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An Ice Sheet Model Initialization Procedure for Smooth Coupling with Climate Forcing

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Estimation of ice sheet initial state

(w/ G. Stadler [Courant], and S. Price [LANL] - PISCEES)

Goal

Find ice sheet initial state that

- matches observations (surface velocity)
- is in ªequilibriumº with climate forcings (SMB)

by inverting for unknown/uncertain parameters

Significantly reduce non physical transients without spin-up.

Bibliography

- *Arthern, Gudmundsson*, J. Glaciology, 2010
- *Price, Payne, Howat and Smith*, PNAS, 2011
- *Petra, Zhu, Stadler, Hughes, Ghattas*, J. Glaciology, 2012
- *Pollard DeConto*, TCD, 2012
- W. J. J.Van Pelt et al., The Cryosphere, 2013
- *Morlighem et al.* Geophysical Research Letters, 2013
- *Goldberg and Heimbach*, The Cryosphere, 2013
- *Michel et al.*, Computers & Geosciences, 2014

Perego, Price, Stadler, **Journal of Geophysical Research**, 2014

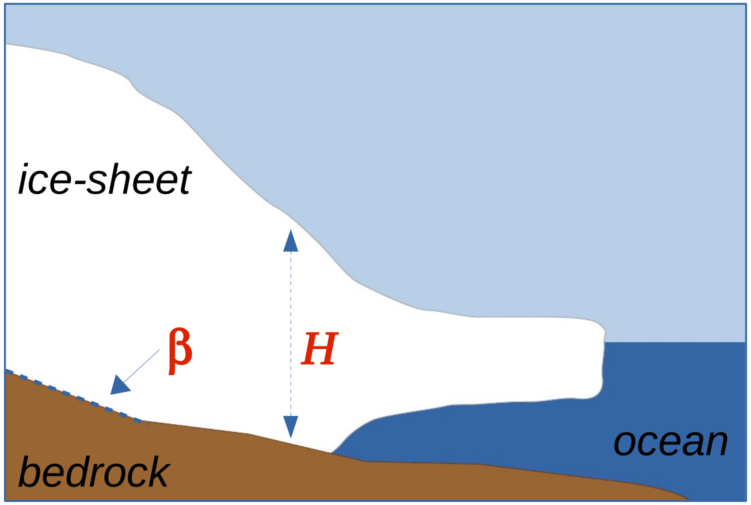
Estimation of ice sheet initial state

(w/ G. Stadler [Courant], and S. Price [LANL] - PISCEES)

Problem: what is the initial thermo-mechanical state of the ice sheet?

Available data/measurements

- *ice extension and surface topography*
- ***surface velocity***
- ***Surface Mass Balance***
- ***ice thickness H (very noisy)***



Fields to be estimated

- ***ice thickness H***
- ***basal friction β***

Additional information

- *ice fulfills* ***nonlinear Stokes equation (here we use FO)***
- *ice is almost* ***at mechanical equilibrium***

Assumption (for now)

- *given* ***temperature field***

Perego, Price, Stadler, **Journal of Geophysical Research**, 2014

Estimation of ice sheet initial state

Steady State equations and basal sliding conditions

How to prescribe ice sheet mechanical equilibrium:

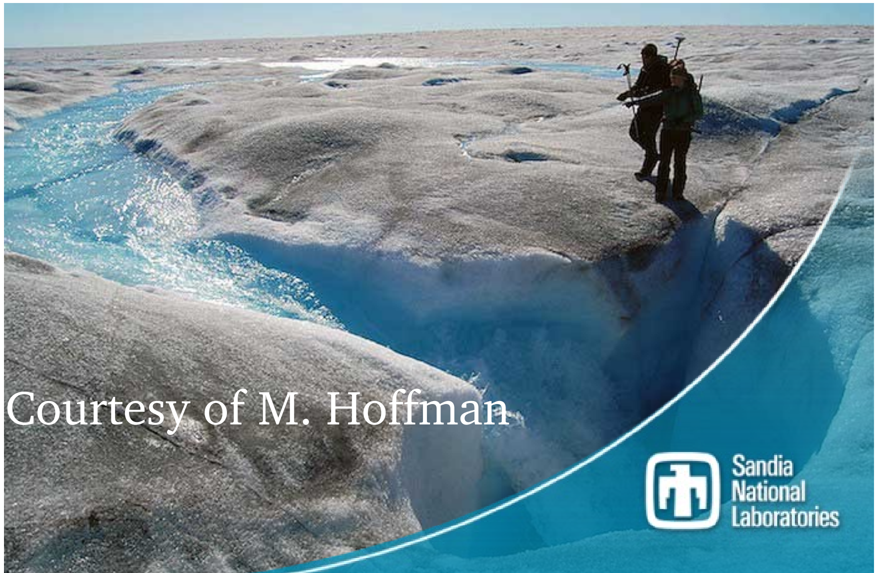
divergence flux

$$\frac{\partial H}{\partial t} = -\mathrm{div}\,(\mathbf{U}H) + \tau_s, \qquad \mathbf{U} = \frac{1}{H}\int_z \mathbf{u}\, dz. \qquad \text{equilibrium} \quad \boxed{\mathrm{div}\,(\mathbf{U}H) - \tau_s = 0}$$

Surface Mass Balance

Boundary condition at ice-bedrock interface

$$(\sigma\mathbf{n} + \beta\mathbf{u})_{||} = \mathbf{0} \quad on \quad \Gamma_\beta$$



Courtesy of M. Hoffman

Estimation of ice sheet initial state

PDE-constraint optimization problem: cost functional

Problem: find initial conditions such that the ice is almost at thermo-mechanical equilibrium given the geometry and the SMB, and matches available observations.

Optimization Problem:
find β and H that minimizes the functional $\mathcal{J}$

$$
\begin{aligned}
\mathcal{J}(\beta, H) &= \int_\Sigma \frac{1}{\sigma_u^2} |\mathbf{u} - \mathbf{u}^{obs}|^2 \, ds && \text{surface velocity mismatch} \\
&+ \int_\Sigma \frac{1}{\sigma_\tau^2} |\mathrm{div}(\boldsymbol{U} H) - \tau_s|^2 \, ds && \text{SMB mismatch} \\
&+ \int_\Sigma \frac{1}{\sigma_H^2} |H - H^{obs}|^2 \, ds && \text{thickness mismatch} \\
&+ \mathcal{R}(\beta, H) && \text{regularization terms.}
\end{aligned}
$$

Common

Proposed

subject to ice sheet model equations (FO or Stokes)

$\boldsymbol{U}$: computed depth averaged velocity
H: ice thickness
β: basal sliding friction coefficient
τ_s: SMB
$\mathcal{R}(\beta)$ regularization term

Estimation of ice sheet initial state

Algorithm and Software tools used

Algorithm	Software Tools
Basal non-uniform triangular mesh	***Triangle***
Linear Finite Elements on tetrahedra	***LifeV***
Quasi-Newton optimization (L-BFGS)	**Rol**
Nonlinear solver (Newton method)	**NOX**
Krylov Linear Solvers	**AztecOO/IfPack**

Details:

Regularization terms: Tikhonov

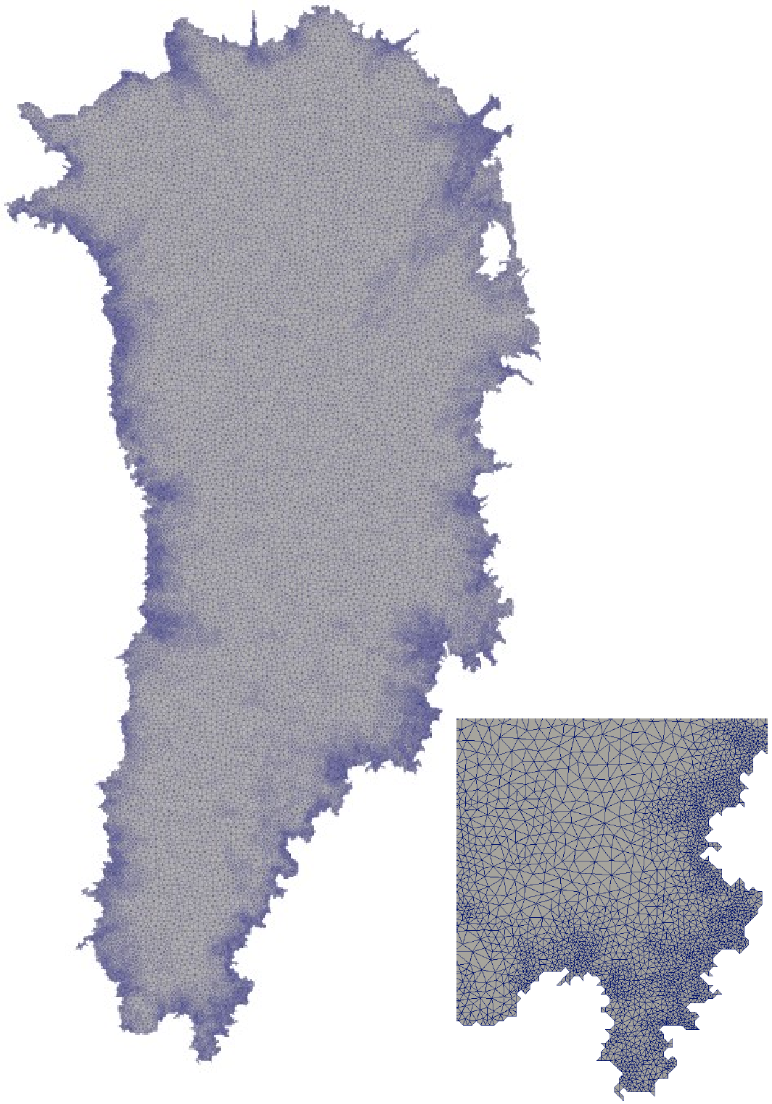
L-BFGS initialized with Hessian of the regularization terms

$$\left(\frac{1}{2}\beta^T L\beta \quad \rightarrow \quad L\right)$$

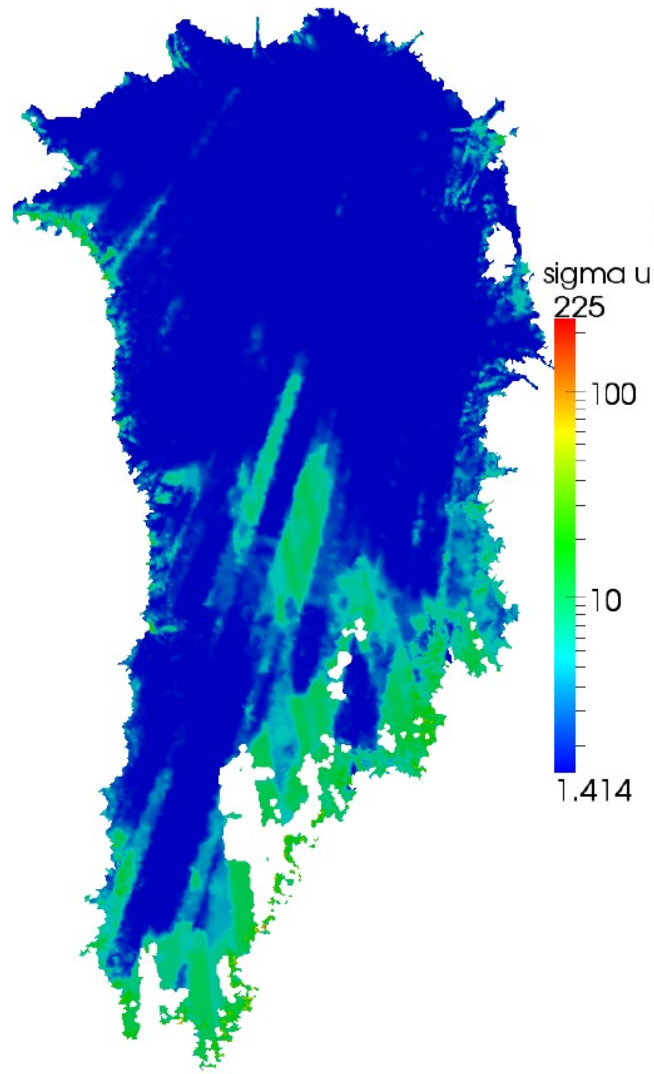
Estimation of ice sheet initial state of Greenland ice sheet

Grid and RMS of velocity and errors associated with velocity and thickness observations

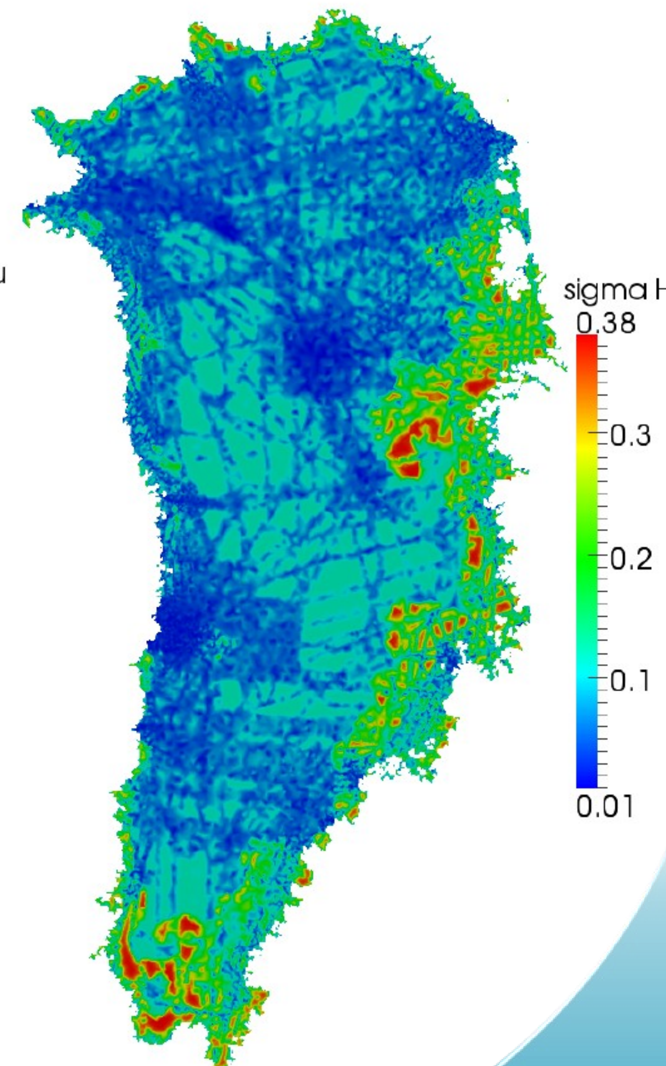
Grid



Velocity RMS (m/yr)



Thickness RMS (km)



Geometry and fields Bamber et al.[2013], temperature computed with CISM (Shannon et al. [2013])

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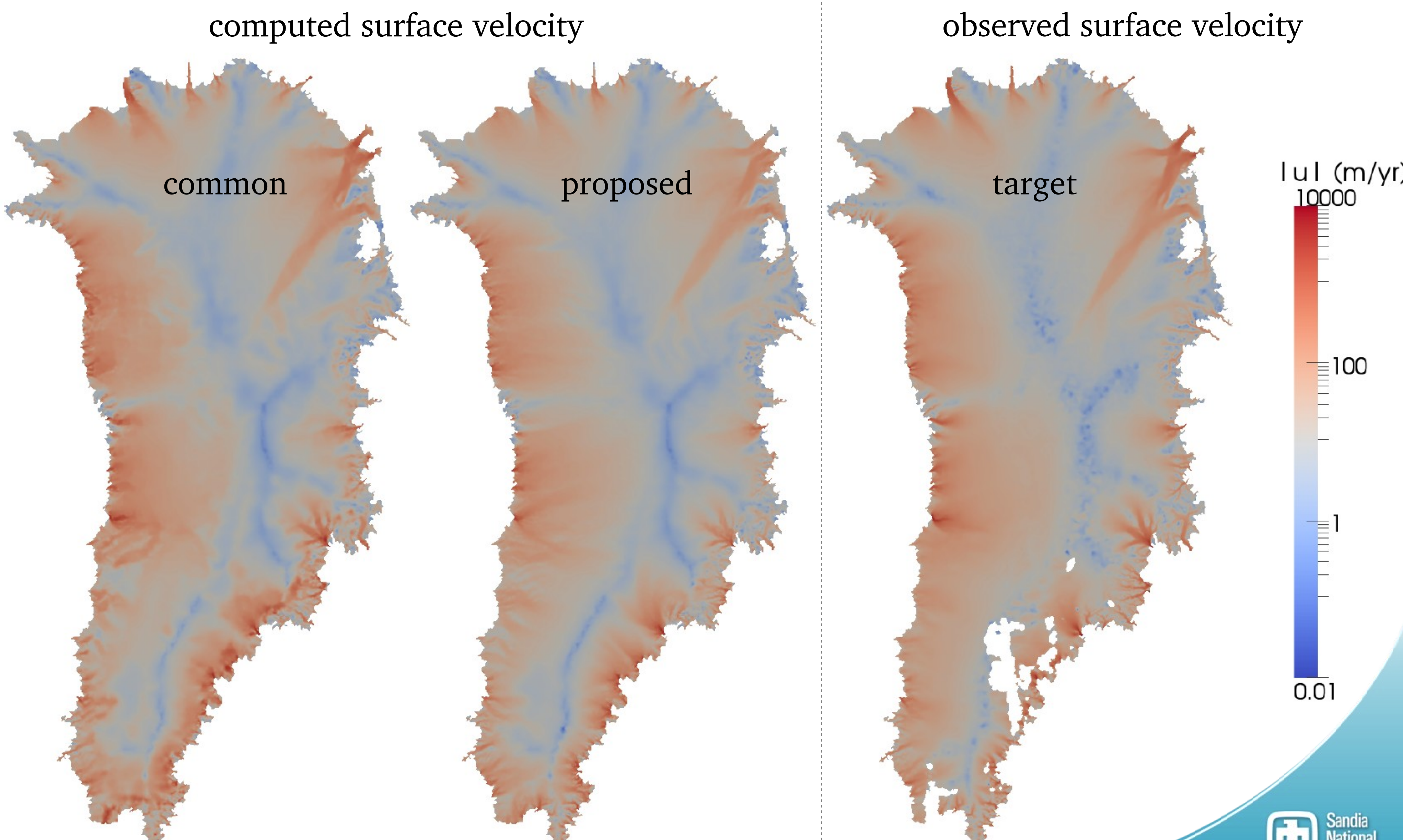
Estimation of ice sheet initial state of Greenland ice sheet

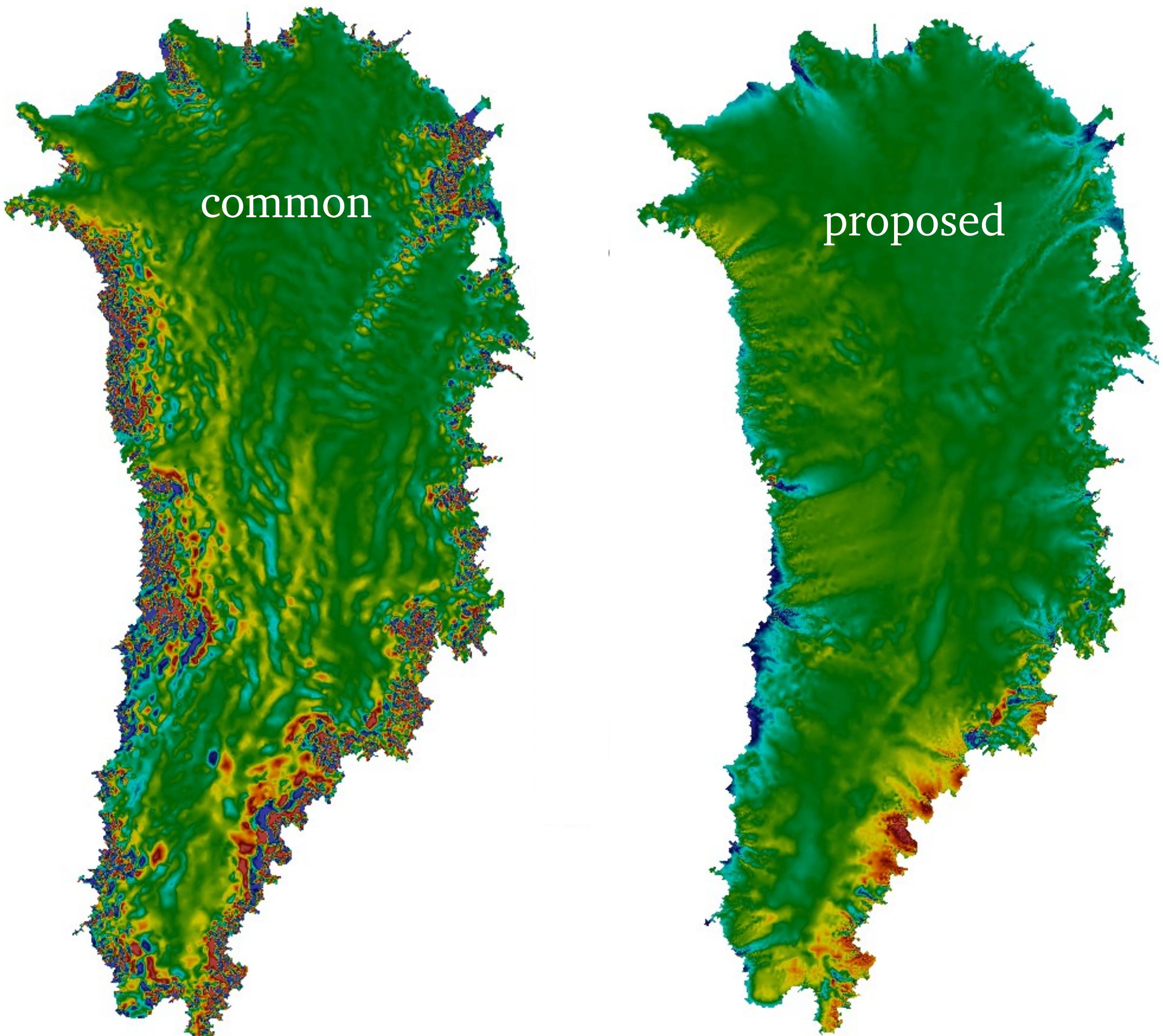
Inversion results: surface velocities



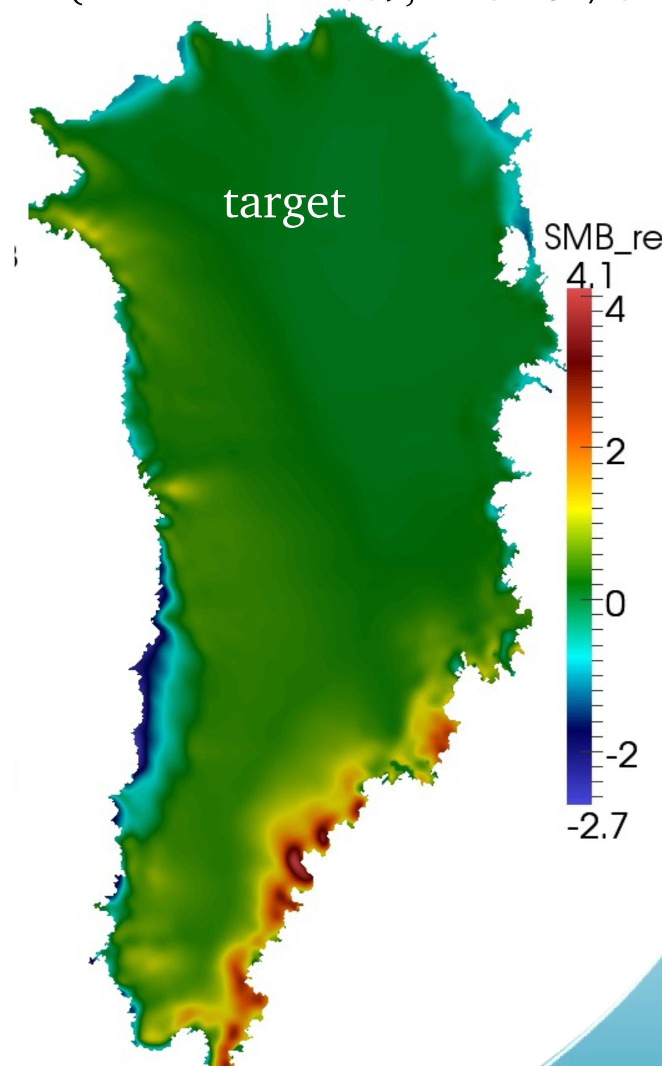
Estimation of ice sheet initial state of Greenland ice sheet

Inversion results: surface mass balance (SMB)

SMB needed for equilibrium



SMB from climate model
(Ettema et al. 2009, RACMO2/GR)



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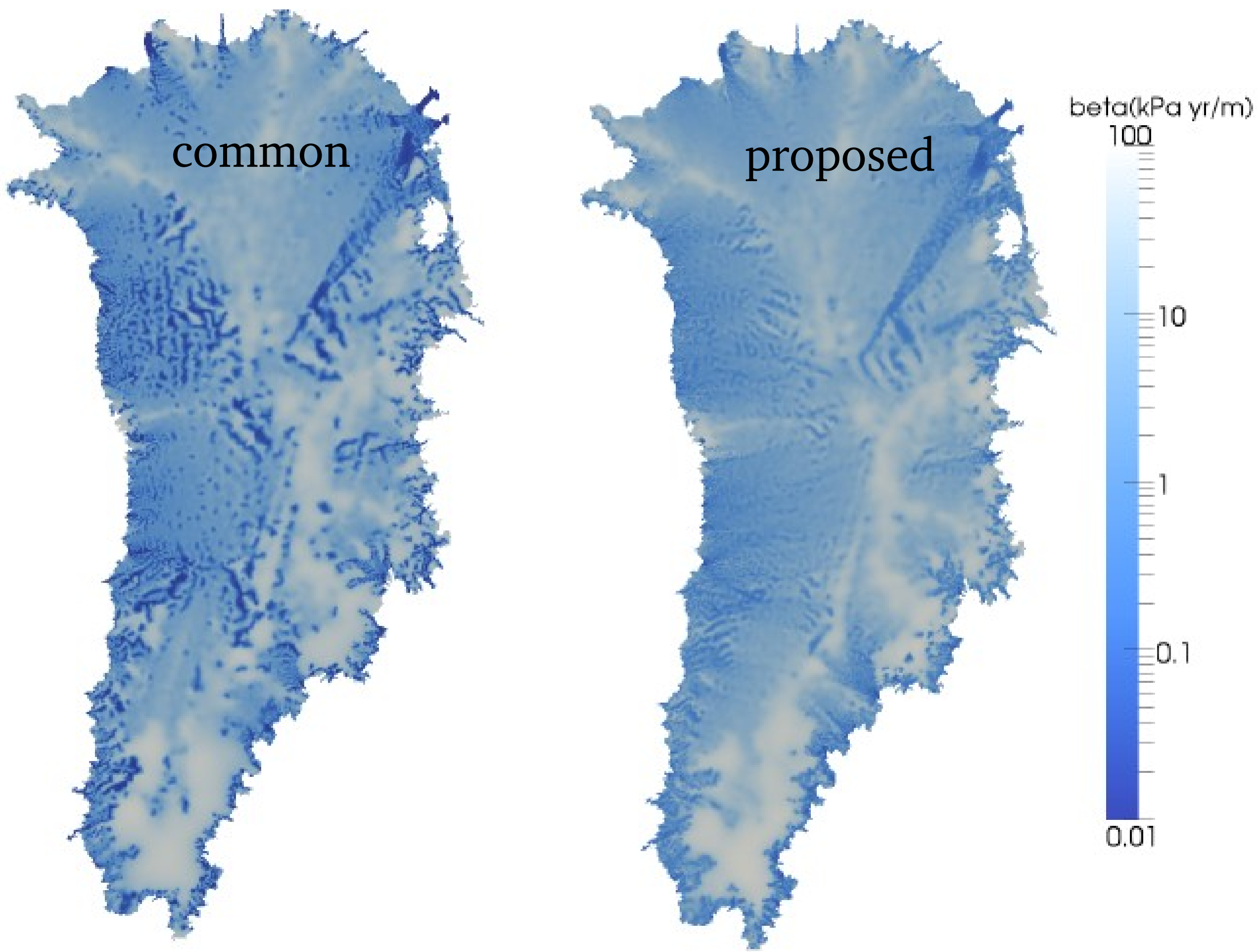
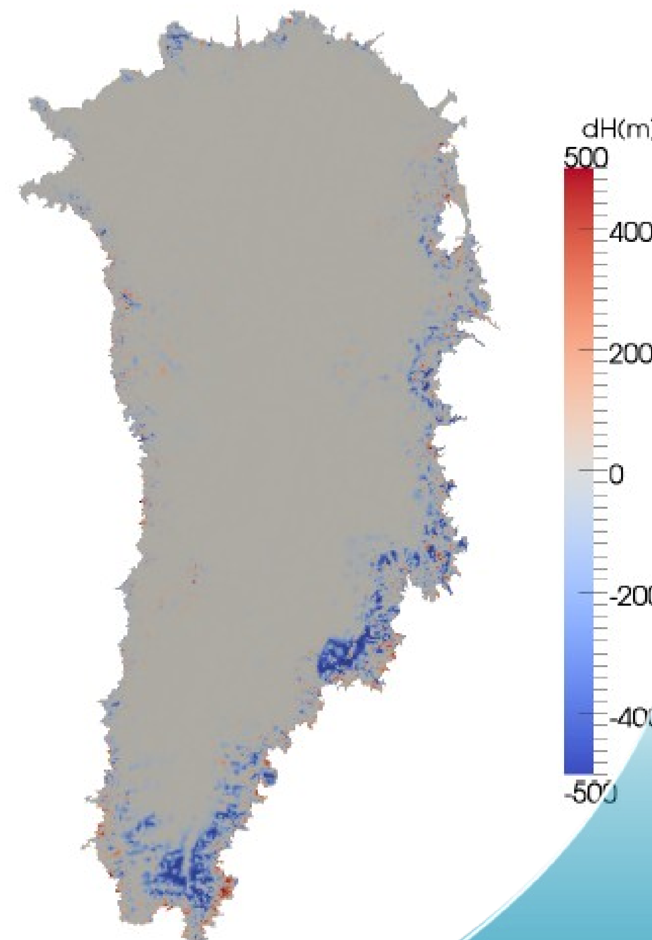
Estimation of ice sheet initial state of Greenland ice sheet

Estimated beta and change in topography

recovered basal friction



difference between recovered and observed thickness



Implementation of adjoints capability in newer code Albany-FELIX

(w/ E. Phipps, A. Salinger, D. Ridzal and D. Kouri [SNL])

Albany-Felix: Albany ice sheet solver (orig. developed by I. Kalashnikova and A. Salinger)

Why?
- to exploit Automatic Differentiation for computing derivatives
- to exploit Albany/Trilinos ecosystem (e.g. for UQ capabilities using Dakota)
- to use in-house software (better maintainability)

Features:
- automatic differentiations to compute adjoints and objective functional derivatives
- coupled with ROL (Rapid Optimization Library) package in Trilinos, to perform reduced gradient based optimization
- coupling with Dakota for UQ capabilities

TODO:
- Implement Hessian to use quasi-Newton methods
- Add shape optimization to be able to invert for bedrock topography
- Improve robustness of inversion and explore different optimization strategies (e.g. SQP)

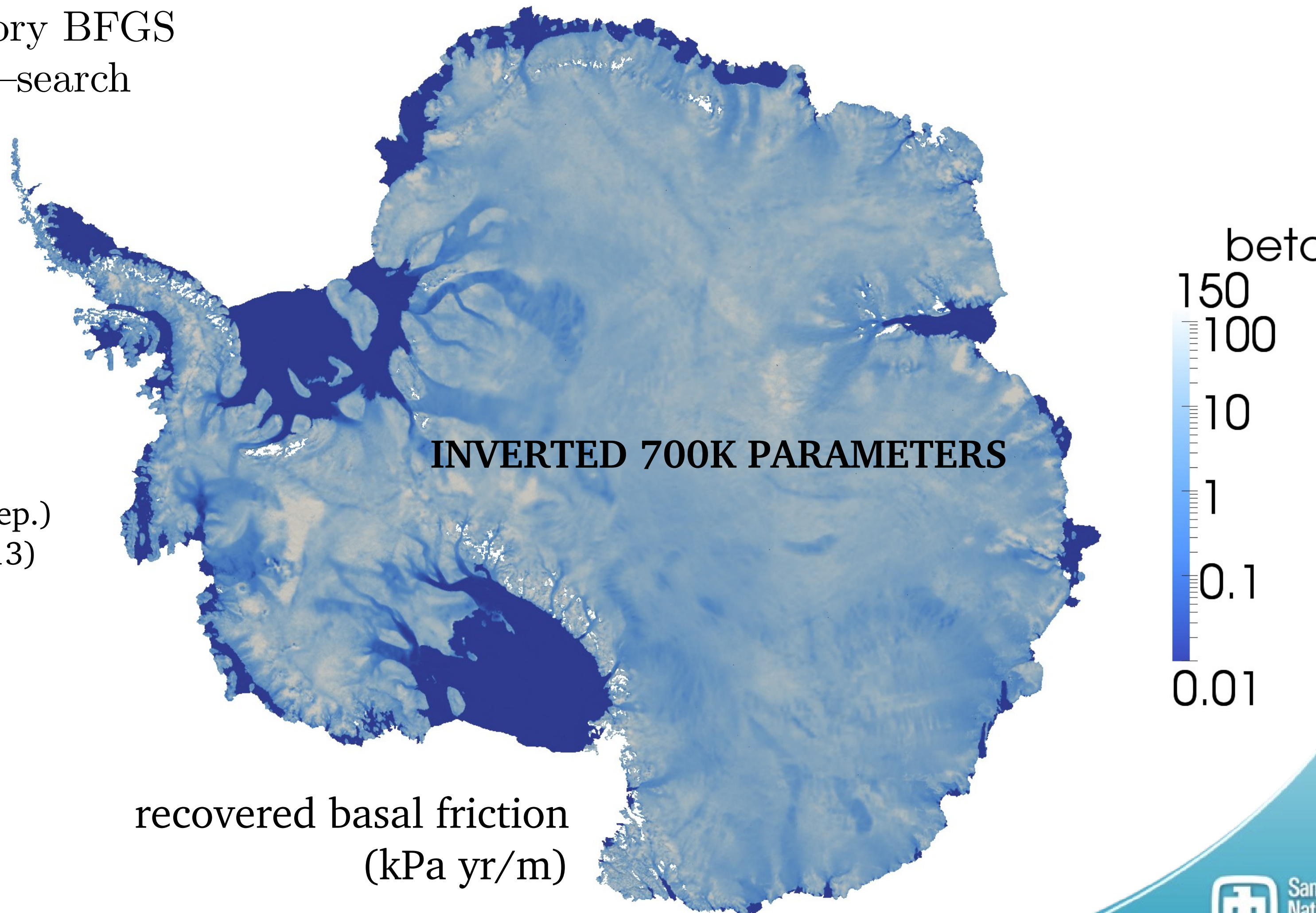
Antarctica Inversion using Albany-Piro-ROL

Objective functional: $\mathcal{J}(\mathbf{u}(\beta),\ \beta) = \int_\Sigma \frac{1}{\sigma_u^2} |\mathbf{u} - \mathbf{u}^{obs}|^2 \, ds + \ \alpha \int_\Sigma |\nabla \beta|^2 \, ds$

ROL algorithm:

- Limited–Memory BFGS
- Backtrack line–search

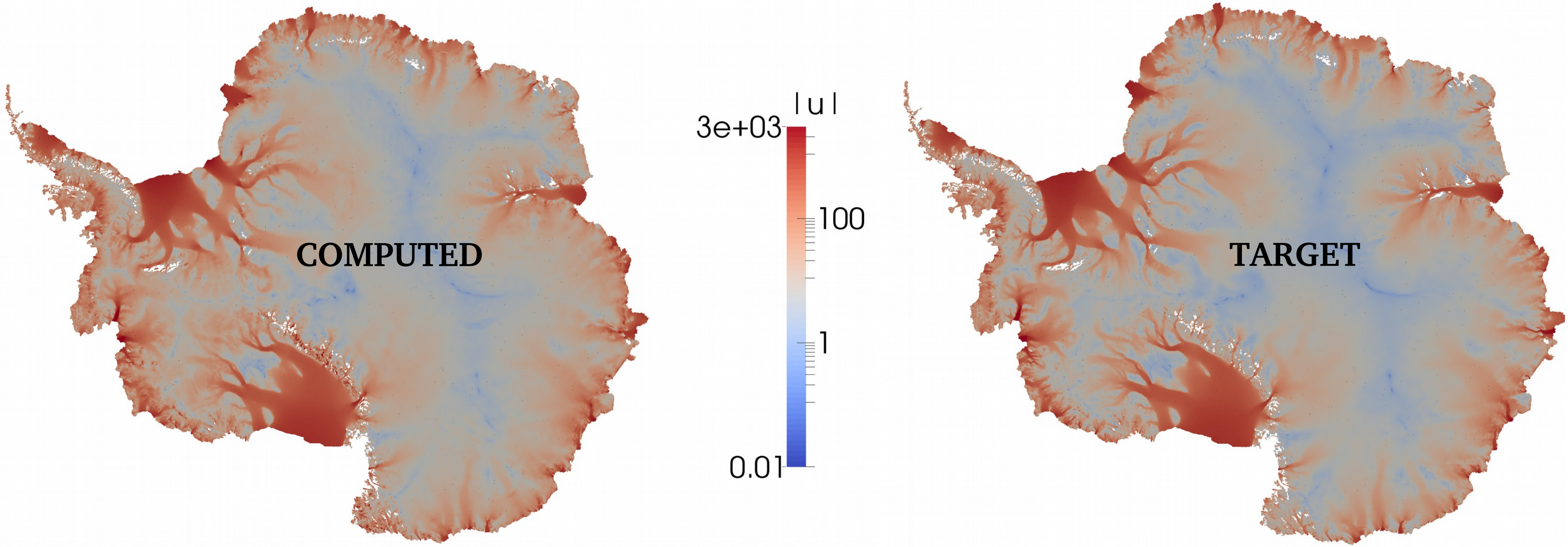
Gometry and fields:
(Cornford, Martin et Al, in prep.)
Bedmap2 (Fretwell et al., 2013)
Temperature (Pattyn, 2010)



recovered basal friction
(kPa yr/m)

Antarctica Inversion using Albany-Piro-ROL

comparison surface velocities, computed vs. target

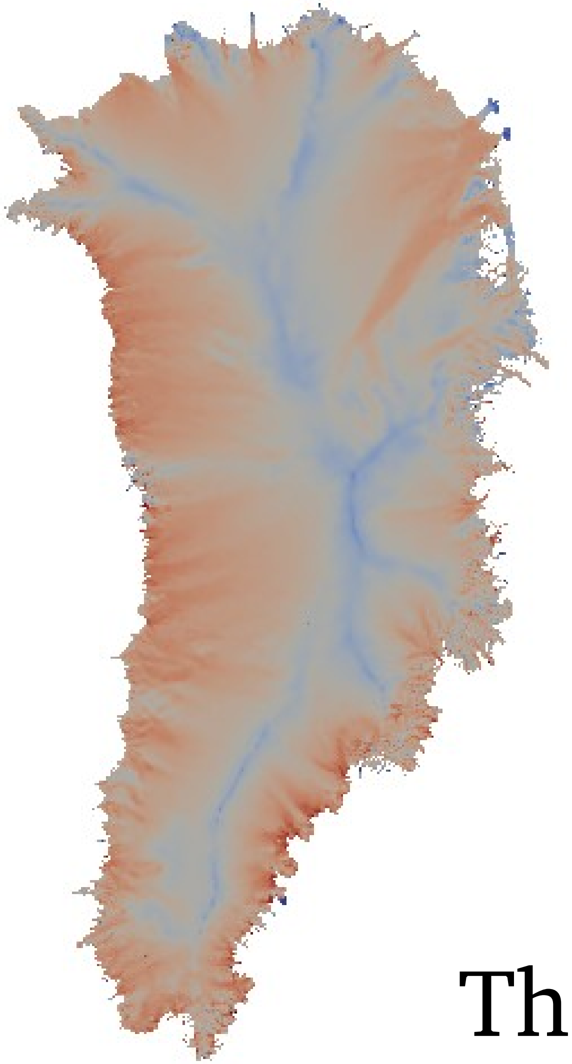


surface velocity magnitude (m/yr)

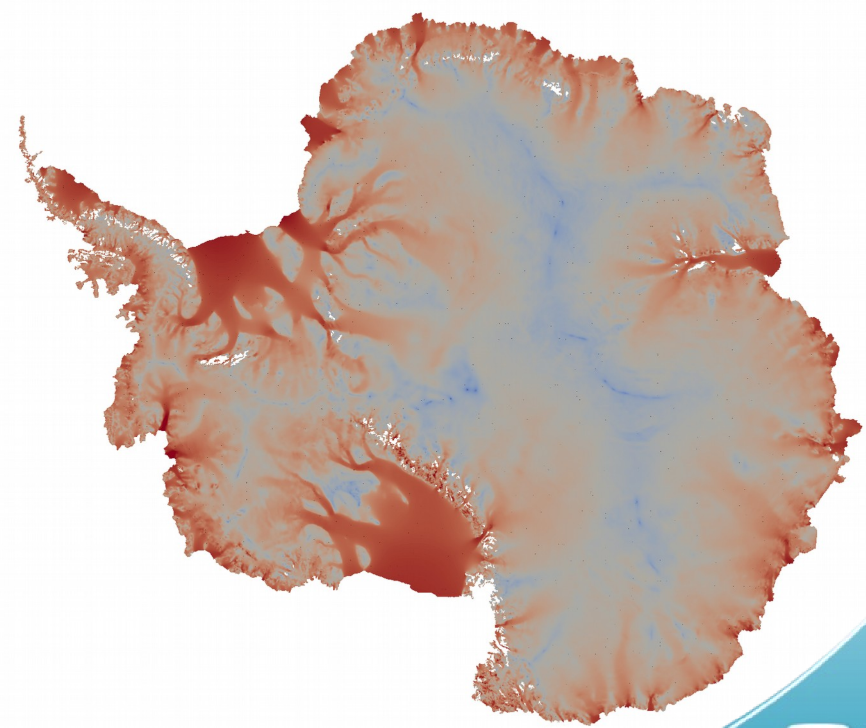
On-going work

Bayesian calibration / Uncertainty propagation (w/ M. Eldred, C. Jackson (U. Texas), J. Jakeman, I. Kalashnikova, G. Stadler (Courant) , A. Salinger)

Use Hessian of deterministic inversion to estimate Covariance of basal friction distribution (N. Petra, G. Stadler, O. Ghattas)



Thank you!



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