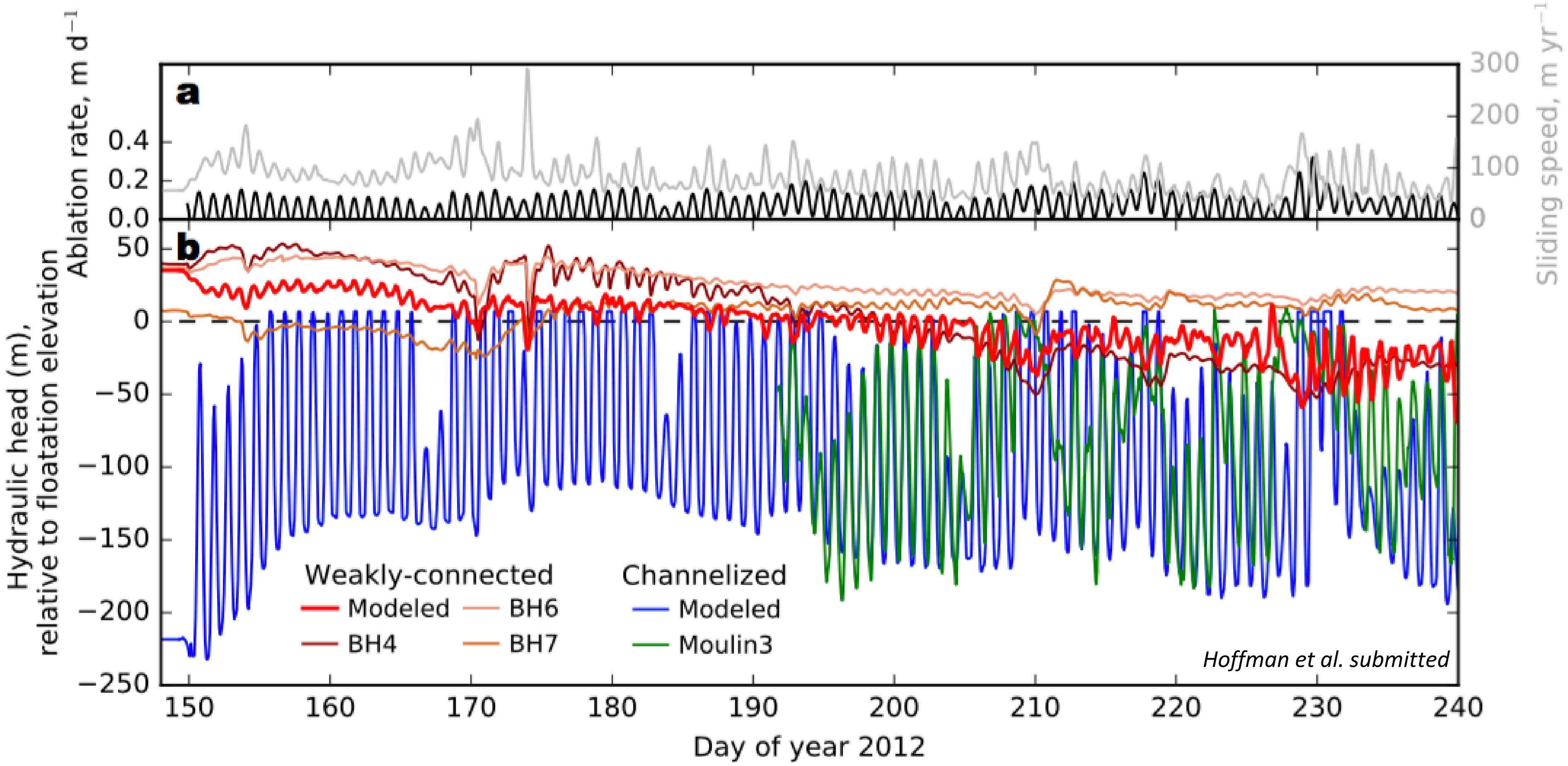
1. **Springtime initial condition:**
   spinup 3-component hydrology to steady state
2. **Summer forcing experiment**:
   - Supraglacial meltwater input along centerline
     - Based on measured daily ablation rates
     - Diurnally-varying sinusoidal shape added
     - Lapse rate extends forcing from ELA to terminus
   - Diurnally-varying sliding based on GPS ice velocity observations





Observe seasonal evolution of each component of drainage system <u>at study location</u>.

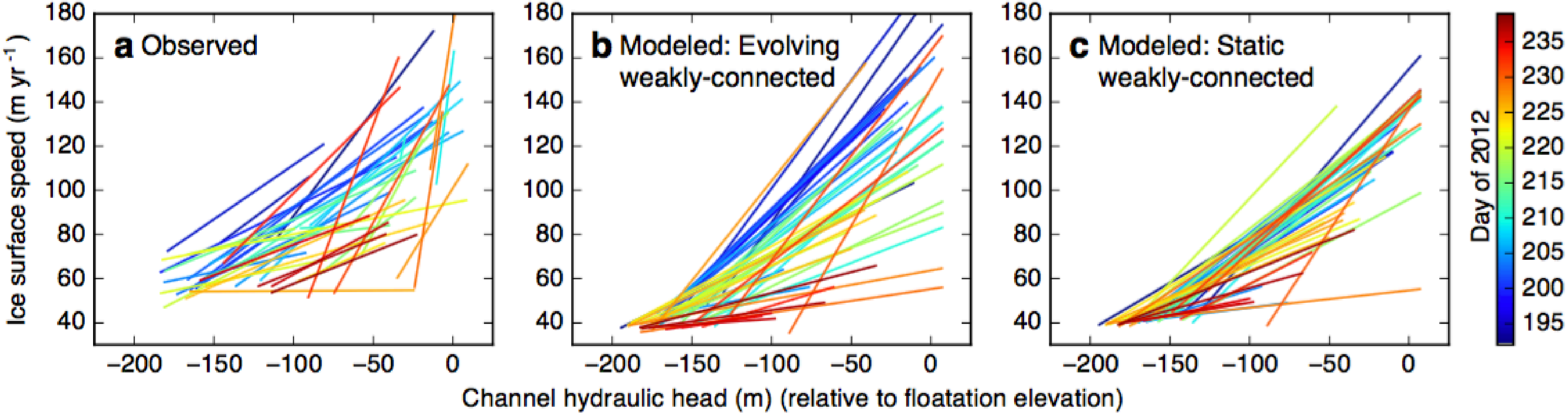
Model results: water pressure



Hoffman et al. submitted

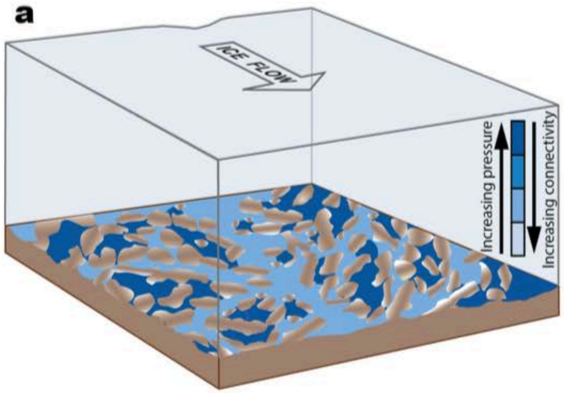
Model results: ice speed

Solve ice surface speed using CISM 2.1 with Coulomb basal friction law

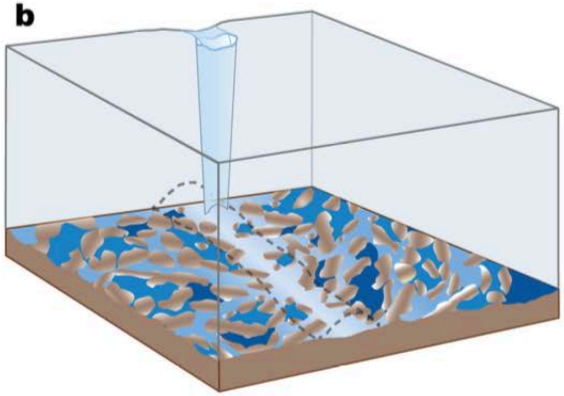


Hoffman et al. submitted

Proposed conceptual model

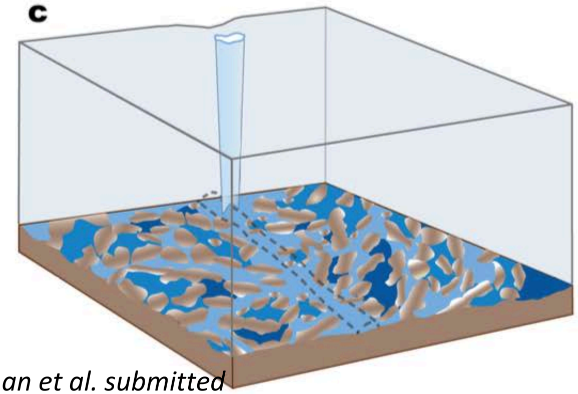


Onset of the melt season
Large fraction of the bed is composed of weakly-connected cavities at a higher water pressure than the surrounding distributed system.



Middle of the melt season
Meltwater draining through moulins is largely accommodated by the formation of efficient channels.

Concurrently, some of the weakly-connected cavities have leaked water, lowering their water pressure.



End of the melt season
Channels collapse within days after melt inputs cease, but the partially drained weakly-connected cavities take months to recharge by basal melting, leaving higher integrated basal traction than before summer began.

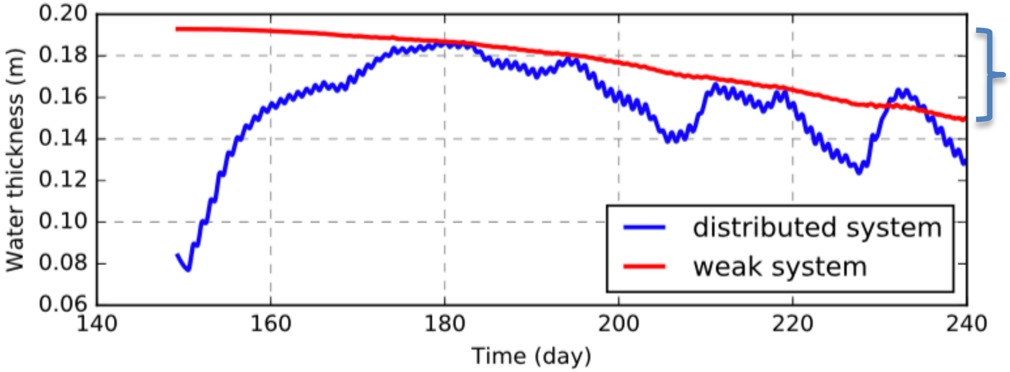
Hoffman et al. submitted

Conclusions

- Observations and modeling suggest a 3-component conceptual model for drainage
    - Distributed
    - Channelized
    - "Isolated" or weakly connected

- Small changes in isolated drainage could play an important role in seasonal evolution due to covering a large area fraction of the bed.

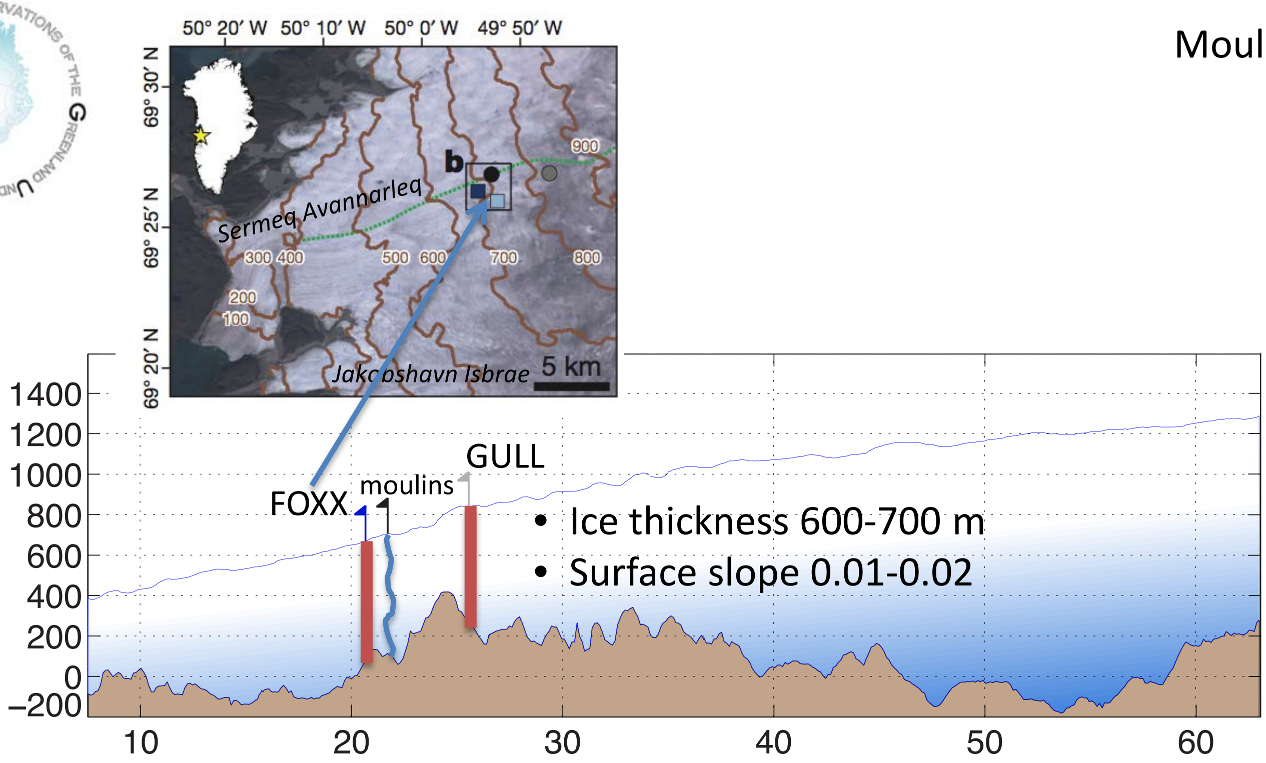
- Isolated system may take longer to recover in fall/winter → winter slowdown mechanism?



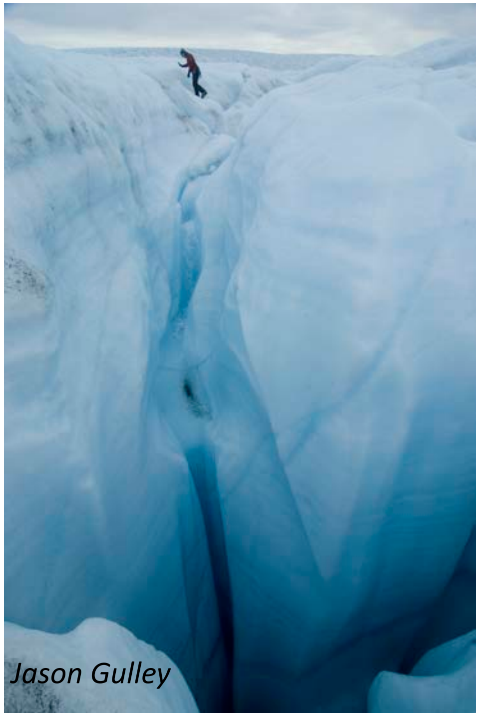
~2-5 years recharge time

Real-Time Observations of the Greenland Under-Ice Environment

Moulin pressure sensor installation: Summers 2011 & 2012



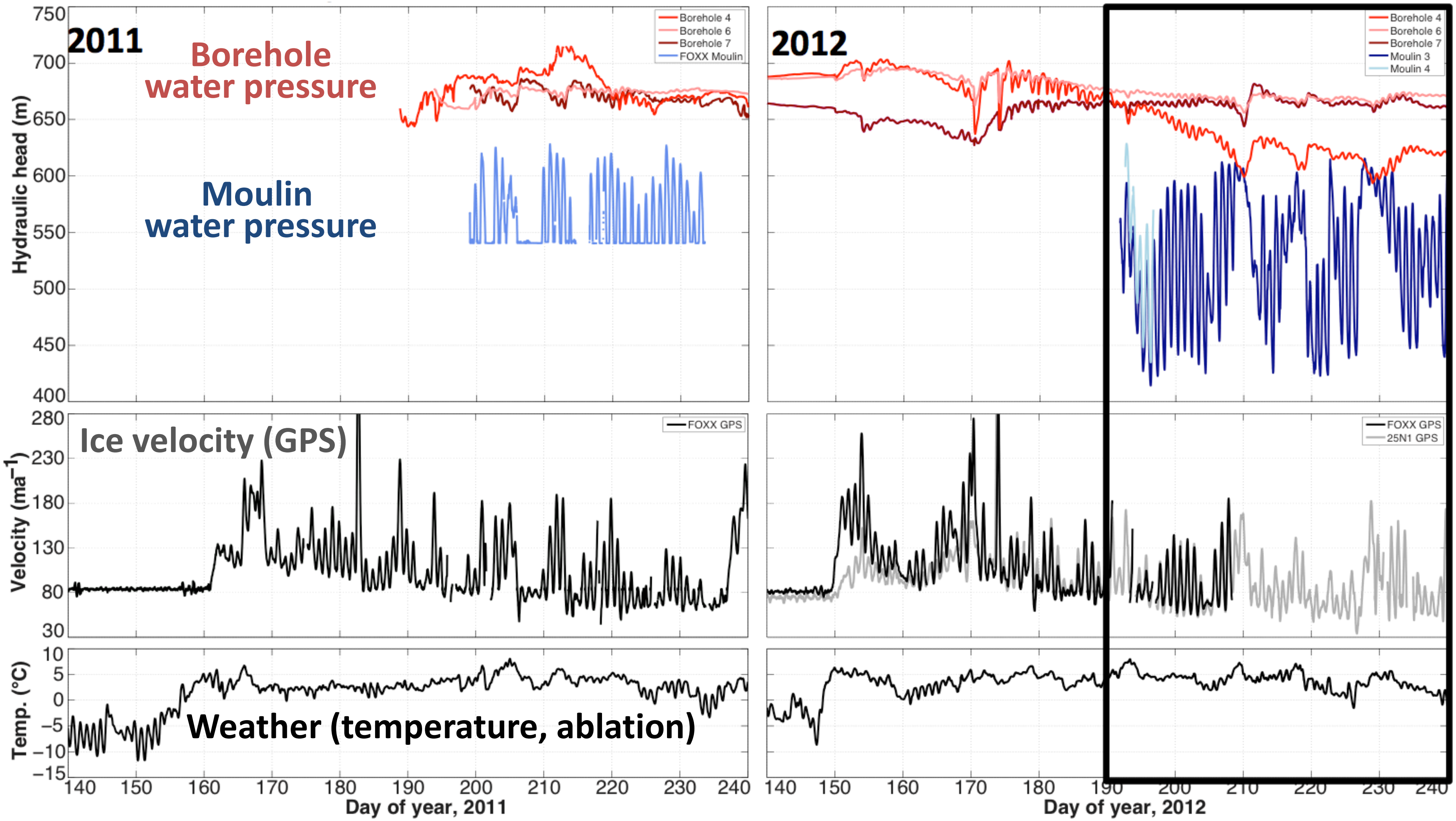
- Ice thickness 600-700 m
- Surface slope 0.01-0.02



Jason Gulley

Hot Water Drilling & Borehole sensor installation: Summer 2011

Measurements during two melt seasons – site FOXX



Borehole water pressure

Moulin water pressure

Ice velocity (GPS)

Weather (temperature, ablation)

Andrews et al. 2014, Nature

Subglacial Hydrology Model

(Modified version of Hoffman & Price, 2014, JGR)

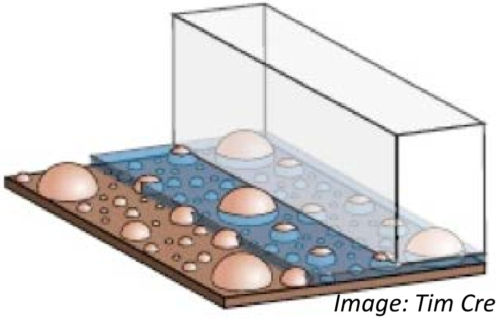


Image: Tim Creyts

Distributed Drainage

e.g. Hewitt 2011, J.Glac.

(Macroporous sheet)

Mass Conservation of Water

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

Evolution of Drainage Element Volume

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

Flow Law

Darcy style:

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

Energy Balance

$$mL = \underbrace{G}_{\text{Geothermal}} + \underbrace{\mathbf{u_b} \cdot \tau_\mathbf{b}}_{\text{Basal friction}}$$

Subglacial Hydrology Model

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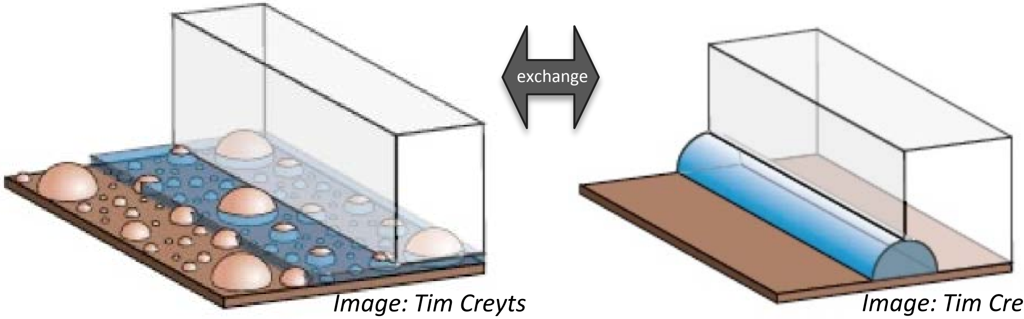

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e.g. Hewitt 2011, J.Glac.
(Macroporous sheet)

Channelized Drainage
e.g. Hewitt 2011, J.Glac.

Mass Conservation of Water

$$\frac{\partial h}{\partial t} + \nabla \cdot \mathbf{q} = \frac{m}{\rho_w} + \omega$$

Flux divergence — Basal melt — Water input from surface & other drainage elements

$$\frac{\partial S}{\partial t} + \frac{\partial Q}{\partial x} = \frac{M}{\rho_w} + \Omega,$$

flow divergence — melt from flow — water input from sheet

Evolution of Drainage Element Volume

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~~Melt opening~~ — Sliding over bumps — Creep closure of ice

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

melt from flow — creep closure of ice

Flow Law

Darcy style:

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

Turbulent flow:

$$FQ^2 = S^{8/3}\left(\Psi + \frac{\partial N_c}{\partial x}\right),$$

Energy Balance

$$mL = G + \mathbf{u_b} \cdot \tau_\mathbf{b}$$

Geothermal — Basal friction

$$ML = Q\left(\Psi + \frac{\partial N_c}{\partial x}\right).$$

Dissipation

Subglacial Hydrology Model

(Modified version of Hoffman & Price, 2014, JGR)

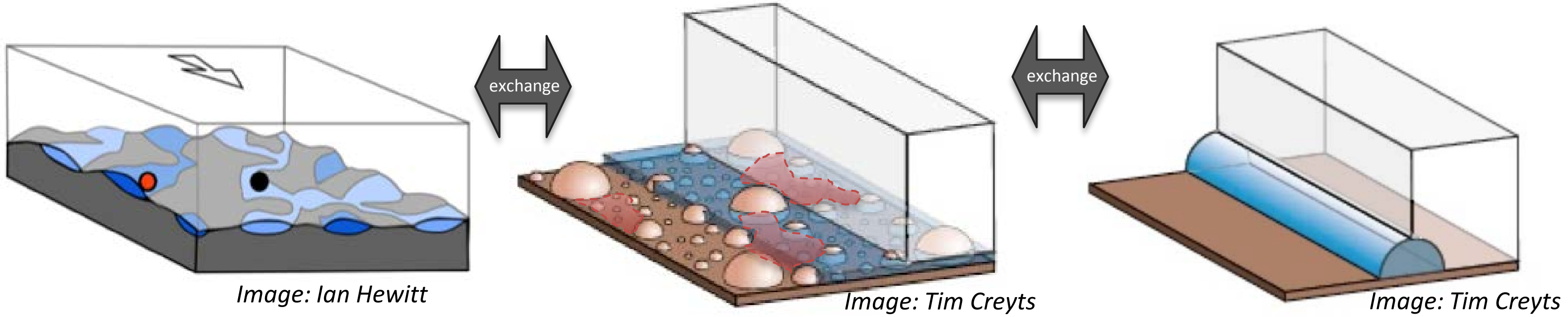

Image: Ian Hewitt

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Isolated Drainage

new component

(0-d subgrid representation)

Distributed Drainage

e.g. Hewitt 2011, J.Glac.

(Macroporous sheet)

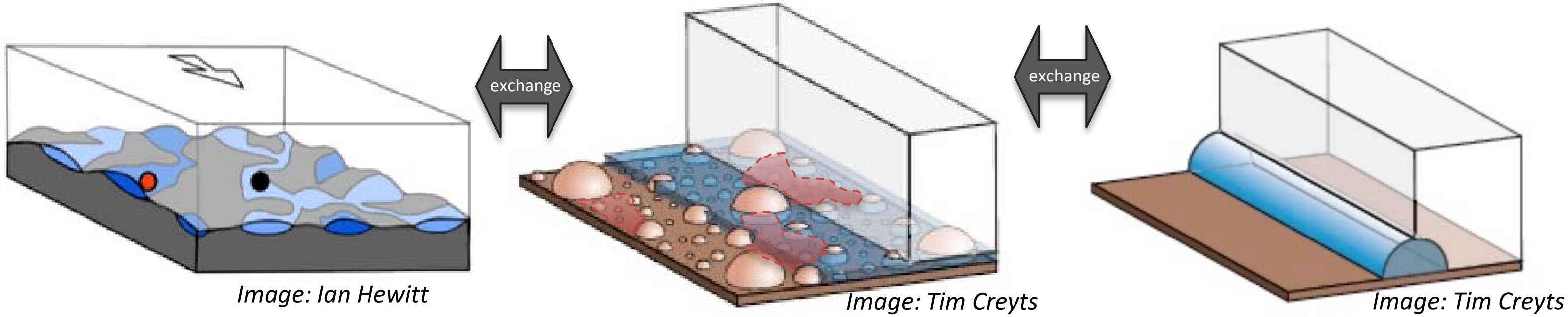
Channelized Drainage

e.g. Hewitt 2011, J.Glac.

Mass Conservation of Water	$\frac{\partial h}{\partial t} = \underbrace{\frac{m}{\rho_w}}_{\text{Basal melt}} + \underbrace{\gamma}_{\text{Water input from sheet}}$	$\frac{\partial h}{\partial t} + \underbrace{\nabla \cdot \mathbf{q}}_{\text{Flux divergence}} = \underbrace{\frac{m}{\rho_w}}_{\text{Basal melt}} + \underbrace{\omega}_{\text{Water input from surface \& other drainage elements}}$	$\frac{\partial S}{\partial t} + \underbrace{\frac{\partial Q}{\partial x}}_{\text{flow divergence}} = \underbrace{\frac{M}{\rho_w}}_{\text{melt from flow}} + \underbrace{\Omega}_{\text{water input from sheet}},$
Evolution of Drainage Element Volume	$\frac{\partial h}{\partial t} = V_O - V_C = \left(\underbrace{\cancel{\frac{m}{\rho_i}}}_{\text{Melt opening}} + \underbrace{\lvert\mathbf{u_b}\rvert \frac{h_r - h}{l_r}}_{\text{Sliding over bumps}}\right) - \underbrace{\left(\frac{hN}{\eta_i}\right)}_{\text{Creep closure of ice}}$	$\frac{\partial h}{\partial t} = V_O - V_C = \left(\underbrace{\cancel{\frac{m}{\rho_i}}}_{\text{Melt opening}} + \underbrace{\lvert\mathbf{u_b}\rvert \frac{h_r - h}{l_r}}_{\text{Sliding over bumps}}\right) - \underbrace{\left(\frac{hN}{\eta_i}\right)}_{\text{Creep closure of ice}}$	$\frac{\partial S}{\partial t} = \underbrace{\frac{M}{\rho_i}}_{\text{melt from flow}} - \underbrace{\frac{SN_c}{\eta_i}}_{\text{creep closure of ice}},$
Flow Law	Darcy style exchange term: $\gamma = -\frac{k_i h^3}{\eta_w} \frac{\phi_i - \phi_s}{ds}$	Darcy style: $\mathbf{q} = -\frac{k_0 h^3}{\eta_w} \nabla \phi$	Turbulent flow: $FQ^2 = S^{8/3}\left(\Psi + \frac{\partial N_c}{\partial x}\right),$
Energy Balance	$mL = \underbrace{G}_{\text{Geothermal}} + \underbrace{\mathbf{u_b} \cdot \boldsymbol{\tau}_\mathbf{b}}_{\text{Basal friction}}$	$mL = \underbrace{G}_{\text{Geothermal}} + \underbrace{\mathbf{u_b} \cdot \boldsymbol{\tau}_\mathbf{b}}_{\text{Basal friction}}$	$ML = \underbrace{Q\left(\Psi + \frac{\partial N_c}{\partial x}\right)}_{\text{Dissipation}}.$

Subglacial Hydrology Model

(Modified version of Hoffman & Price, 2014, JGR)



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e.g. Hewitt 2011, J.Glac.

(Macroporous sheet)

Channelized Drainage

e.g. Hewitt 2011, J.Glac.

Mass Conservation of Water

$$\frac{\partial h}{\partial t} = \frac{m}{\rho_w} + \gamma$$

Basal melt; Water input from sheet

$$\frac{\partial h}{\partial t} + \nabla \cdot \mathbf{q} = \frac{m}{\rho_w} + \omega$$

Flux divergence; Basal melt; Water input from surface & other drainage elements

$$\frac{\partial S}{\partial t} + \frac{\partial Q}{\partial x} = \frac{M}{\rho_w} + \Omega,$$

flow divergence; melt from flow; water input from sheet

Evolution of Drainage Element Volume

$$\frac{\partial h}{\partial t} = V_O - V_C = \left(\cancel{\frac{m}{\rho_i}} + |\mathbf{u_b}|\frac{h_r - h}{l_r}\right) - \left(\frac{hN}{\eta_i}\right)$$

Melt opening; Sliding over bumps; Creep closure of ice

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Melt opening; Sliding over bumps; Creep closure of ice

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

melt from flow; creep closure of ice

Flow Law

Darcy style exchange term: $\gamma = -\frac{k_i h^3}{\eta_w}\frac{\phi_i - \phi_s}{ds}$

Conductivity function of effective pressure: $k_i = \frac{C}{N + \eta}$

(inspired by Murray & Clarke (1995), Gordon et al. (1998))

Darcy style:

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

Turbulent flow:

$$FQ^2 = S^{8/3}\left(\Psi + \frac{\partial N_c}{\partial x}\right),$$

Energy Balance

$$mL = G + \mathbf{u_b} \cdot \tau_{\mathbf{b}}$$

Geothermal; Basal friction

$$mL = G + \mathbf{u_b} \cdot \tau_{\mathbf{b}}$$

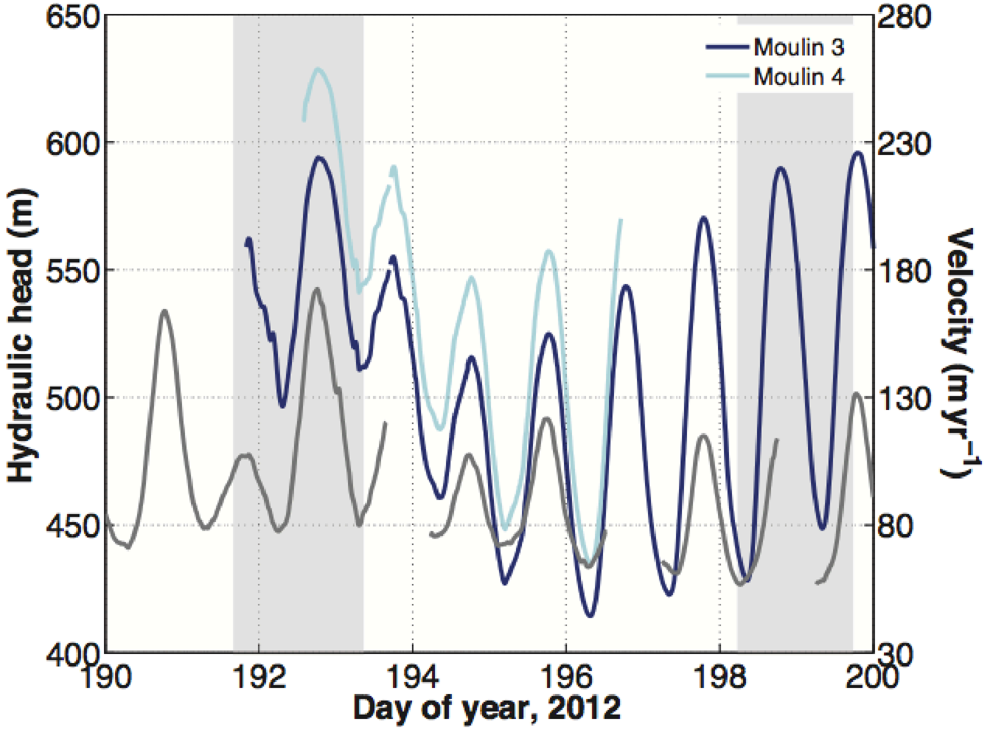
Geothermal; Basal friction

$$ML = Q\left(\Psi + \frac{\partial N_c}{\partial x}\right).$$

Dissipation

Moulin water pressure indicates subglacial channels

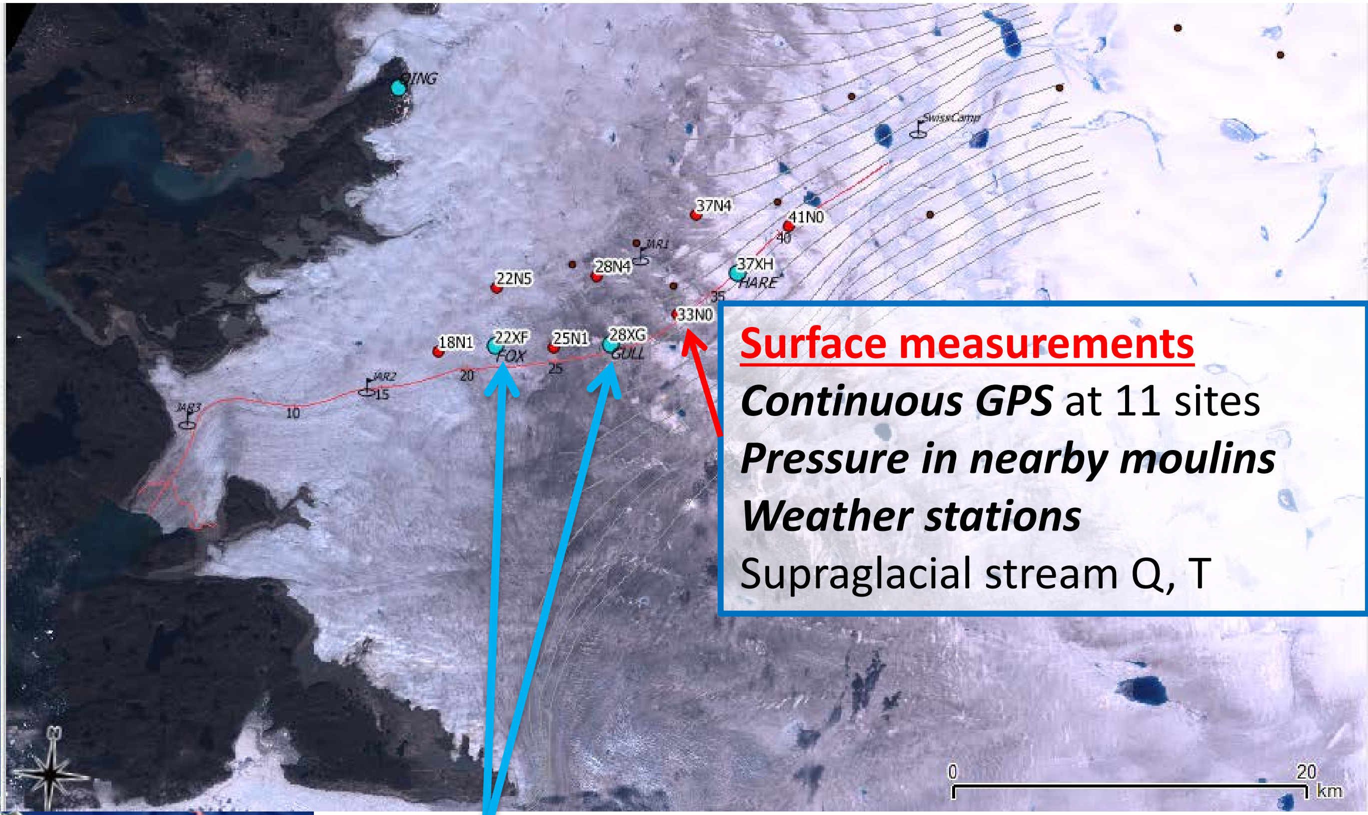
- Large diurnal variability, specifically, low diurnal minima
- In phase with ice velocities
- Neighboring moulins highly correlated
- Channel model used to confirm quasi-steady state behavior during second half of summer



Moulin pressure controls short-term variations in ice speed

(diurnal and melt-event-scale)

REAL-TIME OBSERVATIONS OF THE GREENLAND ENVIRONMENT UNDER-ICE



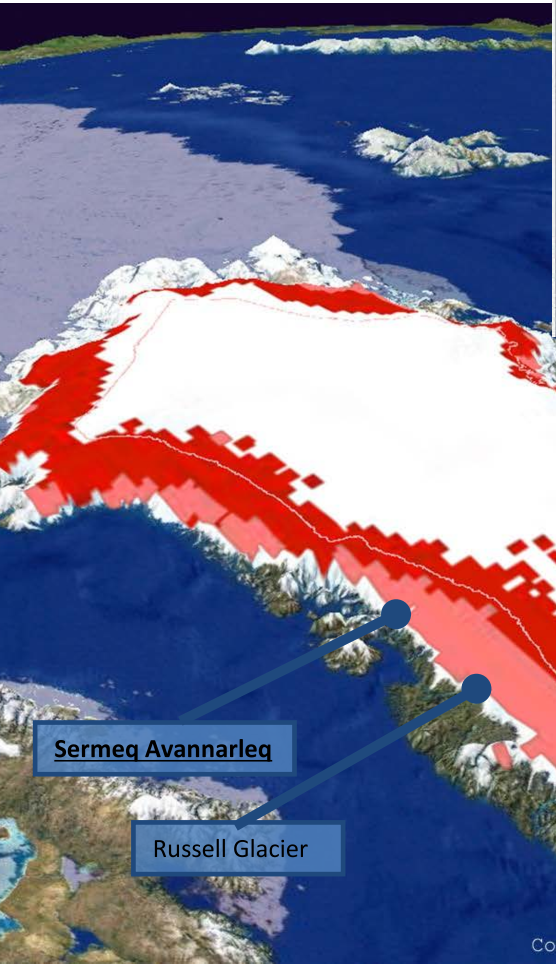
Surface measurements

Continuous GPS at 11 sites

Pressure in nearby moulins

Weather stations

Supraglacial stream Q, T



Courtesy Russell Huff and

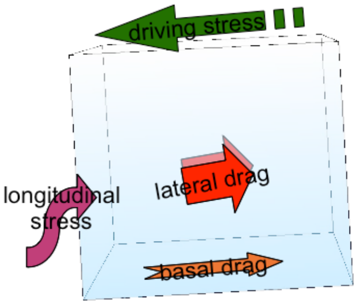
Borehole measurements

Englacial	Subglacial
Temperature	***Water Pressure***
Pressure	Sliding (tethered stake)
Inclination	Water EC
Vertical strain	[Water, bed samples]
Optical Televiewer	

Model Formulation

Ice dynamics:

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



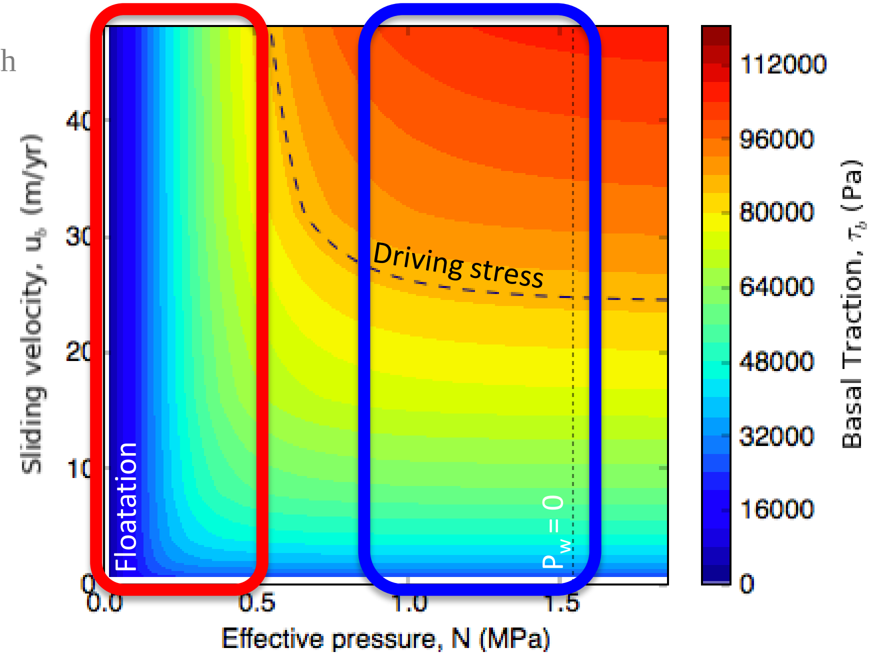
Sliding law: Couples sheet hydrology (N) to dynamics (τ_b, u_b)

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

Bedrock bump wavelength

$$\tau_b = C\left(\frac{u_b}{u_b + N^n\Lambda}\right)^{1/n} N, \qquad \Lambda = \frac{\lambda_{\max} A}{m_{\max}}$$

Bedrock bump slope



At high N, basal traction is independent of N.

$\tau_b \propto u_b^{1/n}$ (nonlinear viscous – the faster the sliding, the more drag from bumps)

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

$\tau_b \propto N$ (near floatation, bumps are drowned)

Distributed Flow Model

sheet flow, e.g. linked cavities

(e.g. Hewitt 2011, J.Glac.)

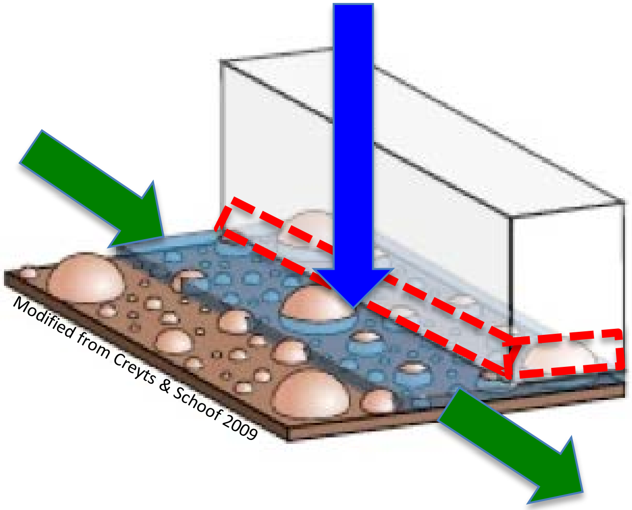
1) Mass conservation of water

$$\frac{\partial h}{\partial t} + \nabla \cdot \mathbf{q} = \frac{\boxed{m}}{\rho_w} + \omega$$

Flux divergence

Basal melt

Water input from surface



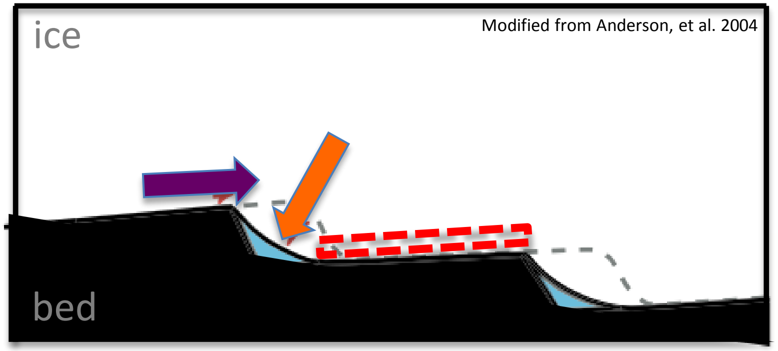
2) Evolution of subglacial cavities

$$\frac{\partial h}{\partial t} = V_O - V_C = \left(\cancel{\frac{m}{\rho_i}} + \boxed{|\mathbf{u_b}|}\frac{h_r - h}{l_r}\right) - \left(\frac{hN}{\boxed{\eta_i}}\right)$$

Melt opening

Sliding over bumps

Creep closure of ice



A Darcy style flow law

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

Heat from passive sources

(heat from water flow neglected)

$$mL = G + \boxed{\mathbf{u_b} \cdot \tau_\mathbf{b}} \cancel{- \mathbf{q} \cdot \nabla\phi}$$

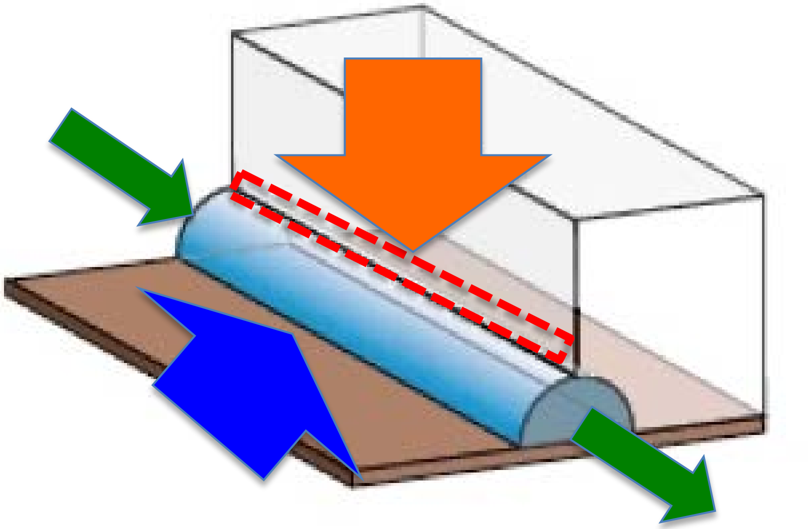
Geothermal

Basal friction

Channelized Flow Model

Hewitt 2011

1) Mass conservation of water



flow divergence

melt from flow

water input from sheet

$$\frac{\partial S}{\partial t} + \frac{\partial Q}{\partial x} = \frac{M}{\rho_w} + \Omega,$$

2) Evolution of subglacial cavities

melt from flow

creep closure of ice

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

A turbulent flow law

$$F Q^2 = S^{8/3}\left(\Psi + \frac{\partial N_c}{\partial x}\right),$$

melt from flow

$$M L = Q\left(\Psi + \frac{\partial N_c}{\partial x}\right).$$

Coupled to the surrounding sheet via the exchange term Ω