Modeled and observed fast flow in the Greenland ice sheet

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Synopsis

- Satellite surface velocity measurements covering 86% of the Greenland Ice Sheet were used to evaluate a prognostic ice dynamics model on a 3 km grid.
- A small-but-systematic exploration of a space of just three critical model parameters:
  - ice softness,
  - nonlinearity of the basal rheology,
  - maximum basal water pressure as a fraction of overburden.
- Parameter combinations were evaluated by comparing the modeled and observed surface speeds.
- Best fit to the observed distribution of fast flow occurred with no enhancement of ice softness, nearly-plastic basal material, and high allowed basal water pressure.
- The use of a standard amount of ice flow enhancement was seen to generate a distribution of fast flow which is fundamentally different from that in the observed flow.

Observations

- The observed velocities were an average of four winter velocity maps (2000,2006–2008) derived from RADARSAT data [Joughin et al.], with the (temporal) average weighted by the formal errors for each individual estimate.
- In a few areas where large changes occurred from 2000 to 2008, the resulting estimate represented some intermediate value.
- The individual maps were derived from a combination of speckle tracking and conventional interferometry synthetic aperture radar (InSAR) [Joughin, 2002].
- The mean measurement and processing errors in each velocity component were less than 2 m/yr in areas of low surface slope, with an additional slope-dependent error of 3%. Therefore, especially for fast flowing ice, observational errors were substantially smaller than the model-versus-observed velocity differences below.

Parallel Ice Sheet Model (PISM)

- is *open source*: get the latest version from www.pism-docs.org
- is a *fully-parallel* ice sheet model: Greenland runs on grids ≤ 3 km and up to 512 processors were performed in which *all* physical processes were computed in parallel
- is *polythermal* by the use of an enthalpy variable [Aschwanden and Blatter, 2009]: both *temperature* and *liquid water fraction* are simulated and energy is conserved better than in “cold ice” simulations
- uses the shallow shelf approximation (SSA) stress balance as-a-sliding-law [Bueler and Brown, 2009], which avoids SIA-sliding-law problems (jump discontinuities in the horizontal velocity field and consequences thereof)
- the basal mechanical model is based on a *plastic till assumption* [e.g. Clarke, 2005]: produces convincing ice-streams
- see poster XY362 for more information about PISM

Model Input

- Ice surface elevation, land elevation in ice-free areas, and bedrock elevation were from Bamber et al. [2001]. Bathymetry from Jakobsson et al. [2008] was combined with the bedrock and ice-free land elevation to create a continuous bed elevation map for the entire model domain. The result had limited resolution for subglacial fjord-like topography, with currently-unavoidable consequences for modeling fast-flowing ice in outlet glaciers.
- The Shapiro and Ritzwoller [2004] data set for geothermal flux was used as a boundary condition at the base of the ice.
- We hypothesized a steady climate for both the “spin-up” preparatory stage and for our parameter study runs.
- The Fausto et al. [2009] parameterization of present, near-surface (2 m) air temperature provided the upper boundary condition for the conservation of energy model.
- A positive degree day melt model determined upper surface mass balance from precipitation [Burgess et al., 2010] and air temperature.
- The base of floating ice melted at a uniform heat flux of 0.5 W m^{-2}.
- Ice shelves (floating tongues) calved-off at the location of the present-day calving front.

Parameter Study

We investigated 3 parameters:

1. An enhancement factor e for the Glen-type flow law:
$$D_{ij} = e\,A|\tau|^{n-1}\tau_{ij}, \tag{1}$$
where D_{ij} is the strain rate tensor, A is an enthalpy-dependent rate factor [Lliboutry and Duval, 1985], $|\tau|$ is a norm (scalar invariant) of the stress tensor τ_{ij}, and $n = 3$.
2. A pseudo-plasticity exponent $0 \le q \le 1$:
The shear stress τ_b applied to the base of the ice sheet was proportional to a power of the sliding velocity $\vec{u}_b$:
$$\vec{\tau}_b = -\tau_c \frac{\vec{u}_b}{|\vec{u}_b|^{(1-q)} u_0^q}, \tag{2}$$
where τ_c is the “yield stress” for any value of q
3. A limit on allowed pore water pressure fraction α:
The basal material (conceptually: till) is partially-saturated, and the modeled pore water pressure controls basal strength (yield stress). We used a simplified, local parameterization [Bueler and Brown, 2009] of pore water pressure p_w as a fraction of the overburden pressure:
$$p_w = \alpha\, w \rho g H \qquad \text{in} \qquad \tau_c = (\tan\phi)(\rho g H - p_w), \tag{3}$$
where $\rho g H$ is the overburden pressure, ϕ is the till friction angle, and $0 \le w \le 1$ is the relative amount of stored water in the till.

Parameter Space

no enhancement (**1**, 0.25, 0.98)		*high enhancement* (**5**, 0.25, 0.98)
less plastic (3, **0.50**, 0.98)	*control run* (3, 0.25, 0.98)	*more plastic* (3, **0.10**, 0.98)
lower pore pressure (3, 0.25, **0.95**)		*higher pore pressure* (3, 0.25, **0.99**)
SIA-only run (no enhancement): (**1**, ***na***, ***na***)		
best run: (**1**, **0.10**, **0.99**)		

Table 1: Parameter triples (e, q, α) used in model parameter study: $e =$ enhancement factor from equation (1); $q =$ pseudo-plasticity exponent from equation (2); $\alpha =$ allowed pore water pressure fraction from equation (3). Parameters which differ from the control run choices are in **bold**. The latter two parameters do not enter into the non-sliding SIA model; “***na***” = not applicable.

Results

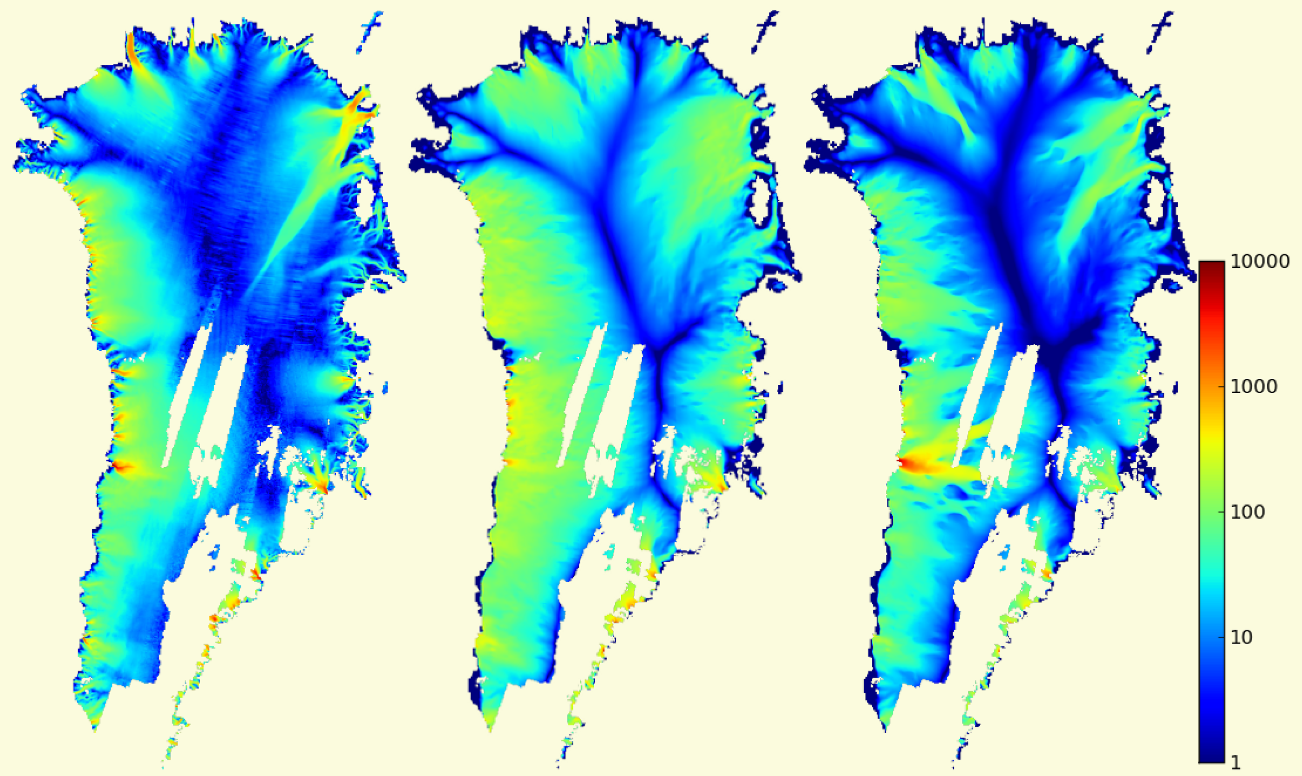

Figure 1: Observed (left) surface speed (m/a) versus results from two model runs: control run (middle) and best run (right), on a common logarithmic color scale. Model results are masked out where there is no observed velocity with which to compare.

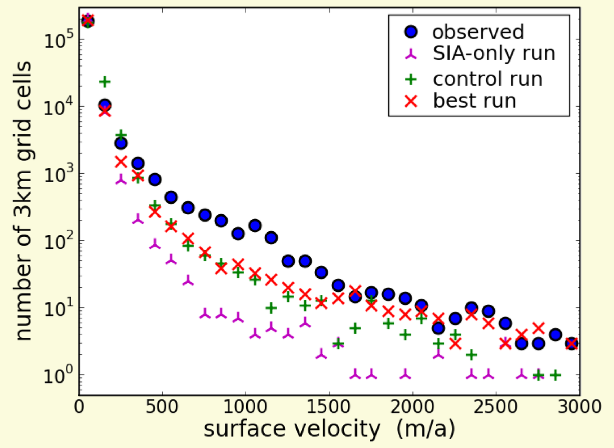

Figure 2: Distribution of surface speeds in observed data and in three model runs. Computed by counting the number of 3 km grid cells with speeds in each of 30 bins with boundaries $0, 100, 200, \dots, 3000$ m/a. See text for parameter choices in model runs.

Discussion

- Figure 1 shows the observed surface speed alongside two model results.
- All nine model results showed slow flow in the interior of the ice sheet, and fast outlet glacier (or ice stream) flow in roughly the right locations.
- Figure 2 shows the histogram of surface speeds in each of 30 bins of width 100 m/a, from 0 m/a to 3000 m/a.
- The non-sliding SIA-only run performs poorly. It has far too few grid cells with speeds above 500 m/a.
- The $e = 1$ run with “control run” sliding performs only slightly better than non-sliding SIA-only because the control run values of q and α do not yet generate adequate sliding.
- In each enhanced($e = 3, 5$) case we note an excessive amount of flow in the 100–300 m/a range, compared to observations.
- The best fast flow distribution was achieved with $(e, q, \alpha) = (1, 0.10, 0.99)$ (“best run”) which reproduced several features of the observed speed map, including a well-delineated NE Greenland ice stream and an appropriately-wide region of very slow flow near the divide.

Conclusions

- By considering only three parameters controlling ice softness and basal resistance, and by using an unprecedented 3km grid resolution uniformly over the entire ice sheet, our model achieved good agreement with newly-assembled observations of the surface velocity of the Greenland Ice Sheet.
- This agreement occurs even though the model is shallow and uses a steady, present-day climate.
- The best fit to observations occured in a run with no enhancement of ice-softness, nearly-plastic basal rheology, and high modeled basal water pressure in fast-flowing regions.

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