Ice sheet modelling at UAF and PISM, a Parallel Ice Sheet Model

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This is joint work on ice sheet modeling and PISM with
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Thanks to Martin Truffer, David Maxwell, Christian Schoof,
and many others for help with theory and methods.

Thanks to Don Bahls *at ARSC for help*
making it all work on the big machines.

Outline

Climate change, climate system computer models, and ice sheets

Earth's ice sheets

Physics of (fairly) slow, cold, shallow ice

PISM = a Parallel Ice Sheet Model

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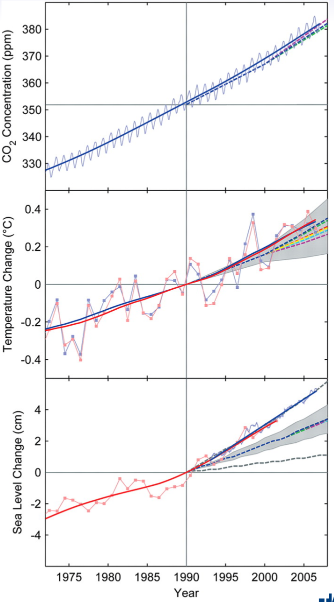
[Our chapter of the 2007 Intergovernmental Panal on Climate Change (IPCC) report] documents the increasingly strong evidence for widespread reductions in the Earth's ice. . . [We] highlight the strong evidence for the dominant role of warming, which is primarily being caused by human activities, in this loss of ice.

. . .

A paper published in the journal Science last week (Rahmstorf et al., 2007) compared the projections made in the 2001 IPCC Third Assessment Report to changes that have occurred. The carbon dioxide in the atmosphere has followed expectations closely. Temperature has increased just slightly faster than projected, but well within the stated uncertainties. Sea level is following near the upper edge of the stated uncertainties, however, well above the central estimate. Changes in the ice sheets help explain this.

Richard Alley, testimony before Committee on Science, U S House of Representatives, February 2007

- Rahmstorf and others (2007) compared
    - IPCC model predictions (scenarios based esp. on various CO_2 assumptions) using 1973–1990 data
    - to climate observations for 1990–2006
- As Alley notes, CO_2 predictions follow the IPCC scenarios closely, and predictions of temperature are reasonable, given its variability. But sea level change is outside the range of predictions.
- Rahmstorf et al. explicitly note that "Sea level closely follows the upper gray dashed line, the upper limit referred to by IPCC [2001] as 'including land-ice uncertainty.'



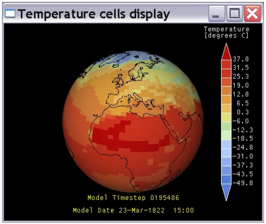
it is important to couple
accurate ice sheet models
to climate system models

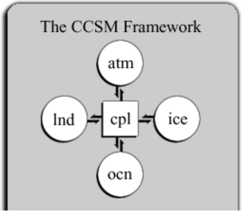
Existing global climate system models

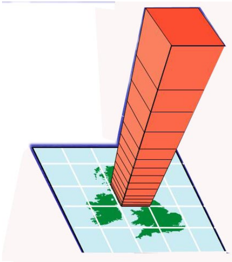
The existing climate models used in the 2007 IPCC report typically involve *atmosphere*, *ocean*, *land*, and *sea ice* components, all coupled together.

Note: floating sea ice is important to the climate system—e.g. albedo feedback—*but melting it does not raise sea level.*

graphics re climate systems models:







Time scales for components of the climate system

Why don't existing climate system models already include an ice sheet (and glacier) component? One reason is their perceived time-scale for major change.

component	time scale for significant change
atmosphere (weather)	days
atmosphere (climate)	years to decades
ocean (climate)	decades
sea ice	decades
ice sheets (old view)	centuries to millenia
ice sheets (new view)	decades to millenia

1508 16 MARCH 2007 VOL 315 SCIENCE www.sciencemag.org

CLIMATE CHANGE

Rethinking Ice Sheet Time Scales

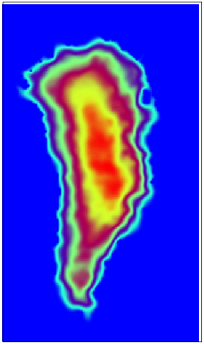
Martin Truffer and Mark Fahnestock

Satellite data show that ice sheets can change much faster than commonly appreciated, with potentially worrying implications for their stability.

Outline

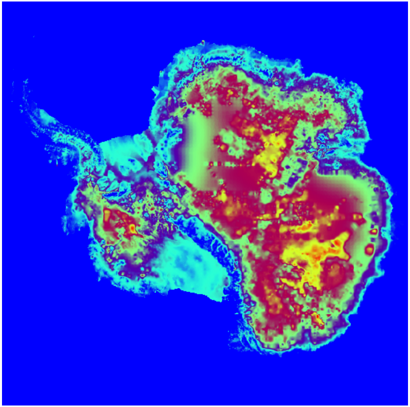
Greenland and Antarctic ice sheets

GREENLAND ICE SHEET



area: 1.70×10^6 km^2
max. thickness: 3200 m

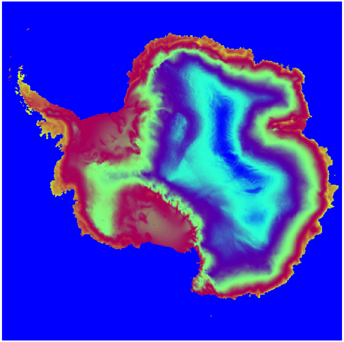
ANTARCTIC ICE SHEET



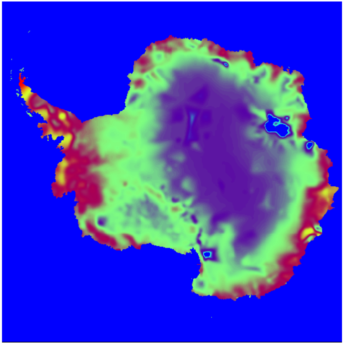
area: 13.7×10^6 km^2
max. thickness: 4400 m

(*plot color is* ice thickness)

the Antarctic ice sheet: surface temperature & accumulation rate

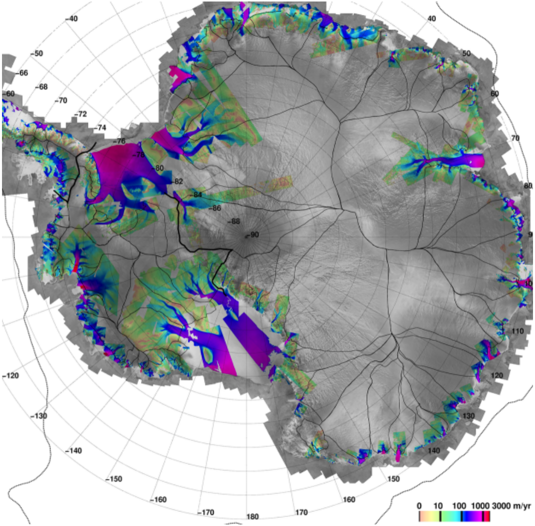


temperature: color is *annual average temperature at the surface of the ice*, with range -61 to $-4 \quad ^\circ C$



accumulation rate: color is *average rate of snowfall* expressed in meters of ice per year; range 0 to 2.3 m/a
(middle of EAIS ~ 5 cm/a; yellow color ~ 1 m/a)

the Antarctic ice sheet: observed ice velocity



(*source*: Eric Rignot, personal communication)

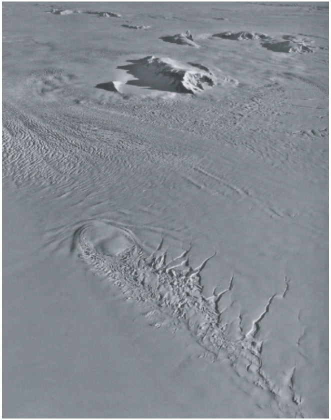
Slow flow (as in molasses)

Previous slide of observed velocities shows flow resulting from different flow *regimes*. For example, *slow flow* by shear deformation.

"Polaris Glacier," northwest Greenland. Photo 122. (Post & LaChapelle 2000)

Faster flow (ice streams)

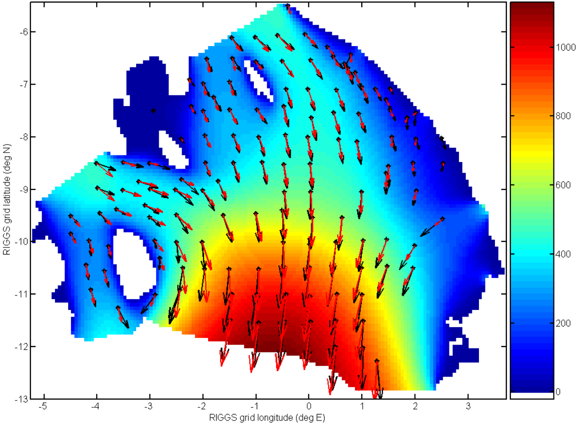
Faster flow mostly from longitudinal deformation (with drag at base).



Palmer Land, Antarctica. Photo 131. (Post & LaChapelle 2000)

Faster flow (ice shelves)

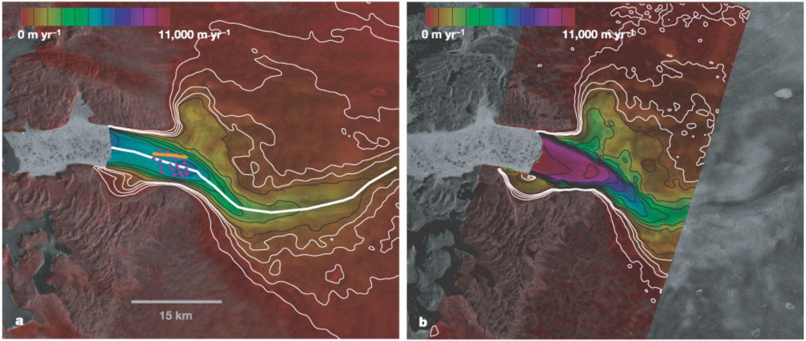
Slightly *faster flow* from longitudinal deformation (with no drag at base, because floating in water). (*THIS IS NOT SEA ICE: thickness* 200–1000 *m*)



PISM model result superimposed on RIGGS observations.

Fastest flow (outlet glaciers)

From Joughin, Abdalati, Fahnestock (2004), where this figure appeared: "Our observations indicate that fast-flowing glaciers can significantly alter ice discharge at sub-decadal timescales, with at least a potential to respond rapidly to a changing climate."



An analogy

	weather prediction	**ice sheet modeling**
scale	1 to 5 days	100 to 10,000 years
large steady feature	jet stream	interior, frozen base part
fast/small feature (needs high res)	major storms and hurricanes	outlet glaciers and ice streams
goal	predict the weather	predict sea level rise

NOTE: fast-changing outlet glaciers and ice streams are fast for an ice sheet, but occur on the time scale of *climate*, not *weather*, simulations

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Ice sheet and glacier models

Principles:

- ice sheets are a slow, nonlinearly-viscous, shallow fluid flow problem [ED: explain "slow" as technical term]
- therefore geometry, ice temperature, and basal drag conditions determine the (3D) velocity field in the ice
- there are flow laws for ice, but the right form is a topic of active debate and experimentation
- ice sheets are heavy; when they change the earth deforms; ice sheet flow must be coupled to earth deformation
- IT IS HARD TO OBSERVE THE FLOW IN, AND AT THE BASE OF, ICE SHEETS

Initialization of an ice sheet model

By "initialization" of a time-dependent Antarctic flow model, for example, we really mean the creation of a model of the current state of the Antarctic ice sheet. *This our current goal for PISM.*

- initializing means *solving obligatory inverse problems*
- we must "fill in" the following to initialize:
  - (i) temperature (note long "spin-up" to meet advection time scale even at steady state)
  - (ii) basal condition (i.e. drag coefficient or yield stress)
  - (iii) melt/freeze rates under ice shelves
  - (iv) distribution of basal water under grounded sheet
- *then* flow equations determine velocities . . .

Equations (i.e. PDEs in PISM)

- map-plane conservation of mass
- incompressibility
- multi-modal, shallow conservation of momentum eqns (below); determines velocity
- 3D (shallow approximation of) conservation of energy including bulk strain heating and friction heating from basal sliding
- computation of basal melt water from conservation of energy; local (column-wise) conservation of melt water; freeze-on can occur
- earth deformation (by new, fast method)

Physics which is *not* in PISM

- full Stokes equations (i.e. *sans* shallowness assumptions)
- polythermal ice
- hydrology of basal water
- anisotropic flow laws

"multi-modal" shallow flow

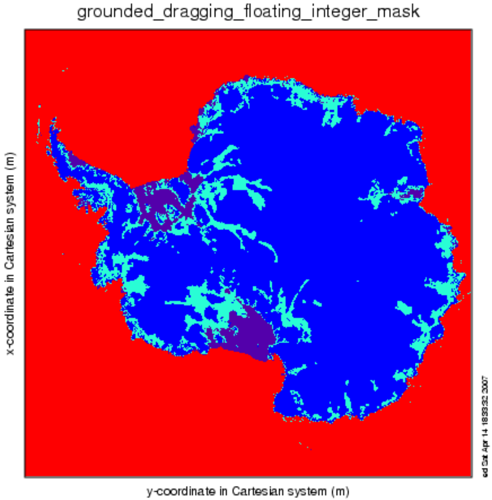
(i) in interior ice sheet we
- apply shallow ice approximation to determine velocity; "SIA equations"
- use Goldsby-Kohlstedt (*2001*) flow law

(ii) in ice streams we apply shallow longitudinal stress balance equations with either linear basal drag or plastic till to determine velocity nonlocally; "MMS equations"

(iii) ice shelves are ice streams *sans* basal drag (also MMS)

fast outlet glaciers like Jakobshavns in Greenland are most like case (ii), but may need more complex equations for velocity

The which-type-of-flow mask



Shown on 14km grid; $401 \times 401 \times 241$ 3D grid.

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Authors: *Jed Brown, Ed Bueler, Craig Lingle*.

- open source:
  - website `https://gna.org/projects/pism/`
  - source via Subversion by `svn co http://svn.gna.org/svn/pism/trunk pism`
  - documentation at `www.dms.uaf.edu/~bueler/PISMdocinstall.htm`
- under active development
- structurally parallel (using PETSc; next talk at 2:30)
- designed originally for Antarctic ice sheet; this summer adding Greenland (Nathan!)
- run on up to 480 processors (`midnight`) and on $\geq$ five different supercomputers worldwide

Verification for ice sheets

DEFINITION:

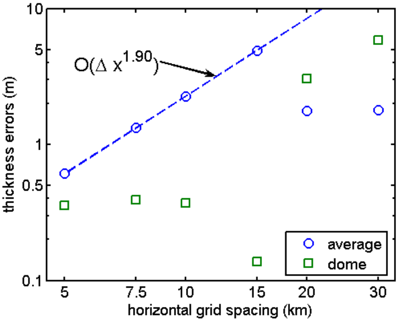
Verification is measuring the difference between numerical results and exact solutions and measuring the rate at which numerics converge to exact continuum values as grid is refined.

Are there enough exact solutions? Perhaps so! These are built into PISM:

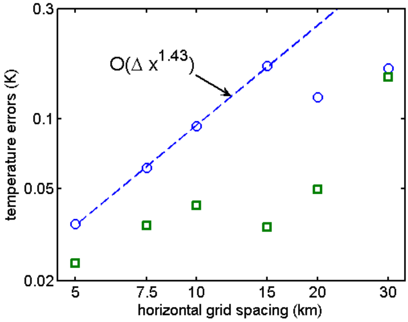
- similarity exact solutions to the isothermal SIA (*Halfar 1983*, *Bueler et al 2005*)
- "manufactured" exact solutions to the isothermal *and thermocoupled* SIA (*Bueler et al 2005*, *Bueler et al, to appear* J. Glaciol.)
- "manufactured" exact solution to MMS with linear drag (*Brown MS Thesis 2006*)
- exact solution to MMS with plastic till (*Schoof 2006*)

Convergence under grid refinement: an SIA example

Verification of PISM's approximation of thermocoupled SIA:



thickness errors



temperature errors

Validation

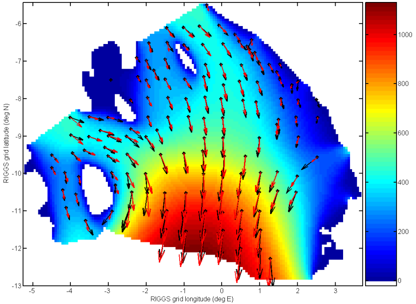
DEFINITION:

Validation is a comparison of numerical model results for and observations of a modelled system in cases where the observations are believed to be reasonably complete and accurate.

Validation of ice shelf flow (an example)

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

- **black** arrows are observed velocities (RIGGS)
- **red** arrows are PISM-modeled velocities at same points

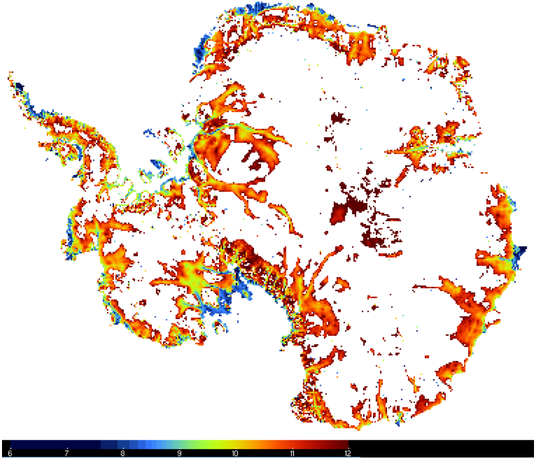


6.8 km seems fine enough to resolve (ice stream/glacier) inputs to shelf

Drag coefficient under Antarctica

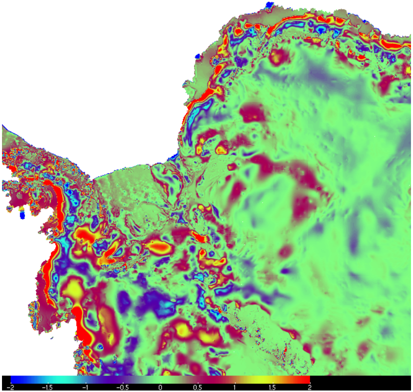
Given balance velocities.
Assume linearly-viscous till.
MMS eqns give drag coefficient.

Figure shows $\log_{10}(\beta)$ where β in Pa s m^{-1} on 14km model grid; β was removed if outside of $[10^5, 10^{13}]$.
Compare $\beta = 2.0 \times 10^9$ used by Hulbe & MacAyeal.



dH/dt over a 100 year run on a 5km grid

- 5km grid of whole Antarctic sheet; totally unprecedented resolution
- 480 processors on `midnight`
- run for 2.5 hours; 100 model years; time steps = 4 model days
- thermocoupled SIA using GK flow law; no MMS
- 3D grid for temperature is $1121 \times 1121 \times 241$
- 500 million unknowns
- MMS equations parallelize, but not as well



caption on Rahmstorf et al 2007 figure

Fig. 1. Changes in key global climate parameters since 1973, compared with the scenarios of the IPCC (shown as dashed lines and gray ranges). (Top) Monthly carbon dioxide concentration and its trend line at Mauna Loa, Hawaii (blue), up to January 2007, from Scripps in collaboration with NOAA. ppm, parts per million. (Middle) Annual global-mean land and ocean combined surface temperature from GISS (red) and the Hadley Centre/Climatic Research Unit (blue) up to 2006, with their trends. (Bottom) Sea-level data based primarily on tide gauges (annual, red) and from satellite altimeter (3-month data spacing, blue, up to mid-2006) and their trends. All trends are nonlinear trend lines and are computed with an embedding period of 11 years and a minimum roughness criterion at the end (6), except for the satellite altimeter where a linear trend was used because of the shortness of the series. For temperature and sea level, data are shown as deviations from the trend line value in 1990, the base year of the IPCC scenarios.