# Modeling weakly transmissive drainage beneath the Greenland Ice Sheet


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Real-time Observations of the Greenland Under-ice Environment


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NASA

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NSF

National Geographic

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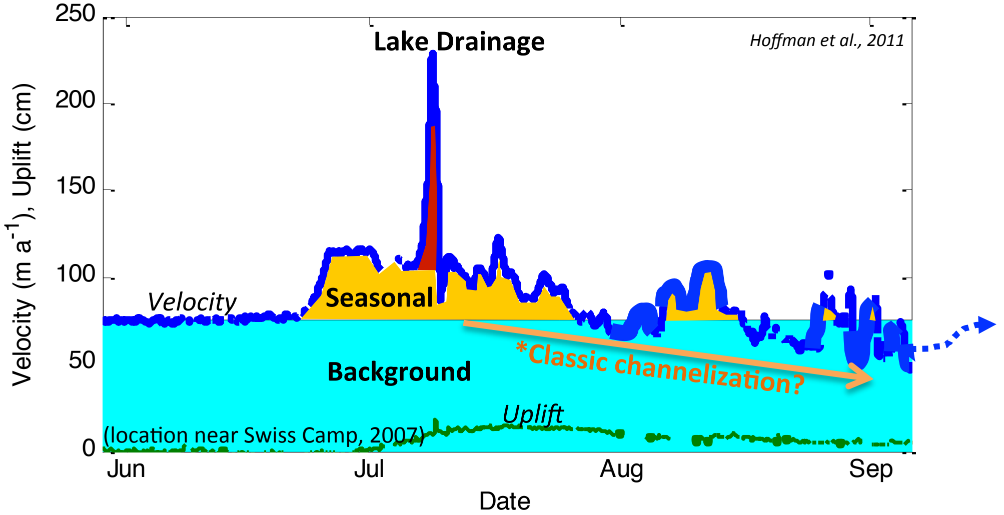
# Greenland subglacial drainage and its influence on ice flow

Mountain glacier "spring speedup" as analog* for Greenland?



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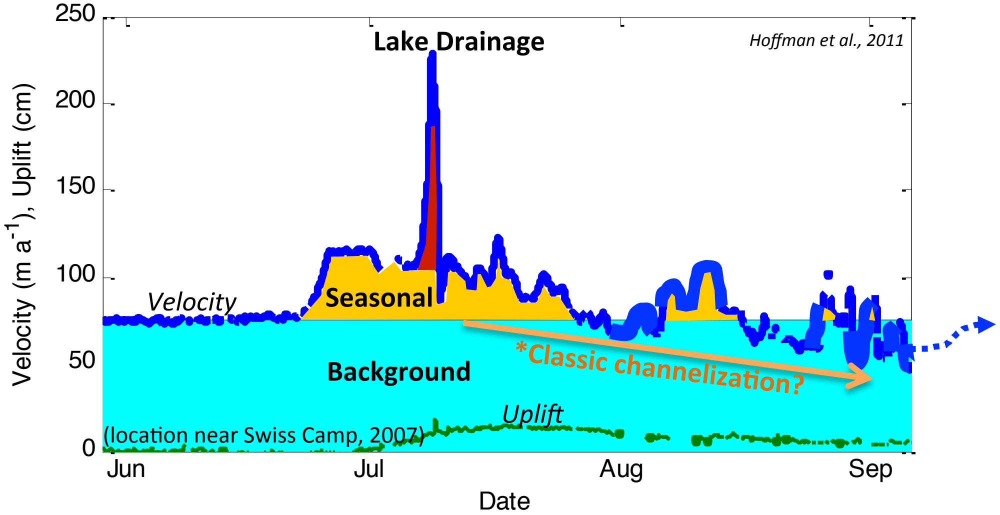
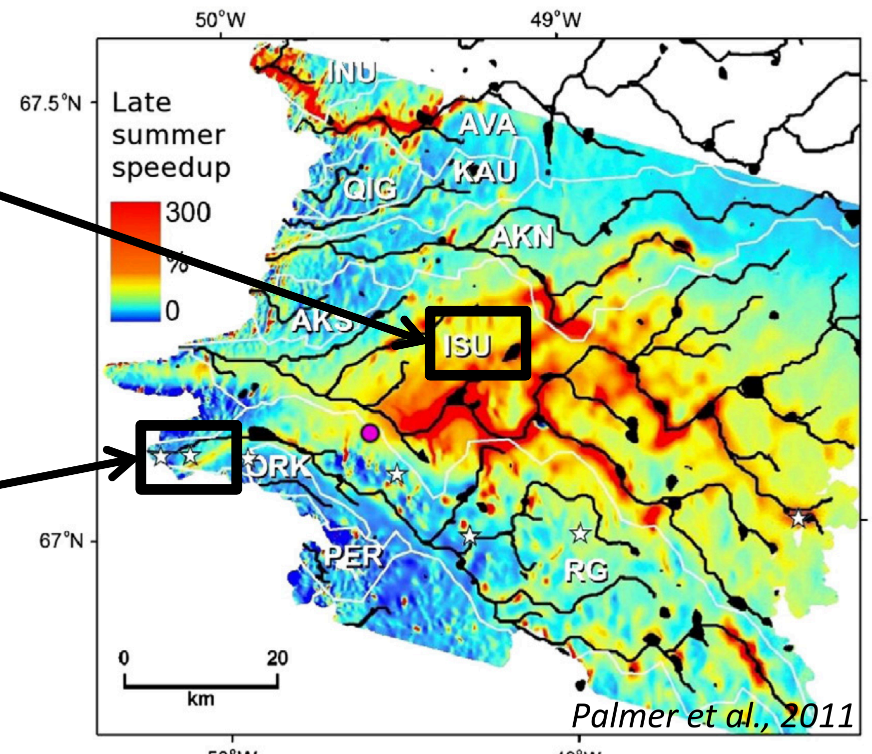
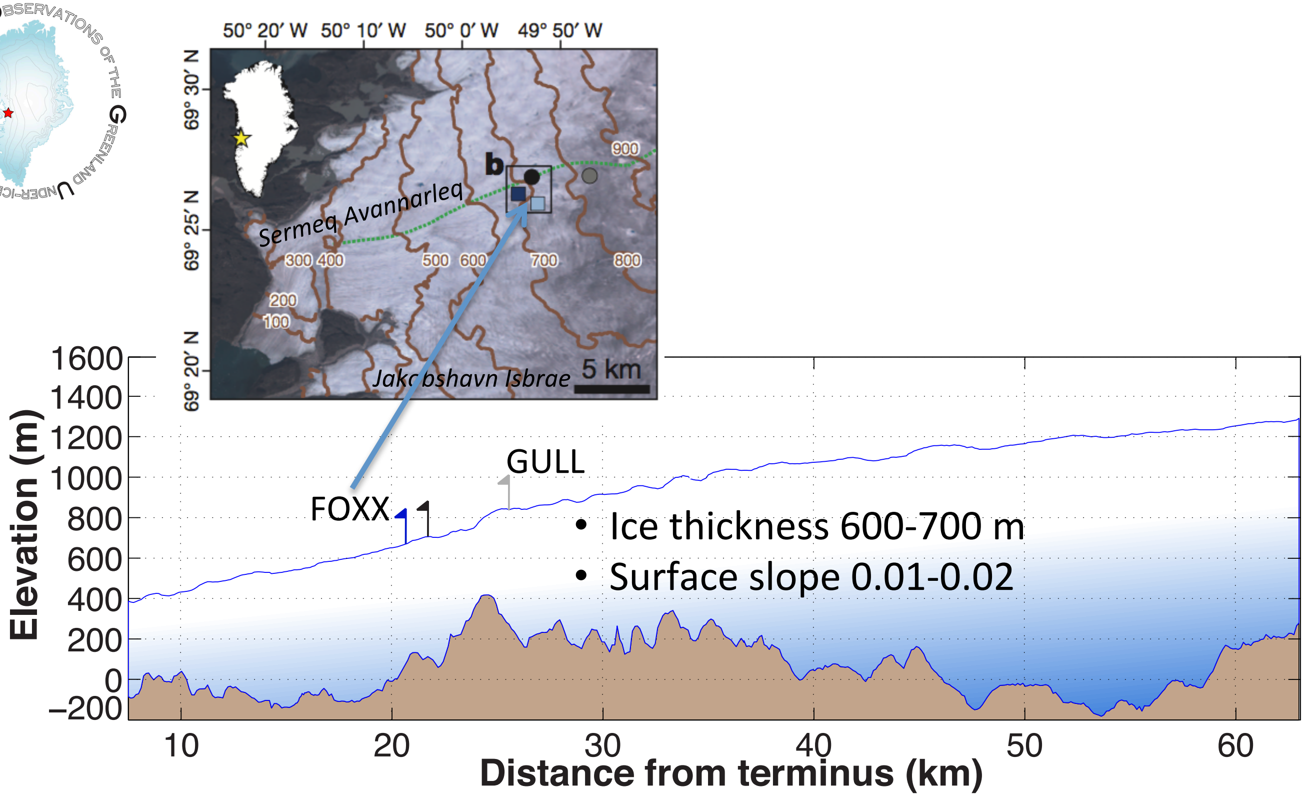



- ✗ **Limited channel stability and efficient distributed pathways** (Meierbachtol et al., 2013)
- ✓ **Unpressurized channels** (Chandler et al., 2013; Cowton et al., 2013)



Real-Time Observations of the Greenland Under-Ice Environment



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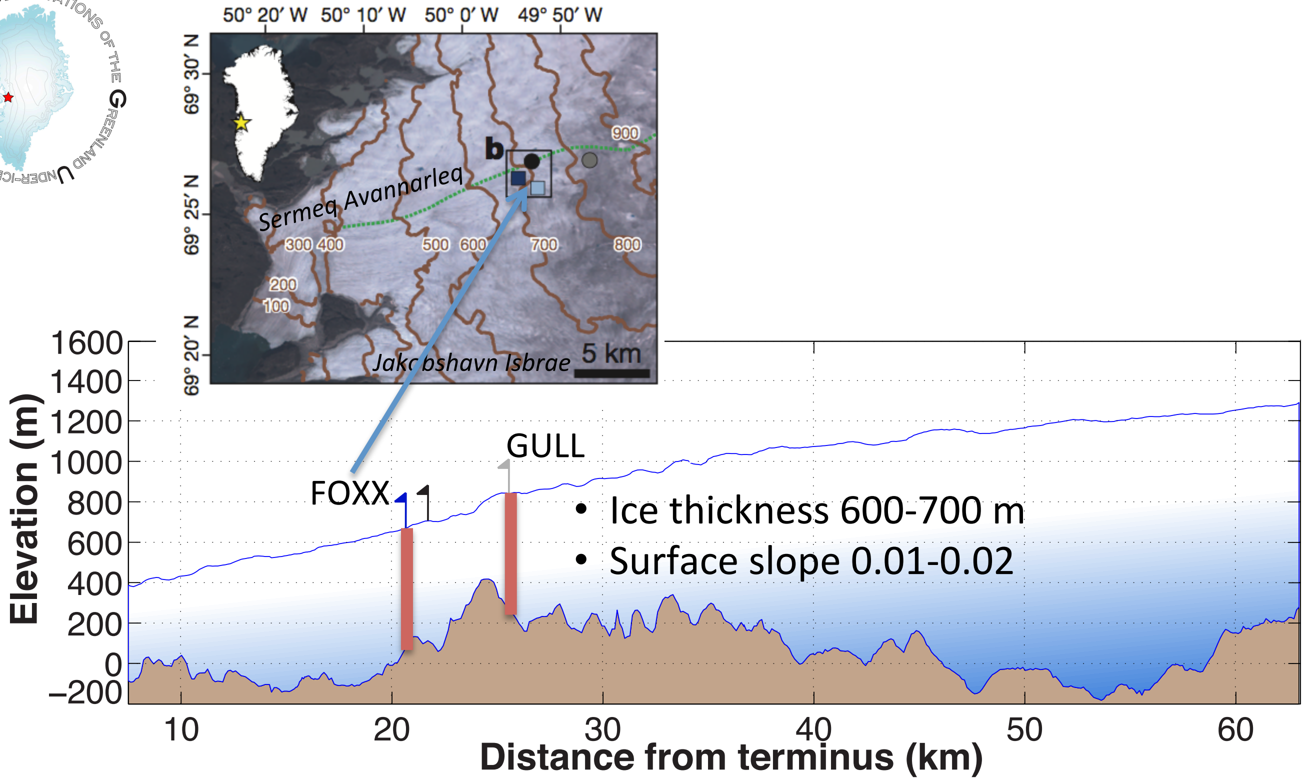
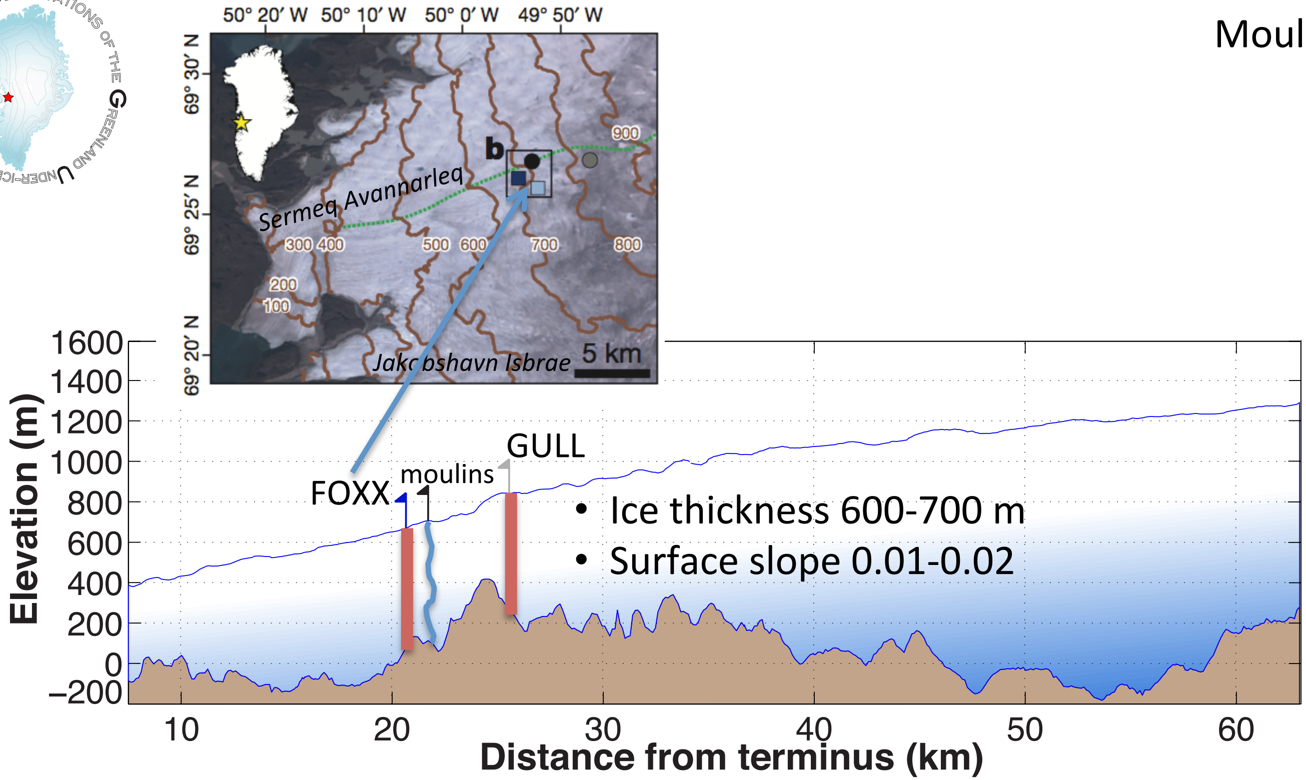
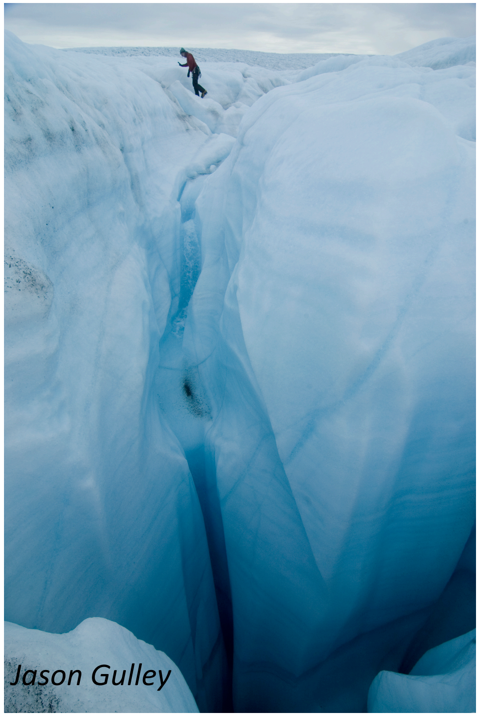



Hot Water Drilling & Borehole sensor installation:
Summer 2011

# Moulin pressure sensor installation: Summers 2011 & 2012




# Hot Water Drilling & Borehole sensor installation: Summer 2011

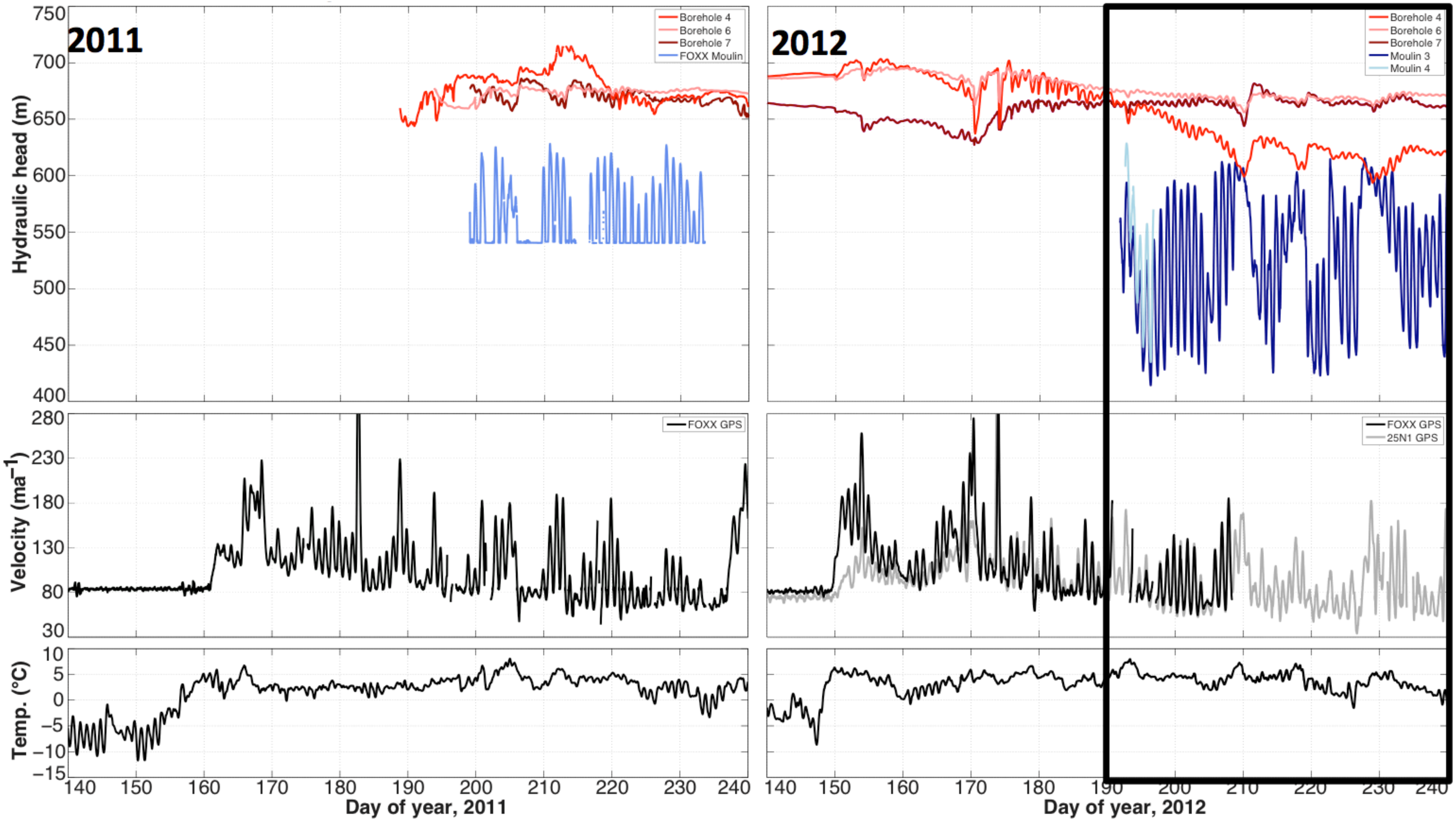
## Measurements during two melt seasons – site FOXX

- Weather (temperature, ablation)
- Ice velocity (GPS)
- Moulin water pressure
- Borehole water pressure

doi:10.1038/nature13796

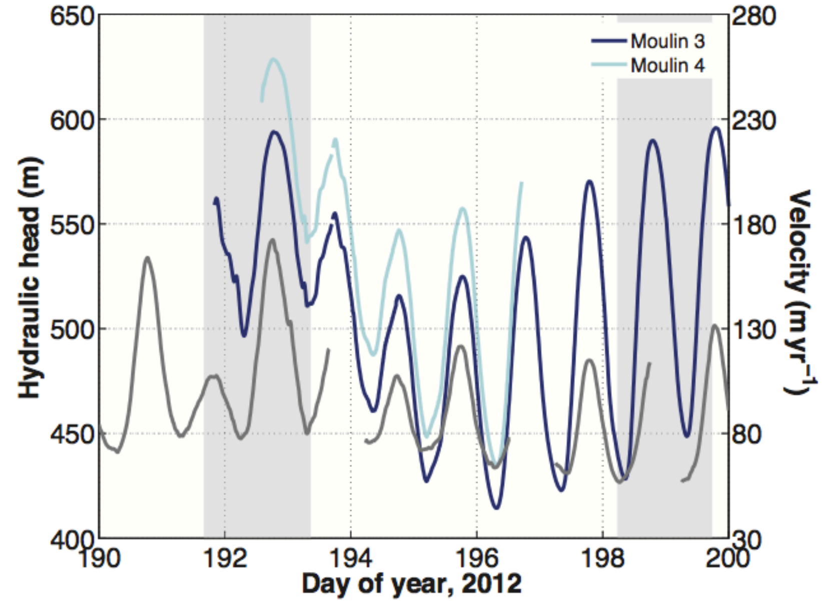
**Direct observations of evolving subglacial drainage beneath the Greenland Ice Sheet**

Lauren C. Andrews[1,2], Ginny A. Catania[1,2], Matthew J. Hoffman[3,4], Jason D. Gulley[1,5], Martin P. Lüthi[6,7], Claudia Ryser[7], Robert L. Hawley[8] & Thomas A. Neumann[4]

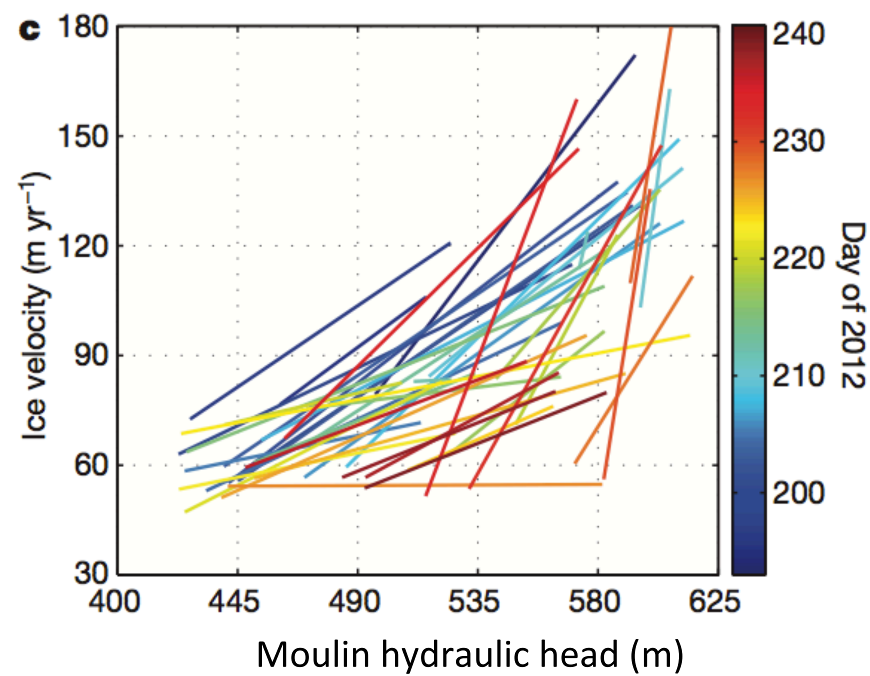


# Moulin observations sample subglacial channels

- Channels control daily and event (few day) variations in velocity.
  - Moulin hydraulic head indicates the presence of stable channels during second half of summer

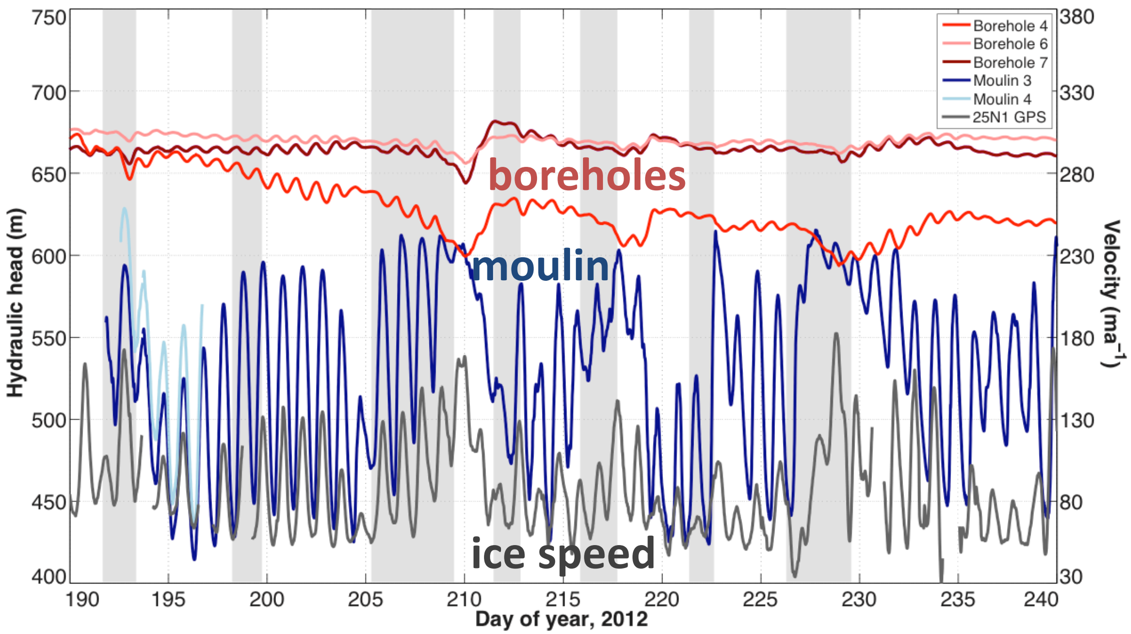



- Channels do not control long-term velocity trends in late summer.



# Borehole observations sample isolated distributed drainage

- Low amplitude diurnal changes in boreholes
- Borehole head out of phase with velocity
- Daily range in borehole head scales well with velocity
- Sampled 'disconnected' or 'isolated' distributed system
    - normal stress transfer and/or 'passive' cavity opening and/or till dilation



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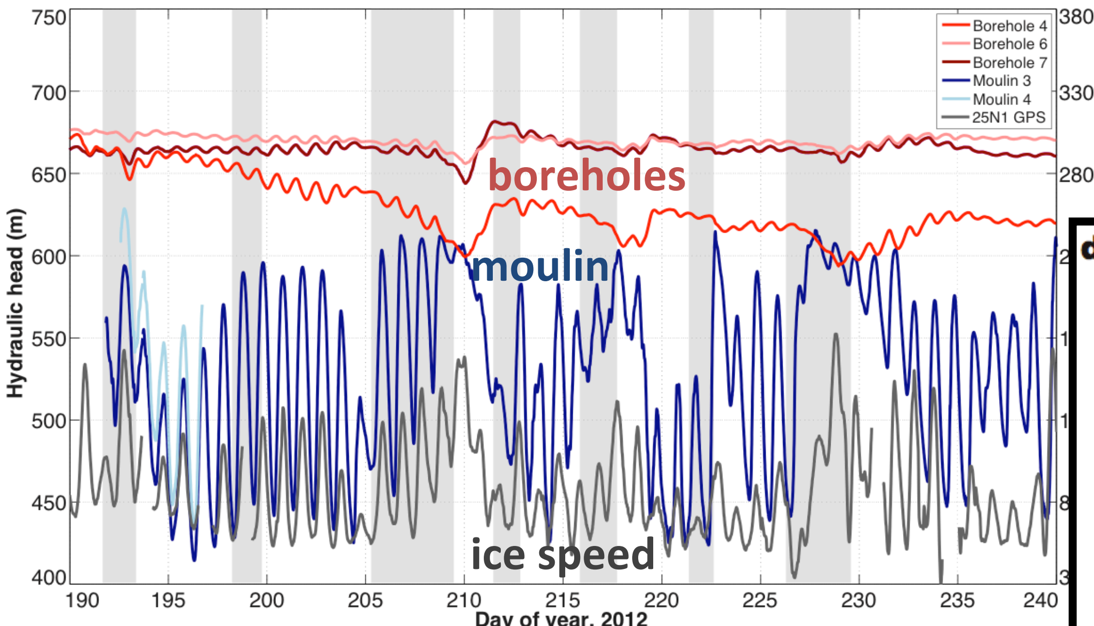
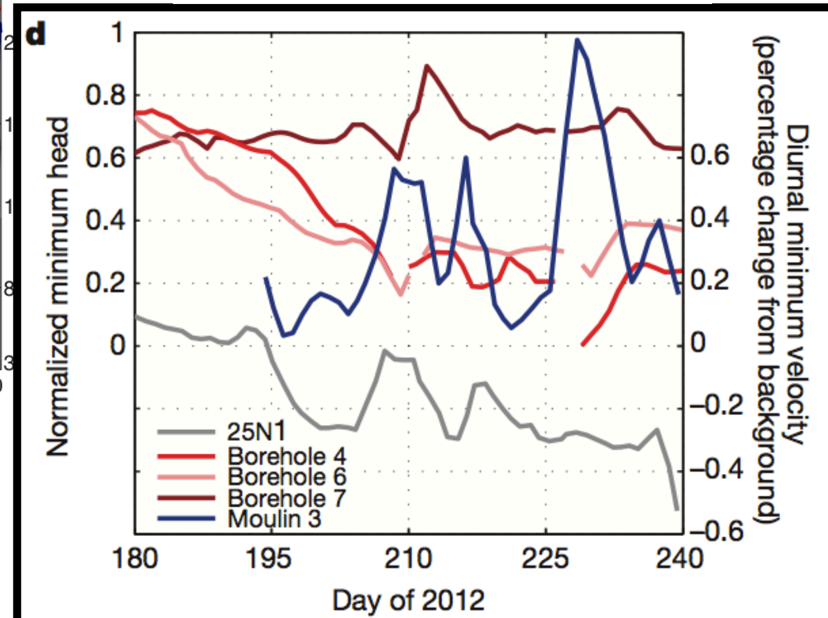



*Seasonal trends in some boreholes match seasonal trends in ice velocity.*

**Seasonal Variation**



# 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.

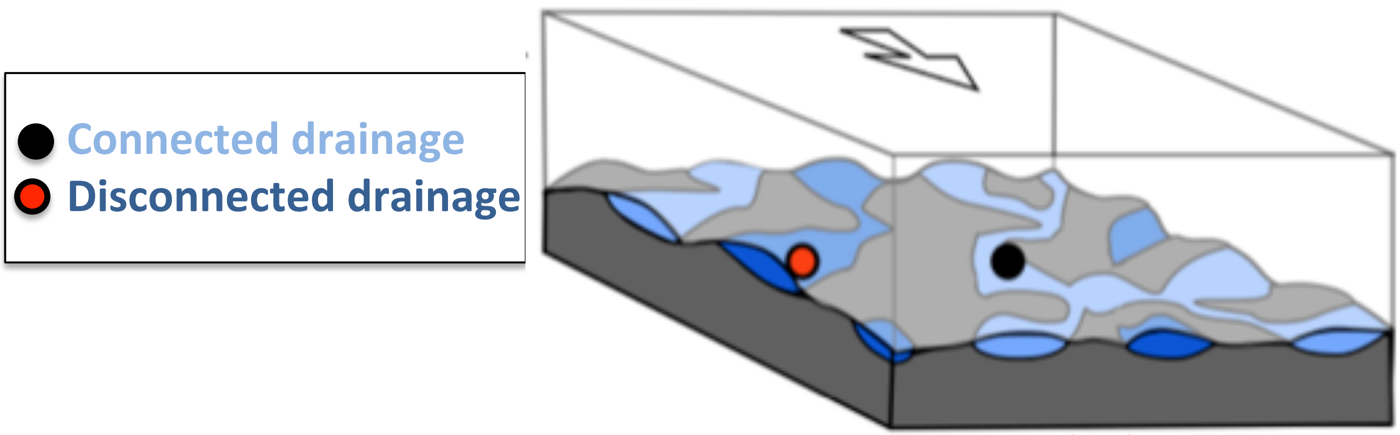



*Figure modified from Ian Hewitt*

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"*
- Iken & Truffer (1997): isolated cavities moderate active drainage regions
- 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.

# Subglacial Hydrology Model

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

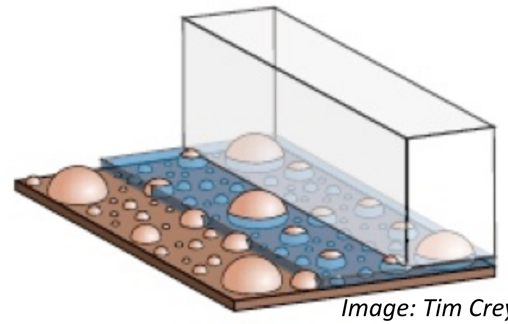


*Image: Tim Creyts*

**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**

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

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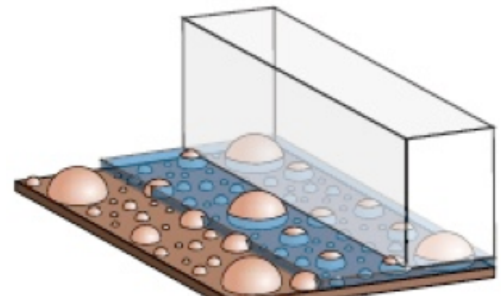

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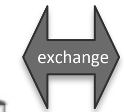


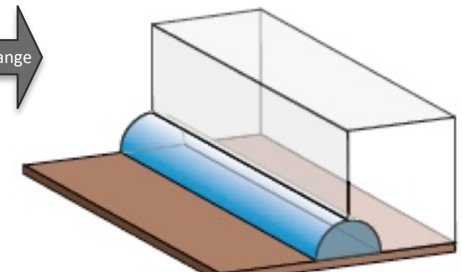

*Image: Tim Creyts*

| | **Distributed Drainage**<br>*e.g. Hewitt 2011, J.Glac.*<br>*(Macroporous sheet)* | **Channelized Drainage**<br>*e.g. Hewitt 2011, J.Glac.* |
|---|---|---|
| **Mass Conservation of Water** | $\frac{\partial h}{\partial t} + \nabla \cdot \mathbf{q} = \frac{m}{\rho_w} + \omega$<br>Flux divergence; Basal melt; Water input from surface & other drainage elements | $\frac{\partial S}{\partial t} + \frac{\partial Q}{\partial x} = \frac{M}{\rho_w} + \Omega,$<br>flow divergence; melt from flow; water input from sheet |
| **Evolution of Drainage Element Volume** | $\frac{\partial h}{\partial t} = V_O - V_C = \left(\cancel{\frac{m}{\rho_i}} + \lvert\mathbf{u_b}\rvert \frac{h_r - h}{l_r}\right) - \left(\frac{hN}{\eta_i}\right)$<br>Melt opening; Sliding over bumps; Creep closure of ice | $\frac{\partial S}{\partial t} = \frac{M}{\rho_i} - \frac{S N_c}{\eta_i},$<br>melt from flow; creep closure of ice |
| **Flow Law** | Darcy style:<br>$\mathbf{q} = -\frac{k_0 h^3}{\eta_w} \nabla \phi$ | Turbulent flow:<br>$F Q^2 = S^{8/3} \left(\Psi + \frac{\partial N_c}{\partial x}\right),$ |
| **Energy Balance** | $mL = G + \mathbf{u_b} \cdot \boldsymbol{\tau}_\mathbf{b}$<br>Geothermal; Basal friction | $ML = Q\left(\Psi + \frac{\partial N_c}{\partial x}\right).$<br>Dissipation |

# Subglacial Hydrology Model

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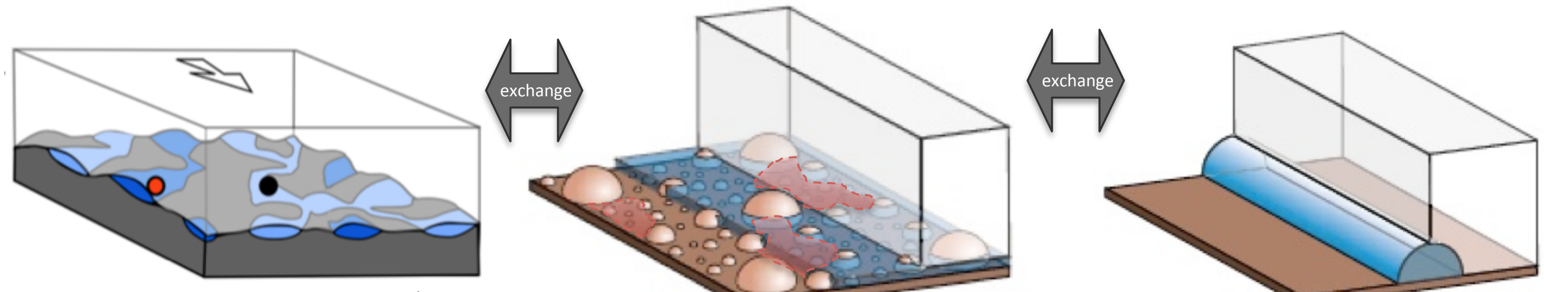


*Image: Ian Hewitt* — *Image: Tim Creyts* — *Image: Tim Creyts*

| | **Isolated Drainage**<br>*new component*<br>*(0-d subgrid representation)* | **Distributed Drainage**<br>*e.g. Hewitt 2011, J.Glac.*<br>*(Macroporous sheet)* | **Channelized Drainage**<br>*e.g. Hewitt 2011, J.Glac.* |
|---|---|---|---|
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| **Flow Law** | Darcy style exchange term: $\gamma = -\frac{k_i h^3}{\eta_w} \frac{\phi_i - \phi_s}{ds}$<br>Conductivity function of effective pressure: $k_i = \frac{C}{N + \eta}$<br>*(inspired by Murray & Clarke (1995), Gordon et al. (1998))* | Darcy style: $\mathbf{q} = -\frac{k_0 h^3}{\eta_w} \nabla \phi$ | Turbulent flow: $FQ^2 = S^{8/3}\left(\Psi + \frac{\partial N_c}{\partial x}\right),$ |
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# Idealized "ROGUE" Experiment

- 100km long domain
- "Plastic" glacier shape (constant $Tau_d$=$10^5$ Pa)
- 5 km wide "catchment-scale" domain with laterally periodic boundaries & potential channel along centerline
- Study site:
  30km inland, H=~700m, ds/dx = ~0.01

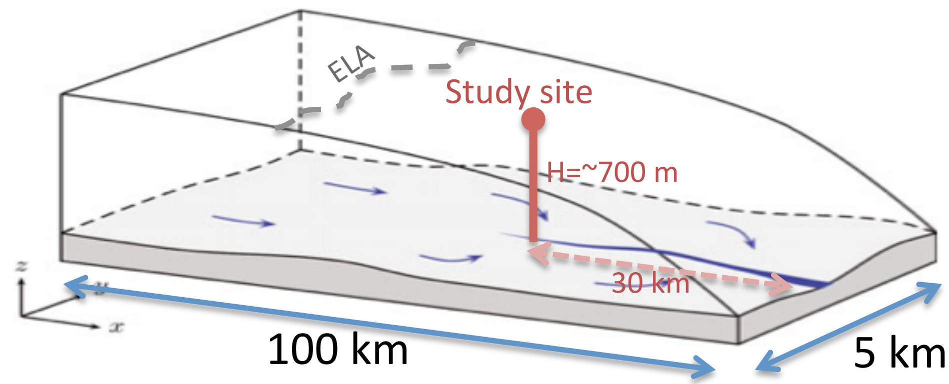
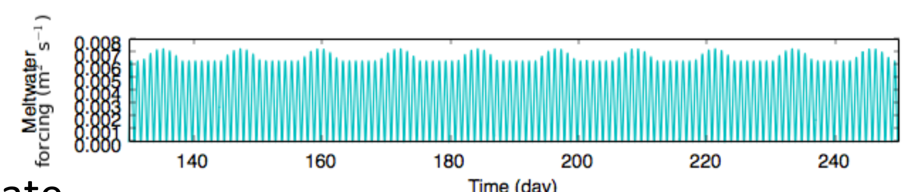
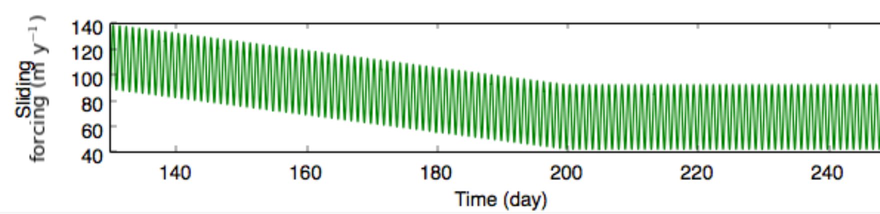



*Figure modified from Ian Hewitt (2011) J. Glac.*

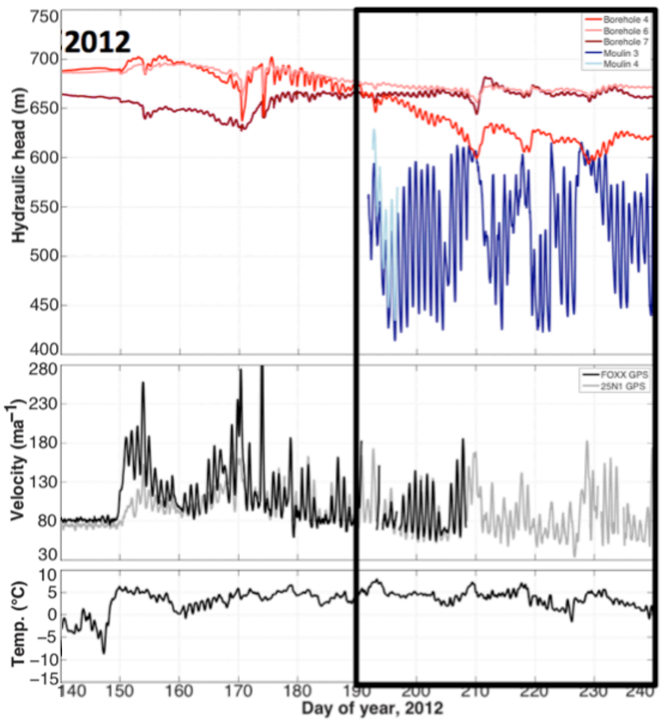
1. Springtime initial condition:
   spinup 3-component hydrology to steady state
2. **Summer forcing experiment**:
   - Supraglacial meltwater source term along centerline of domain
     - Based on observed melt rates with a lapse rate
     - Diurnally-varying sinusoidal shape
     - Quasi-steady with "melt events"
   - Diurnally-varying sliding forcing based on GPS velocity observations

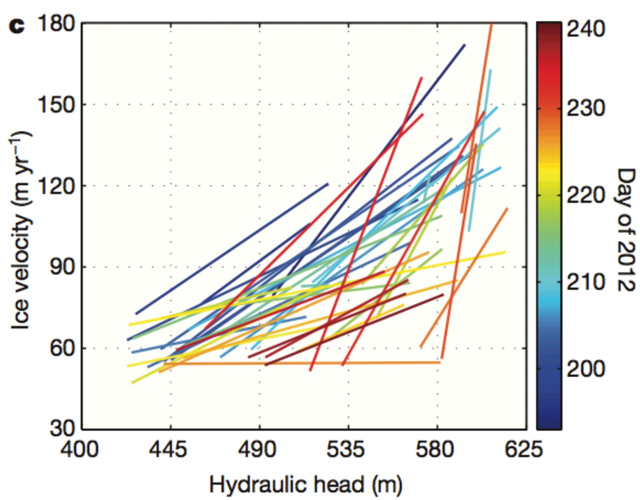



**Observe seasonal evolution of each component of drainage system at study location.**

# Observations



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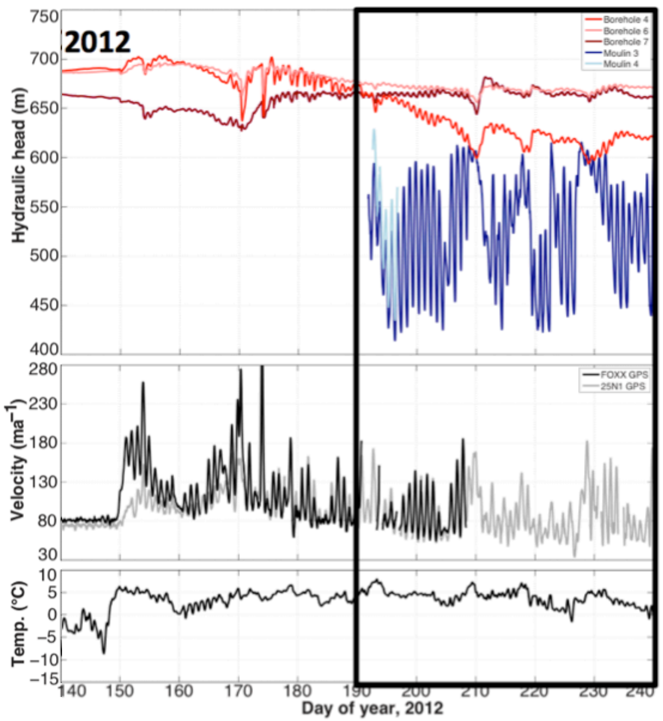


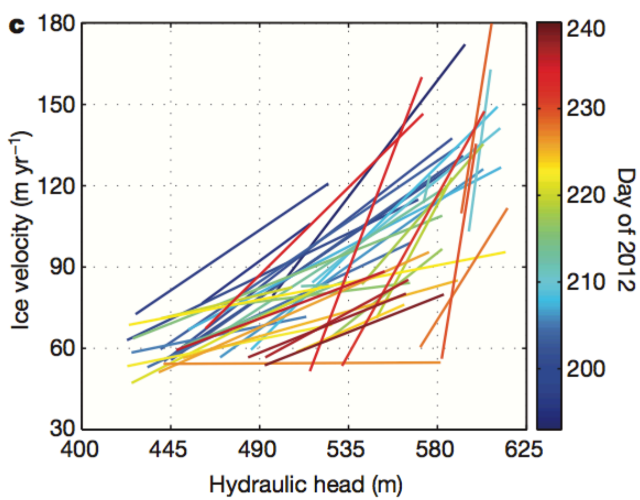


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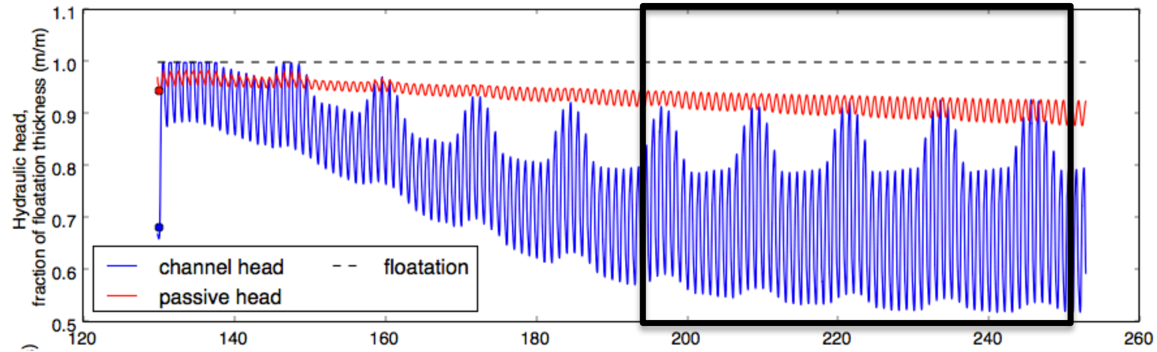

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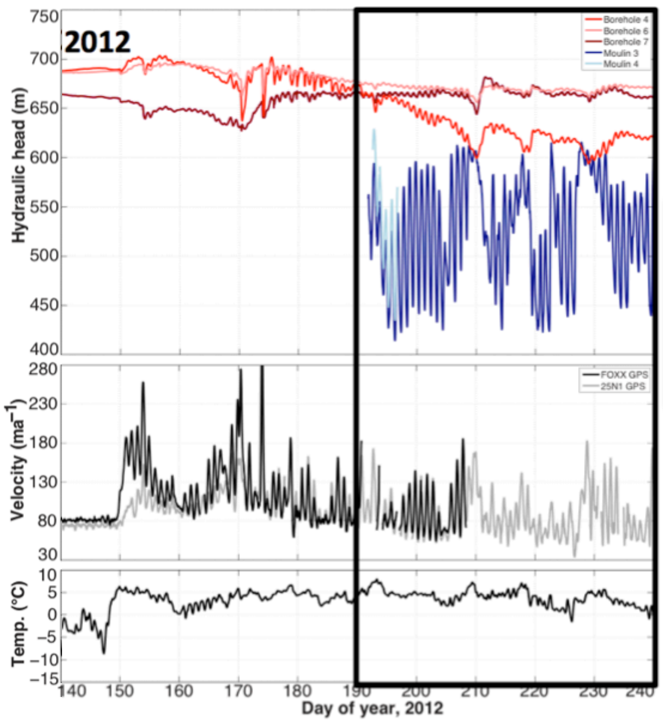


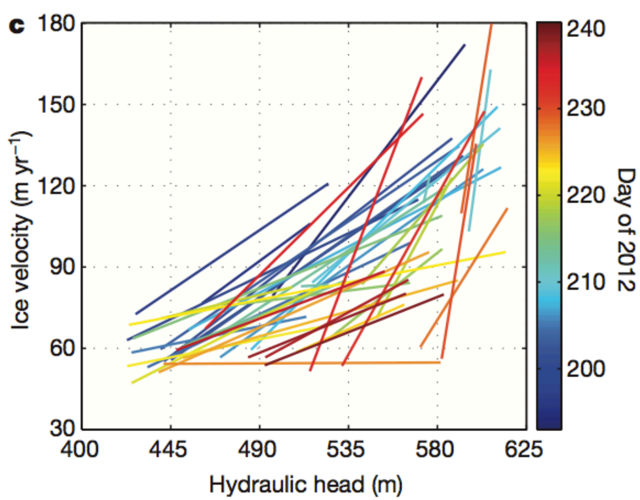


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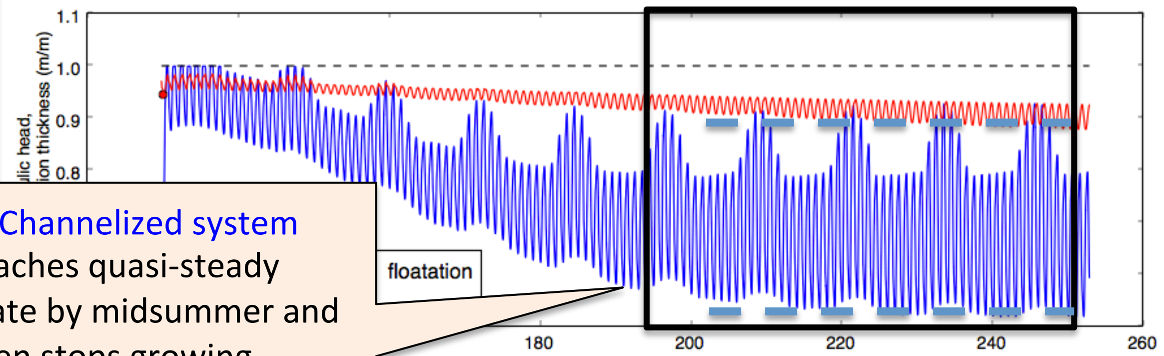


1. Channelized system reaches quasi-steady state by midsummer and then stops growing.

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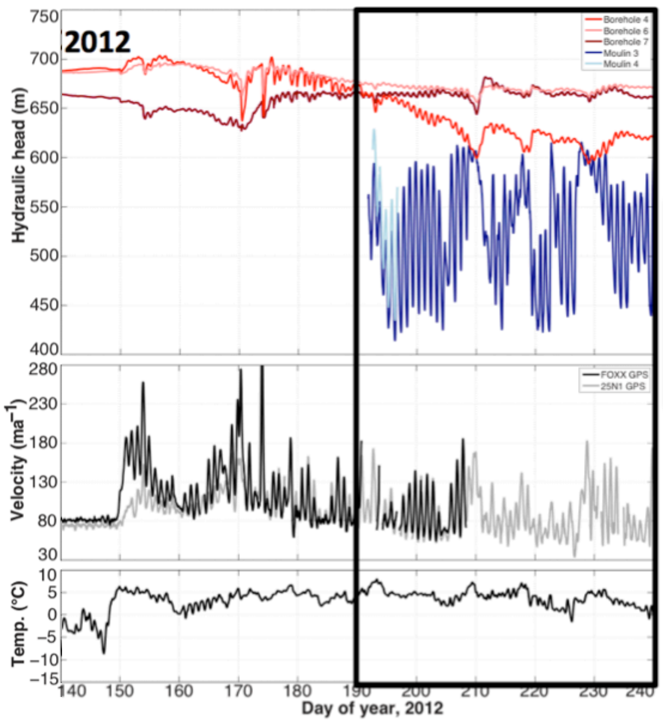
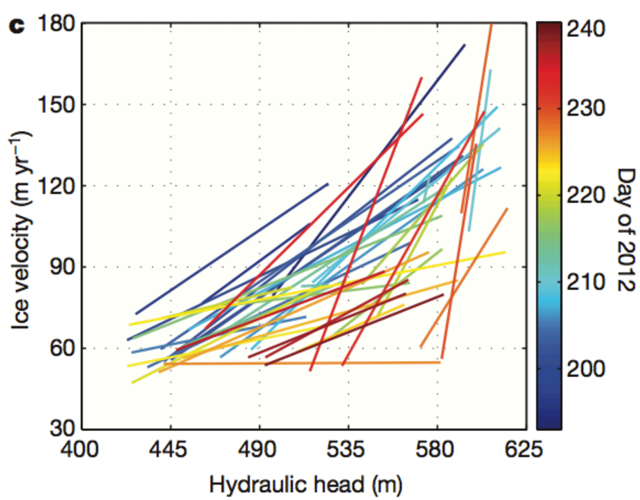
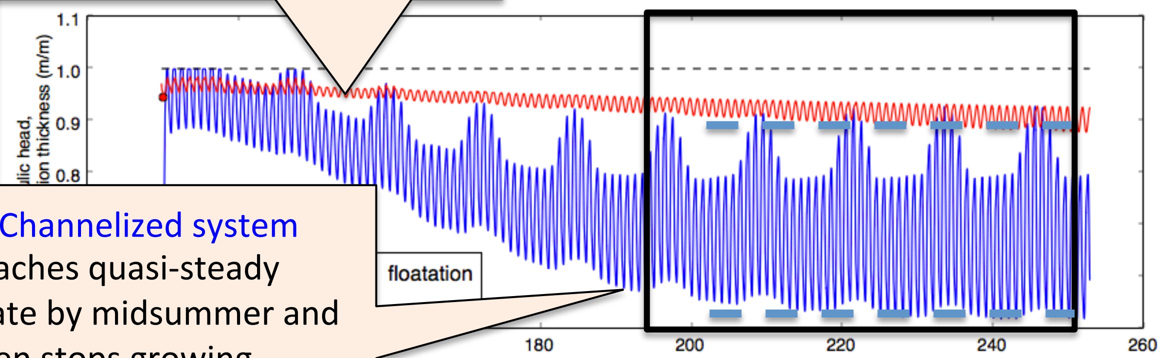



# Model

2. Cavity opening can induce out-of-phase pressure variations in isolated system.

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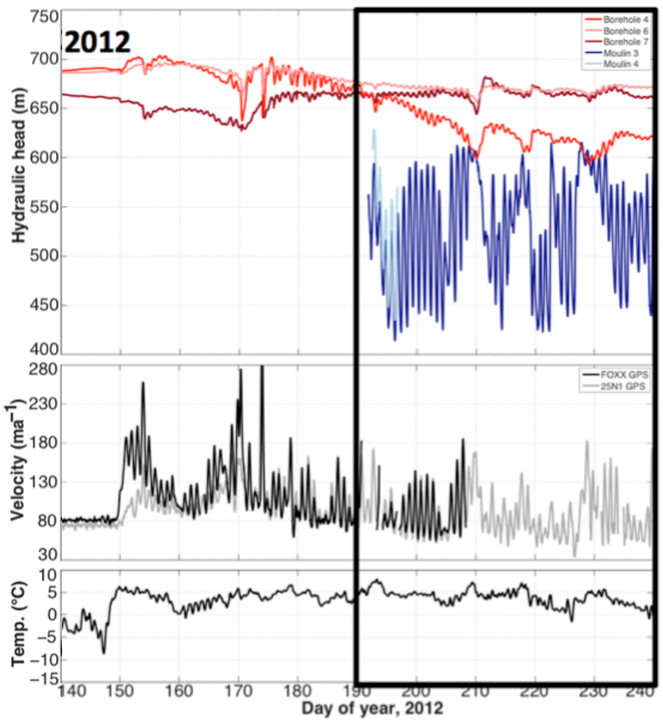


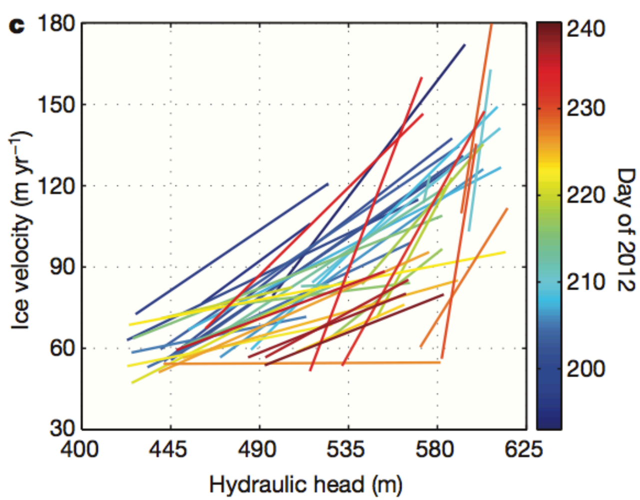


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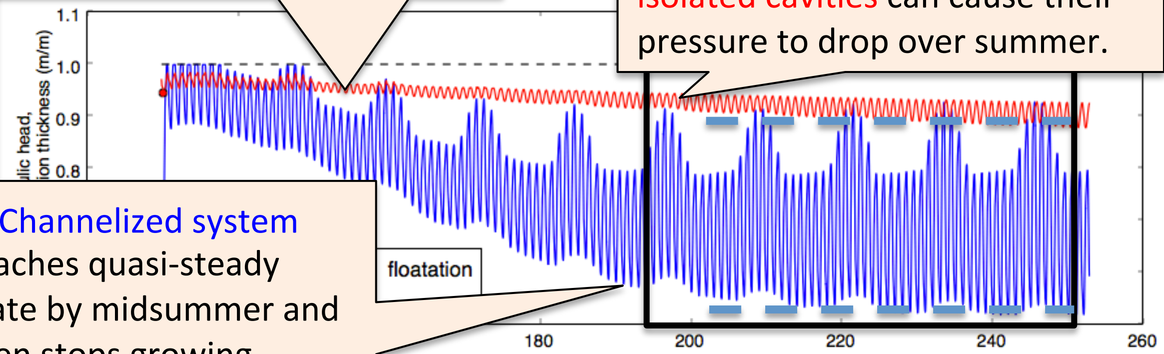
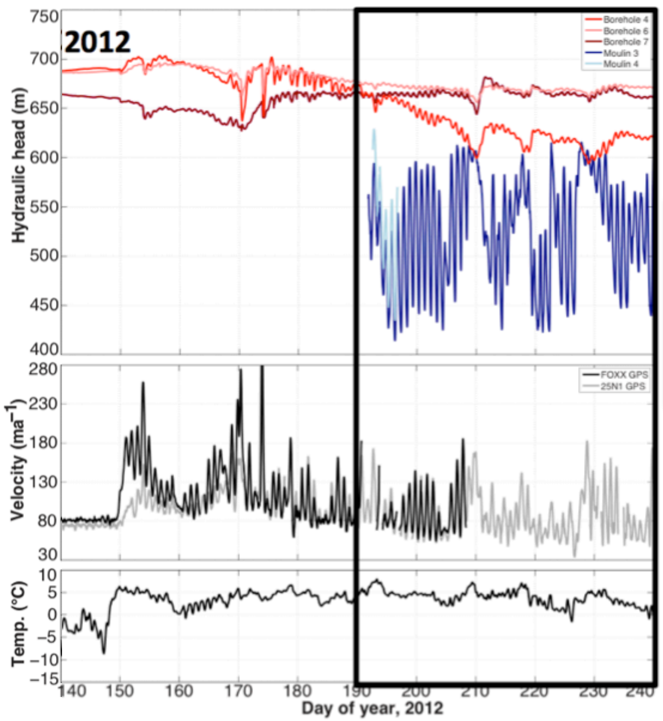


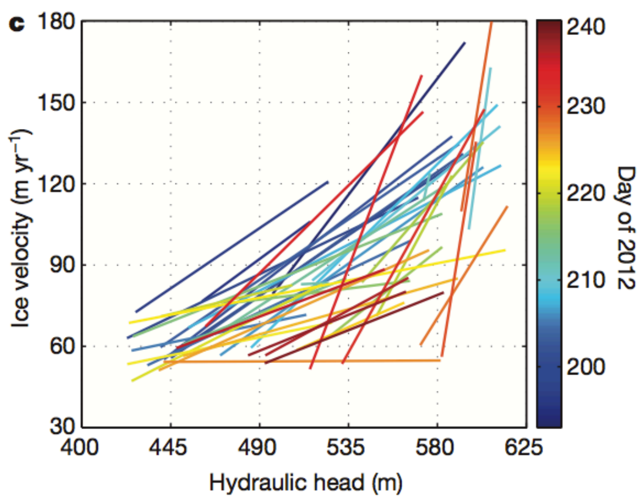

2. Cavity opening can induce out-of-phase pressure variations in isolated system.

3. Changing connectivity to isolated cavities can cause their pressure to drop over summer.

1. Channelized system reaches quasi-steady state by midsummer and then stops growing.

# Observations

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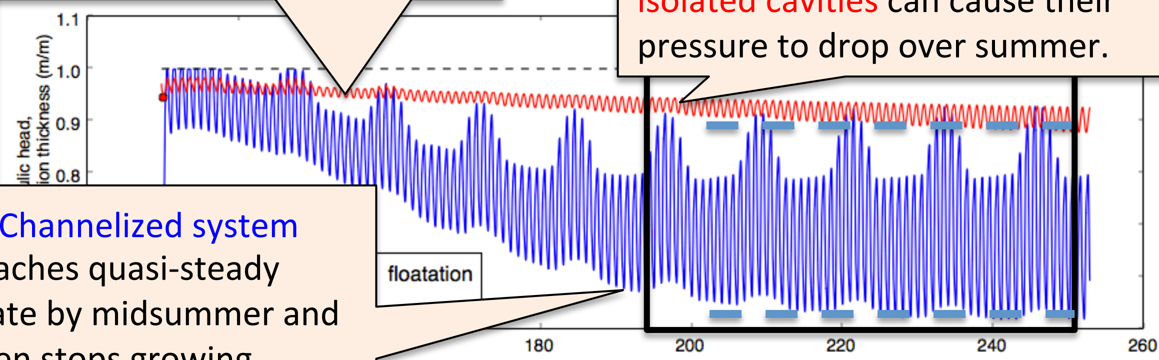
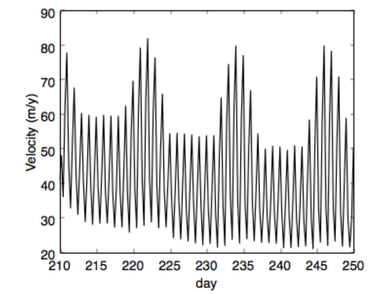



1. Channelized system reaches quasi-steady state by midsummer and then stops growing.

Use CISM2.0* with Coulomb friction law (Schoof 2005) to calculate ice velocity:
Offline forcing with effective pressure field weighted between isolated (75%) and connected (25%) systems.
*http://oceans11.lanl.gov/cism/*



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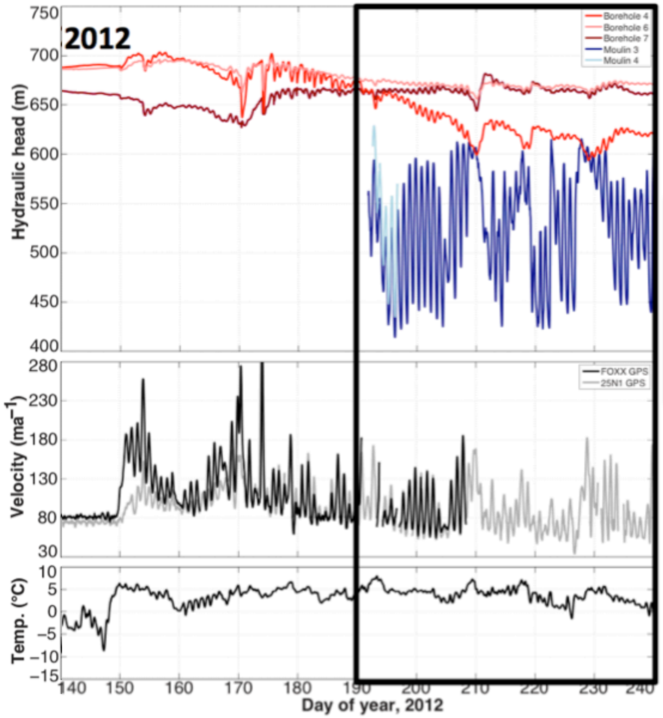


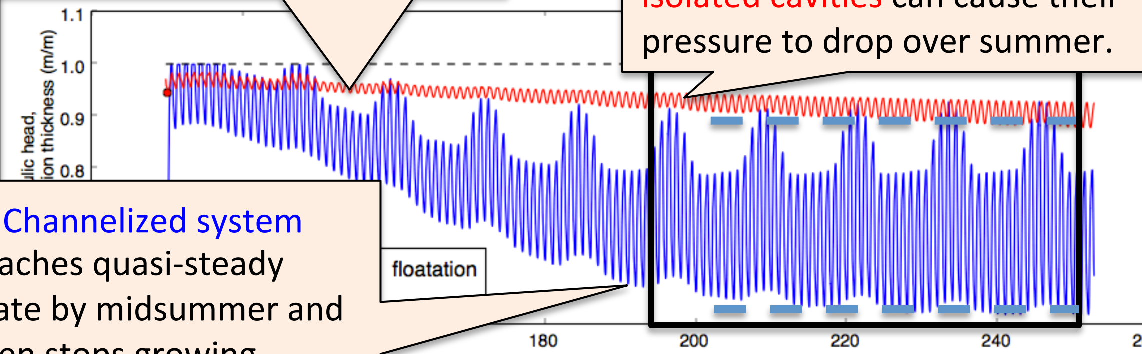


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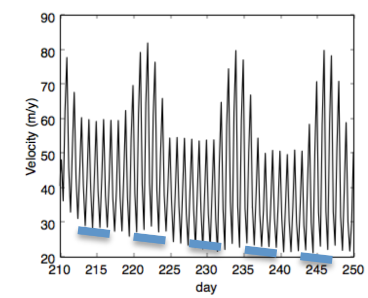
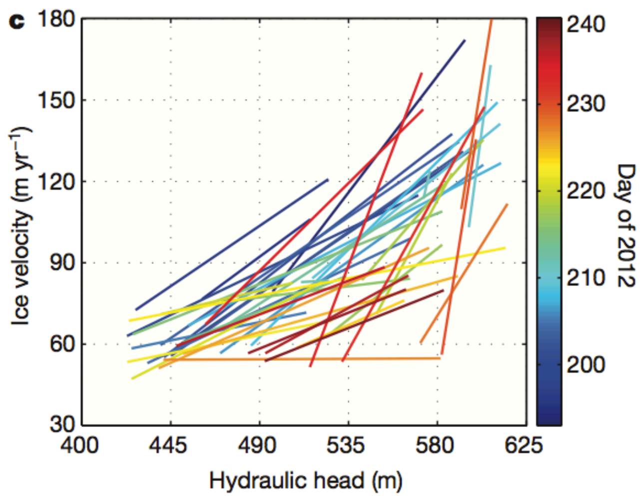
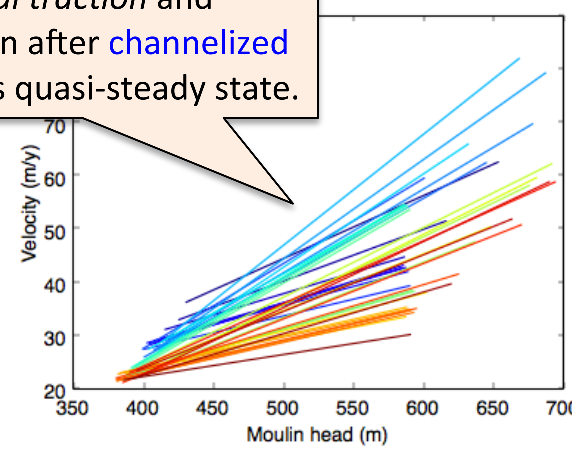


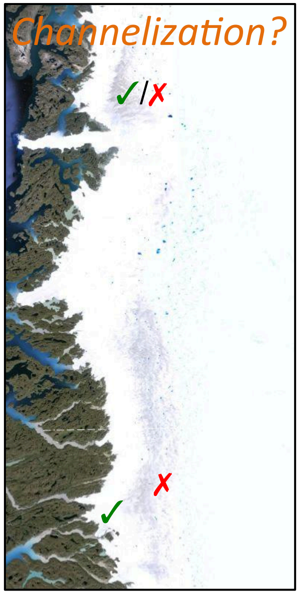




4. Lowering pressure in isolated system can result in increase of *integrated basal traction* and slowdown, even after channelized system reaches quasi-steady state.



# Summary

- Extent of channelization in west Greenland ablation zone appears to be highly variable.
  (depending on slope and surface melt rate / catchment size)
- Observations and Modeling support a 3-component hydrology model (Distributed, Channelized, Isolated) for Greenland.




# Questions

- How to assess variability in channelization in Greenland?
- Importance of isolated hydrology in mountain glaciers?
  Or does more extensive channelization 'swamp' these effects there?
- Can these subtleties be incorporated into ice sheet models in a meaningful way?