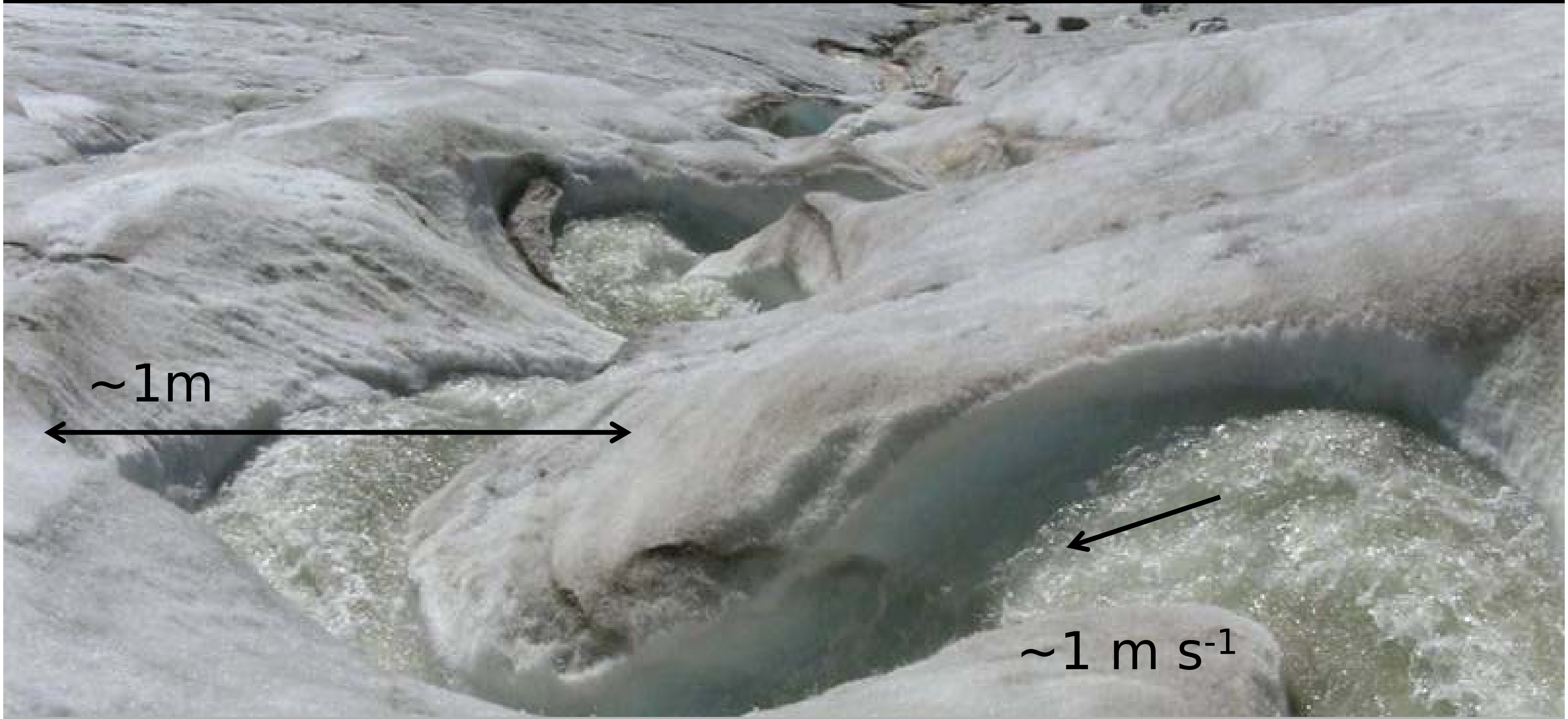
Progress in modeling glacier hydrology



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CESM Land Ice Working Group Meeting
NCAR, Boulder, CO, 12-13 Jan 2011

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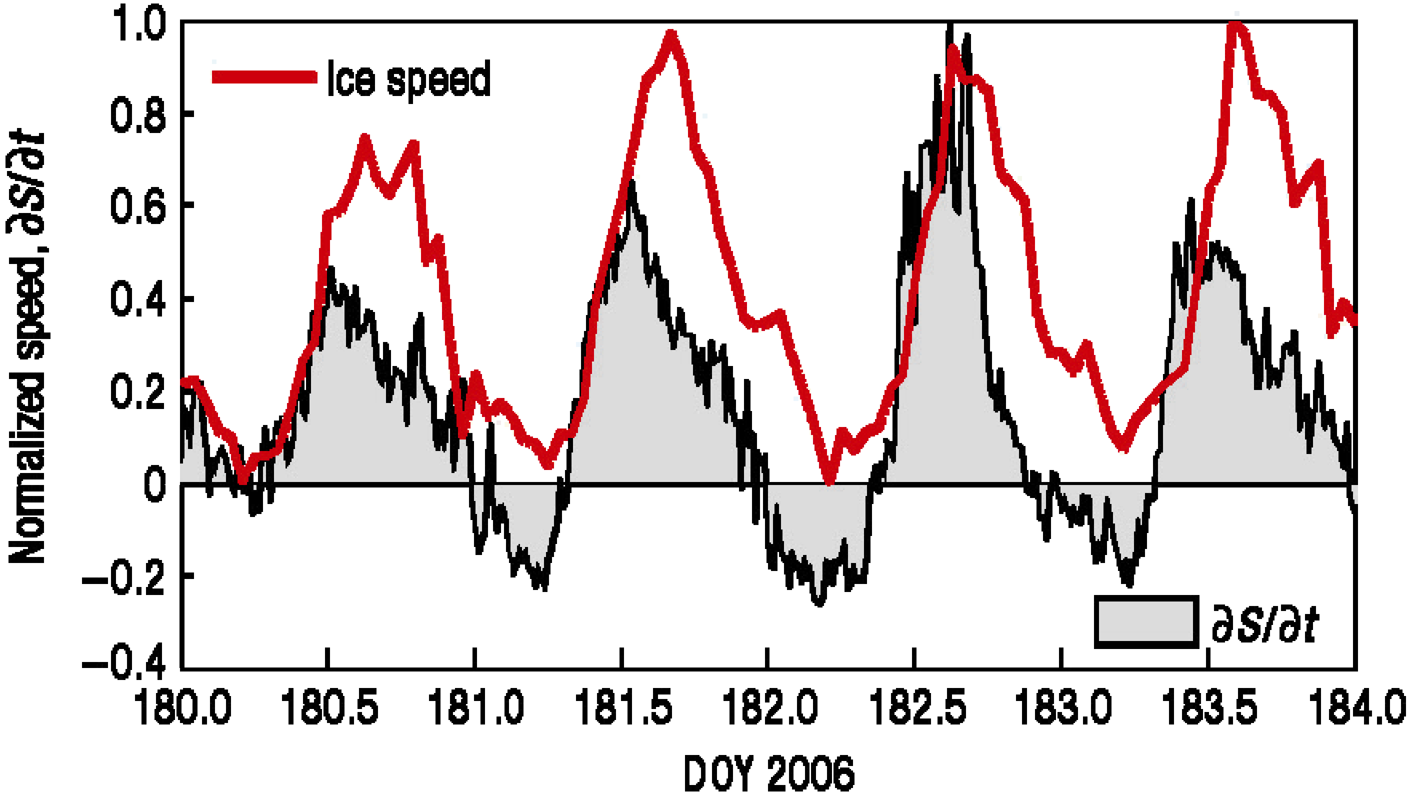
Introduction & background

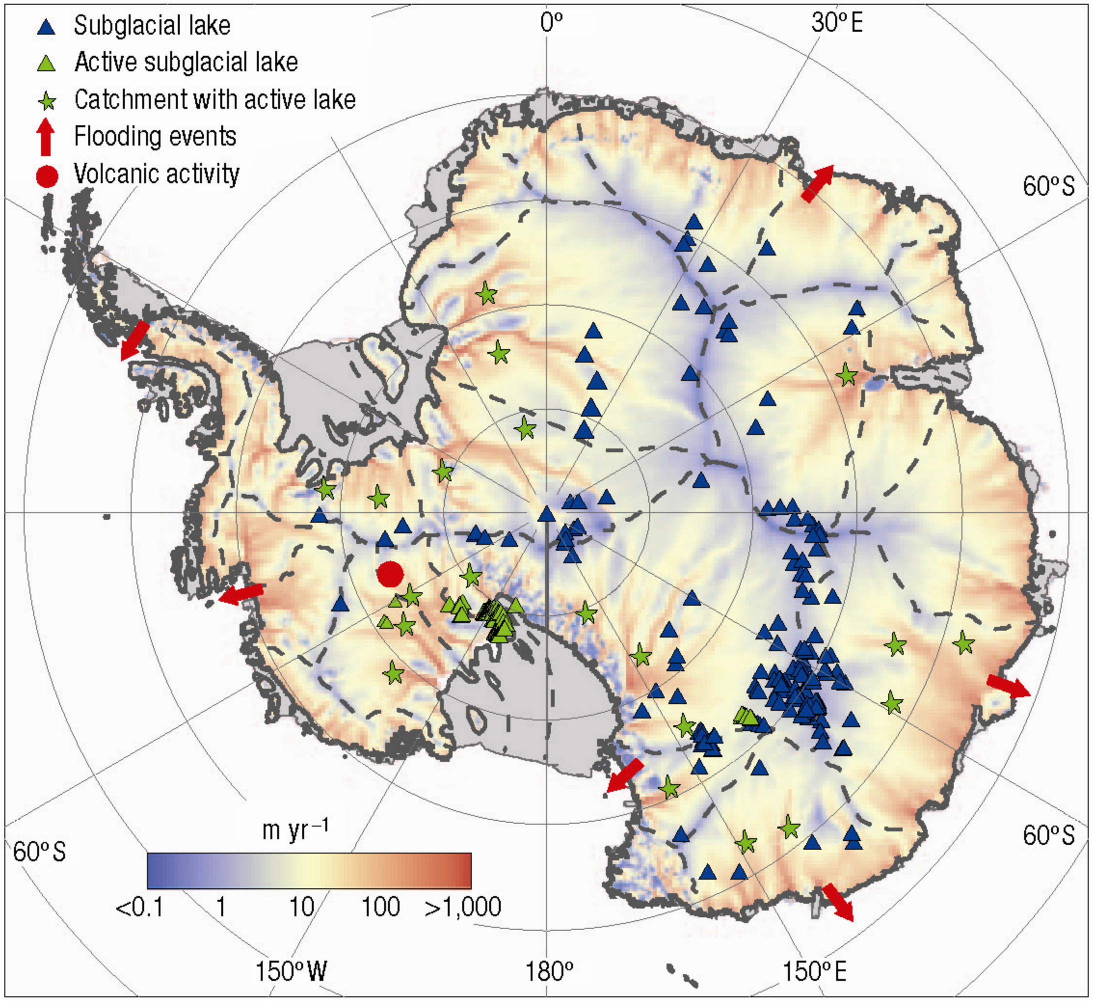
Hydrology and dynamics are linked in alpine glaciers ...



Change in subglacially stored water,
Kennicott Glacier, Alaska, 29 Jun–3 Jul, 2006
(Bartholomaus et al., 2008)

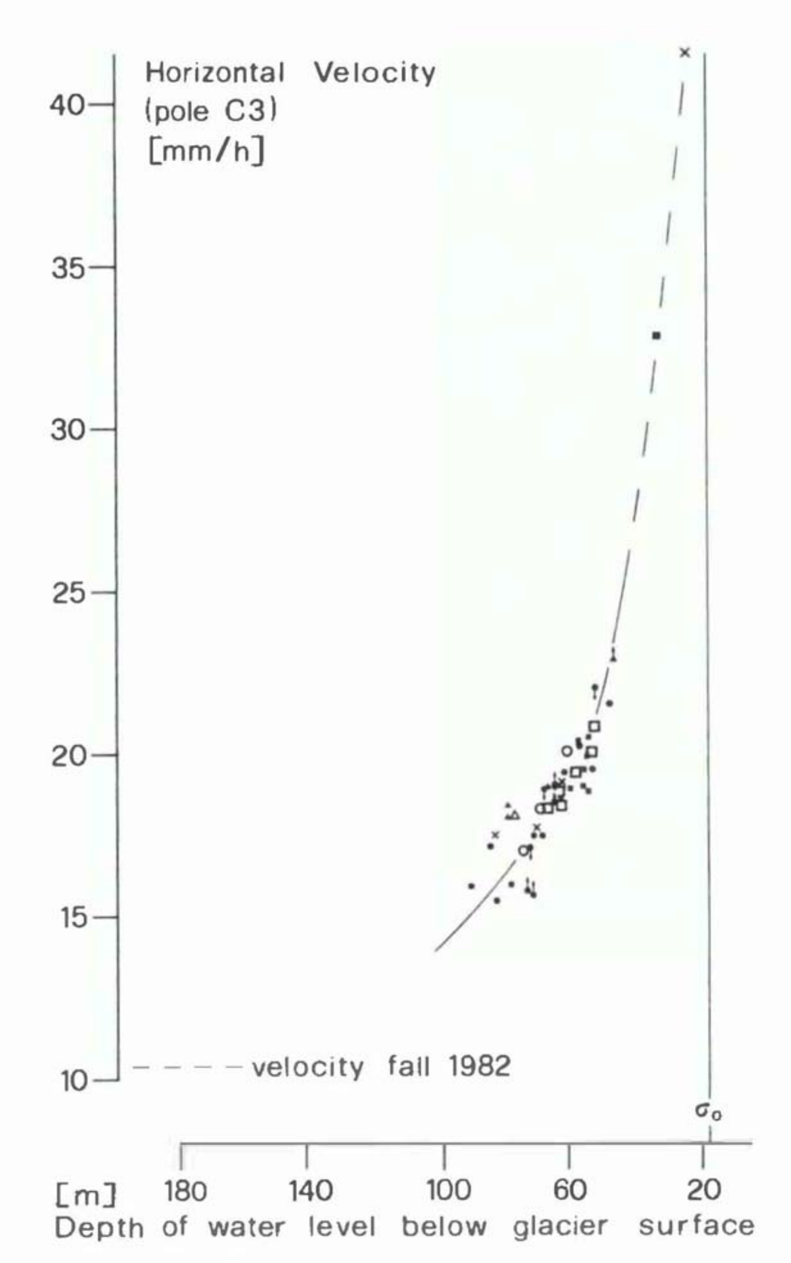
Introduction & background

... and in the continental ice sheets



Subglacial lakes and active drainage systems in Antarctica (Bell, 2008)

Introduction & background

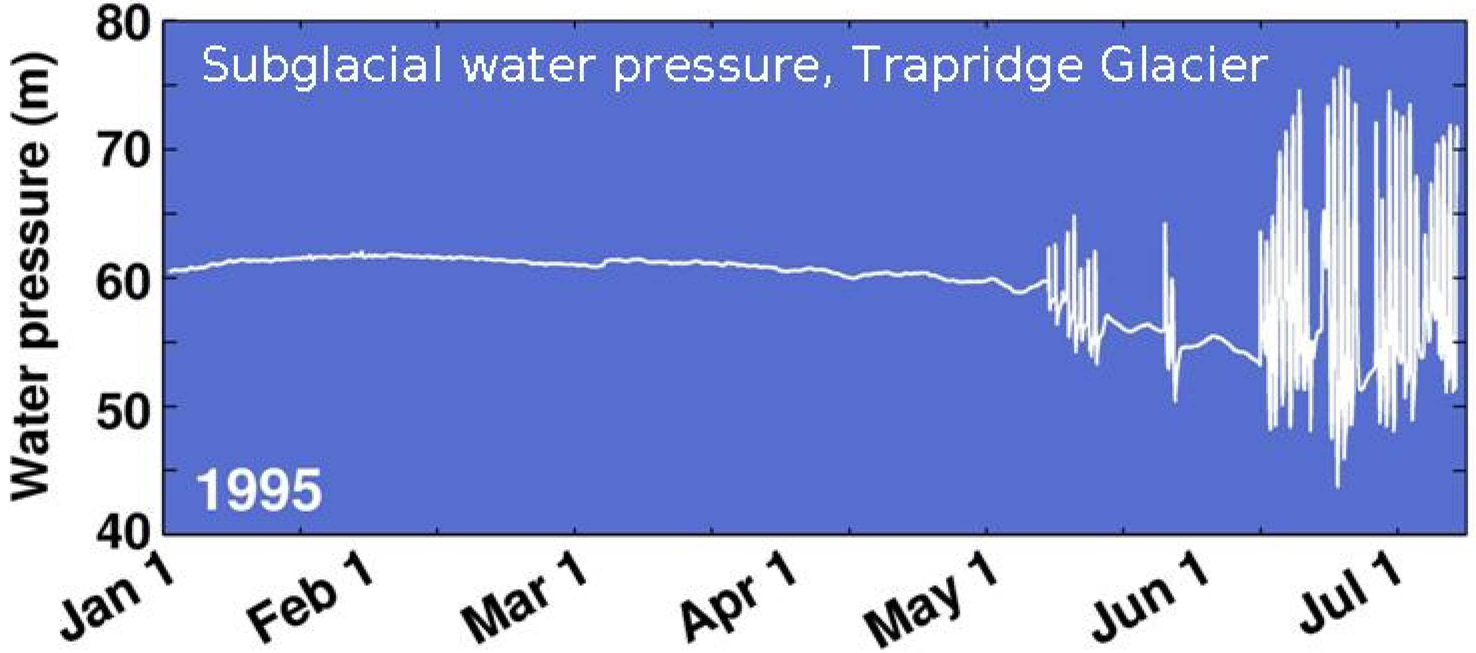


$N = P_i - P_w$

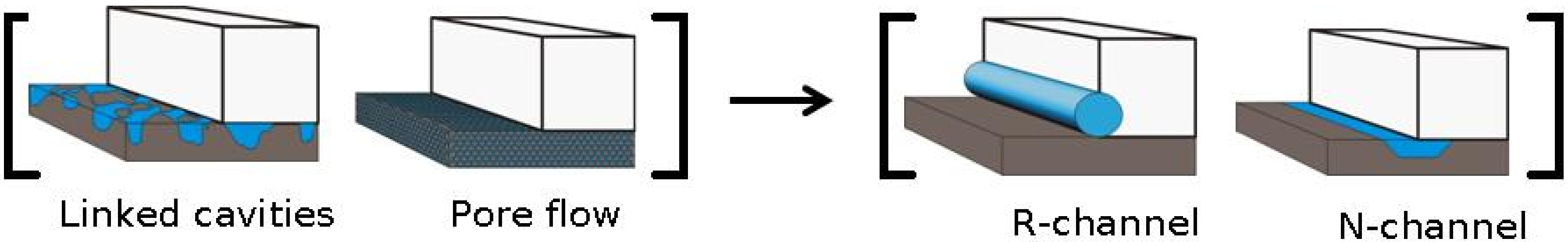
Basal effective pressure, and hence basal water pressure (over the relevant length scales), is a key link between hydrology and dynamics

Left: glacier surface speed vs. borehole water level at Findelengletscher, 1980-82 (Iken and Bindschadler, 1986)

Introduction & background



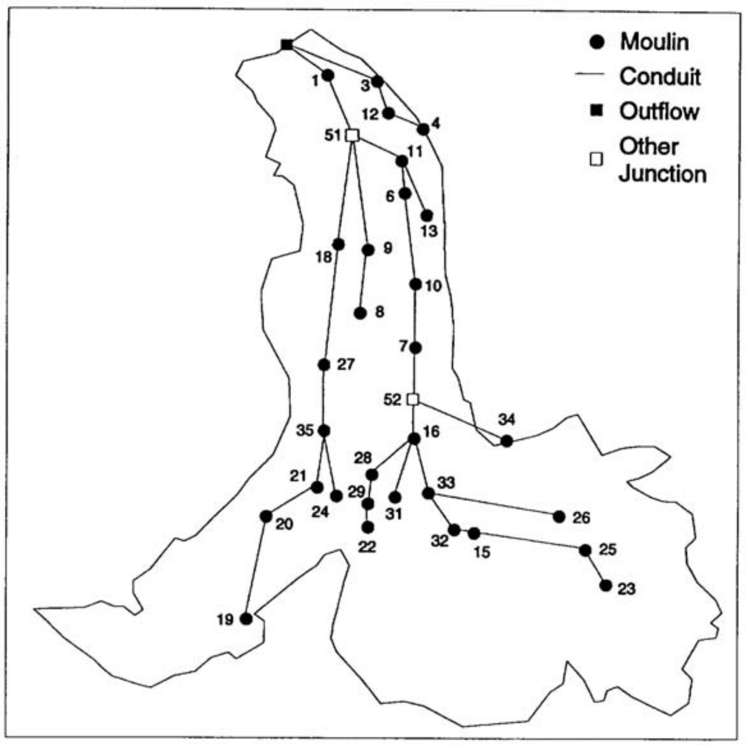
"Slow" systems: $\mathrm{P_w} \uparrow u_\mathrm{b} \uparrow$ "Fast" systems: $\mathrm{P_w} \downarrow u_\mathrm{b} \downarrow$

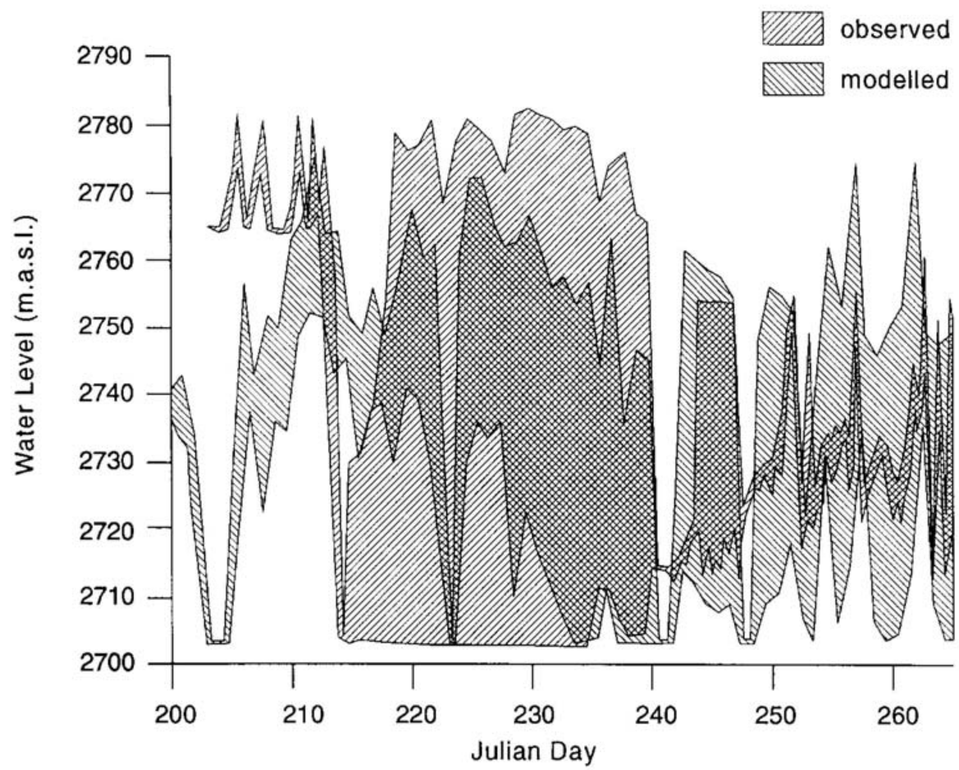


Diagrams courtesy of T. Creyts

Comprehensive modeling efforts (Arnold et al. 1998)

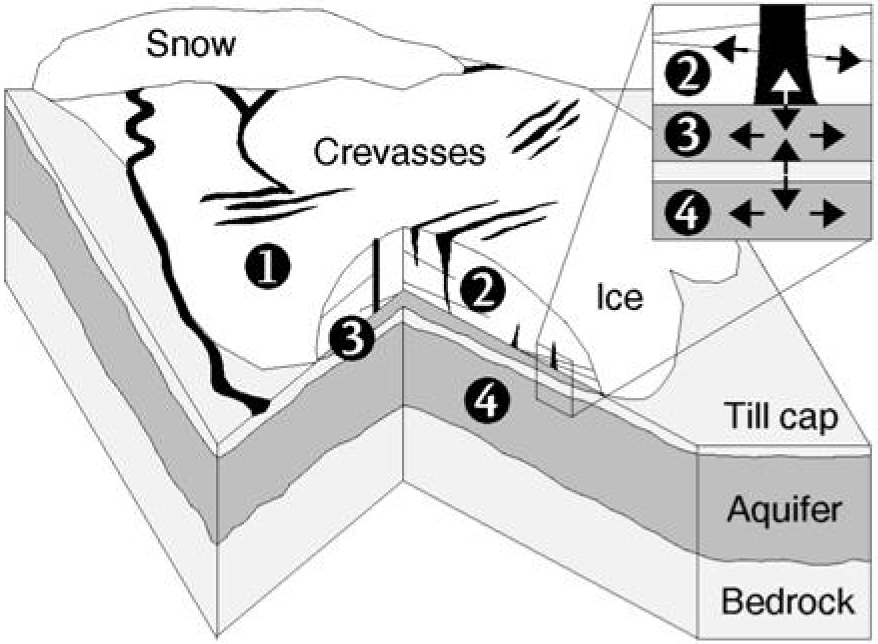
- spatially fixed, temporally evolving conduit network
- slow system approximated as small or wide conduits
- slow-to-fast transition prescribed as snowline passes moulins
- surface melt (calculated from energy balance) routed to moulins
- simulations performed with EPA storm water management model





Arnold et al., 1998

Previous work: 2.5-D multicomponent modeling



Glacier drainage systems

1. Supraglacial
2. Englacial
3. Subglacial
4. Subsurface

For each system (in 2-D plan view):

$h = \text{fluid volume [L]}$

$K(h) = \text{system conductivity [L/T]}$

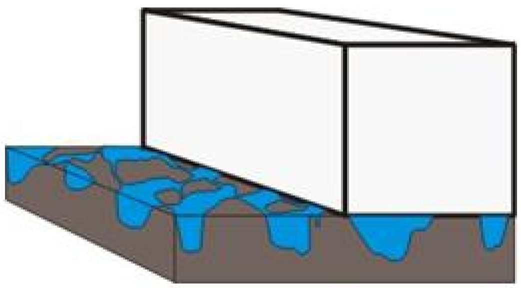
$\psi(h) = \text{fluid potential } [\mathrm{M/LT^2}]$

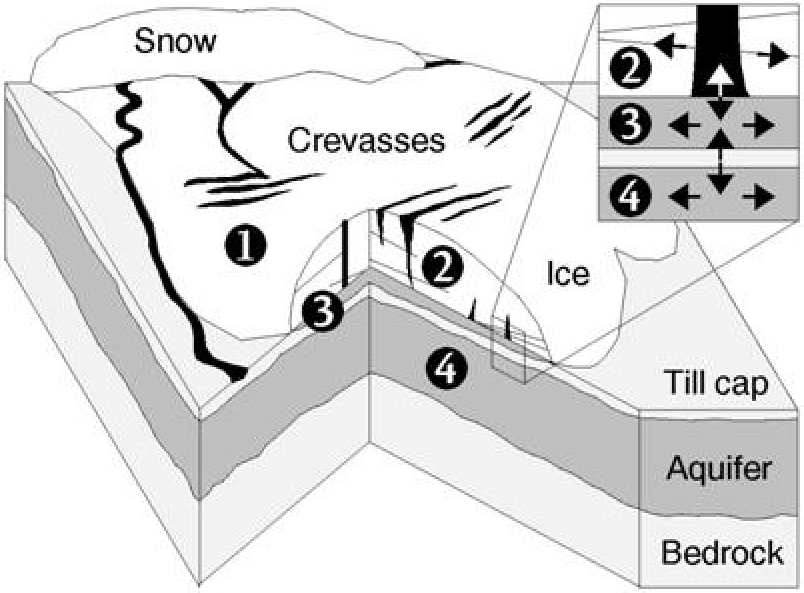
$Q(K, h, \nabla\psi) = \text{fluid flux } [\mathrm{L^2/T}]$

Previous work: 2.5-D multicomponent modeling

Example: subglacial drainage (3)

$$h = \text{fluid volume } [\text{L}]$$





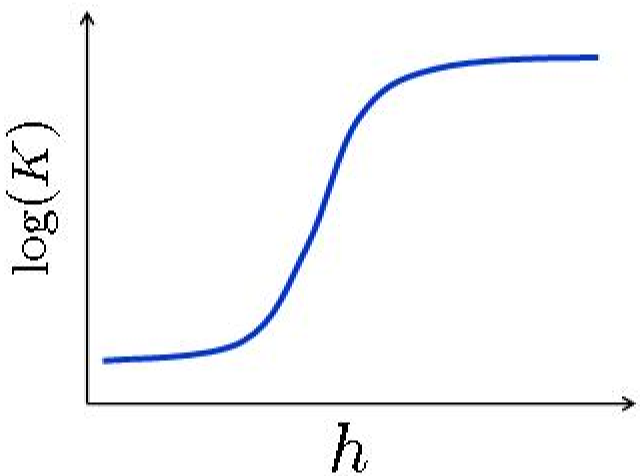
h is an areally-averaged water volume and may depend on the effective porosity or configuration of the subglacial drainage system

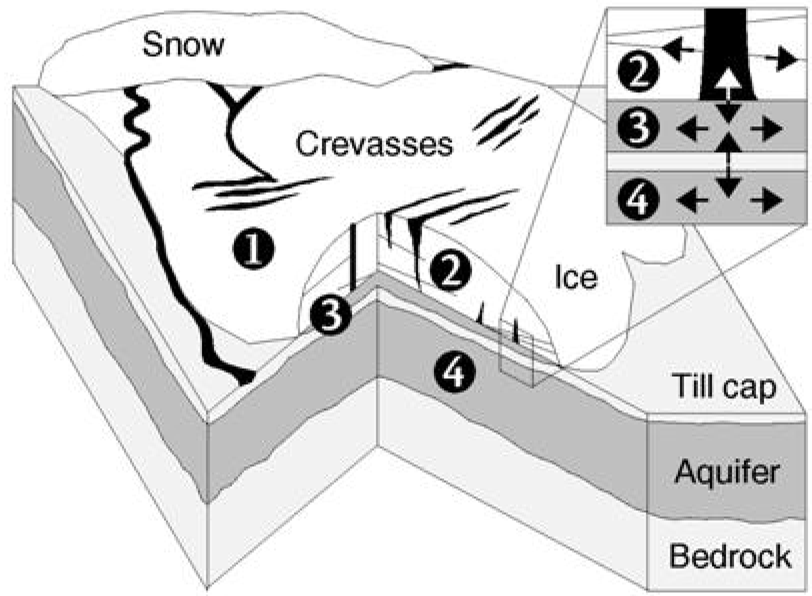
Diagram (left) courtesy of T. Creyts

Previous work: 2.5-D multicomponent modeling

Example: subglacial drainage (3)

$$K(h) = \text{system conductivity } [\text{L/T}]$$





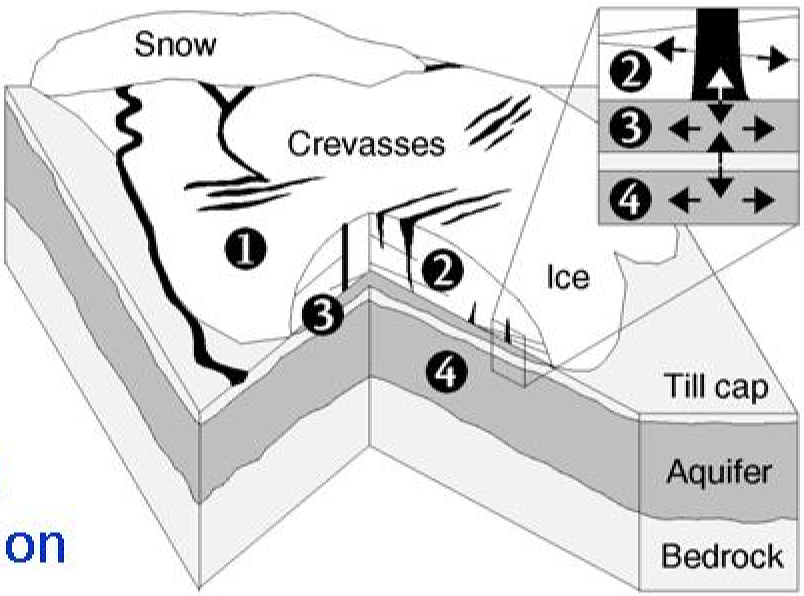
Hydraulic conductivity, $K(h)$, is a measure of subglacial hydraulic "connectivity", and can be used to emulate a transition between fast and slow drainage systems

Previous work: 2.5-D multicomponent modeling

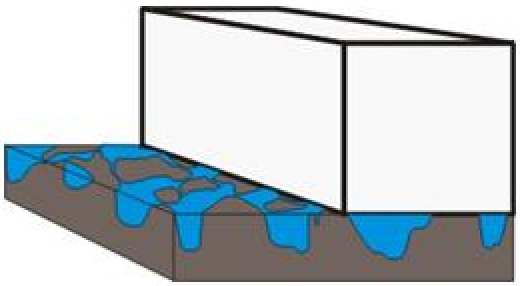
Example: subglacial drainage (3)

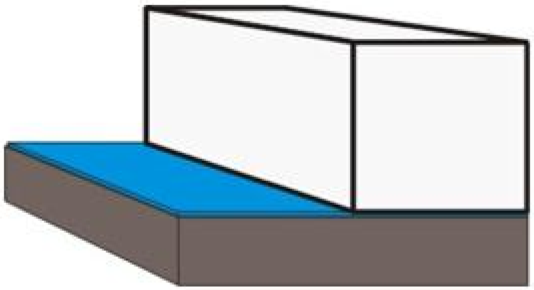
$$\psi(h) = \text{fluid potential } [\mathrm{M/LT^2}]$$

$$\psi = p + \rho_{\mathrm{w}}\, g\, z_{\mathrm{b}}$$



Fluid potential depends on subglacial water pressure, *p(h)*, which depends on character of the glacier bed





Diagrams (lower left) courtesy of T. Creyts

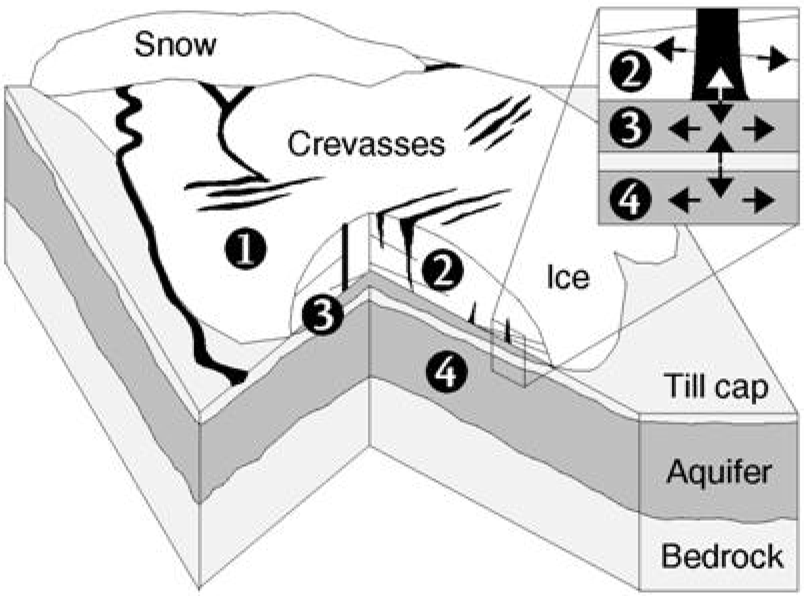
Previous work: 2.5-D multicomponent modeling

Example: subglacial drainage (3)

$$Q(K, h, \nabla\psi) = \text{fluid flux } [\mathrm{L}^2/\mathrm{T}]$$

$$Q = -\frac{K(h)\, h}{\rho_{\mathrm{w}}\, g} \nabla\psi$$

Fluid flux is described by a non-linear form of Darcy's Law



Previous work: 2.5-D multicomponent modeling

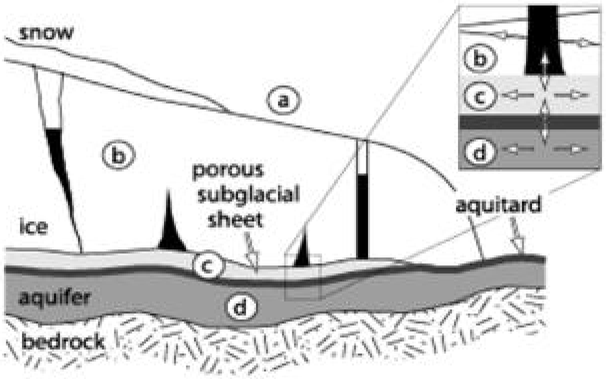
Mass conservation in each drainage system:

1. Supraglacial

$$\frac{\partial h^r}{\partial t} + \frac{\partial Q_j^r}{\partial x_j} = M + R - \boxed{\phi^{r:e}} - \boxed{\phi^{r:a}}$$

2. Englacial

$$\frac{\partial h^e}{\partial t} + \frac{\partial Q_j^e}{\partial x_j} = \boxed{\phi^{r:e}} - \boxed{\phi^{e:s}}$$



3. Subglacial

$$\frac{\partial h^s}{\partial t} + \frac{\partial Q_j^s}{\partial x_j} = \dot{b}^s + \boxed{\phi^{e:s}} - \boxed{\phi^{s:a}}$$

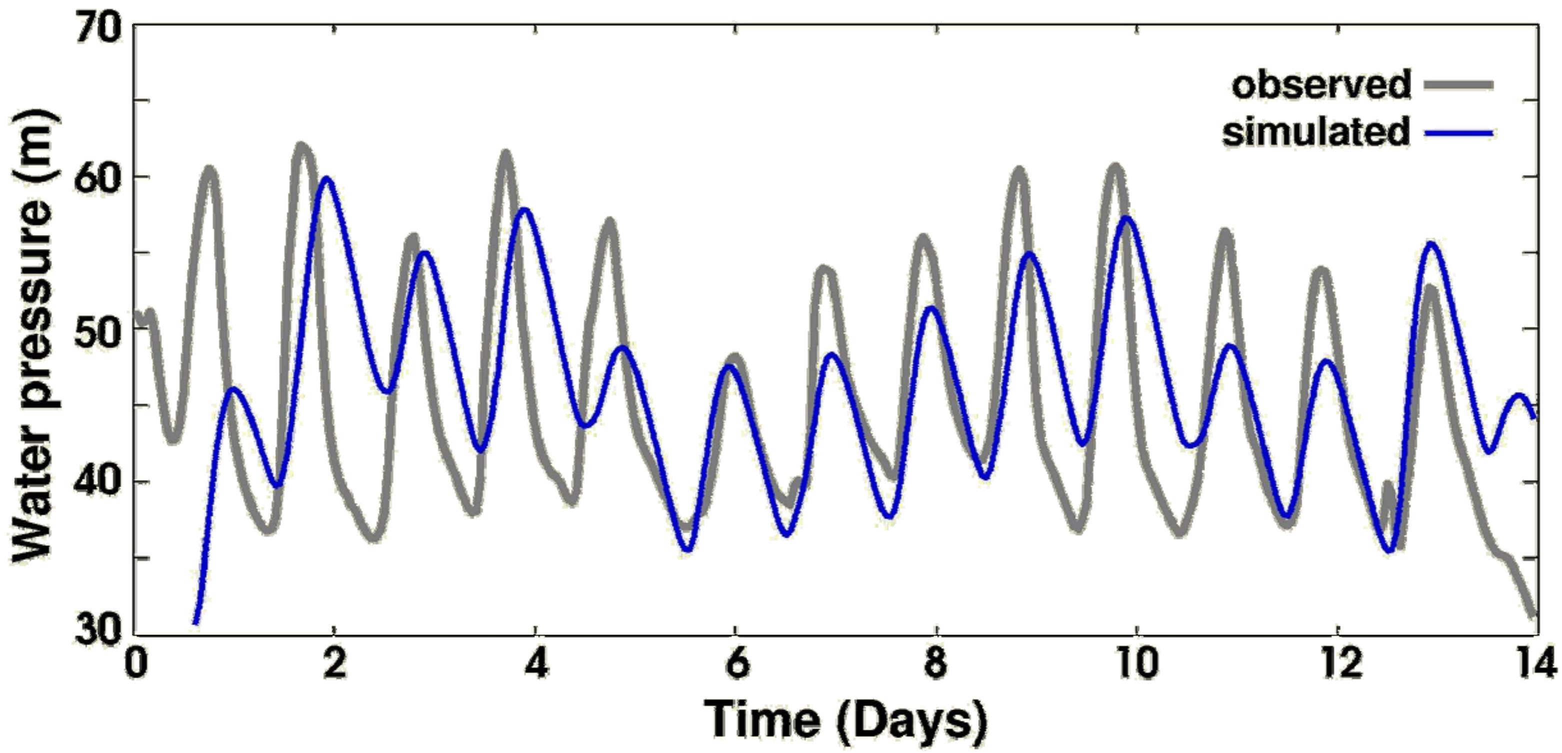
4. Subsurface

$$\left(\frac{h^a}{\rho^a}\right)\frac{\partial \rho^a}{\partial t} + \frac{\partial h^a}{\partial t} + \frac{\partial Q_j^a}{\partial x_j} = \boxed{\phi^{s:a}} + \boxed{\phi^{r:a}}$$

Flowers and Clarke, 2002

Previous work: 2.5-D multicomponent modeling

This simple model can reproduce various qualitative features of borehole water pressure records

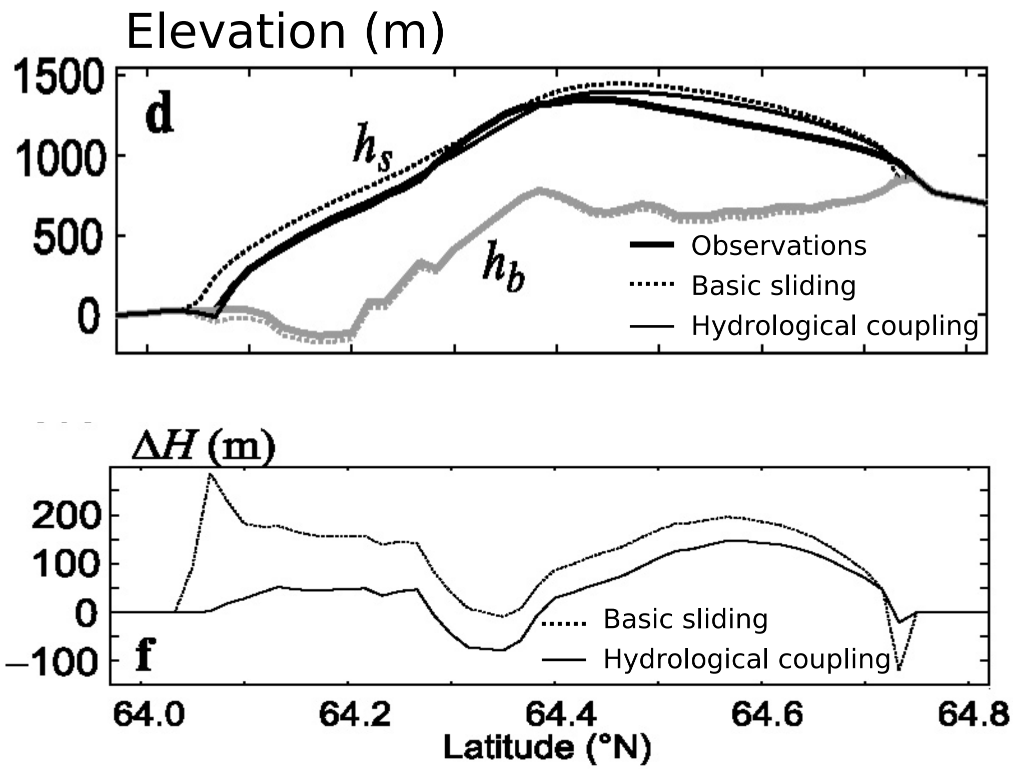


Subglacial water pressure data from Trapridge Glacier, Yukon Territory, 9-23 July 1997

Flowers and Clarke, 2002

Previous work: coupling hydrology and dynamics

NASA MODIS image, 9 September 2002



Parameterization of basal sliding including hydrology

$$u_b = C\,\tau_b\,\frac{P_{\mathrm{w}}}{P_{\mathrm{i}}}$$

This implementation of hydrology can enhance or reduce sliding, as opposed to a parameterization based on surface melt volume.

Marshall et al., 2005

Previous work: 2.5-D multicomponent modeling

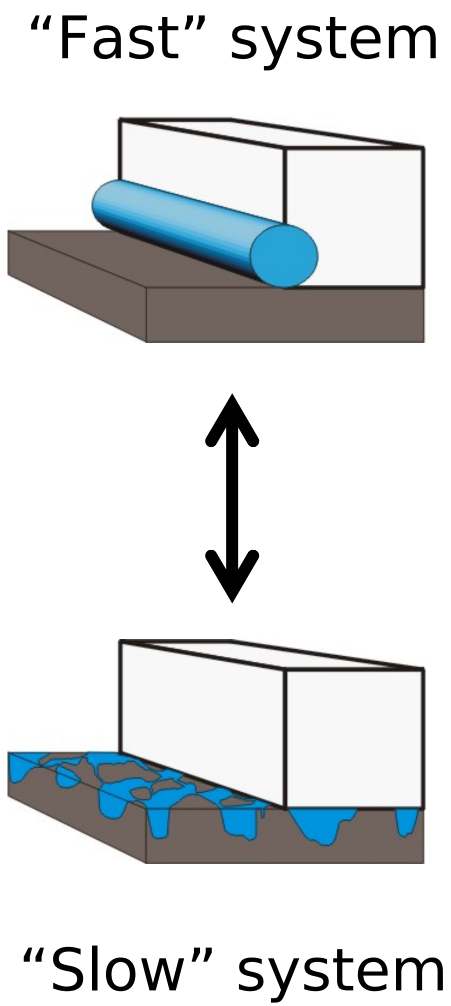
Pros:

- Harmonized treatment of each drainage system (model layer)
- Description of each system tied loosely to system morphology
- Parameterized vertical coupling replaces prescribed vertical fluxes or full 3-D model
- Explicit description of each system potentially allows more objective simulation of observed behavior
- Fast and slow subglacial drainage systems emulated with extreme simplicity at grid scale

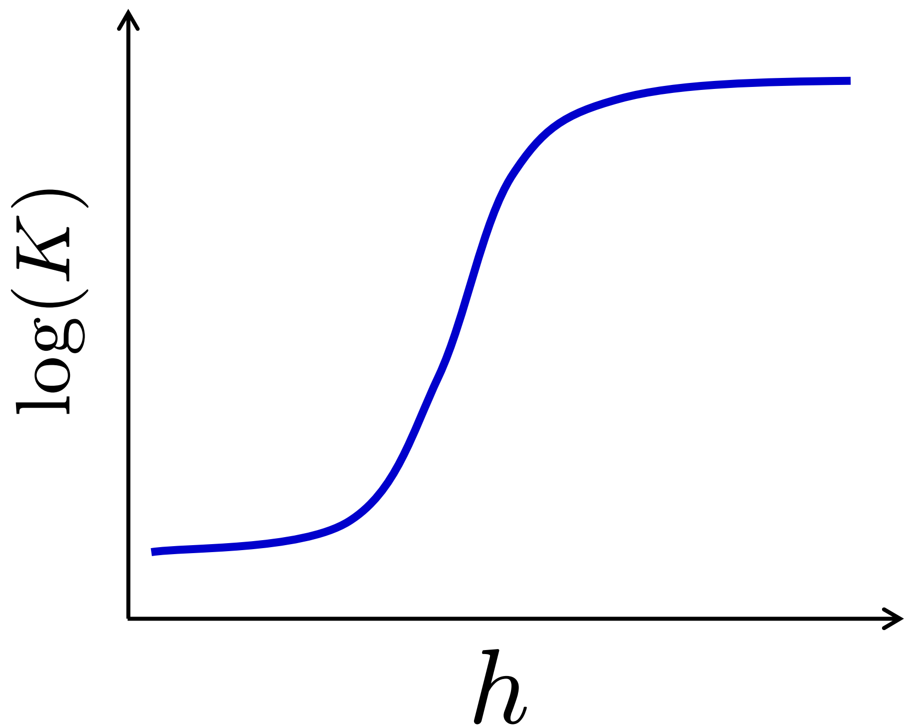
Cons:

- Description of each system tied loosely to system morphology
- Physics of subgrid channelized drainage missing
- Simple treatment of subglacial drainage system requires prescribed relationship between basal water volume & pressure
- Explicit description of each system introduces more parameters, necessitating more data for model calibration
- Ice dynamics absent from description of subglacial system

Subglacial drainage morphology

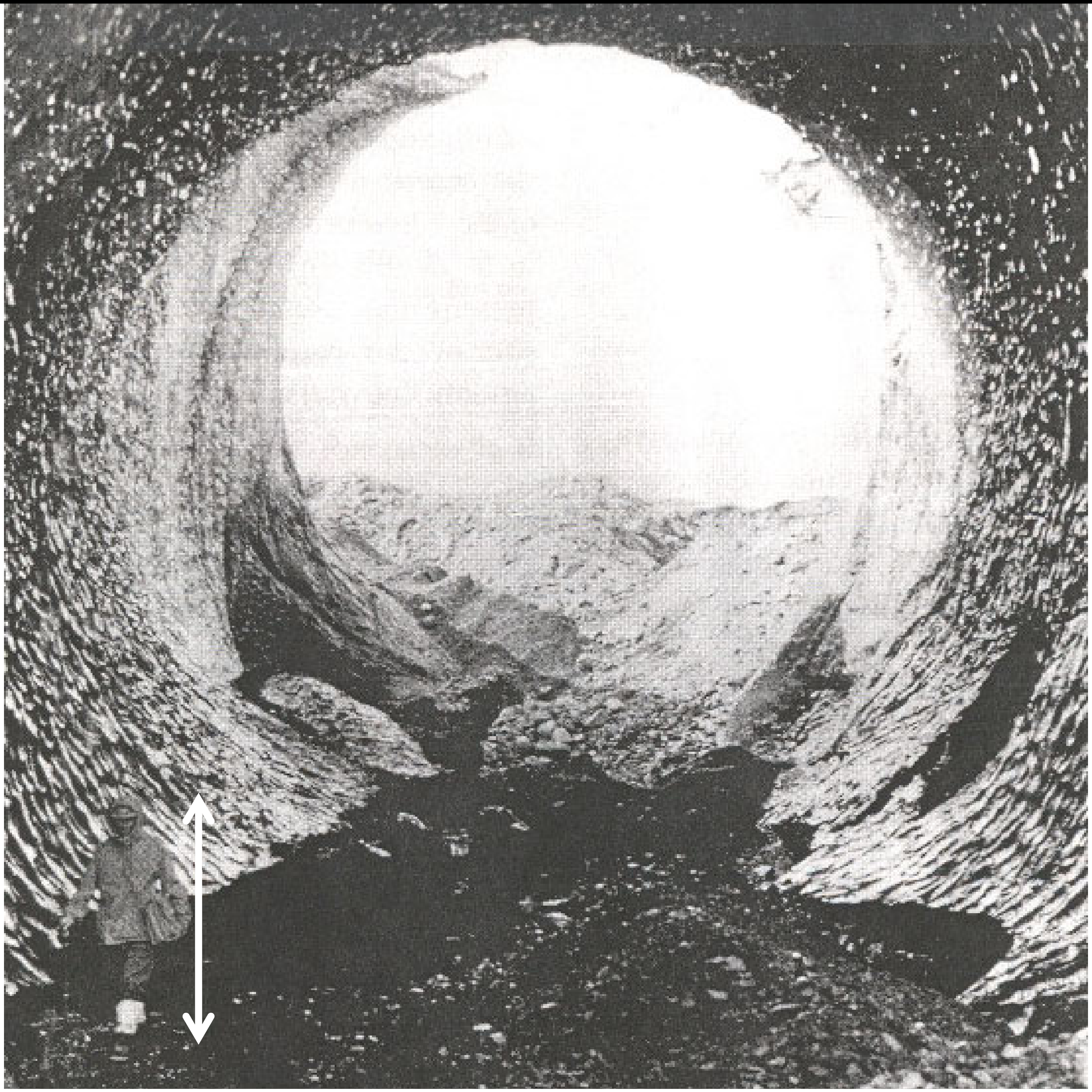


$K(h) = \text{system conductivity [L/T]}$



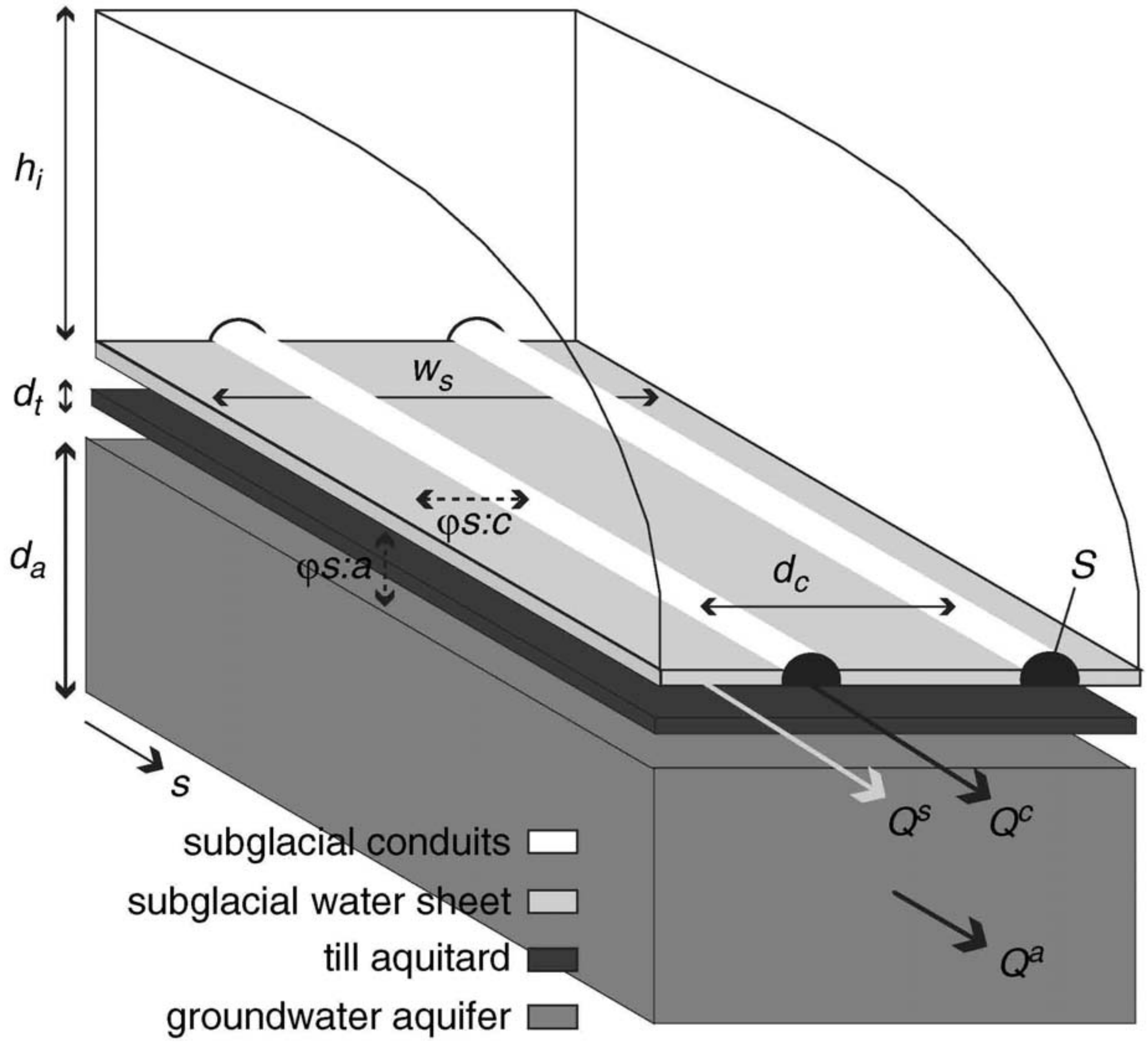
Diagrams courtesy of T. Creyts

Subglacial drainage morphology



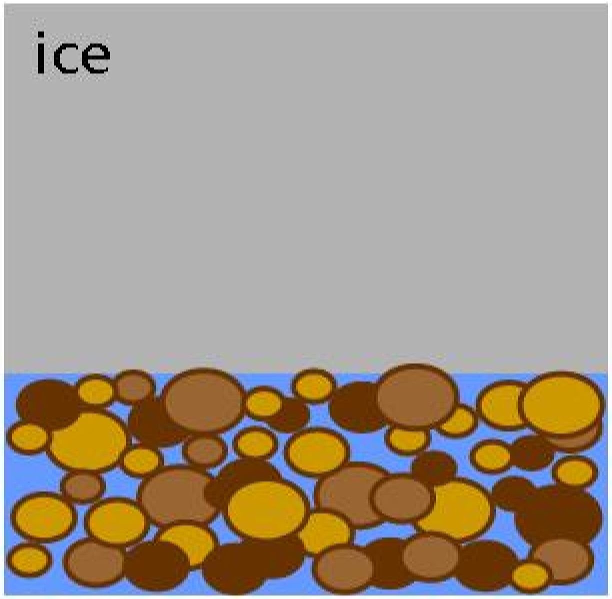
Conduit in Kötlujökull, Iceland (Näslund and Hassinen, 1996)

Two-component flowband model of basal hydrology



Flowers, 2008

Flowband model description: hydrology



h_s = effective water-sheet thickness
Q_{sx} = water flux
b_s = source term
$\phi_{s:c}$ = water exchange term
K_s = hydraulic conductivity
ψ_s = fluid potential
p_s = basal water pressure
t = time
x = horizontal position
ρ_w = density of water
g = gravitational acceleration

Water balance (continuity):

$$\frac{\partial h_s}{\partial t} + \frac{\partial Q_{sx}}{\partial x} = b_s - \phi^{s:c}$$

Water flux:

$$Q_{sx} = -\frac{K_s\, h_s}{\rho_w\, g}\,\frac{\partial \psi_s}{\partial x}$$

Fluid potential:

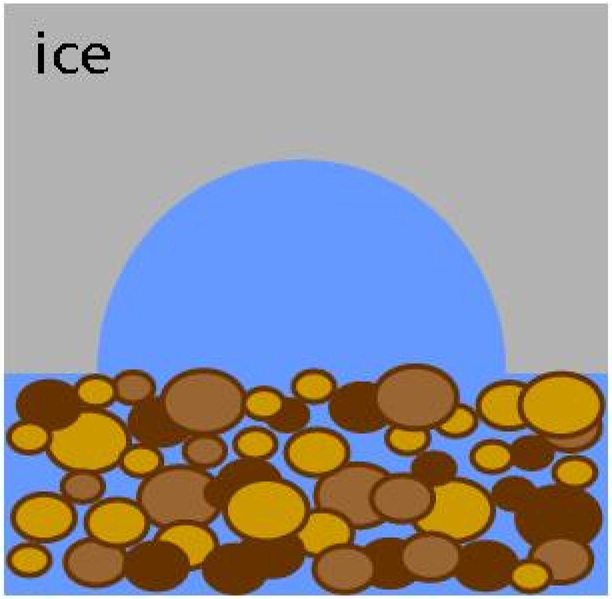
$$\psi_s = p_s + \rho_w\, g\, z$$

Basal water pressure:

$$p_s = p_s(h_s)$$

function of bed character, geometry

Flowband model description: hydrology



S = conduit cross-sectional area
Q_{sc} = conduit discharge
f_R = friction coefficient
P_w = conduit wetted perimeter
n = flow law exponent
B = flow law coefficient
ψ_c = conduit fluid potential
p_s = basal water pressure
p_c = conduit water pressure
L = latex heat of fusion
c_t = pressure melting coefficient
c_w = heat capcity of water

Conservation of mass:

$$\frac{\partial S}{\partial t} = -\frac{Q_{cx}}{\rho_i L}\left(\frac{\partial \psi_c}{\partial x} - c_t \rho_w c_w \frac{\partial p_c}{\partial x}\right) - 2\,S\left(\frac{p_i - p_c}{nB}\right)^n$$

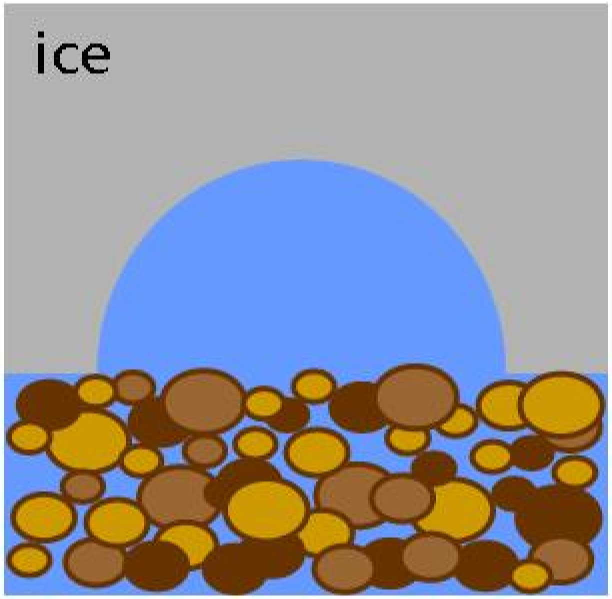
Conduit discharge:

$$Q_{cx} = -\left(\frac{8\,S^3}{P_w\,\rho_w\,f_R}\right)^{1/2} \frac{\partial_x \psi_c}{|\partial_x \psi_c|^{1/2}}$$

Sheet-conduit water exchange:

$$\phi_{s:c} = \chi_{s:c}\,\frac{K_{s:c}\,h_{s:c}}{\rho_w\,g\,d_c^2}\,(p_s - p_c)$$

Flowband model description: hydrology



Allows representation of parallel, non-interacting conduits, given a conduit density per unit width d_c

Conservation of mass:

$$\frac{\partial S}{\partial t} = -\frac{Q_{\mathrm{c}x}}{\rho_{\mathrm{i}} L}\left(\frac{\partial \psi_{\mathrm{c}}}{\partial x} - c_{\mathrm{t}}\rho_{\mathrm{w}} c_{\mathrm{w}} \frac{\partial p_{\mathrm{c}}}{\partial x}\right) - 2\,S\left(\frac{p_{\mathrm{i}} - p_{\mathrm{c}}}{nB}\right)^n$$

Conduit discharge:

$$Q_{cx} = -\left(\frac{8\,S^3}{P_{\mathrm{w}}\,\rho_{\mathrm{w}}\,f_R}\right)^{1/2} \frac{\partial_x\,\psi_{\mathrm{c}}}{|\partial_x\,\psi_{\mathrm{c}}|^{1/2}}$$

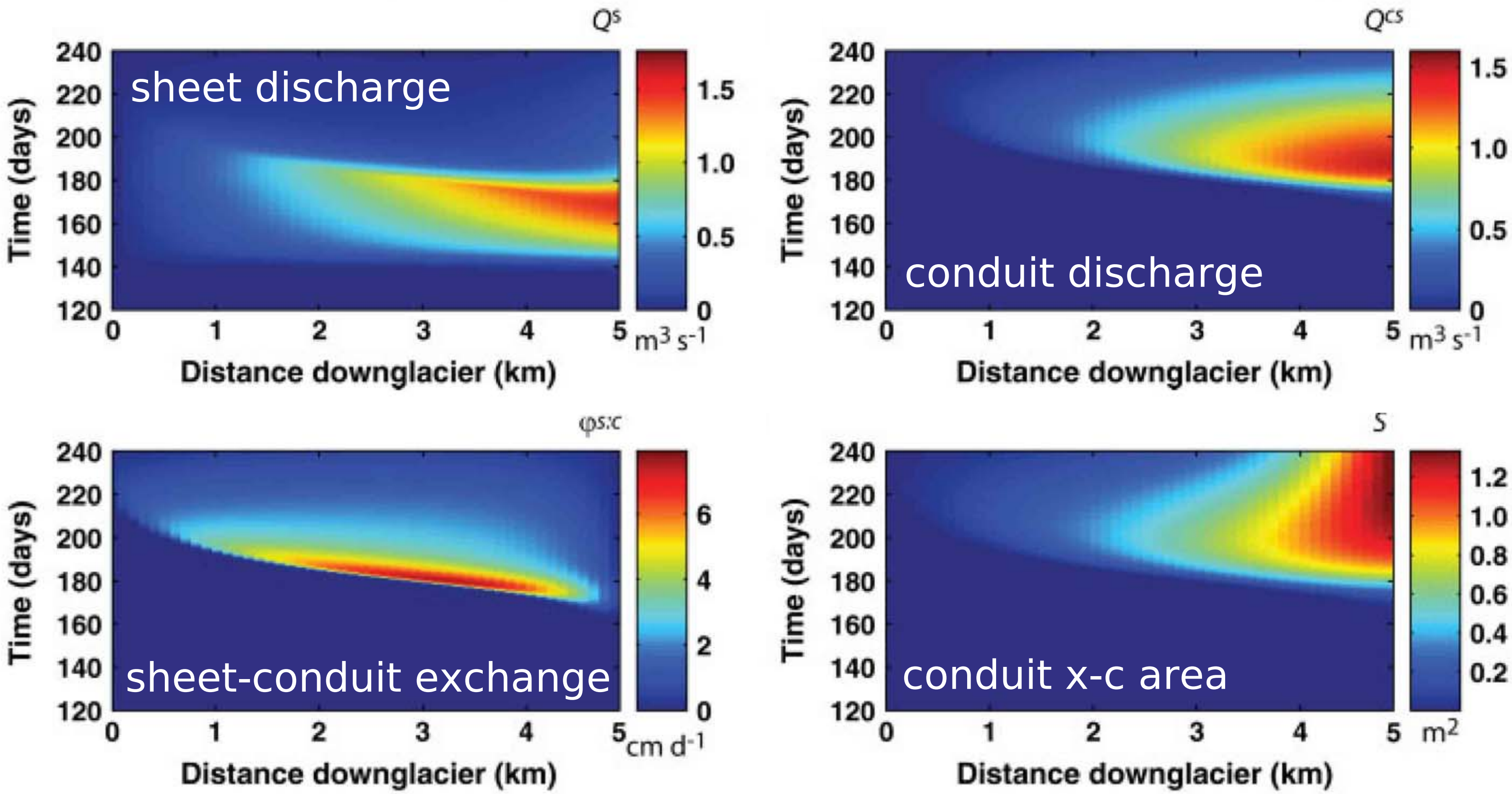
Sheet-conduit water exchange:

$$\phi_{s:c} = \chi_{s:c}\,\frac{K_{s:c}\,h_{s:c}}{\rho_{\mathrm{w}}\,g\,\boxed{d_c^2}}\,(p_s - p_c)$$

Simulated seasonal evolution of glacier hydrology

Prescribed: annual & diurnal sinusoidal variations in water input for an idealized glacier geometry

ice flow →



Coupling to ice dynamics described tomorrow by Sam Pimentel

Flowers, 2008

Final comments and outlook

- Details of the subgrid physics are important in glacier hydrology and have significant implications for ice dynamics: they (or their effects) must be parameterized or described in a fashion that can be implemented in current continuum models
- May be worth investigating statistical descriptions of subgrid conduit networks for large-scale modeling
- Neglecting short-term transient events in the drainage system probably leads to an underestimation of the influence of hydrology, thus asynchronous coupling with steady-state hydrology may not be the best method of coupling with ice dynamics
- Oversimplified parameterizations of the effects of basal hydrology (e.g. sliding proportional to degree-days) can produce behavior inconsistent with well-established physics and should probably be avoided
- How can we effectively use data to increase the validity of these models? What data would be most appropriate?

Belcher Glacier (A. Gardner)