Ice Sheet System Model
ISSM Capabilities

Eric Larour\textsuperscript{1}, Eric Rignot\textsuperscript{1,3}, Mathieu Morlighem\textsuperscript{1,2}, Hélène Seroussi\textsuperscript{1,2}, Chris Borstad\textsuperscript{1}, Feras Habbal\textsuperscript{1,3}, Daria Halkides\textsuperscript{1,4}, Behnaz Khakbaz\textsuperscript{1}, John Schiermeier\textsuperscript{1}, Nicole Schlegel\textsuperscript{1}

\textsuperscript{1} Jet Propulsion Laboratory - California Institute of Technology
\textsuperscript{2} Laboratoire MSSMat, École Centrale Paris, France
\textsuperscript{3} University of California, Irvine
\textsuperscript{4} Joint Institute for Regional Earth System Science & Engineering, UCLA
Introduction

History of ISSM

1960s

FEM

1991

SSA

Rifting

Drag inv.

Rigidity inv.

HO

2001

NASTRAN

Cielo

Cielo ice (2005)

D. MacAyeal

Eric Larour

Marjorie Schmeltz

2008

HO

FS

Transient

Mesh adaptation

2009

Dakota

Model coupling

Balance thickness

2011

Model coupling

Balance thickness

Grounding line mig.

NASA

Jet Prop. Lab.

Ecole Centrale Paris

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Diagnostic models of ice flow

Solve mechanical stress-equilibrium for the entire ice sheet/ice shelf. Can be done in 2D (SSA) or 3D (SIA, Higher-order, Full-Stokes). Material is isotropic nonlinear (Glen’s law) in the creep regime of deformation.

\[ \nabla \cdot \vec{V} = 0 \]

\[ \rho \frac{d\vec{V}}{dt} = \nabla \cdot \sigma + \rho \vec{g} \]

\[ \sigma_{ij} = 2\eta \epsilon_{ij} \]

\[ \eta = \frac{1}{2} A(\theta)^{-1} (\epsilon + \epsilon_0)^{(1-n)} \]
Rely on surface velocities (InSAR) to invert unknown parameters in the ice flow equations, such as viscosity, ice rigidity or basal drag.

\[
J' = \iint_S \frac{1}{2} \left\{ (u - u_{obs})^2 + (v - v_{obs})^2 \right\} dxdy +
\]

\[
\iint_S \lambda(x,y) \left[ \frac{\partial}{\partial x} \left( 2vH \left( 2 \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) \right) + \frac{\partial}{\partial y} \left( vH \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right) - \rho g H \frac{\partial z_s}{\partial x} - \beta^2 u \right] dxdy +
\]

\[
\iint_S \mu(x,y) \left[ \frac{\partial}{\partial y} \left( 2vH \left( 2 \frac{\partial v}{\partial y} + \frac{\partial u}{\partial x} \right) \right) + \frac{\partial}{\partial x} \left( vH \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right) - \rho g H \frac{\partial z_s}{\partial y} - \beta^2 v \right] dxdy
\]

\[
\frac{dJ'}{d\beta} = -2 \iint_S \left\{ \lambda u + \mu v \right\} \beta \delta \beta dxdy
\]
Inversion

Capabilities
Larour et al.

Introduction
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Rifting/Faulting
Higher-order, Full-Stokes
Anisotropic
Adaptation
Prognostic Models
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Sensitivity Analysis
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Assimilation
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Grounding Line
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Nightly Runs
Test Suite
Doxygen
Conclusions
Parallel computing

- ISSM can run on any platform (multi-core desktop), shared or distributed cluster
- C++ implementation of computational core using MPICH and PETSc libraries + array of parallel libraries for partitioning, iterative and direct solvers
- Multi-threading of pre and post-processing modules to increase speed significantly
Rifting/Faulting

ISSM can account for the presence of rifts and faults in an ice shelf by carrying out a steady-state computation of the contact within the rifts/faults.
Rifting/Faulting

- Rifting and faulting account for contact stresses and the presence of melange
- This is not an initiation or propagation capability
- Relies on penalty methods to enforce contact conditions between flanks of rifts
- Relies on diagnostic model to compute stresses across ice shelf
  - This is not an LEFM capability. It assumes the entire ice shelf is creeping, and there is no inclusion of elastic stresses
Higher-order and Full-Stokes modeling

- ISSM relies on the the 2D SSA to capture longitudinal stresses, 3D Blatter/Pattyn to capture vertical shear stresses and full-Stokes equations to capture all stresses within the ice sheet
- Activation of all three formulations is seamless, relying on almost the same model setup → experimentation is easy
- Coupled with parallel computing and anisotropic meshing, higher-order modeling at the continental scale is achievable with reasonable resolutions
Anisotropic adaptation

- Adapt mesh according to a metric, such as surface velocity
- Static capability, not transient adaptation
- Relies on a rewrite of the BAMG anisotropic mesher [Hecht, 2006]
Prognostic modeling

- Mass transport equations:

\[
\frac{\partial H}{\partial t} + \nabla \cdot (H \nabla) = \dot{M}_s - \dot{M}_b
\]

- Update of surface and bed is hydrostatic on ice shelves. For ice sheets, surface is updated assuming the bedrock is fixed.
- Mass transport equations are coupled with diagnostic and thermal models to allow for complete transient models to be run (SeaRISE 2011).
- Boundary conditions assume fixed thickness at the ice divide, and free flux of mass at the calving front or the grounded margins.
- Calving front dynamics not included yet.
- Grounding line dynamics is hydrostatically treated.
Thermal modeling

- Thermal model, full-advection and full-diffusion in 3D + viscous heating. Mesh velocity in vertical direction.

\[
\frac{\partial T}{\partial t} = (\mathbf{w} - \mathbf{v}) \cdot \nabla T + \frac{k_{th}}{\rho c} \Delta T + \frac{\Phi}{\rho c}
\]

- Boundary conditions:
  - \( T = T_s \) at surface
  - At ice/bed interface:
    \[
k_{th} \nabla T \cdot \mathbf{n} = G - \tau_b \cdot \mathbf{v}_b
    \]

- [Holland and Jenkins, 1999] at the ice/ocean interface:

\[
k_{th} \nabla T \cdot \mathbf{n} = -\rho_w c_p M_\gamma (T - T_f)
\]
Melting at the ice/bed interface

- Two models for computing melting rates:
  - Linear model where computation of temperatures is updated once for each temperature that goes above pressure melting point
  - Non-linear model where fixed-point scheme is used, where temperatures are updated until all of temperature field is below or at pressure melting point

Melting rate is recovered using:

\[ S = \frac{\lambda}{\rho_{\text{ice}}L} \left( \frac{dT^*}{dz} - \frac{dT}{dz} \right) \]

where \( T^* \) is the temperature without pressure melting point constraints and \( T \) is the temperature after application of constraints. Non-linear model results in much lower melting rates, even though locations for melting are similar. It is critical to take into account non-linearity of thermal model, at least in steady-state!

\[ T^* \text{ and } T \]
Sensitivity analysis

- Sampling and local reliability methods to study the impact of different areas of the mesh
- Sampling of the mesh using Chaco, Scotch and Metis partitioners
- Partition the mesh into equal area sections, which can be then updated for each sample of a Monte-Carlo or local reliability simulation
Sensitivity analysis

- Results can then be plotted in histograms for sampling analysis or importance factors for local reliability methods.
Assimilation of ice thickness (balanced thickness)

- Ice thickness can be optimized to ensure smooth divergence of the flux (thinning rate). Optimization can be constrained (on satellite or airborne tracks where data was measured) or unconstrained.
3D Hydrostatic grounding line migration

• At each time step of the transient ice flow solution, we check the following for every vertex of the mesh:

\[ b \leq b_a \] where \( b_a \) is the depth of the glacier bed or seafloor. For most ice sheet/ice shelf configurations, \( b \) is negative. If this condition is verified for a floating vertex (i.e., on an ice shelf), we ground the vertex and force \( b = b_a \)

\[ b > b_{HE} \] where \( b_{HE} \) is the depth of the bottom of the ice in hydrostatic equilibrium: \( b_{HE} = H \rho / \rho_w \). If this condition is verified for a grounded vertex (i.e., on the ice sheet), we unground the vertex and force \( b = b_{HE} \)
3D Hydrostatic grounding line migration

Time: 30.1 yr

Distance from 96 grounding line (km)

-100 -50 0 50

0 1000 2000 3000

\[ V(\text{m/yr}) \]
\[ V_{\text{obs}} \text{ in 1996 (m/yr)} \]

Spatial distribution of ice, water, and bedrock.

Legend:
- Ice
- Water
- Bedrock
3D Hydrostatic grounding line migration
3D Hydrostatic grounding line migration

Time: 86.6 yr

Elevation (m)

Distance from 96 grounding line (km)

V(m/yr)

V_{obs} in 1996 (m/yr)

Grounding line position in 1996
3D Hydrostatic grounding line migration

Elevation (m)

Time: 115 yr

Ice
Water
Bedrock

V(m/yr)

V_{\text{obs}}$ in 1996 (m/yr)

Grounding line position in 1990

Distance from 96 grounding line (km)
3D Hydrostatic grounding line migration
3D Hydrostatic grounding line migration
3D Hydrostatic grounding line migration
3D Hydrostatic grounding line migration

![Graph showing 3D Hydrostatic grounding line migration](image)

- **Elevation (m)**
  - Ice
  - Water
  - Bedrock

- **Distance from 96 grounding line (km)**
- **V(m/yr)**
  - $V_{obs}$ in 1996 (m/yr)
  - Grounding line position in 1996

**Time:** 228 yr
3D Hydrostatic grounding line migration
3D Hydrostatic grounding line migration

Time: 284 yr

Elevation (m)

Ice
Water
Bedrock

Distance from 96 grounding line (km)

V(m/yr)

V_{obs} in 1996 (m/yr)
Grounding line position in 1996
3D Hydrostatic grounding line migration

Time: 313 yr

Elevation (m)

Ice
Water
Bedrock

Distance from 96 grounding line (km)

V(m/yr)

V_{obs} in 1996 (m/yr)

Grounding line position in 1996
3D Hydrostatic grounding line migration

![Graph showing 3D hydrostatic grounding line migration with time and distance](image)
3D Hydrostatic grounding line migration

Time: 369 yr

Elevation (m)

Distance from 96 grounding line (km)

V (m/yr)

V_{obs} in 1996 (m/yr)

Grounding line position in 1996
3D Hydrostatic grounding line migration

- Ice
- Water
- Bedrock

Time: 397 yr

V(m/yr)

V_{obs} in 1996 (m/yr)

Grounding line position in 1996

Distance from 96 grounding line (km)

Elevation (m)

500

-500

-1000

-10

-50

0

50

0

50
3D Hydrostatic grounding line migration
3D Hydrostatic grounding line migration
3D Hydrostatic grounding line migration

The 3D model simulates grounding line migration and ice flow acceleration after 1996.
3D Hydrostatic grounding line migration

The island glacier grounding line migration and ice flow acceleration after 1996

Elevation (m)

Time: 510 yr

V (m/yr)

V_{obst} in 1996 (m/yr)
Grounding line position in 1996

Distance from 96 grounding line (km)
3D Hydrostatic grounding line migration

The Island Glacier grounding line migration and ice flow acceleration after 1996.
3D Hydrostatic grounding line migration

The Island Glacier grounding line migration and ice flow acceleration after 1996

- Ice
- Water
- Bedrock

Time: 567 yr

V(m/yr)

V_{obs} in 1996 (m/yr)

Grounding line position in 1996
3D Hydrostatic grounding line migration

The Island Glacier, grounding line migration and ice flow acceleration after 1995.
3D Hydrostatic grounding line migration

The Island Glacier, grounding line migration and ice flow acceleration after 1996.
3D Hydrostatic grounding line migration
3D Hydrostatic grounding line migration

The Island Glacier: grounding line migration and ice flow acceleration after 1996

- Ice
- Water
- Ice-rock

Elevation (m)
-1000 -500 0 500

Distance from 96 grounding line (km)
-100 -50 0 50

Time: 680 yr

V(m/yr)
-1000 -500 0 500 1000 2000 3000

V_{obs} in 1996 (m/yr)
Grounding line position in 1996
3D Hydrostatic grounding line migration

- Fine Island Glacier: grounding line migration and ice flow acceleration after 1996.
3D Hydrostatic grounding line migration

Fig. Island Glacier: grounding line migration and ice flow acceleration after 1996
3D Hydrostatic grounding line migration

**Figure**: Fine Island Glacier: grounding line migration and ice flow acceleration after 1996.
3D Hydrostatic grounding line migration

Fine Island Glacier: grounding line migration and ice flow acceleration after 1996

Time: 793 yr

Elevation (m)

Distance from 96 grounding line (km)

V(m/yr)

V_{obs} in 1996 (m/yr)

Grounding line position in 1996
3D Hydrostatic grounding line migration

**Plot:**
- Time: 821 yr
- Elevation (m)
- Distance from 96 grounding line (km)

**Graphs:**
- Ice
- Water
- Bedrock
- V (m/yr)
  - V_{obs} in 1996 (m/yr)
  - Grounding line position in 1996
3D Hydrostatic grounding line migration

Pine Island Glacier: grounding line migration and ice flow acceleration after 1996

- Elevation (m)
  - Ice
  - Water
  - Bedrock

- Time: 849 yr

- Distance from 96 grounding line (km)
  - V(m/yr)
    - V_{obs} in 1996 (m/yr)
    - Grounding line position in 1996

- 3D Hydrostatic
  - Grounding Line Migration
3D Hydrostatic grounding line migration

Pine Island Glacier: grounding line migration and ice flow acceleration after 1996
3D Hydrostatic grounding line migration

Pine Island Glacier: grounding line migration and ice flow acceleration after 1996
3D Hydrostatic grounding line migration

Pine Island Glacier: grounding line migration and ice flow acceleration after 1996

- Ice
- Water
- Bedrock

Elevation (m)

Time: 934 yr

Distance from 96 grounding line (km)

V(m/yr)

- V(m/yr) in 1996
- Observed in 1996
- Grounding line position in 1996
3D Hydrostatic grounding line migration

Pine Island Glacier: grounding line migration and ice flow acceleration after 1996

- Time: 962 yr
- Distance from 96 grounding line (km)
- V̇ (m³/yr)

- Ice
- Water
- Bedrock

- \( V_\text{obs in 1996 (m³/yr)} \)
- Grounding line position in 1996

Elevation (m)

-1000
-500
0
50

Hydrology
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3D Hydrostatic grounding line migration

Pine Island Glacier: grounding line migration and ice flow acceleration after 1996

Elevation (m)

Time: 991 yr

Distance from 96 grounding line (km)

$V_\text{obs} \text{ in } 1996 \text{ (m/yr)}$

Grounding line position in 1996
3D Hydrostatic grounding line migration

Pine Island Glacier: grounding line migration and ice flow acceleration after 1996

Time: 1.02e+03 yr

V(m/yr)

V_{obs} in 1996 (m/yr)

Grounding line position in 1996

Distance from 96 grounding line (km)
3D Hydrostatic grounding line migration

Pine Island Glacier: grounding line migration and ice flow acceleration after 1996
3D Hydrostatic grounding line migration

Pine Island Glacier: grounding line migration and ice flow acceleration after 1996

Time: $1.08 \times 10^3$ yr

Elevation (m)

Distance from 96 grounding line (km)

$V$ (m/yr)

$V_{\text{obs}}$ in 1996 (m/yr)

Grounding line position in 1996
3D Hydrostatic grounding line migration

Pine Island Glacier: grounding line migration and ice flow acceleration after 1996

Time: 1.1e+03 yr

Elevation (m)

Ice
Water
Bedrock

Distance from 96 grounding line (km)

V(m/yr)

V_{obs} in 1996 (m/yr)

Grounding line position in 1996
3D Hydrostatic grounding line migration

Time: 1996.8 yr

2009 Grounding Line

1996 Grounding Line
3D Hydrostatic grounding line migration

Time: 1997.1 yr
3D Hydrostatic grounding line migration

Time: 1997.5 yr
3D Hydrostatic grounding line migration
3D Hydrostatic grounding line migration
3D Hydrostatic grounding line migration

Time: 1998.6 yr

1996 Grounding Line

2009 Grounding Line
3D Hydrostatic grounding line migration
3D Hydrostatic grounding line migration
3D Hydrostatic grounding line migration

Time: 1999.8 yr

1996 Grounding Line

2009 Grounding Line
3D Hydrostatic grounding line migration

Time: 2000.1 yr

1996 Grounding Line

2009 Grounding Line
3D Hydrostatic grounding line migration

Time: 2000.5 yr
3D Hydrostatic grounding line migration

Time: 2000.9 yr

1996 Grounding Line

2009 Grounding Line
3D Hydrostatic grounding line migration
3D Hydrostatic grounding line migration
3D Hydrostatic grounding line migration
3D Hydrostatic grounding line migration

Time: 2002.4 yr
3D Hydrostatic grounding line migration

Time: 2002.8 yr

1996 Grounding Line

2009 Grounding Line
3D Hydrostatic grounding line migration
3D Hydrostatic grounding line migration

Time: 2003.5 yr

1996 Grounding Line

2009 Grounding Line
3D Hydrostatic grounding line migration

Time: 2003.9 yr

1996 Grounding Line
2009 Grounding Line
3D Hydrostatic grounding line migration

Time: 2004.3 yr
3D Hydrostatic grounding line migration
3D Hydrostatic grounding line migration

Time: 2005 yr

1996 Grounding Line

2009 Grounding Line

x 10^5

-2.55

-2.65

-2.75

-2.85

-2.95

-3

-1.62

-1.61

-1.6

-1.59

-1.58

-1.57

x 10^6
3D Hydrostatic grounding line migration

Time: 2005.4 yr
3D Hydrostatic grounding line migration

Time: 2005.8 yr

2009 Grounding Line

1996 Grounding Line
3D Hydrostatic grounding line migration

Time: 2006.2 yr

2009 Grounding Line
1996 Grounding Line
3D Hydrostatic grounding line migration

Time: 2006.5 yr

1996 Grounding Line

2009 Grounding Line

x 10^5

x 10^6

1.62 1.61 1.6 1.59 1.58 1.57
3D Hydrostatic grounding line migration

Time: 2006.9 yr

1996 Grounding Line

2009 Grounding Line
3D Hydrostatic grounding line migration

Time: 2007.3 yr

1996 Grounding Line

2009 Grounding Line

-1.62 -1.61 -1.6 -1.59 -1.58 -1.57

x 10^6

-3 -2.95 -2.9 -2.85 -2.8 -2.75 -2.7 -2.65 -2.6 -2.55

x 10^5
3D Hydrostatic grounding line migration
3D Hydrostatic grounding line migration

Time: 2008.1 yr

2009 Grounding Line

1996 Grounding Line
3D Hydrostatic grounding line migration

Time: 2008.4 yr

-3

-1.62 -1.61 -1.6 -1.59 -1.58 -1.57

x 10^5

2009 Grounding Line

1996 Grounding Line
3D Hydrostatic grounding line migration
3D Hydrostatic grounding line migration

Time: 2009.2 yr

1996 Grounding Line

2009 Grounding Line
3D Hydrostatic grounding line migration

Time: 2009.6 yr

1996 Grounding Line

2009 Grounding Line
3D Hydrostatic grounding line migration

Time: 2010.3 yr

2009 Grounding Line

1996 Grounding Line
3D Hydrostatic grounding line migration

Time: 2010.7 yr

1996 Grounding Line

2009 Grounding Line

x 10^5

-2.55
-2.6
-2.65
-2.7
-2.75
-2.8
-2.85
-2.9
-2.95
-3

-1.62
-1.61
-1.6
-1.59
-1.58
-1.57

x 10^6
Hydrology model

[Le Brocq et al., 2009]: the evolution of the water-film thickness \( w \) is given by:

\[
\frac{dw}{dt} = S - \nabla \cdot (w \bar{u}_w) 
\]

With \( w \) the water thickness, \( S \) the basal melting rate and \( \bar{u}_w \) the depth-averaged water velocity vector.

Assuming a laminar flow between two parallel plates:

\[
\bar{u}_w = \frac{w^2 \nabla \Phi}{12 \mu} \quad \text{and} \quad \Phi = \rho_i g z_s + (\rho_w - \rho_i) g z_b - N
\]

where \( \mu \) is the water viscosity, \( z_s \) and \( z_b \) the surface and bed elevations, \( N \) the effective pressure and \( \Phi \) the pressure potential.
Hydrology model

Because we assume a non-arborescent drainage system, we cancel the effective pressure $N$:

$$\nabla \Phi = \rho_i g \nabla z_s + (\rho_w - \rho_i) g \nabla z_b$$

This set of assumptions results in the following non-linear system:

$$\frac{dw}{dt} = S - \nabla \left( \frac{w^3}{12\mu} \nabla \Phi \right)$$
Svn/Trac

Download page:
http://issm.jpl.nasa.gov/installation/download/

- Install SVN (Apache Subversion)
- Checkout ISSM:
  $ svn -username anon -password anon checkout
  https://issm.ess.uci.edu:80/svn/issm/issm
- Update ISSM:
  $ svn update
Trac system with wiki

Welcome to ISSM (Ice Sheet System Model) developer's site

General info

• The general website of ISSM is here: [http://issm.jpl.nasa.gov](http://issm.jpl.nasa.gov)
• Code guidelines for developers

ISSM's Development

• TODO list.
• Correspondence between old model fields and new model fields
• Debugging status of ISSM's next version.
• Comparison of solution elapsed times between different releases.

Projects

• ISSM ISSM Meetings.
• ISSM-ECCO2 coupling work plan.
• ISSM-GIA Towards GIA.
• ISSM-Planetary Towards GIA.

Download in other formats:
Plain Text
# Nightly runs

## ISSM Nightly run report

- **host**: larsen
- **OS**: astrid
- **status**: all test desks have been run
- **number of successes**: 2511/2658
- **number of errors**: 141/2658
- **number of failures**: 6/2658
- **date**: Dec-10-2011 23:00:01
- **user**: seroussi
- **release**: trunk-jpl
- **total elapsed time**: 10:03:27
- **installation elapsed time**: 3:19:25
- **execution elapsed time**: 6:44:02

## List of tests

<table>
<thead>
<tr>
<th>Result</th>
<th>Tolerance</th>
<th>Test id</th>
<th>Test name</th>
<th>Field checked</th>
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</thead>
<tbody>
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<td>3.3e-15&lt;1e-13</td>
<td>101</td>
<td>Square Shelf Constrained Diag M2d Serial</td>
<td>Vx</td>
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<td>Pressure</td>
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<td>Vx</td>
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<td>103</td>
<td>Square Shelf Constrained Diag M3d Serial</td>
<td>Vy</td>
</tr>
<tr>
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<td>5.3e-16&lt;1e-13</td>
<td>103</td>
<td>Square Shelf Constrained Diag M3d Serial</td>
<td>Vz</td>
</tr>
<tr>
<td>SUCCESS</td>
<td>1.4e-15&lt;1e-13</td>
<td>103</td>
<td>Square Shelf Constrained Diag M3d Serial</td>
<td>Vel</td>
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<tr>
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<td>Vx</td>
</tr>
<tr>
<td>SUCCESS</td>
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Test suite

• 626 tests run on a nightly-basis
• Serial/Parallel run comparisons
• Internal checks
• Solution checks
• Numerical accuracy checks
• Run several times a day, to capture code updates which break the software
Welcome!
This is the searchable browsing tool for ISSM (the Ice Sheet System Model).
These pages were automatically generated by doxygen, from comments in the ISSM source code.
Navigate the tabs above and browse through ISSM's C++ source code, files/directories, and data structures.
To find additional information regarding the use of ISSM, its current release, or the ISSM team, please visit http://issm.jpl.nasa.gov.

Helpful Links
- Fill out an ISSM download request here.
- ISSM Installation instructions are found here.
- For help using ISSM, see our online User's Manual. Other documentation is also available including simple tutorials and FAQ.
- A current publication list is kept here.
- Contact us by e-mail at issm@jpl.nasa.gov

Code Stats

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Conclusions

- ISSM represents a wide array of capabilities, geared toward solving specific cryosphere challenges such as projections of future sea level rise
- Extensive software and architecture support, as well as wide array of numerical solutions and physics implemented
- Challenges remain, such as grounding line dynamics using FS, moving margins and ice/ocean interactions
Bibliography I


Thanks!