PISM, a Parallel Ice Sheet Model

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Outline

What are we modeling?

Why model ice sheets now?

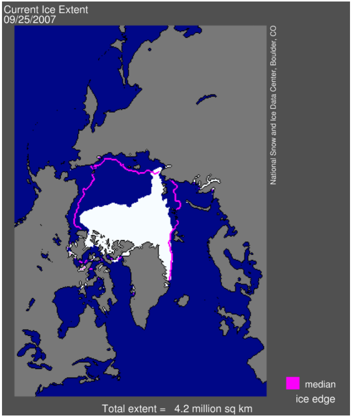
How do you model ice sheets? What's hard?

Evaluating PISM: several meanings of "performance"

Conclusion

NOT!: floating, short-lived sea ice

- modeling sea ice is important for climate prediction (*it couples to arctic atmospheric, and ocean, energy balance/circulation*)
- but sea ice has no direct effect on sea level (small indirect effects)



Sea ice extent for Sept 25, 2007. Magenta line shows the median Sept monthly extent (1979 to 2000).

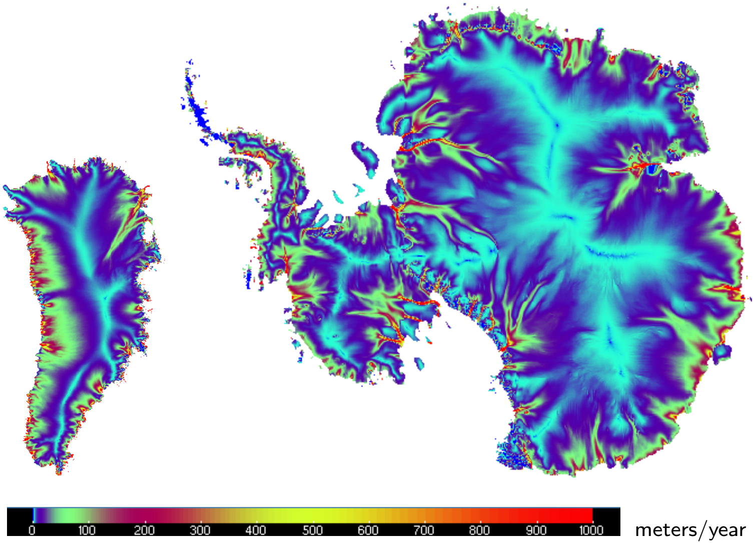
Glaciers and ice sheets

- earth has about $29 \times 10^6 \text{km}^3$ of ice sitting on land
- equivalent to about 76 m = 250 ft of sea level rise (*if it all melted completely; not likely!*)
- mostly in two ice sheets: Antarctica (90.3%) and Greenland (9.2%)
- year-to-year view: sits there
- longer view: flows
- meaning of "longer view" depends on how warm the climate is!

Edge of the Greenland ice sheet; "Polaris glacier", Hall Land, NW Greenland *(Post & LaChappelle 2000)*

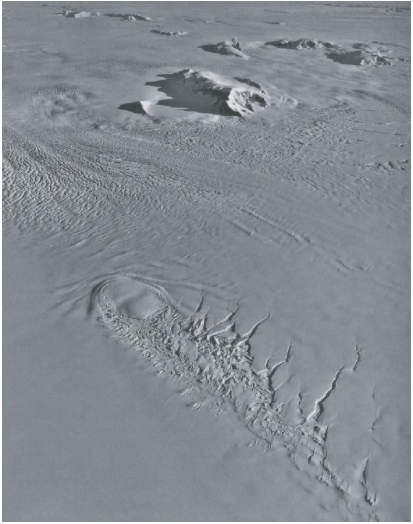
(*middle* of an ice sheet is "the most monotonous scenery on earth"!)

Highly variable flow speeds



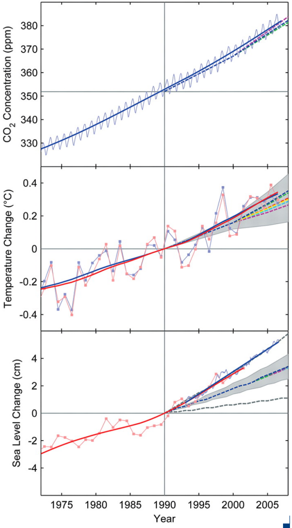
(balance velocities from J. Bamber (Greenland) and D. Vaughan (Antarctica); NOT a PISM model result)

Sticking *or* sliding flow



Climate change versus climate model abilities

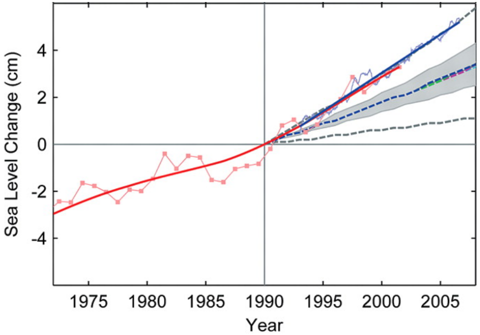
- world has 2 or 3 decades of (supercomputer-based) climate prediction experience
- ~ 10 (worldwide) existing GC models include: *atmospheric circulation, atmospheric chemistry, ocean circulation, sea ice mechanics, land types (w associated surface gas/water balances), human source models, . . .*
- none include land ice flow
- comparing 1990 predictions to last ~ 15 years of data has lessons . . .



Rahmstorf and others (2007) *Science*

Sea level prediction: another look . . .

- sea level in last 15 years is *not* erratic
- it is steadily increasing
- it is increasing at rate far outside model uncertainty range of IPCC scenarios (grey shading)

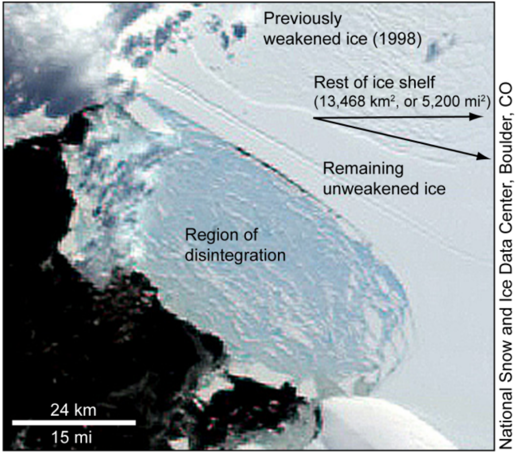


- Rahmstorf et al. note "Sea level closely follows the upper gray dashed line, the upper limit referred to by IPCC [2001] as 'including land-ice uncertainty.' "

Ice sheets are changing *now* in three new ways

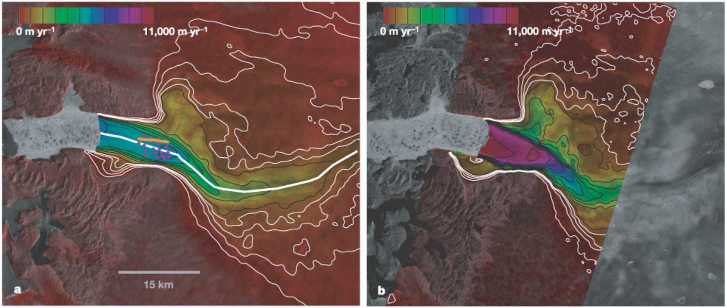
- ice shelf & "floating tongue" breakup: Jacobshavn (last 15 years), Larsen B shelf (2002), Wilkins shelf (last month)
- acceleration of ice streams and outlet glaciers, which is sometimes clearly linked to above
- surface melt ponds draining to bed in Greenland, causing apparent basal lubrication and observed flow acceleration

Ice shelf breakup



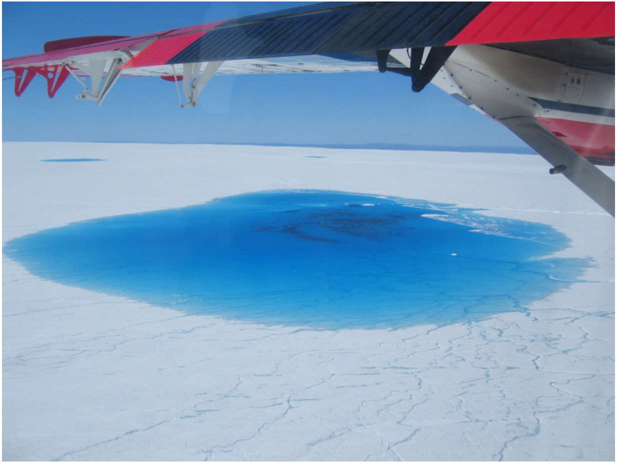
partial breakup of Wilkins ice shelf; MODIS image 6 March 2008; disintegration area is 160 square miles

Outlet glacier acceleration following floating tongue breakup



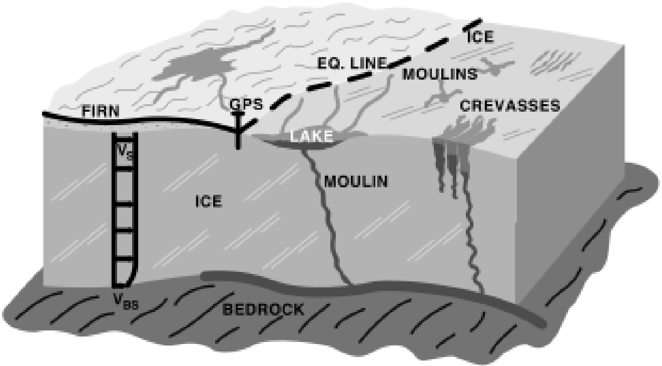
comparison of observed Jakoshavn isbrae, Greenland flow speeds in 1992 (left) and 2000 (right), from (Joughin et al 2004)

Surface melt ponds in Greenland



source: Sarah Das, Woods Hole (website)

Importance of melt ponds



source: Zwally et al 2002

Flow in ice sheets, streams, & shelves: basic facts

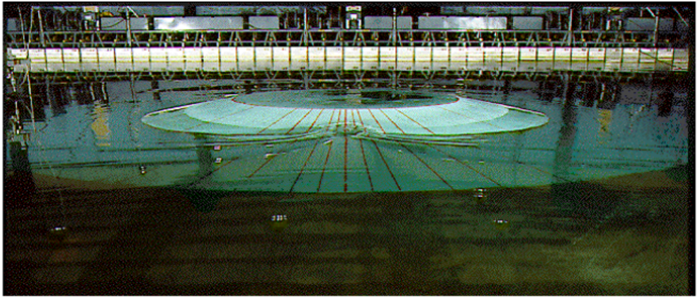
- it is computational fluid dynamics (CFD), but a highly unusual case
- ice flow, *unlike* ocean and atmosphere, is slow (*inertial force can be tossed out*)
- ice sheets are as shallow as a piece of paper!
- incompressible like oceans
- upper surface of ice is free to move; finding domain of flow is part of the problem
- "flow law" is wildly nonlinear (while linear for ocean and atmosphere)
- ice is a solid near its melting point; softness of ice depends strongly on temperature and there is strain heating feedback
- ice flow is coupled to mantle flow! ("isostatic rebound")

Fluids “context”: Lack of good observations

- hard to measure ice temperature
- flow depends strongly on ice/bed interface mechanics, which is nearly unobservable
- time scale for interesting flow behavior is long, so we have seen just a snapshot in time in 50 years of modern observation
- observability intermediate between *earth’s interior* (harder to observe) and *ocean circulation* (easier to observe)

Fluids "context": Lack of physical scale models

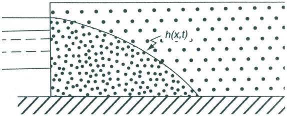
wouldn't it be nice to validate numerical ice sheet models with something like this:



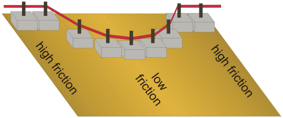
(wavetank for simulating tsunami runup on a conical island)

PISM approximates lots of continuum eqns . . .

- instead of listing equations, here are simpler systems
- ice behaves like each of these; PISM solves equations like each of these in parallel



porous medium equation ($\sim$ isothermal ice sheet)



sliders and (nonlinear) springs ($\sim$ ice stream)

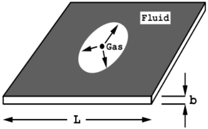


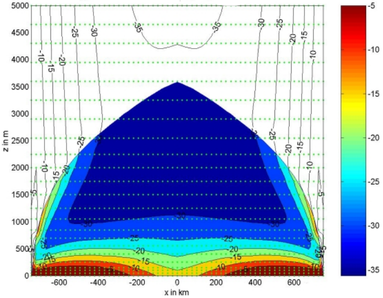
Figure 1: Hele-Shaw cell

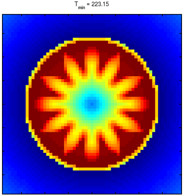
Hele-Shaw flow ($\sim$ thermo-coupled ice sheet)

thin layer of oil on water ($\sim$ ice shelf)

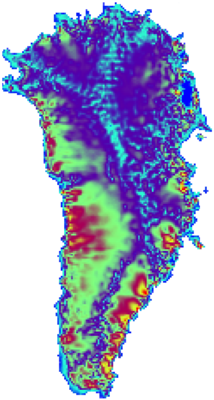
Temperature-dependent ice flow can be unstable

- basal boundary layer of temperate ice (close to melting point)
- thin layer of soft ice underneath a thick strong cap
- soft ice "squirts" out from underneath strong cap
- strain heating feeds back to maintain "squirting"
- like Hele-Shaw gas-squirted-into-liquid instability

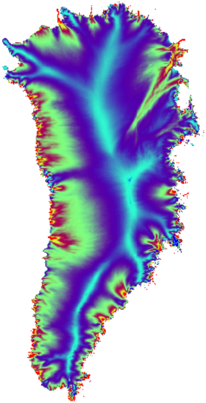




PISM applied to Greenland ice sheet



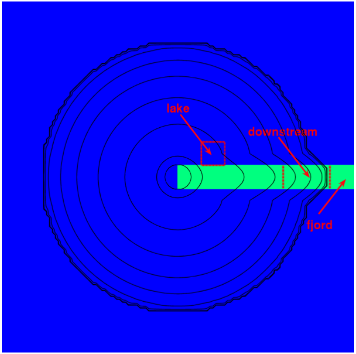
preliminary PISM result on 10km grid



balance velocites on 5km grid (not observed velocity; minimally processed surface mass balance)

meters/year

experiment: ice streams with "plastic till". . .



green strip has till friction angle $\phi = 5^\circ$

blue area has $\phi = 20^\circ$

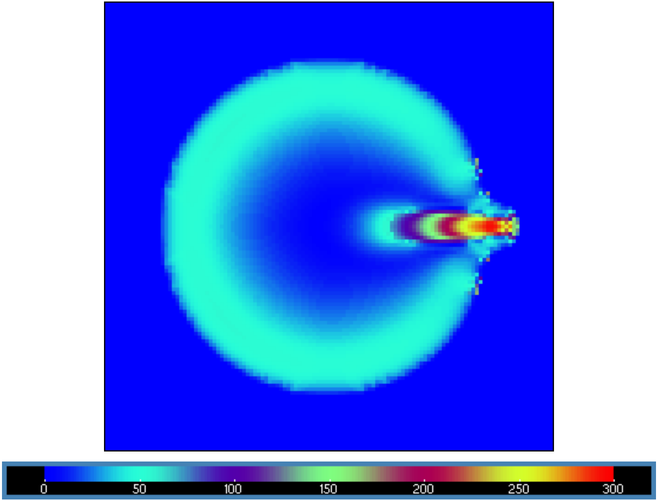
contours show ice thickness

("lake", "downstream", and "fjord" apply to particular experiments; later)

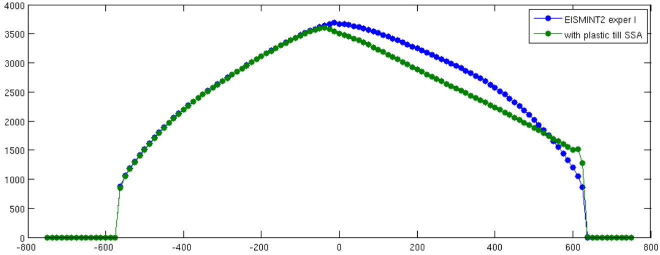
- till yield stress is strength of saturated silt/sand/gravel under ice
- yield stress is $(\tan\phi)(\rho g H - p_w)$ where ϕ is till "friction angle"
- antlion trap illustrates "friction angle" $\Longrightarrow$
- beaches on Tanana River illustrate saturated till weakness

result is steady sliding flow balanced by membrane stresses

vertically-averaged horizontal velocity:

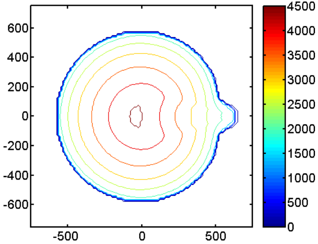


ice thickness

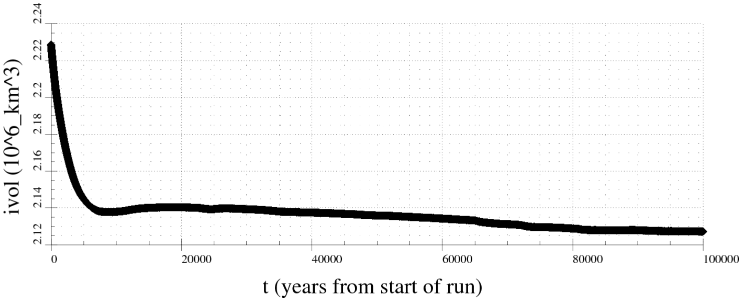


Above: ice thickness along centerline of trough (x-axis)

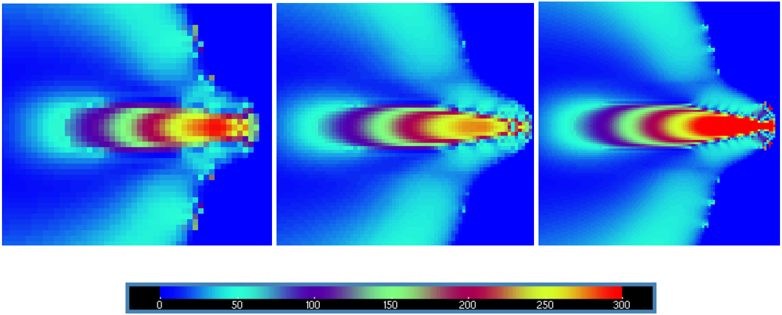
Right: surface elevation contours for plastic till SSA version



total ice volume over 100,000 year run on 12.5km grid



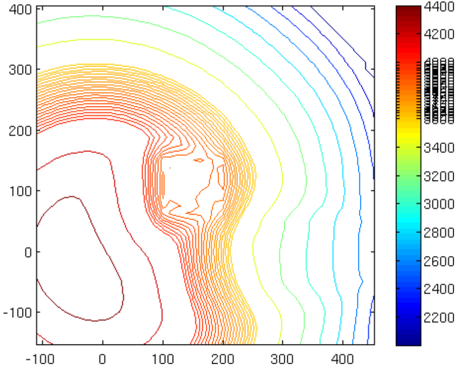
ice stream detail: 12.5 km, 7.5km, and 5km grids

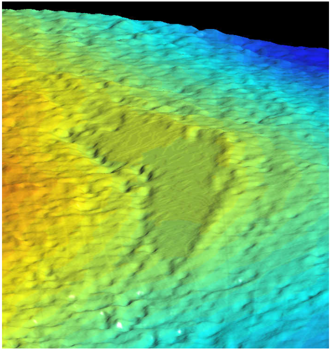


common velocity scale (m/a)

- each shown at 5k model years after start of sliding
- weak till strip is 100km wide but ice stream narrows dynamically
- about 5000 processor-hours for 5km grid result (`midnight`)

“Lake” result: surface elevation





Left: Detail of surface topography above $\theta = 0°$ till “lake” in experiment P4. Contours every 20 m between 3600 m and 4000 m.

Right: a perspective view of the ice surface above Lake Vostok compiled from ERS-1 radar altimeter data provided by the National Snow and Ice Data Center. Lake Vostok is the flat, featureless area. From Michael Studinger’s web page.

PISM = Parallel Ice Sheet Model

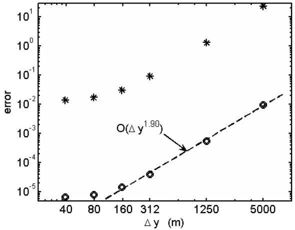
- open source; project hosting at `https://gna.org/projects/pism/`
- about 25,000 lines of our C++ code calling PETSC (calls MPI)
- documentation at www.pism-docs.org
- 75 page *User's Manual* includes how to perform verification, intercomparisons, Ross ice shelf modeling tutorial, Greenland ice sheet tutorial
- 80 page *Reference Manual* describes both C++ class structure and continuum model and numerical analysis aspects
- started 2003; under very active development
- has run on 500 processors (`midnight` at ARSC)
- solves shallow sheet/stream/shelf stress balances all in parallel

Verification and Validation

- "verification" means measuring the difference between numerical results and exact solutions
- "validation" means measuring the difference between model results and (trusted) observations of real systems
- validation is hard because of lack of 3d flow observations!
- this makes verification even more important

Convergence to an exact solution

- we have spent a lot of our time on verification (it has not been done much by others)
- verification-by-exact-solution is built into PISM
- example: exact solution exists for "plastic till ice stream on a slope" (Schoof, 2006)
- PISM result converges to this soln at nearly optimal rate of $O(\Delta y^2)$



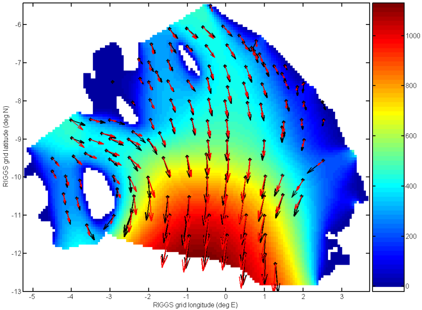
stars: maximum velocity errors; *circles*: average velocity errors (relative)

Validation of an ice shelf flow model

color shows PISM's modeled speed (m/a) on Ross Ice Shelf with 6.8 km grid

black arrows are observed velocities (RIGGS 1983)

red arrows are PISM model velocities



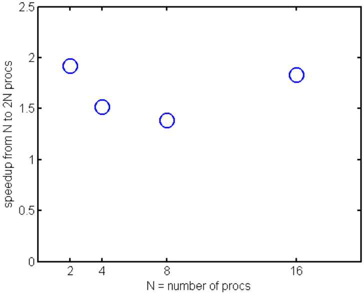
- 6.8 km grid is fine enough to resolve geometry and ice stream/glacier inputs

Parallelization of PISM

- PISM is an MPI code
- but we don't call MPI! (not much, anyway)
- PISM calls PETSc = Portable Extensible Toolkit for Scientific computation (Argonne)
- PETSc is right level of abstraction for managing scientific computation like this
- we use boring regular finite difference grid
- and some PETSc iterative linear algebra (GMRES for ice streams and shelves)
- but PETSc can manage triangulations, FE, multigrid, ...

Parallelization performance

- experiment done last night . . .
- built and ran PISM in 20 minutes on `midnight`
- grabbed 32 cores (two 16way nodes) on debug queue
- very boring performance analysis $\Longrightarrow$
- goal for summer 2008: ARSC undergrad intern will do this a lot better!



Acknowledgements

- Don Bahls
- everyone who helped make PETSc work on `midnight` (and `iceberg` before ...)
- and NetCDF and Subversion and Python and scipy and pycdf and ...
- intern program:
  - Nathan Shemonski (2007 summer intern) used PISM on Greenland for first time
  - Greg Newby
- Dave Covey in GI Computer Resource Center

Conclusion

- ice sheet modeling is worthwhile . . .
- now
- ice sheet modeling is, for now,
    1. science first
    2. mathematics second
    3. HPC third
- PISM is open, scalable, verifiable: www.pism-docs.org
- it's a new fluids model, for global climate model use, built entirely at UAF with ARSC's help
- it's nowhere near completion
- THANKS FOR YOUR ATTENTION
- questions?