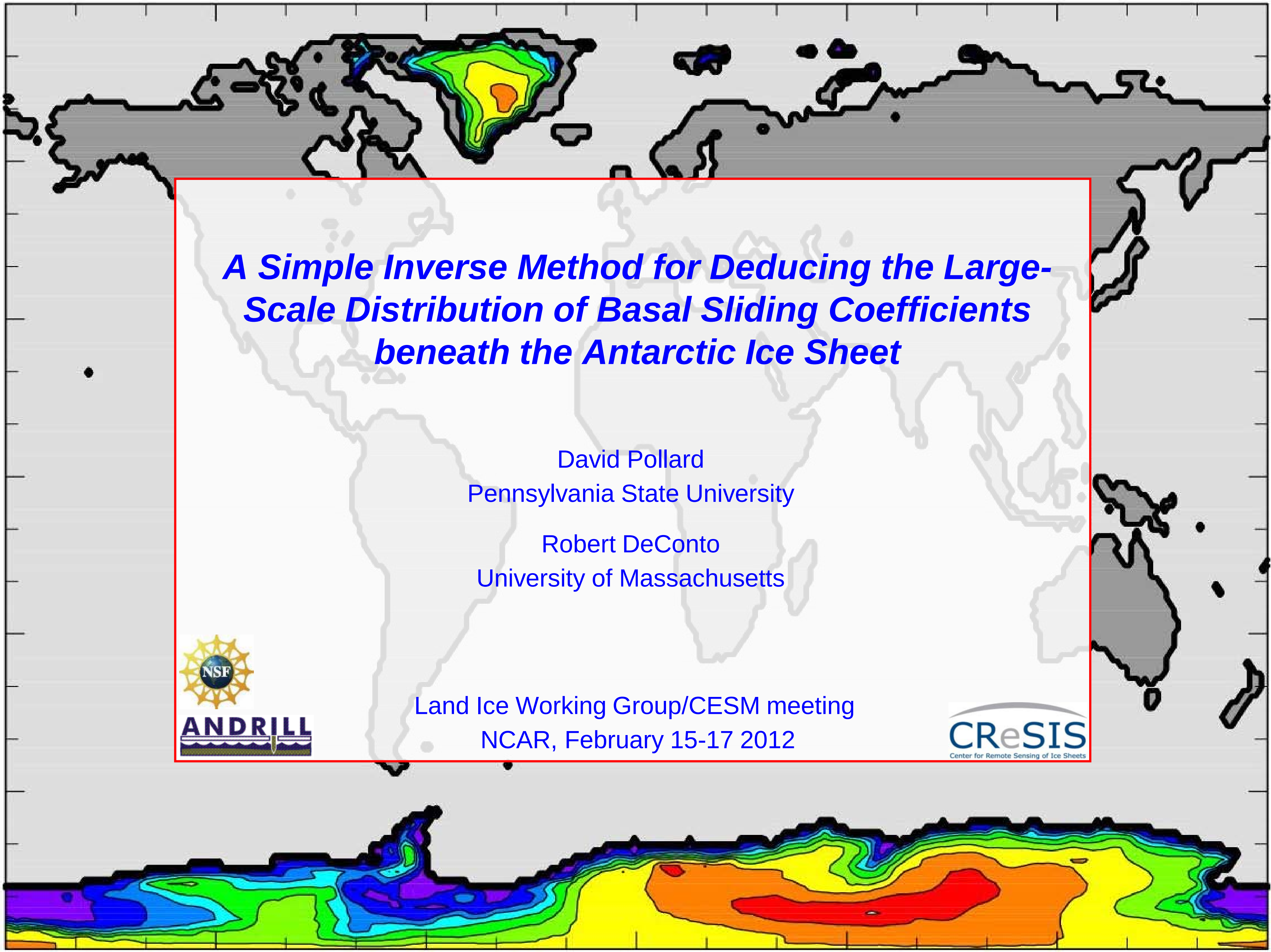

A Simple Inverse Method for Deducing the Large-Scale Distribution of Basal Sliding Coefficients beneath the Antarctic Ice Sheet

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Outline

1. Motivation, previous work

2. Simple inverse method # 1

3. Simple inverse method # 2 (with basal temperature)

4. Comparison with previous work

5. Summary

Motivation

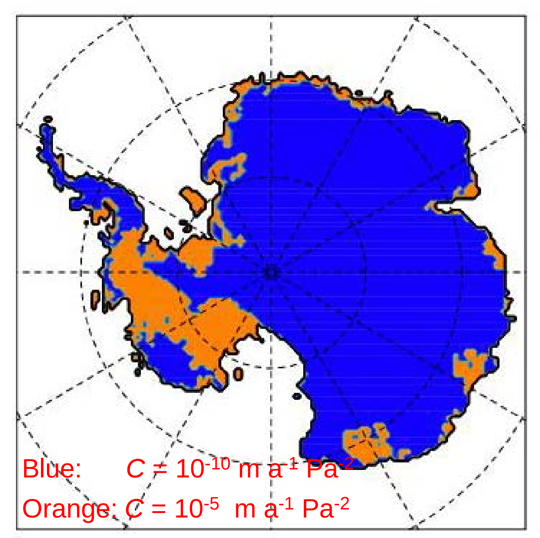
- Ice sheet geometry is sensitive to basal boundary conditions, mainly deformable sediment ($C=10^{-5}$) vs. hard bedrock ($C=10^{-10}$)

$$u_b = C(x,y)\, f(T_b)\, \tau_b^2$$

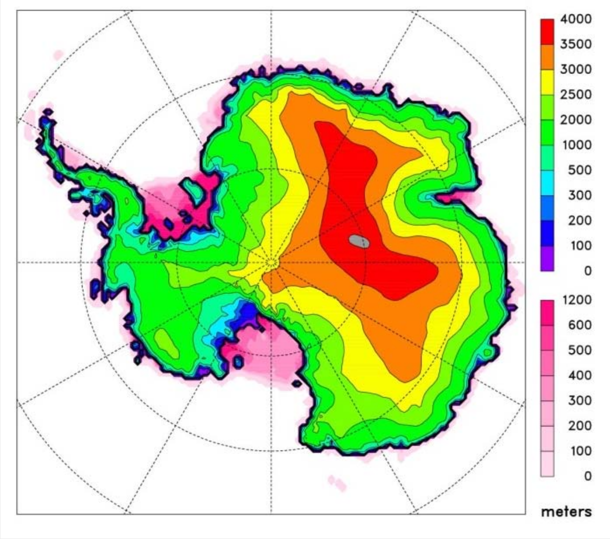
- Primary cause of O(500 m) elevation errors in Antarctic continental paleo ice-sheet models?

where
u_b = basal ice velocity,
τ_b = basal shear stress ,
T_b = basal temperature,
$f(T_b) = 0$ if bed is frozen,
1 if bed is at melt point

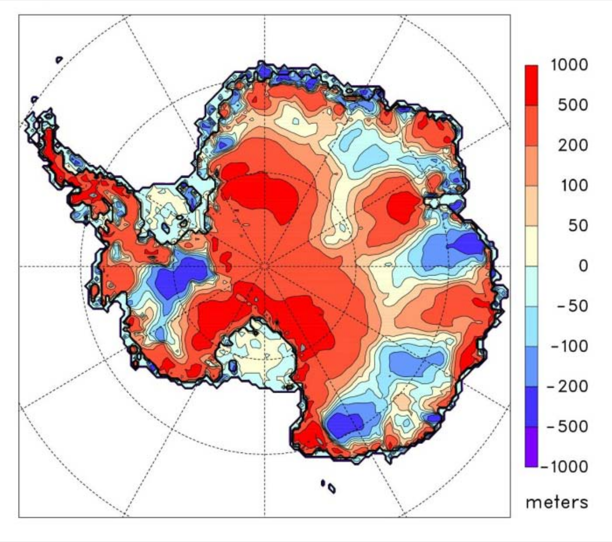
crude $C(x,y)$ map:
sediment if rebounded bed is below sea level, hard bedrock if above



Observed surface elevation



Model minus observed surface elevation



Typical surface elevation or thickness errors
In continental (paleo) Antarctic models

Ritz et al., JGR, 2001

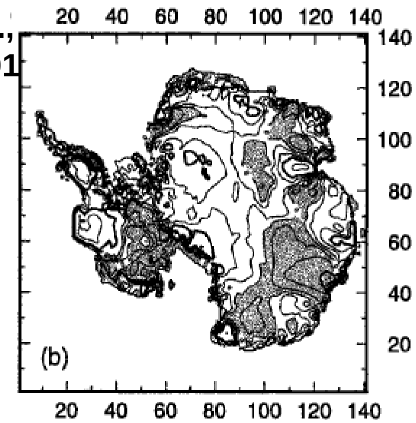
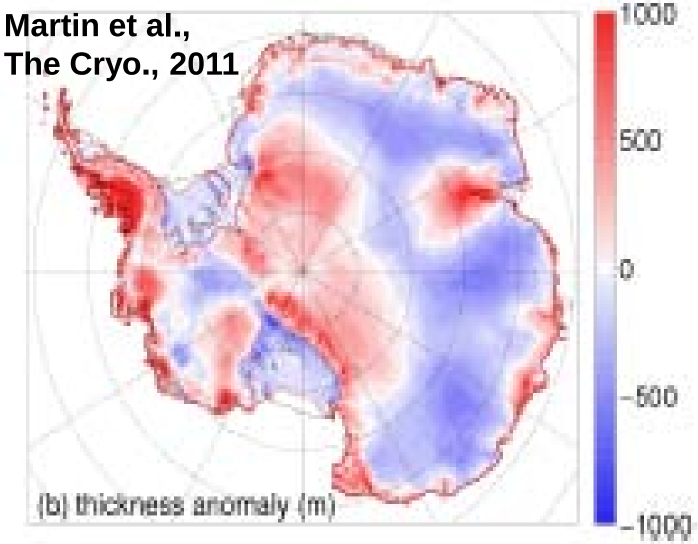


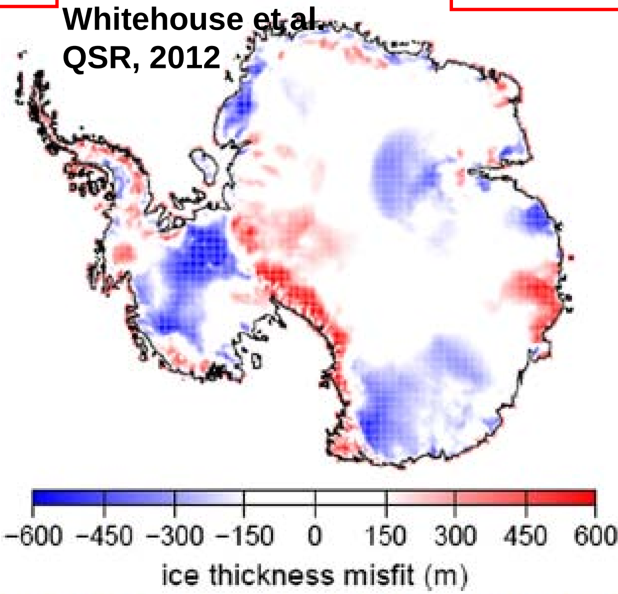
Figure 4. Comparison between observed and modeled surface elevation for the present-day geometry of the grounded ice. (a) Elevation contours: Continuous lines represent observed configuration and dotted lines represent modeled configuration. Thick lines represent grounding lines, thin lines represent isolines for every 1000 m intervals. (b) Altitude difference map: in grey the modeled surface is below the observed one (negative isolines). Isolines are for -1000,-500 (thick line),-250,-100,0,100,250,500 (thick line) and 1000 m. Horizontal scales are as in Figure 3.

Modern surface elevations, model minus observed

Martin et al., The Cryo., 2011



Whitehouse et al. QSR, 2012

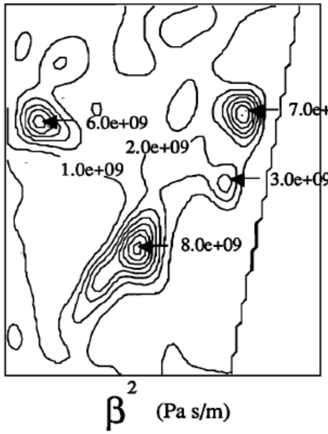


Previous basal inversions for Antarctica

- Previous work has deduced basal-stress or sliding-coefficient maps using control theory (Lagrangian multiplier/adjoint) methods,
  fitting modeled vs. observed velocities, with ice geometry (thickness, elevation) fixed from observations.

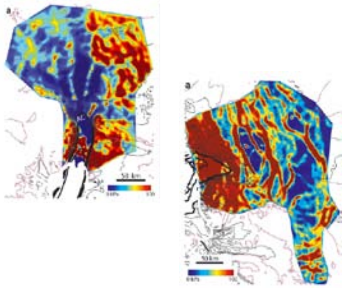
- Regional: MacAyeal,1992; Vieli and Payne, 2003; Joughin et al. 2009; Morlighem et al., 2010.
  Continental: ISSM, Larour et al., ISSM, issm.jpl.nasa.gov; Bueler et al., PISM, www.pism-docs.org.
  Also Price et al. (PNAS, 2011), Greenland, local method.

Ice Stream E
(MacAyeal, 1992):

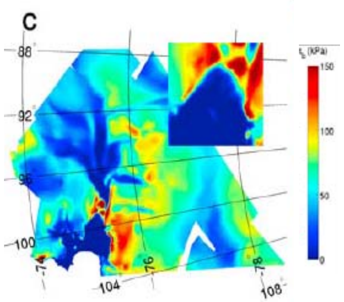


Basal drag coefficient, Ice Stream E. Macayeal JGR, 1992.

Pine Island and Thwaites Glaciers
(Joughin et al., 2009; Morlinghem et al., 2010):

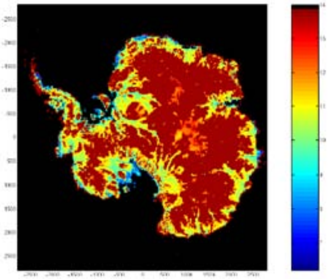


Basal stress, Pine Isl;and and Thwaites Glaciers. Joughin et al., J. Glac., 2009



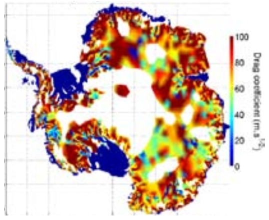
Basal stress, Pine Island Gl: Morlighem et al., GRL, 2010

PISM (U. Alaska):



PISM basal drag coefficient (Pa s m^{-1}). Lingle et al., JPL PARCA meeting, 2007

ISSM (JPL):



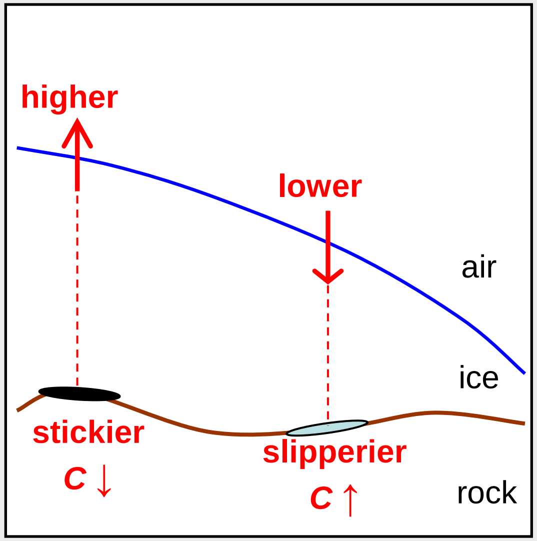
ISSM basal drag coefficient (ms$^{1/2}$). Larour et al., JPL PARCA meeting, 2009

The Inversion Method

- Very simple procedure to deduce basal sliding coefficients *C(x,y)*, fitting to observed ice geometry (surface elevation).
- *Run model forward, and every 5 kyrs adjust C locally depending on current ice surface elevation mismatch with observed*

Details:

- Every 5000 years, decrease (stiffen) *C(x,y)* if the *local* ice surface is too low, or increase (soften) *C(x,y)* if *local* surface is too high:
  - $C_{new} = C\ 10^{\Delta z / 500}$
    where Δz = model – observed surface elevation (m)
  - Constrain *C* to remain in range 10^{-20} to 10^{-5} m a^{-1} Pa^{-2}
- Run model forward for ~200,000 years until convergence



Ignore ∂/∂x, ∂/∂y's….as if effects are local

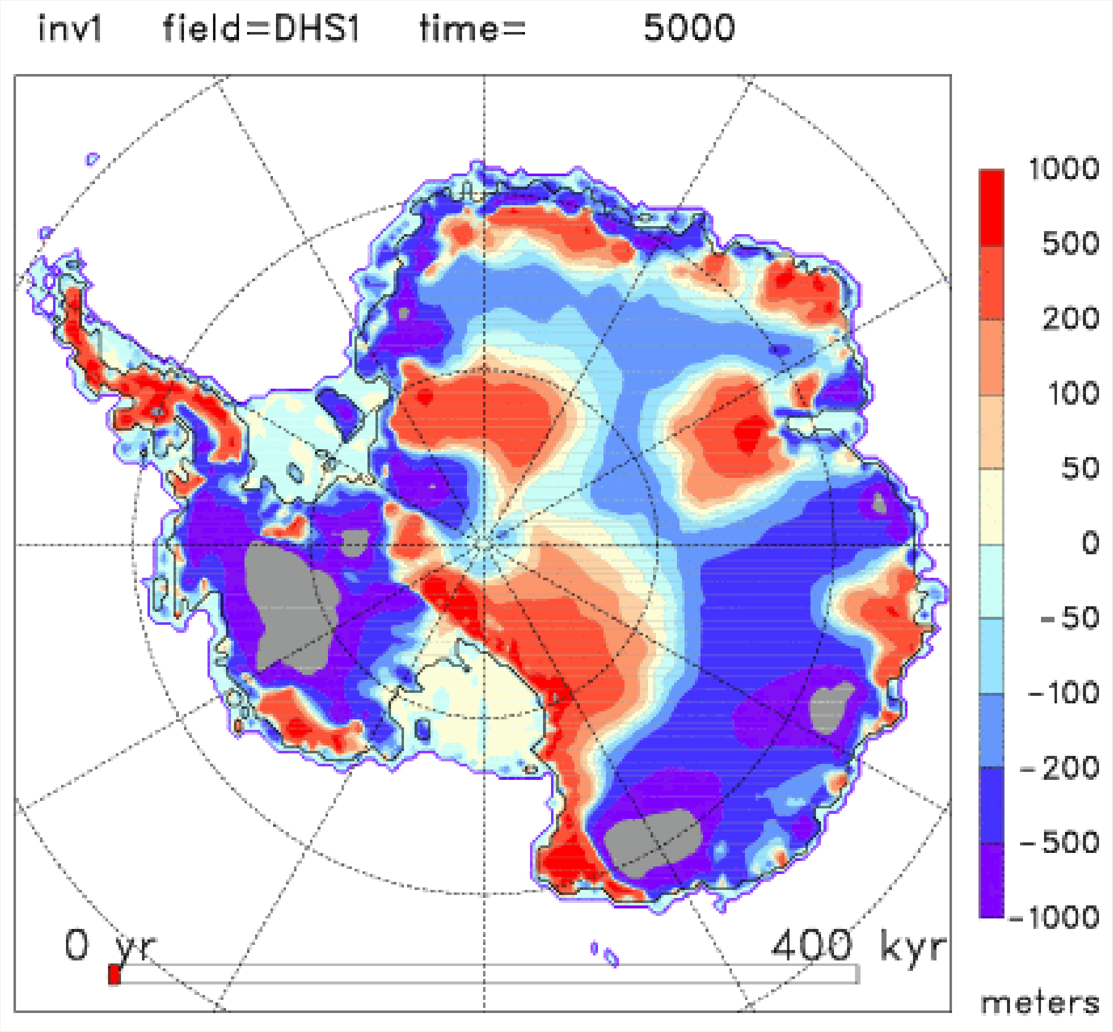
Ignore all other potentially canceling model errors ! (e.g. internal deformation ∂u/∂z)

Ignore GIA - assume modern ice sheet is in equilibrium

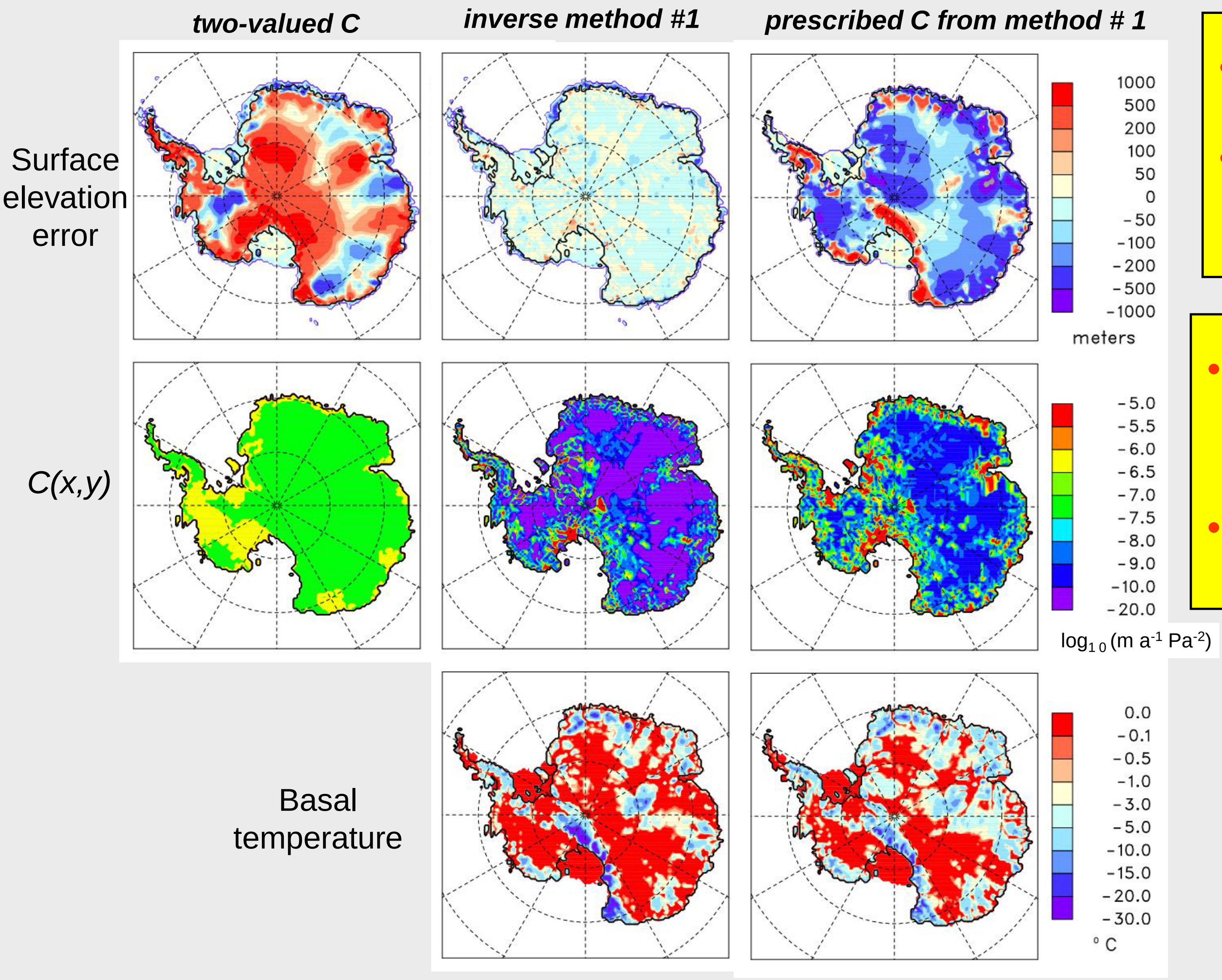
Spinup in a 400,000 year run. The method converges!

years

Model surface elevations minus observed



Results of Method # 1 (no basal temperature effect)



- Turn off effect of basal temperature on sliding
- Allow minimum *C* =10^{-20}, so inverse procedure can find “frozen” (stuck) areas

- But when run full model with *C(x,y)* prescribed, frozen areas differ from inverse-deduced stuck areas.
- Large surface elevation errors re-occur.

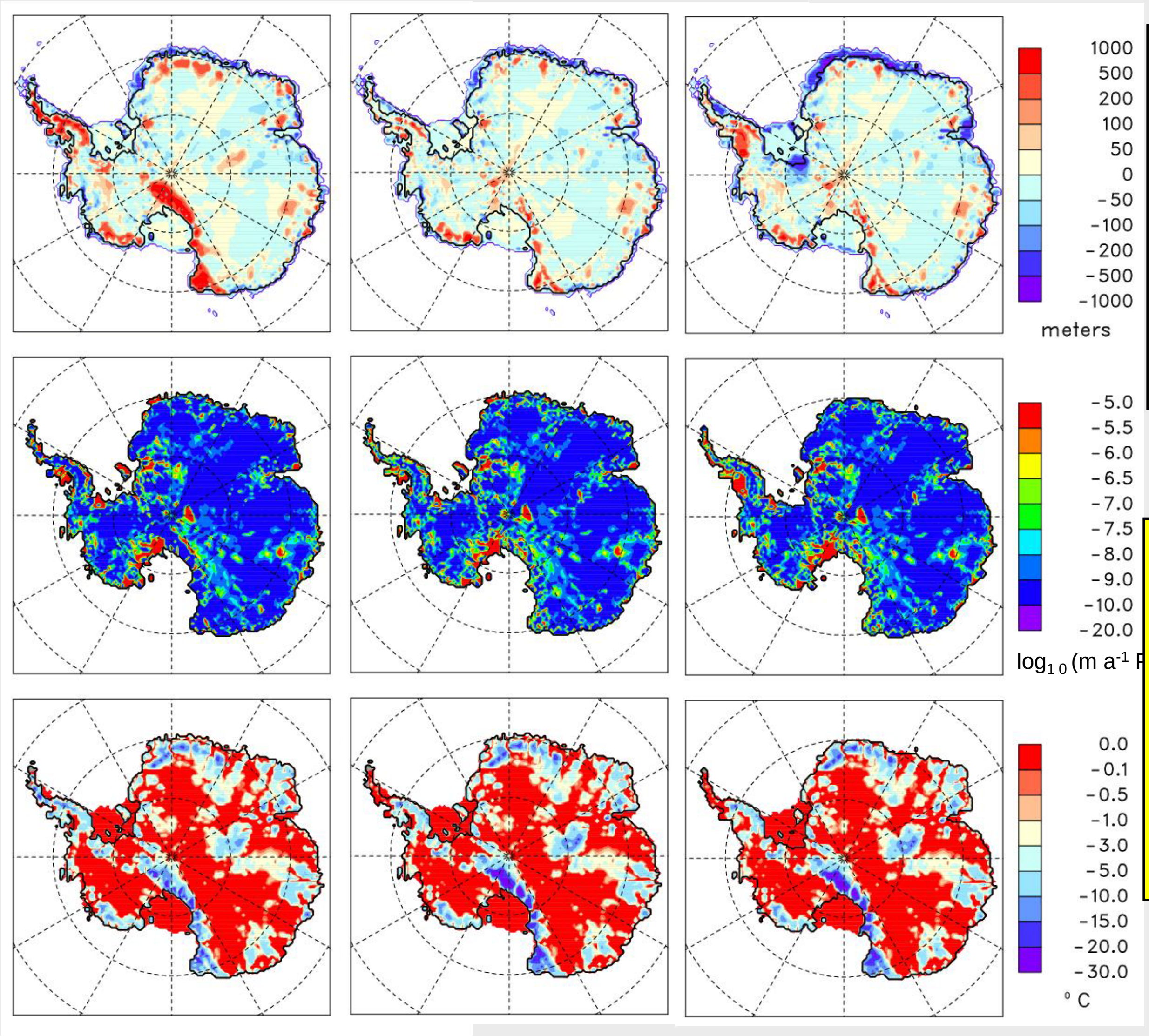
Results of Method # 2 (with basal temperature effect)

inverse method # 2 | *2^{nd} method + s.a.* | *full model, prescribed C (2^{nd} + s.a.)*

Δh_s

$C(x,y)$

T_b

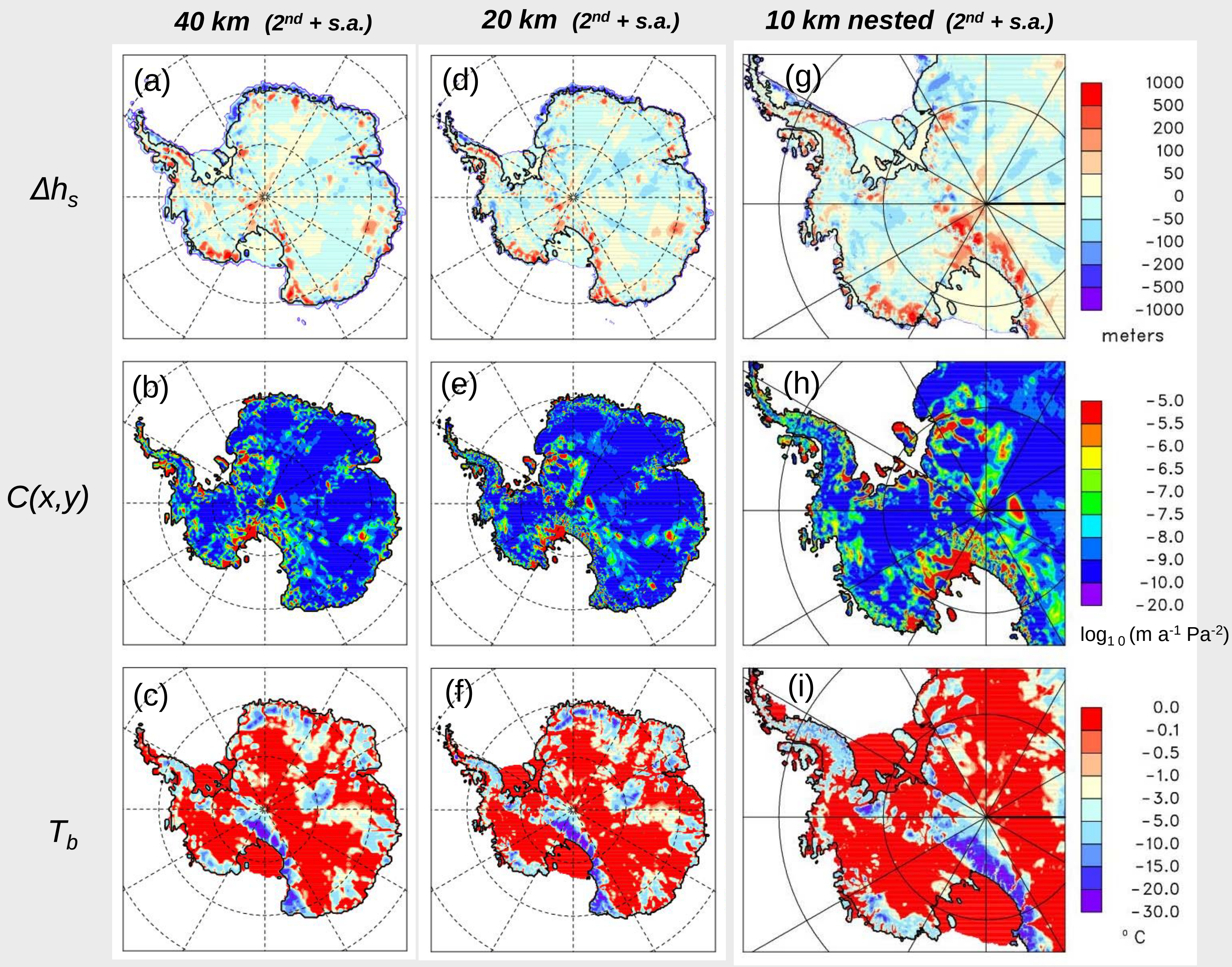


- T_b affects sliding during inversion procedure
- Minimum $C = 10^{-10}$ (hard bedrock)
- Guarantees same results when full model is run with resulting *C(x,y)* prescribed

- Remaining errors over mountain ranges
- Reduce further by modifying $f(T_b)$ in sliding law, using sub-grid slope amplitude *s.a*.

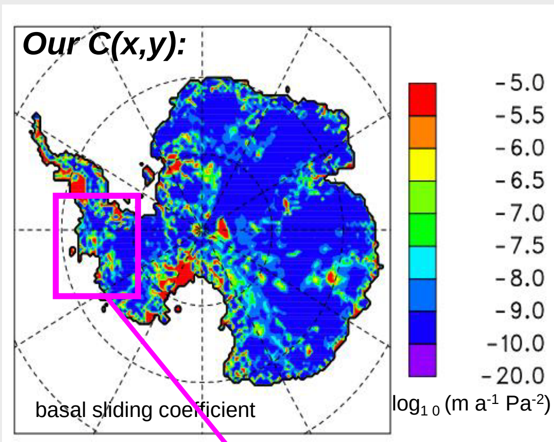
  $u_b = C(x,y)\ f(T_b, s.a)\ \tau_b^2$

Different grid resolutions: results are ~unchanged

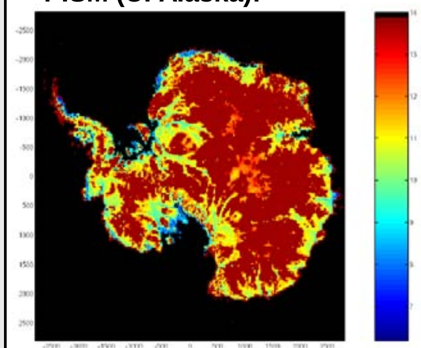


Comparison with previous basal inversions

- Previous studies have fitted model to observed velocities, with ice geometry fixed from observations.
- The method here fits model to observed ice geometry, with no constraints on velocities.
- In principle, this should yield ~same results for *C(x,y),* due to unique relationship between surface mass balance, ice thickness and balance velocity.

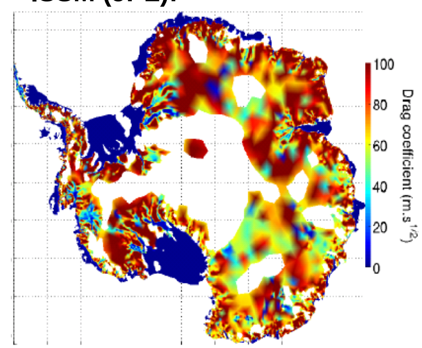


PISM (U. Alaska):



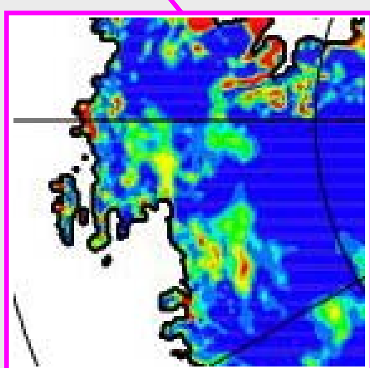
PISM basal drag coefficient (Pa s m^{-1}). Lingle et al., JPL PARCA meeting, 2007

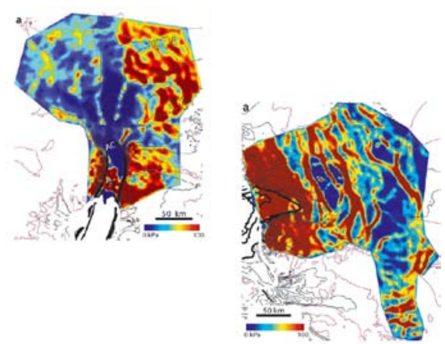
ISSM (JPL):



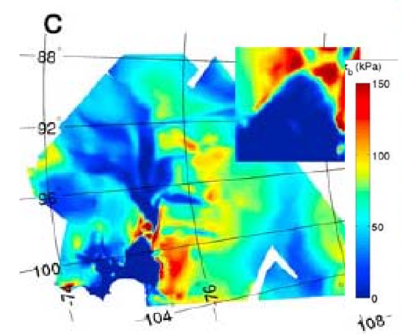
ISSM basal drag coefficient ($ms^{1/2}$). Larour et al., JPL PARCA meeting, 2009

Pine Island and Thwaites Glaciers:





Basal stress, Pine Isl;and and Thwaites Glaciers. Joughin et al., J. Glac., 2009



Basal stress, Pine Island Gl: Morlighem et al., GRL, 2010

Summary

- Simple inverse method "works":

  (a) converges, (b) reduces surface elevation errors, (c) deduces reasonable $C(x,y)$ patterns.

- Independent of ice model. Just needs:

  (a) run for ~200,000 years, (b) bedrock parameter(s) that make u_b increase or decrease.

- ***BUT*** some of the deduced $C(x,y)$ *must* be due to other model errors, not real bed conditions.

  Lesser of two evils: cancelling errors vs. O(500m) biases in surface elevation

- Next steps:

  - Combine with large-ensemble techniques? (Stone et al., The Cryo. 2010; Tarasov et al., EPSL, 2011)

  - Apply to last deglaciation (Briggs et al., ISAES abs., 2011.; Whitehouse et al., QSR, 2012)