Better subglacial hydrology into the Parallel Ice Sheet Model

a work in progress

Ed Bueler* and Ward van Pelt†

*University of Alaska Fairbanks

†IMAU, Utrecht, Netherlands

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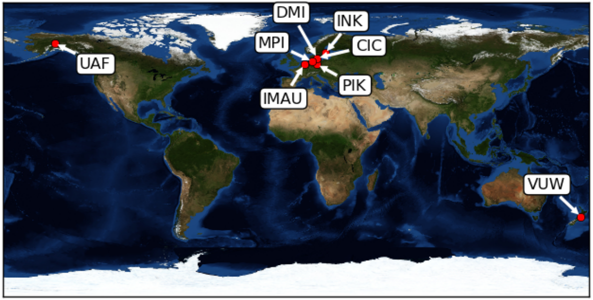
PISM = Parallel Ice Sheet Model



- www.pism-docs.org and help@pism-docs.org
- runs on laptops to supercomputers
- documented releases once a year
- *User's Manual* with real modeling examples including Greenland Ice Sheet, Ross Ice Shelf, and Störglaciaren

- supported by the NASA Modeling, Analysis and Prediction

- jointly developed by UAF and Potsdam Inst. for Climate Impact Research

why we need better subglacial hydrology

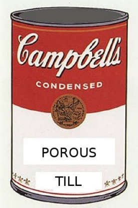
motivation 1

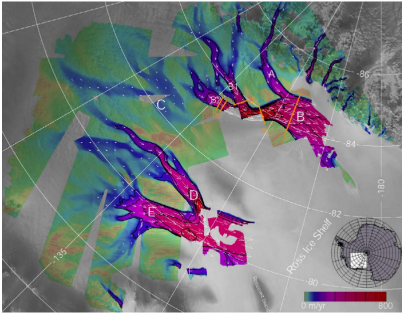
we are **NOT** conserving mass (of liquid water)

- current basal hydrology in PISM has an independent "can" of porous till at each location
  - "can" receives basal melt
  - "overflows" at 2m of water

    . . . *overflow lost*
  - provides till yield stress
  - suitable for Siple coast ice streams (Tulaczyk et al 2000)
- missing:

  lateral transport of water



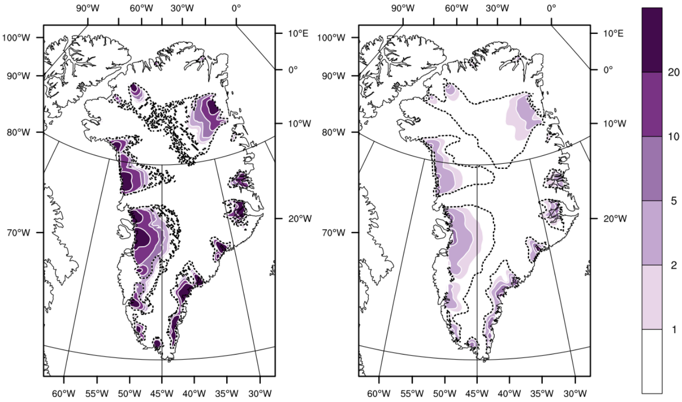


why we need better subglacial hydrology

motivation 2

we **ARE** conserving energy (better than before)

- better energy conservation using enthalpy
- new basal melt rate distribution ($\mathrm{mm\,a^{-1}}$):

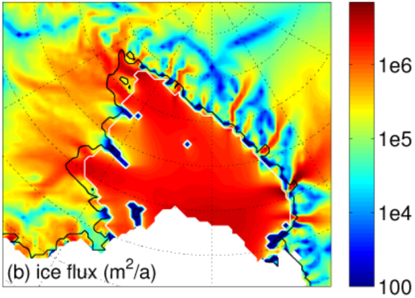


left: using enthalpy **right**: using temperature

Aschwanden et al (2012), *An enthalpy formulation for glaciers and ice sheets*, J. Glaciol.

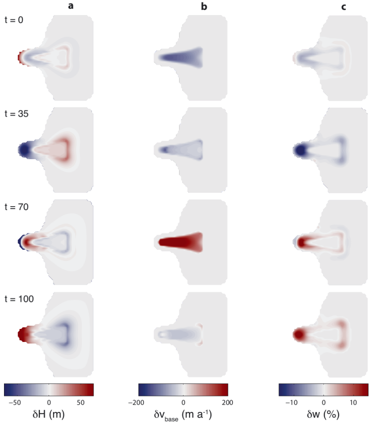
example existing uses of PISM subglacial hydrology

model locations of Antarctic ice streams without inversion



(Martin et al., 2011, *The Cryosphere*)

study sliding and cyclicity/surging



(van Pelt & Oerlemans, 2012, *J. Glaciol.*)

the goal

improve PISM by adding mass-conserving subglacial hydrology

subgoals:

1. provide reasonable default behavior
2. introduce minimum number of new tunable parameters
3. provide playground for testing sliding models

elements of subglacial hydrology

can we agree on these?

- **conservation of mass**:

$$W_t + \nabla \cdot \mathbf{q} = m/\rho_w$$

where W = spatially-averaged thickness of water layer, $\mathbf{q}$ = flux, m = supply rate ($\mathrm{kg\,m^{-2}\,s^{-1}}$)

- **hydraulic potential** for top of water sheet:

$$\phi = p_w + \rho_w g(b+W)$$

where ϕ = hydraulic potential, b = bedrock elevation

- **some kind of Darcy flow**:

$$\mathbf{q} = -\frac{KW}{\rho_w g}\nabla\phi$$

where K = hydraulic conductivity (*not* constant in general)

or $\quad \mathbf{q} = -kW^\alpha |\nabla\phi|^{\beta-2}\nabla\phi \quad$ etc.

elements of subglacial hydrology

whence pressure?

- combine previous three equations to get one equation in two unknowns
    * water thickness W and pressure p_w are unknown
- an *closure* equation is needed to determine p_w

closure alternatives

- creep dominates so ice presses on water (classical?):

$$p_w = \rho_i g H$$

  - e.g. static subglacial lake
  - zero effective pressure
  - ...but we could try: $p_w = s\,\rho_i g H$ with $0 < s < 1$

- generates porous medium equation (Flowers & Clarke 2002):

$$p_w = \rho_i g H \left(\frac{W}{W_{\text{crit}}}\right)^{\gamma}$$

  - where $\gamma = 7/2$ and $W_{\text{crit}} = 0.1$ m, for example
  - e.g. on Trapridge Glacier

more closure alternatives

- physical models for opening and closure of a distributed system
  - evolution equation for [Y = average cavity depth] must be of the form (Hewitt, 2011)
  $$Y_t = W_O - W_C$$
    - W_O is total from opening processes (wall melt, sliding, . . .)
    - W_C is total from closing processes (ice creep, sedimentation, . . .)
  - indirectly determines water pressure p_w

- but wait: there are channels, too! (Röthlisberger 1972)

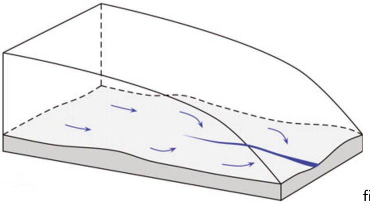
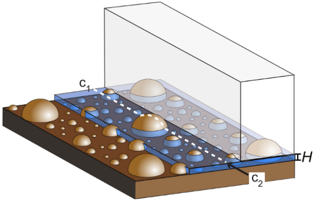


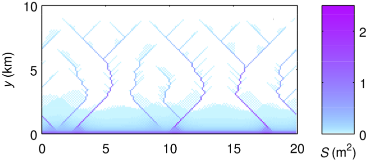
figure from (Hewitt, 2011)

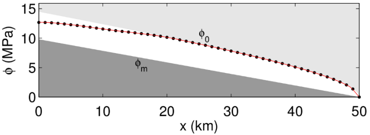
yet more alternatives

…from Vancouver, B.C. area as usual

- Creyts & Schoof (2009): bed protrusions stabilize sheet flow
  - vs Walder (1982): sheet flow unstable
- Schoof (2010): fixed-location 2D network of channels
  - grid-refinement limit not known?
- Hewitt & Schoof & Werder (2012):
  - water pressure bounds: $0 \le p_w \le \rho_i g H$
  - elliptic variational inequality for p_w
  - large areas where $p_w = \rho_i g H$ anyway?







too many tunable parameters!

- we hope to explore above possibilities in PISM
- but it has finally dawned on us:

exploring processes through modeling is different from improving default behavior for ice sheet simulation

back to something basic

- recall the simple model where creep dominates:

$$p_w = \rho_i g H$$

- hydraulic potential:

$$\phi = \rho_i g H + \rho_w g(b + W) = \rho_i g\, h + (\rho_w - \rho_i) g\, b + \rho_w g\, W$$

- combining all equations gives:

$$\boxed{W_t + \nabla \cdot (\mathbf{v} W) = \nabla \cdot (K W \nabla W) + m/\rho_w}$$

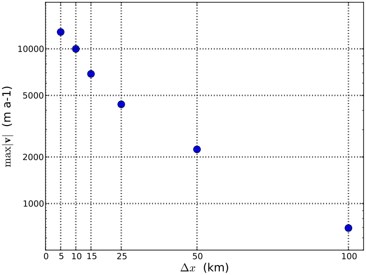
  * $\mathbf{v} = -K\left[r \nabla h + (1 - r) \nabla b\right]$ where $r = \rho_i/\rho_w$
  * an advection-diffusion equation

velocity and time scales in the "basic" model

- velocity from spatial gradients of elevations:

$$\mathbf{v} = -K\Big[r\nabla h + (1-r)\nabla b\Big]$$

- what happens with real data (*ALBMAPv1*) for $h(x,y)$ and $b(x,y)$?

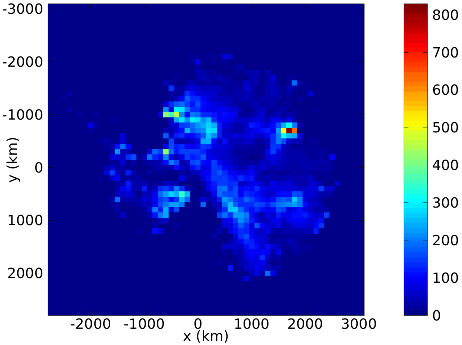


  * may need a regularization (smoothing or cap) on $\mathbf{v}$

- diffusivity $D = KW$ small but K uncertain …another regularization?

toy Antarctic Ice Sheet example

- toy *Matlab* results: uniform 1 cm a^{-1} melt rate, 20ka run



  - far too much water (PISM run would give mostly frozen bed ...)
  - convergence under grid refinement evident (100km, 50km, 25km)
- Johnson (2002) studied distribution of subglacial lakes with related model

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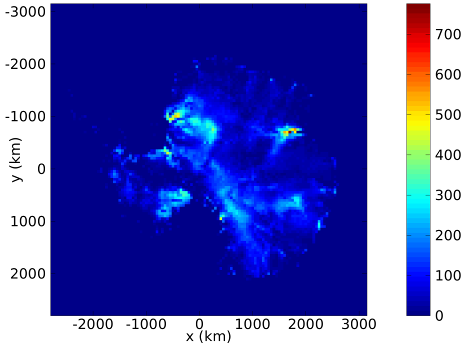

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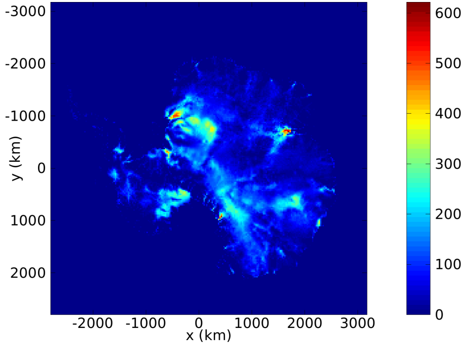

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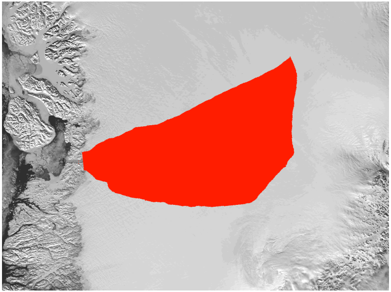
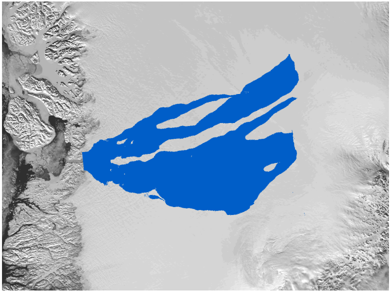
practical benefit with the basic model

- **report the amount of subglacial water delivered at each outlet**
- . . . as we can already report the amount of ice delivered at an outlet, through automatic identification of "drainage basins"
  - e.g. Jakobshavn basins below



basin for $-\nabla h$ flow,

for ice



basin for $-\nabla \phi$ flow,
where $\phi = \rho_i g H + \rho_w g b$,
for subglacial water

summary

- we will put the "basic" model in PISM
  - mass conservation
  - numerical stability provable for low-order scheme
  - allows (needs?) over-regularization
  - degree of coupling to sliding: needs exploration
- next: extend basic model to more dynamic subglacial drainage systems
  - nontrivial job: wall melt and channelization (*as we all know*)
  - the 2D spatial averages must be captured
- we are aware of the danger of building a model whose parameters cannot be identified
  - too much depends on surface observations of flow

Thanks for help with figures: Andy Aschwanden, Sarah Child, Brad Gooch