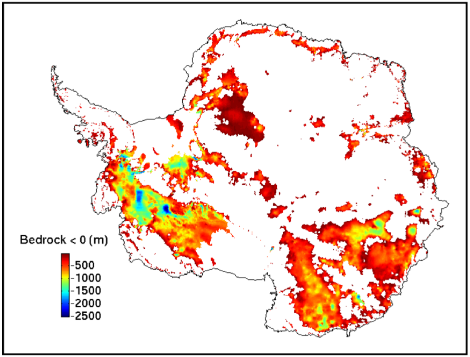
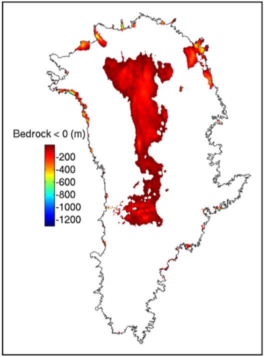
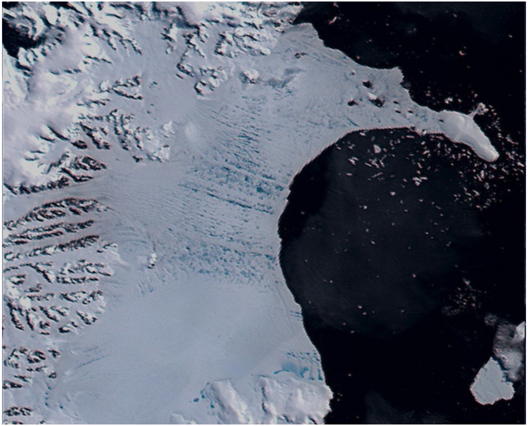
Antarctica and Greenland bedrock is in large part below sea level





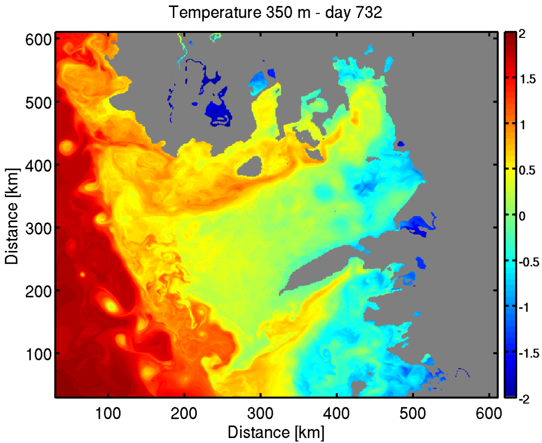
Prone to "Marine Instability".

Catastrophic collapse of ice shelves



Larsen B Ice Shelf, Jan-31st $->$ March-7th 2002. 3,250 km^2 of ice 220 m thick disintegrated (size of US state of Rhode Island). Larsen B was stable for up to 12,000 years. Poor understanding of mechanisms leading to collapse (formation of melt-water ponds that weaken the shelf by creating tabular slabs of ice).

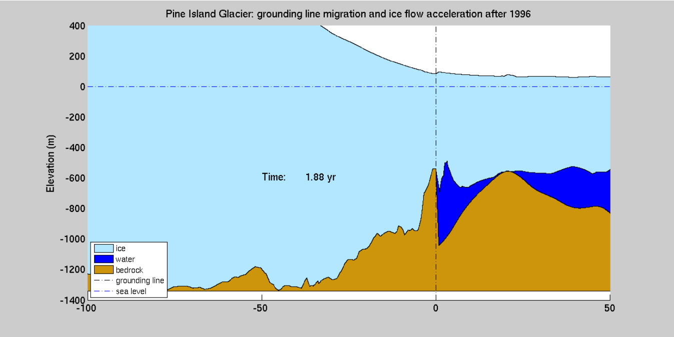
Ice/Ocean Interactions



Schodlok et al, 2012:

- Warm Circumpolar Deep Water (CDW) pathways onto Pine Island Bay.
- Impact on melt-rates at the grounding line and grounding-line dynamics.

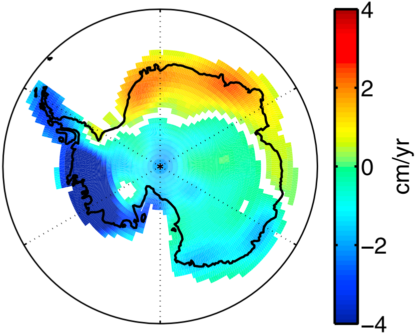
Grounding line retreat



Larour et al, proceedings FRISP 2012

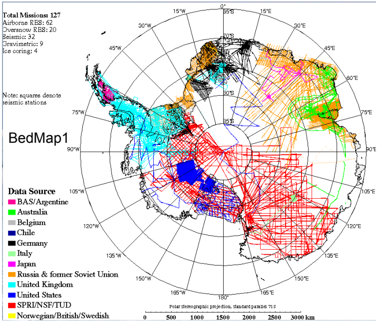
Ice/Atmosphere Interactions

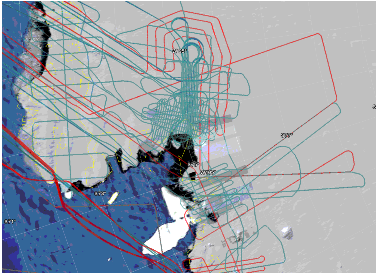
- Extreme precipitation events along the East Antarctic Coast
- Significant regional accumulation.
- Compensates for some of the recent global ice mass losses in West Antarctica



GRACE mass trends from 2004 to 2011 in cm/yr. Boening et al, 2012.

Unknown geometry

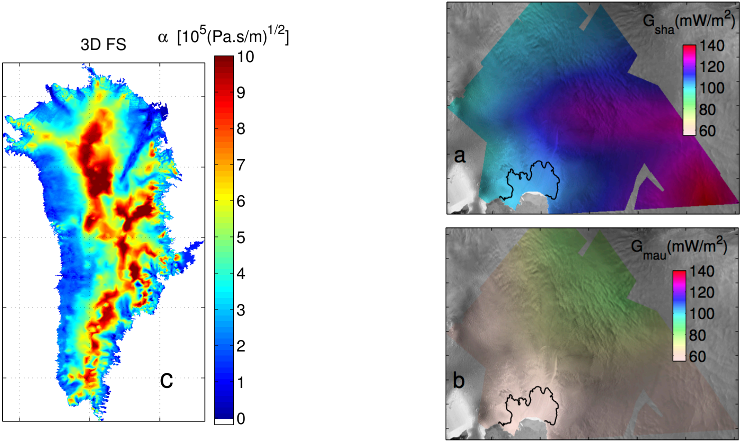




NASA Mission "Operation IceBridge" collecting airborne observations on an unprecedented scale.

- Altimetry
- Bedrock
- Bathymetry
- Snow-firn layer
- position of margins and calving fronts in the past 150 years, past 20,000 years

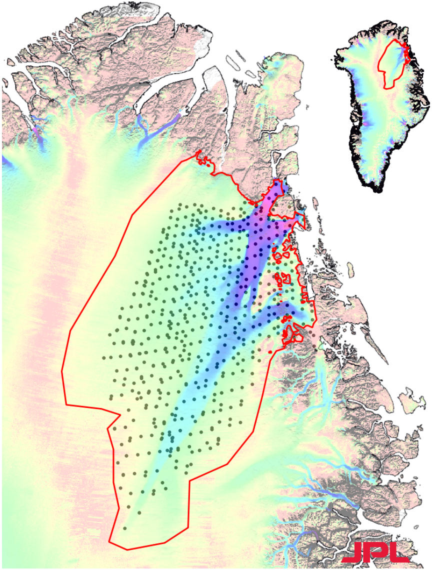
Unknown boundary conditions at the base



- Unknown basal stress at the base: inferred from InSAR surface velocities and adjoint-based inversions.
- Poorly resolved geothermal heat flux.

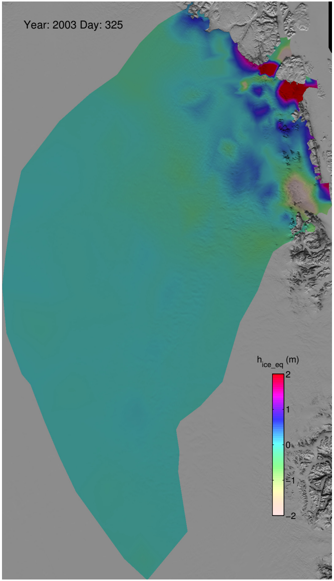
Surface elevation dataset from ICESat (2003-2009)

- North Eastern Greenland Ice Sheet (NEGIS), fast-flowing ice stream.
- Time series of ice-sheet elevation from ICESat 2003-2009 (Schenk and Csatho, 2012)



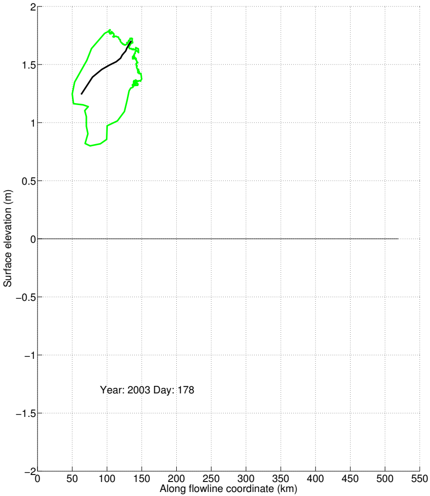
Surface elevation time series for NEGIS

- Large inter-annual and intra-seasonal variability
- Increased variability near the coastline.
- Increased loss in 2005 from propagation of dynamic thinning upstream.
- Alternation of thinning and thickening from SMB anomalies (according to dh/dt record)
- Surface altimetry converted to ice equivalent thicknesses using firn densification model (ISSM is an incompressible ice flow model)



Surface elevation time-series along 79 North flowline

- Complex patterns of surface elevations changes, especially over floating tongue of 79 North
- Weak signal inland, magnified near the coastline which is in an extended ablation zone.
- Abrupt temporal transitions which are difficult to assimilate.



Forward Model

- Stress balance (2D SSA, MacAyeal, 1989)

$$\frac{\partial}{\partial x}\left(4H\bar{\mu}\frac{\partial u}{\partial x}+2H\bar{\mu}\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial y}\left(H\bar{\mu}\frac{\partial u}{\partial y}+H\bar{\mu}\frac{\partial v}{\partial x}\right)=\rho g H\frac{\partial s}{\partial x}+\tau_{bx} \quad (1)$$

$$\frac{\partial}{\partial y}\left(4H\bar{\mu}\frac{\partial v}{\partial y}+2H\bar{\mu}\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial x}\left(H\bar{\mu}\frac{\partial u}{\partial y}+H\bar{\mu}\frac{\partial v}{\partial x}\right)=\rho g H\frac{\partial s}{\partial y}+\tau_{by} \quad (2)$$

- Mass transport:

$$\frac{\partial H}{\partial t}+\nabla\cdot H\bar{\mathbf{v}}=SMB-\dot{M}_b \quad (3)$$

- Rheology:

$$\mu=\frac{B}{2\,\dot{\varepsilon}_e^{\frac{n-1}{n}}} \quad (4)$$

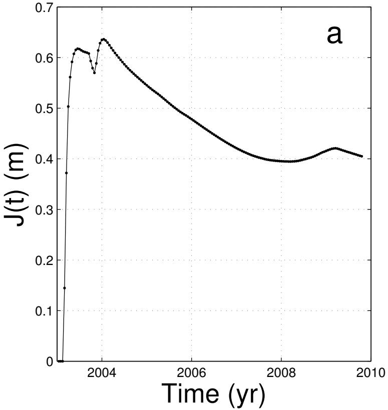
- Friction:

$$\tau_{\mathbf{b}\|}=-\alpha^2 N_{eff}\mathbf{v}_{\|} \quad (5)$$

ISSM: Ice Sheet System Model. Open source framework

- Jet Propulsion Laboratory/University of California at Irvine collaboration
- Transient thermo-mechanical ice-flow model.
- Funded by NASA (Modeling Analysis and Prediction as well as Cryosphere Programs), JPL (Research and Technology Development Program) and NSF (Office of Polar Programs, EAGER)
- Extensive capabilities:
  - Transient thermo-mechanical ice-flow
  - Higher-order and full-Stokes modeling, multi-scale, multi-model
  - Inverse methods (adjoint-based) and data assimilation (automatic differentiation)
  - Uncertainty Quantification (SNL's DAKOTA framework)
  - Static adaptation of mesh
  - Fracture modeling (rifts, faults on ice shelves) + damage propagation
  - Hydrology at the ice/bed interface
  - GIA (Glacio-Isostatic Adjustmnet)
  - ...
- Public domain (http://issm.ess.uci.edu/svn/issm/issm/trunk)
- Support (Skype Channel, email list)
- Core team of developers (5 Scientists + growing community of users across the world)
- Yearly Workshop. Bergen, Norway, 2-4 June 2014 (registration still open at http://issm.jpl.nasa.gov/issmworkshops/)

Best-fit to observed surface elevations



- Cost function:

$$J = \frac{1}{S_\Omega}\frac{1}{T}\int_\Omega \int_{t=0}^{t=T} \frac{(s(t) - s(t)_{obs})^2}{2}\, dxdydt \tag{6}$$

where Ω is the spatial domain, and [0,T] the time domain over which surface elevation data is available.

- Time series zero-level calibrated for 2006 (minimum misfit), super-imposed on existing Howatt 2007 DEM.

Automatic differentiation of ISSM using ADOLC

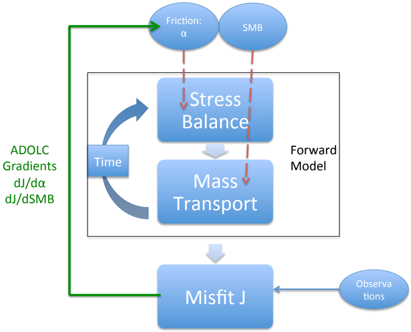
ADOLC (Automatic Differentiation by OverLoading in C++) facilitates the evaluation of first and higher derivatives of vector functions that are defined by computer programs written in C or C++. ISSM was modified to link against ADOLC:

- ADOL-C uses the operator overloading concept to compute in forward and reverse mode of automatic differentiation:
  - derivatives of any order
  - one-sided derivatives in non-smooth cases (e.g. temperature near the pressure melting point)
- ISSM was modified to:
  - use the adouble type for all double operations
  - specify independent variables (for which gradients are computed) and dependent variables (diagnostics such as ice volume or misfit to observations)
  - call drivers (Jacobian, Gradient) at the end of the forward runs

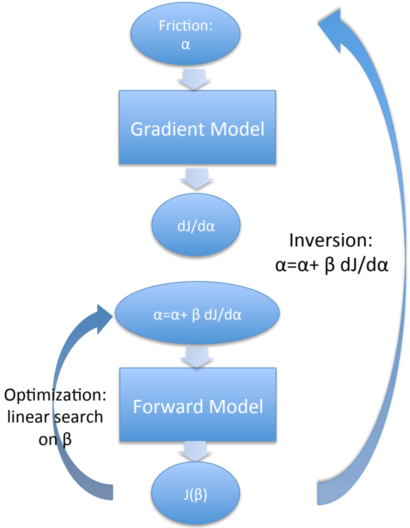
Goals:

- Compute gradients of non self-adjoint problem such as a transient ice-flow model
- Compute sensitivities of an ice-flow model free of truncation errors

Inversion algorithm using automatic differentiation



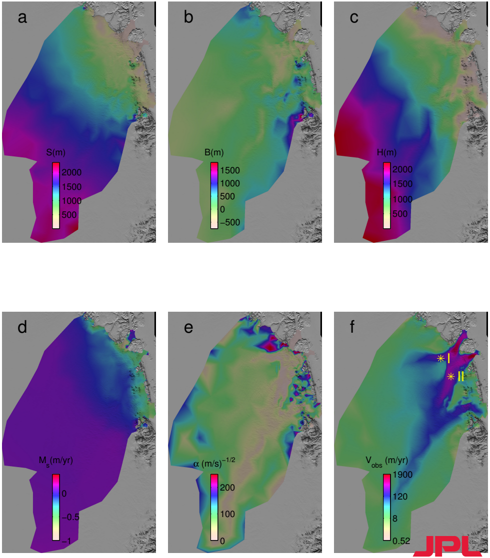
Gradient Model



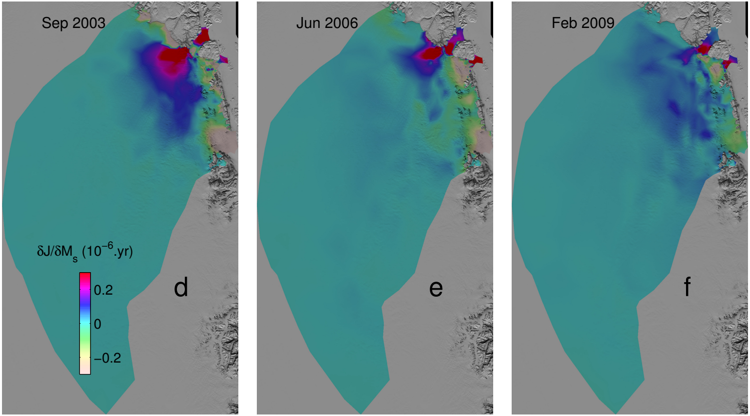
Inversion Model

Model Setup

- Bedrock from Mass Conservation (Morlighem et al, 2013)
- SMB time series from 1850 to present-time based upon regression between PMM5 accumulation output and ice core measurements (Box et al, 2013)
- Basal friction α inverted using adjoint-based model inversion of InSAR surface velocities, Rignot 2012
- Model is transiently relaxed for 5000 years.
- Inversion is carried out on friction and SMB.

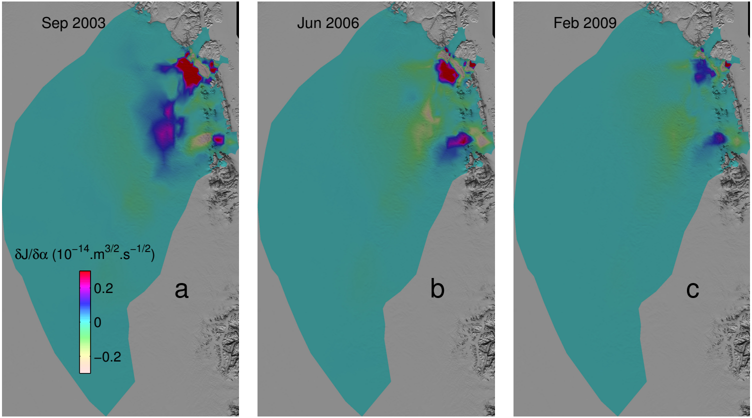


Sensitivity of cost-function J to surface mass balance (SMB)



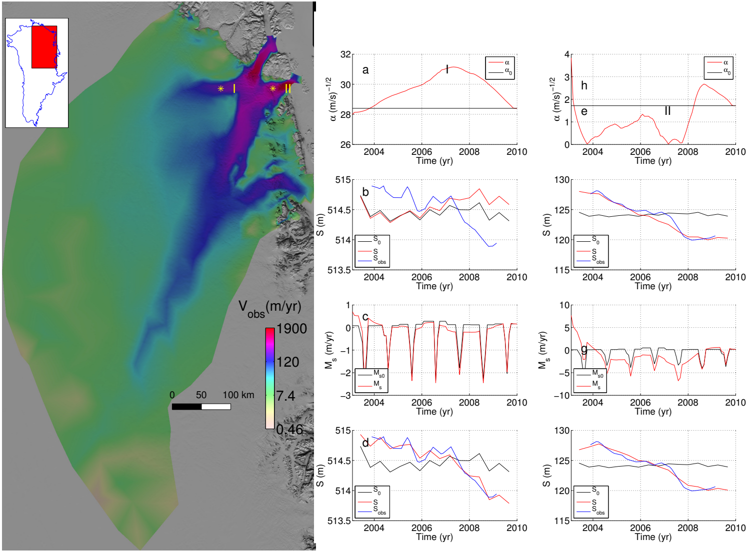
- Based on partitioning height change between dynamic and SMB, Csatho et al (in review), we expect sensitivity to be high at the beginning in 2003 (thinning-thickening variations)
- Large sensitivity over the entire coastline, constant biases inland.
- High sensitivity to SMB in recovering surging glacier: difficult to interpret.

Sensitivity of cost-function J to basal friction α

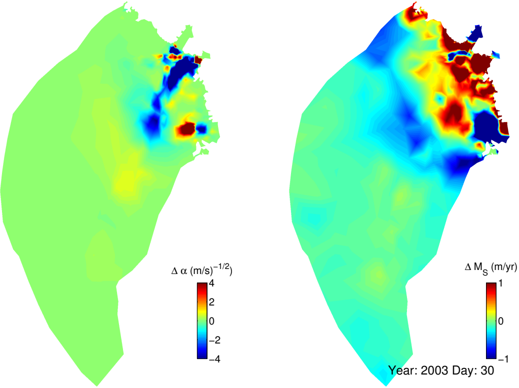


- High sensitivity to dynamic thinning or ungrounding near the grounded line.
- Sensitivity maps well against ice-flow dynamics
- Increased sensitivity in 2005 to dynamic thinning with propagation inland

Inversion results

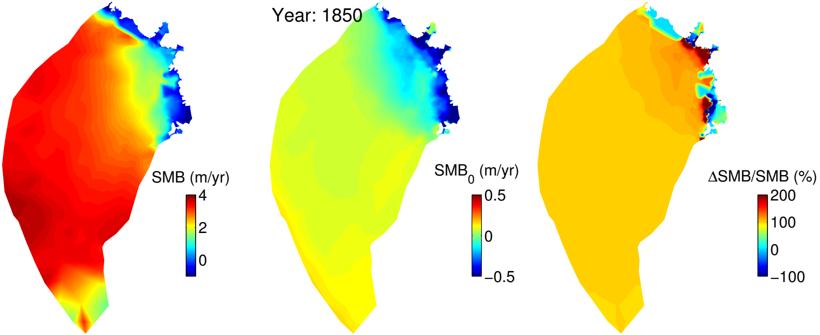


Corrections to SMB and Drag



- SMB corrections essentially near the coastline, below the ELA. Variations are large, even in areas of low SMB.
- Drag corrections not able to reduce misfit everywhere (increase inland), focused mainly near the trunks of both 79 North and Storstrømmen Glacier and near the grounding line.
- Inland, constant biases are corrected for.
- Complex interplay between friction and SMB.

Corrections to SMB from LIA to present-day

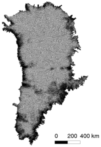


- Similar approach to correcting SMB to match surface DEM in 2006.
- Large corrections which fall outside the range of error margins $->$ need for larger time-series during spin-up of the model.

Greenland Transient Model. Schlegel et al, 2013 (JGR)

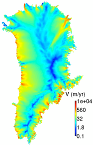
Configuring a modern ISSM Greenland model

MESH



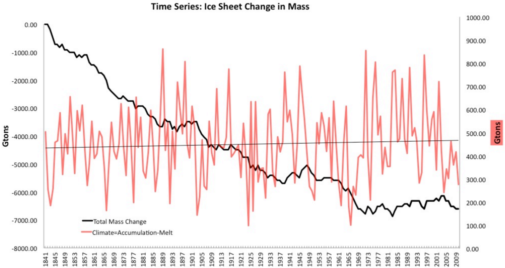
Over 70,000 grid elements

MODELED ICE VELOCITY



Calibrated to UCI InSAR data

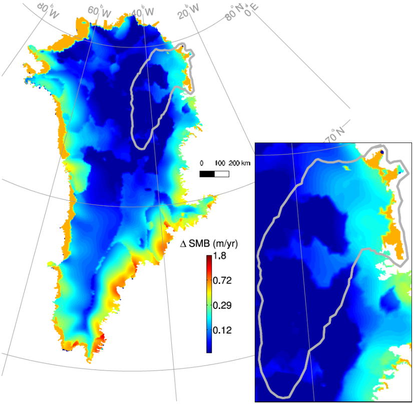
Transient simulation driven by historical climate conditions



Model:
ISSM 2D MacAyeal Shelfy-Stream Approximation momentum equations

Forcing:
Regional climate model reanalysis correlated with observations [station/ ice core data] (Jason Box, Byrd Polar Research Center)

Surface climate uncertainties

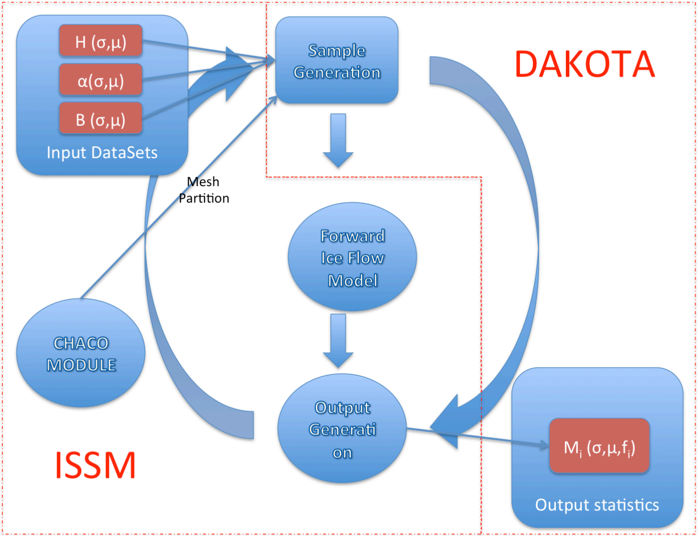


Greenland Ice sheet estimated standard error in surface mass balance used as standard deviation in DAKOTA sampling (m/yr water equivalent). The sampled domain includes one of the few ice streams in Greenland, the Northeast Greenland Ice Stream, outlined in gray.

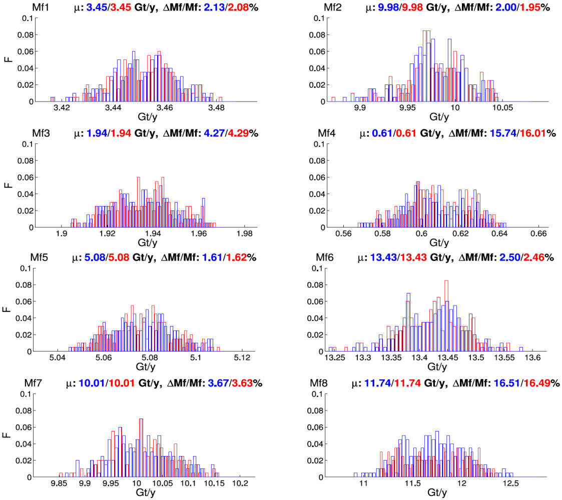
Given these errors, we use ISSM uncertainty quantification tools to determine how the model responds over decades to:

- **random errors in surface forcing withir the specified range (SAMPLING)**
- **small errors in surface forcing from different areas (SENSITIVITY)**

Dakota/ISSM Uncertainty Quantification Framework

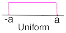


Distribution Frequencies of Mass Flux

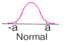


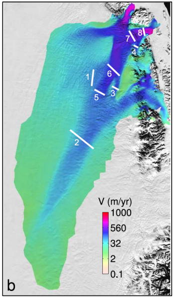
Error Sampling:

Red – Uniform



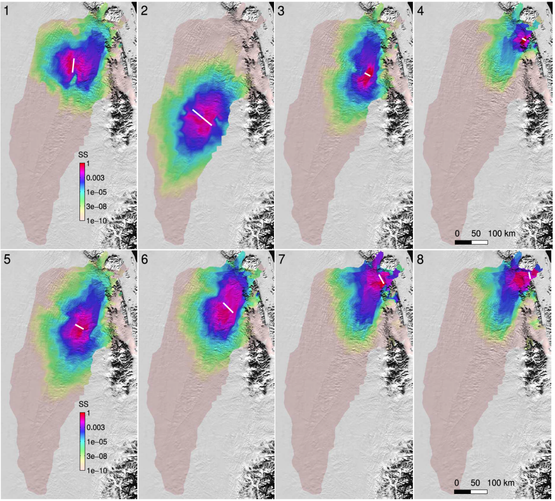
Blue – Normal





⇒ **Mass flux responds normally**

Scaled sensitivities



Scaled sensitivities (SS, unitless) of mass flux through gates 1-8 due to 0.1% perturbation in surface mass balance over 22 year period (1989-2010).

$$SS_i = \frac{\theta_i^2}{\sum_{i=1}^{N} \theta_i^2}$$

where

θ_i = sensitivity of domain partition *i*

Radius of influence

Radius of influence

Gate n°	-1	-2	-3	-5	-10
1	44.7	66.6	110.0	172.9	233.6
2	74.2	89.2	105.0	155.4	292.4
3	36.2	44.3	81.2	149.4	223.2
4	15.7	35.7	49.5	104.0	199.6
5	40.9	57.0	90.6	151.1	251.5
6	58.6	91.7	114.5	173.0	246.7
7	39.1	59.6	125.6	180.5	257.5
8	52.1	70.2	102.5	180.4	260.2
Mean	40.1	56.9	86.2	140.2	217.2

The maximum radius of influence (km**) for a range of importance factors (order of magnitude,** log**10).**

The radius of influence is the maximum distance between each flux gate and all locations that have scaled sensitivities less than a specified value.

Conclusions

- Ice flow models such as ISSM are now at a stage where sensitivities and error margins can be explored, and where NASA data can be efficiently integrated into such uncertainty estimates.
- Some of the challenges that remain include among others:
  - better constraints on the geometry of ice sheets (IceBridge, IceSat-2, Grace Follow-On...)
  - coupling with ocean and atmosphere
  - constraining of geothermal heat flux rates in Antarctica and Greenland
  - parameterization of basal friction and basal hydrology using observed surface velocities
- It is now possible to compute sensitivities and gradients of higher-order ice flow models using automatic differentiation.
- Preliminary studies show the feasability of assimilating altimetry records to temporally invert for ice state variables such as friction and SMB
- Ranges of errors can be quantified for short-term mass-balance projections.

Perspectives

- Data assimilation of long hindcast reconstructions of Greenland and Antarctica.
- Uncertainty Quantification of Antarctica and Greenland projections
  - Extensive parameter space (ice viscosity, basal friction, surface mass balance, bedrock and surface altimetry, etc ...)
  - Large scale, high resolution
  - Multiple time scales (20, 50, 200 and 500 year projections)
  - Post-Doc Position at JPL, starting October 2014 to cover Antarctica.
- Increase our understanding of atmospheric constraints, in particular impact of albedo feedback, surface temperature and density, firn densification, etc ... $->$ Post-Doc position, `http://postdocs.jpl.nasa.gov` (look for Snowpack/Larour)