Projecting Ice Sheet and Climate Evolution at Extreme Scales (PISCEES): Overview, Update & Challenges

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SciDAC
Scientific Discovery through Advanced Computing

Motivation and Project Overview

Focus Areas, Progress, & Challenges

Summary & Future Work

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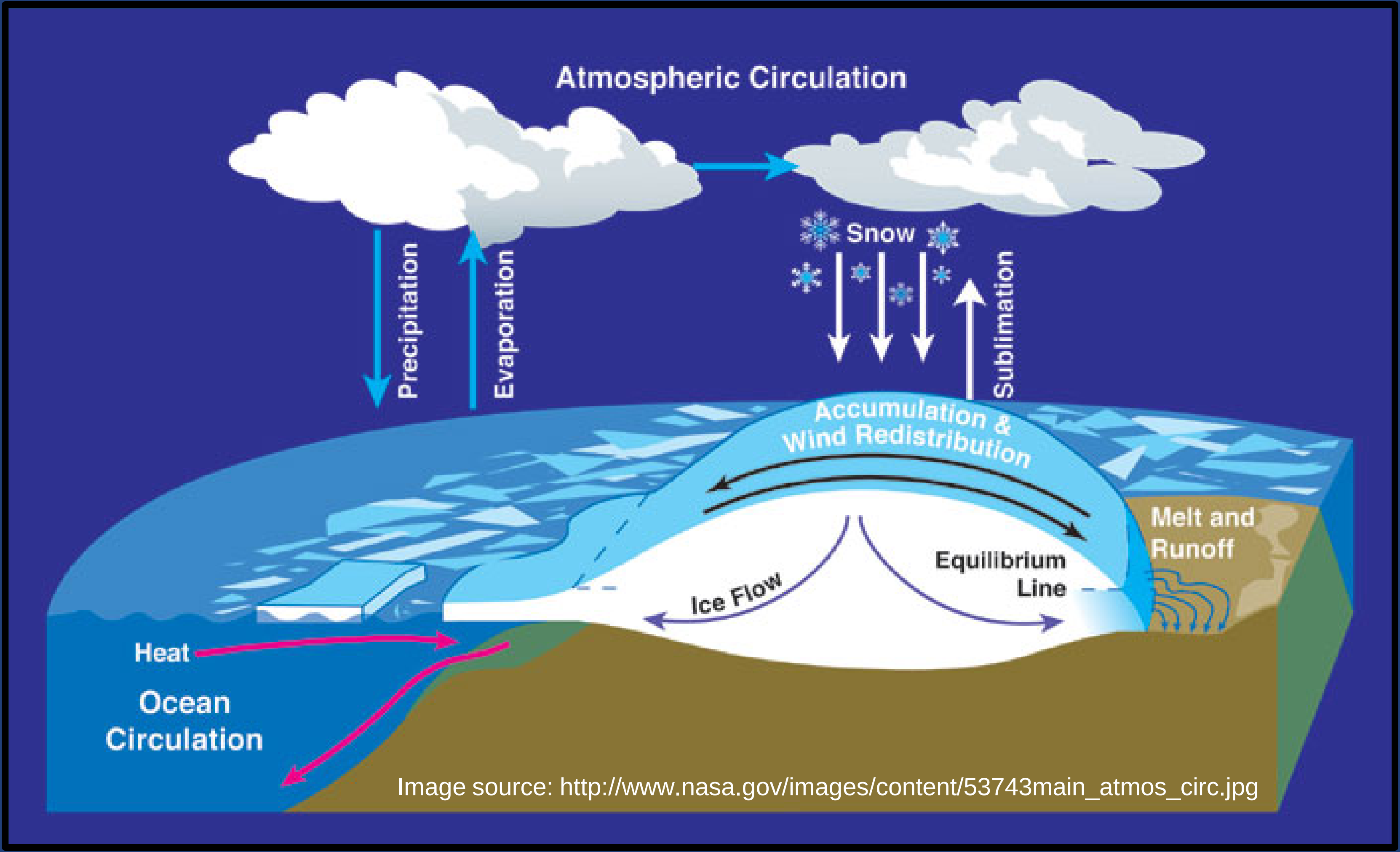
Motivation

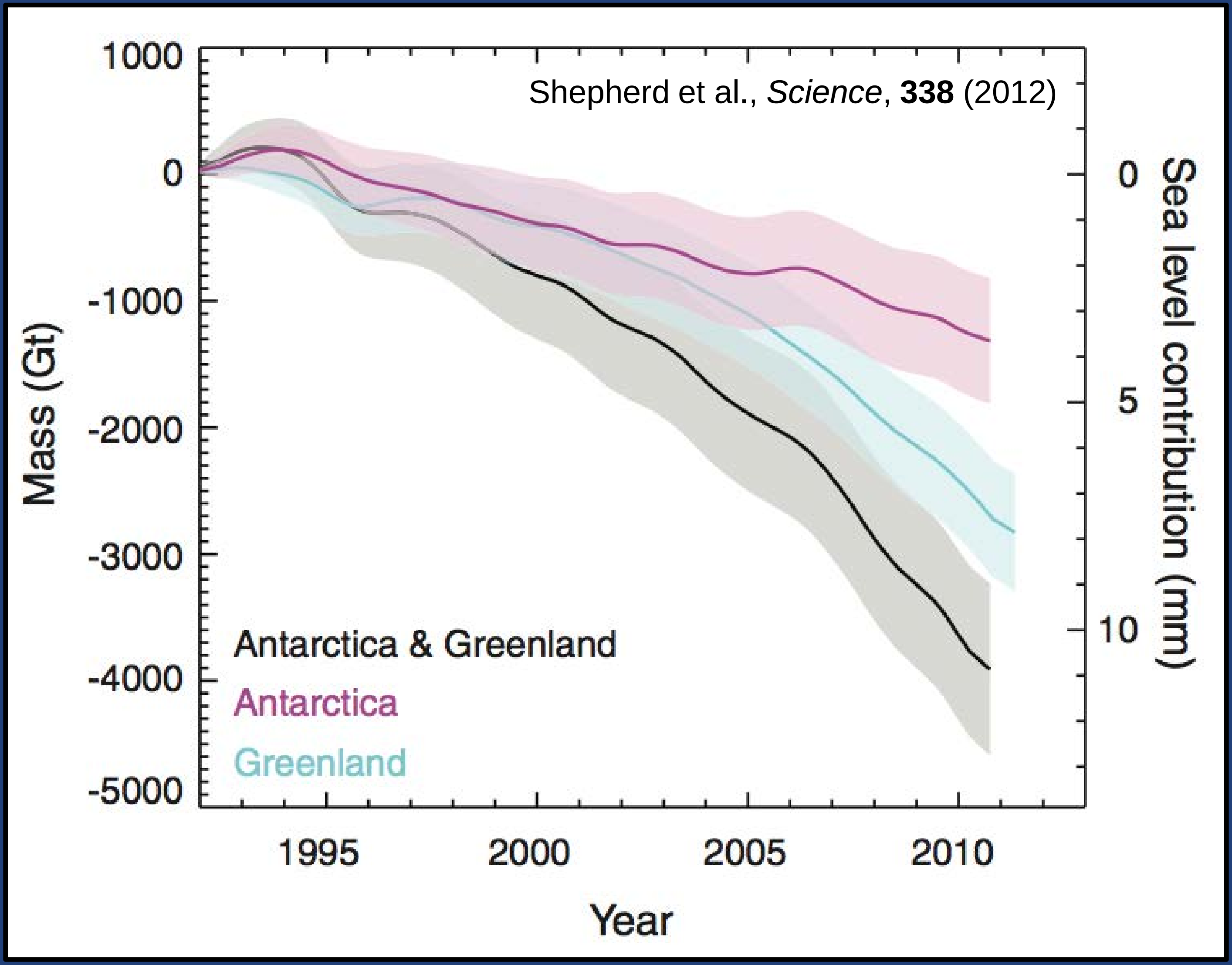
Ice Sheets and Sea Level Rise



Mass Balance: Change in ice sheet mass = mass in – mass out
sea level change *snowfall* *melt, calving*

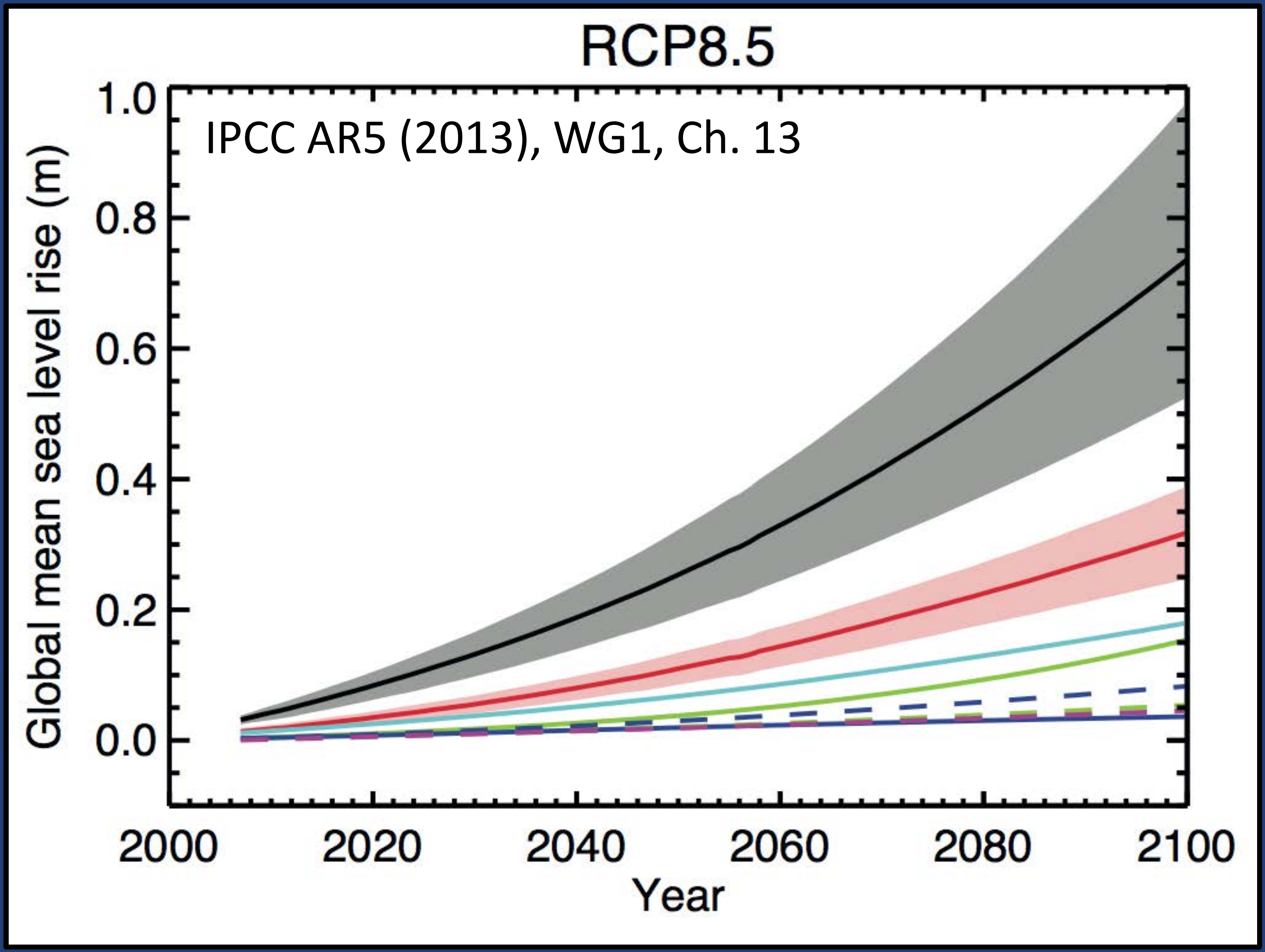
Motivation

Mass loss from the Greenland & Antarctic ice sheets is accelerating.



Future Sea Level Rise (SLR)

For RCP8.5, [projected] global mean SLR for 2081–2100 (relative to 1986–2005) [is] 0.45–0.81 m … range at 2100 is 0.53–0.97 m



Project Overview

Mass loss from the Greenland and Antarctic ice sheets is accelerating. Although ice sheet models have improved in recent years, much work is needed to make these models robust and efficient on continental scales and to quantify uncertainties in their projected outputs.

<u>PISCEES aims to</u> :

1) develop / apply robust, accurate, scalable dynamical cores (dycores) for ice sheet modeling on structured and unstructured meshes with adaptive refinements **(FASTMath; SUPER)**

1) evaluate models using new tools and data sets for verification and validation and uncertainty quantification **(QUEST)**

2) Integrate models / tools into DOE-supported Earth System Models

Project Overview

PISCEES builds on past BER / ASCR investments:

- **SciDAC2:** initial coupling of Glimmer ice sheet model to CESM
- **IMPACTS:** coupling between ice sheets and ocean circ. models; simulations of Antarctic ice sheet & ocean coupled evolution
- **ISICLES:** addition of scalable parallelism & interface to FASTMath libraries in CISM; initial devel. of next gen. dycores

Project Overview

PISCEES contributes to ongoing BER / ASCR investments:

- **RGCM**: long-term stability of the Greenland Ice Sheet, freshwater flux to oceans & related climate feedbacks
- **ACME:** future sea-level rise commitment from ongoing Antarctic ice sheet evolution
- **SciDAC Institutes:** strong collaborations with FASTMath, SUPER, QUEST, and SDAV (see below)

Motivation and Project Overview

Focus Areas, Progress, & Challenges

Dynamical Core Development

Summary & Future Work

Dynamical Core Development

FELIX-S (FEM)	**STOKES (3d)**	
FELIX-FO (FEM)	**First-Order (3d)**	Increased fidelity & comp. cost
BISICLES (FVM)	**“L1L2” (quasi-3d)**	

Solution:

- nonlinear, elliptic PDE (sym. pos. def. or sym. indef. system)
- sparse coeff. matrices
- precond. Krylov methods (linear solve)
- Picard and/or Newton iteration (nonlinear solve)

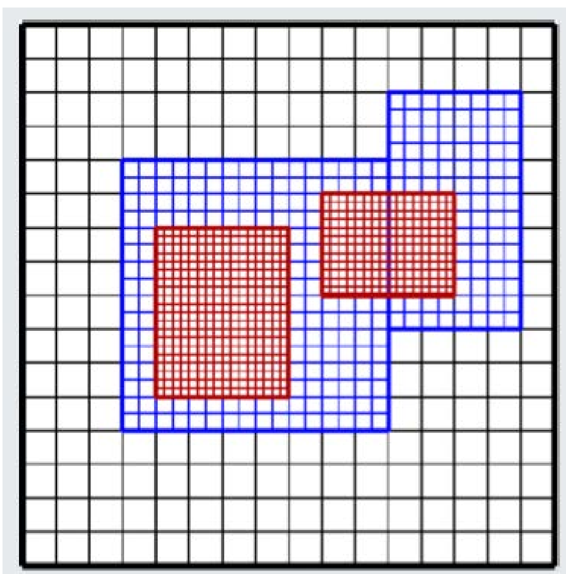
Dynamical Core Development

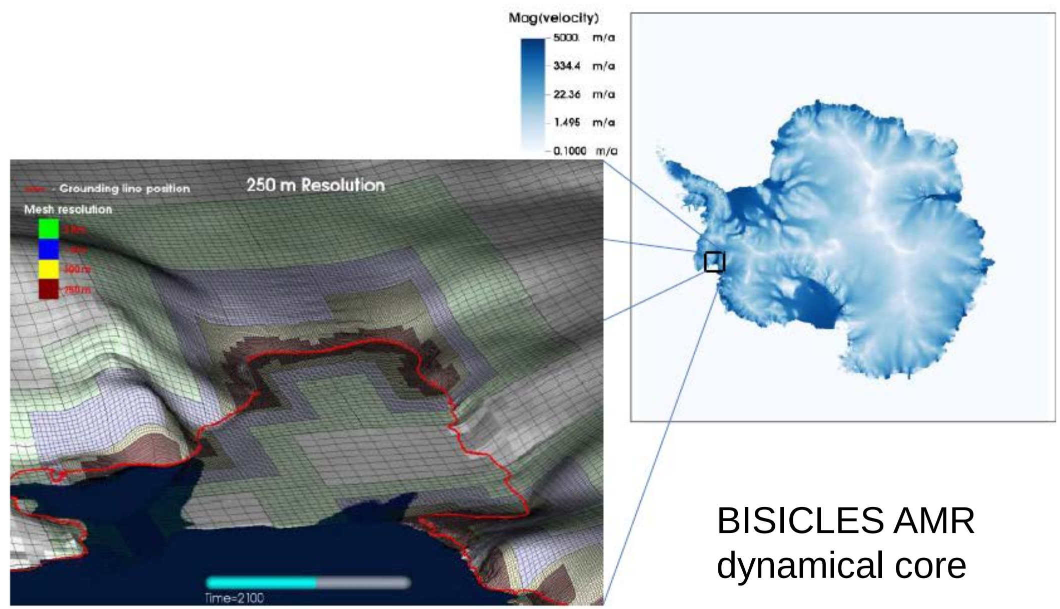
Land Ice Modeling Framework #1:

Community Ice Sheet Model (CISM)

- regular, structured grid
- relatively mature, fully-functioning ice sheet model
- coupled to CESM (& thus ACME 0.x)
- focus on BISICLES dycore under PISCEES

block structured AMR





BISICLES AMR
dynamical core

BISICLES Dynamical Core

"L1L2" momentum balance [1] (with planned upgrades)

- formally 1st-order approximation to Stokes equations [2]
- 2d elliptic solve + column solve for vertical shear

Built using FASTMath libraries: *Chombo* + *PETSc* AMG

Block-Structured, *dynamic* AMR for improved accuracy in regions of dynamic complexity (e.g., grounding lines)

Performance metrics and tuning through SUPER

Marine ice sheet dynamics - similar to (much more expensive) high-resolution Stokes [3,4]

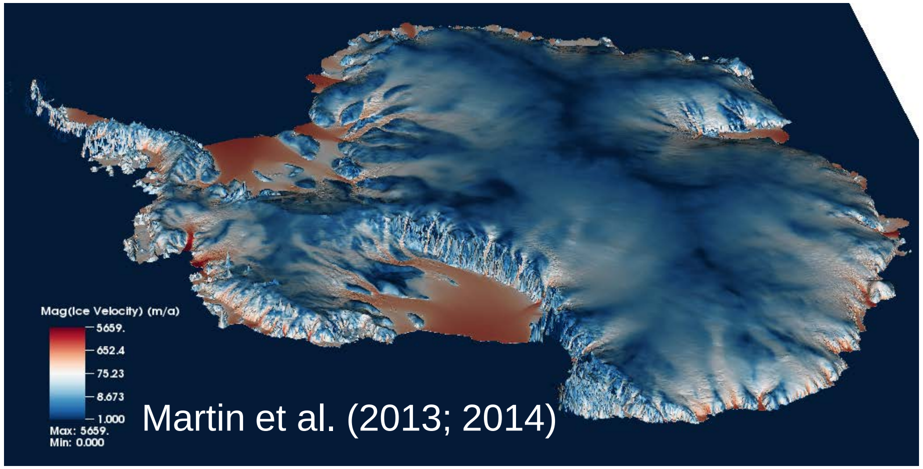
Optimization of sliding param. & ice softness to match obs. vels.

Coupled to Community Ice Sheet Model (CISM) (& thus to ACME v0.x)

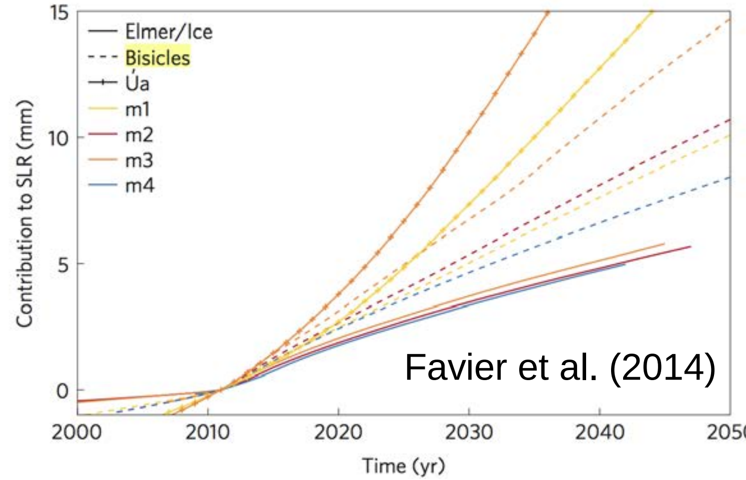
**** See poster by Martin et al. ****

[1]Cornford et al. (2012); [2]Schoof and Hindmarsh (2010); [3]Pattyn et al. (2013); [4]Pattyn & Durand (2013)

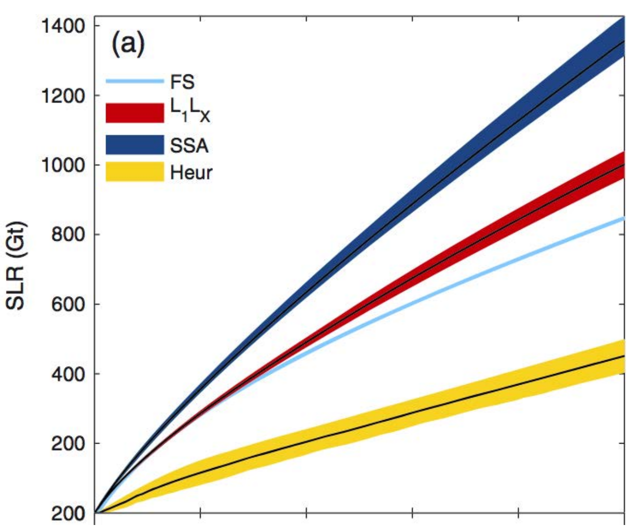
BISICLES Science Results: SLR from Antarctica due to marine ice sheet dynamics and ice-ocean interactions



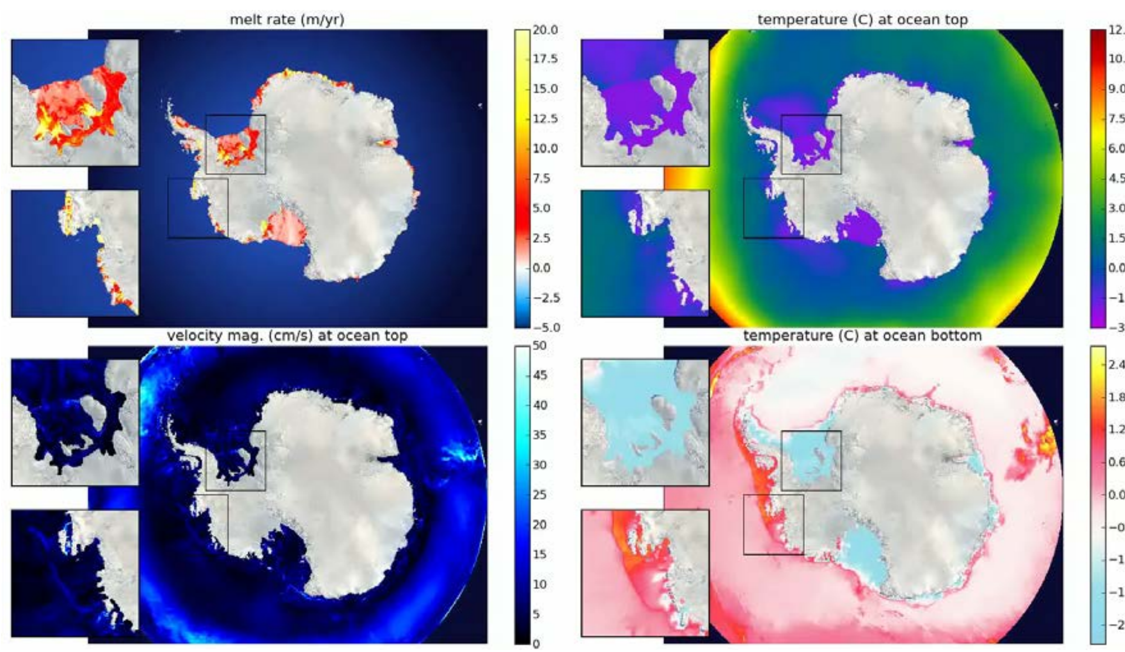
Martin et al. (2013; 2014)



Favier et al. (2014)



Pattyn and Durand (2013)



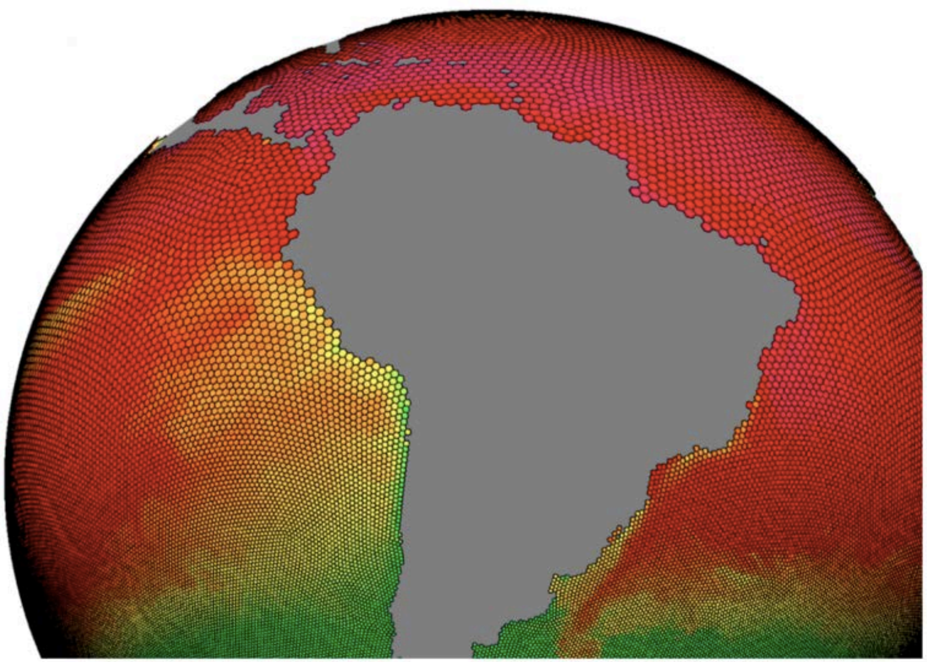
Asay-Davis et al. (2013; 2014)

Dynamical Core Development

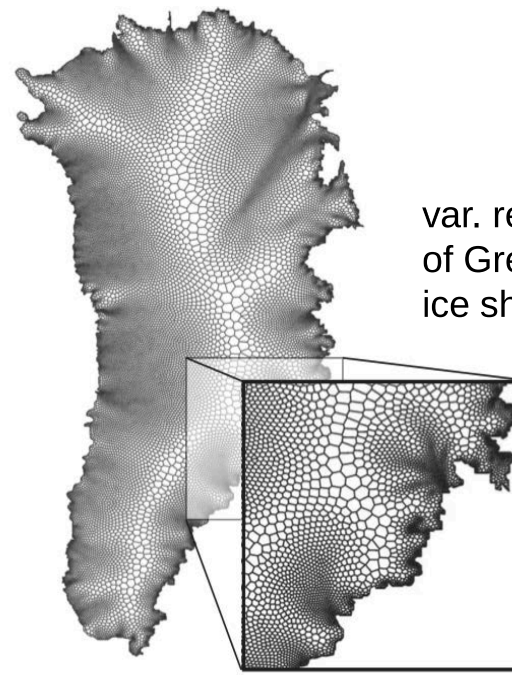
Land Ice Modeling Framework #2:

Model for Prediction Across Scales – Land Ice (MPAS-LI)

- unstructured, variable resolution, Centroidal Voronoi Tesselations
- functioning model but still under active development
- less mature coupling (but focus under ACME)
- focus on FELIX dycore



global, var. res. ocean SCVT



var. res. CVT of Greenland ice sheet

FELIX Dynamical Cores

FELIX-FO [1]

first-order (FO) Stokes approx.**:** *u, v* (*w, P* from hyd. & incomp)

FEM using struct. or unstruct. hex. and tet. elements of variable order

Built using FASTMath libraries: *Trilinos* + *Albany*

Built for advanced analysis (e.g., Jacobians, adjoints "baked in")

Performance metrics and tuning through SUPER

Good weak / strong scalability out to ~10^3 cpus (ILU limited -> ML)

Capability for solving ~1 billion unknowns on 16 k cpus

Robust convergence of nonlinear system using Newton with homotopy

Linear system using ILU precond. CG; currently working on ML

Built-in verification using method of manufactured solutions

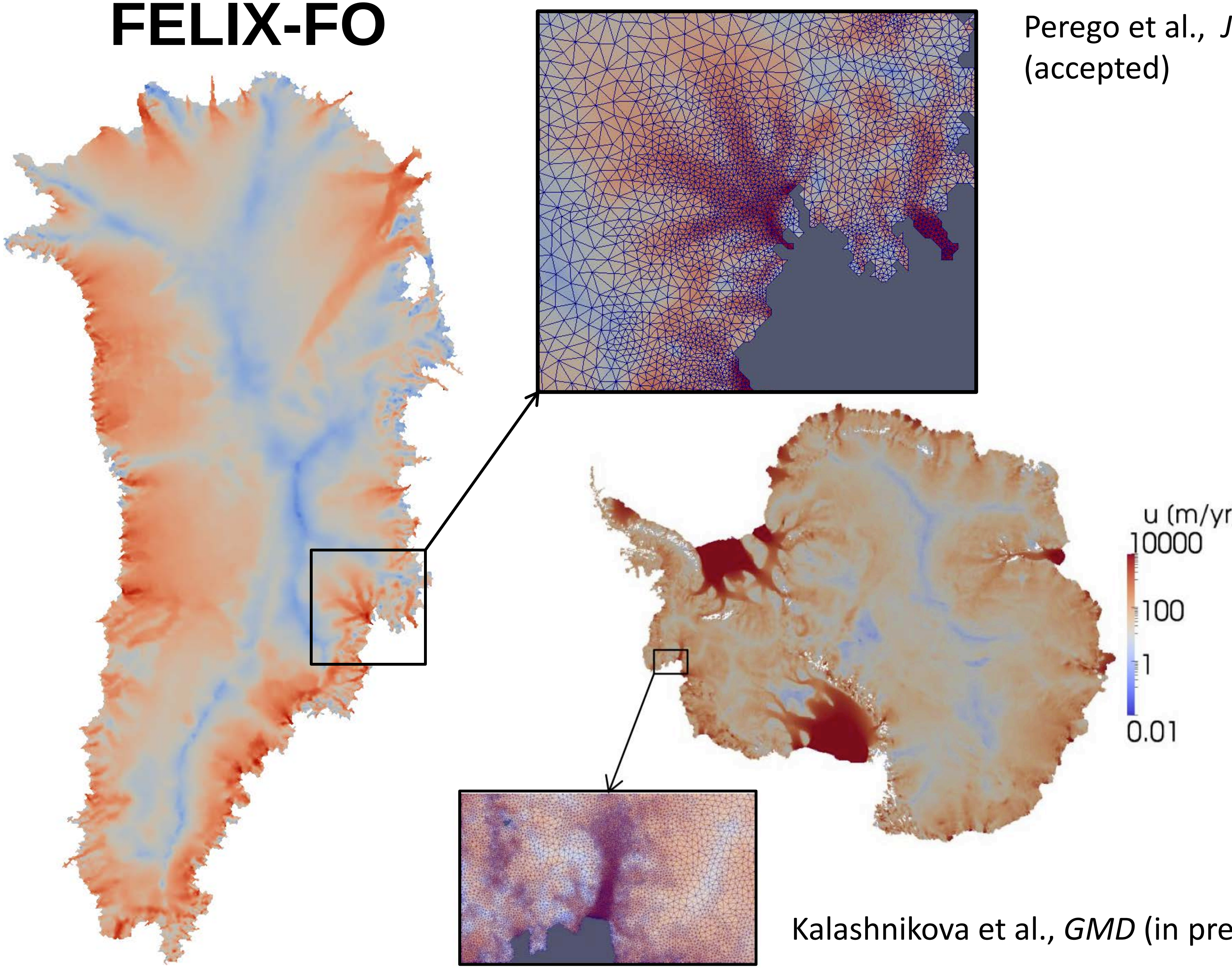
Coupled to CISM *and* MPAS-LI (& thus to ACME)

Prototype model used in *Ice2Sea* simulations

**** See poster by Perego et al. ****

[1] Kalashnikova et al. (in prep.)

FELIX-FO



Perego et al., *JGR* (accepted)

Kalashnikova et al., *GMD* (in prep.)

FELIX Dynamical Cores

FELIX-S [1]

Nonlinear ("full") Stokes momentum balance**:** *u, v, w, P*

FEM tet. Taylor-Hood (P1-P2) and enhanced Taylor-Hood elements

FEM temperature and thickness evolution (or MPAS native)

Robust convergence using hybrid Newton-Picard (nonlinear) solve

Linear system solve:

- domain decomp. + precond. FGMRES
- precond. = additive Scwartz + local direct solver

Strong and weak scalability to ~10^2 -10^3 cpus

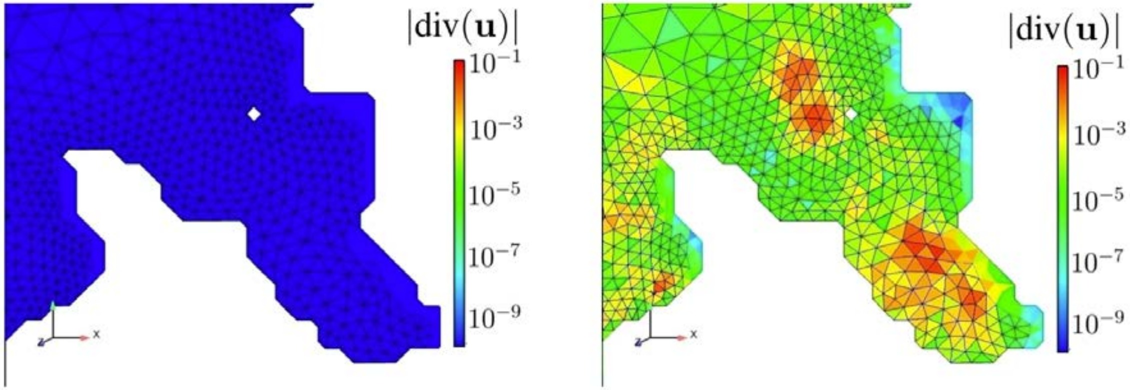
Built-in verification using method of manufactured solutions[2]

Coupled to MPAS-LI (& thus eventually to ACME)

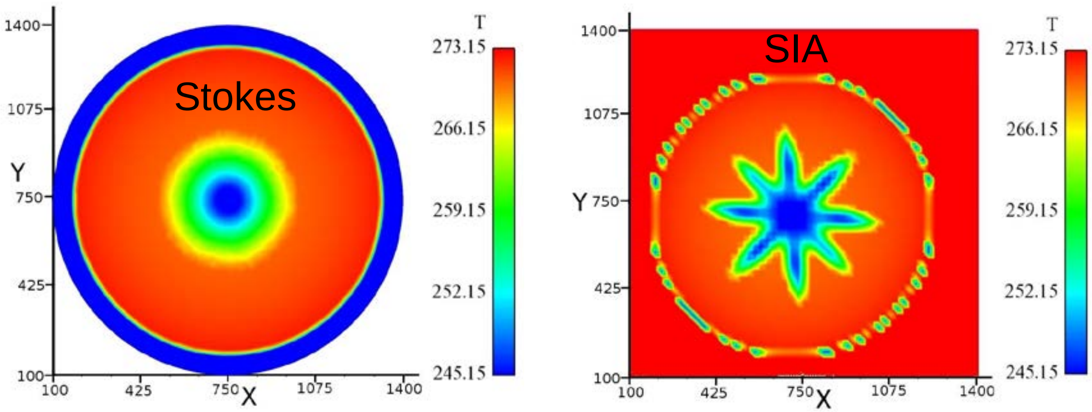
**** See poster by Perego et al. ****

[1]Leng et al. (2012a; 2012b; 2014)

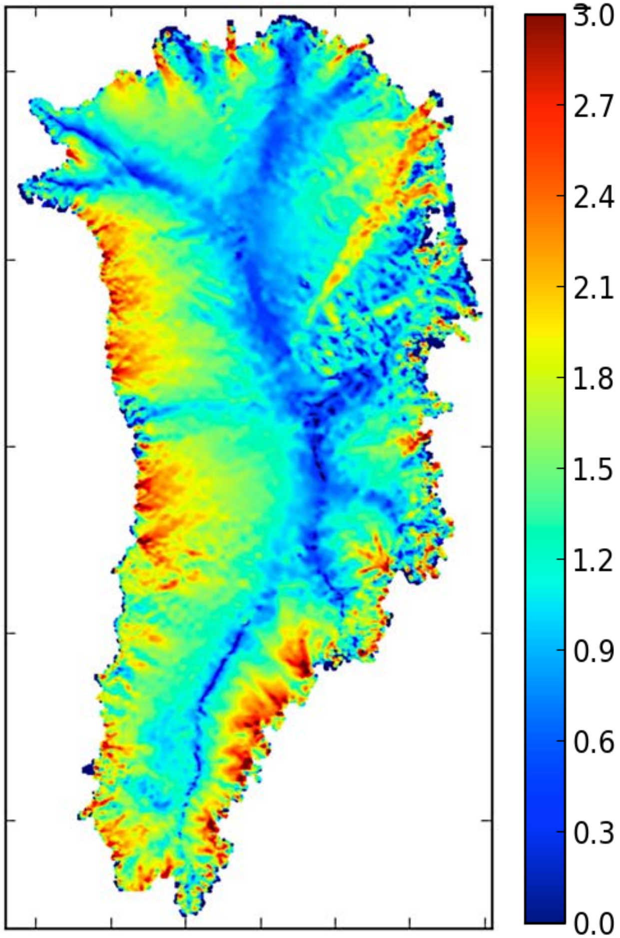
FELIX - S



Improved local mass cons. using enhanced Taylor-Hood

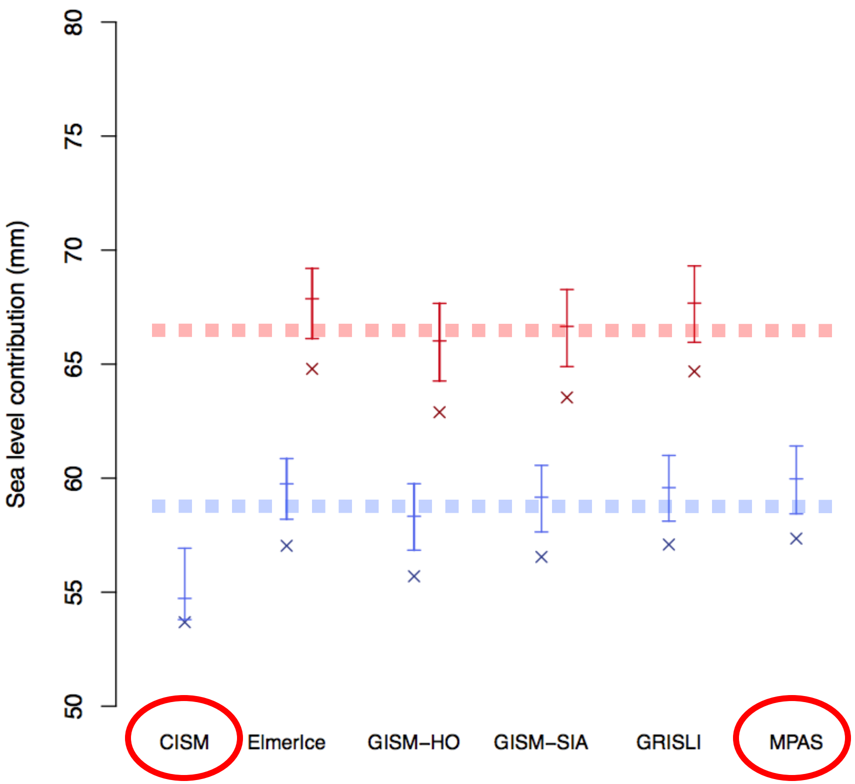


Disappearance of symmetry breaking using thermomechanically Coupled Stokes

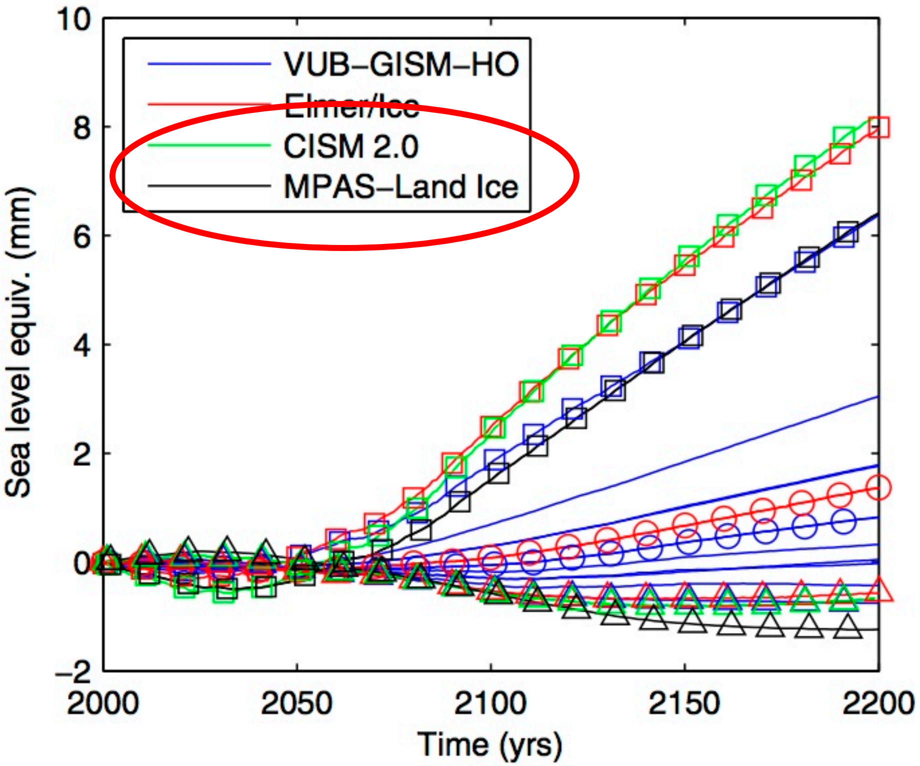


Greenland Ice sheet simulation using realistic basal sliding coefficient

FELIX Science Results: SLR from Greenland due to feedbacks between ice dynamics and climate



Edwards et al. (*The Cryos.*, 2014a; 2014b)



Shannon et al. (*PNAS*, 2013)

Dynamical Core Development

Ongoing & Future work

- Fully functioning MPAS-LI model
- Additional stand-alone and coupled science applications
- Increased integration with optimization and UQ approaches
- Performance / scalability (particularly for Stokes system)

Challenges

- Further improvements in efficiency & reliability of solvers (needed for optimization & UQ)
- Performance gains through node level parallelism - still a research problem for solution algorithms in land ice dycores
- Automated testing on LCFS (launch jobs via scripts / automated tools; dedicated nodes, partition or machine for testing)
- Data management and analysis

Motivation and Project Overview

Focus Areas, Progress, & Challenges

Verification and Validation (V&V)

Summary & Future Work

Verification and Validation (V&V)

Initial implementation of Land Ice Verif. And Valid. (LIVV) toolkit within CISM framework (MPAS-LI to follow)

Initial implementation of *Performance* LIVV (pLIVV) with CISM framework (solver perf. instrumentation via SUPER)

Automated, nightly builds and testing (range of compilers & configurations) using standard verification test cases

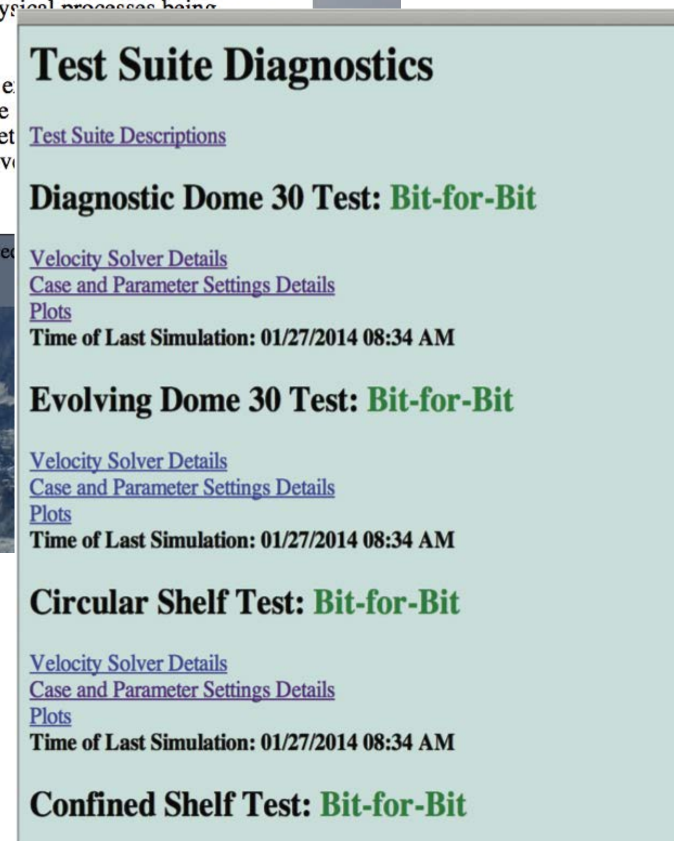
Supported on *Titan*, *Hopper* (*Edison* underway) and smaller devel. platforms (e.g., Mac, Linux clusters)

Starting on including climate model diagnostics so that changes in relevant forcing fields (for coupled runs) are flagged by LIVV

**** See poster by Evans et al. ****

Verification

Screenshot from LIVV homepage



Report for recent nightly test

Verification

Performance and Analysis Test Suite

Test Suite Descriptions

Diagnostic Dome 60 Test: Test Faster Than Expected Performance Range

Velocity Solver Details
Case and Parameter Settings Details
Timing Details
Time of Last Simulation: 05/05/2014 06:53 PM

Diagnostic Dome 120 Test: Test Within Expected Performance Range

Velocity Solver Details
Case and Parameter Settings Details
Timing Details
Time of Last Simulation: 05/05/2014 06:54 PM

Report from most recent pLIVV test

JFNK: Timing Data

	Avg	Max	Min	Current Run
Simple Glide	344.780460069	347.8940625	342.401523437	341.3459375
Glissade Initial Diag Var Solver	340.290125868	341.254296875	339.491875	338.019882812
Glam Velo Driver	340.281848958	341.246757812	339.485625	338.013554688
Calc F	15.3121831597	15.4598554687	15.210359375	15.1675976563
Belos: Operation Prec*x	309.514726562	309.783046875	308.902382812	307.428164063
Nox Preconditioner U	158.868489583	159.48859375	158.395742187	157.851328125
Nox Preconditioner V	150.631193576	151.029257812	150.250195313	149.561796875
Glide IO Writeall	1.12322664931	1.20909335937	1.08116679688	1.17100390625

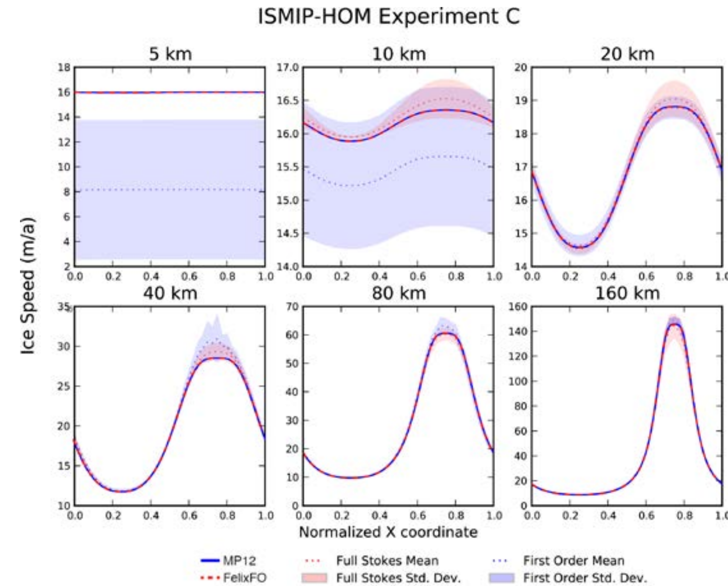
Less than the Min

Greater than the Max

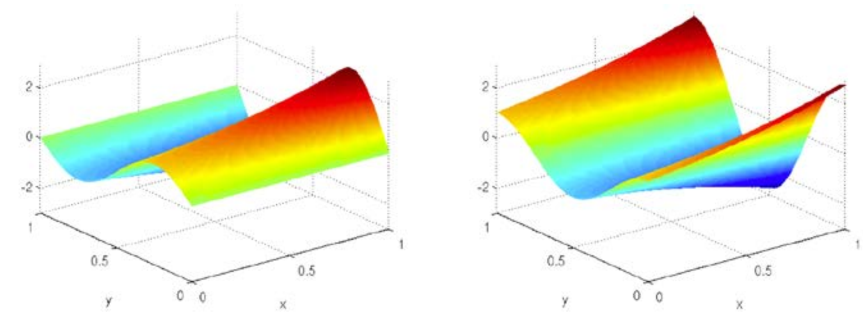
test highlighting improved performance

Verification

Verification of codes using using:
- community benchmarks
- manufactured solutions (MS)

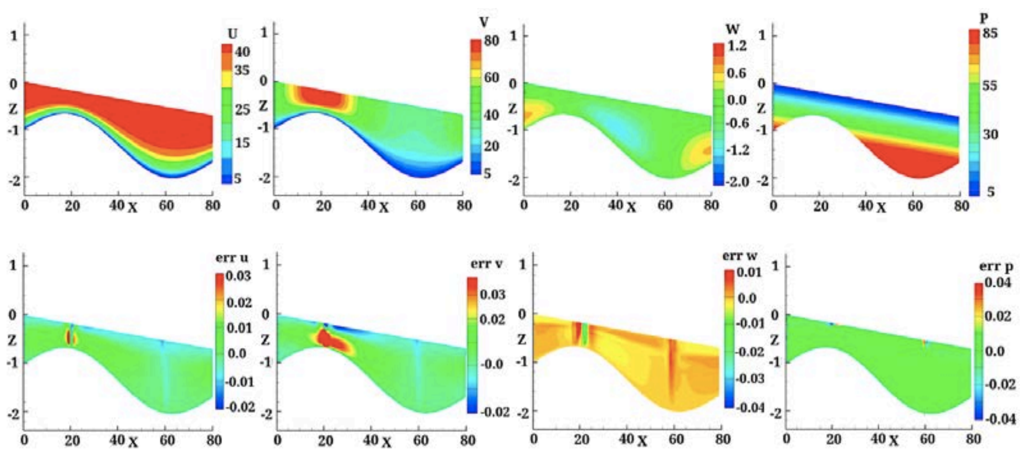


FELIX vs. ISMIP-HOM benchmark

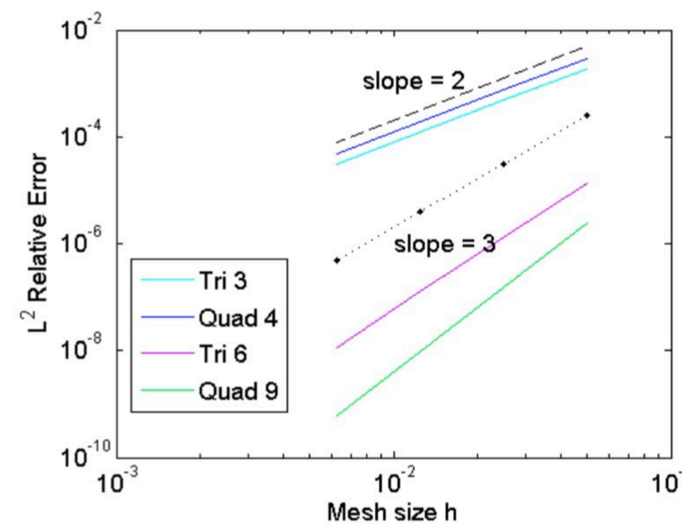


(a) u (b) v

MS for 1st-order Stokes approximation



u, v, w, and P (top) and errors (bottom) for FELIX-S MS



FELIX-FO convergence with refinement

Kalashnikova et al. (in prep.) Leng et al. (2012)

Validation

Ice sheet model validation is not yet standard because of …

Timescale: ice sheets respond to climate forcing over 10^3-10^5 yrs but good observations of relevant fields (and rates of change) exist for only the past few decades (satellite era)

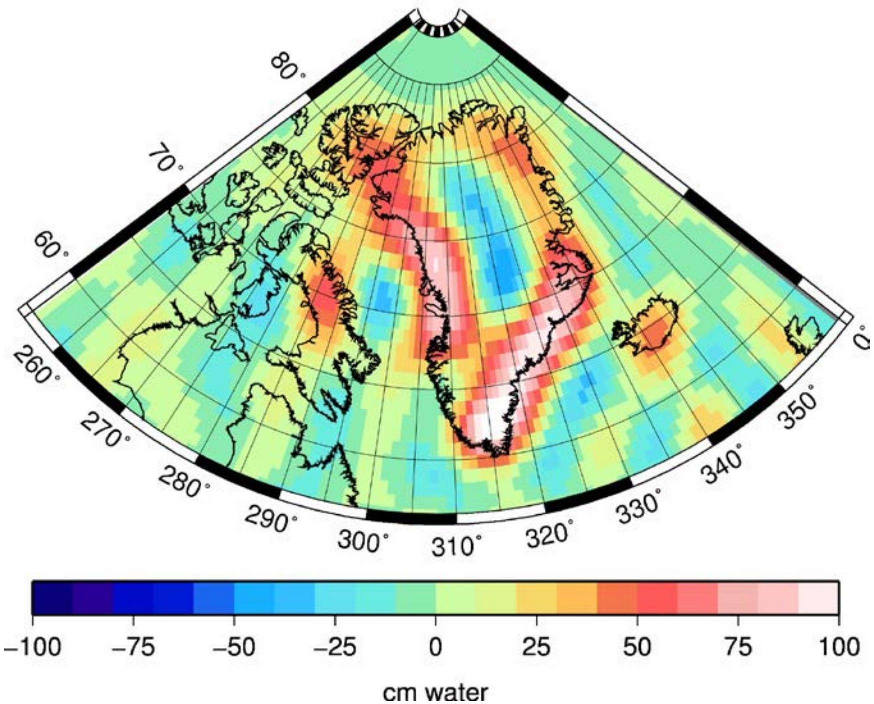
Sparse data: many observational datasets are needed as constraints for model optimization (and thus can't be used for validation)

Data formats: many useful datasets are not in "model friendly" formats or involve processing & interpretation requiring non-DOE expertise

Validation

Greenland Ice Sheet mass loss as seen from GRACE satellite (2003-2013)

GRACE[1] in 60x60 harmonics (unsmoothed)



[1] processing and figures courtesy of J. Bonin & D. Chambers (USF)

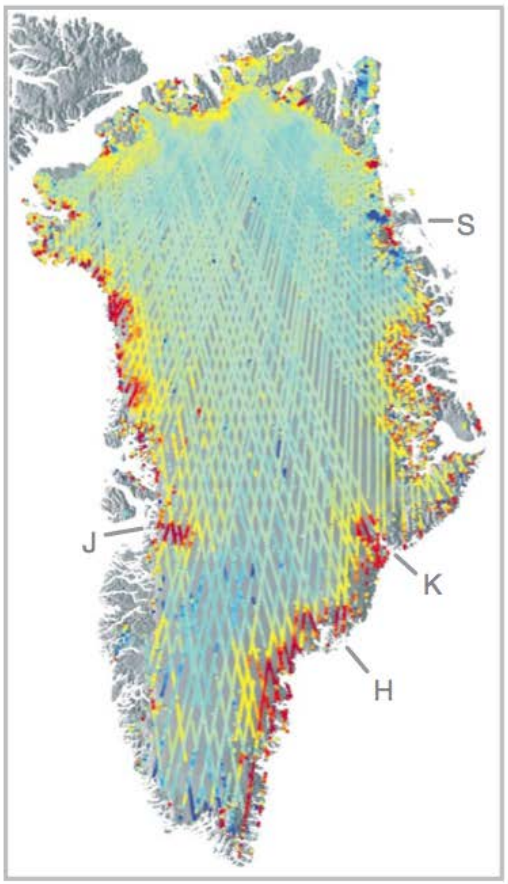
[2] Shannon et al. (*PNAS*, 2013)

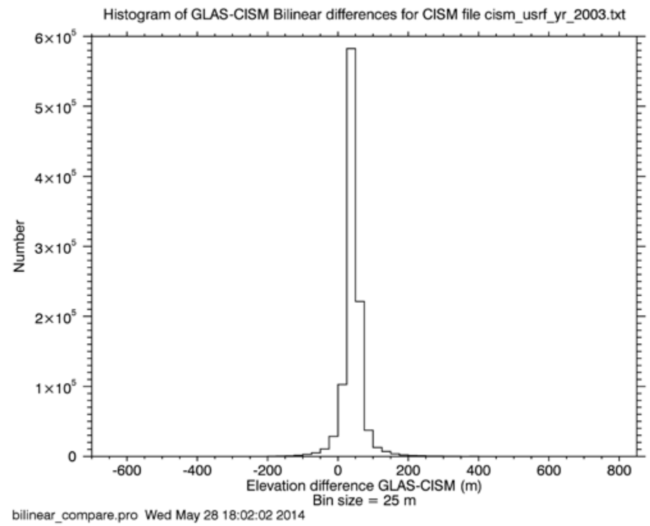
Validation

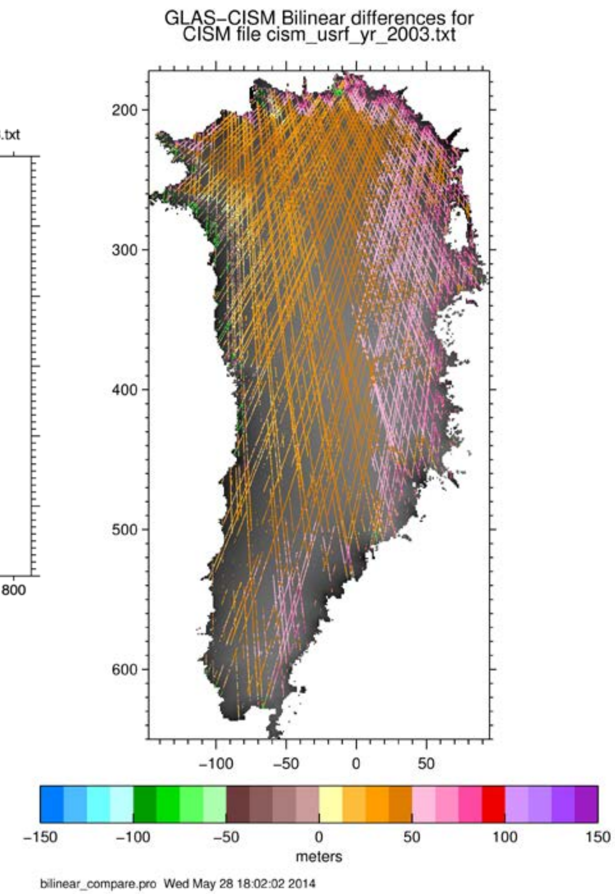
Greenland Ice Sheet elevation change from ICESat[1] satellite (2003)

[1] processing and figures courtesy of T. Neumann (NASA)

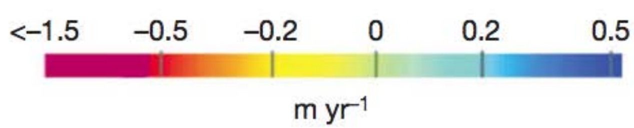
Pritchard et al. (2009)







ICESat (dh/dt)



Verification and Validation (V&V)

Ongoing & Future work

- “historical forcing” validation test cases for Greenland & Antarctica
- Define and implement metrics for validation and for gauging future model improvement (leverages & contributes to ACME & RGCM)

Challenges

- Metrics and validation - uncharted territory w.r.t. ice sheet models
- Validation - work with large, remotely-sensed datasets requires (unfunded) external collaborations (e.g., NASA) and non-DOE, “domain science” expertise

Motivation and Project Overview

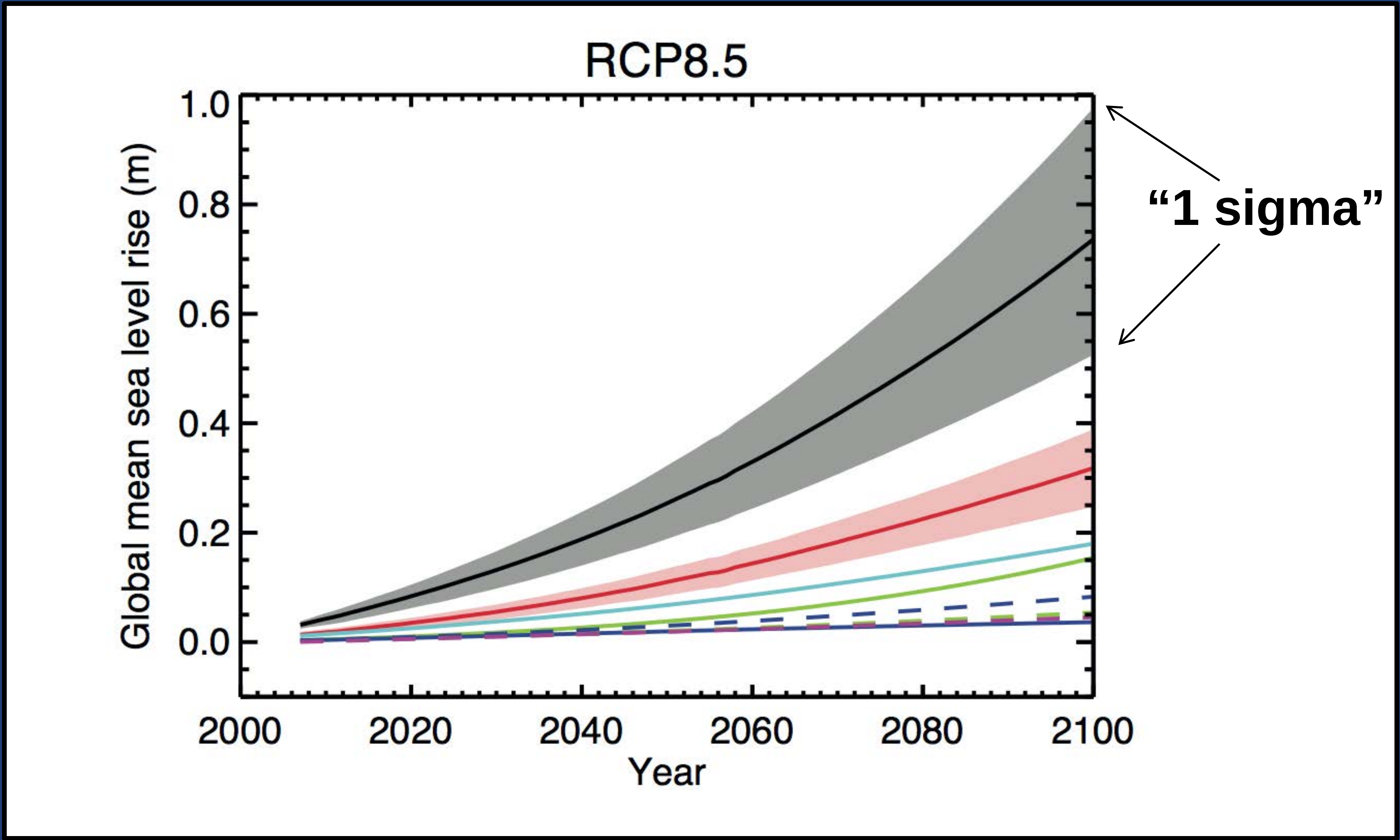
Focus Areas, Progress, & Challenges

Uncertainty Quantification (UQ)

Summary & Future Work

Uncertainty Quantification

For RCP8.5, [projected] global mean SLR for 2081–2100 (relative to 1986–2005) [is] 0.45–0.81 m … range at 2100 is 0.53–0.97 m



Uncertainty Quantification

Uncertainty in predictions from ice sheet models come from:

(1) forcing uncertainties - related to uncertainties in future climate (explored through emissions-scenario-dependent and perturbed physics ensembles)

(1) model uncertainties – related to uncertainties in initial and boundary conditions (largely unexplored)

With the help of QUEST, PISCEES UQ is focusing primarily on the latter:

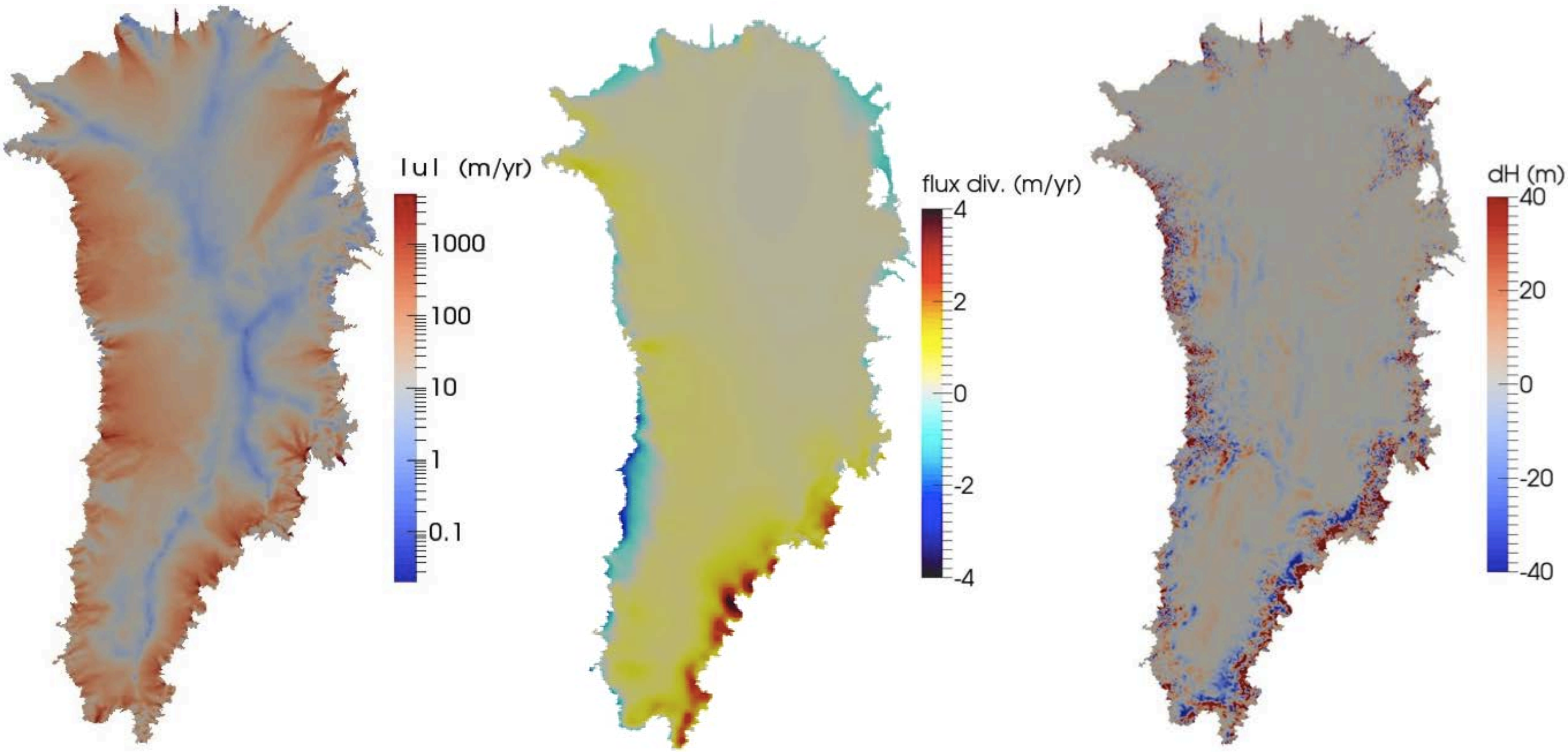
(i) Optimizing uncertain initial and boundary condition parameters

(ii) Estimating parameter uncertainties using a combination of intrusive (adjoint) and non-intrusive (sampling) approaches

(iii) Forward propagation of input parameter uncertainties to assign uncertainties to ice sheet model outputs of interest

**** See poster by Jackson et al. ****

Optimal Parameter Estimation: Motivation



At equilibrium, the SMB is balanced by the flux divergence

SMB = surface mass balance = ice accumulation less melting & sublimation

PDE-Constrained Optimization

Find β, H that minimize the objective functional

$$\mathcal{J}(\beta, H) = \int_\Sigma \frac{1}{2\sigma_u^2} |\boldsymbol{u} - \boldsymbol{u}^{\text{obs}}|^2 \, ds$$

surface velocity mismatch — *Common*

$$+ \int_\Sigma \frac{1}{2\sigma_\tau^2} |\nabla \cdot (\boldsymbol{U} H) - \tau_s|^2 \, ds$$

SMB mismatch

$$+ \int_\Sigma \frac{1}{2\sigma_H^2} |H - H^{\text{obs}}|^2 \, ds$$

thickness mismatch — *Novel*

$$+\mathcal{R}(\beta, H)$$

Regularization terms

subject to ice-sheet model equations

(high-order approximation of nonlinear Stokes equations).

Perego, Price, Stadler (*JGR Earth Surface*, in press)

Numerical / Computational Details

Fwd model (PDE constraint)

- 1^{st}-order Stokes approximation[1] (FELIX prototype model)
- FEM discretization
- variable resolution, tetrahedral mesh (min. res. ~4 km)

Numerical method

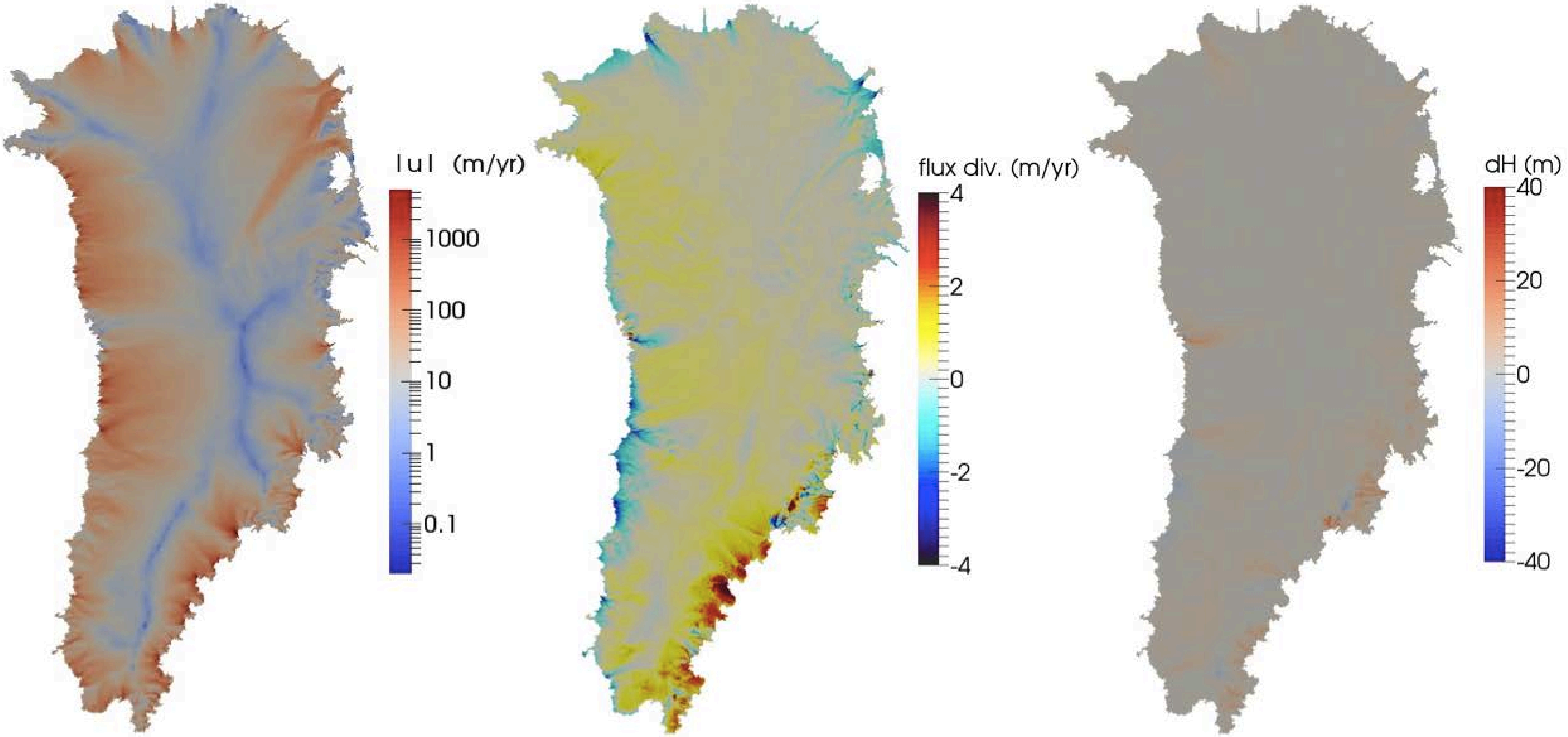
- Quasi-Newton using LBFGS for cost function minimization
- cost function gradients provided by fwd model adjoint [1]

Software Frameworks (FASTMath & QUEST)

- *LifeV* FEM library (soon -> *Albany*)
- *Trilinos:*
  - *NOX* – Newton nolinear solver in fwd model
  - *AztecOO* – PCG linear solver in fwd model
  - *ROL* – Rapid Optimization Library (ROL) for LBFGS

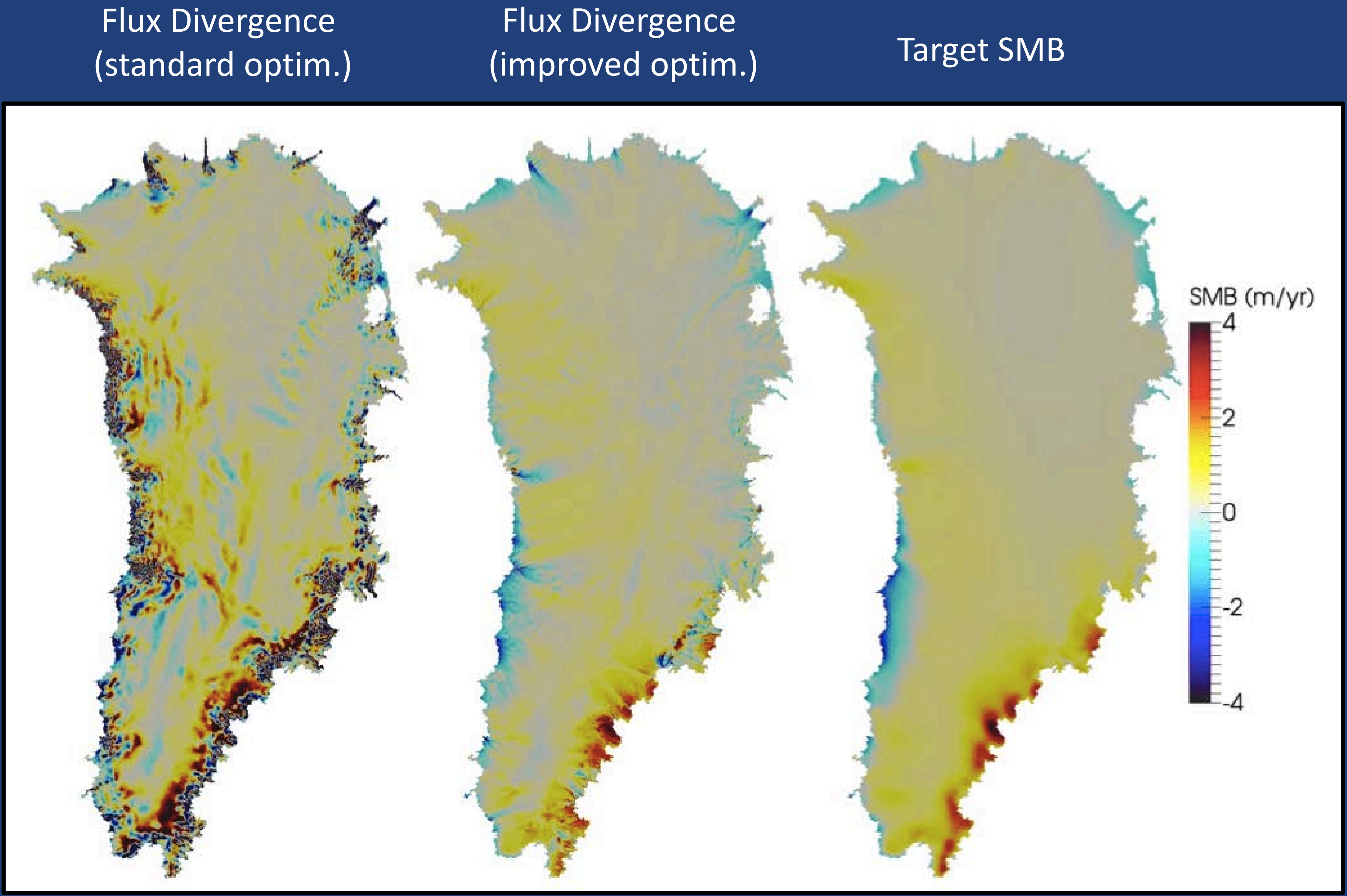
[1] Perego et al. (2012)

Progress: Optimal Initial Conditions



Perego, Price, Stadler (*JGR Earth Surface*, in press)

Progress: Optimal Initial Conditions



Perego, Price, Stadler (*JGR Earth Surface*, in press)

Uncertainty Quantification

Ongoing & Future Work

- Use approx. Hessian to improve sampling of posterior parameter distributions (i.e., in addition to optimization for MAP point)
- Forward simulations using posterior param. distributions to assess uncertainties on model outputs of interest (e.g., ice sheet mass loss and sea-level rise)

Challenges

- Need both human and software support for combined intrusive (adjoint) and non-intrusive (sampling) approaches
- Problem-size reduction: EV's of Hessian reduce unknown params. from ~10^6 to ~10^{2-3} … but still very challenging for existing methods to sample and approximate the posterior distribution
- Efficient, scalable forward & adjoint solves necessary pre-requisite

Motivation and Project Overview

Focus Areas, Progress, & Challenges

Earth System Model Integration

Summary & Future Work

Earth System Model Integration

Coupling between ice sheet, atmos. & land (surface mass balance forcing) is largely “complete”:

- temperature & moisture fluxes downscaled from coarse-res. land / atmos. grid to high-res. ice sheet grid
- results (for Greenland) are in good agreement with both obs. and high-res., regional model simulations

New / recent coupling development:

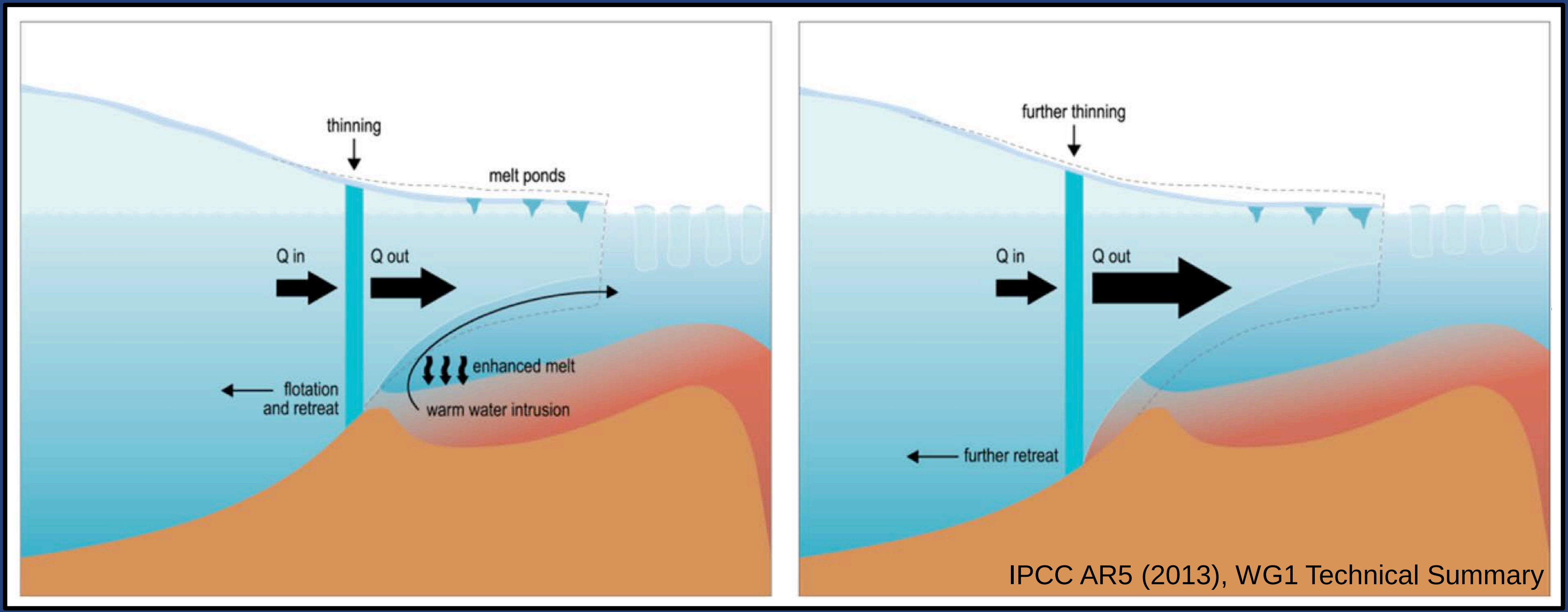
- solid / liquid freshwater flux to ocean from land ice
- ice sheet elev. & atmos. circ. feedbacks
- “dynamic” land units
- ice sheet / ocean model coupling (w/ IMPACTS)

** Initial ACME model will have these capabilities **

Earth System Model Integration: ice sheet / ocean coupling

IPCC WG1 (2013): "*Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause [21st century SLR] substantially above the likely range.*"

Marine Ice Sheet Instability (MISI)

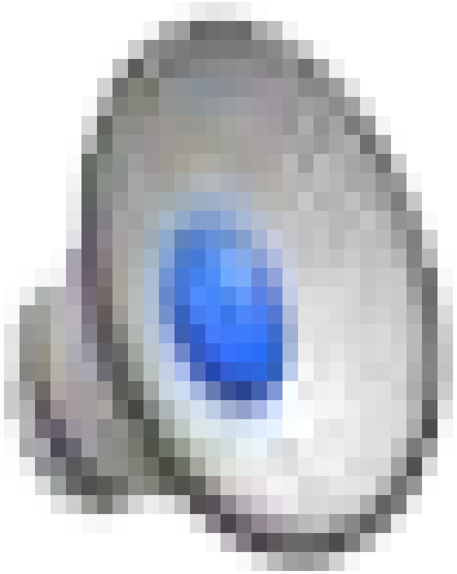


Boundary layer between grounded and floating ice ("grounding line") requires very-high spatial resolution in ice sheet models (~100's of meters)

Ice sheet / ocean interactions affect submarine melt, with dynamic ice sheet response (grounding line retreat & increased mass flux to the oceans.[1, 2])

[1]Joughin & Alley (*Nat. Geosc.*, **4**, 2011) [2] Straneo et al. (*BAMS*, **94**, 2013)

Ice-Ocean Coupling: 20 yrs of fully coupled evolution using POPSICLES **



Movie: X. Asay-Davis (LANL / PIK) and D. Martin (LBNL)

** IMPACTS + ISICLES + PISCEES

Ice-Ocean Coupling: Sub-shelf Melt Validation

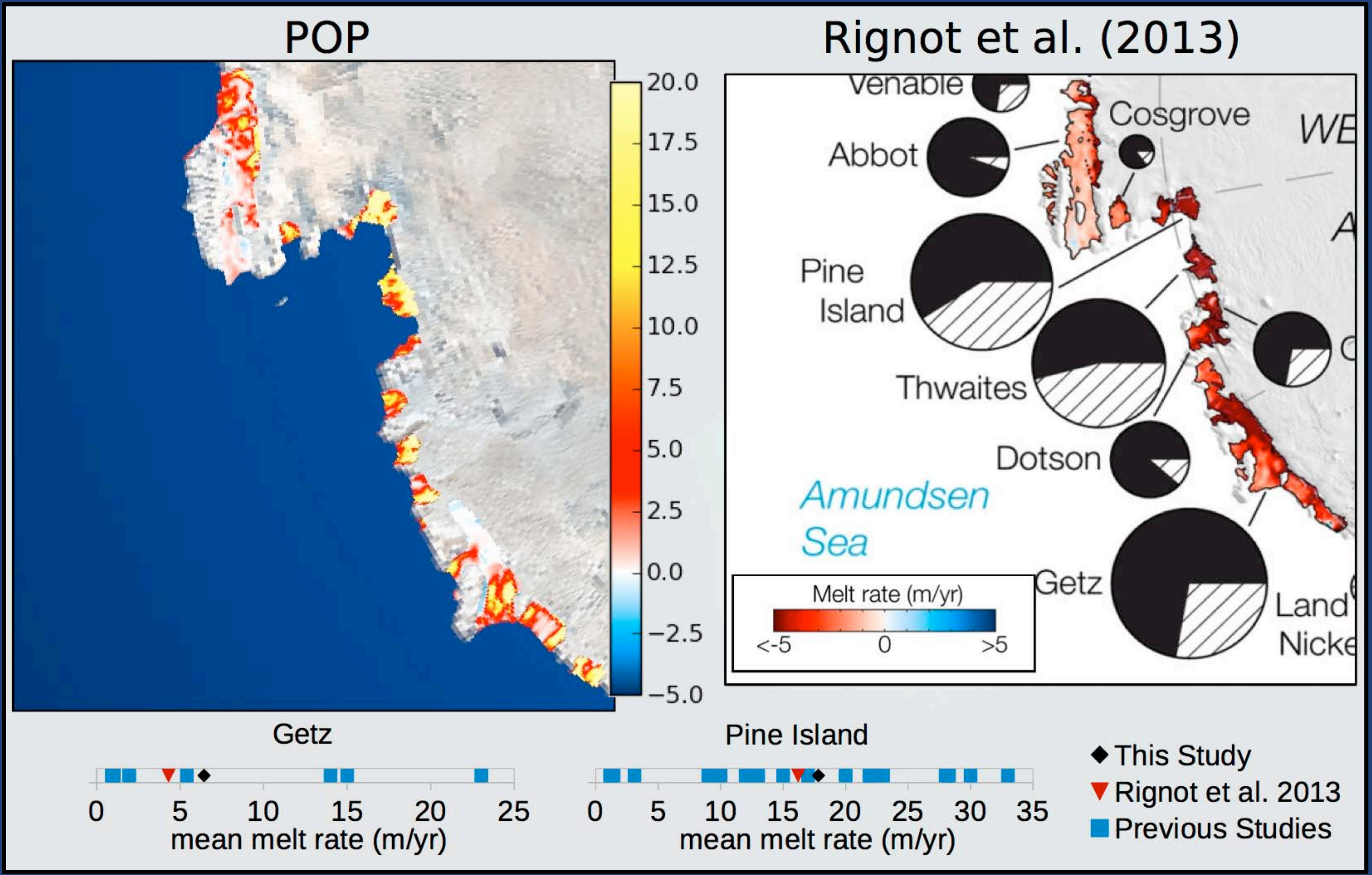


Figure courtesy of X. Asay-Davis (LANL / PIK)

ESM Integration

Ongoing & Future Work

- Integration of PISCEES dycores with ACME
- Generalize climate downscaling for use w/ unstruc. Meshes
- Finish & report on initial ice sheet / ocean coupled simulations

Challenges

- Integration of optim. init. cond. approach with “real” ESM forcing
- Ice sheet / ocean coupling within full ESM framework
- Diagnosing and fixing coupled climate model biases that (negatively) affect ice sheet simulations

Motivation and Project Overview

Focus Areas, Progress, & Challenges

Summary & Future Work

Summary & Future Work

CISM

- mature ice sheet modeling framework
- access to HPC-ready, robust, next-generation dynamical cores (CISM-BISICLES, CISM-FELIX)
- advanced level of ESM coupling
- these capabilities can be / are being applied for science now

MPAS-LI

- working but relatively less mature ice sheet modeling framework
- access to FELIX, var. res. dynamical cores
- relatively less advanced level of ESM coupling, but will …
- … leverage advances and experience gained w/ CISM / CESM
- … benefit from more straightforward coupling w/ MPAS-O and more robust vertical coordinate

Summary & Future Work

Verification and Validation

- Nightly test suite running using standard test cases & benchmarks (testing code and model performance)
- Ongoing / future work will focus more on validation efforts

Uncertainty Quantification

- Focus is on uncertainties from boundary & init. conds.
- Progress on parameter optimization & init. Framework
- Future focus on param. unc. estimation & propagation

ESM integration

- ice / atmos / land / partial-ocean coupling in CESM -> ACME
- Significant progress on ice / ocean coupling (science coming)

Summary & Future Work

SciDAC Institutes

FASTMath: *Chombo* AMR dycore and *Trilinos-Albany* unstructured mesh dycore allowing for unprecedented, sub-km resolution, whole-Antarctic ice sheet simulations; advanced analysis, "UQ-ready" dycore; solving 10^9 unknowns on 16 k cpus

SUPER: optimal dynamical core settings for LCFs; performance instrumentation for dycores and FASTMath solver libraries (used for performance component of LIVV); optimized communication-avoiding smoothers, Krylov methods, and MG for LCFs

QUEST: definition of intrusive + non-intrusive approach for high-dimensional UQ, using *Dakota* and *Trilinos* based workflow; dim. reduction, stochastic emulation, and Bayesian calibration using *Dakota* & *Trilinos* on idealized ice sheet problems; optimization tools applied to realistic, large-scale problems

SDAV: current collaboration on analysis of BISICLES output, others pending …

Project Co-PIs: E. Ng (LBNL), S. Price (LANL)

Dycore Development & Performance

- **CISM:** M. Hoffman, S. Price, W. Lipscomb (LANL)
  - **BISICLES**: D. Martin, E. Ng, S. Williams (LBNL)

- **MPAS-LI:** M. Hoffman, S. Price, W. Lipscomb (LANL)
  - **FELIX-FO:** I. Kalashnikov, M. Perego, A. Salinger (SNL)
  - **FELIX-S:** M. Gunzburger (FSU), L. Ju (USC)

- **Performance:** R. Tuminaro (SNL), S. Williams (LBNL), P. Worley (ORNL)

Verification & Validation: K. Evans, M. Norman, P. Worley, A. Boghozian (ORNL)

Uncertainty Quantification: M. Eldred, J. Jakeman, A. Salinger (SNL); C. Jack-son, O. Ghattas, G. Stadler (UT Austin); P. Heimback (MIT)

ESM Integration: J. Fyke (LANL); W. Sacks , M. Vertenstein (NCAR)

Future Sea Level Rise (SLR)

"Only the collapse of the marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level (GMSL) to rise substantially above the likely range during the 21st century." (IPCC AR5 (2013), WG1, Ch. 13)

Paleorecord

Pliocene warm intervals: CO_2 levels 250-400 ppm; temperatures 2° C to 3.5° C warmer than pre-industrial; records suggest deglaciation of West Antarctica and parts of East Antarctica *with global mean sea level not >20 m above present*

Last Interglacial: global temperatures were not more than 2° C above pre-industrial; global mean sea level at least 5 m higher than present; Greenland likely contributed 1.4 - 4.3 m *(implying a contribution from Antarctica)*

IPCC AR5 (2013), WG1 Technical Summary

Sea Level Rise: Current versus Future Potential

Current rate of SLR is **3 mm / yr**:

1 mm/yr from thermosteric (thermal expansion and salinity changes)

1 mm/yr from glaciers and ice caps

1 mm/yr total from Greenland & Antarctic ice sheets (2/3, 1/3, respectively)

Future potential SLR:

Glaciers and Ice Caps (G&IC):	**0.4 m**
Greenland Ice Sheet (GrIS):	**7 m**
Antarctic Ice Sheet (AIS):	**58 m**

Largest land-ice contribution to SLR is currently from G&IC

Largest future potential is from ice sheets, especially Antarctica

IPCC AR5 (2013), WG1, Ch. 4

Dynamical Core Development

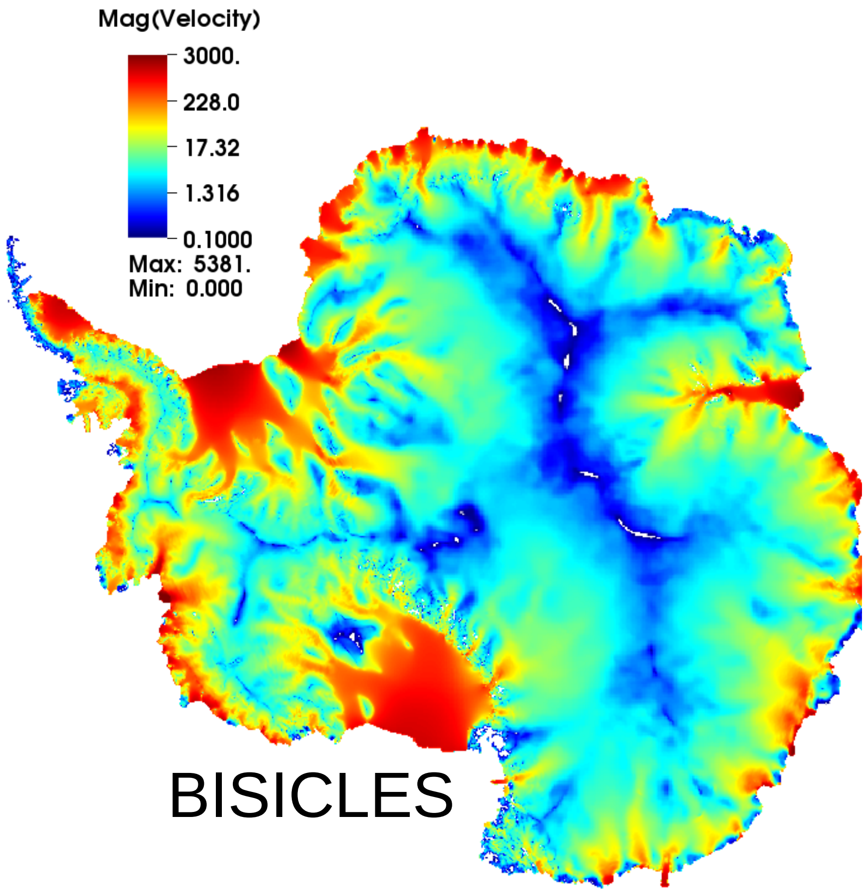
BISICLES (**B**erkley **ISICLES**)

- first-order accurate Stokes approximation (quasi-3d)
- Finite Volume
- block-structured, adaptive mesh refinement (AMR)
- coupled to CISM

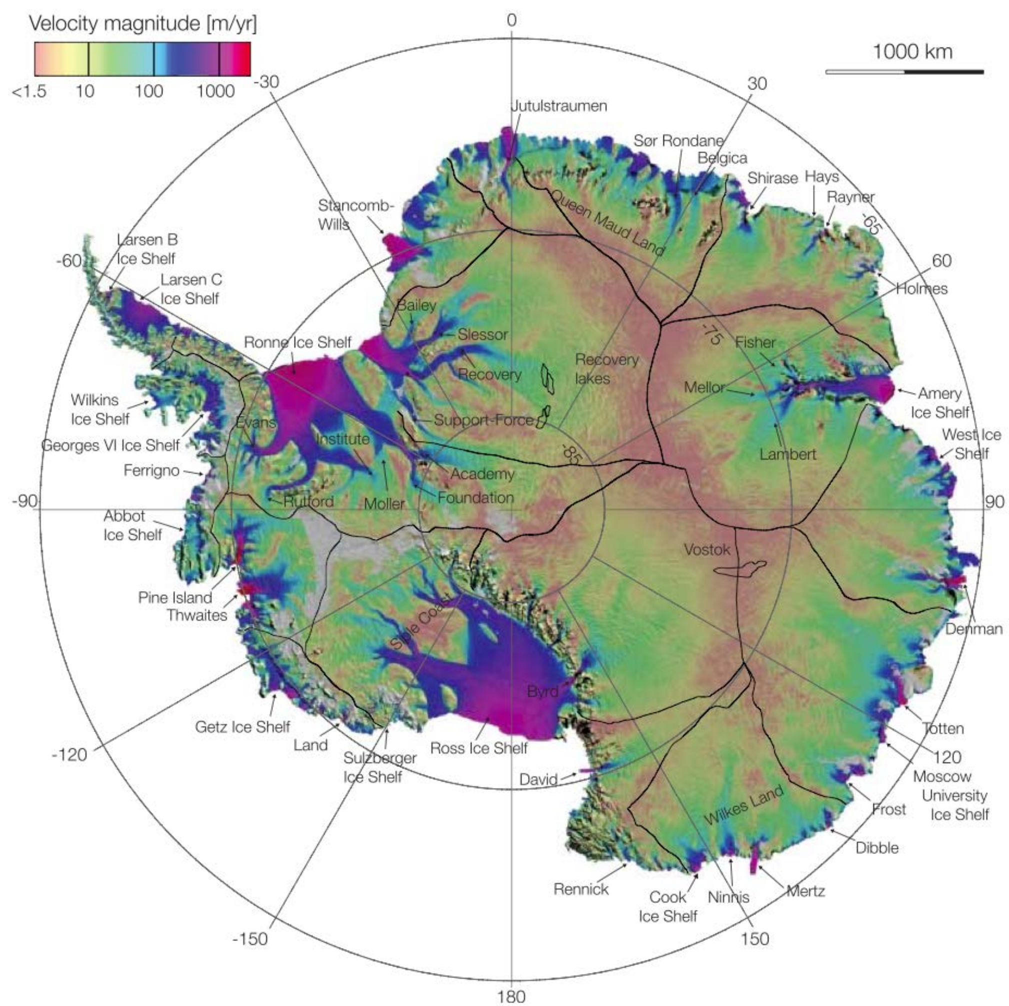
FELIX (**F**inite **E**lements for **L**and **I**ce e**X**periments)

- **FELIX-S**
  - nonlinear Stokes momentum balance (3d)
  - coupled to MPAS-LI
- **FELIX-FO**
  - first-order accurate Stokes approximation (3d)
  - coupled to CISM and MPAS-LI

BISICLES: Resolved, Whole Antarctic Ice Sheet Simulations



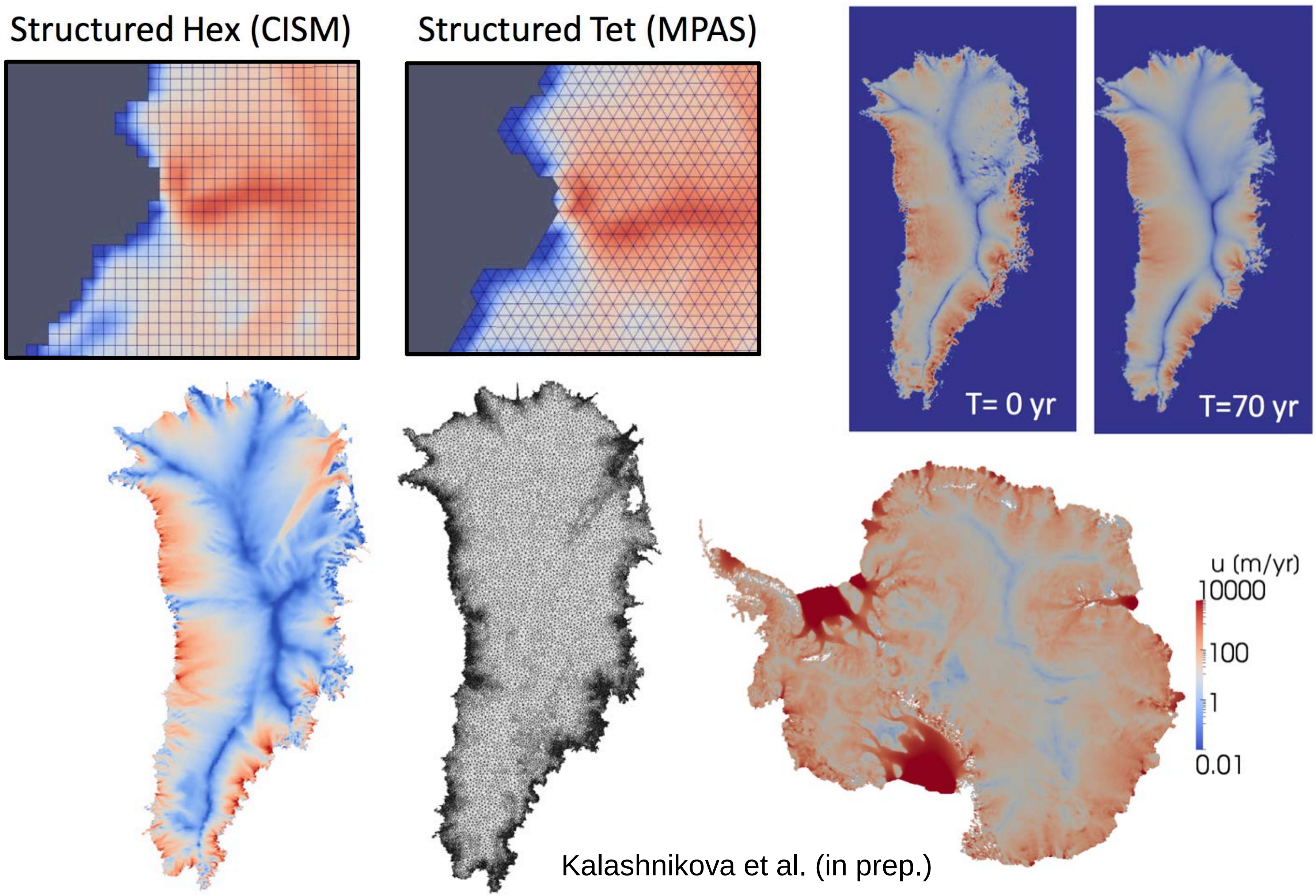
- base level res. of 5 km, refinement to 625 m -



(courtesy of D. Martin & S. Cornford)

Rignot et al., *Science*, **333** (2011)

FELIX-FO



Kalashnikova et al. (in prep.)

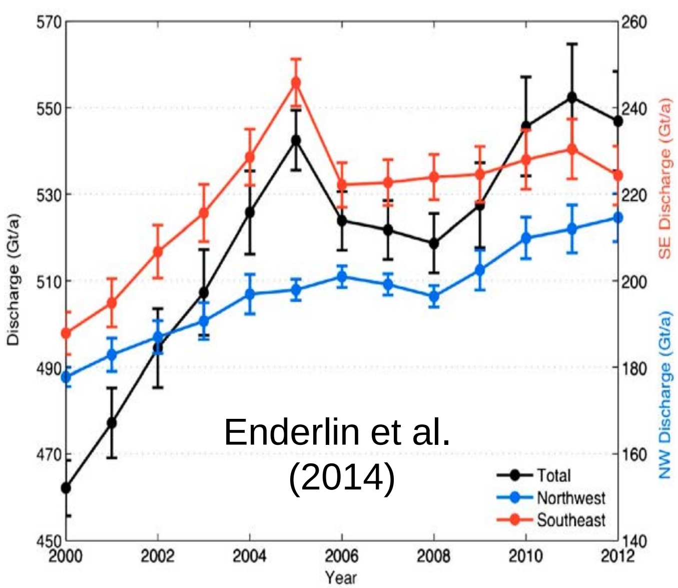
Verification and Validation (V&V)

Greenland Ice sheet (GIS) hind casting test case (OSU, UW, NASA):

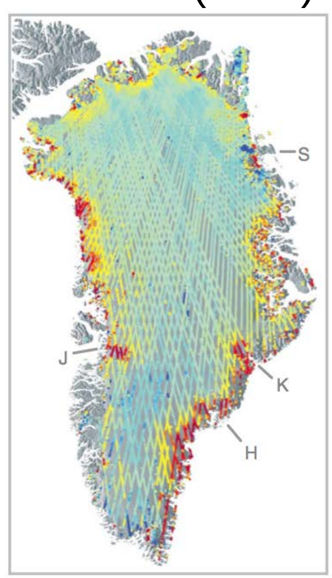
- obs. provide time series of outlet glacier flux over last ~15 yrs (~178 glaciers, 15 of which account for ~80% of discharge)
- regional climate modeling + reanalysis gives climate forcing

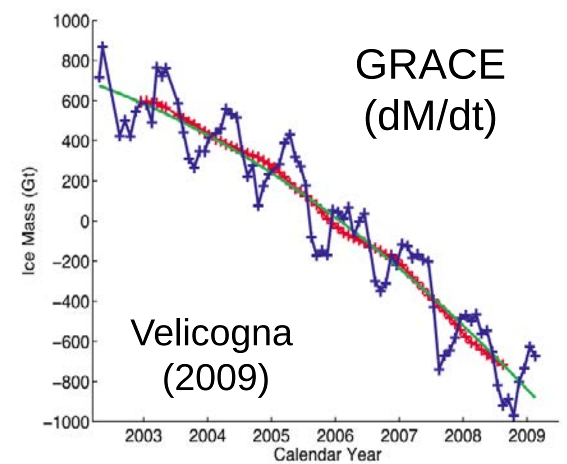
These provide the model forcing. Dynamic response will be compared to:

- rates of surface elevation change observed by ICESat (NASA, UW)
- rates of ice sheet mass change observed by GRACE (NASA, USF)

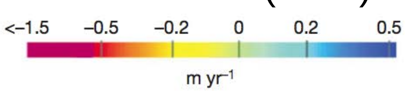


ICESat (dh/dt)





Pritchard et al. (2009)



Optimal Parameter Estimation: Motivation

Existing ice sheet model initialization methods do not couple smoothly with realistic climate forcing (from models or observations).

1. **Spin-up:** initial condition is consistent with climate forcing & long-term transients, but difficult (impossible?) to combine with the goal of closely matching present-day obs. (geometry, flux, etc.)

1. **Optimization:** fix model geom. to obs., tune model parameters (e.g., basal sliding coeff.) to provide optimal match to observed vels.

Method (1) is impractical because (i) ice dynamic response on 10^1-10^2 yr timescales is very strong function of initial geom. and vel., and (ii) spin-up of appropriate duration (10^4-10^5 yr) not practical for high-res., next-gen. ice sheet models.

Method (2) provides good match to present-day obs. but generally leads to unphysical “shock” when coupling to SMB from climate model.

Optimization Problem

To avoid non-physical shocks when coupling ice sheet models to ESMs, the model flux divergence must be balanced by the model SMB.

$$\frac{\partial H}{\partial t} = \underbrace{-\mathrm{div}\,(\mathbf{U}H)}_{\text{flux divergence}} + \overbrace{\tau_s}^{\text{surface mass balance}}, \qquad \mathbf{U} = \frac{1}{H}\int_z \mathbf{u}\,dz$$

At equilibrium: $\mathrm{div}\,(\mathbf{U}H) = \tau_s$

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

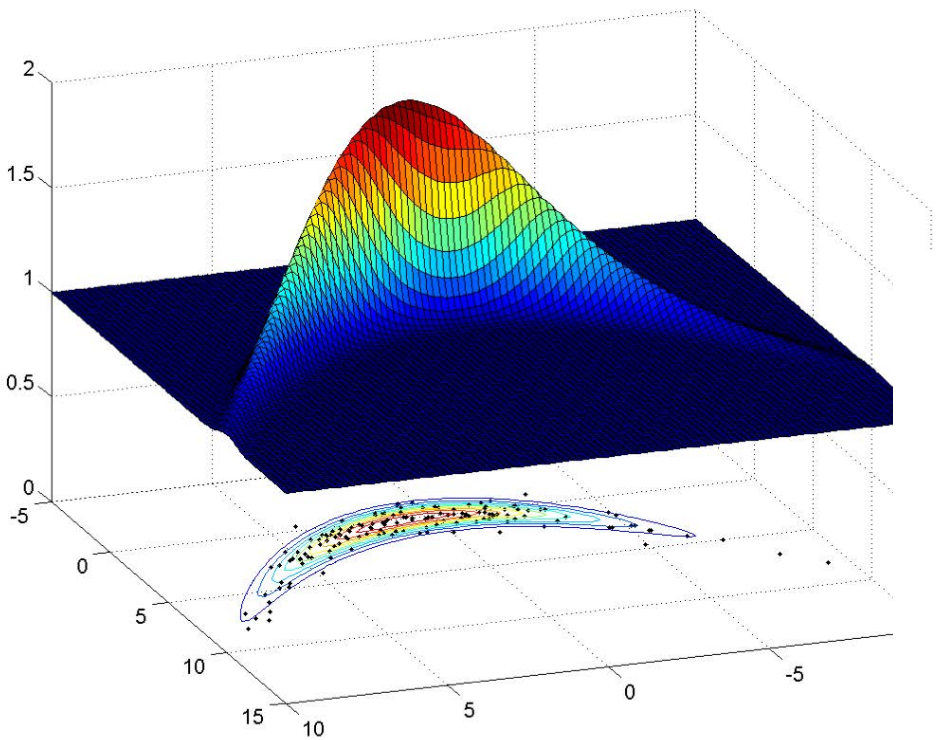
At the same time, we want the initial model geometry and velocity field to match present-day observations (obtained by optim. “beta” field)

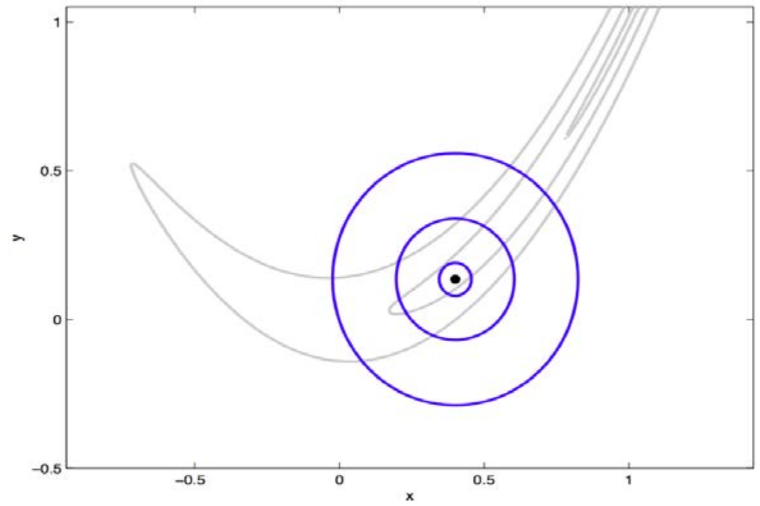
Solution: PDE-constrained optimization with constraints on both velocity (commonly applied) *and* flux divergence (novel), *additionally* accounting for uncertainties in ice sheet geometry (thickness)

Perego, Price, Stadler (*JGR Earth Surface*, in press)

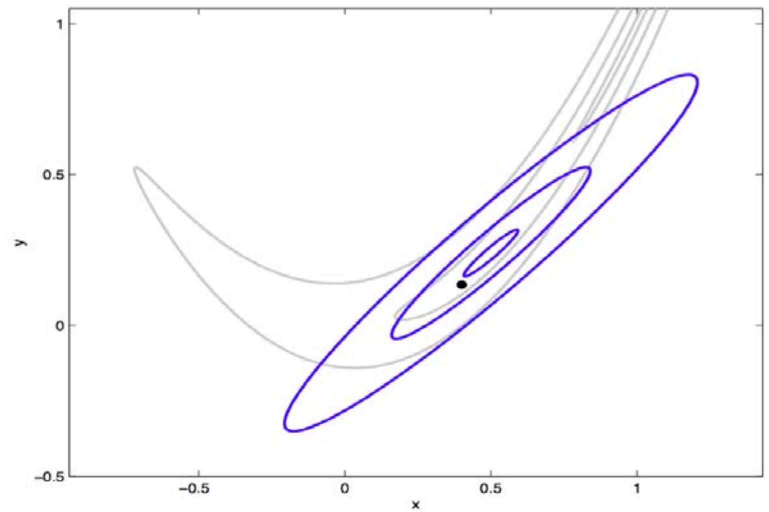
Future: Optimize & Assign Uncertainties

Use of approximate Hessian to increase acceptance rate of MCMC sampling of posterior parameter distribution





The contours of the random walk proposal function overlayed on the Rosenbrock contours.

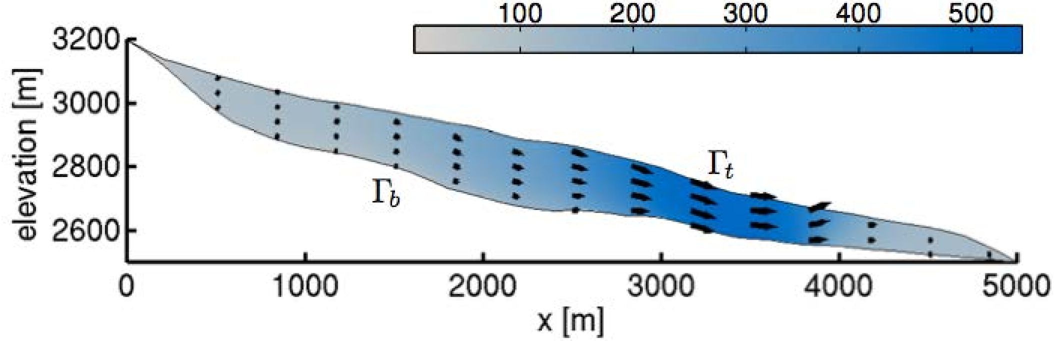


The contours of the stochastic Newton method proposal function overlayed on the Rosenbrock contours.

Figures courtesy of G. Stadler

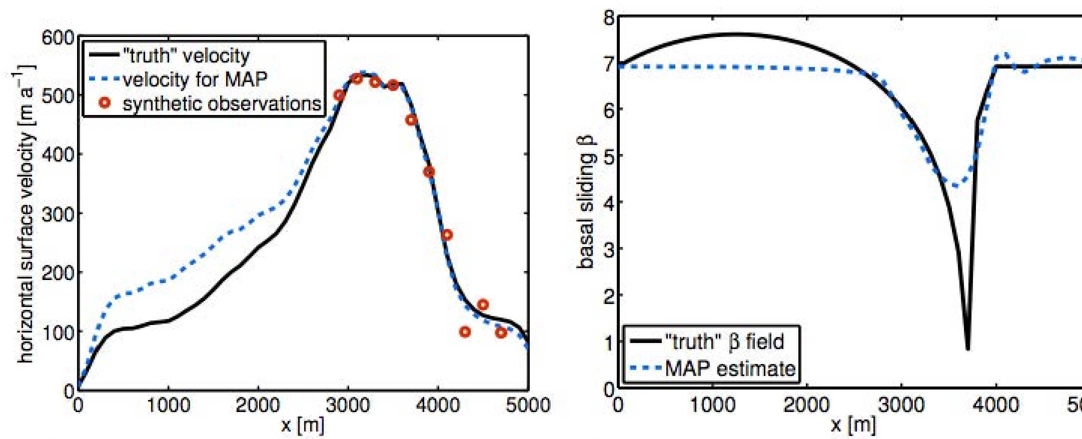
Future Work

Modeled 2d (x,z) velocity field with basal sliding coefficients tuned to match observations



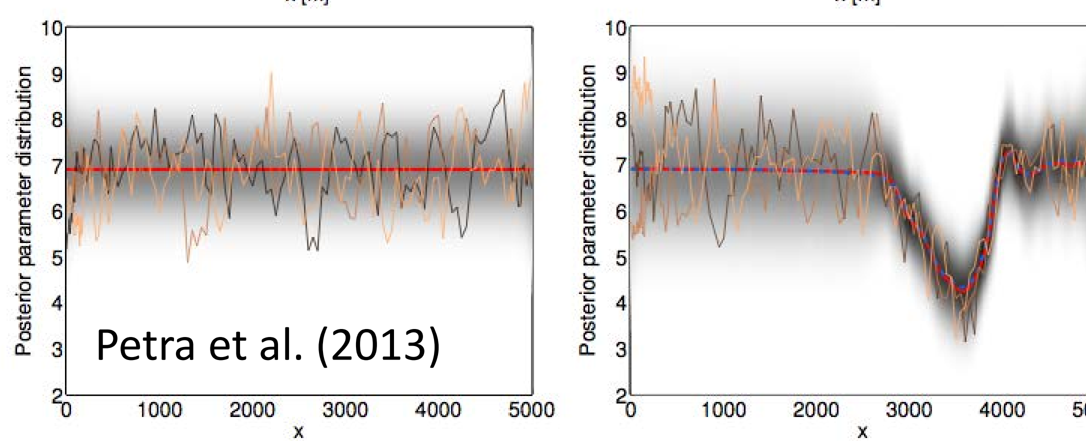
Left: modeled (blue) and "true" (blk) surface velocity profile and synthetic observations (red)

Right: MAP estimate (blue) and "true" basal sliding coefficient (blk)



Left: prior estimate for basal sliding coefficient distribution

Right: posterior coefficient distribution obtained using Hessian-informed MCMC sampling



Earth System Model Integration

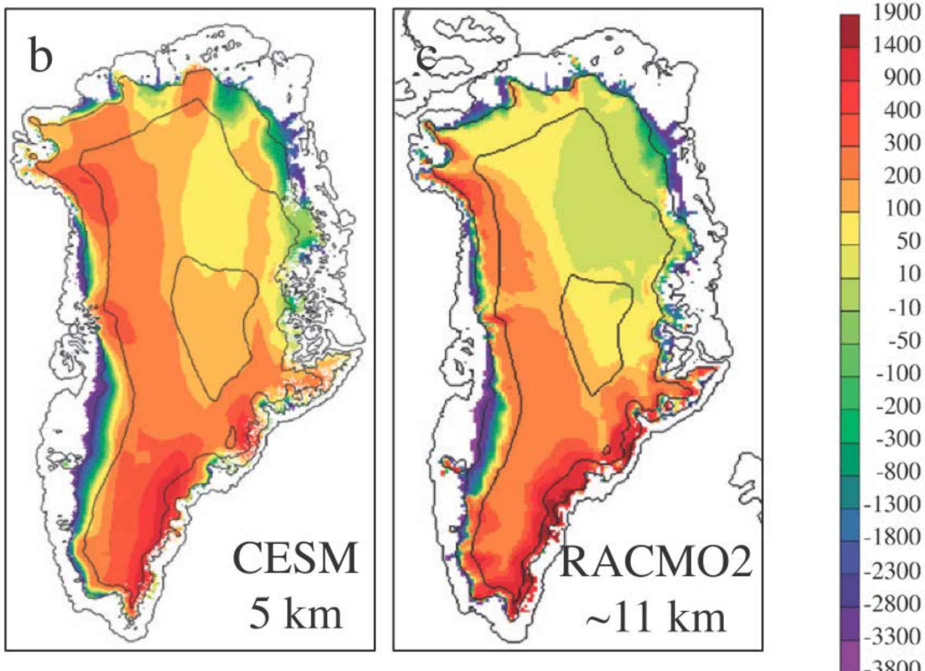
Coupling b/w land ice, atmosphere, & land models largely “complete”

Land ice SMB[1] is calculated w/ snowpack model in land model:

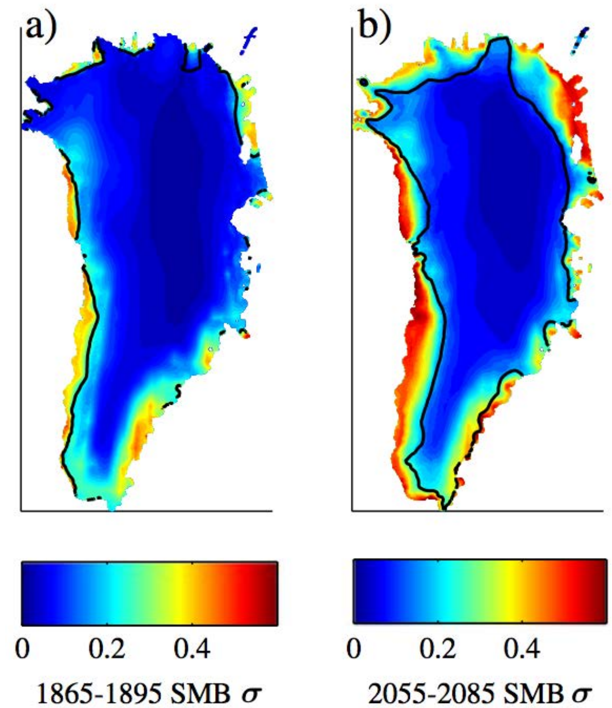
- temperature / moisture fluxes downscaled from coarse-res. land / atmos. grid to high-res. ice sheet grid
- results (for GIS) are in good agreement with both obs. and high-res., regional model simulations

[1] SMB = surface mass balance = ice accumulation less melting

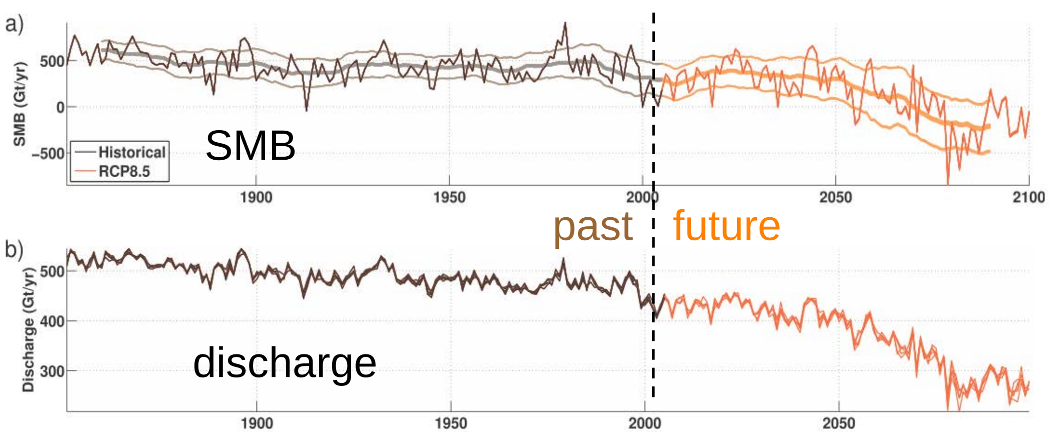
Earth System Model Integration



Vizcaino et al. (*J. Clim.*, 2013)



Fyke et al. (*GRL*, 2013)
Fyke et al. (*GRL, accepted*)



Lipscomb et al.
(*J. Clim.*, 2013)