Projecting Ice Sheet and Climate Evolution at Extreme Scales (PISCEES): Overview, Update & Integration with other DOE Climate Modeling Activities

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SciDAC
Scientific Discovery through Advanced Computing

Motivation and Project Overview

Focus Areas & Progress

Summary & Future Work

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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.

PISCEES aims to:

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

2) evaluate ice sheet models using new tools and data sets for verification and validation (V&V) and uncertainty quantification (UQ)

3) integrate these models and tools into DOE-supported Earth System Models (ESMs), including DOE's new Accelerated Climate Model for Energy (ACME) and the Community Earth System Model (CESM)

Project Overview

PISCEES builds on past BER / ASCR investments in devel. of next-gen. ice sheet models & coupling to ESM's:

- **SciDAC2:** initial coupling of Glimmer ice sheet model to CESM
- **IMPACTS:** addition of sub-ice shelf circulation capability, coupling between dynamic land ice and ocean circ. models, and initial simulations of Antarctic ice sheet and S. Ocean coupled evolution
- **ISICLES:** addition of scalable parallelism and *Trilinos* and *Chombo* software hooks to CISM, initial development of next gen. land ice dycores including BISICLES, Stokes, and first-order Stokes approx. dycores for MPAS-Land Ice

Project Overview

PISCEES has strong links to ongoing BER / ASCR investments:

- **RGCM**: long-term stability of the Greenland Ice Sheet; changes in Arctic / N. Atlantic freshwater flux on sea ice, AMOC, BGC
- **ACME:** continuation & extension of ice sheet coupling and application to address one primary science question (sea-level rise commitment from future Antarctic ice sheet evolution)
- **ASCR:** heavy use of ASCR supported libraries (*Trilinos, Chombo, PETSc*); collaborations with SciDAC FASTMath, SUPER, and QUEST institutes

Motivation and Project Overview

Focus Areas & Progress

dynamical core development

Summary & Future Work

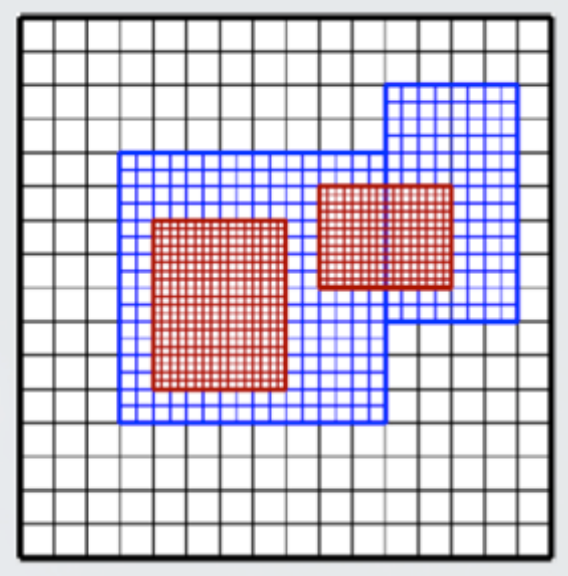
Dynamical Core Development

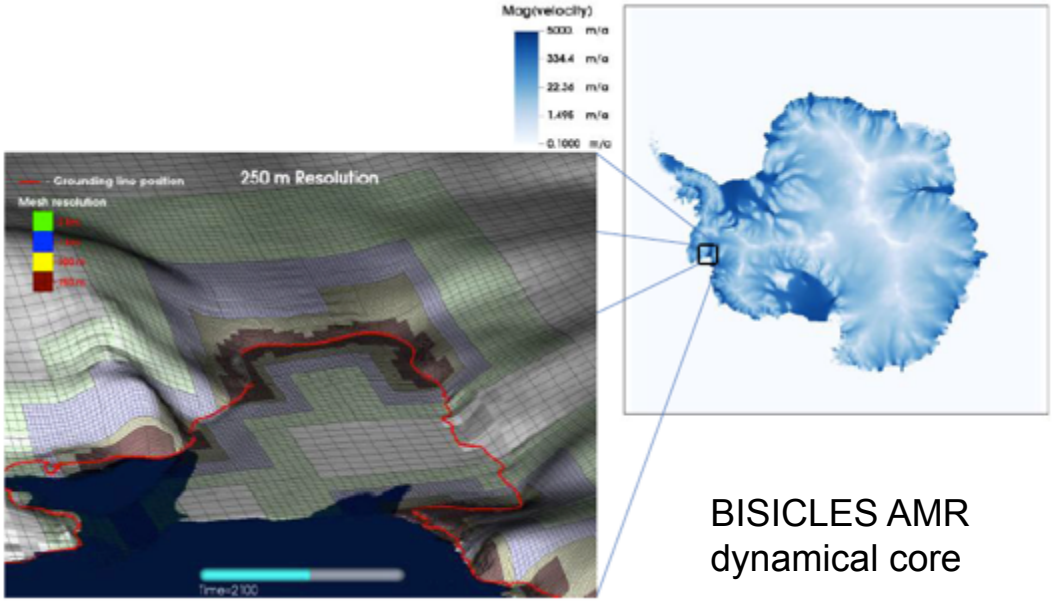
Land Ice Modeling Frameworks:

Community Ice Sheet Model (CISM)

- regular, structured grid
- relatively mature, fully-functioning ice sheet model
- coupled to CESM
- focus on BISICLES dycore

block structured AMR





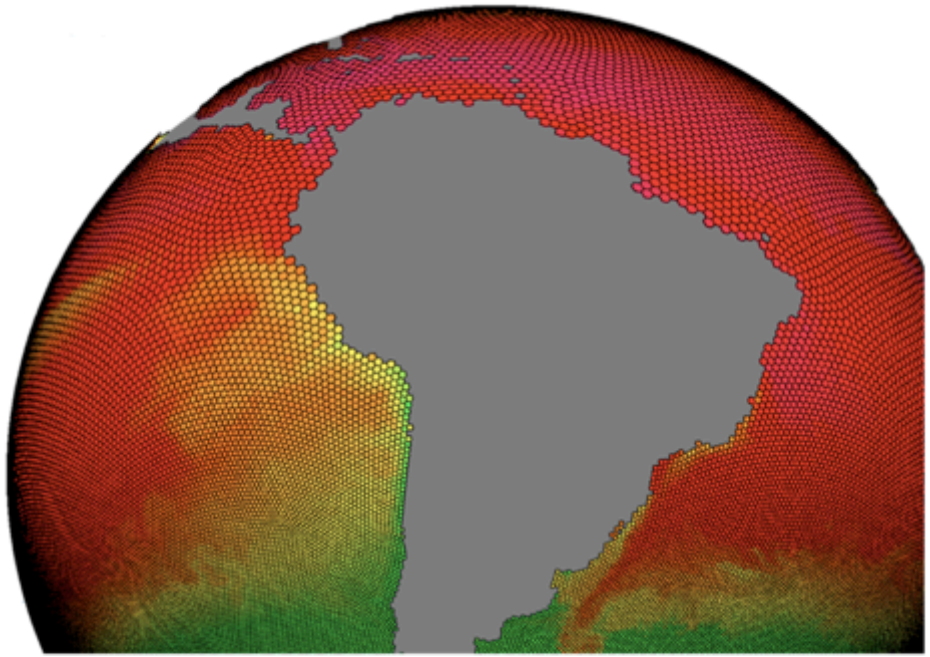
BISICLES AMR
dynamical core

Dynamical Core Development

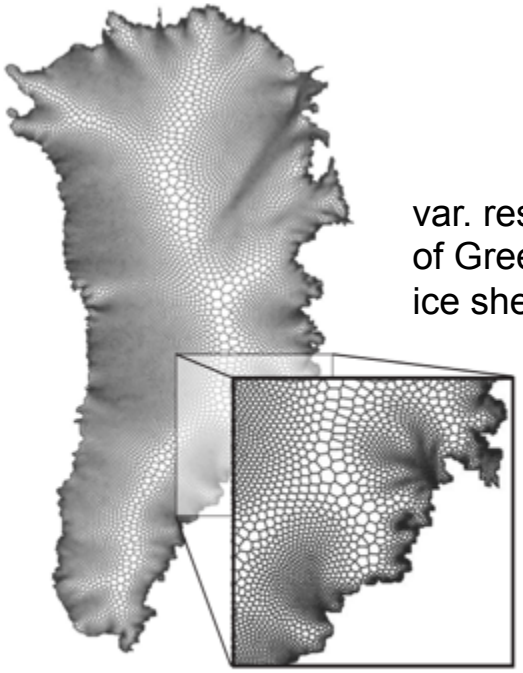
Land Ice Modeling Frameworks:

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
- focus on FELIX dycore



global, var. res. ocean SCVT



var. res. CVT of Greenland ice sheet

Dynamical Core Development

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

- first-order, L1L2 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
  - coupled to MPAS-LI
- **FELIX-FO**
  - first-order approx. to Stokes mom. bal.
  - coupled CISM and MPAS-LI

BISICLES Dynamical Core

"L1L2" momentum balance [1]

- formally 1st-order approximation to Stokes equations [2]
- velocities: 2d elliptic solve + SIA vertical column solve

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

Chombo solver library; *PETSc* Algebraic Multi-Grid

MISMIP3d [3] – demonstration of marine ice sheet dynamics very similar to (much more expensive) high-resolution Stokes [4]

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

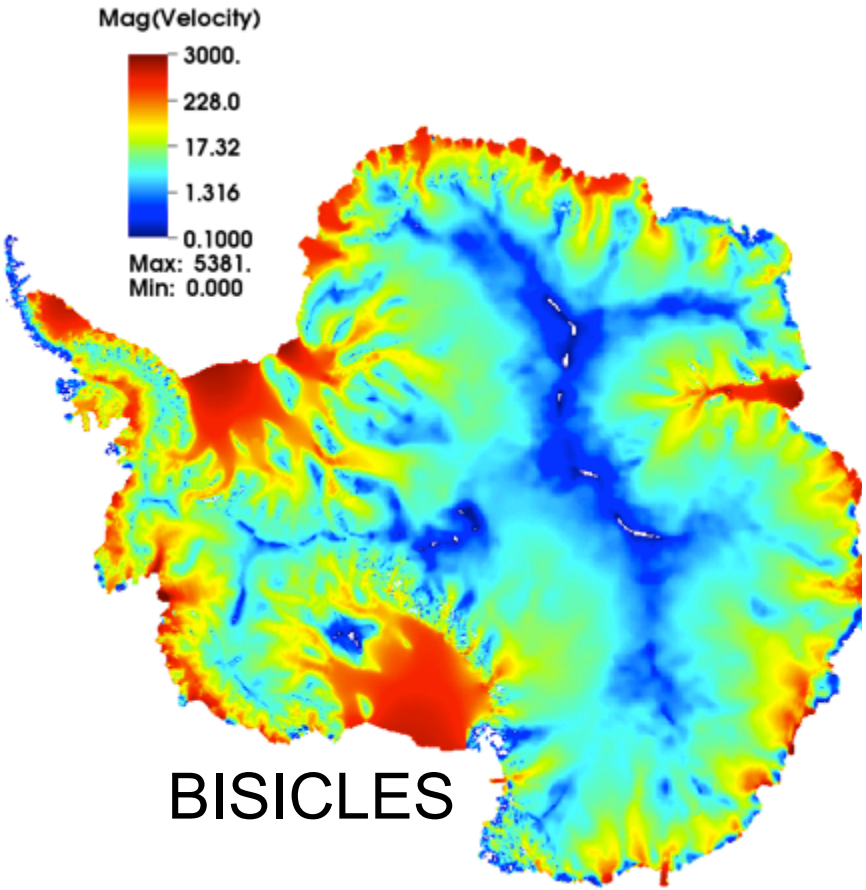
Coupled to Community Ice Sheet Model (CISM)

Collaboration between LBNL, UOB, & LANL

*** See poster by Martin et al. (#85, room 20) ***

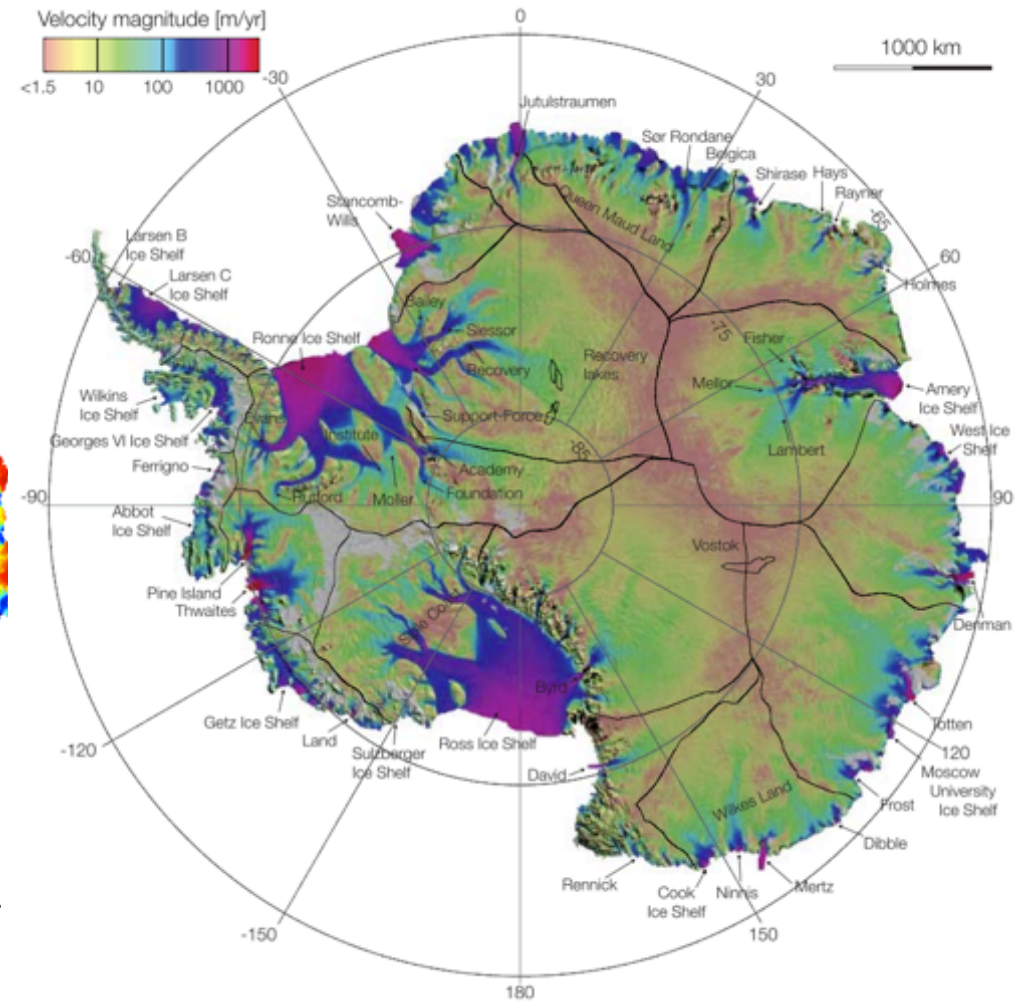
[1]Cornford et al. (2012); [2]Schoof and Hindmarsh (2010); [3]Pattyn et al. (2013); [4]Pattyn & Durand (2013)

BISICLES: Resolved, Whole Antarctic Ice Sheet Simulations



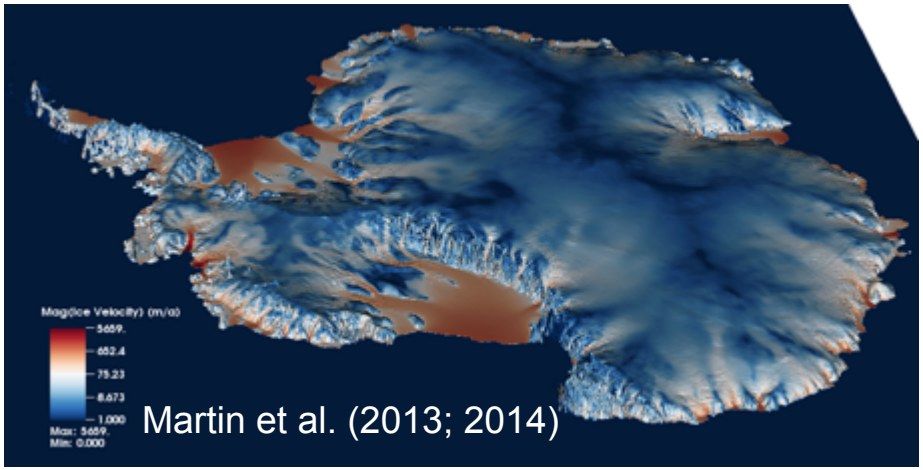
- base level res. of 5 km, refinement to 625 m -

(courtesy of D. Martin & S. Cornford)

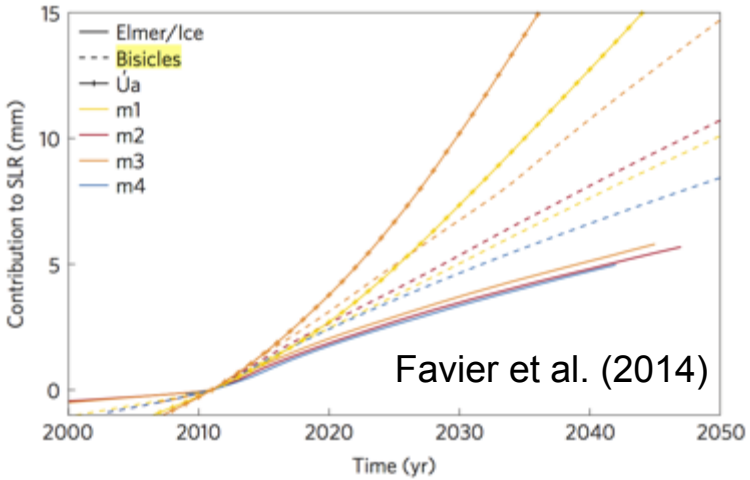


Rignot et al., *Science*, **333** (2011)

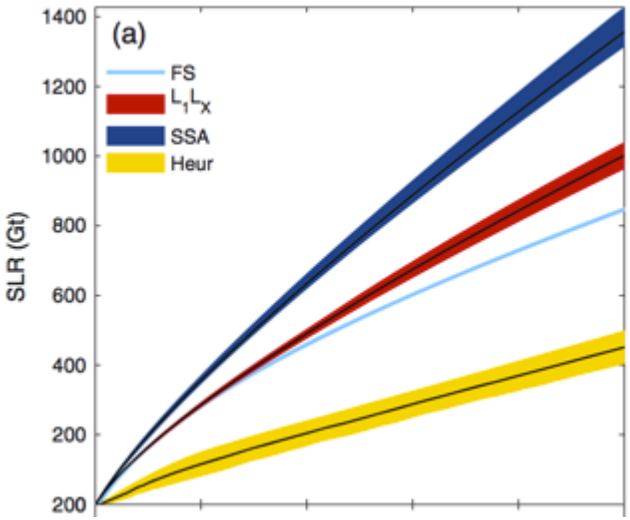
BISICLES Science Results: SLR from Antarctica due to marine ice sheet dynamics and ice-ocean interactions



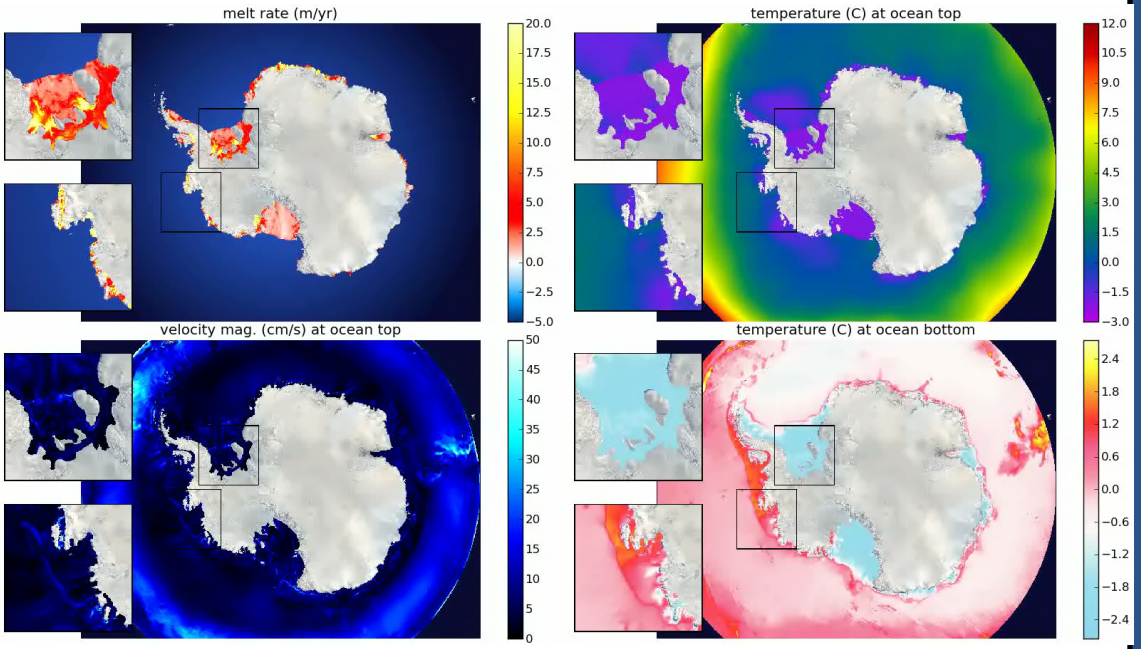
Martin et al. (2013; 2014)



Favier et al. (2014)



Pattyn and Durand (2013)



Asay-Davis et al. (2013; 2014)

FELIX Dynamical Cores

FELIX-FO [1]

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

Leveraging MPAS-native temperature and thickness solvers

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

Built on *Albany* and *Trilinos* solver libraries

Robust convergence of nonlinear system using Newton with homotopy

Linear system using ILU precond. CG (working on ML)

Demonstration of solving for 1 billion unknowns on 16 k cpus

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

Built-in verification using method of manufactured solutions

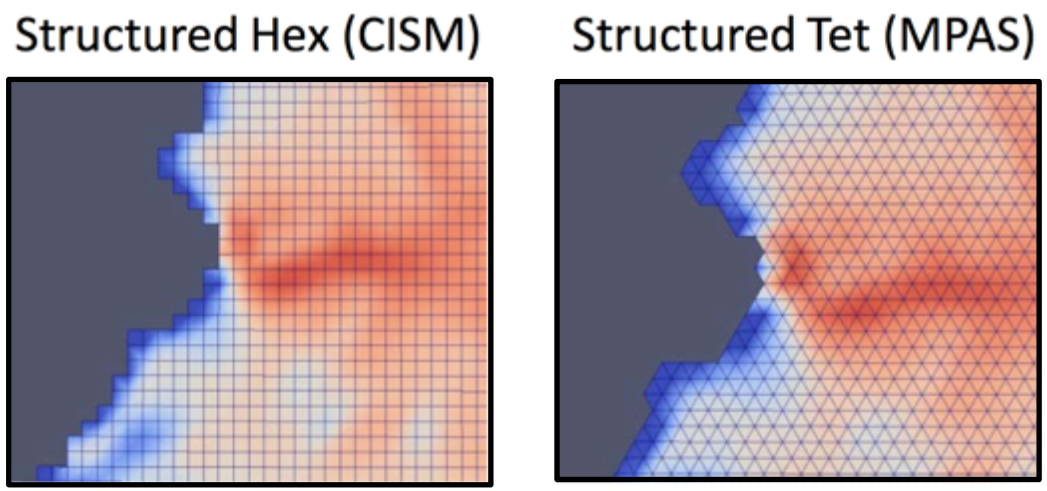
Coupled to CISM and MPAS-LI

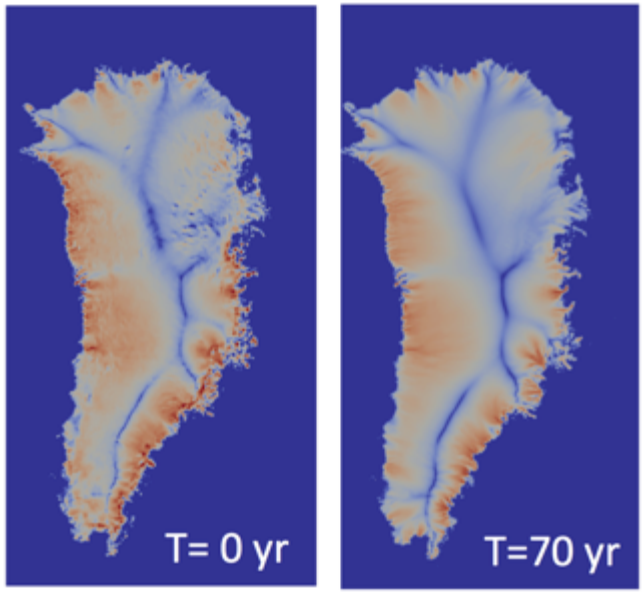
Prototype model used in *Ice2Sea* simulations

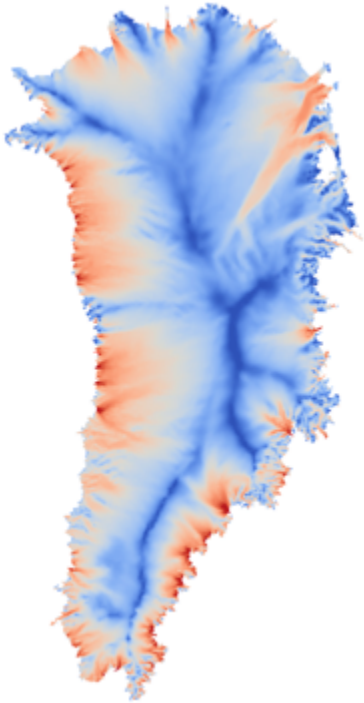
*** See poster by Salinger et al. (#43, room 1) ***

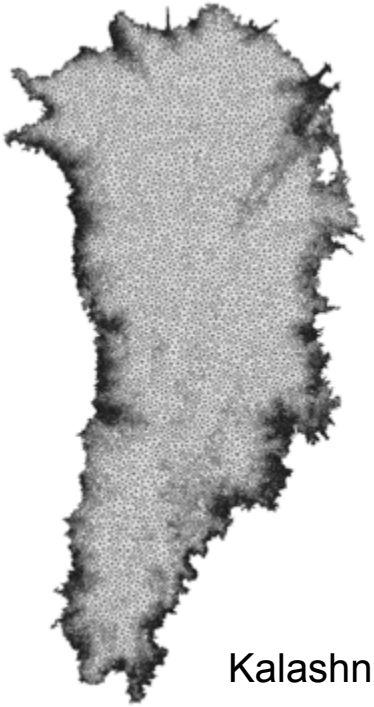
[1] Kalashnikova et al. (in prep.)

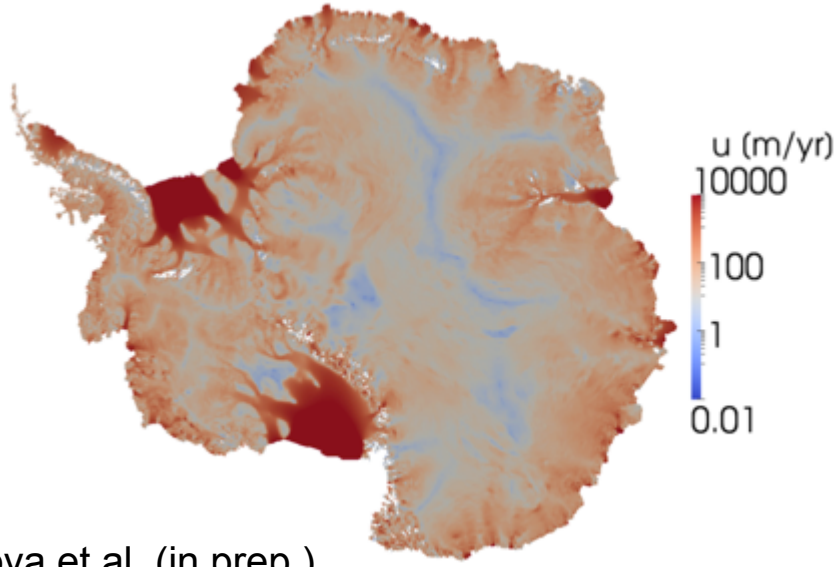
FELIX-FO











Kalashnikova et al. (in prep.)

FELIX Dynamical Cores

FELIX-S

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)

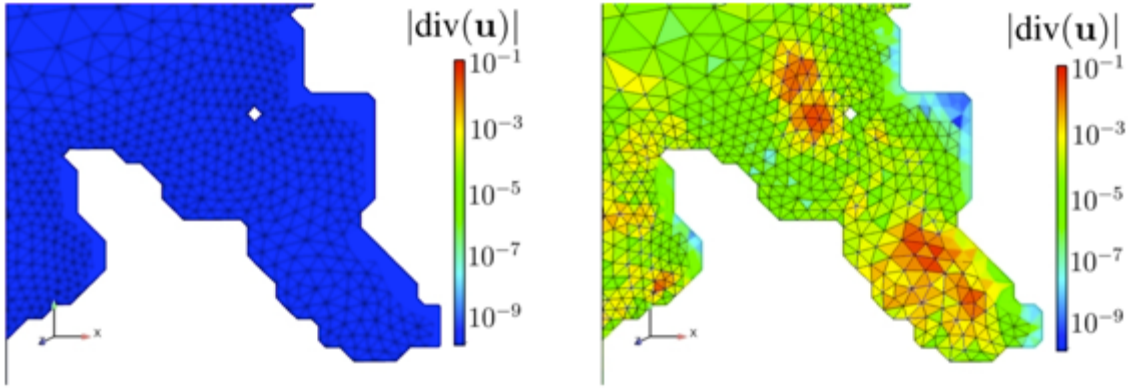
Strong and weak scalability to ~10^2 -10^3 cpus

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

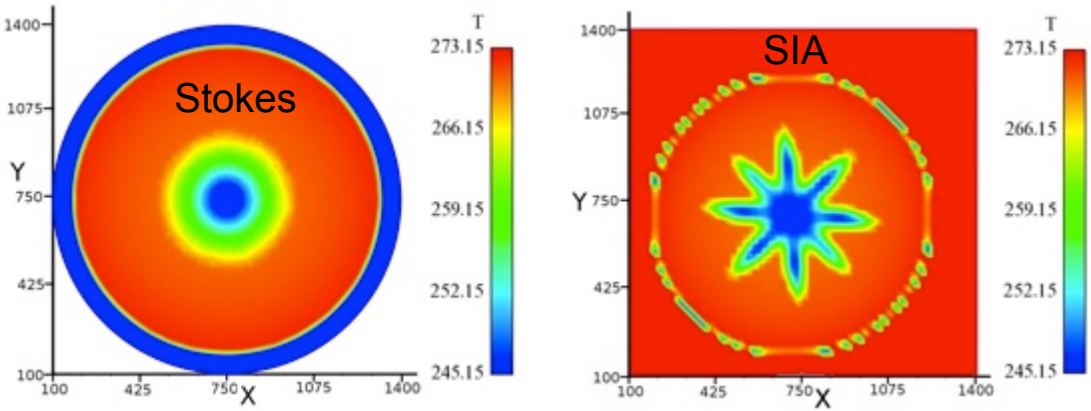
Coupled to MPAS-LI

Leng et al. (2012a; 2012b; 2014)

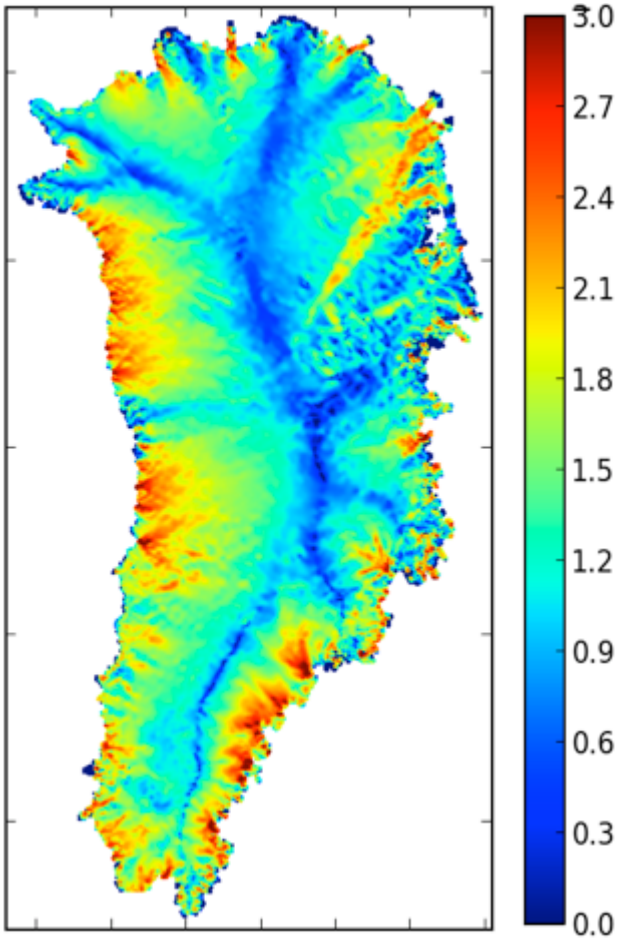
FELIX - S



Improved local mass cons. using enhanced Taylor-Hood

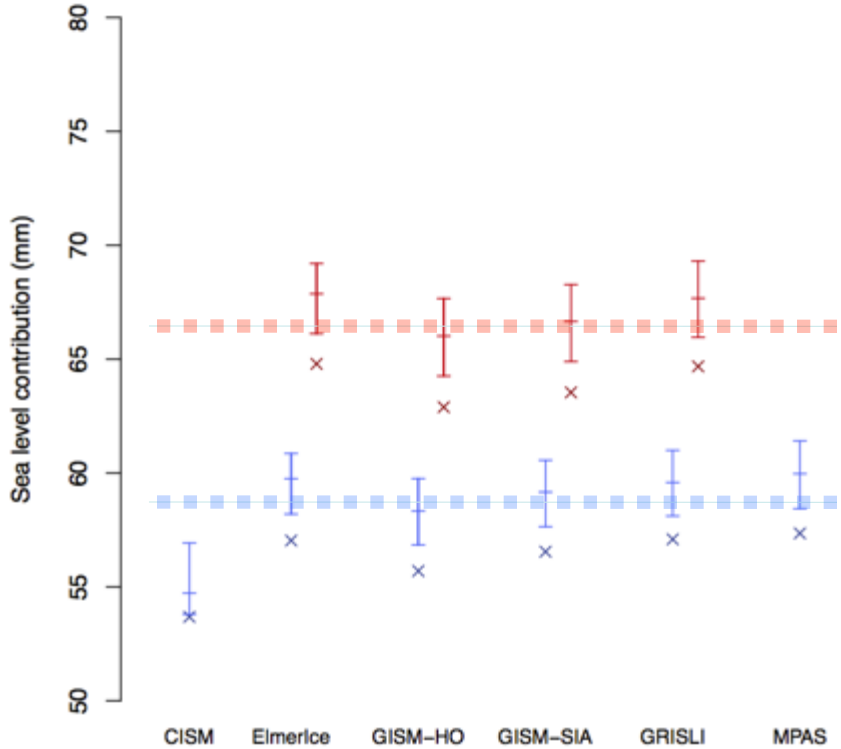


Disappearance of symmetry breaking using thermomechanically Coupled Stokes

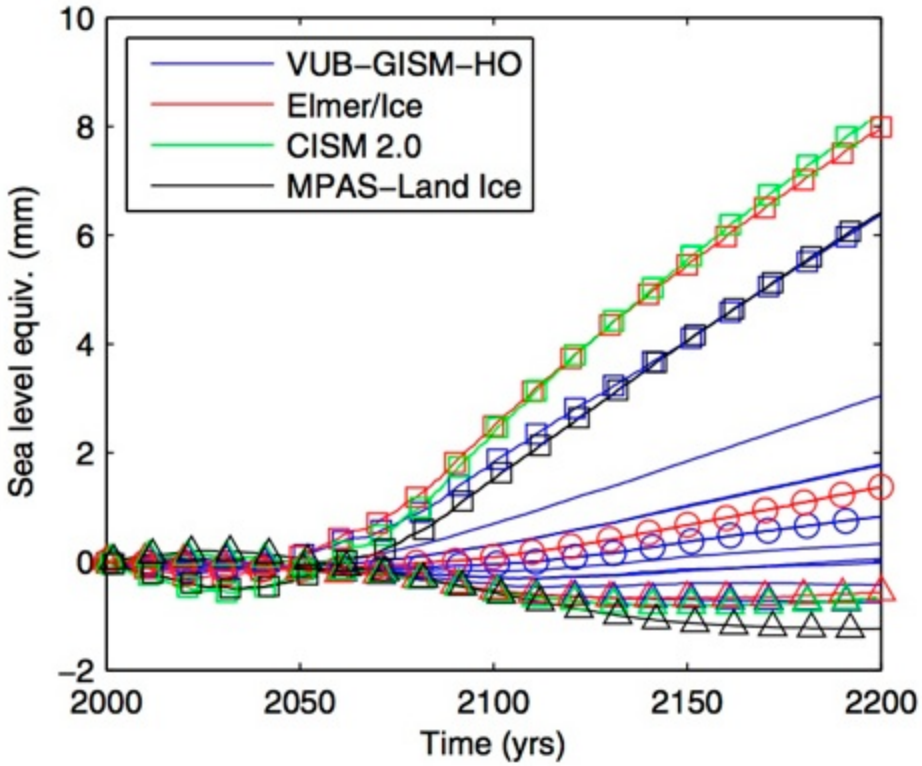


Greenland Ice sheet simulation using realistic basal sliding coefficient

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



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



Shannon et al. (*PNAS*, 2013)

Motivation and Project Overview

Focus Areas & Progress

verification and validation (V&V)

Summary & Future Work

Verification and Validation (V&V)

Initial implementation of Land Ice Verification & Validation (LIVV) toolbox working with CISM

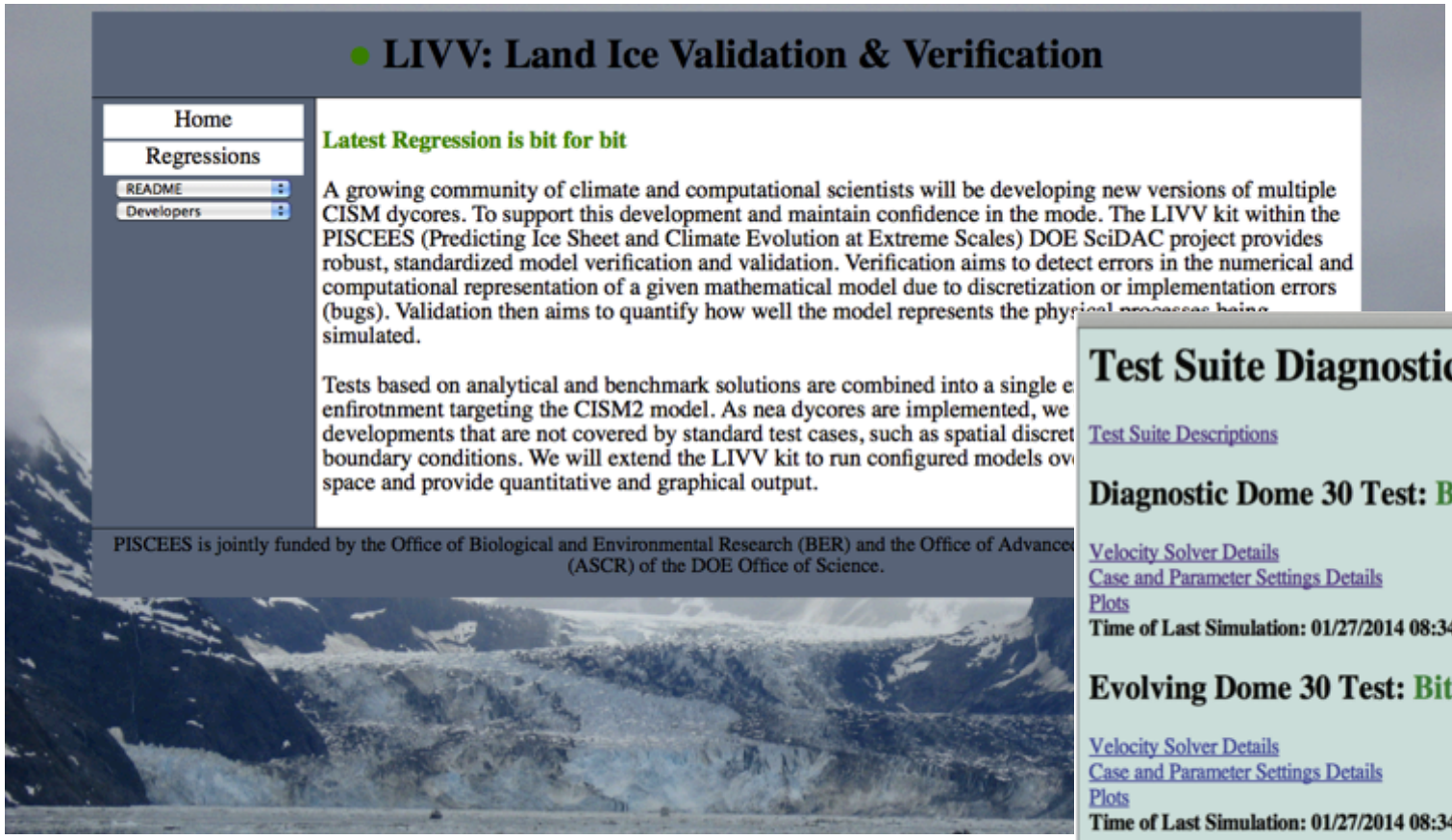
Initial implementation of *Performance* LIVV Land Ice Verification & Validation (pLIVV) toolbox working with CISM

Nightly builds and testing of supported compilers and model configurations using standard CISM test cases

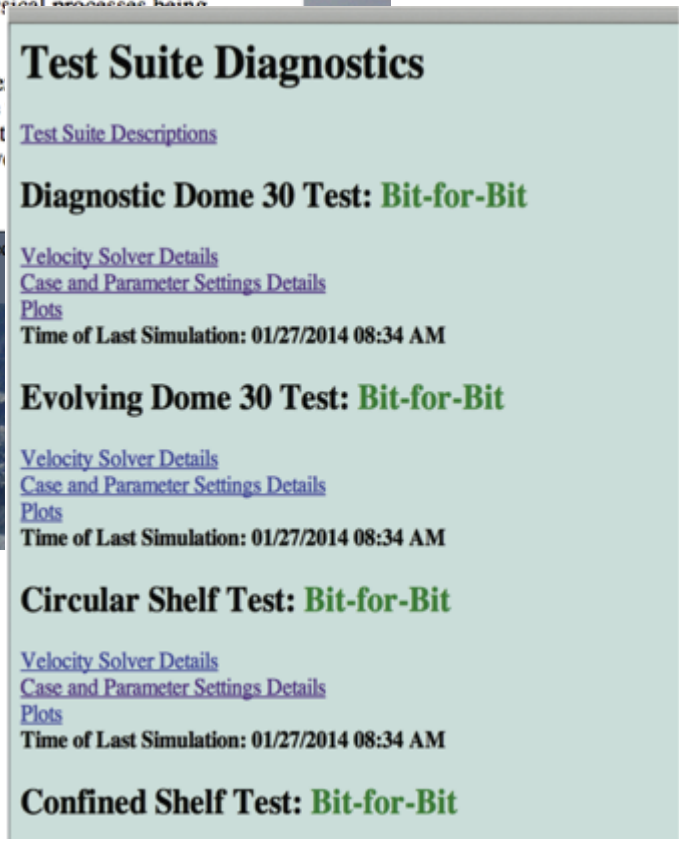
Starting on collection of relevant diagnostics from CESM so that changes in fields relevant to CISM-CESM coupled runs (e.g. energy and moisture fluxes) can be flagged by LIVV

*** See poster by Evans et al. (#88, room 20) ***

Verification and Validation (V&V)



Screenshot from LIVV homepage



Report for most recent nightly test

Verification and Validation (V&V)

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

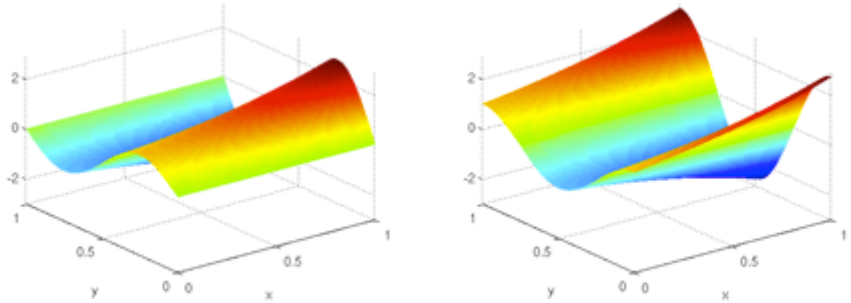
Less than the Min

Greater than the Max

test highlighting improved performance

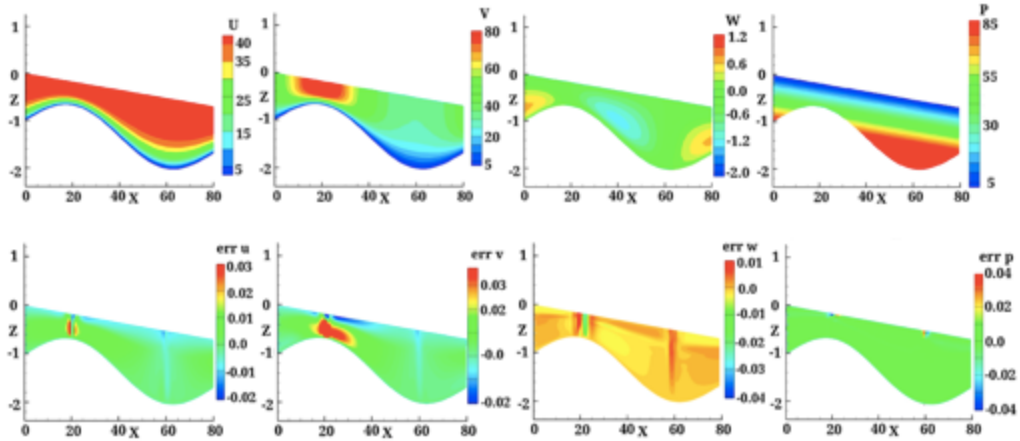
Verification and Validation (V&V)

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

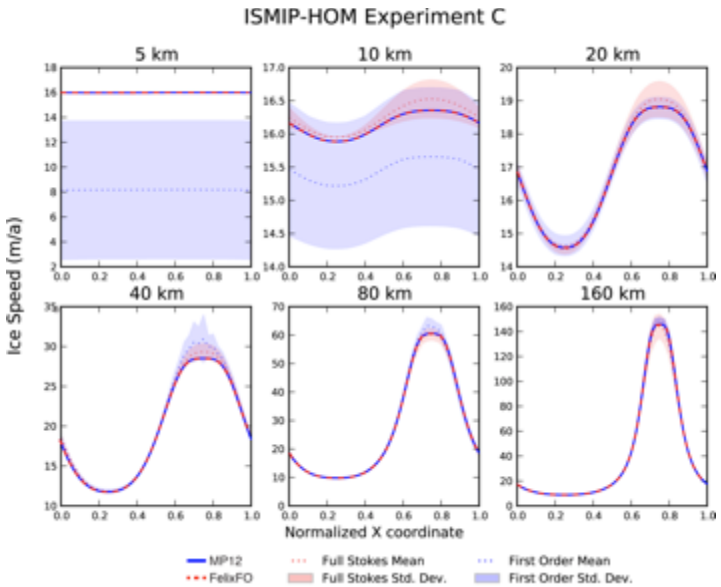


(a) u (b) v

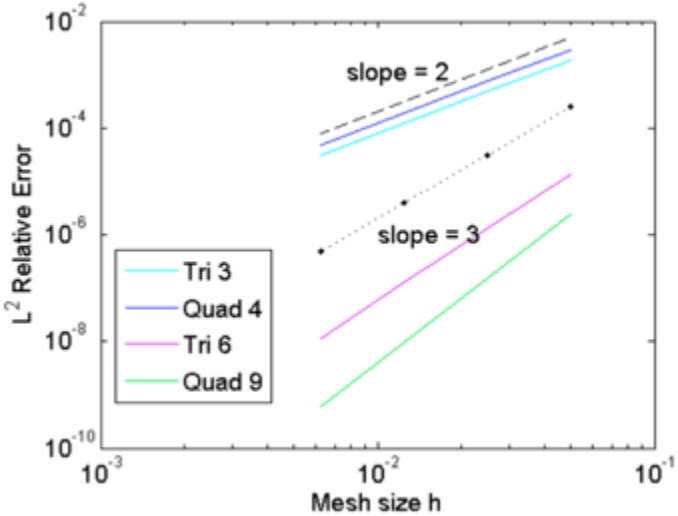
MS for 1st-order Stokes approximation



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



FELIX vs. ISMIP-HOM benchmark



FELIX-FO convergence with refinement

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

Verification and Validation (V&V)

Validation** for ice sheet models is far from being a standard practice because of …

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

Sparse data: many observational datasets that might be useful for validation are often also needed as constraints for model optimization (e.g. surface velocities from InSAR)

Data formats: many of the datasets that might be useful for validation are not yet in “model friendly” formats or involve processing / interpretation complications that require non-DOE expertise (e.g. ICESat, GRACE)

** **Validation**: Is our model is a good representation of the natural system we hope to mimic?

Verification and Validation (V&V)

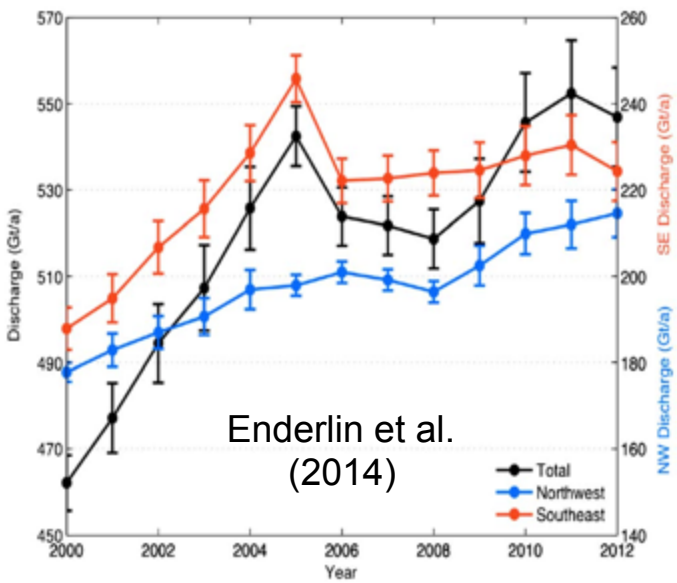
Greenland Ice sheet (GIS) hind casting test case (OSU, UW, NASA):

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

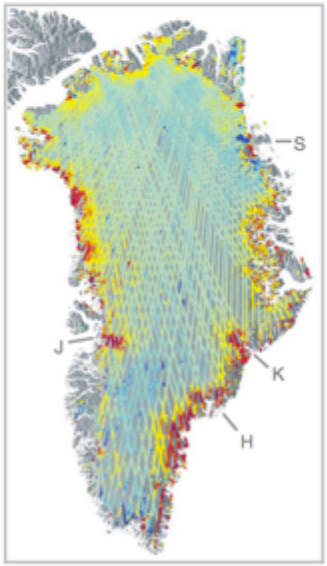
These provide the model forcing, with response to be compared to …

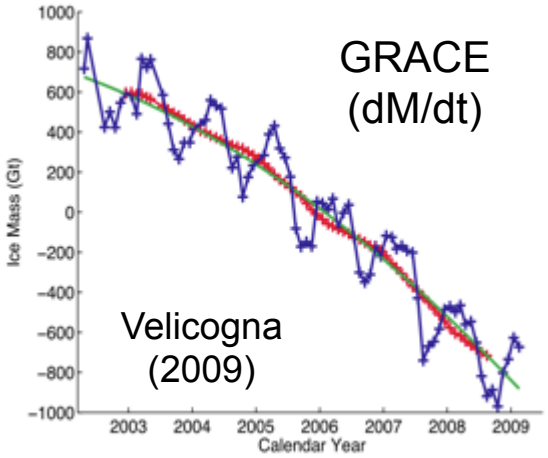
… rates of surface elevation change observed by ICESat (NASA, UW)

… rates of ice sheet mass change observed by GRACE (NASA, USF)

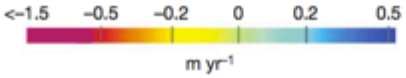


ICESat (dh/dt)





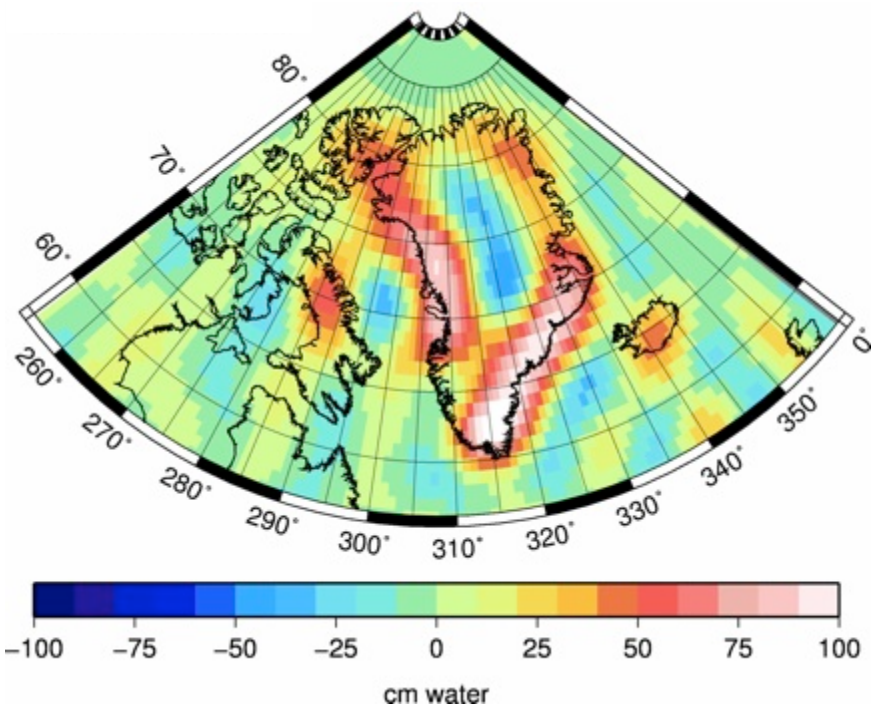
Pritchard et al. (2009)



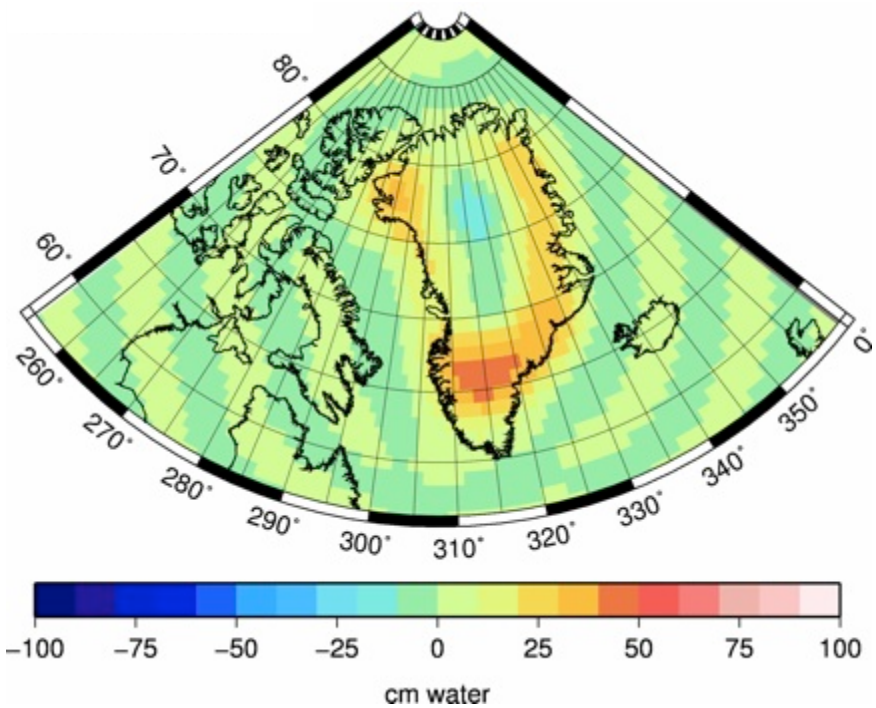
Verification and Validation (V&V)

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

GRACE[1] in 60x60 harmonics (unsmoothed)



CISM simulation[2] converted to 60x60 harmonics



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

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

Motivation and Project Overview

Focus Areas & Progress

uncertainty quantification (UQ)

Summary & Future Work

Uncertainty Quantification

Uncertainty in predictions from ice sheet models (e.g. sea-level rise) come from multiple sources, including predominately:

(1) Uncertainties in model forcing - largely related to uncertainties in future climate, which are being explored through emissions-scenario-dependent and perturbed physics ensemble analyses **

(2) Model uncertainties – largely due to uncertainties in initial and boundary conditions **

PISCEES UQ will focus on the latter, specifically:

(i) Constraining 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 talks by: Heimbach et al., Jackson et al., Price et al. ****
& poster by Salinger et al. (#43, room 1)

Motivation and Project Overview

Focus Areas & Progress

Earth System Model Integration

Summary & Future Work

Earth System Model Integration

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

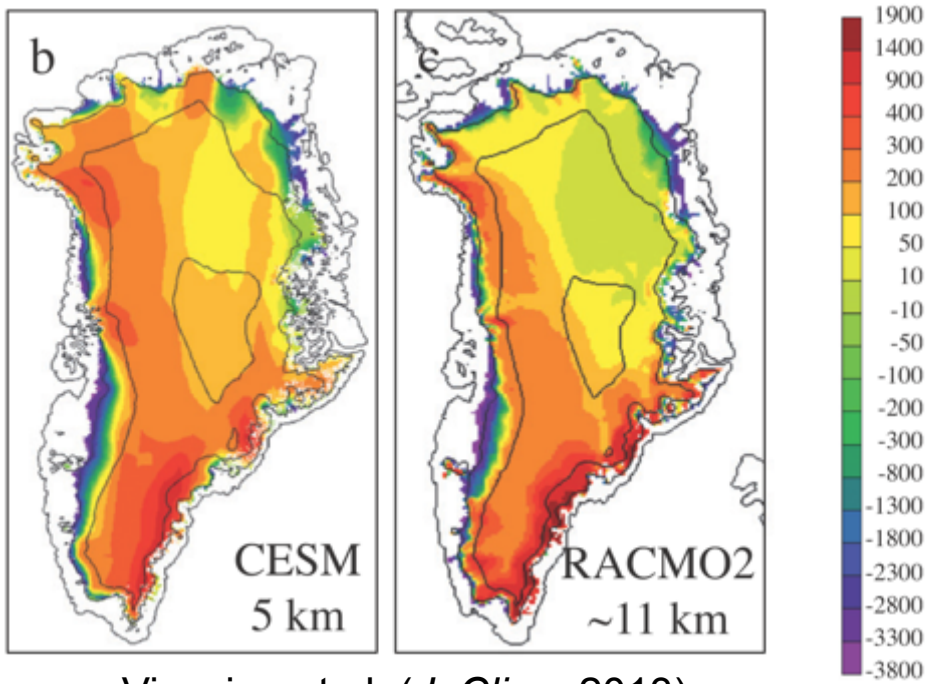
Land ice SMB[1] is calculated w/ snowpack model in land model:

- temperature / moisture fluxes downscaled from coarse-res. land / atmos. grid to high-res. ice sheet grid

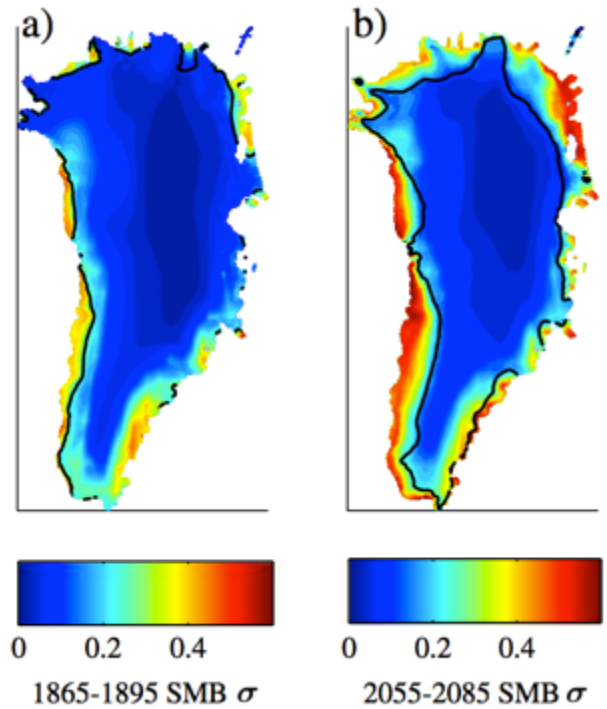
- results (for GIS) are in good agreement with both obs. and high-res., regional model simulations

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

Earth System Model Integration

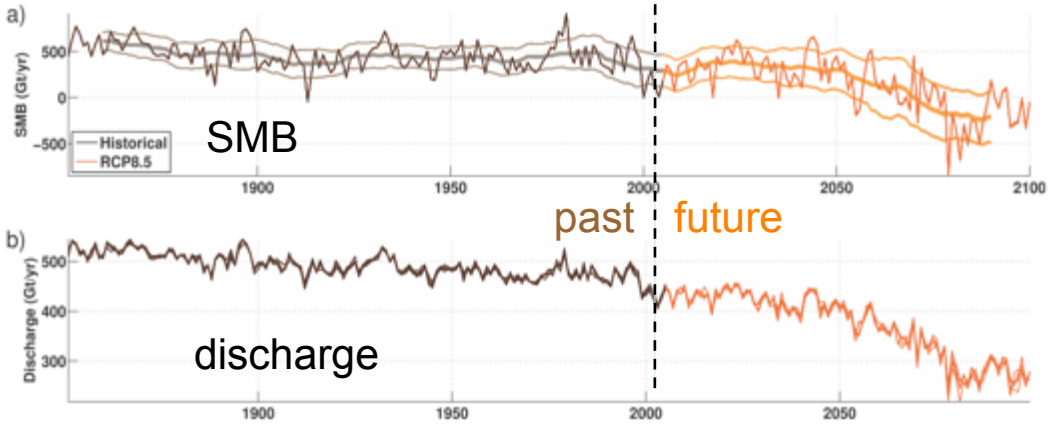


Vizcaino et al. (*J. Clim.*, 2013)



Fyke et al. (*GRL*, 2013)
Fyke et al. (*Nat. Geosc.*, submitted)

*** see poster by Fyke et al. ***
(#22, room 1)



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

Earth System Model Integration

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

Land ice SMB 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

New / recent coupling development:

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

** Coupling w/ CESM; ACME v0.1 *should* also have these capabilities

Earth System Model Integration: ice / 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.*"

Paleorecord supports at least partial Antarctic Ice Sheet (AIS) deglaciation during past warm periods (with similar CO_2 forcing)

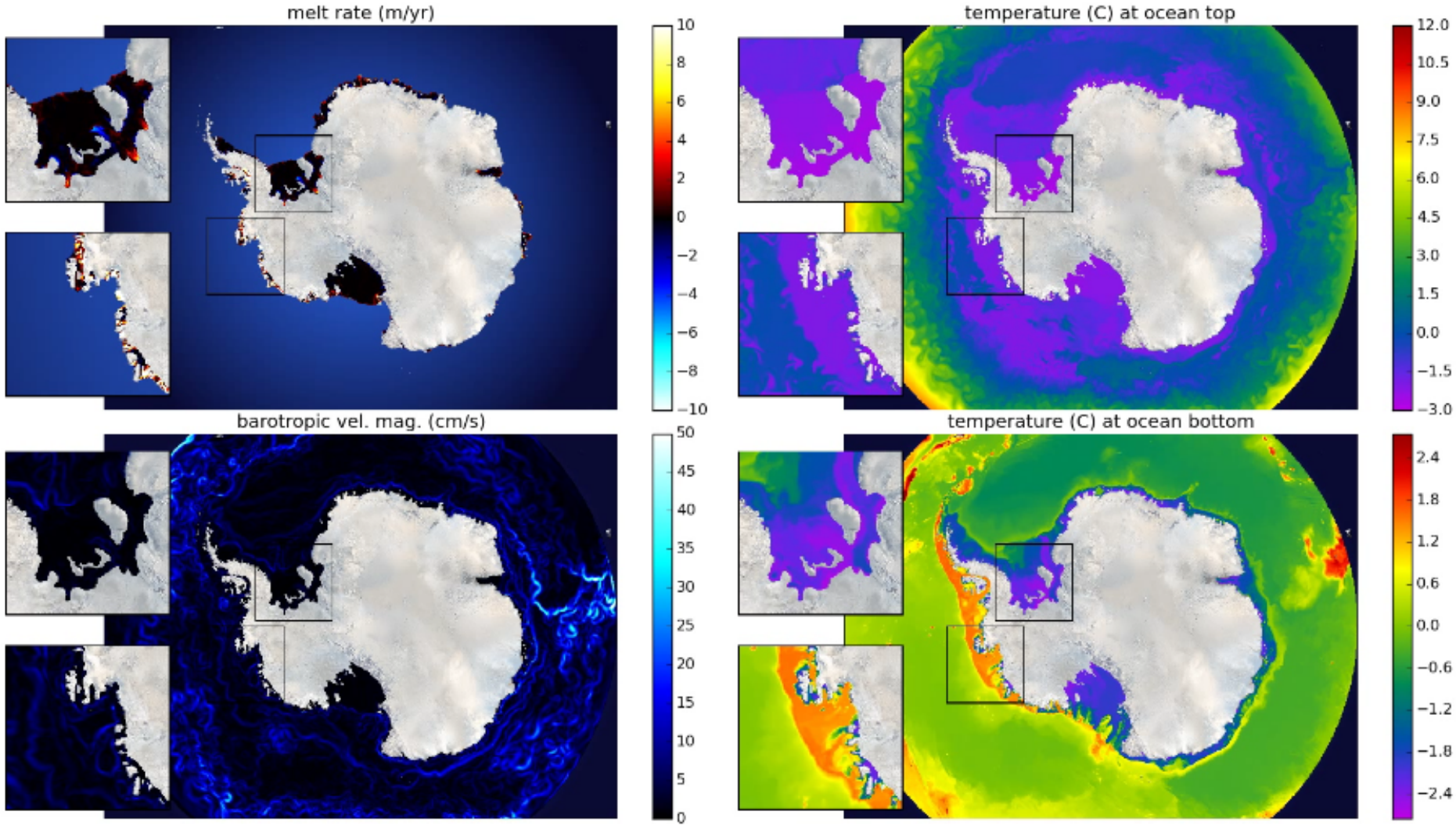
Committed future sea-level rise (SLR) from AIS is focus area for ACME

Ice sheet – ocean interactions are *the* mechanism for forcing rapid SLR from marine-based sectors of AIS

DOE BER & ASCR investments have lead to significant progress on ice sheet – ocean coupling and the resultant ice dynamic response **

** progress through IMPACTS, ISICLES, & PISCEES

Ice-Ocean Coupling: 20 yrs of fully coupled evolution using POP2x and CISM-BISICLES



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

*** See Martin et al. poster this afternoon for more details ***

Ice-Ocean Coupling: submarine melt validation

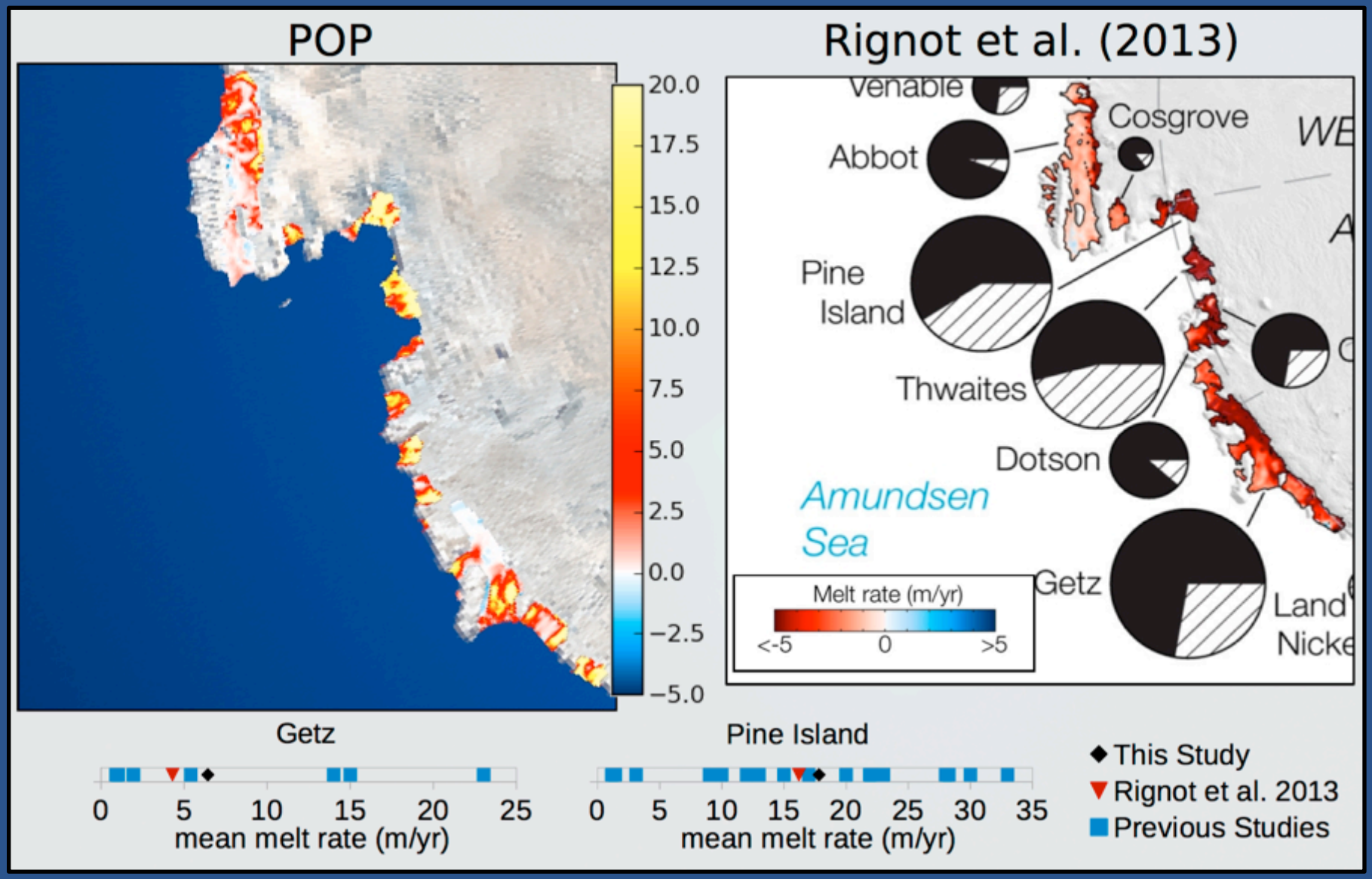


Figure courtesy of X. Asay-Davis (LANL / PIK)

Motivation and Project Overview

Focus Areas & Progress

Summary & Future Work

Summary & Future Work

CISM

- fairly 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 applied *now* under RGCM and ACME

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 focussing on (1) addition of verification using MS and (2) validation

Uncertainty Quantification

- Focus on uncertainties from boundary & init. conds.
- Good progress on model parameter optimization framework
- Next steps: addition of param. unc. estimation

ESM integration

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

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)