* Response of ice motion to tidally influenced subglacial hydraulic systems

Wais'er's delight!

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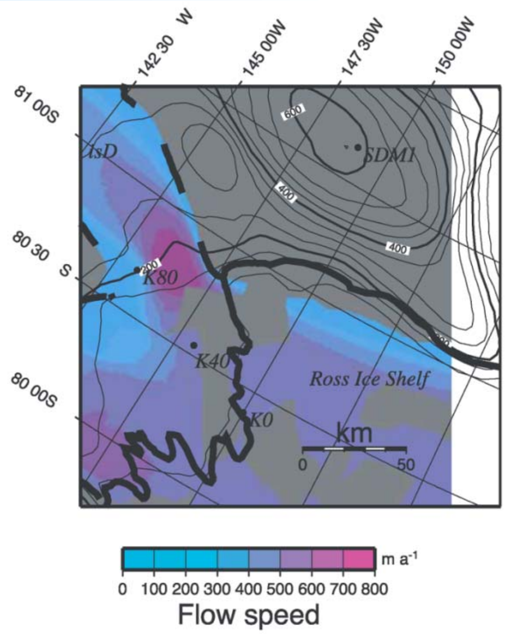
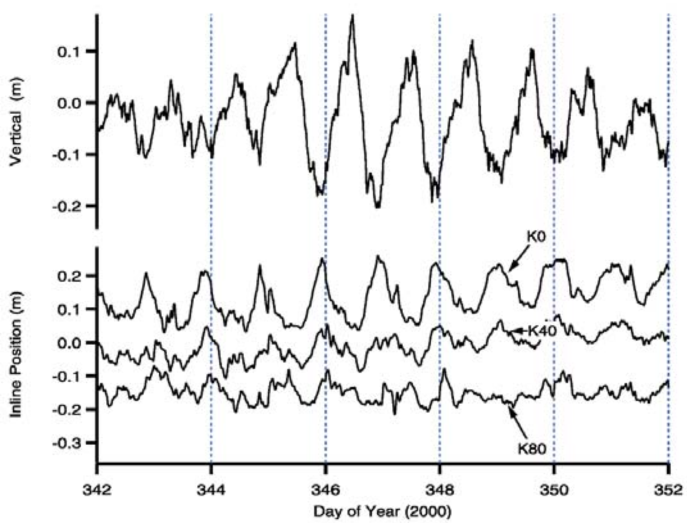
* Responses: Siple Coast





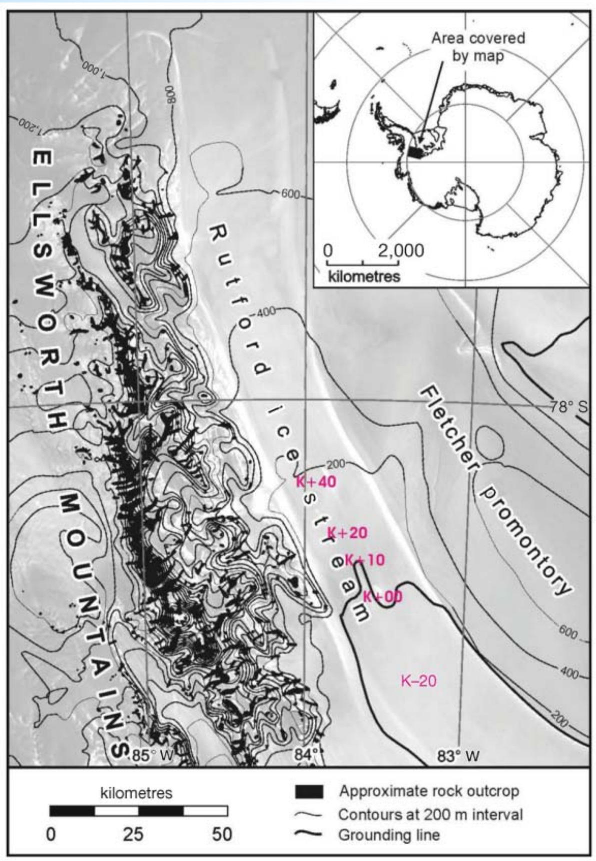
Anandakrishnan and Alley, 2003

Range of behaviors in tidal responses:

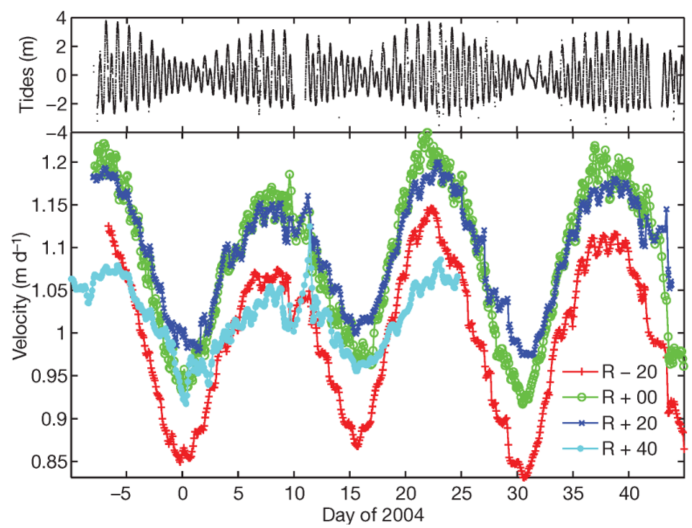
- Stick Slip on Whillans (Tulaczyk & Winberry talks on Monday)
    - Response at both low and high tides
- Velocity variations on Bindschadler Ice Stream (ISD)
- Seismic response (but no slip) on Kamb Ice Stream
- Highly likely that most of the ice streams exhibit responses as well as the outlet glaciers throught the Transantarctics

For the Siple Coast, Much work has been done and numerous papers:
Anandakrishan and Alley, (1997,2003) and Anandakrishnan, 1997, Bindschadler et al, 2003, Also papers by P. Winberry + coauthors, O. Sergienko, …. Lots of WAIS'ers!

* Responses: Rutford

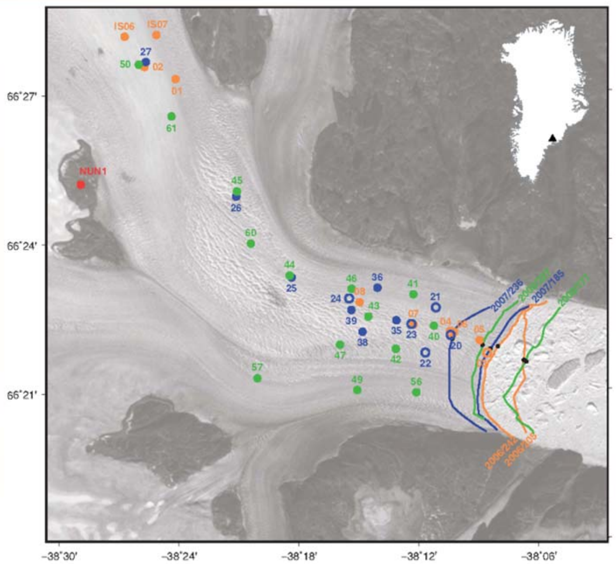


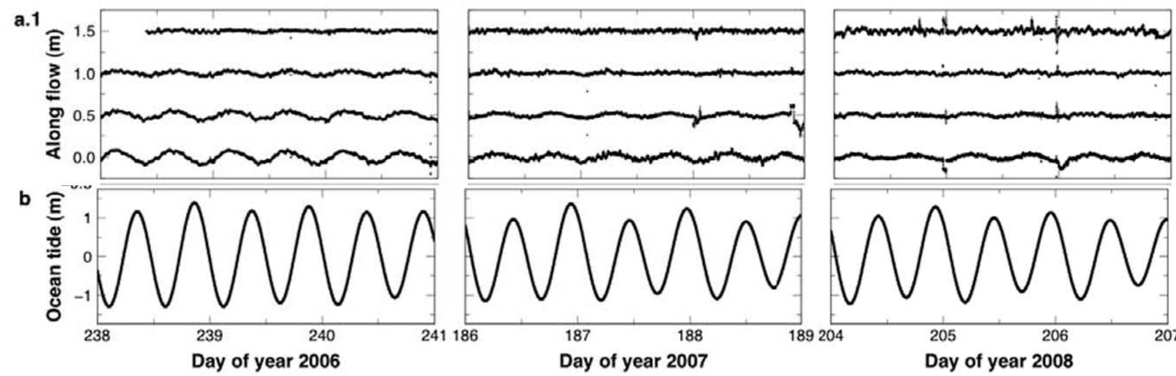
Gudmundsson, 2006



* Diurnal tides with power in three components
  * 2 Diurnal
  * 1 Fortnightly (2 week)
* The ice stream filters out much of the diurnal response
* The fortnightly response is strongest
* True headscratcher!

* Responses: Helheim





De Juan et al, JGRES, submitted

* 3 years of GPS data: 2006, 2007, 2008
* Tidal response in the along flow, cross flow, and vertical position
* Decays upstream
* Initiation of the velocity on the falling tide
* Maximum displacement on the low tide
* Does *not* correspond to a thin plate because there is no shelf

* Similar results for Store Gletscher, Greeland:
  * **Initiation of the velocity on the falling tide**
  * **Maximum displacement on the low tide**

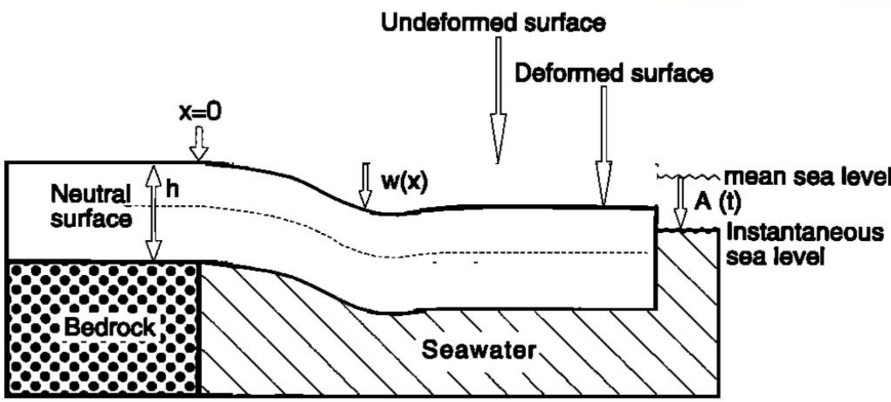
* Responses: general

* *Things that matter*
* Movement
  * Particularly on the low tide
* Diurnal signals
* Lagged responses

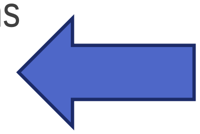
* *Things that might matter*
* Seismicity only (Kamb)
* Large stick-slip areas

* Types of models

* Thin plate/beam:
  * Elastic thin plate for ice shelves: Holdsworth '69, Vaughan '95,
  * Adapted for an ice stream on till Anandakrishnan and Alley '97,
  * Viscoelastic thin plate, Walker et al, 2013
  * Coupled V-E thin plate: Walker et al, this meeting
* Velocity-based
  * Gudmundsson, 2007, King et al, 2010
* Stokes flow with extra basal conditions
  * Gudmundsson, 2011
* Moving grounding line (Extra ODE)
  * Elastic: Sayaig and Worster, 2011
  * Stokes Flow: Schoof, 2011
* Hydrologic effects
  * Laminar: Anandakrishnan and Alley, 1997
  * This study

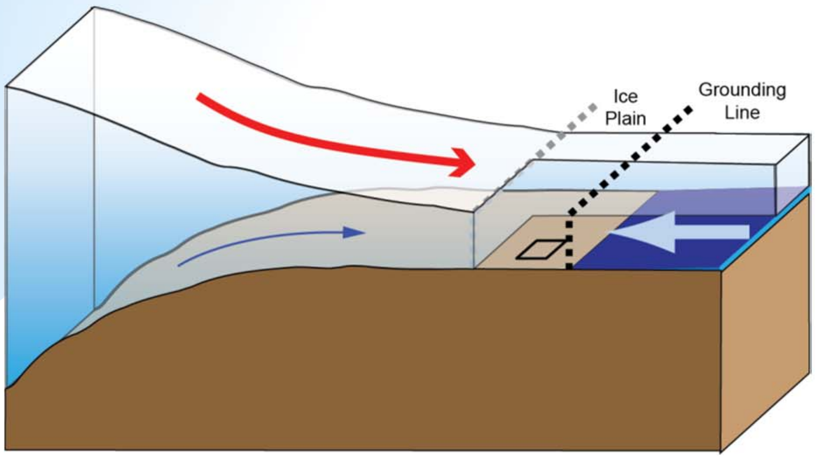


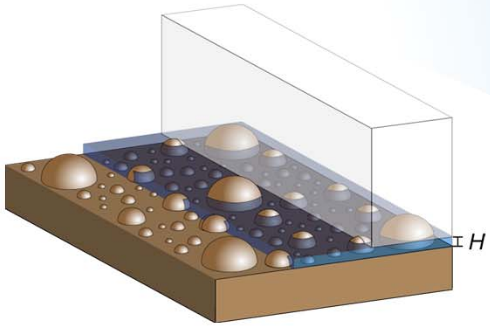
Vaughan 1995



- Arguably the most complex glaciologically
- Power law slip
- Hydrology Agnostic (no drainage)
- Really cool deformation results from this model

Hydrologic model



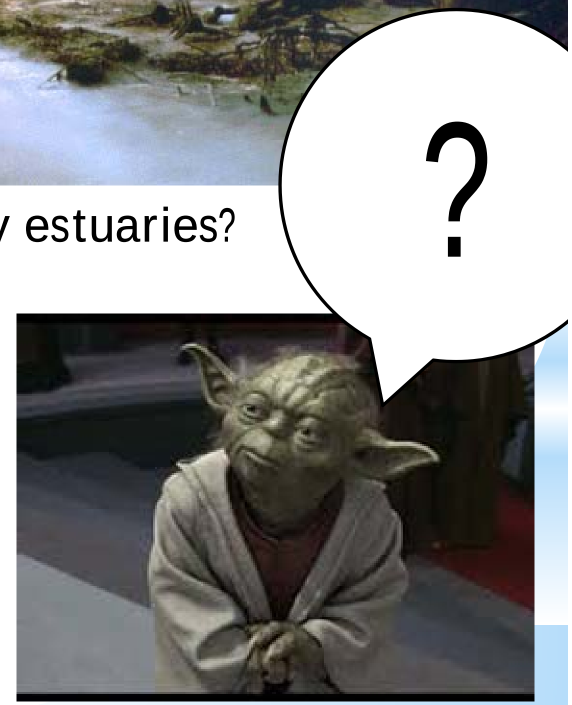


- A distributed water system forced by the tides from downstream
- Do not want to deal with specific pathways (yet)
- Yes, they exist, but I'm ignoring them
- Low Grounding line amplitude in order to move water upstream
- High local hydraulic conductivity to be able to move water through a basal system
  - Obvious water drainage features (now)

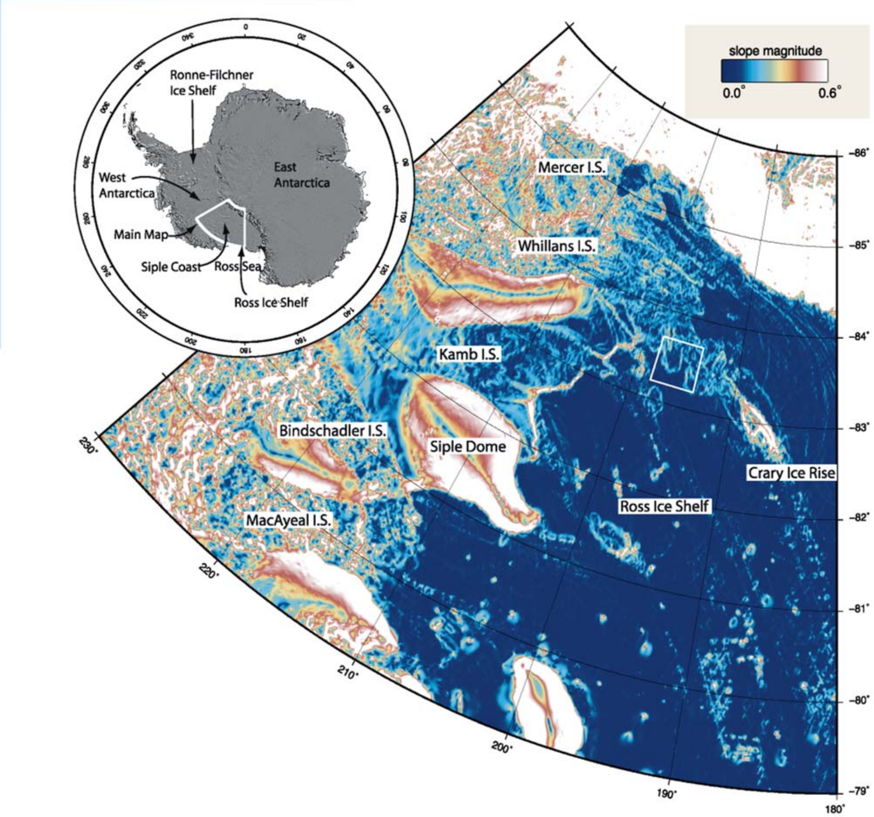
* Hydrologic Model

Drainage with no free surface

Swampy estuaries?



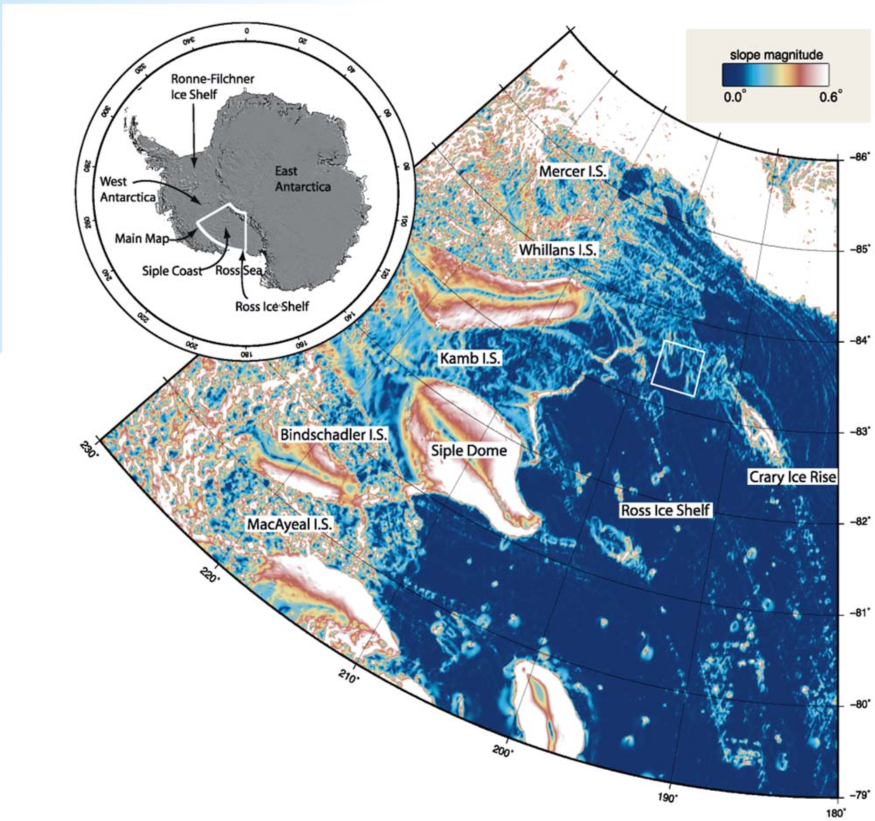
* Low slope areas

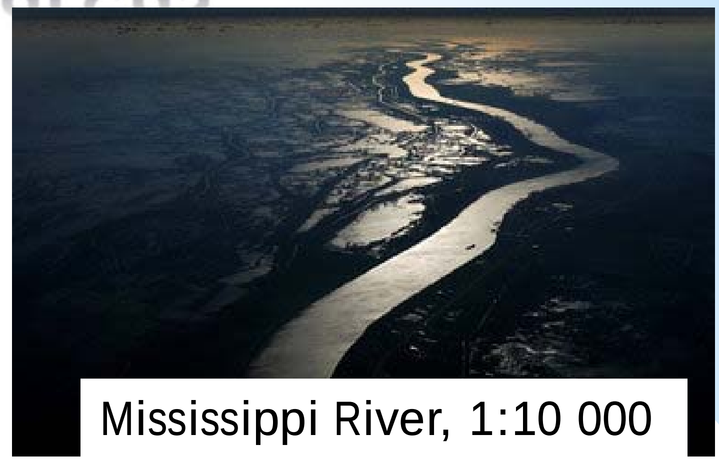


Horgan and Anandakrishnan, 2006

* Steep slopes on Kamb IS lessen the chances of moving pressure pulses upstream
* Do not necessarily need return flow because pressure travels much faster than water discharge.

Low slope areas





Mississippi River, 1:10 000

- Lower Siple Coast, 1:100 000
- Hydraulically super duper flat

Lower Tigris & Euphrates, 1:27 000

* Model formulation

$$\psi = \rho_{\mathrm{w}} g z_b + p_{\mathrm{w}}$$
$$= \rho_{\mathrm{w}} g z_b + \sigma_{\mathrm{i}} - N$$

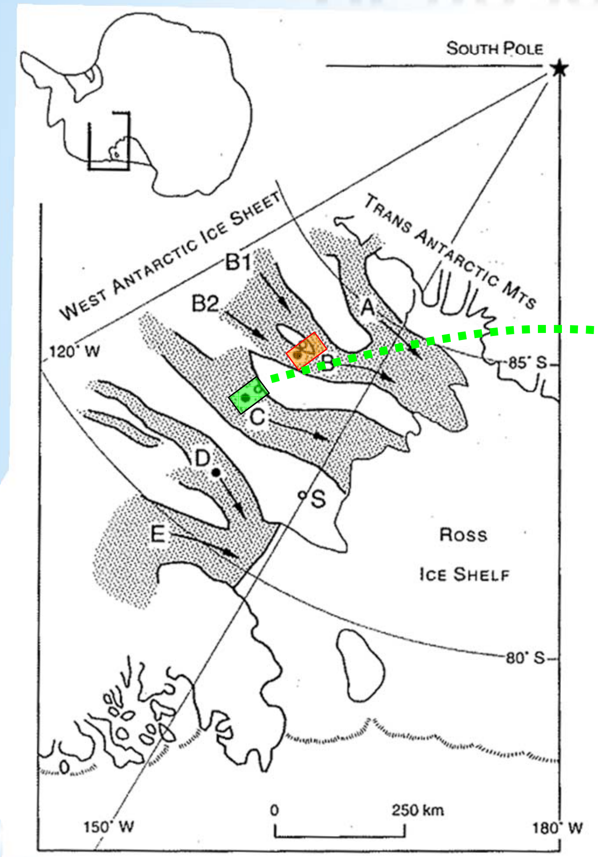
$$N = \sigma_{\mathrm{i}} - p_{\mathrm{w}}$$

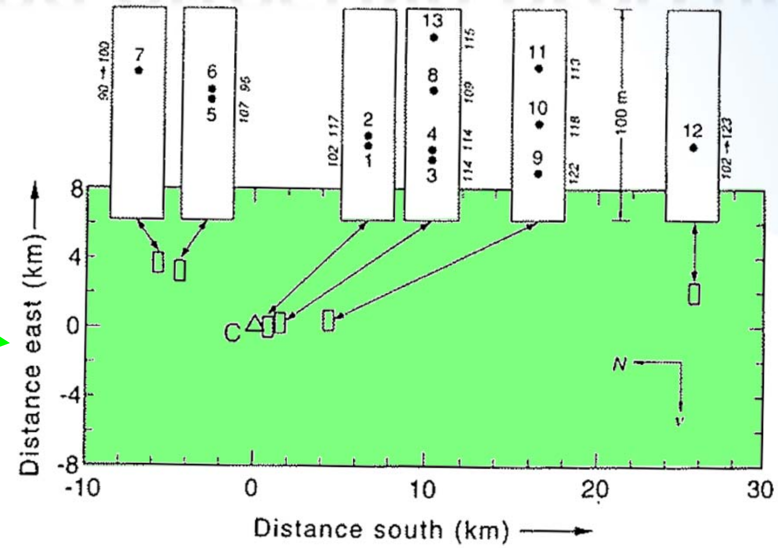
$$\tau_c = N \tan\phi + c_a$$

* Hydraulic Potential
  * Bed slope info + water pressure
* Effective pressure
* Assume a Coulomb plastic bed

<u>How important is effective pressure?</u>

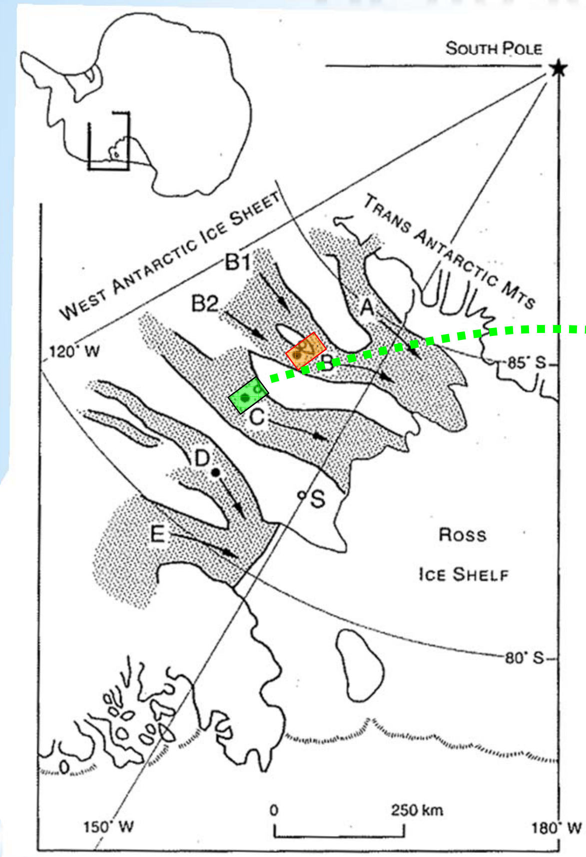
Drainage and effective pressure

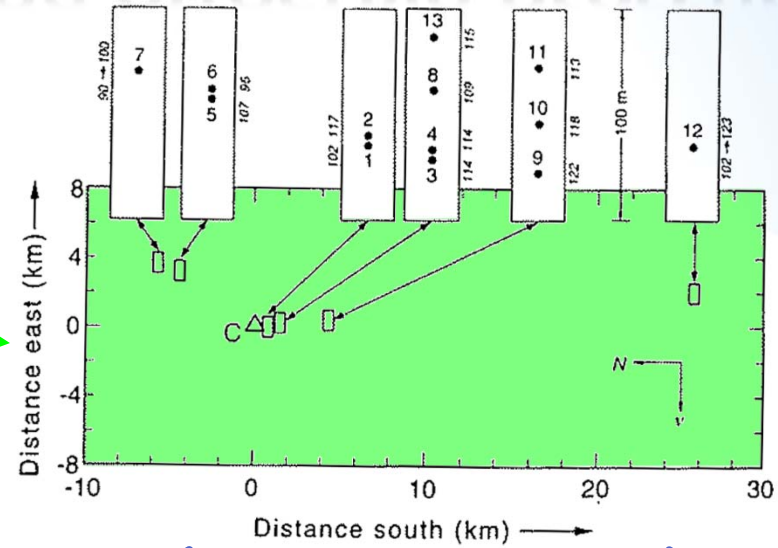




- Kamb (2001) reported data on effective pressure from >40 boreholes in contact with the bed.
- Effective pressure range:
  - -1×10^5 to 1.7×10^5 Pa
  - (<2% of ice overburden)
- These effective pressures are small relative to ice thickness.

* Drainage and effective pressure





Maximum ice overburden pressure gradient ~ 44 Pa/m

Maximum effective pressure gradient ~ 22 Pa/m

- ***<u>Effective pressure is not negligible based on existing data in West Antarctica</u>***

* Model formulation

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$$= \rho_{\mathrm{w}} g z_b + \sigma_{\mathrm{i}} - N$$

* Hydraulic Potential
  * Bed slope info + water pressure

$$N = \sigma_{\mathrm{i}} - p_{\mathrm{w}}$$

* Effective pressure

$$\tau_c = N \tan\phi + c_a$$

* Assume a Coulomb plastic bed

$$\frac{\partial p}{\partial t} = -\frac{1}{\gamma} \nabla \cdot u$$

* Water mass balance: compressibility formulation

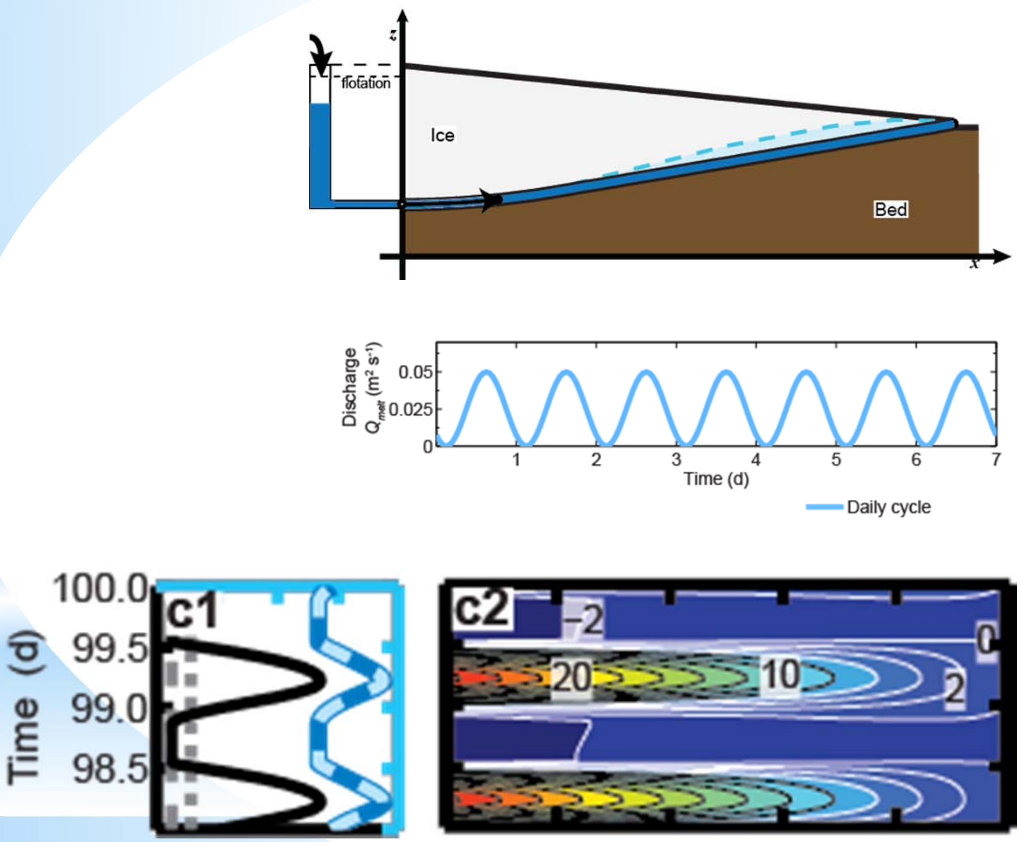
$$u = -\sqrt{\frac{4H}{\rho_{\mathrm{w}} f_d}} \left| \frac{\partial \psi}{\partial x} \right|^{-1/2} \frac{\partial \psi}{\partial x}$$

* Water velocity

$$p = \overline{p} + p' \exp(i\omega t + kx)$$
$$\psi = \overline{\psi} + \psi' \exp(i\omega t + kx)$$

* Perturb the system via a tidal pressure at the grounding line

Digression on pressure



Creyts et al, 2013

* For an overdeepening that has a diurnal, sinusoid of water input ...
* Using a similar model
* The water pressures do not equilibrate over a diurnal cycle
* For this case, there are negative effective pressures

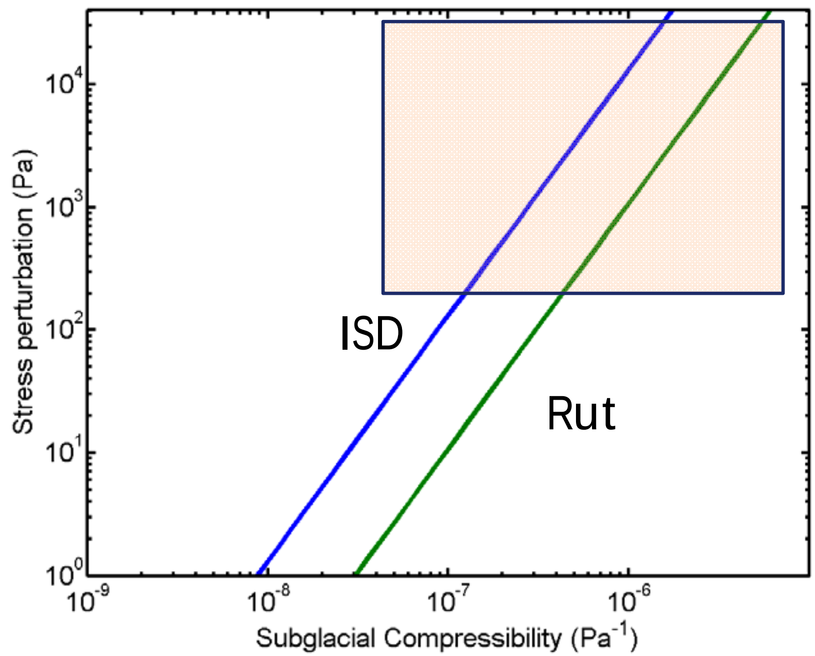
* After some fiddling with the equations

$$\psi' = 4k^{-3}\frac{\rho_{\mathrm{w}} f_d}{4H}\left(\gamma\omega p'\right)^2$$

* The perturbed hydraulic potential is dependent on a few parameters that are either known, such as pressure perturbation at the grounding line
* Or can be guessed such as water depth, H

* H=0.01 m,
* k=40 km,
* water density=1000 kg m-3,
* fd=0.16

* Model: simple results



$$\psi' = 4k^{-3}\frac{\rho_{\mathrm{w}} f_d}{4H}\left(\gamma\omega p'\right)^2$$

- Compressibility winds up being the only adjustable parameter

- Use 1 m tides for Bindschadler IS, Diurnal
- Use 4 m tides for Rutford, fortnightly signal
- Subglacial compressibility is in a reasonable range for the physical system

Conclusions

- Many responses of tidally forced systems
  - Some are consistent regardless of whether there is a shelf
  - Falling tide seems to matter (A lot)
- Wealth of information to be learned
- The tides act to probe the ice sheet and tell us about responses
- Water pressure plays a role in the slip condition
  - Not necessarily water flux
- A >really< simple model seems to capture some portion of the system dynamics fairly well

*Outlook

* Up next: 2D solution
* With water flow
  * Stripped down Creyts-Schoof hydrology
* Work with till characteristics

* Thanks to: NSF OPP for funding
* Meeting organizers, and the many scientists I’ve talked to about this