Greenland ice sheet flow computations

scaling-up to high spatial resolution and fast boundary processes

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Arctic Region Supercomputing Center

NASA

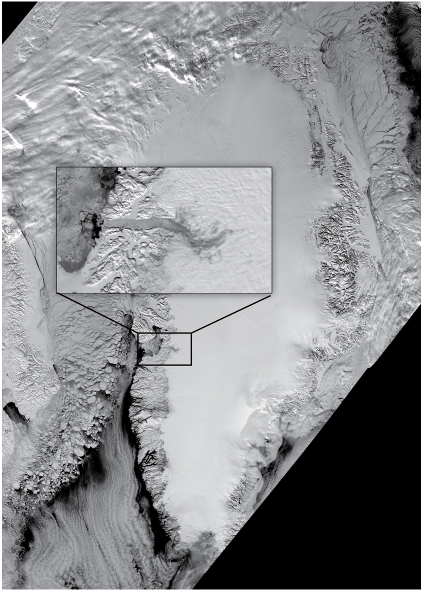
Outline

why compute Greenland's flow?

ice sheets: modeling and observations

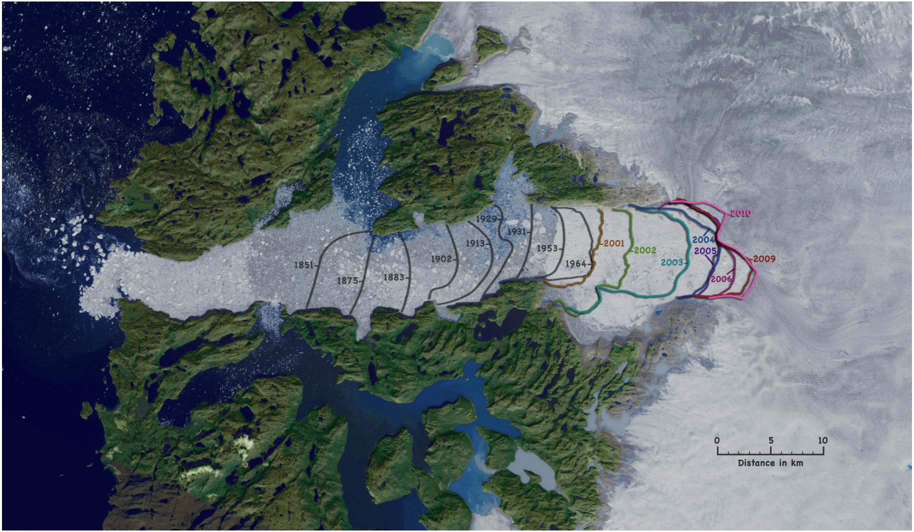
scaling-up: how to get more ISM from HPC

Jakobshavn Isbræ, west Greenland



MODIS image
M. Fahnestock

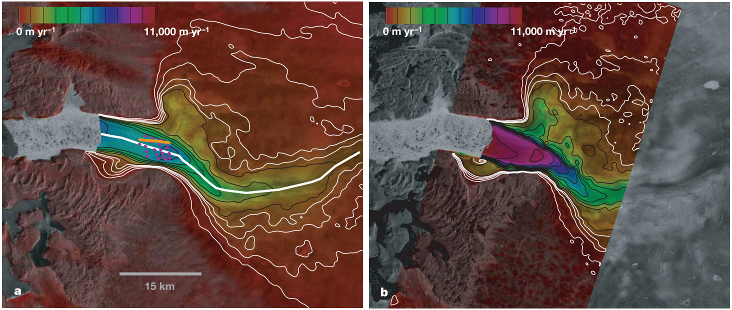
Jakobshavn Isbræ, west Greenland



NASA/Goddard Space Flight Center Scientific Visualization Studio

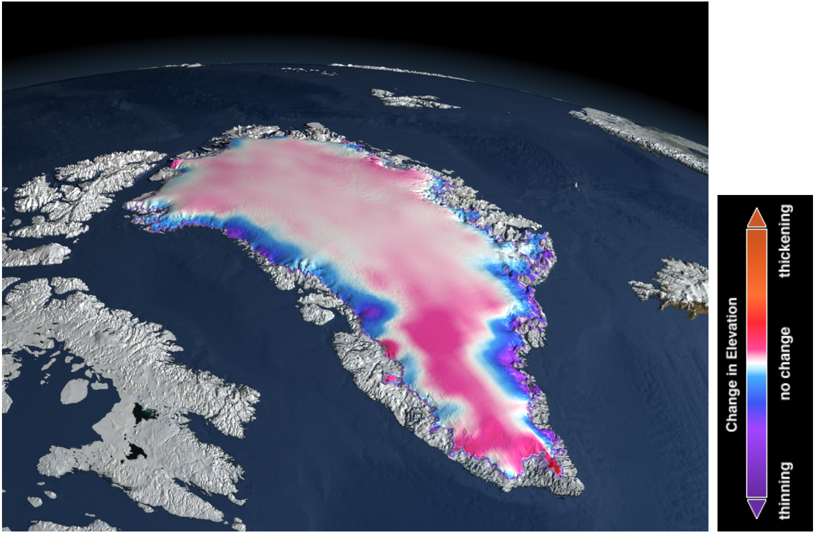
Speed-up of Jakobshavn Isbræ

- almost doubled its flow speed between the 1992 and 2000:
  - probably started by increase in ocean temperature from 1.7 C° in 1995 to 3.3 C° in 1998
  - . . . thus increased melting under floating tongue
  - loss of floating tongue and its "backpressure" on upstream grounded ice
  - speed-up of grounded ice
- now drains about 7% of the entire ice sheet



Joughin et al. (2004)

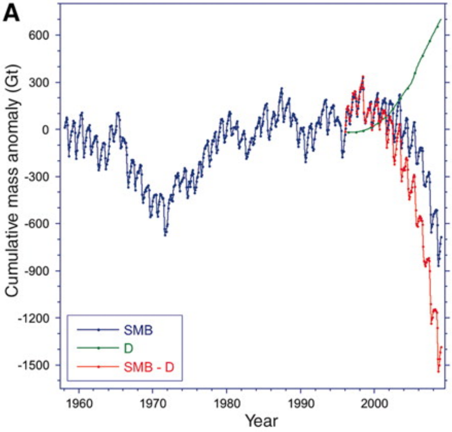
Elevation changes: surface melt and “discharge”



IceSAT observations over 2003–2006 period; NASA/Goddard Space Flight Center Scientific Visualization Studio

The future of Greenland is the question

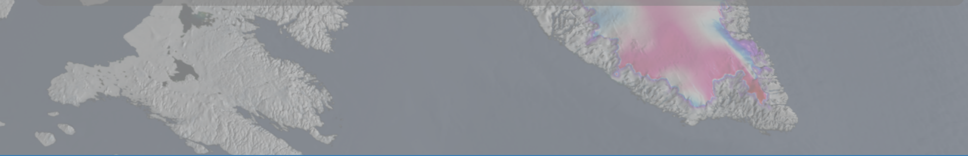
- before mid-90s mass loss was dominated by surface mass balance (= precipitation minus surface melt/runoff)
- since 2000, mass balance has been persistently negative
  - decrease in surface mass balance (more melting beats more precipitation)
  - increase in discharge (calving) from ice flow
- future mass loss partitioning: unknown
- models need to predict which climate changes have which effects



van den Broeke et al. (2009)

Why Greenland?

- its changes affect future sea level rise
  - 7 m rise if completely melted . . . unlikely . . . is 1 or 2 m likely?
- observations over the past decades show:
  - rapid acceleration of outlet glaciers
  - thinning around the margin
  - increased mass loss
- it's a testbed for ice sheet modeling:
  - recent observational attention: lots of flights, ground measurements
  - exhibits the kind of worrying dynamics we want to "explain"
  - Antarctic ice sheet has 10× the area thus 10× the cost



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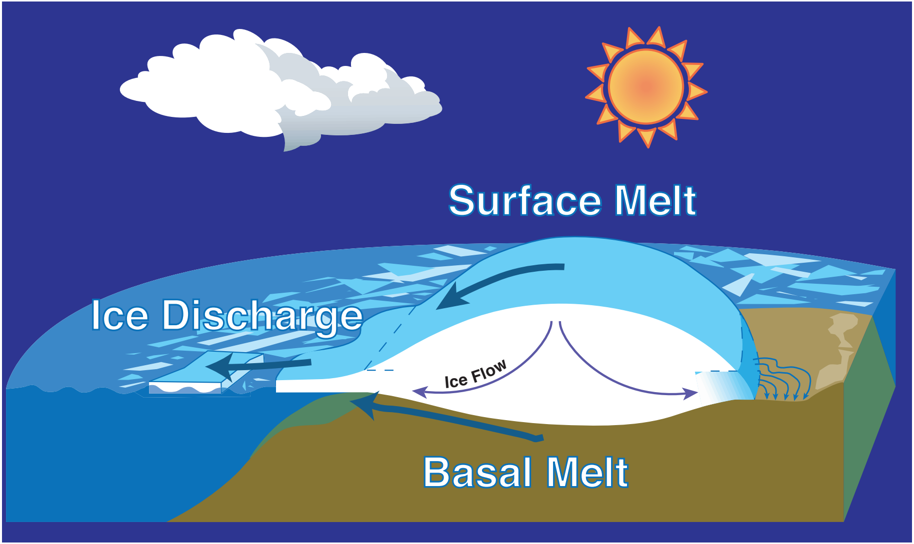
How does an ice sheet lose mass?



modified from ICESat brochure

IPCC and ice sheet models

IPCC (2007), Box 4.1: Ice Sheet Dynamics and Stability

"...but recent changes in ice sheet margins and ice streams cannot be simulated accurately with these models, ..."

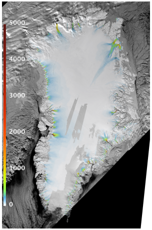
- IPCC = Intergovernmental Panel on Climate Change
  $= \{2007 \text{ Nobel Peace Prize winners}\} \setminus \{\text{Al Gore}\}$
- above statement $\Longrightarrow$ lots of attention from modelers

progress report 2011:

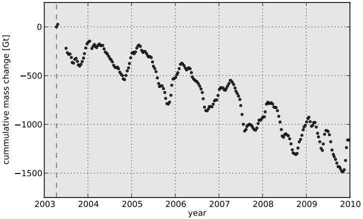
- PISM is doing a decent job reproducing the past two decades
  - before anything else, get the present, observed period right!
  - model validation

Ice sheet model validation using

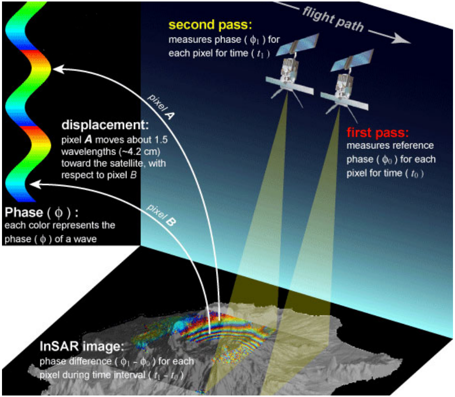
- observed mean flow speed from 2000,2006–2008 (InSAR)



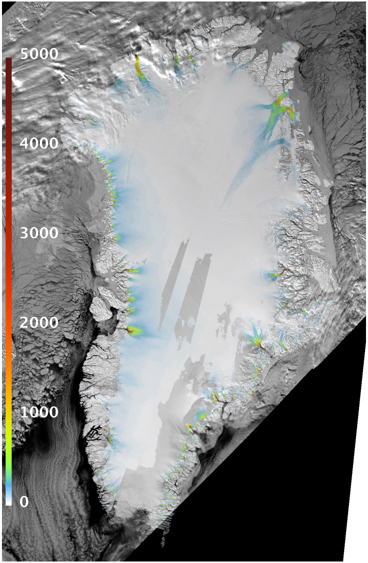
- observed cumulative mass change from 2003–2009 (GRACE)



Flow speed from InSAR

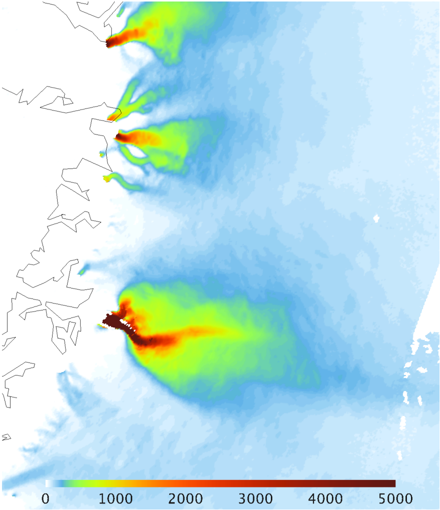


credit: USGS

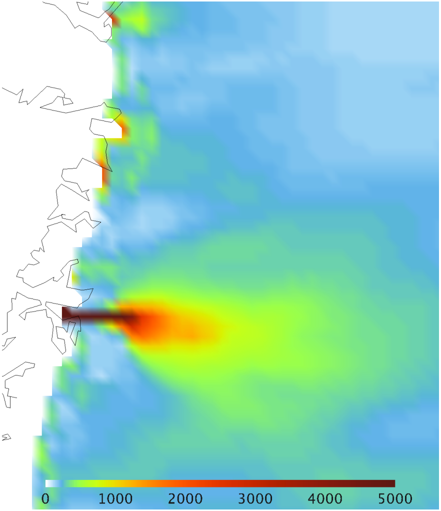


credit: I. Joughin

Results: Jakobshavn Isbræ

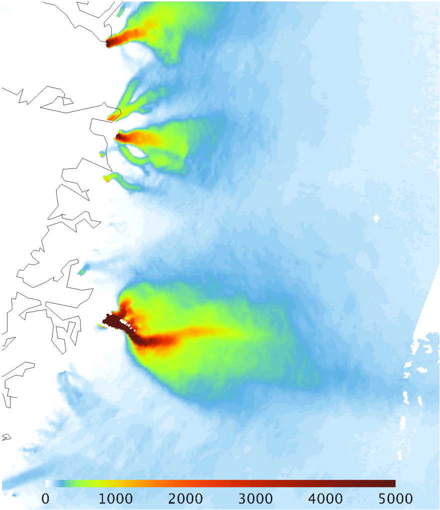


InSAR (*Joughin et al., 2010*)



PISM: 5 km grid resolution

Results: Jakobshavn Isbræ



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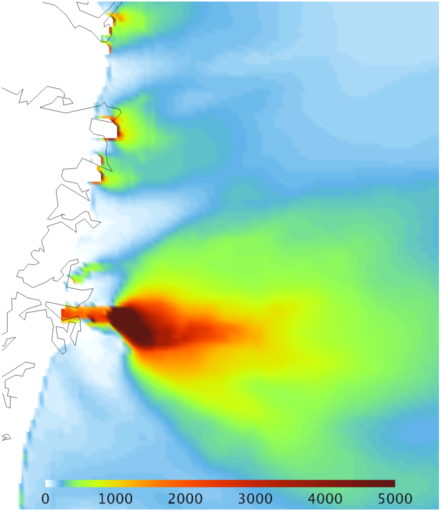
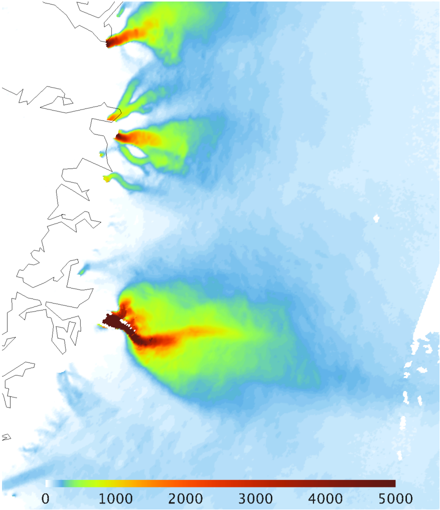


PISM: 2 km grid resolution

Results: Jakobshavn Isbræ



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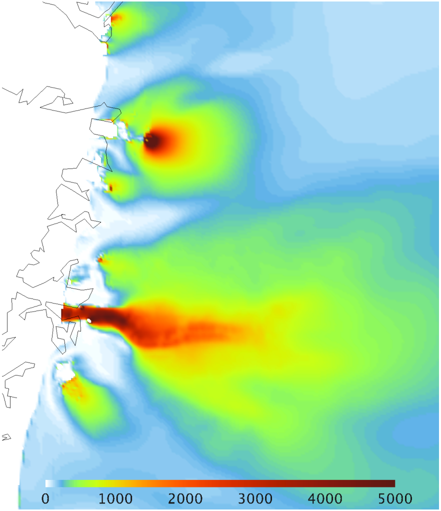
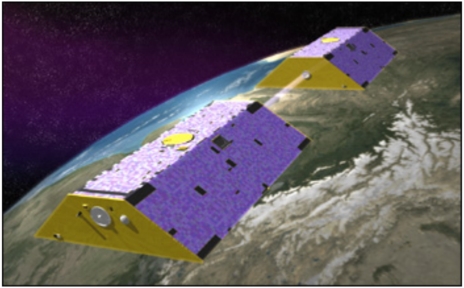
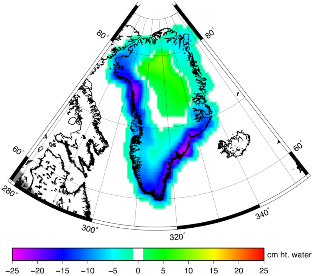


PISM: 1 km grid resolution

Gravity Recovery and Climate Experiment (GRACE)

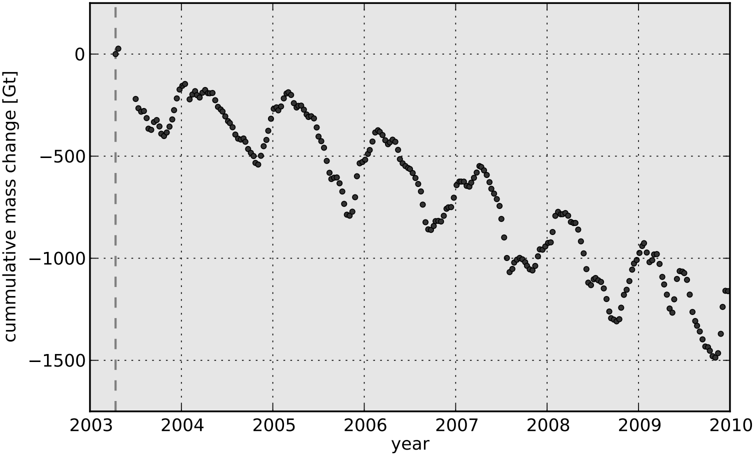




thanks to A. Arendt

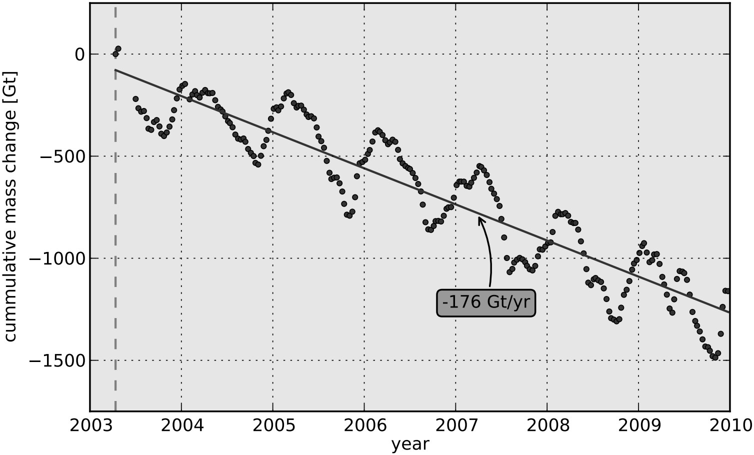
- precisely measures distance between pair of satellites
- estimates deviation of gravity field from uniform sphere shape

Observed mass changes



Luthcke, et al. (unpublished; new high-resolution solutions)

Observed mass changes



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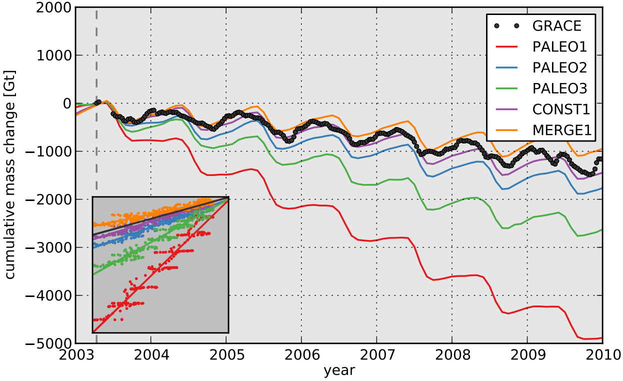
Modeled and observed mass changes



- new coupled models of Greenland
  - PISM + regional climate model (HIRHAM at DMI Copenhagen)

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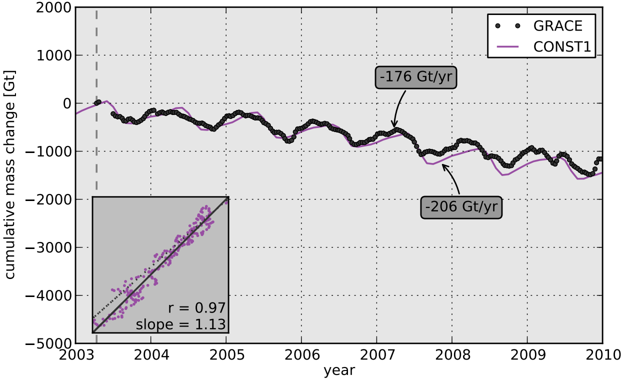

- new coupled models of Greenland
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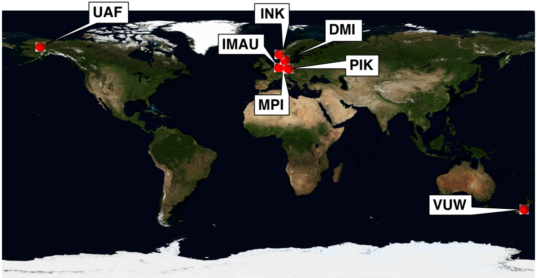
What is PISM?

- PISM = Parallel Ice Sheet Model   www.pism-docs.org
- open source (C++, python), PETSc-over-MPI, regular grid
- adaptive time-stepping
- supported by NASA; now a joint project with PIK in Germany
- the best ice sheet model in the world
- ...was developed in Fairbanks

user base:



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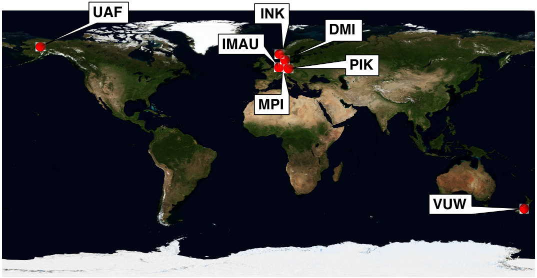

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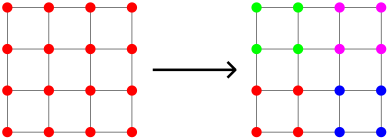
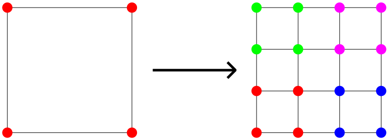
Scaling

- plan for the rest of my talk: beat up PISM because it scales badly
- ...though it scales *way* better than any other current ISM
- definitions in convenient 2D grid case:
  - strong scaling: for fixed problem,
    $4\times$ the number of processors $\implies$ (1/4)th the execution time



  - weak scaling: for fixed number of d.o.f.s *per processor*,
    $4\times$ the number of processors $\implies$ *same* execution time

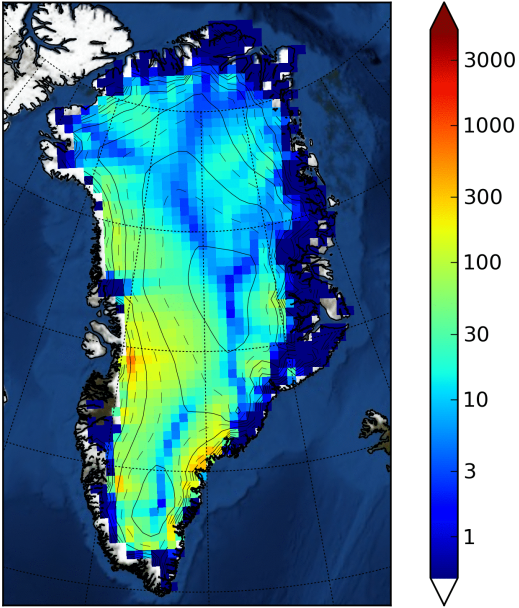


Min prerequisite for weak scaling: convergence

- six runs, each 100 model year with same data
- on refining grids: 40, 20, 10, 5, 2.5 km
- surface velocity (m/year) →
- my first informal study
- results:

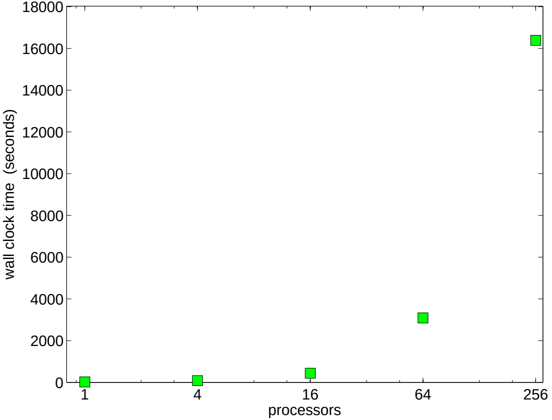
res	procs	wall clock
40 km	1	8 sec
20 km	1	75 sec
10 km	64	57 sec
5 km	64	14 min
3 km	128	56 min
2 km	128	285 min

- on Cray XT5
  - pingo.arsc.edu



Weak scaling: the reality

- here's the problem →
  - 100 model year runs
  - increase d.o.f.s and processors in proportion
    - a la weak scaling
  - it is not giving constant-time for whole run
  - it is giving constant-time per model time step
    - but who cares
- we observe: short time steps on fine grids blocks weak scaling



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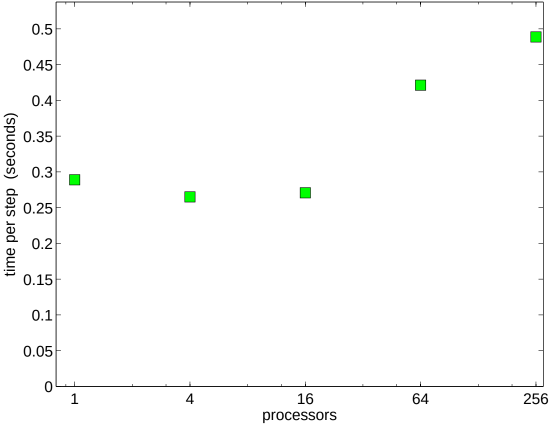

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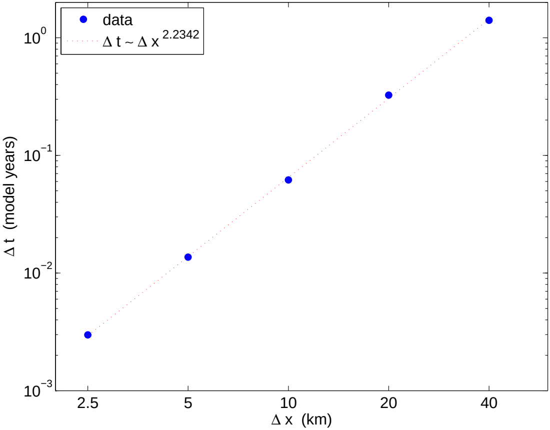


Weak scaling: the troubles

1 PISM evolves temperature and geometry by explicit time-stepping

- major evolution equation is wildly-nonlinear diffusion
- ice thickness H changes by

$$\frac{\partial H}{\partial t} \overset{*}{=} \nabla \cdot \left(C H^5 |\nabla H|^2 \nabla H \right)$$

- explicit method scales badly because

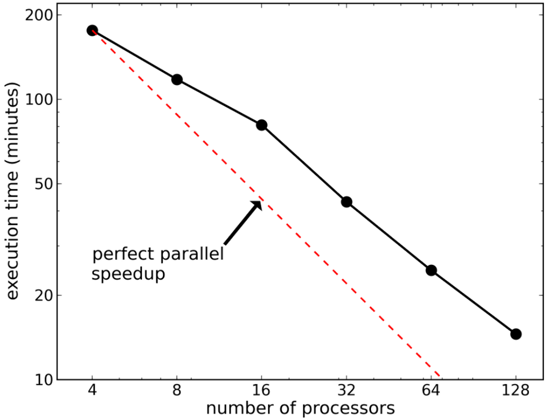
$$\Delta t \sim \Delta x^2$$

- *implicit time steps, you idiot!*
- but we are not solving PDEs; boundary value problem is $*$ subject to inequality

$$H \geq 0$$

- so we don't really know how to solve well-posed implicit time steps

Scaling: results so far; idealized ice sheets



- PISM: strong scaling on time-dependent run including many 2D stress solutions
- Jed Brown's hydrostatic ice solver [*submitted 2011*]: awesome weak scaling on time-independent 3D stress solver; *not yet in PISM!*

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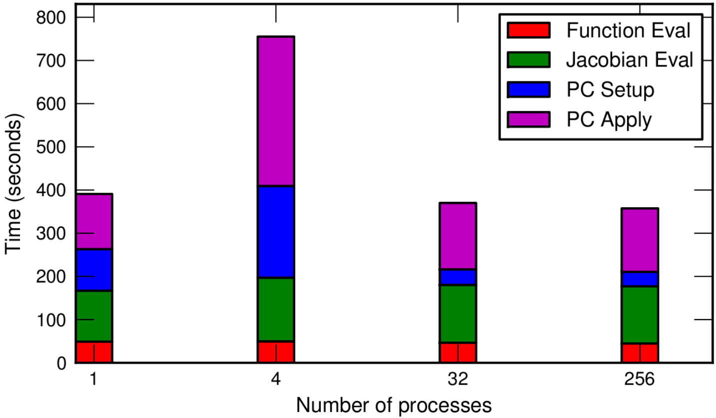

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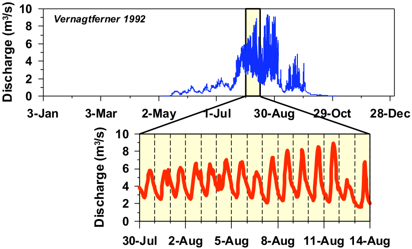
Weak scaling: the troubles

2 liquid water at boundaries

- ▷ big lakes form and drain . . . in 90 minutes (upper)
- ▷ hydrograph shows brief summer period of surface melt (lower)
- ▷ ice flow model must "see" liquid runoff at surface *and* its effect on subglacial resistance
    - ▶ boundary liquid timescales are minutes–weeks
    - ▶ ice sheet model runs are decades–millenia

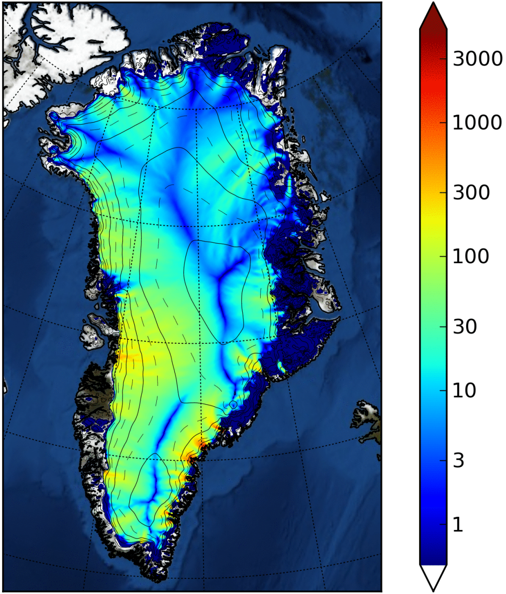
S. Das



R. Hock et al. (2005)

Weak scaling: the troubles

3 solve PDEs on domain with fractal boundary
  - ▷ velocity is big near the boundary
  - ▷ boundary is a coastline …Mandelbrot warned us about those things
  - ▷ at each timestep, want to solve nonlinear elliptic problems on this fractal



Summary

- model Greenland ice sheet flow! it is on the move!
- PISM is getting good fit to observed flow speeds, mass changes
- challenges to scaling:
  - equations need new thinking
    - need well-posed implicit time steps
    - and better solvers too
  - short time-scale processes on all ice sheet surfaces
    - liquid water
  - fast ice dynamics along fractal boundaries
- much bigger Antarctic ice sheet in the background
- thanks for your attention!