Verification, Validation, and Uncertainty Quantification for PISCEES*

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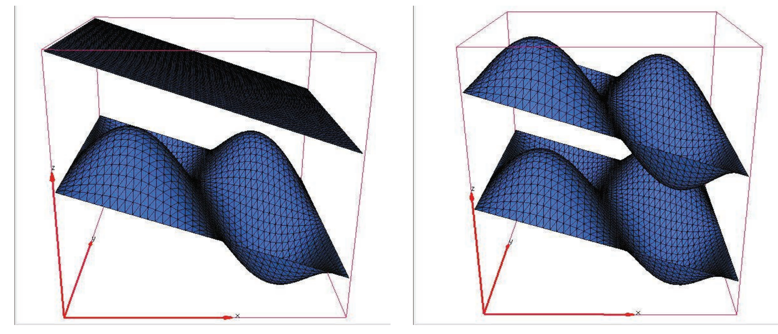
Verification

The continental-scale ice sheet community relies on a suite of test cases to verify model results and CISM and its predecessor Glimmer (Rutt et al. 2009) are no exception. The move to a dynamical core that solves the higher-order velocity approximation with the release of CISM2.0 and near term development that will enable Stokes flow (see equations to the far right), as well significant development to incorporate a nonlinear solver framework and parallel capability (Evans et al., 2012) has highlighted the need for more comprehensive and automated verification tools.

The existing suite of test cases are being combined into a collection of cases designed for easy use and extension to aid in the development of the FELIX and BISICLES dycores. As the model becomes more complex, new exact (Bueler et al., 2005) and manufactured (Leng et al., 2012) solutions are crucial for proper verification, and recent and additional efforts in this area will be incorporated into the verification test suite. For example, manufactured analytic solutions developed to verify a three-dimensional, nonlinear, Stokes-flow based finite element model (Leng et al., 2012) will be included as model development within CISM focuses on Stokes flow.

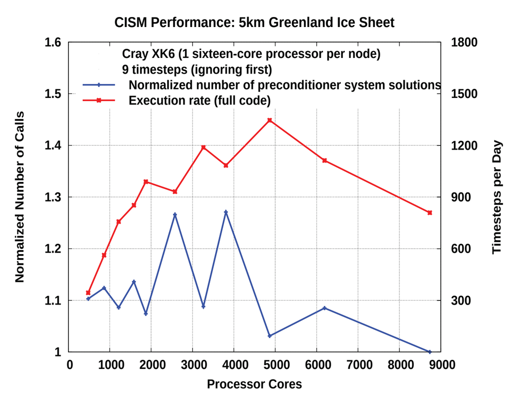


Simulation results for the ice sheet geometry (the top and bottom surfaces) to compare to the manufactured solutions at the time t = 0 (left) and at at the time t = 1000yr (right).(from Leng et al., 2012).

Performance V&V: Solver robustness and validation as a function of expense (simulation value)

We propose to create a performance V&V capability to provide information to model developers as to whether new model features (1) introduce undesirable solution or parallelism issues that affect model solution time and robustness (model is verified for performance) and (2) provide acceptable simulation value (model solves the problem of interest with acceptable expense). Also, we will include performance benchmarks to uncover issues with simulation at scale as the model is developed on novel architectures.

Right Figure: Performance variability of the JFNK velocity solver due to changes in the additive Schwartz preconditioner as the number of processes and associated domain decomposition change. The blue curve is the number of calls to solve the preconditioner system, normalized by the fewest number of calls, indicating the efficacy of the preconditioner. The red curve is the execution rate for the code, including an increasing percentage of parallel overhead for large processor core counts.



Citations:

Bueler, E., C.S. Lingle, J.A. Kallen-Brown, D.N. Covey, and L.N. Bowman (2005). Exact solutions and verification of numerical models for isothermal ice sheets. Journal of Glaciology, **51,** 291-306.
Evans, K.J., A.G. Salinger, P.H. Worley, S.F. Price, W.H. Lipscomb, J.A. Nichols, J.B. White III, M. Perego, M. Vertenstein, J. Edwards, J.-F. Lemieux (2011) "A modern solver interface to manage solution algorithms in the Community Earth System Model." Int. J. High Perf. Comp. Appl. **26,** 54-62.
Leng, W., L. Ju, M. Gunzburger, and S. Price (2012). Manufactured solutions and the numerical verification of isothermal, nonlinear, three-dimensional Stokes ice-sheet models, The Cryosphere Discussions, **6**: 2689-2714.
Perego, M. and M. Gunzburger, John Burkardt (2012) "Parallel Finite Element Implementation for Higher-Order Ice-Sheet Models," Journal of Glaciology, **58,** 76-88.
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V&V within CISM and CESM

Land Ice Validation package, beta02 09/04/2012

GIS Configure Diagnostics
GIS Ijob Output Diagnostics
GIS Thickness

An automated software package is being developed to aid in the V&V of the dycore development occurring in PISCEES, the coupled CESM, and the ice sheet modeling community. Currently it is just begun, and provides:

> simulation information
> performance diagnostics, including failures
> plots of the simulation, and its difference from a selected benchmark

Link to CISM Diagnostics

Above: screenshot from the initial python based V&V software package applied to a CISM 5km Greenland test case

Configure File Diagnostics

CF Output
----
variables = artm beta topg thk usurf uvel vvel wvel flwa velnorm temp

Grid
----
upn = 11
ewn = 501
nsn = 601
dew = 5000
dns = 5000

Time
----
tstart = 51.0
tend = 100.0
# of time steps = 49.0

Parameters
----
flow_factor = 1

Options
----
flow_law = 0
evolution = 3
temperature = 3

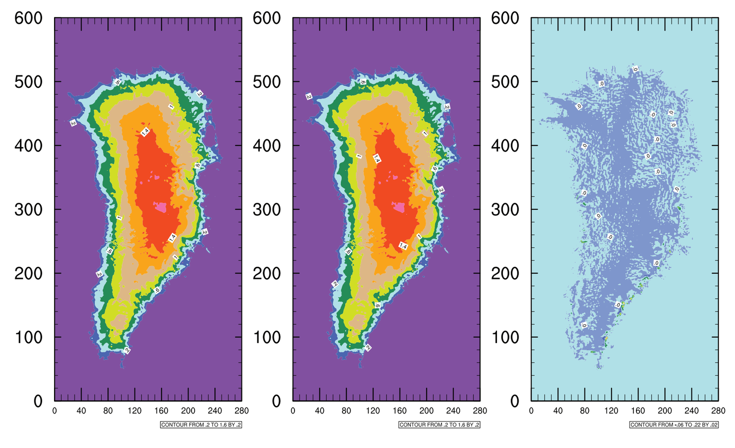
Model run incomplete, pick a new ijob output file for diagnostics!

Ijob Output Diagnostics

Number of Processors = 1500
Number of Nonlinear Iterations = 11, 8, 15, 21, 5, 17, 25, 5, 20, 17, 11, 15, 150***, 30, 16, 19, 20, 5, 15, 12, 11, 9, 5, 5, 5, 5, 17, 150***, 48, 57, 18, 14, 11, 4, 10, 4, 9, 4, 4, 4, 4, 24, 4, 20, 5, 5, 15, 5, 38, 23,
***TIME STEP(S) WHICH FAILED TO CONVERGE
Average Number of Linear Iterations per Time-Step = 10.455, 10.875, 10.067, 8.048, 16.4, 10.471, 14.08, 16.6, 12.4, 9.882, 12.0, 10.8, 16.607, 12.133, 11.438, 8.737, 10.75, 14.8, 9.533, 9.833, 10.273, 11.667, 15.2, 15.8, 15.0, 15.0, 11.588, 14.06, 13.938, 7.018, 11.944, 8.929, 10.455, 16.0, 10.1, 15.5, 10.0, 16.25, 15.75, 16.75, 15.75, 12.375, 13.0, 9.45, 14.8, 15.4, 9.133, 10.4, 9.921, 15.13,

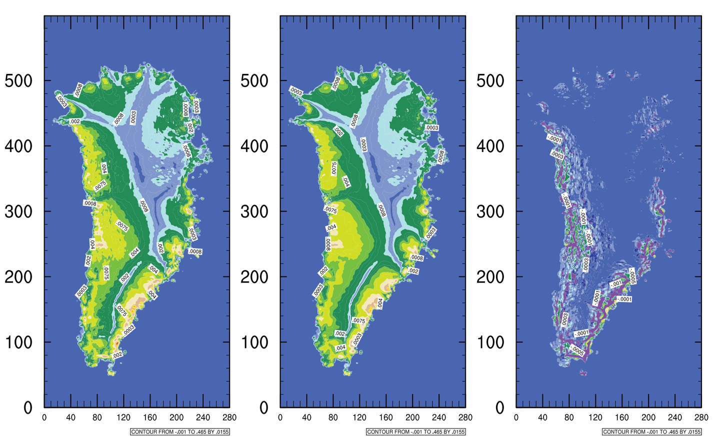
Above: screenshot from solver statistics for a GIS run where several timesteps did not converge successfully.

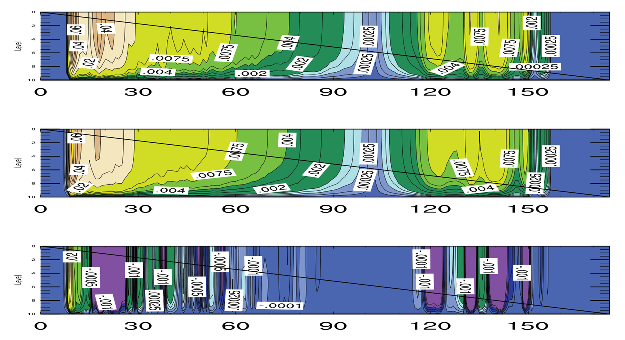
Thickness



Individual links to plots and stats of the CISM simulation compared to benchmark (simulated, observed, and/or reanalysis) for a range of desired fields. Both 2D (thickness), and 3D (velocity magnitude and direction) will be provided, and in multiple formats to aid in evaluation. Significant interaction with the CISM and CESM community is underway.

Velocity Norm





3D fields such as velocity can be viewed in several dimensions, and both as a magnitude and vectors. Above: velocity magnitude for a GIS 5km simulation after 50 years (left) compared to the initial values (center) and the difference (right). To the left, a plot of the velocity magnitude as a vertical slice about halfway up the GIS for the same 50 year simulation as above (top) compared to the initial values (center) and the difference (bottom). This plot is used to aid in determining subsurface characteristics.

Validation

With the release of version 2.0 this fall, Glimmer-CISM solves the higher-order (HO) longitudinal and transverse stress gradients (Pattyn, 2003). This is an extension of the shallow ice approximation used in Glimmer, and allows a more complete representation of ice flow near the ice divides and ice sheet margins (e.g. grounding lines and outlet glaciers). Nonetheless HO is still an approximation to the full Stokes equations as follows:

$$\nabla \cdot \mathbf{v} = 0$$
Mass conservation: For HO, simplified to an ice thickness relation.

$$\frac{d\mathbf{v}}{dt} = \nabla \cdot \sigma + \rho \mathbf{g}$$
Momentum conservation: For HO, set acceleration terms to zero but keep more stress terms.

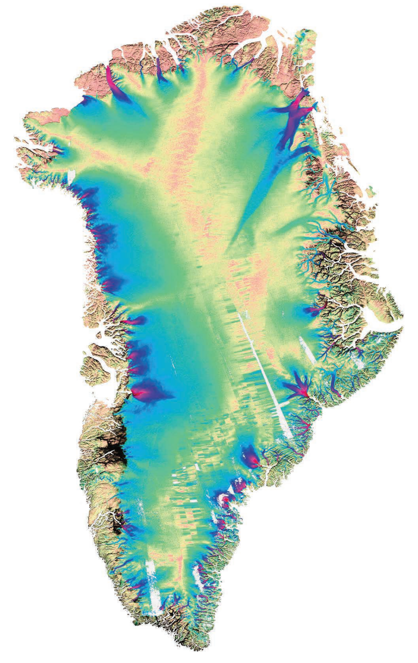
$$\rho \frac{c_P \theta}{dt} = \nabla(k_i \nabla \theta) + \Phi$$
Energy conservation: For HO, simplified to a heat transfer relation.

The simplification of the equations to the HO approximations are presented by Pattyn (2003). The velocity vector is $\mathbf{v} = \{u, v, w\}$, the two-dimensional divergence, gradient operators are $\nabla\cdot, \nabla$. The stress tensor, ice density, gravity, heat capacity, thermal conduction, and the internal friction and temperature of ice are given by $\sigma, \rho, \mathbf{g}, c_P, k_i, \Phi, \theta$, respectively.

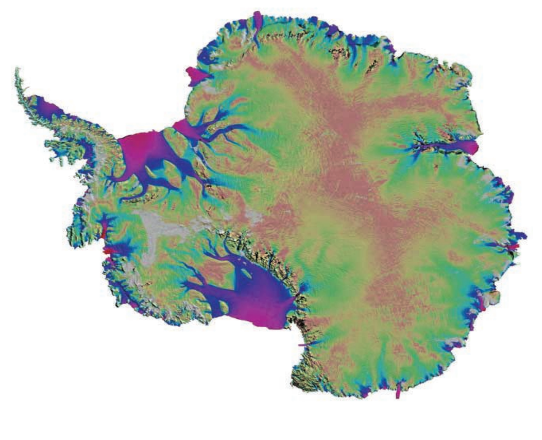
The PISCEES V&V effort is tasked to evaluate the ability of CISM to simulate ice sheet behavior by using observations and data from independently validated models as comparison. From this we will connect closely with UQ efforts and build model-data mismatch functions to create cost/objective functions for optimization work (e.g., for tuning basal sliding coefficients).

Near Term Target Simulation Problems: Greenland Ice Sheet

We will incorporate the very recently available comprehensive, high-resolution, digital mosaic of Greenland ice sheet velocities assembled from satellite radar interferometry data acquired during the Int'l Polar Year 2008-9 (Rignot and Mouginot, 2012). These will initialize the model and provide a benchmark for comparison for tuning and stability. New regions of enhanced flow pose new accuracy constraints but also an opportunity for more comprehensive validation: a grand challenge for continental ice sheet models. By contrast, ice thickness mapping is less comprehensive, to date.



Ice velocity map of the GIS assembled from SAR (from Rignot and Mouginot, 2012).



Balanced ice velocity magnitude of Antarctica assembled from SAR (from Rignot et al., 2011).

Antarctic Ice Sheet

We will also incorporate data of the Antarctic ice sheet velocities acquired during the Int'l Polar Year 2007-9 (Rignot et al., 2011) to perform similar validation work, but with the additional challenge of problem size and the revelation from this data that basal-slip-dominated tributary flow is more important than previously thought. Again, this presents an opportunity for continental ice sheet models to provide enhanced understanding once comprehensive data model comparisons have been performed as part of the validation procedure.

Other datasets to be incorporated as they become available include:
1) 3d maps of internal layers (isochrons) observed by ice penetrating radar
2) ice sheet internal temperatures as measured in (a handful of) ice core boreholes (vertical profiles at point locations on the ice sheet)
3) 2d maps of thawed vs. frozen basal conditions

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Uncertainty Quantification

Problem

Controls on basal friction or sliding are very important to ice flow. However we have very little information about these conditions:

Sediments

Topography

Geothermal fluxes

Water pressure and distribution

The initialization process can approximate observed surface geometry and velocities with compensating errors in conditions and properties in quantities we know little about.

Experiment Strategy

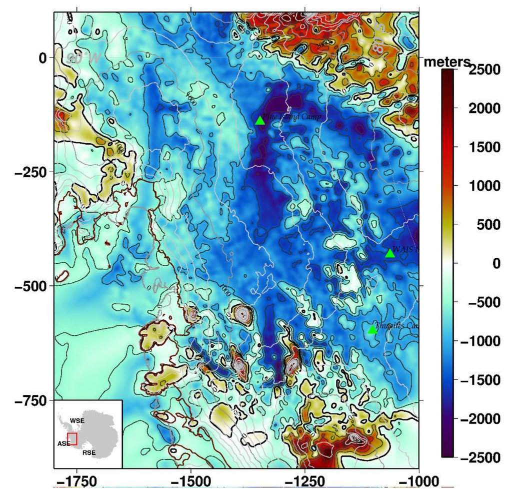
Sample the different ways to initialize an ice sheet consistent with observations. Estimate impacts on response to environmental change.

However, ice sheet initialization is expensive. Testing effects of 10 dimensions (e.g. parameters) would need around 500 experiments for an approximate cost of 27 million cpu hours. Many of the uncertainties are high dimensional (e.g. basal boundary condition).

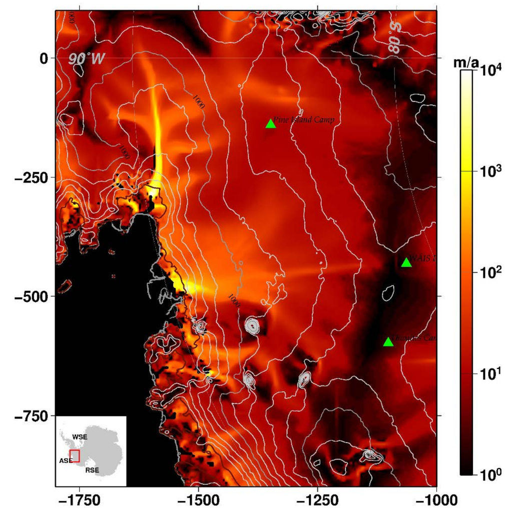
The initialization process can approximate observed surface geometry and velocities with compensating errors in conditions and properties in quantities we know little about.

Observations of the "Weak Underbelly" currently the region of largest mass loss in Antarctica

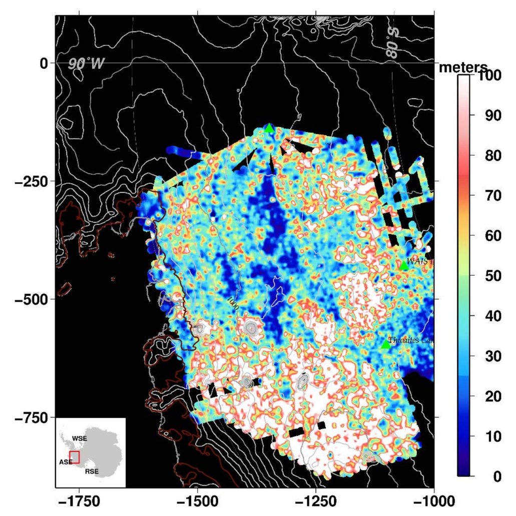
5-km grid bed topography



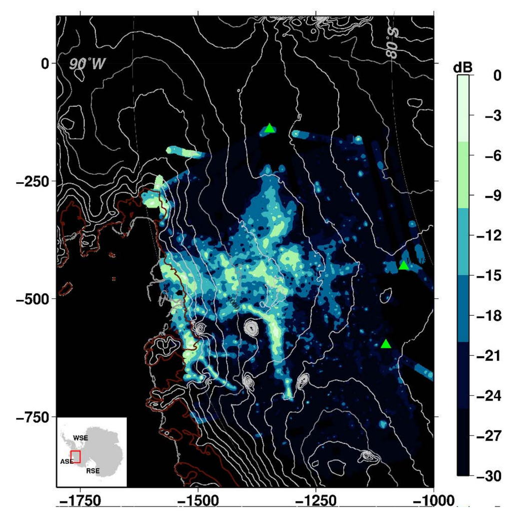
surface geometry and velocity



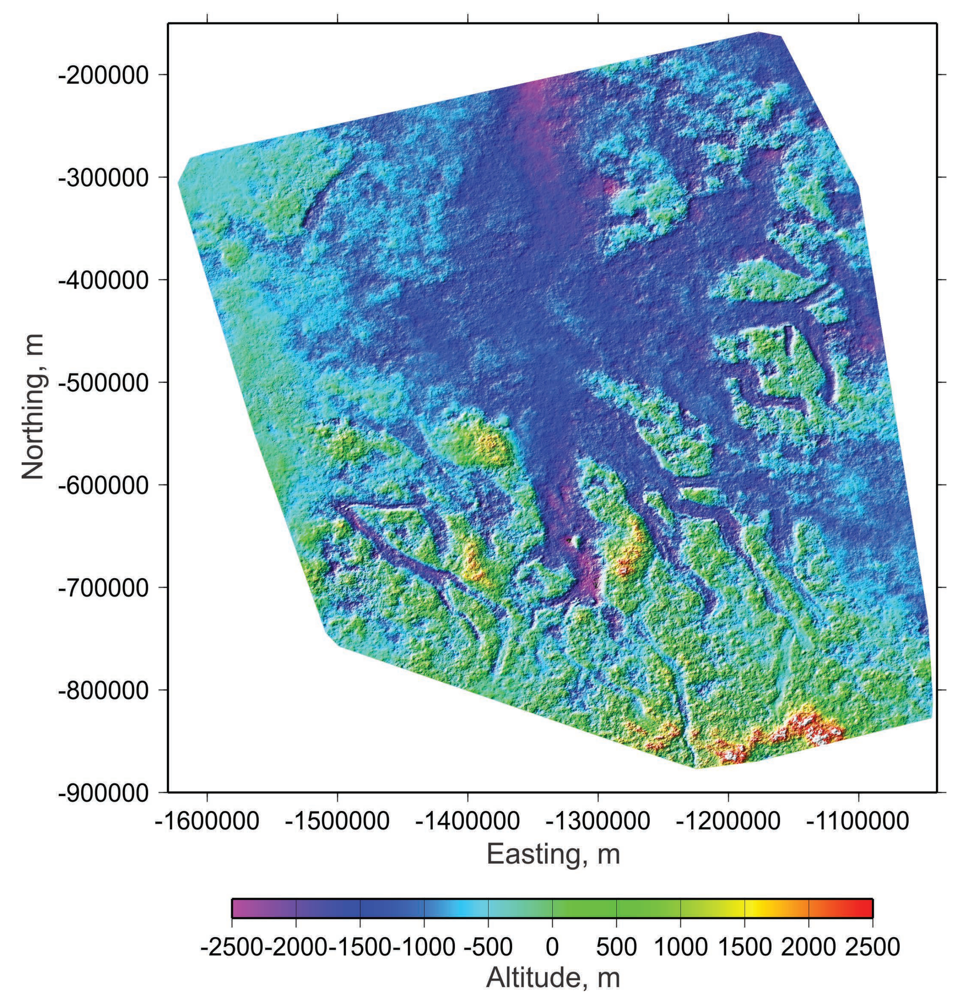
Bed roughness at 800 meter scale



Basal water indicator

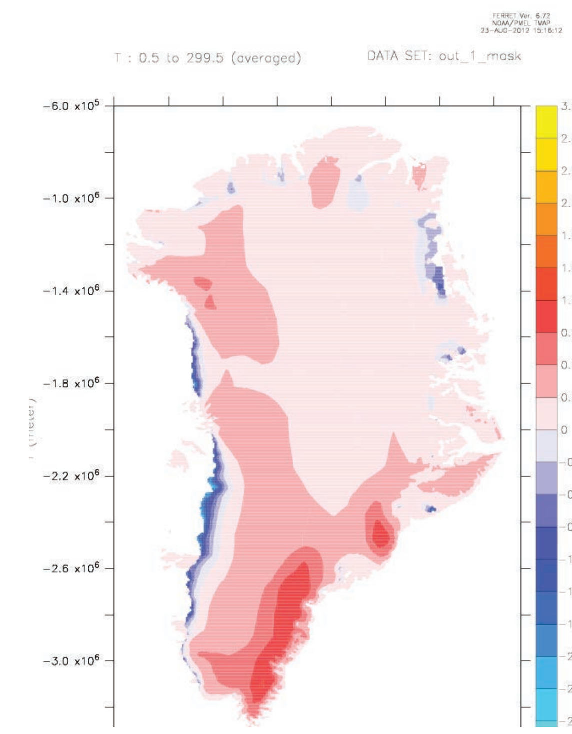


"New" statistical Thwaites bed topgraphy at 250 m resolution.
Based on same data as 5-km grid but using along track data to characterize unknowns.

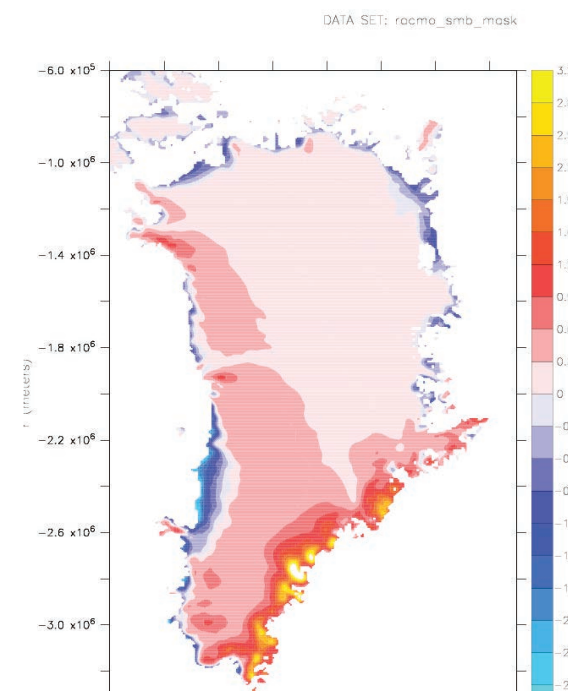


Greenland Surface Mass Balance

CESM Simulated



RACMO data constrained



***Predicting Ice Sheet and Climate Evolution at Extreme Scales**