SEA-CISM: A scalable, efficient, and accurate Community Ice Sheet Model

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Forecasts of sea level rise are going to be included in the next IPCC reports.

Deadline for journal articles based on production model runs: Spring 2011

The last IPCC report did not provide Sea Level Rise predictions due to uncertainties associated with the dynamical response to ice sheets from key physical processes.

Mendenhall Glacier, Juneau, AK July, 2008

SEA-CISM: Provide a state-of-the-art ice sheet model to the climate community

- **Implement parallel, scalable capability as soon as possible to allow high-resolution simulations with code extensions with reasonable throughput and accuracy**
- **Maintain consistency and interaction with the production-level CCSM.**
- **Enable seamless inclusion of incremental developments such as new parameterizations and higher-order flow equations**

EVENTUAL GOAL: coupled simulations with other climate components

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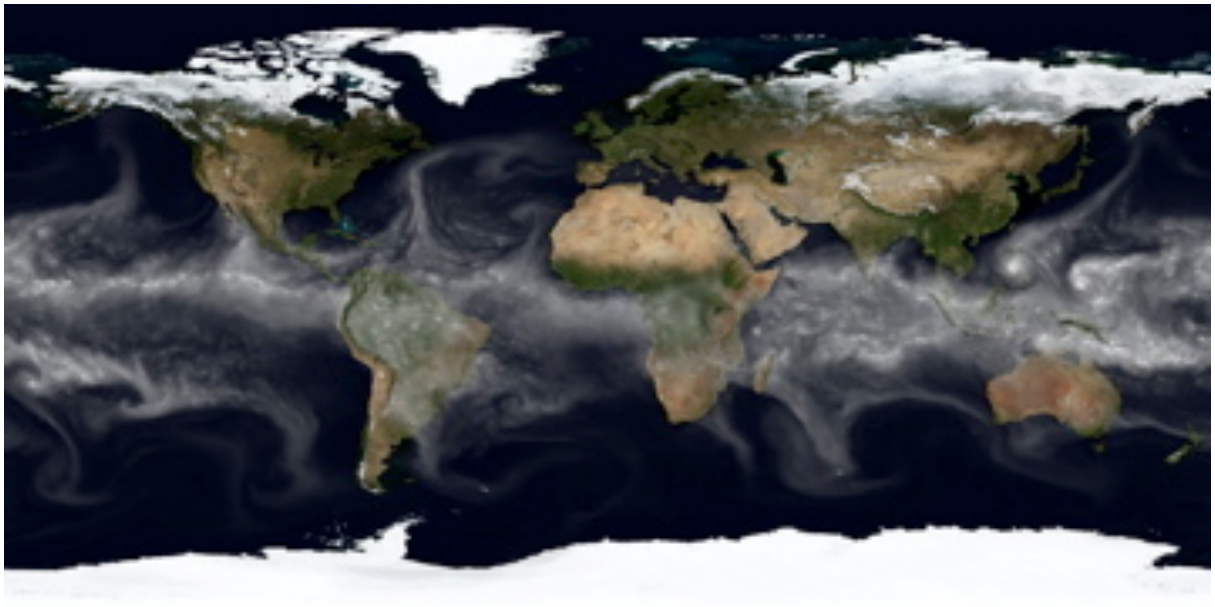
The Community Climate System Model



- Fully-coupled, global climate model with atmosphere, ocean, land, and sea ice components.
- Production runs for various 'scenarios' of GHG emissions over the 21st century to assess climate impact
- sponsored by the National Science Foundation (NSF) and the U.S. Department of Energy (DOE)

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The Community Climate System Model from an ice sheet perspective

- GLIMMER is connected to the CCSM through the coupler to the CLM
- Currently:
  - computes the ice sheet surface mass balance (snow – melt/evap) on the coarse 100km grid.
  - results are downscaled to the finer 10km ice sheet grid.
- Previous versions of CCSM have used a static representation of the Greenland and Antarctic Ice Sheets
- First task of GLIMMER: recreate realistic Greenland ice sheet in a control climate run

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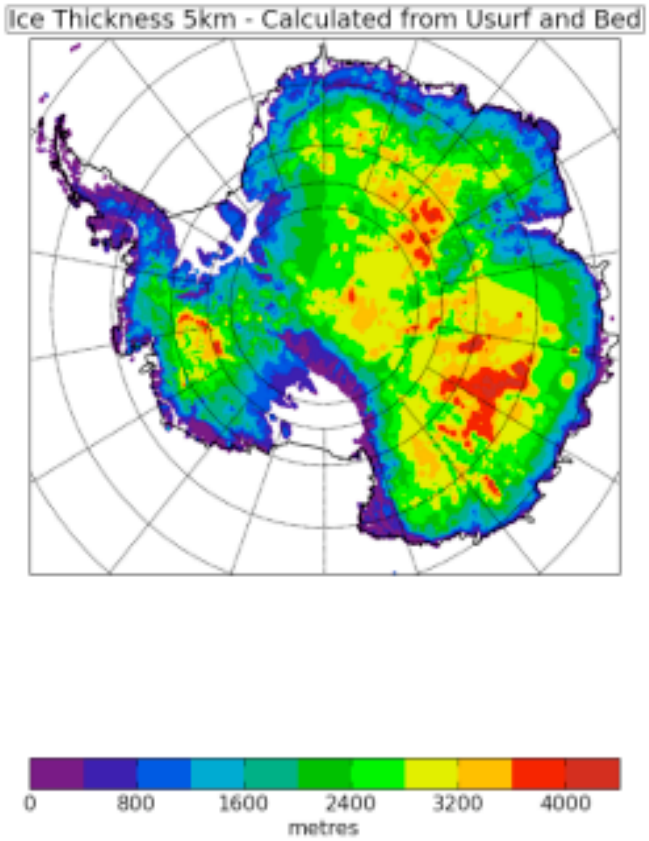
Current Status of Global Ice Sheet Modeling Capability in CCSM

- GLIMMER: serial, coarse grid, SIA based modular open source code
- Many extension plans to increase model realism and complexity in various stages of implementation
- Climate community needs constant access to a basic CISM, with the ability to test and post model improvements

Input dataset, present day Antarctica. 5km resolution



SEA-CISM: Goals

SEA-CISM: Parallel capability

- Consistency with CCSM
  - component specific discretization
  - parallel input-output in netcdf format (PIO)
  - MPI and OpenMP
- Incorporate features to take advantage of next generation computing resources
  - hierarchical block structure for multi-thread, multi-core systems
  - decomposition and load balancing to allow for future unstructured grids

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SEA-CISM: Efficient solution algorithm

- **Explicit method**
  - chosen for ease of implementation, scalability
  - limited throughput with uneven grid sizes and refinement
- **Splitting methods used in CCSM**
  - Fast barotropic waves split-off (semi-implicit)
  - Subcycling dynamics below slower tracers
- **Fully implicit solution method**
  - Option in 2 development track climate components
  - Being developed for operational BGC spin up
  - Needs a custom designed preconditioner

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SEA-CISM: Accurate solutions

- **Ice sheet modeling is going to undergo significant growth of complexity in the short term**
  - **Algorithm design must account for increased coupling and multiscale behavior**
  - **Equations will no longer be SPD nor lend themselves to explicit Jacobian formation**
- **Unstructured grids are going to be implemented in the short term (1-2 years)**
  - **Load balancing (ice sheet edges vs. source)**
  - **Decomposition (e.g. block structure)**

Through all this we need to simulate ice sheet behavior accurately

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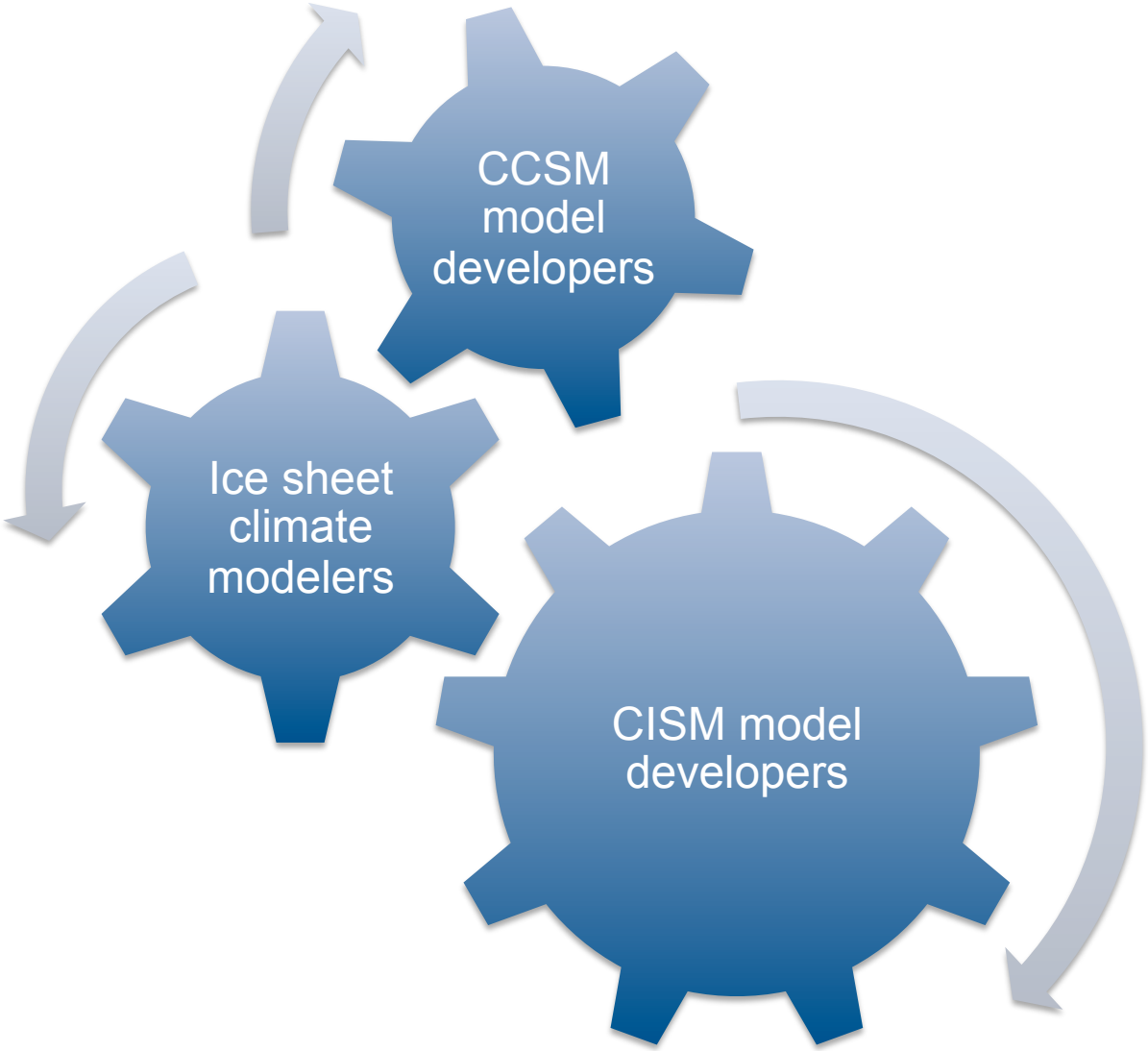
How to accomplish these goals:

- Design for climate AND methods developers
- Incorporate the Trilinos community of software packages
- Use a preconditioned fully implicit solution algorithm

Foster a symbiotic relationship between Earth System and ice sheet modeling



Use a community of software packages

FOR-Trilinos

- ForTrilinos, a Fortran interface for C++ based Trilinos using F95 interoperability features
- Compile time option in SW HOMME, an unstructured version of CAM, and POP
- Will be expanded to allow additional functions in CISM (e.g. load balancing and sensitivity analysis)

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Fully implicit scheme: Jacobian-Free Newton-Krylov, or JFNK

Goal: minimize the residual of the full nonlinear equations, F(**x**), at new time level to a specified nonlinear tolerance

$$M\mathbf{x} - b = F(\mathbf{x}) = 0$$

M = continuous nonlinear operator matrix

$$F(\mathbf{x}^k) = -J(\mathbf{x}^k)\delta\mathbf{x}$$

Take the 1st order Taylor series approximation

$$\mathbf{x}^{k+1} = \mathbf{x}^k + \delta\mathbf{x}$$

Generate a good update to test for convergence at iteration k

ForTrilinos Interface calls: LOCA -> NOX -> AztecOO/Belos

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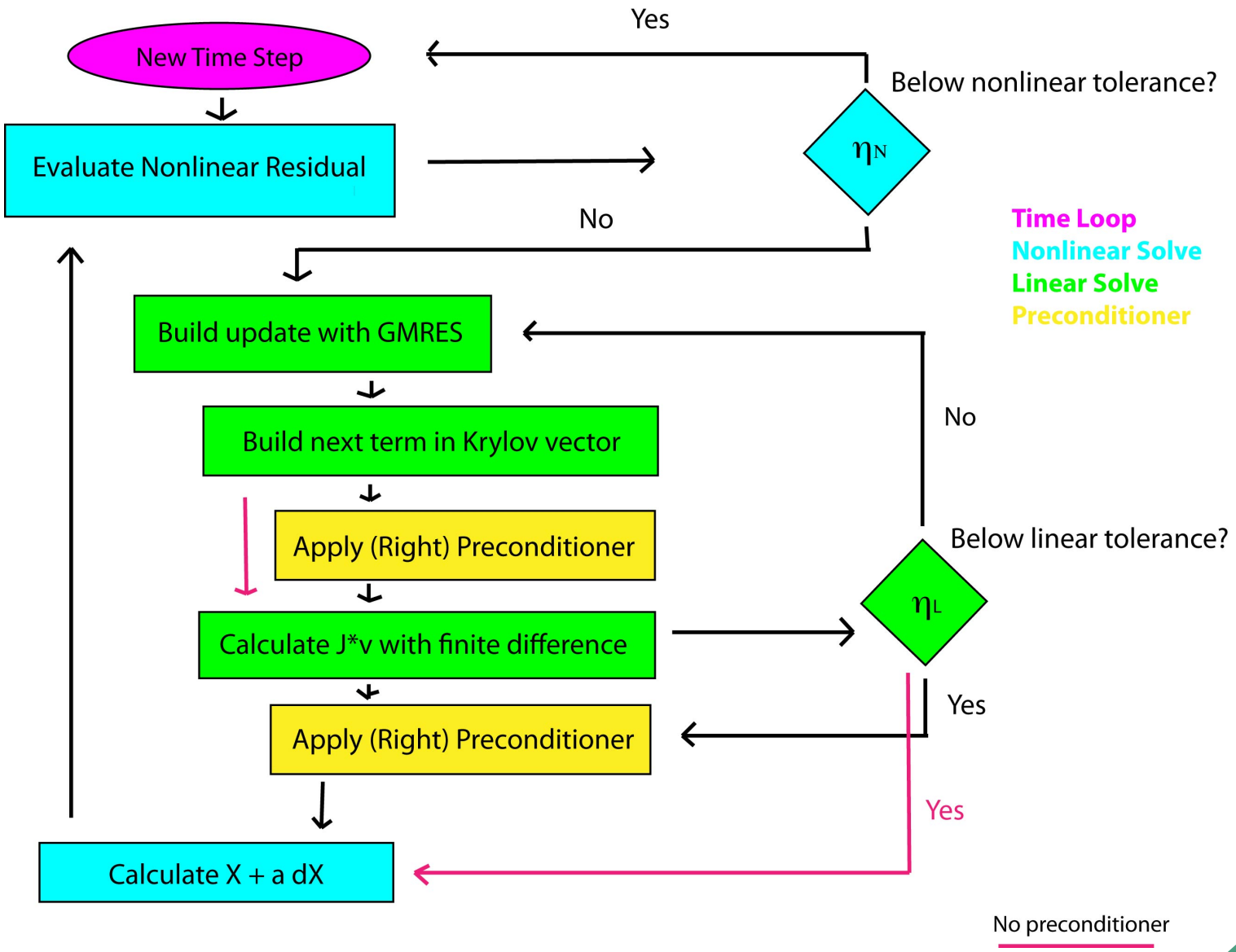
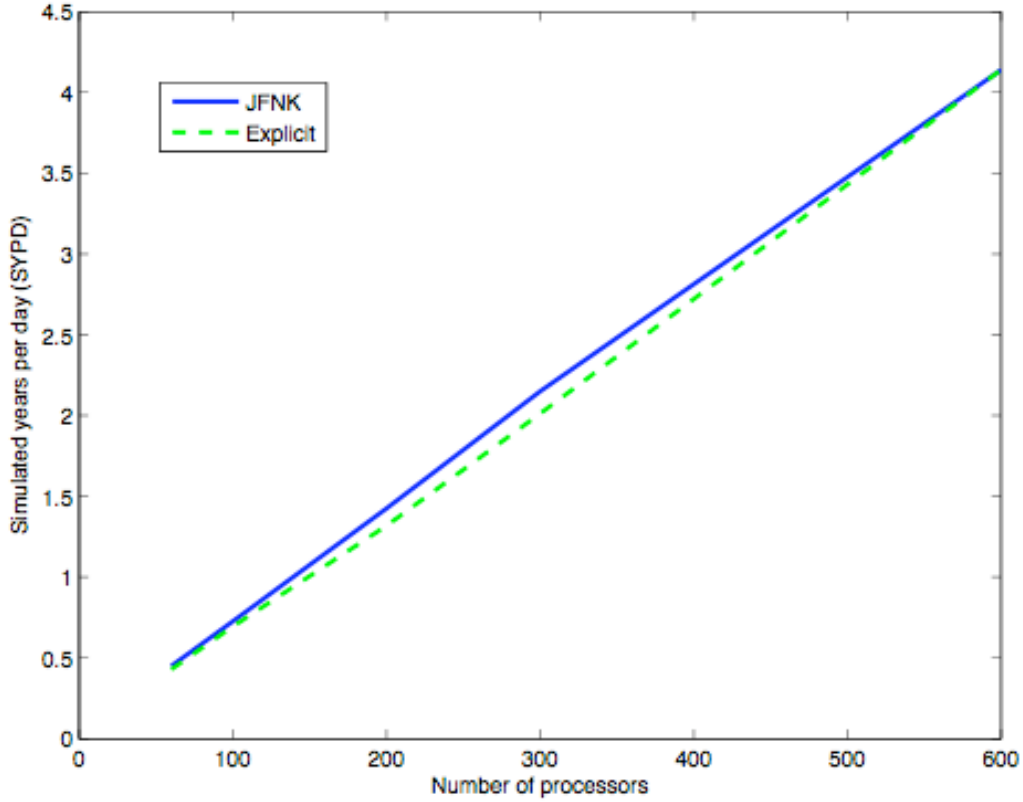
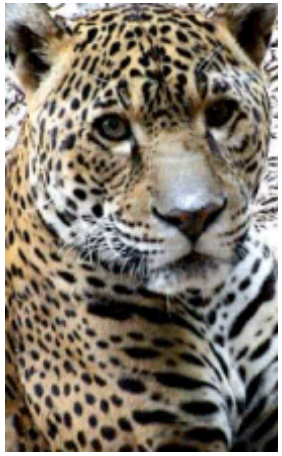
JFNK Algorithm



Strong scaling of the JFNK scheme for an atmospheric linear test case (unstructured grid CAM)



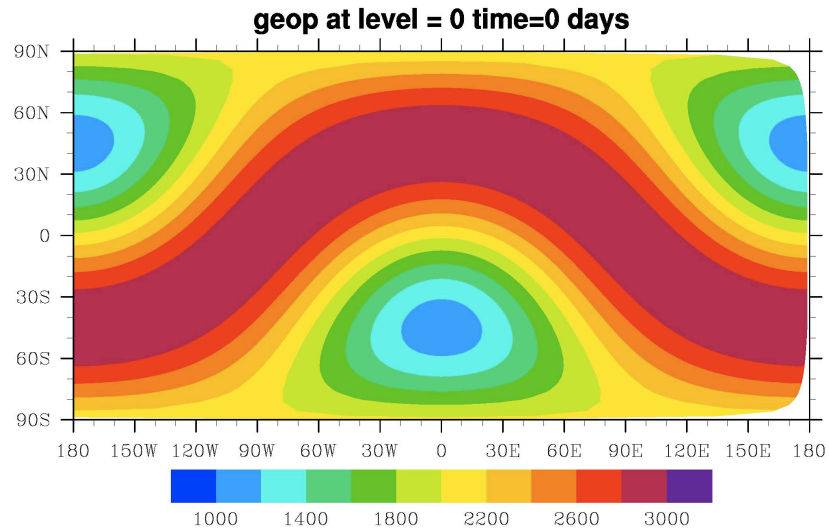


From ORNL Jaguar xt4

Unpreconditioned JFNK = fully explicit simulation time
Uses exact configuration of linear test case from previous work, scaled up

Shallow water, steady-state nonlinear geostrophic flow for 12 days, $\alpha = \pi/4$

- Wind corresponds to solid body rotation
- Tests performance and treatment of nonlinearities
- #elements=216, NP=12 (~150km resolution)



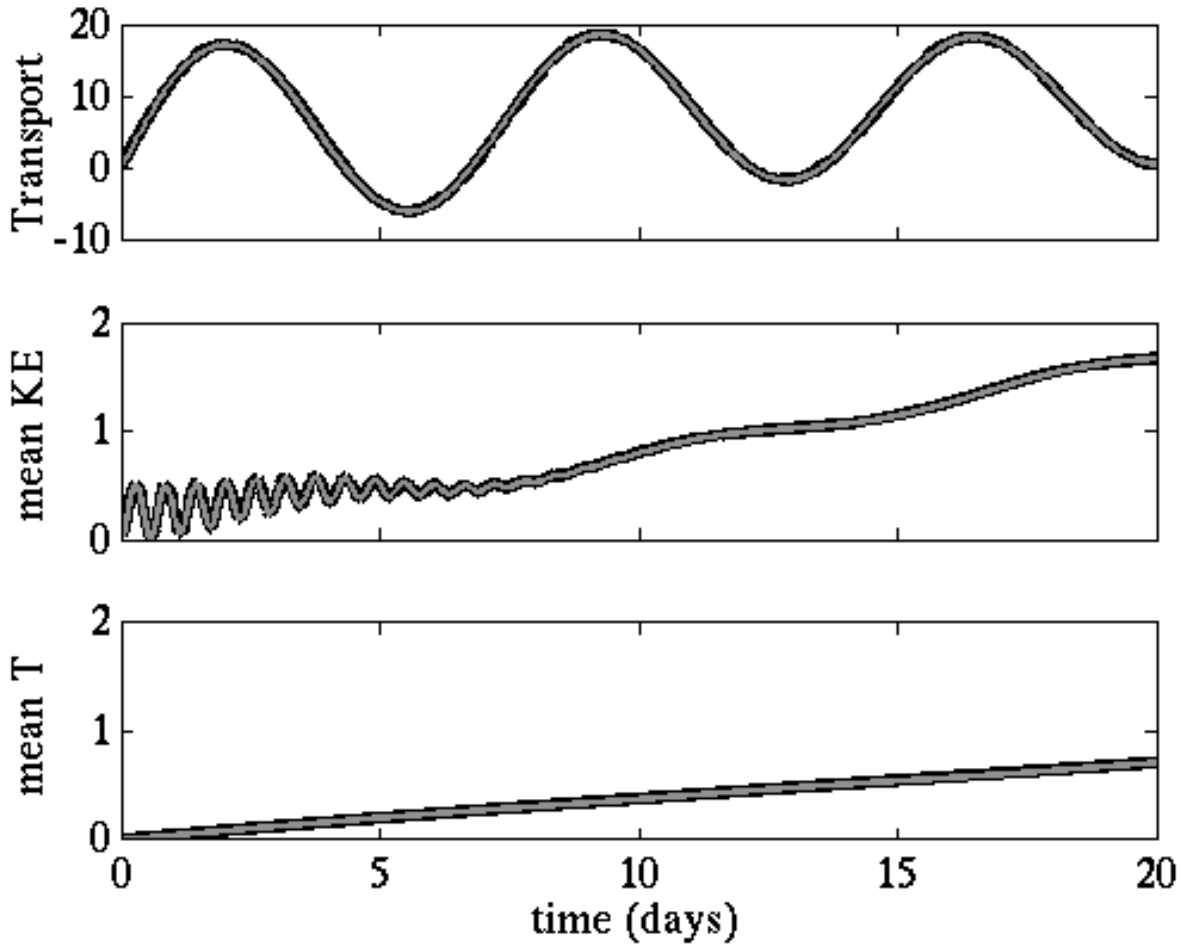
Time Integration Method	Time Step	Wall Clock (s)	L2 error
Leapfrog	100s	1m2s	6.0e-16
BDF2	86400s	8.3s	1.9e-15

The implicit configuration took 1 Newton iterations, 56 Krylov iterations for the one time step.

JFNK method implementation in POP

- Currently, barotropic mode is split-off and solved separately
- Leveraged implementation structure used in HOMME
- Added structure to allow general non-time split algorithms (e.g. 4th order RK)
- Currently implementing preconditioner to maximize methods efforts (with Jonas Theis and Erik Berman @ Utrecht)

POP Test Case: Reentrant channel with undersea bump forced by wind stress



For real climate problems, a custom scalable preconditioner is the key

- HOMME: direct solve of simplified flow fields that takes advantage of the spectral element dynamic core
- POP: 3 stage, Trilinos-based preconditioner that uses matrix information
- CISM: ice sheet equations will be changing, so design must be extensible.
  - Equations are more elliptic. Multigrid likes elliptic.
  - Simpler balanced flow often makes for a good update to full problem

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SEA-CISM Project Wish List

- More sophisticated tools to modernize code (e.g. load balancing)
  - grid points disappear/reappear
  - Variable coupling to other climate components
- Active coupling to other climate components has unique issues with ice sheets
  - Variable coupling
  - Atmosphere has scales of ~100km over hours, whereas ice sheets are ~10km over decades
- Field Trip to visit ice sheets first hand …

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Marguerite Glacier in Glacier National Park. Alaska, July 2008.

Questions?