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Seasonal Changes in Ice Sheet Motion due to Melt Water Lubrication

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Summary

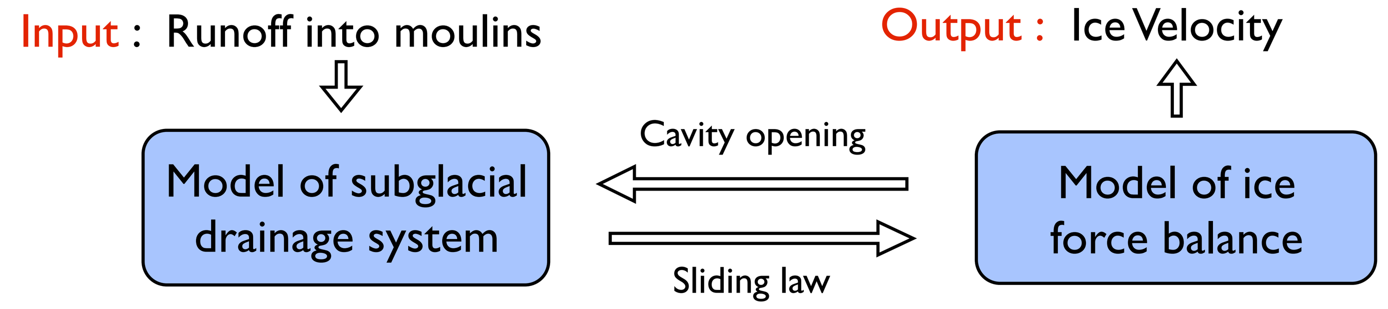
- ▷ Numerical model used to estimate how mean annual velocity is affected by surface melting rate for an 'ideal' ice sheet.
- ▷ More melting generally results in faster flowing ice, but with complex pattern of acceleration and deceleration.

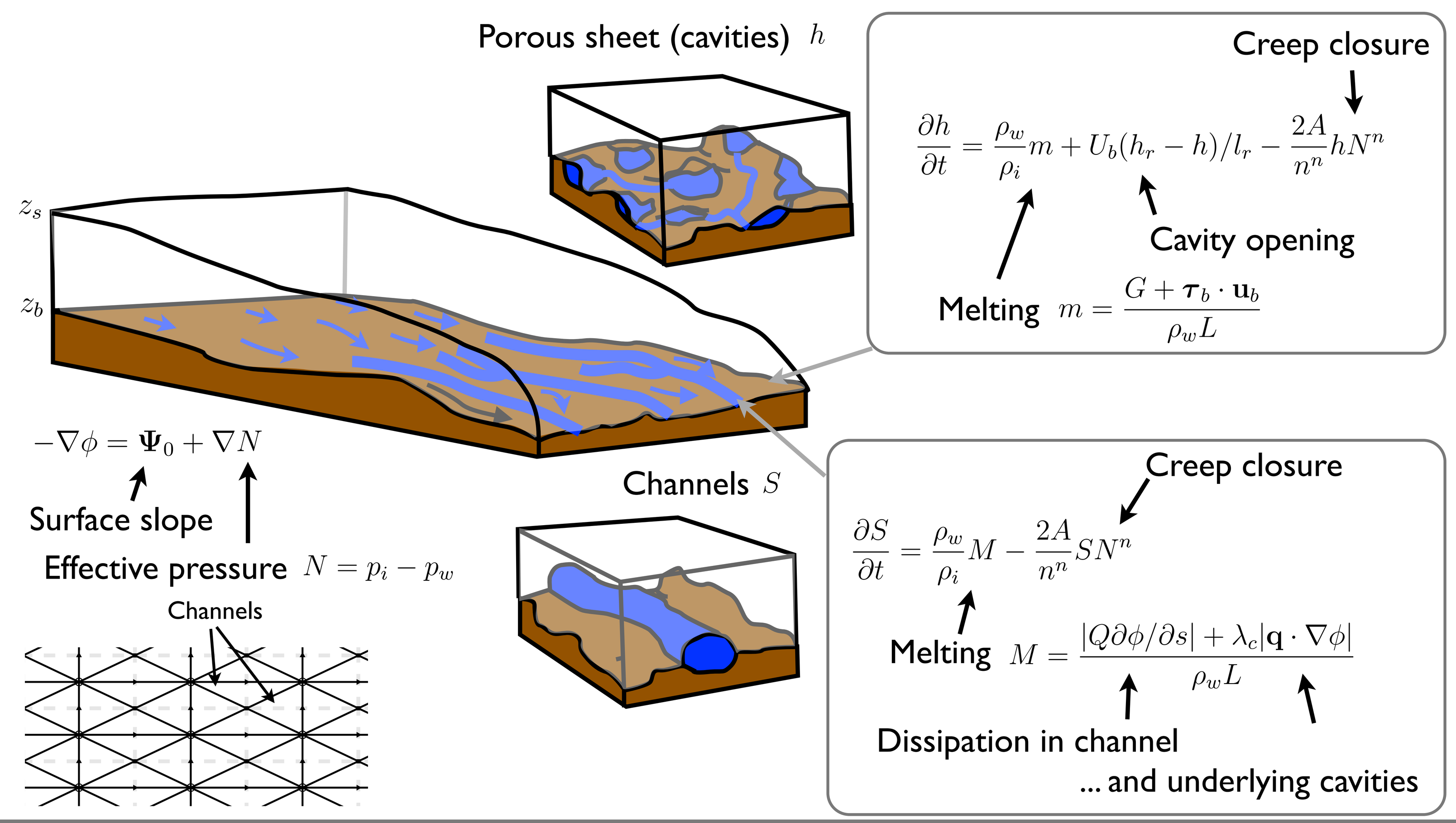
Why?

- ▷ Motion of the Greenland Ice Sheet is influenced by routing of surface meltwater to its bed on seasonal and diurnal timescale.
- ▷ Meltwater lubrication is not accounted for in current ice sheet models.

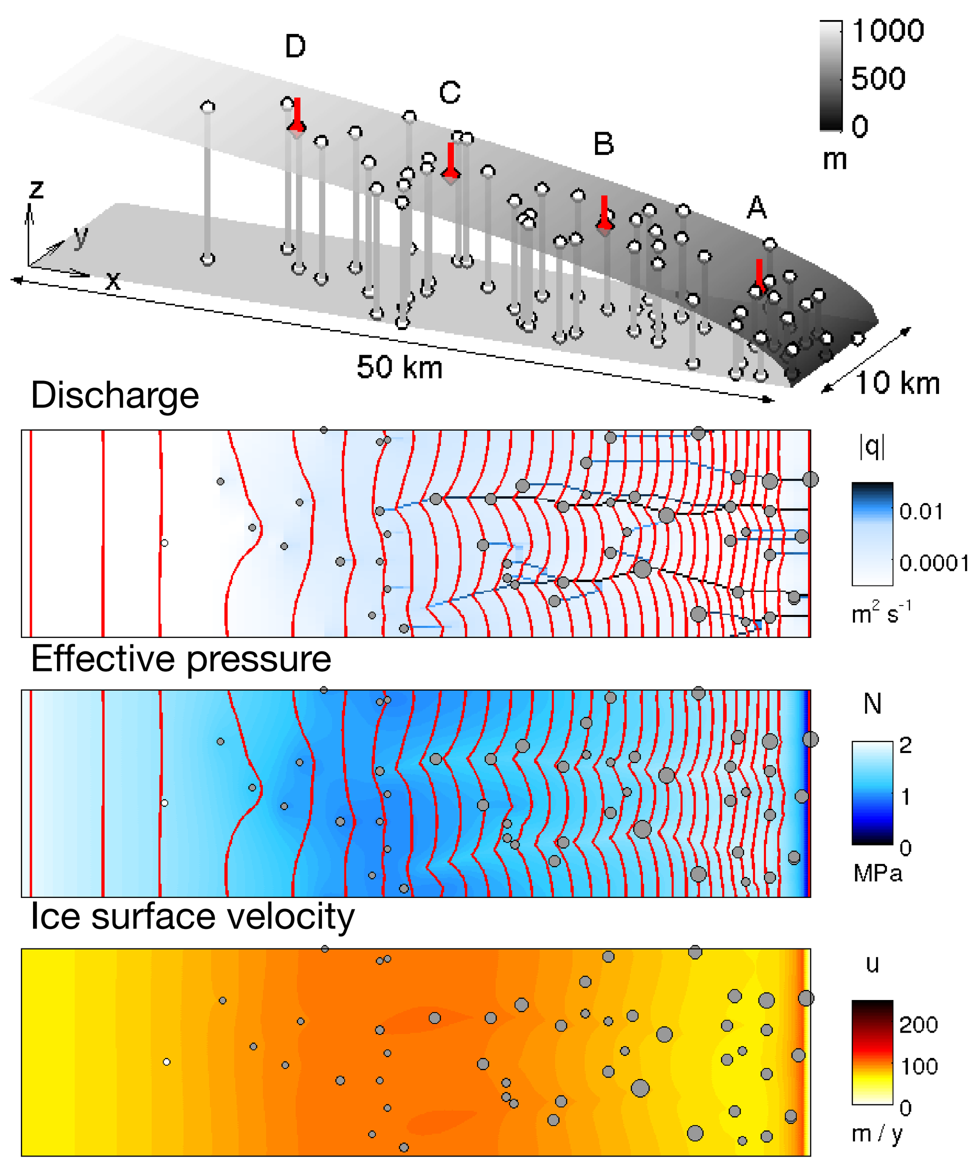
Methods

- ▷ Vertically-integrated model for ice flow; incorporates membrane stresses and internal shearing.
- ▷ Sliding law depends on effective pressure : $\boldsymbol{\tau}_b = f(U_b, N)\frac{\mathbf{u}_b}{U_b}$
- ▷ Drainage model incorporates flow in cavities and channels.
- ▷ Fixed ice geometry. Surface melting decreases with elevation.



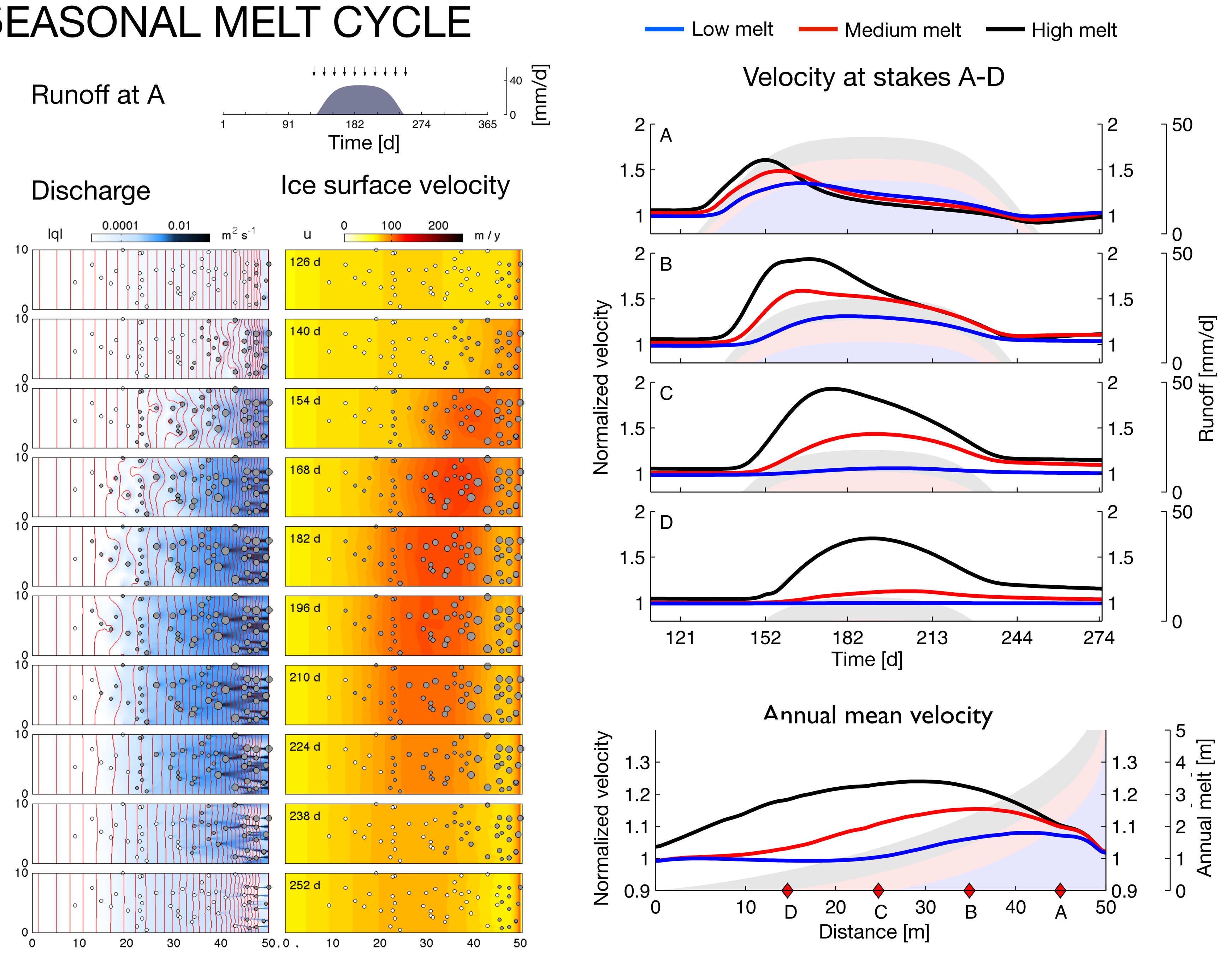


Steady State



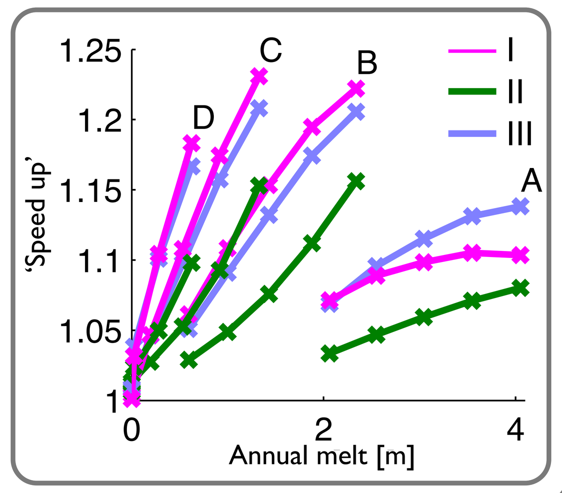
- ▷ Steady state never realized in practice

Seasonal Melt Cycle



Model Observations

- ▷ Highest velocities occur during early summer near margin and progressively later further inland, due to evolution of drainage system.
- ▷ More melting provokes larger initial acceleration, followed by compensating deceleration near margin.
- ▷ Channelization reduces ice velocities, but it is hard to generate significant slow down when averaged over the year.
- ▷ Sensitivity to annual melt rate is generally higher further from the margin.



Future Issues

- ▷ Some parameters are very uncertain : need to fit to observations.
- ▷ Channels shrink entirely over winter : rejuvenation in early summer takes too long (?)
- ▷ Quasi-steady sliding law used here : need to develop transient sliding law
- ▷ Model is overly sensitive to extreme water pressures : need improvements to cope with rapid drainage events.

Model

Sliding law

I $f(U_b, N) = \mu_I N U_b$ II $f(U_b, N) = \mu_{II} N^{1/3} U_b^{1/3}$ III $f(U_b, N) = \mu_{III} N \left(\frac{U_b}{U_b + \lambda_b A N^n}\right)^{1/n}$

Mass conservation

$$\frac{\partial h}{\partial t} + \nabla\cdot\mathbf{q} + \left[\frac{\partial S}{\partial t} + \frac{\partial Q}{\partial s}\right]\delta(\mathbf{x}_c) + \frac{\partial \Sigma}{\partial t} = m + M\delta(\mathbf{x}_c) + R\delta(\mathbf{x}_m)$$

Water flow parameterizations

$$\mathbf{q} = -\frac{Kh^3}{\rho_w g}\nabla\phi$$

$$Q = -K_c S^{5/4}\left|\frac{\partial\phi}{\partial s}\right|^{-1/2}\frac{\partial\phi}{\partial s}$$

Evolution parameterizations

$$\frac{\partial h}{\partial t} = \frac{\rho_w}{\rho_i}m + U_b(h_r - h)/l_r - \frac{2A}{n^n}h|N|^{n-1}N$$

$$\frac{\partial S}{\partial t} = \frac{\rho_w}{\rho_i}M - \frac{2A}{n^n}S|N|^{n-1}N$$

Energy conservation

$$m = \frac{G + \boldsymbol{\tau}_b\cdot\mathbf{u}_b}{\rho_w L} \qquad M = \frac{|Q\partial\phi/\partial s| + \lambda_c|\mathbf{q}\cdot\nabla\phi|}{\rho_w L}$$

Englacial storage

$$\Sigma = \sigma\frac{p_w}{\rho_w g}$$

Basal force balance

$$\frac{f(U_b,N)}{U_b}u_b = -\rho_i g H\frac{\partial s}{\partial x} + \frac{\partial}{\partial x}\left[H\left(2\bar{\tau}_{xx} + \bar{\tau}_{yy}\right)\right] + \frac{\partial}{\partial y}\left[H\bar{\tau}_{xy}\right]$$

$$\frac{f(U_b,N)}{U_b}v_b = -\rho_i g H\frac{\partial s}{\partial y} + \frac{\partial}{\partial y}\left[H\left(\bar{\tau}_{xx} + 2\bar{\tau}_{yy}\right)\right] + \frac{\partial}{\partial x}\left[H\bar{\tau}_{xy}\right]$$

In-plane force balance

$$\tau_{xz} = -\rho_i g(s-z)\frac{\partial s}{\partial x} + \frac{\partial}{\partial x}\left[\int_z^s\left(2\tau_{xx} + \tau_{yy}\right)\,\mathrm{d}z\right] + \frac{\partial}{\partial y}\left[\int_z^s \tau_{xy}\,\mathrm{d}z\right]$$

$$\tau_{yz} = -\rho_i g(s-z)\frac{\partial s}{\partial y} + \frac{\partial}{\partial y}\left[\int_z^s\left(\tau_{xx} + 2\tau_{yy}\right)\,\mathrm{d}z\right] + \frac{\partial}{\partial x}\left[\int_z^s \tau_{xy}\,\mathrm{d}z\right]$$

Approximate constitutive law

$$\tau_{xz} = \eta\frac{\partial u}{\partial z}, \quad \tau_{yz} = \eta\frac{\partial v}{\partial z} \quad \tau_{xx} = 2\tilde{\eta}\frac{\partial u_b}{\partial x}, \quad \tau_{yy} = 2\tilde{\eta}\frac{\partial v_b}{\partial y}, \quad \tau_{xy} = \tilde{\eta}\left(\frac{\partial u_b}{\partial y} + \frac{\partial v_b}{\partial x}\right)$$

$$\eta = \tfrac{1}{2}\overline{A}^{-1}\left[\tau_{xz}^2 + \tau_{yz}^2 + \tau_{xy}^2 + \tau_{xx}^2 + \tau_{xx}\tau_{yy} + \tau_{yy}^2\right]^{(1-n)/2}$$

$$\tilde{\eta} = \tfrac{1}{2}\overline{A}^{-1}\left[\tilde{\tau}_{xz}^2 + \tilde{\tau}_{yz}^2 + \tau_{xy}^2 + \tau_{xx}^2 + \tau_{xx}\tau_{yy} + \tau_{yy}^2\right]^{(1-n)/2}$$

$$\tilde{\tau}_{xz} = -\rho_i g(s-z)\frac{\partial s}{\partial x} \qquad \tilde{\tau}_{yz} = -\rho_i g(s-z)\frac{\partial s}{\partial y}$$

Diurnal Variability