

## Ice Sheet System Model

### ISSM Capabilities

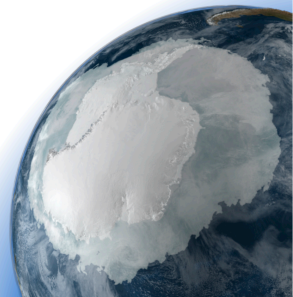
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Continuous

1960s

2001

2008

2009

2011

FEM

SSA  
Rifting  
Drag inv.  
Rigidity inv.  
HOHO  
FS  
Thermal  
Transient  
Mesh adaptationDakota  
Model coupling  
Balance thicknessModel coupling  
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Grounding line mig.

NASTRAN

Cielo

Cielo ice (2005)

ISSM

Ice

D. MacAyeal

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NASA

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## Diagnostic models of ice flow

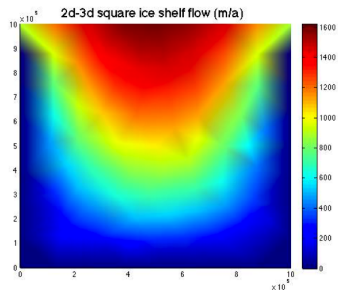
Solve mechanical stress-equilibrium for the entire ice sheet/ice shelf. Can be done in 2D (SSA) or 3D (SIA, Higher-order, Full-Stokes). Material is isotropic nonlinear (Glen's law) in the creep regime of deformation.

$$\nabla \cdot \vec{V} = 0$$

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

$$\sigma'_{ij} = 2\eta \dot{\epsilon}_{ij}$$

$$\eta = \frac{1}{2} A(\theta)^{\frac{-1}{n}} \left( \dot{\epsilon} + \dot{\epsilon}_0 \right)^{\frac{(1-n)}{n}}$$



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## Inversion

Rely on surface velocities (InSAR) to inver unknown parameters in the ice flow equations, such as viscosity, ice rigidity or basal drag.

$$J' = \iint_S \frac{1}{2} \left\{ (u - u_{obs})^2 + (v - v_{obs})^2 \right\} dx dy +$$

$$\iint_S \lambda(x,y) \left\{ \frac{\partial}{\partial x} \left( 2\nu H \left( 2 \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) \right) + \frac{\partial}{\partial y} \left( \nu H \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right) - \rho g H \frac{\partial z_s}{\partial x} - \beta^2 u \right\} dx dy +$$

$$\iint_S \mu(x,y) \left\{ \frac{\partial}{\partial y} \left( 2\nu H \left( 2 \frac{\partial v}{\partial y} + \frac{\partial u}{\partial x} \right) \right) + \frac{\partial}{\partial x} \left( \nu H \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right) - \rho g H \frac{\partial z_s}{\partial y} - \beta^2 v \right\} dx dy$$

$$\frac{dJ'}{d\beta} = -2 \iint_S \{ \lambda u + \mu v \} \beta \delta \beta \, dx dy$$

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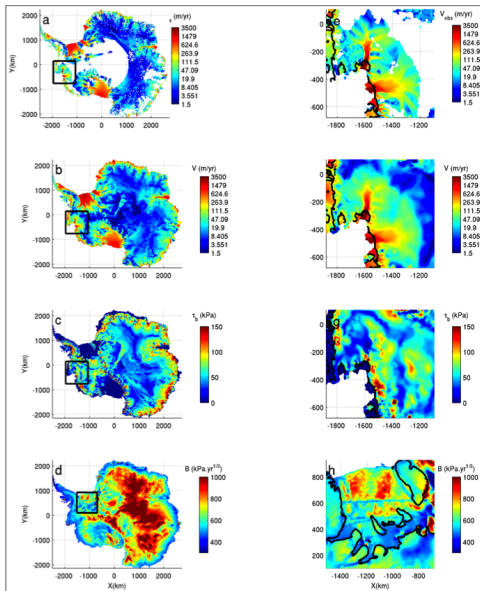
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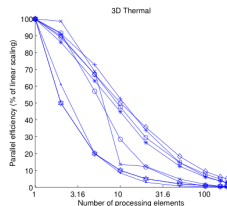
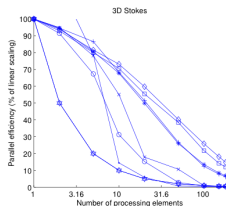
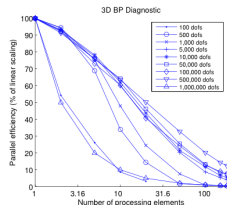
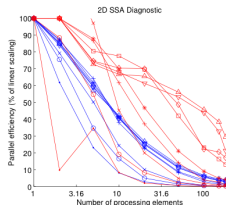


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## Parallel computing

- 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

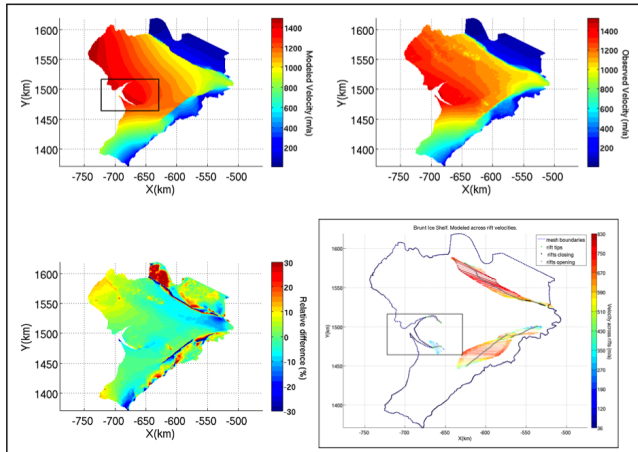


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## Rifting/Faulting

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.



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- 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

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## 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

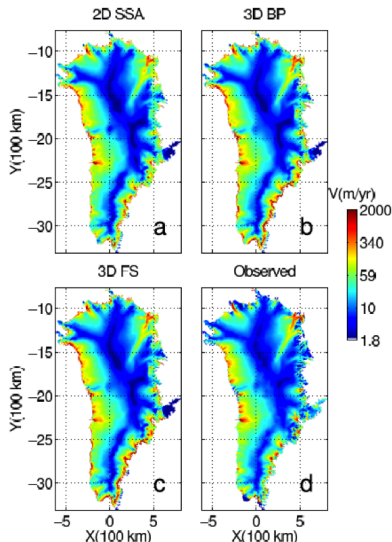


Figure 8. Modeled surface velocity (in m/yr) (using inverted basal drag coefficient) for the 2D Shallow-Stream model (a), the 3D Blatter/Pattyn model (b) and the 3D full-Stokes model (c). d) Observed InSAR surface velocities (in m/yr) of the Greenland Ice Sheet.

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## 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]

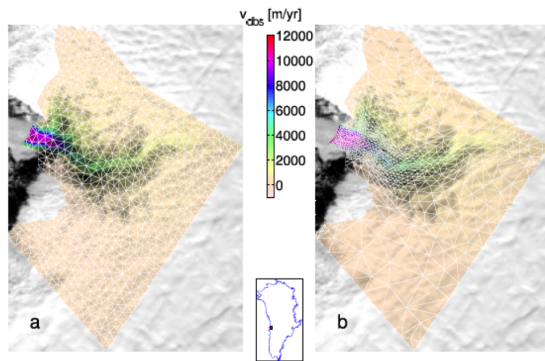


Figure 2. Anisotropic adaptive mesh of Jakobshavn Isbrae, West Greenland. a) InSAR surface velocity interpolated on a uniform mesh, b) InSAR surface velocity from Rignot [2008] interpolated on adapted mesh (in white). Both meshes comprise 1,500 elements.

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## Prognostic modeling

- Mass transport equations:

$$\frac{\partial H}{\partial t} + \nabla \cdot H \bar{\mathbf{v}} = \dot{M}_s - \dot{M}_b$$

- 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

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## Thermal modeling

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

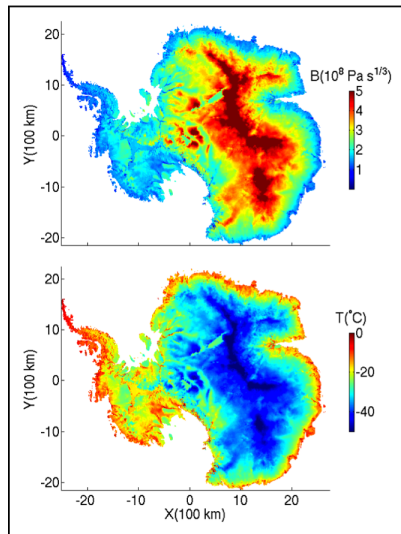
$$\frac{\partial T}{\partial t} = (\mathbf{w} - \mathbf{v}) \cdot \nabla T + \frac{k_{th}}{\rho C} \Delta T + \frac{\Phi}{\rho C}$$

- 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:

$$k_{th} \nabla T \cdot \mathbf{n} = -\rho_w c_p M \gamma (T - T_f)$$



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## Melting at the ice/bed interface

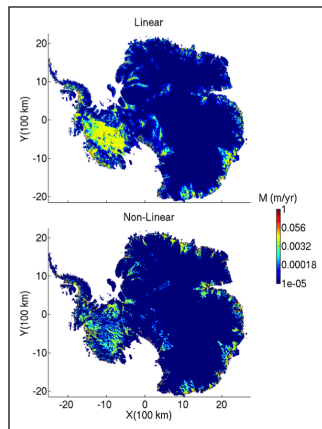
- Two models for computing melting rates:

- 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:

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

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!



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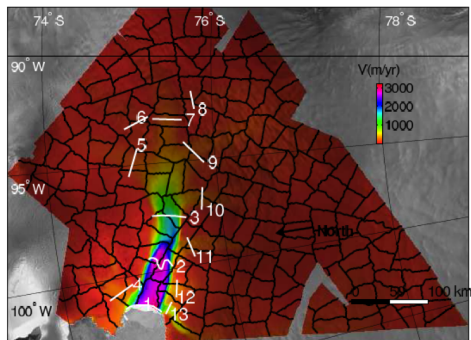
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## Sensitivity analysis

- 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



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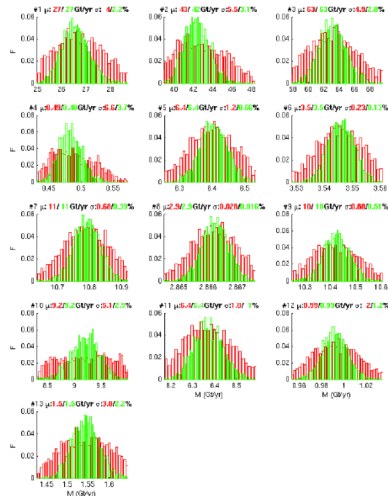
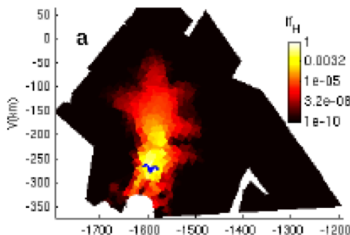
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- Results can then be plotted in histograms for sampling analysis or importance factors for local reliability methods



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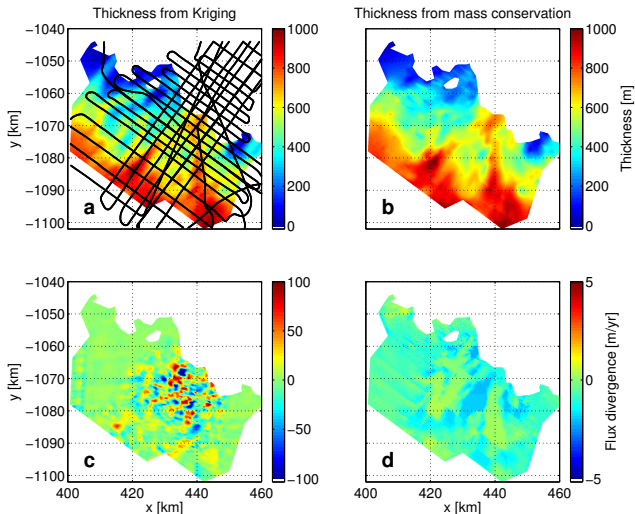
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## Assimilation of ice thickness (balanced thickness)

- Ice thickness can be optimized to ensure smooth divergence of the flux (thinning rate) [Morlighem et al., 2011]



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- 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  $b = b_{HE}$

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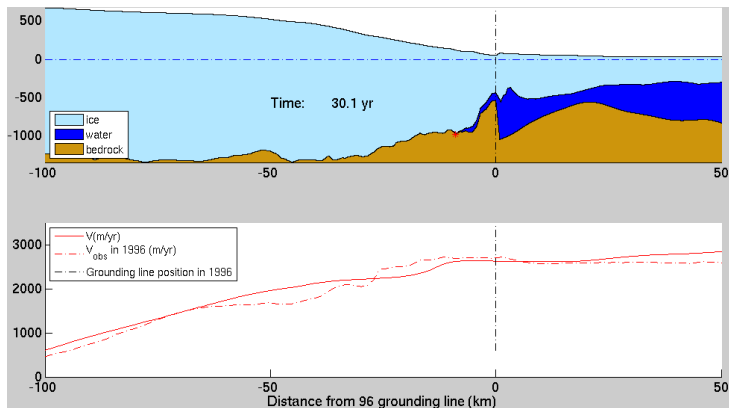
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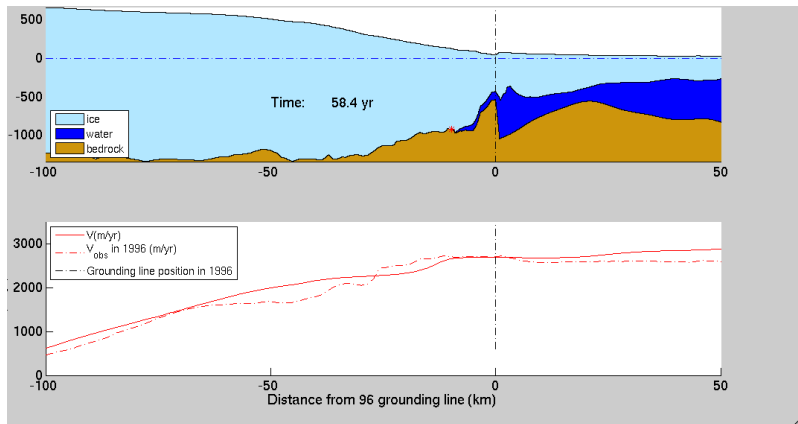
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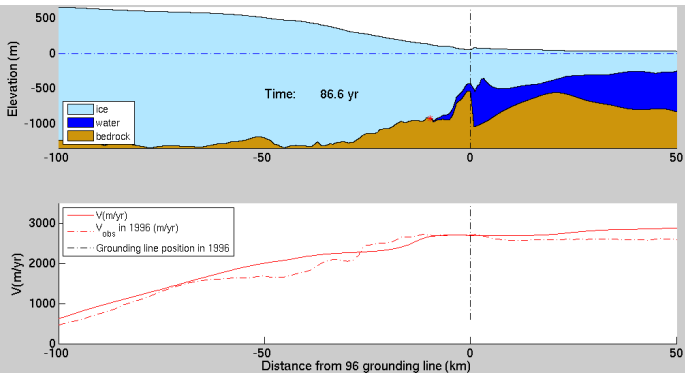
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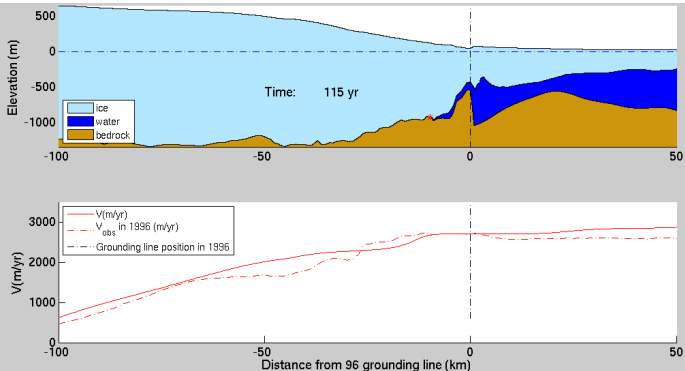
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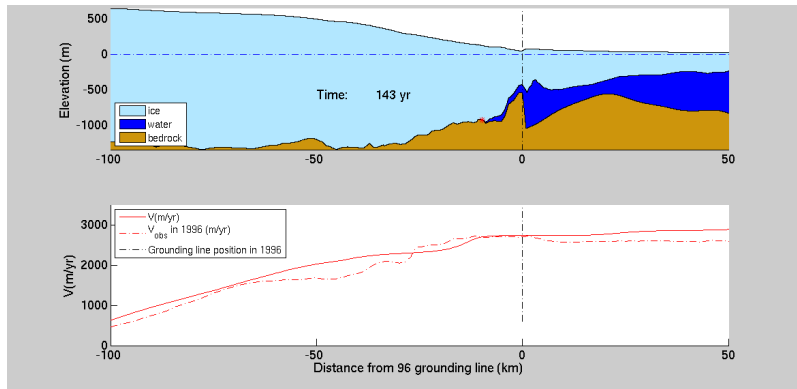
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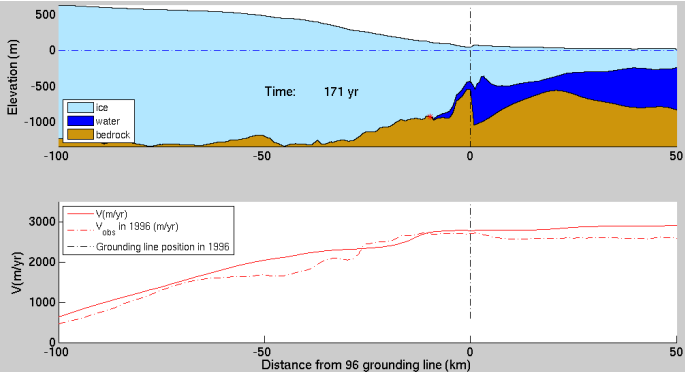
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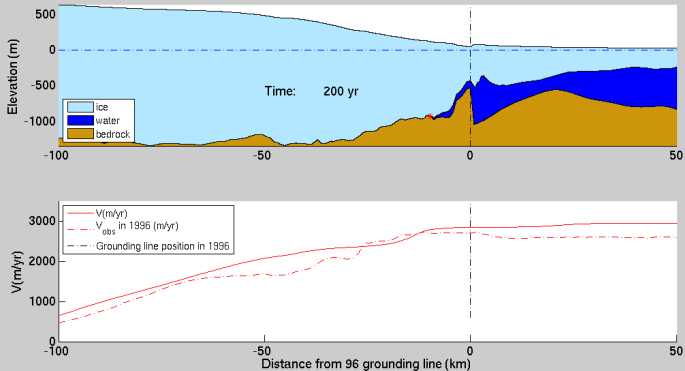
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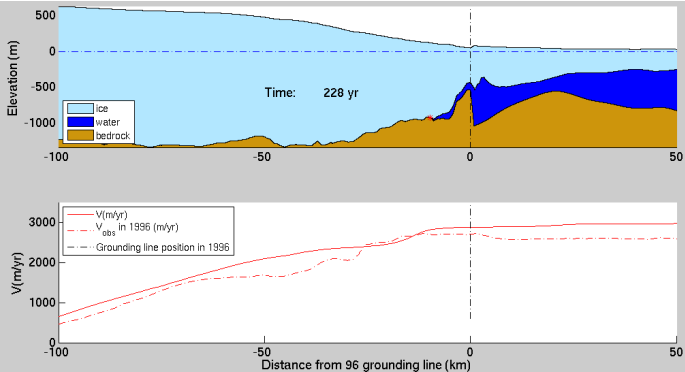
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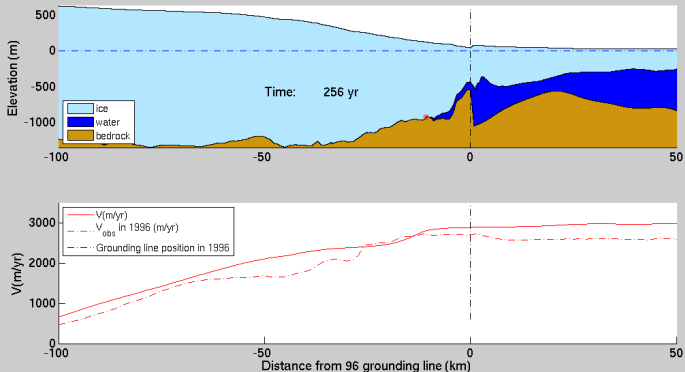
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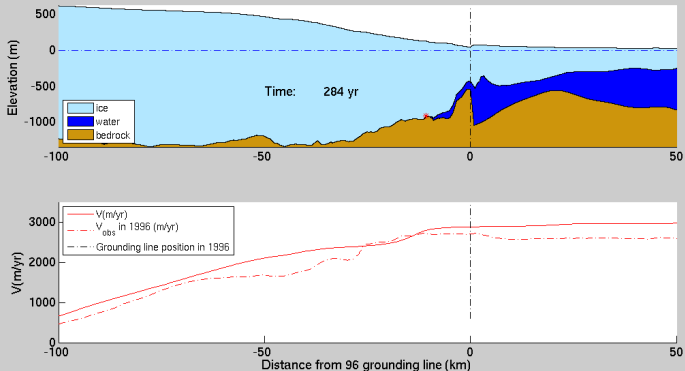
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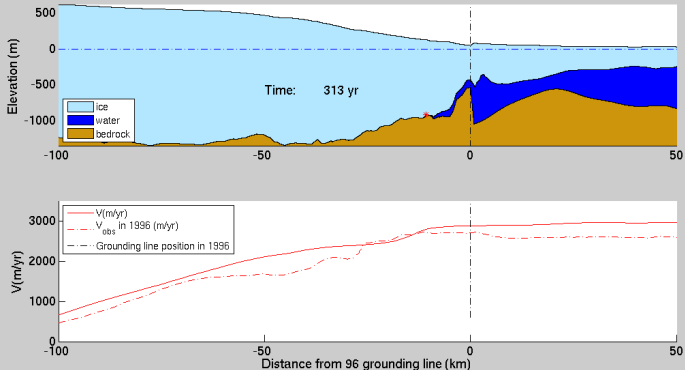
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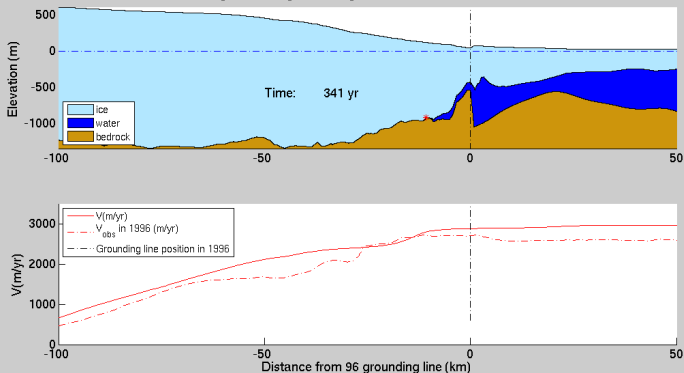
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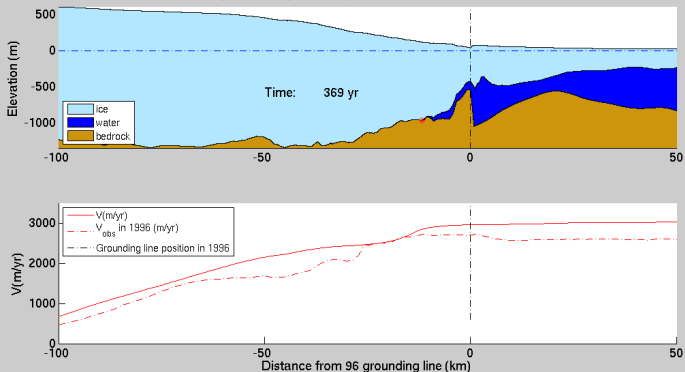
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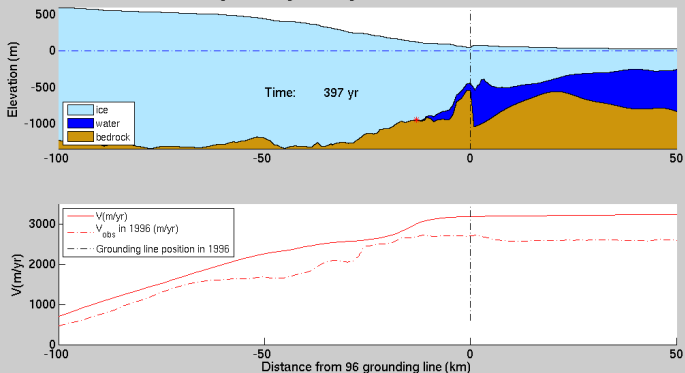
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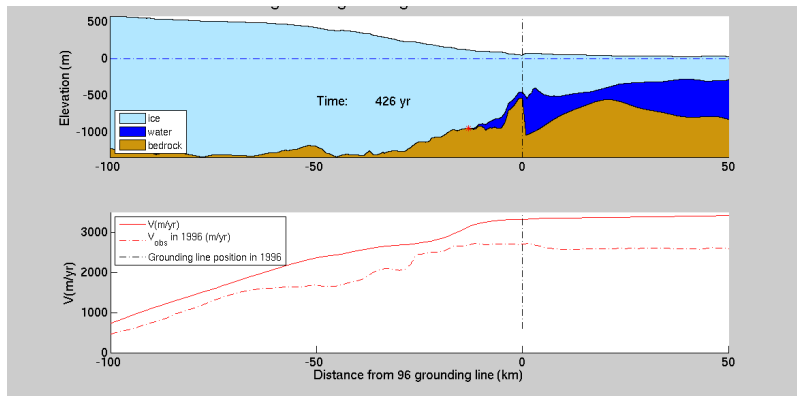
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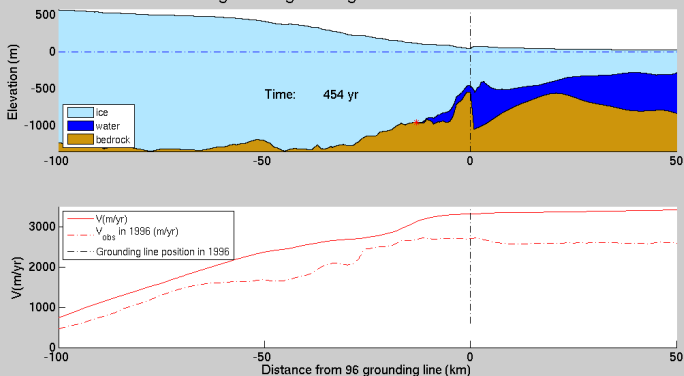
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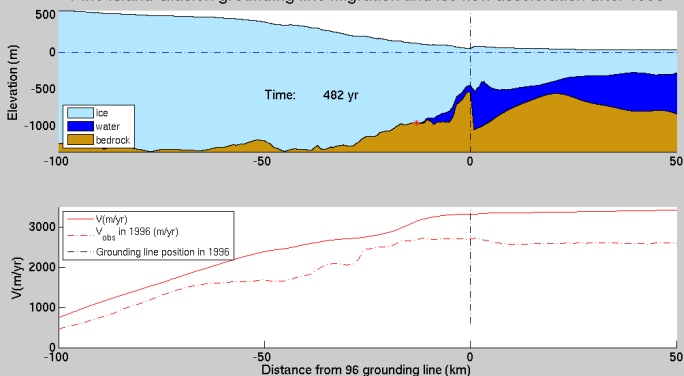
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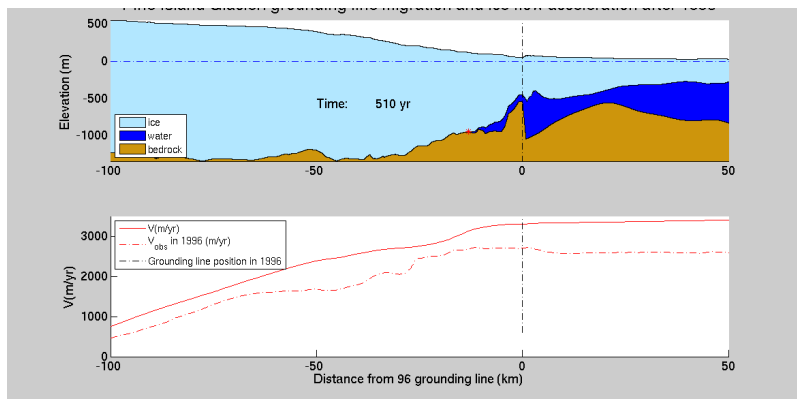
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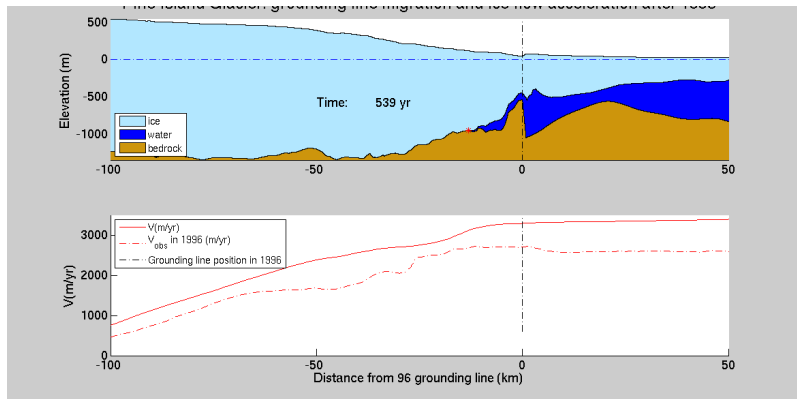
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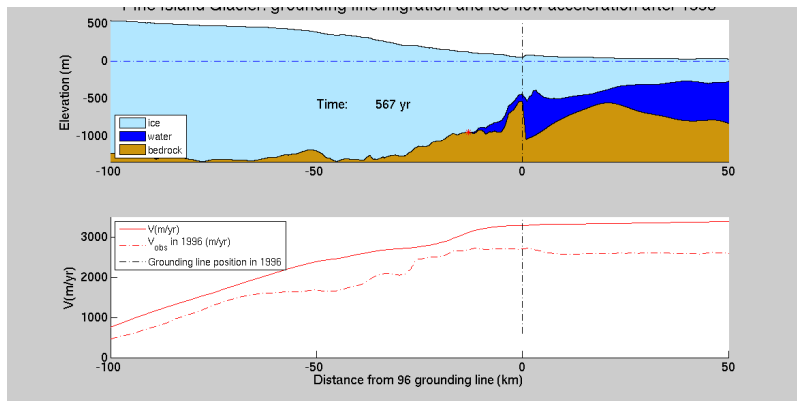
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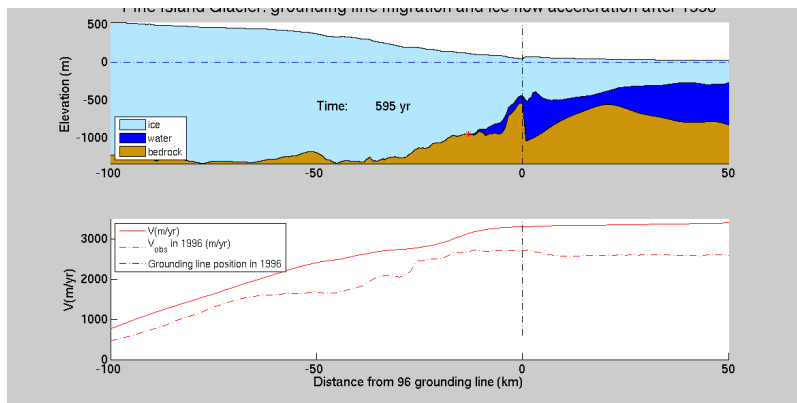
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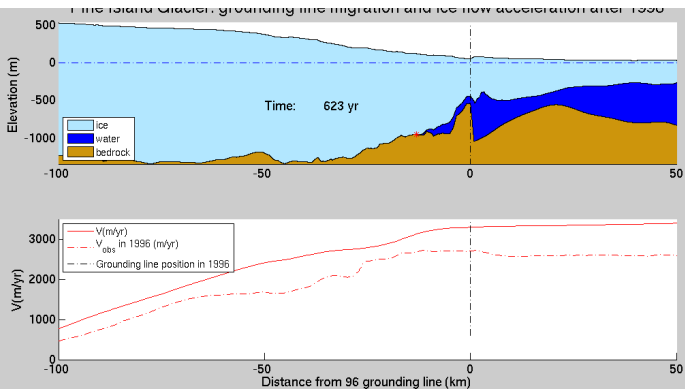
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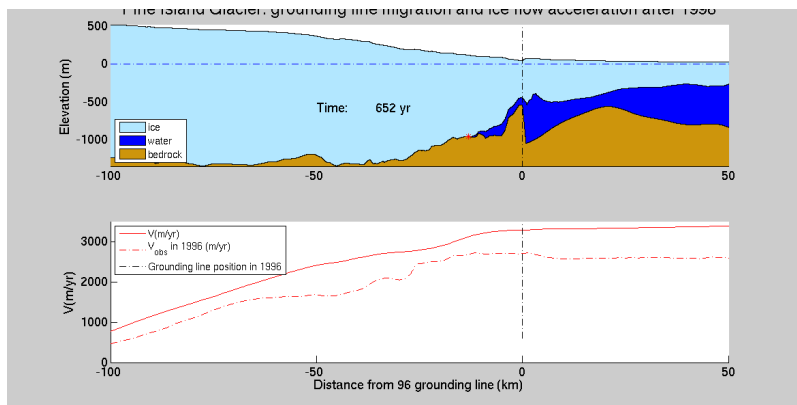
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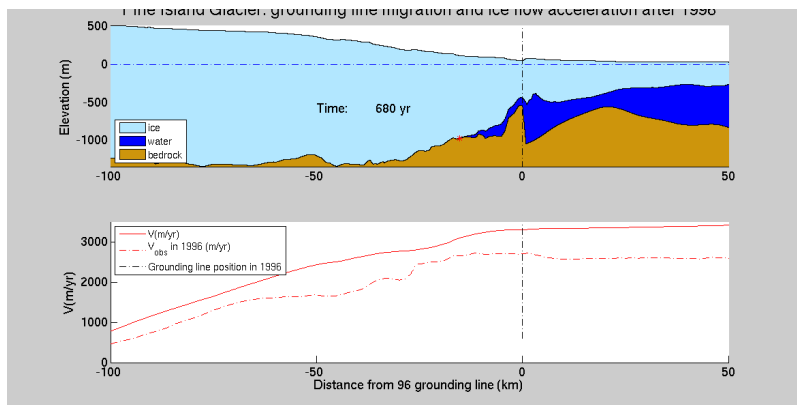
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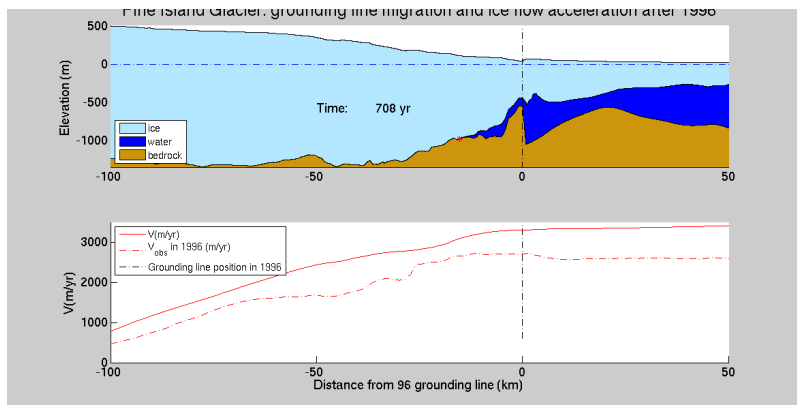
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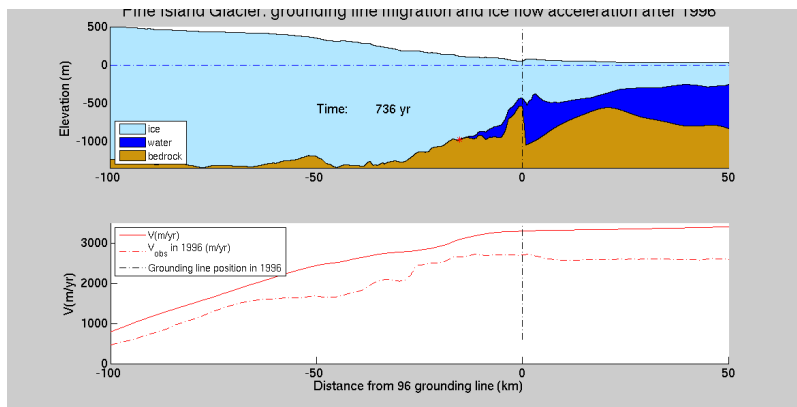
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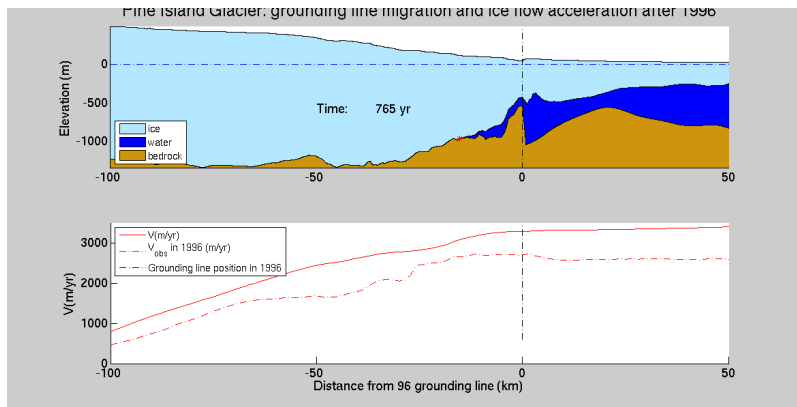
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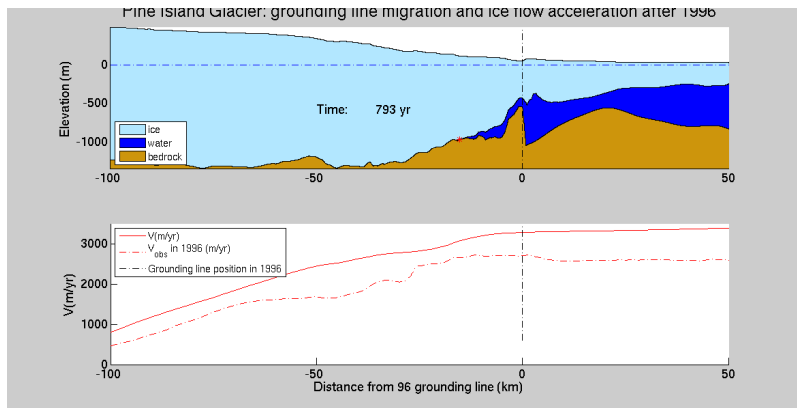
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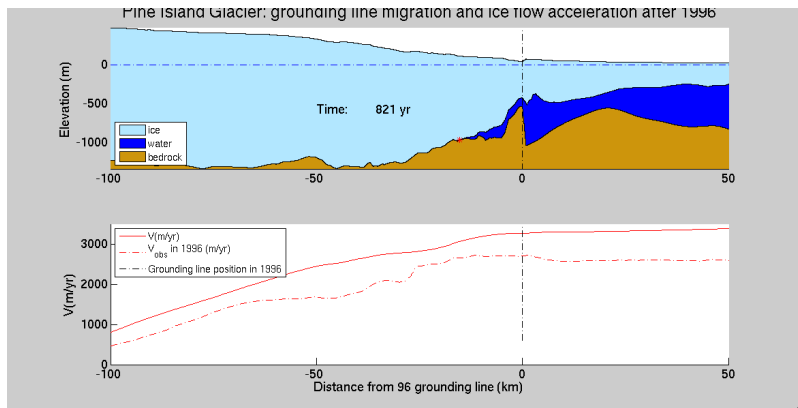
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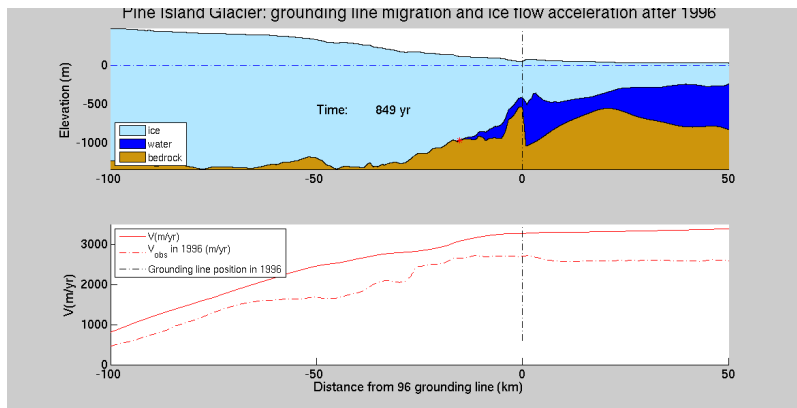
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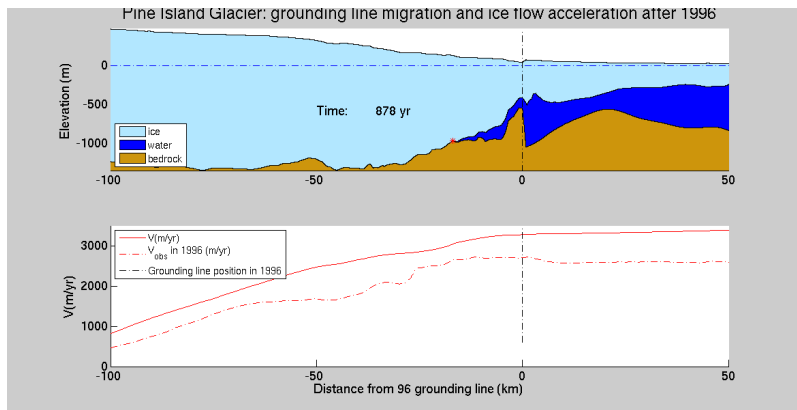
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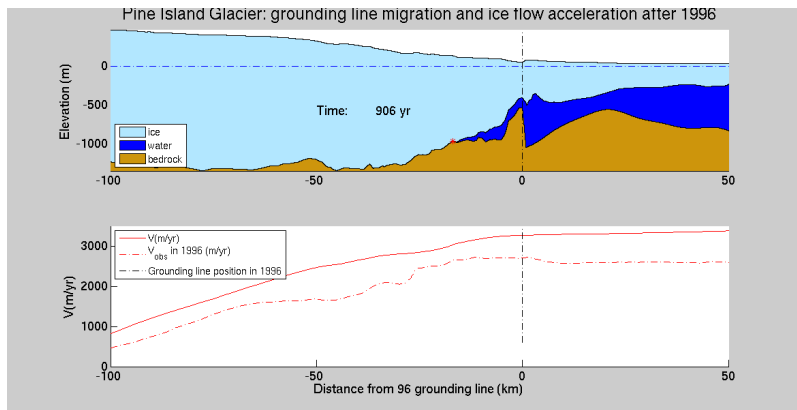
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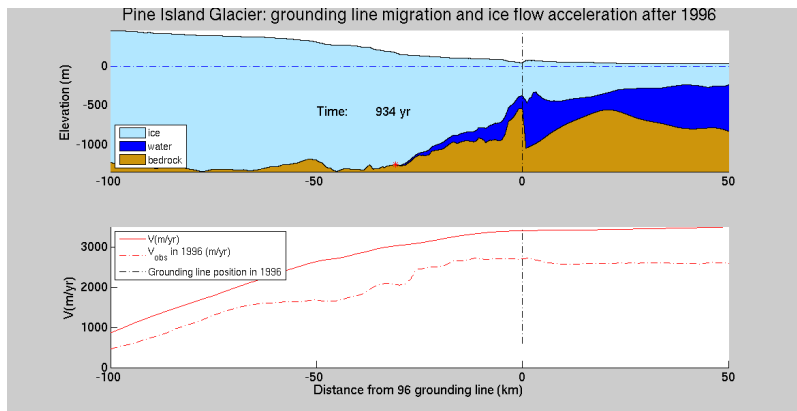
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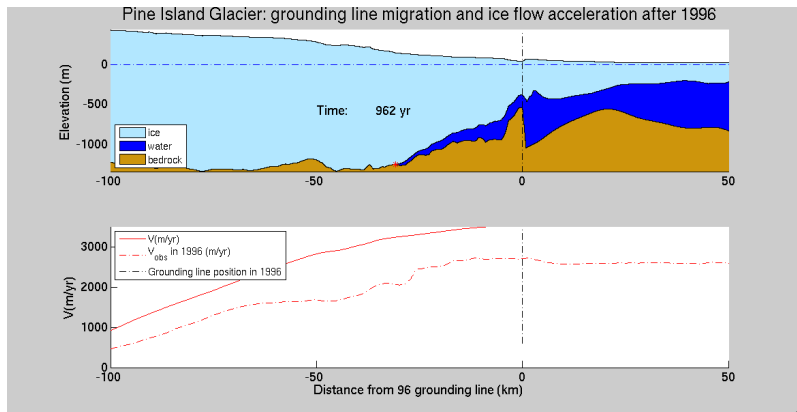
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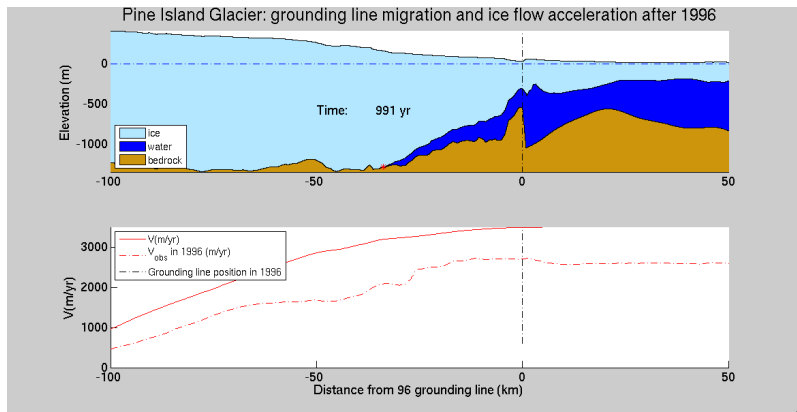
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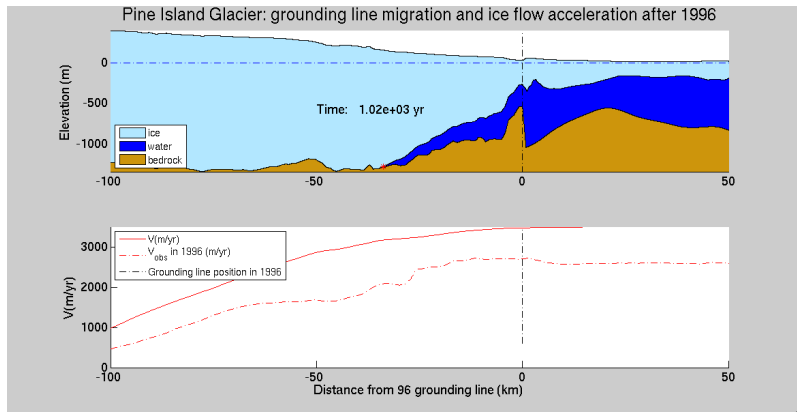
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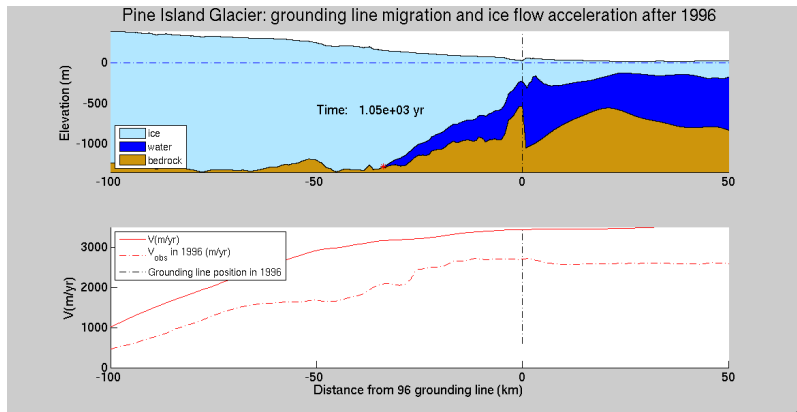
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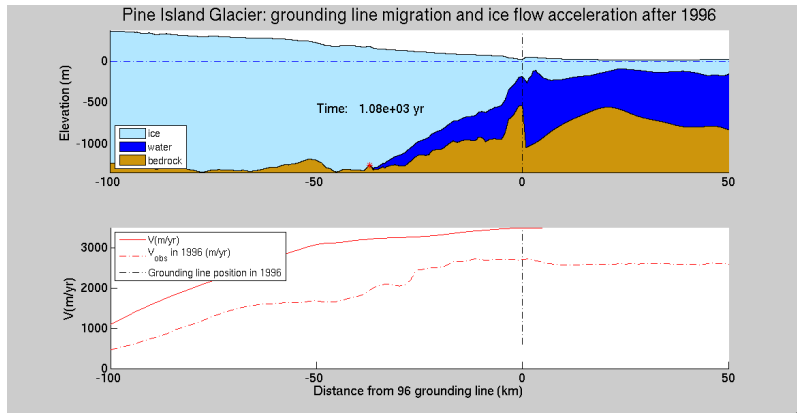
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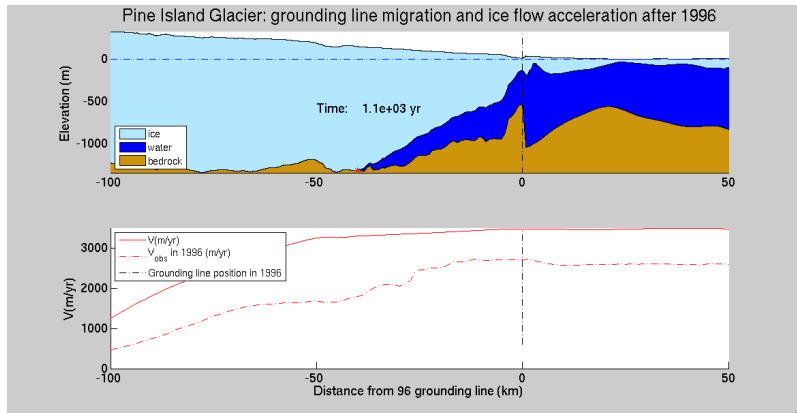
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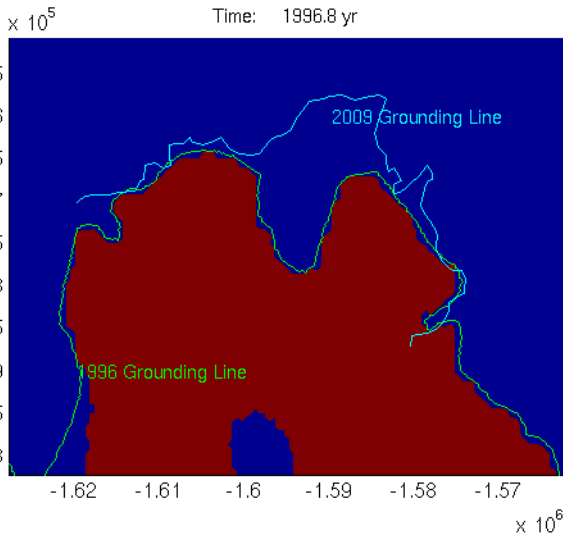
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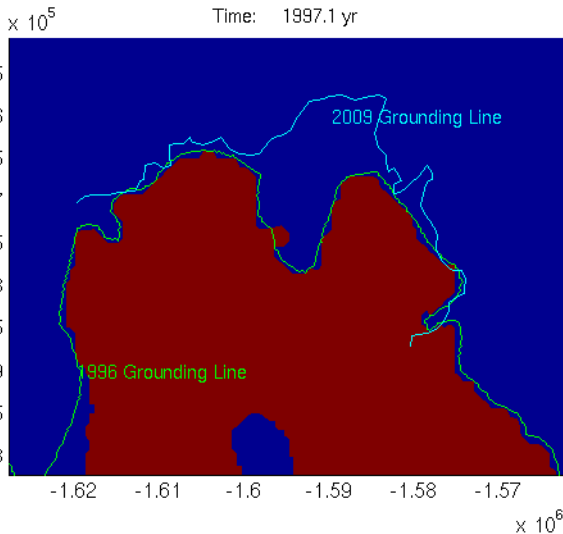
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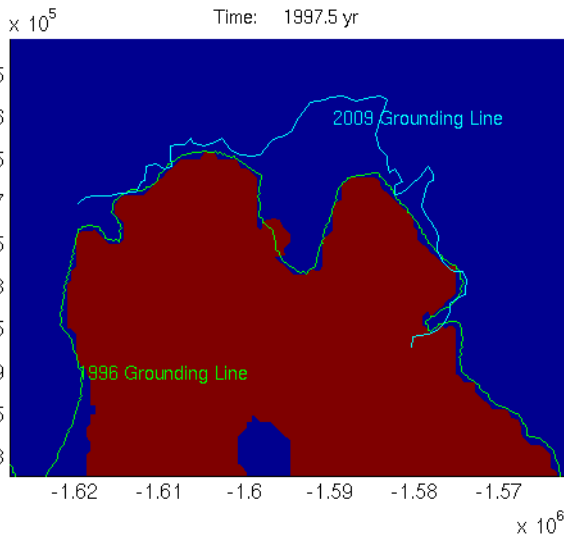
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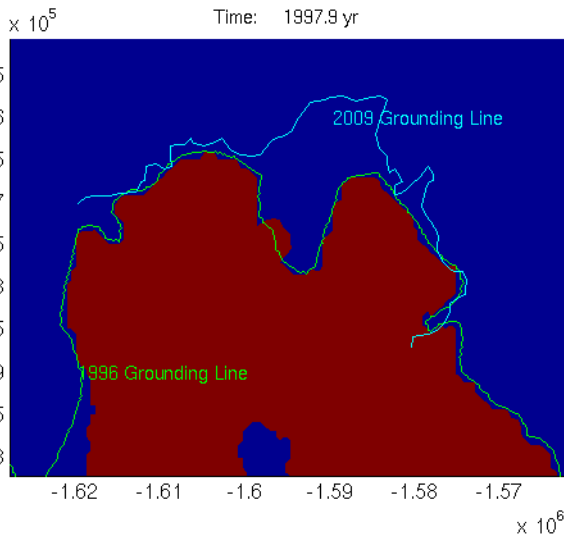
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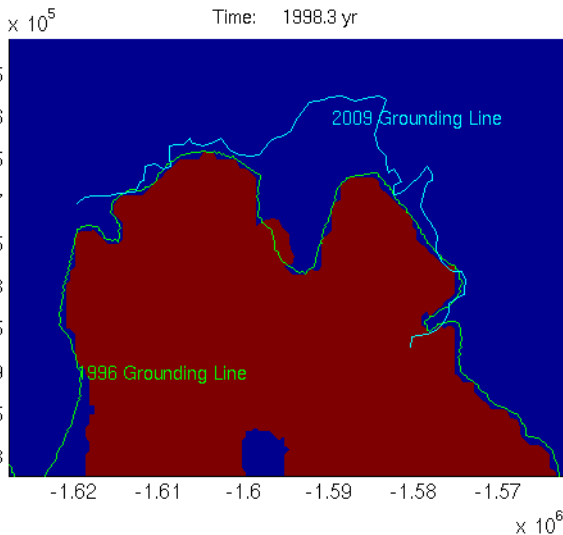
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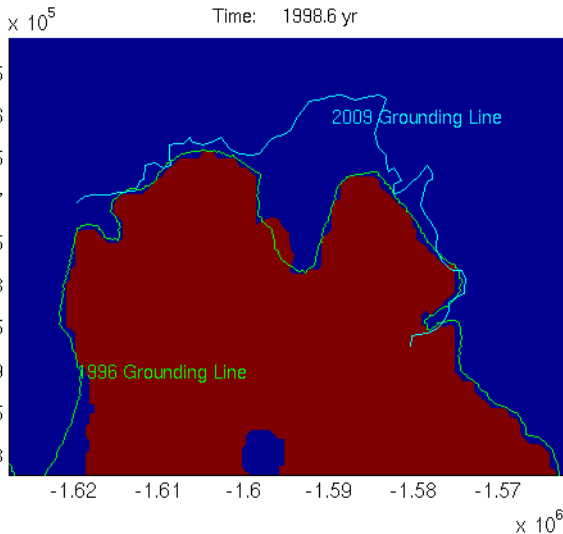
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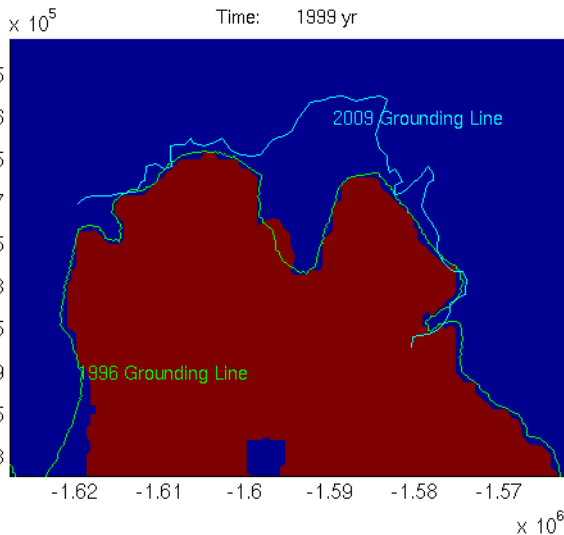
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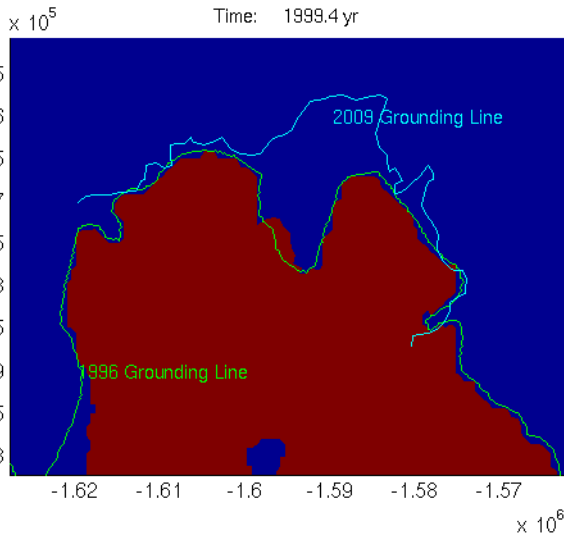
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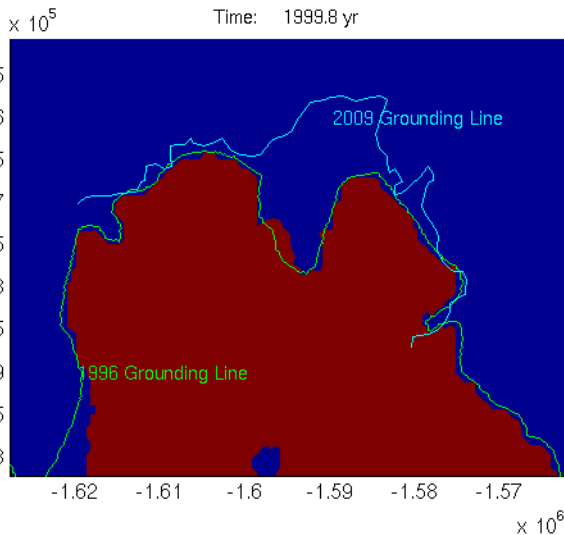
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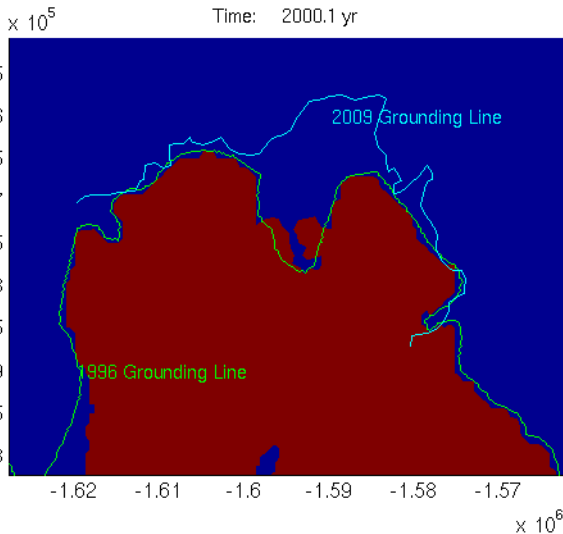
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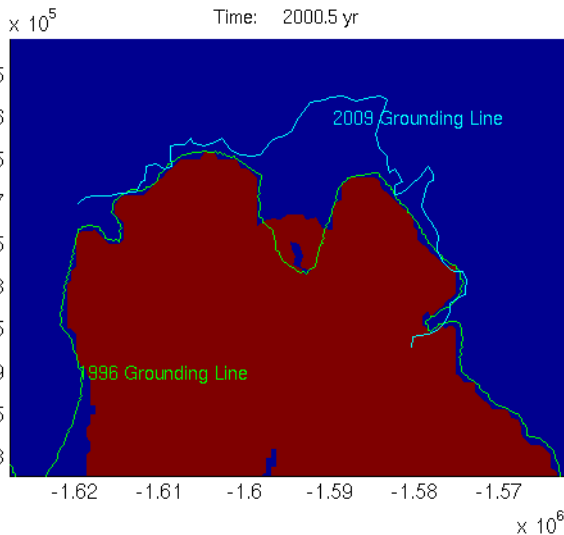
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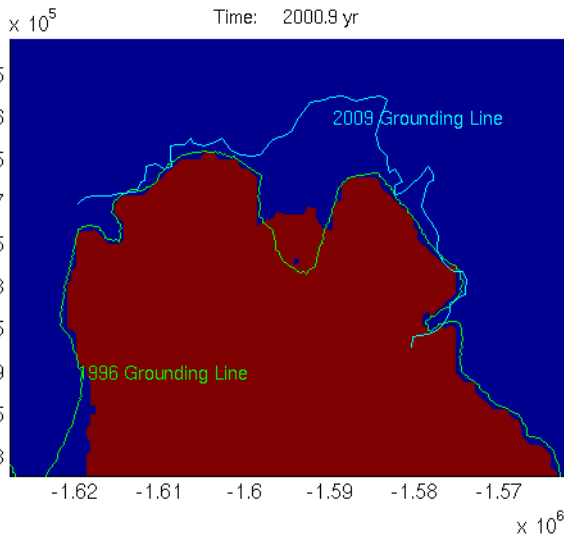
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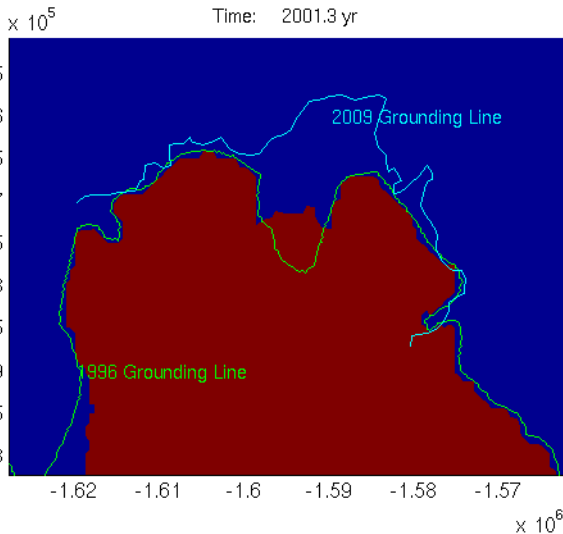
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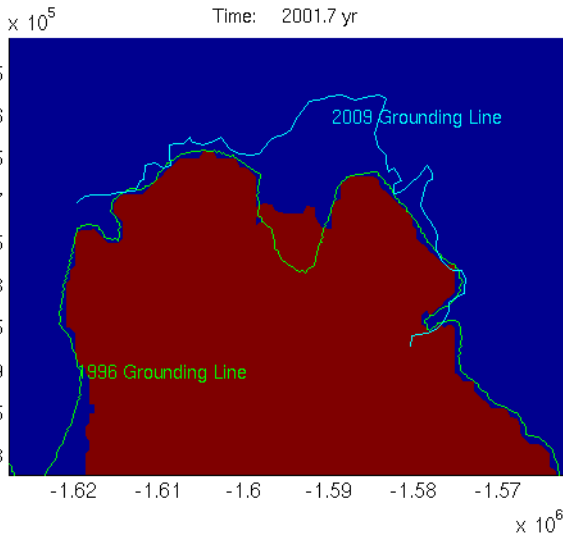
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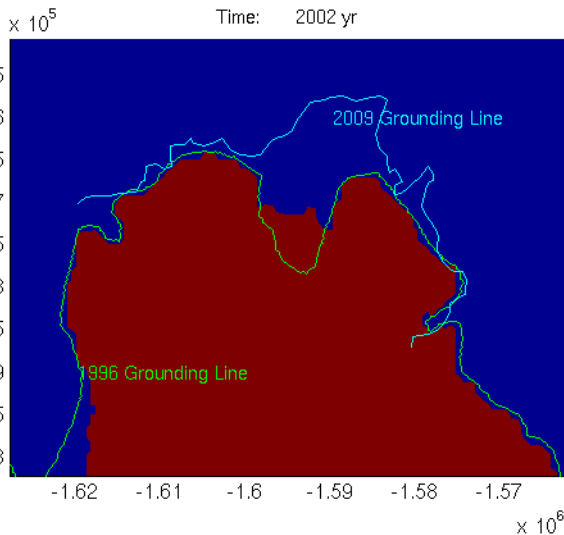
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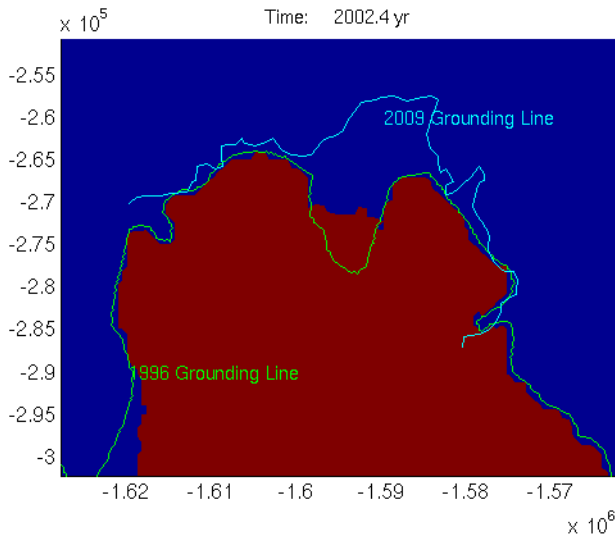
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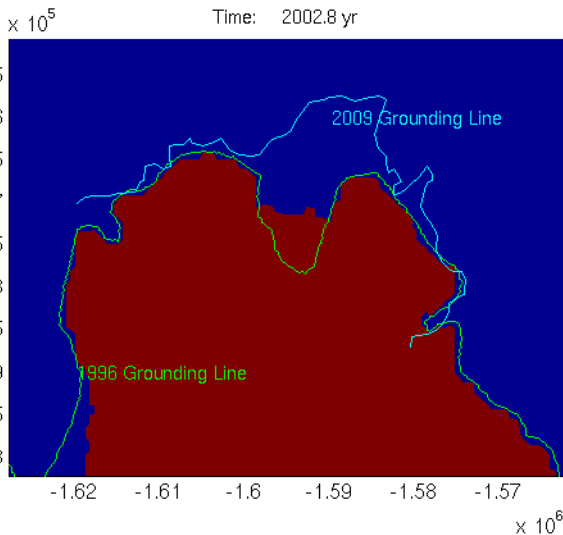
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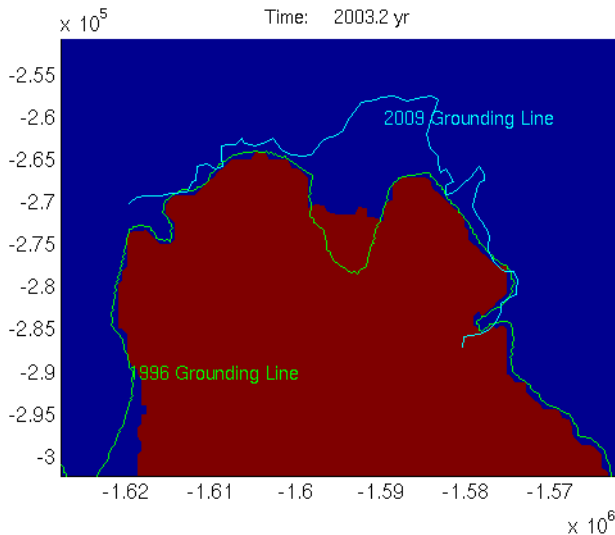
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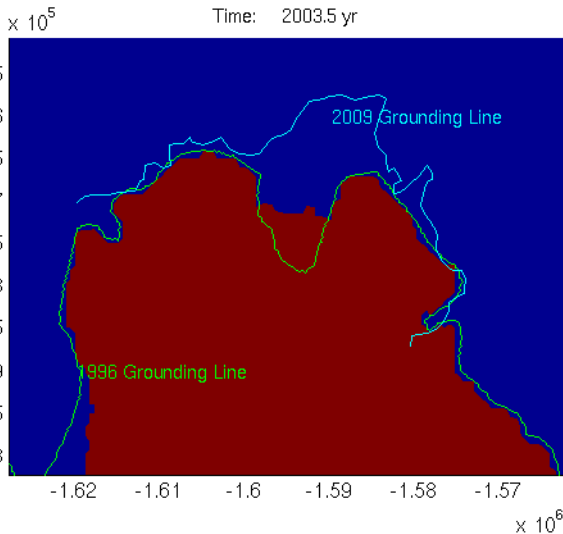
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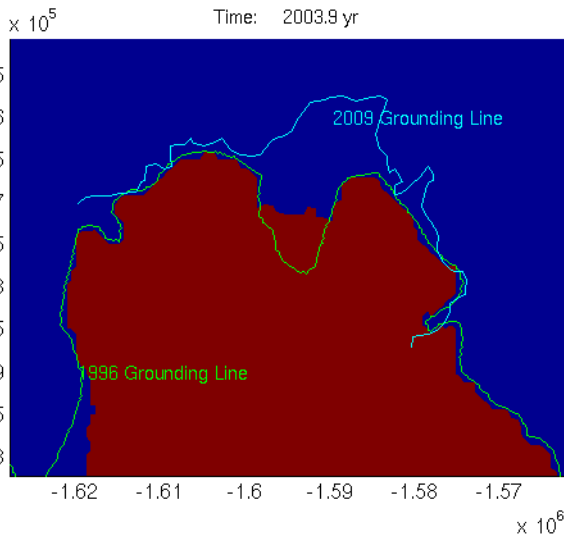
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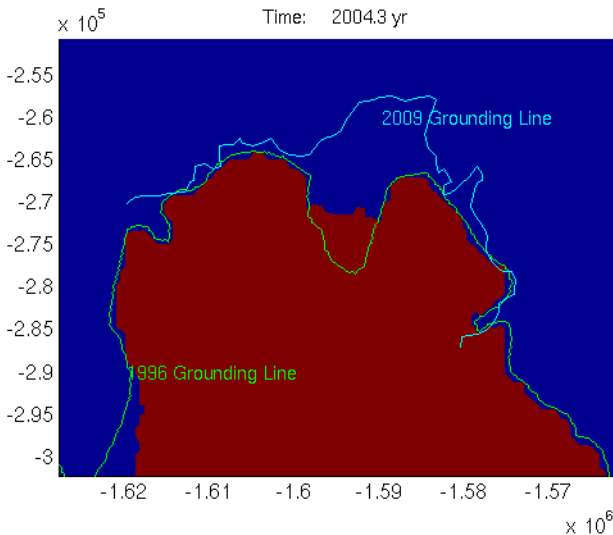
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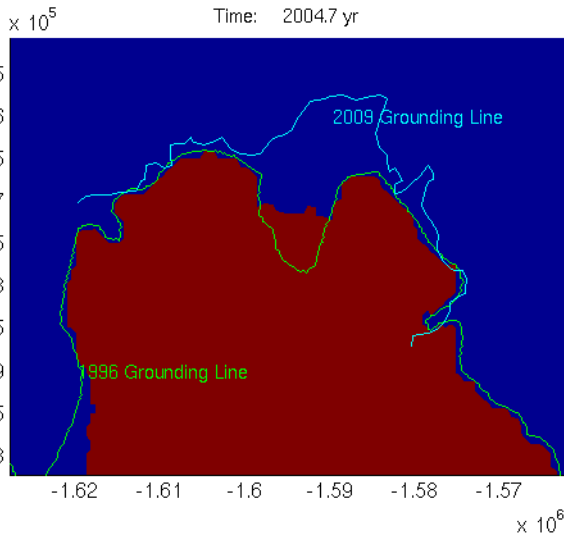
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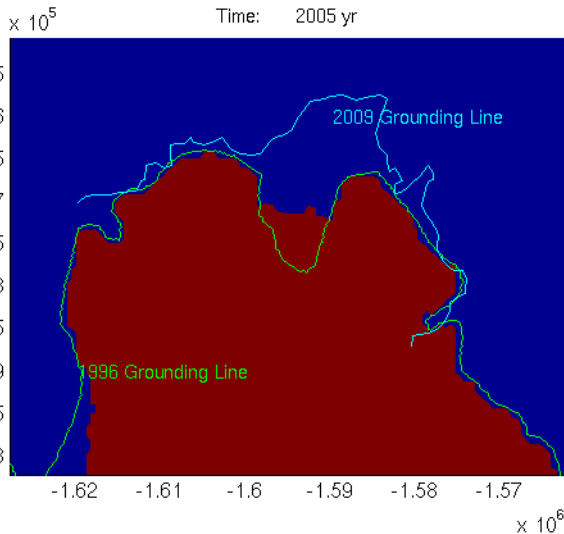
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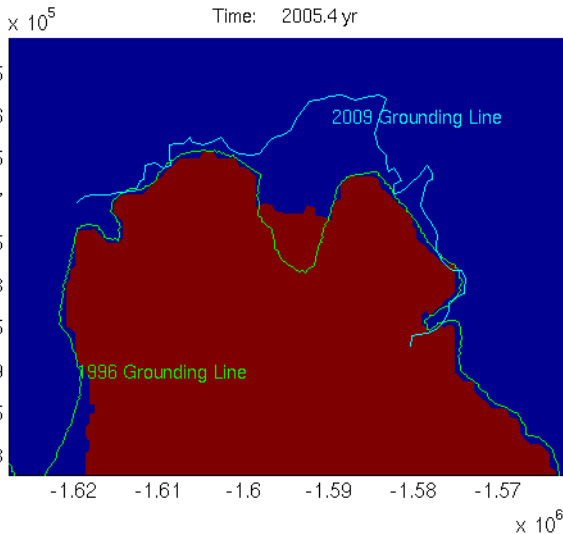
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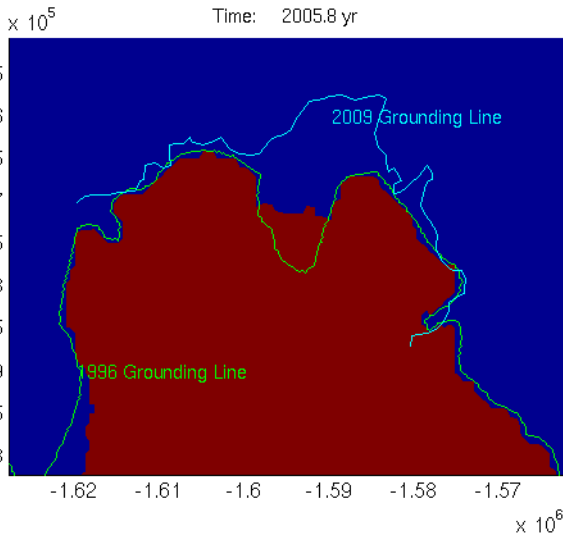
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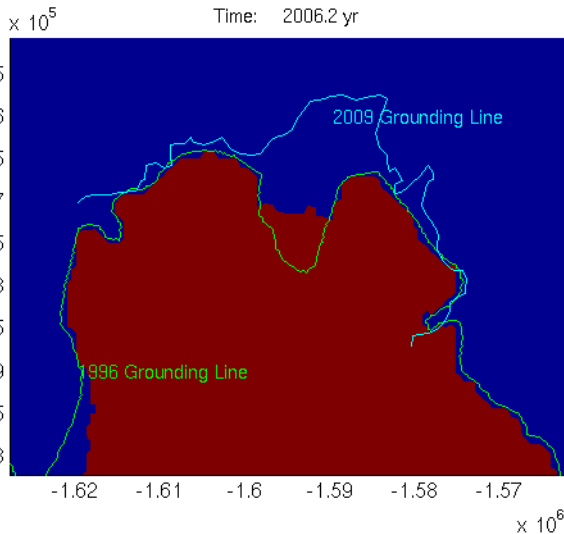
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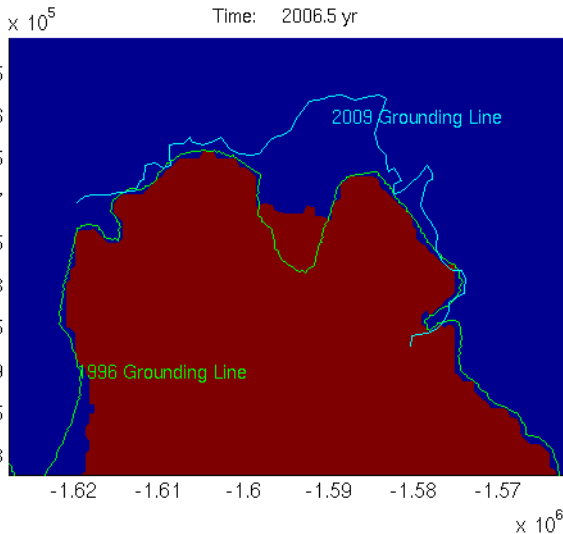
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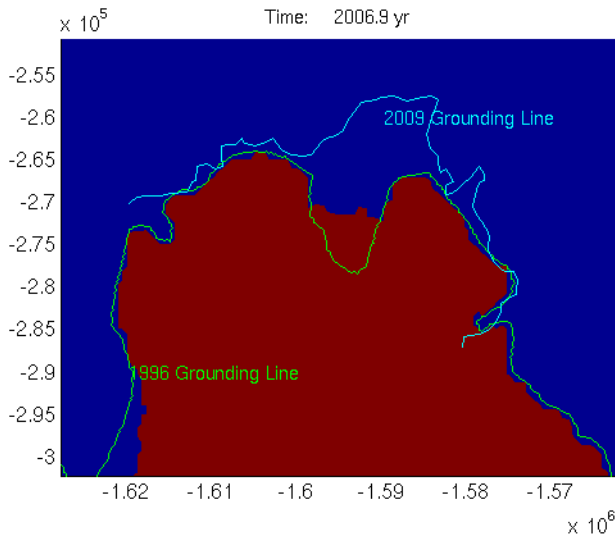
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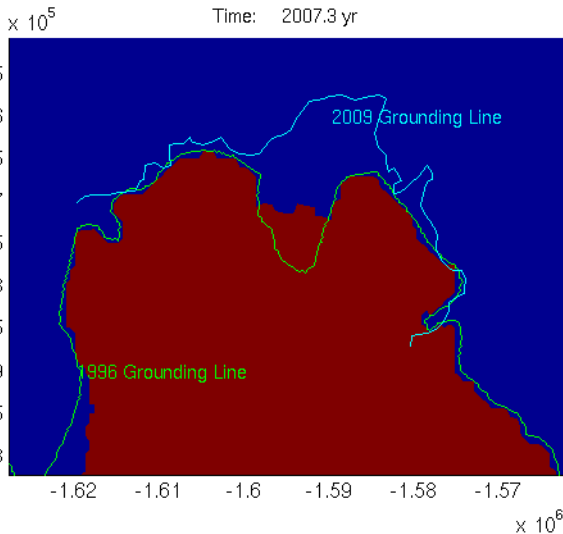
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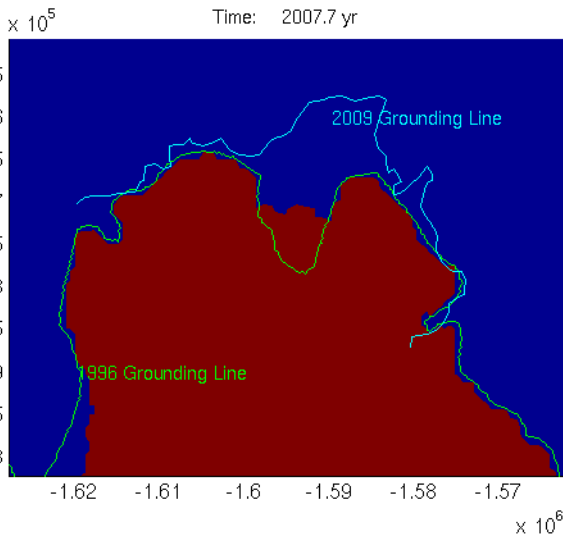
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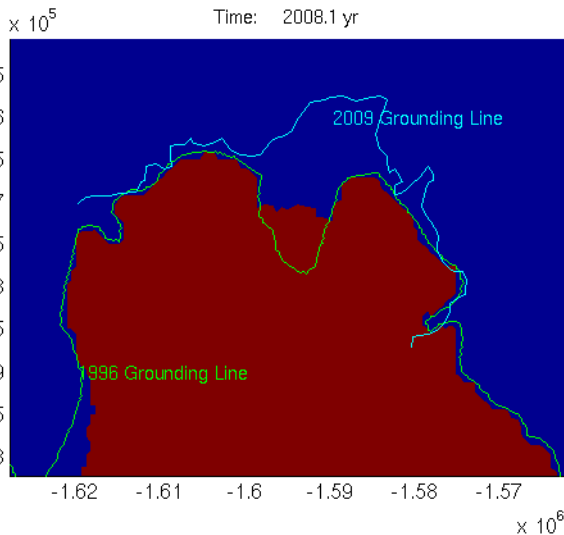
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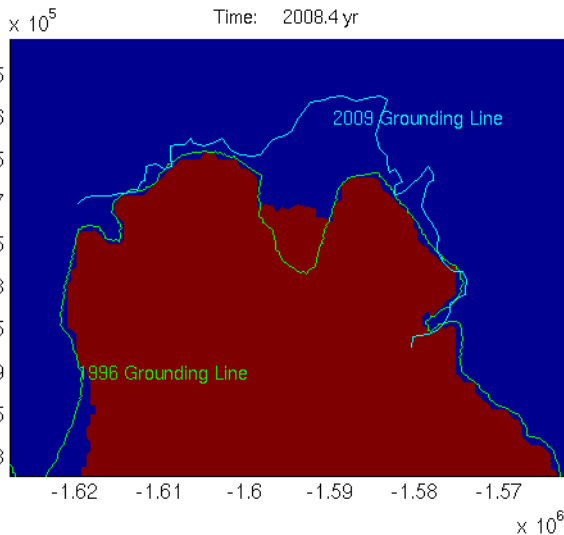
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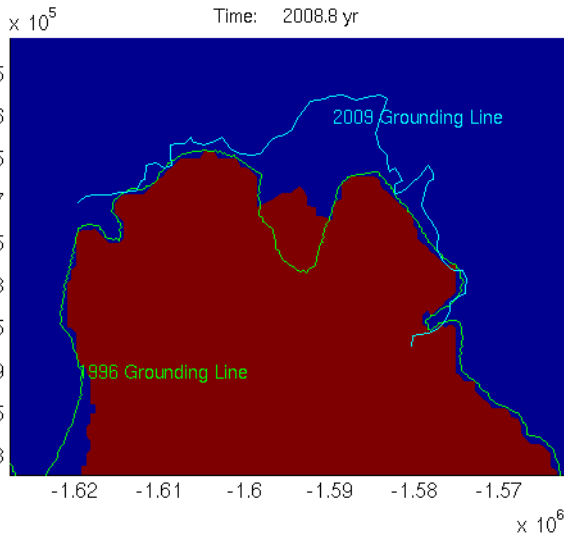
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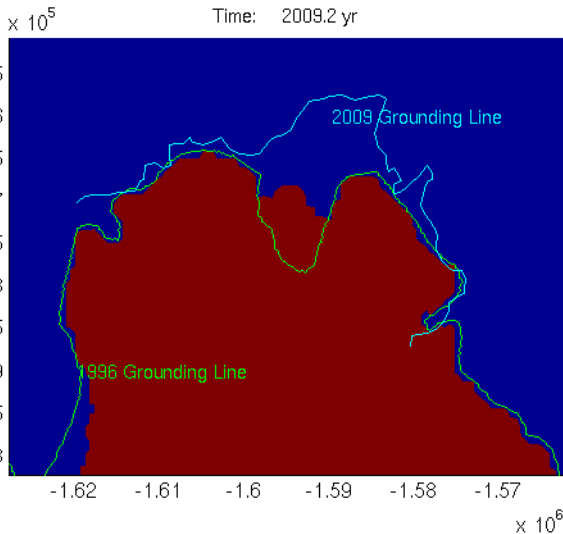
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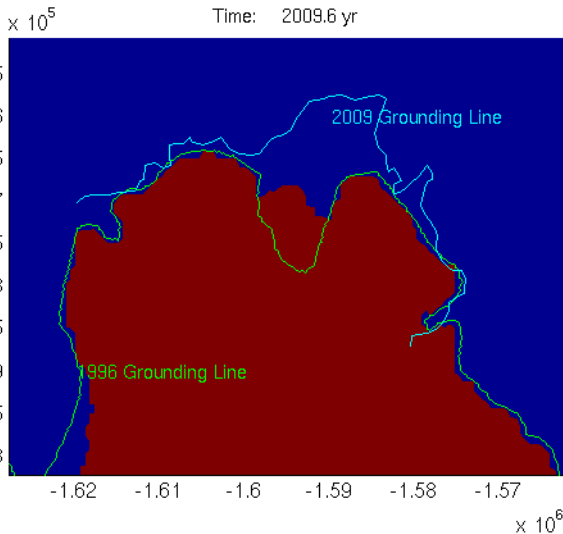
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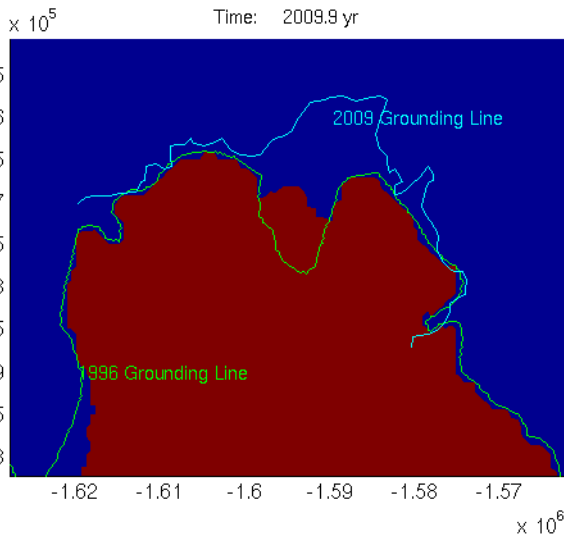
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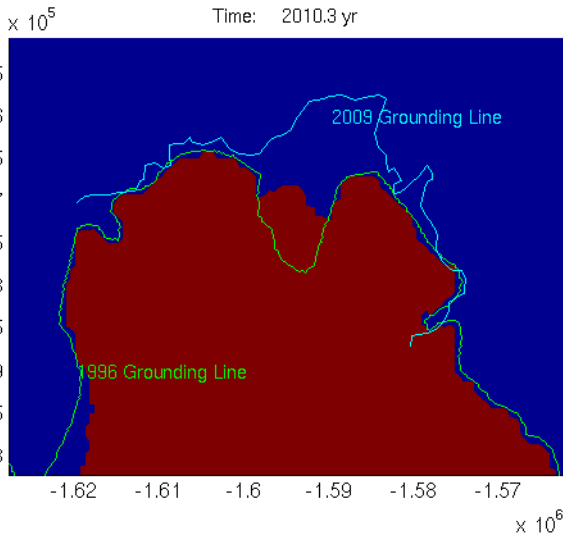
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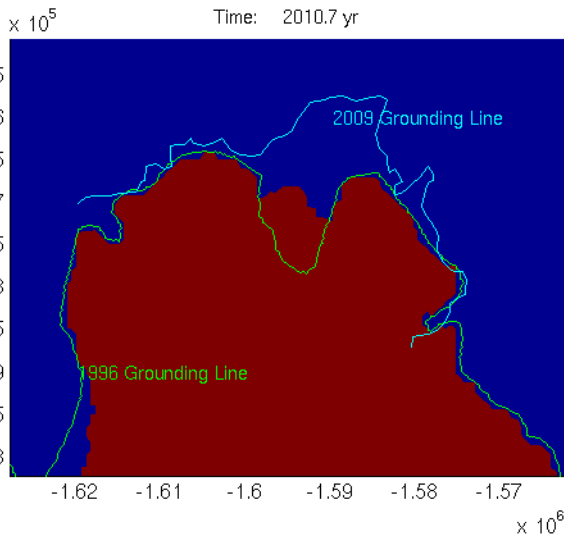
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## Hydrology model

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

$$\frac{dw}{dt} = S - \nabla \cdot (w \cdot \overline{u_w})$$

With  $w$  the water thickness,  $S$  the basal melting rate and  $\overline{u_w}$  the depth-averaged water velocity vector.

Assuming a laminar flow between two parallel plates:

$$\overline{u_w} = \frac{w^2 \nabla \Phi}{12\mu} \quad \text{and} \quad \Phi = \rho_i g z_s + (\rho_w - \rho_i) g z_b - N$$

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.

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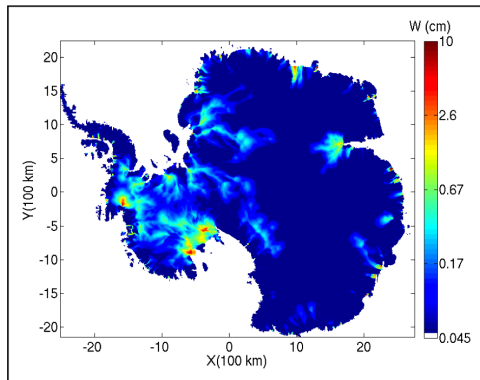
## Hydrology model

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:

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



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## 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
```

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## Trac system with wiki



logged in as larour | [Logout](#) | [Preferences](#) | [Help/Guide](#) | [About Trac](#)

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

## General info

- The general website of ISSM is here: <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](#).

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## Nightly runs

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## ISSM Nightly run report

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

## List of tests

Result	Tolerance	Test Id	Test name	Field checked
SUCCESS	3.3e-15<1e-13	101	SquareShelfConstrainedDiagM2dSerial	Vx
SUCCESS	1.9e-15<1e-13	101	SquareShelfConstrainedDiagM2dSerial	Vy
SUCCESS	2e-15<1e-13	101	SquareShelfConstrainedDiagM2dSerial	Vel
SUCCESS	1e-16<1e-13	101	SquareShelfConstrainedDiagM2dSerial	Pressure
SUCCESS	3.4e-15<1e-13	102	SquareShelfConstrainedDiagM2dParallel	Vx
SUCCESS	1.3e-15<1e-13	102	SquareShelfConstrainedDiagM2dParallel	Vy
SUCCESS	1.3e-15<1e-13	102	SquareShelfConstrainedDiagM2dParallel	Vel
SUCCESS	1e-16<1e-13	102	SquareShelfConstrainedDiagM2dParallel	Pressure
SUCCESS	2.1e-15<1e-13	103	SquareShelfConstrainedDiagM3dSerial	Vx
SUCCESS	9.4e-16<1e-13	103	SquareShelfConstrainedDiagM3dSerial	Vy
SUCCESS	5.3e-16<1e-13	103	SquareShelfConstrainedDiagM3dSerial	Vz
SUCCESS	1.4e-15<1e-13	103	SquareShelfConstrainedDiagM3dSerial	Vel
SUCCESS	0<1e-13	103	SquareShelfConstrainedDiagM3dSerial	Pressure
SUCCESS	3e-15<1e-13	104	SquareShelfConstrainedDiagM3dParallel	Vx
SUCCESS	1.1e-15<1e-13	104	SquareShelfConstrainedDiagM3dParallel	Vy



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## Test suite

## Test Suite

**JPL**  
Corporation

- 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

```

Users\larour\sam-cut-trunk-jpl-test\NightlyRun
dhp-79-157-NightlyRun larours ls
IDFromString.m test126.m test227.m test311.m test412.m test599.m
IDOnName.m test127.m test228.m test312.m test413.m test510.m
Makefile test128.m test229.m test313.m test414.m test511.m
README test129.m test230.m test314.m test415.m test512.m
dok.m test130.m test232.m test315.m test416.m test513.m
runme.c test131.m test233.m test316.m test417.m test514.m
test102.m test132.m test234.m test317.m test418.m test515.m
test102.m test133.m test235.m test318.m test419.m test516.m
test103.m test134.m test236.m test319.m test420.m test517.m
test104.m test131.m test237.m test320.m test421.m test518.m
test105.m test132.m test238.m test321.m test422.m test519.m
test106.m test133.m test239.m test322.m test423.m test520.m
test107.m test134.m test240.m test323.m test424.m test521.m
test108.m test135.m test241.m test324.m test425.m test522.m
test109.m test136.m test242.m test325.m test426.m test523.m
test110.m test137.m test243.m test326.m test427.m test524.m
test111.m test138.m test244.m test327.m test428.m test525.m
test1102.m test1402.m test245.m test328.m test429.m test526.m
test1103.m test1501.m test246.m test329.m test430.m test527.m
test1104.m test1502.m test247.m test330.m test431.m test529.m
test1105.m test1601.m test248.m test331.m test432.m test530.m
test1106.m test1602.m test249.m test332.m test434.m test531.m
test1107.m test1603.m test250.m test333.m test435.m test532.m
test1108.m test201.m test251.m test334.m test437.m test601.m
test1109.m test202.m test252.m test335.m test438.m test602.m
test111.m test203.m test253.m test336.m test439.m test603.m
test1110.m test204.m test254.m test337.m test440.m test604.m
test112.m test205.m test255.m test338.m test441.m test605.m
test113.m test206.m test256.m test339.m test442.m test606.m
test114.m test207.m test257.m test340.m test443.m test607.m
test115.m test208.m test258.m test341.m test444.m test608.m
test116.m test209.m test259.m test342.m test445.m test609.m
test117.m test210.m test260.m test343.m test446.m test610.m
test118.m test211.m test261.m test344.m test447.m test611.m
test119.m test212.m test262.m test345.m test448.m test612.m
test120.m test213.m test263.m test346.m test449.m test613.m
test121.m test214.m test264.m test347.m test450.m test614.m
test122.m test215.m test265.m test348.m test451.m test615.m
test1203.m test216.m test266.m test401.m test452.m test616.m
test1204.m test217.m test267.m test402.m test453.m test617.m
test1205.m test218.m test268.m test403.m test454.m test618.m
test1206.m test219.m test269.m test404.m test451.m test619.m
test1207.m test220.m test304.m test405.m test502.m test620.m
test1208.m test221.m test305.m test406.m test503.m test621.m
test121.m test222.m test306.m test407.m test504.m test622.m
test1210.m test223.m test307.m test408.m test505.m test623.m
test1211.m test224.m test308.m test409.m test506.m test624.m
test1212.m test225.m test309.m test410.m test507.m test625.m
test125.m test226.m test310.m test411.m test508.m test626.m

```

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## Doxygen



## Ice Sheet System Model 3.3

C/C++ code documentation

Main Page	Data Structures	Files	Directories
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## ISSM C/C++ Source Code Browser

*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](mailto:issm@jpl.nasa.gov)

## Code Stats

Language	files	blank	comment	code	Total
C++	531	15433	17169	57344	89946
MATLAB	970	7248	13716	31608	52572
C/C++ Header	397	3047	2706	10262	16015
Objective C	32	99	0	402	501
Bourne Shell	9	59	98	272	429
Perl	3	21	23	240	284

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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

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Thanks!

