

## Ice Sheet System Model

### ISSM Capabilities

Chris BORSTAD<sup>1</sup>, Bao DUONG<sup>5,1</sup>, Feras HABBAL<sup>2,1</sup>, Daria HALKIDES<sup>1,3</sup>,  
Michiel HELSEN<sup>2</sup>, **Eric LAROUR**<sup>1</sup>, Mathieu MORLIGHEM<sup>2</sup>, Lan NGUYEN<sup>5,1</sup>,  
Gilberto PÉREZ<sup>4,1</sup>, Eric RIGNOT<sup>2,1</sup>, John SCHIERMEIER<sup>1</sup>,  
Nicole SCHLEGEL<sup>1</sup>, Hélène SEROUSSI<sup>1</sup>

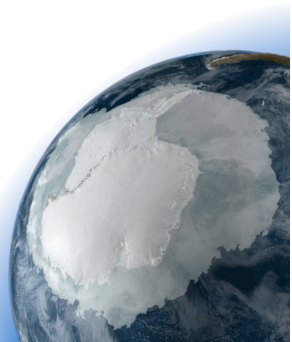
<sup>1</sup>Jet Propulsion Laboratory - California Institute of Technology

<sup>2</sup>University of California, Irvine

<sup>3</sup>Joint Institute for Regional Earth System Science & Engineering, UCLA

<sup>4</sup>University of Southern California

<sup>5</sup>Cal Poly Pomona



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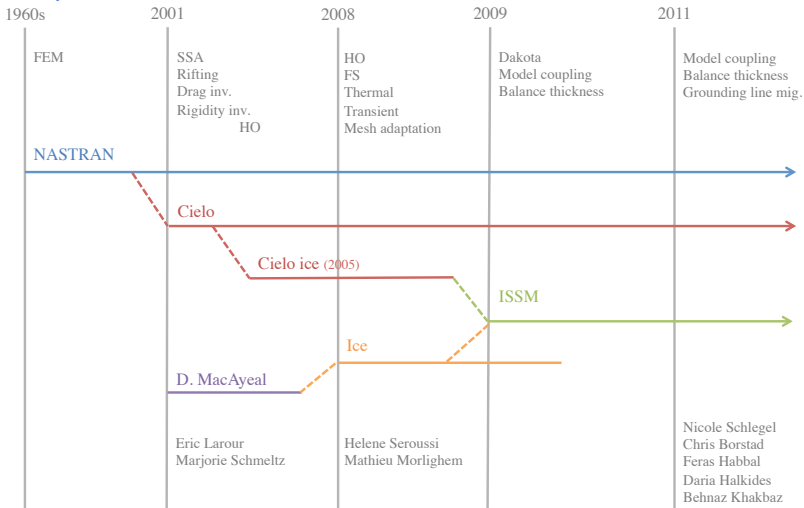
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Jet Prop. Lab.

Ecole Centrale Paris

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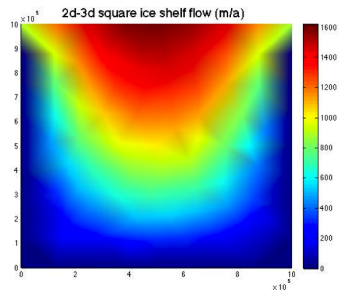
Solve mechanical stress-equilibrium for the entire ice sheet/ice shelf. Can be done in 2D (SSA) or 3D (SIA, Higher-order, Full-Stokes). Material is isotropic nonlinear (Glen's law) in the creep regime of deformation.

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

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

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

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





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

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

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

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

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

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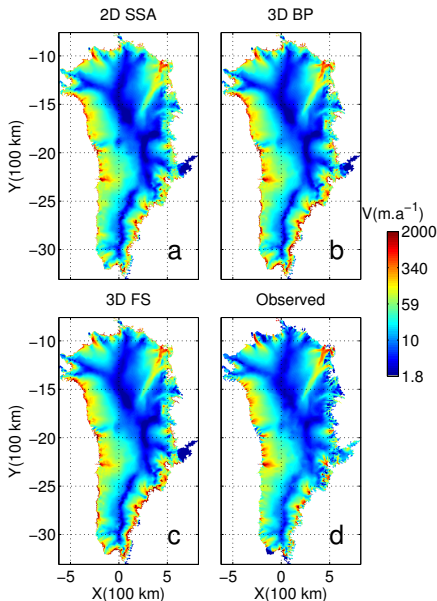
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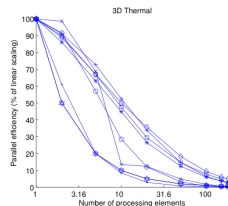
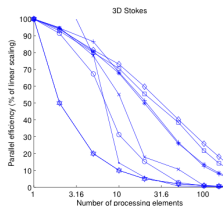
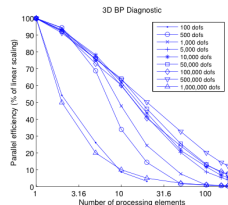
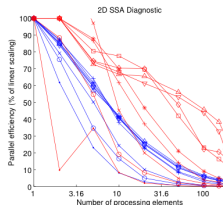
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- ISSM can run on any platform (multi-core desktop), shared or distributed cluster
- C++ implementation of computational core using MPICH and PETSc libraries + array of parallel libraries for partitioning, iterative and direct solvers
- Multi-threading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



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## Parallel libraries

ISSM relies on a series of libraries to implement parallelism:

- PETSc Portable, Extensible Toolkit for Scientific Computation [Balay et al., 1997, Balay et al., 2008, Balay et al., 2009]. PETSc is a suite of data structures and routines for the scalable solution of scientific applications modeled by partial differential equations. Used mainly for its parallel structures (Vec and Mat objects) and iterative parallel solvers.
- MPICH1,2: Message Passing Interface [Gropp et al., 1996, Gropp and Lusk, 1996] to manage parallel communications between all cpus during solution sequences.
- METIS: Software Package for Partitioning Unstructured Graphs, Partitioning Meshes, and Computing Fill-Reducing Orderings of Sparse Matrices [Karypis and Kumar, 1998]. This package is used to partition objects such as elements and vertices across a cluster. This partitioning scheme results in partitions that have equal numbers of elements on each cluster node.
- MUMPS: Multifrontal Massively Parallel Sparse direct solver [Amestoy et al., 2001, Amestoy et al., 2006]. Direct solver that suffers few convergence issues. Relied upon often for the solution of any system of equations.

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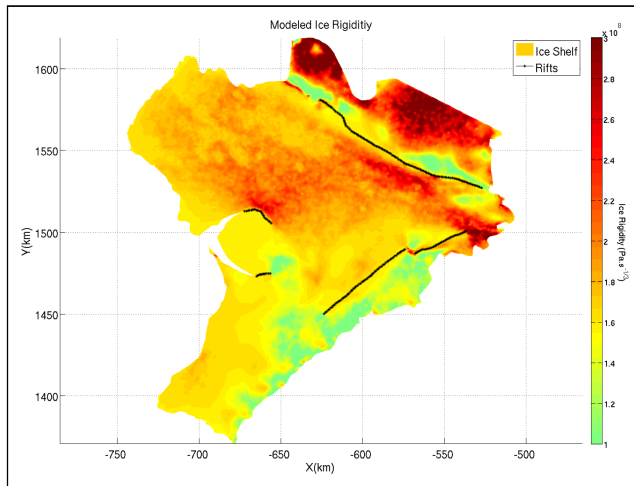
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## Rifting/Faulting

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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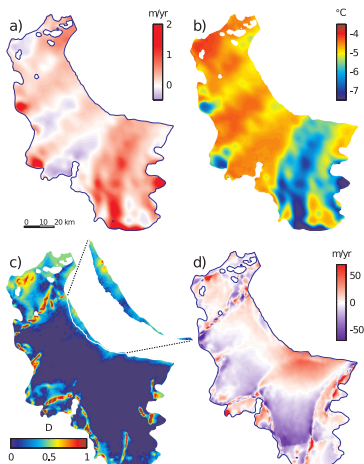
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## Damage Mechanics

ISSM can also introduce a damage variable into Glen's law, to account and invert for the presence of damage through the thickness of an ice shelf. For more details, we refer to Borstad et al, 2012.



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- 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

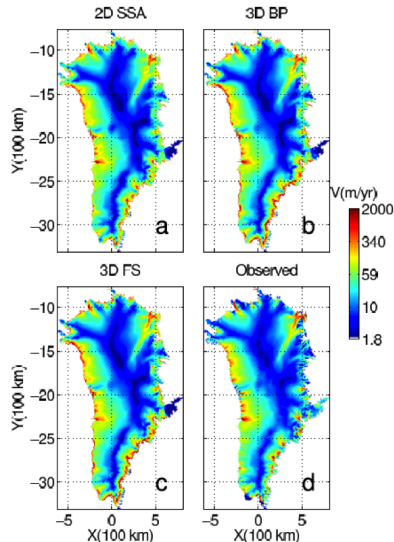


Figure 8. Modeled surface velocity (in m/yr) (using inverted basal drag coefficient) for the 2D Shallow-Stream model (a), the 3D Blatter/Pattyn model (b) and the 3D full-Stokes model (c). d) Observed InSAR surface velocities (in m/yr) of the Greenland Ice Sheet.



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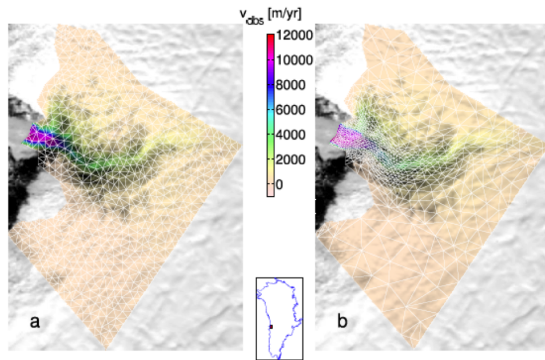
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- Adapt mesh according to a metric, such as surface velocity
- Static capability, not transient adaptation
- Relies on a rewrite of the BAMG anisotropic mesher [Hecht, 2006]



**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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- 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 model, full-advection and full-diffusion in 3D + viscous heating. Mesh velocity in vertical direction. Solve for temperature.

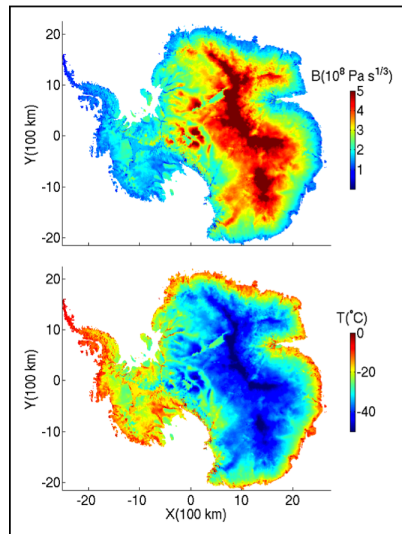
$$\frac{\partial T}{\partial t} = (\mathbf{w} - \mathbf{v}) \cdot \nabla T + \frac{k_{th}}{\rho C} \Delta T + \frac{\Phi}{\rho C}$$

- 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

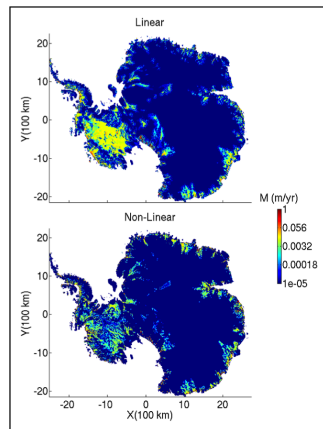
- Two models for computing melting rates:

- 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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New thermal model, based on [Aschwanden et al., 2012]. Enthalpy formulation, allows to recover more physically consistent melting rates.

Avoids relying on penalty formulations to constrain temperature to pressure melting point. System of equations is better conditioned – > more favourable for iterative solvers.

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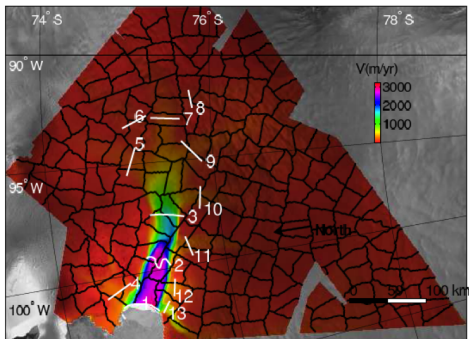
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- Sampling and local reliability methods to study the impact of different areas of the mesh
- Sampling of the mesh using Chaco, Scotch and Metis partitioners
- Partition the mesh into equal area subsections, which then can be updated for each sample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



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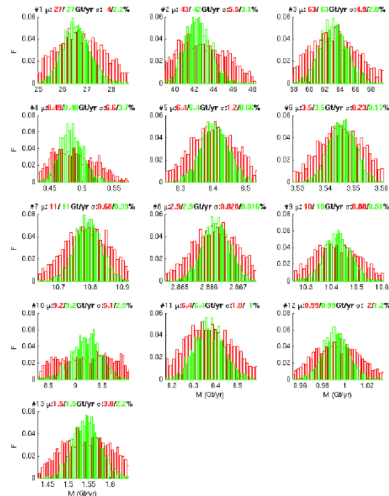
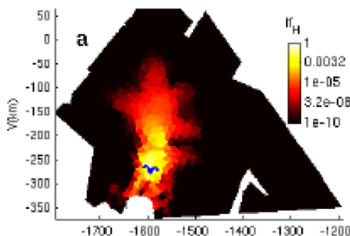
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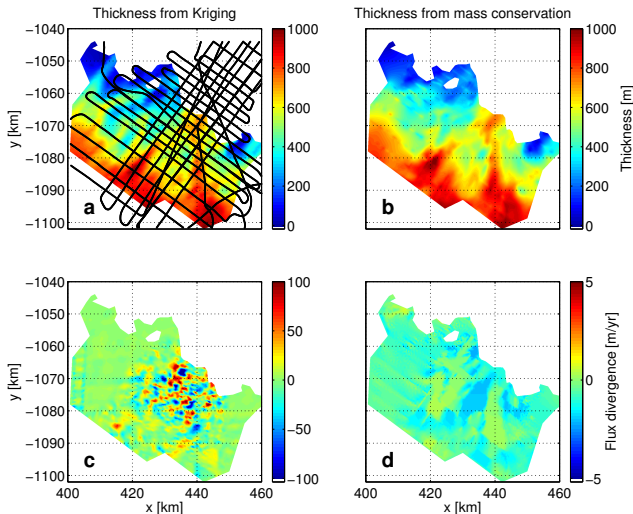
- Results can then be plotted in histograms for sampling analysis or importance factors for local reliability methods



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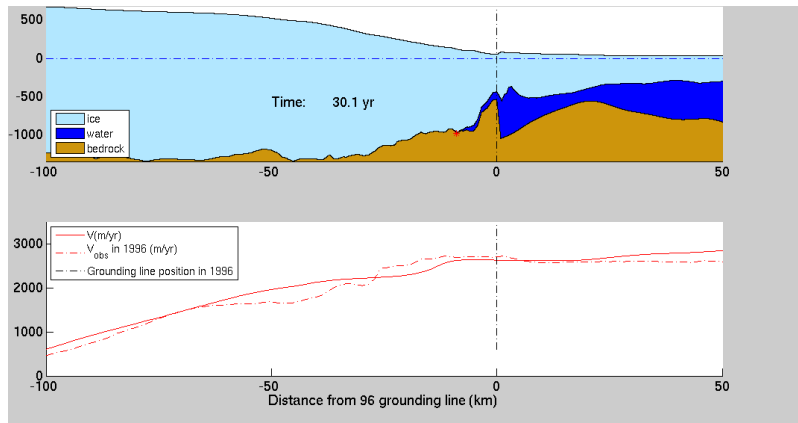
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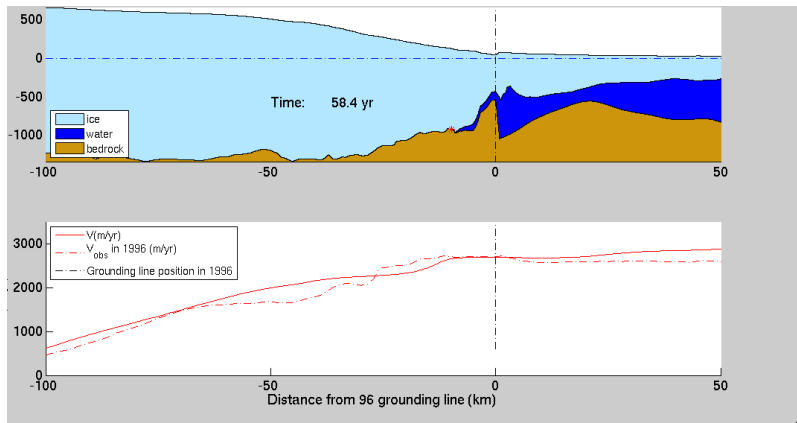
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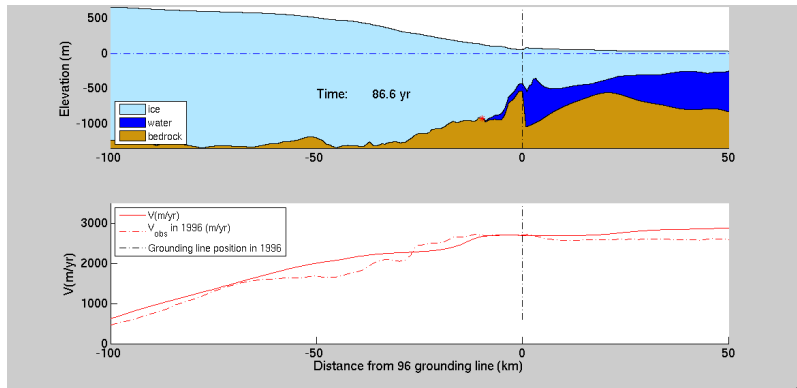
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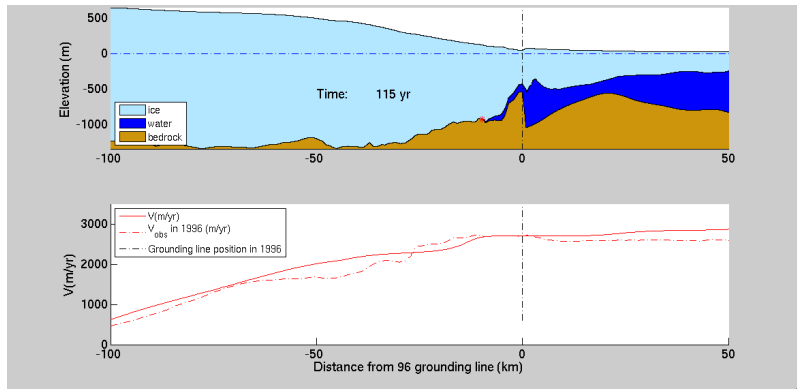
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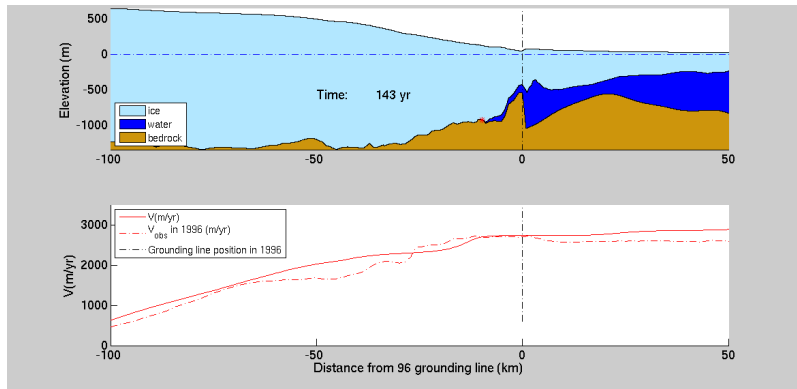
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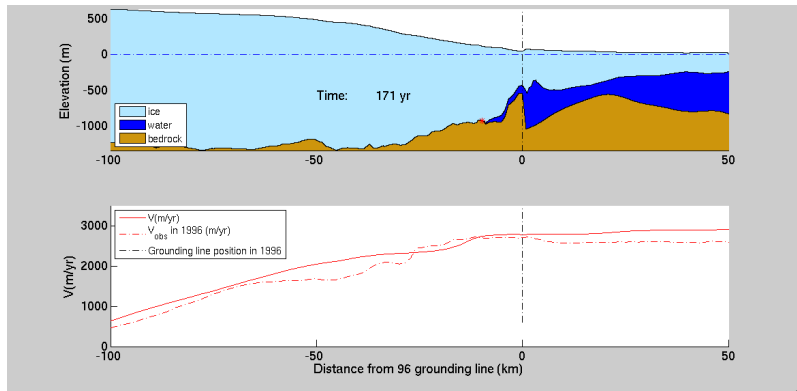
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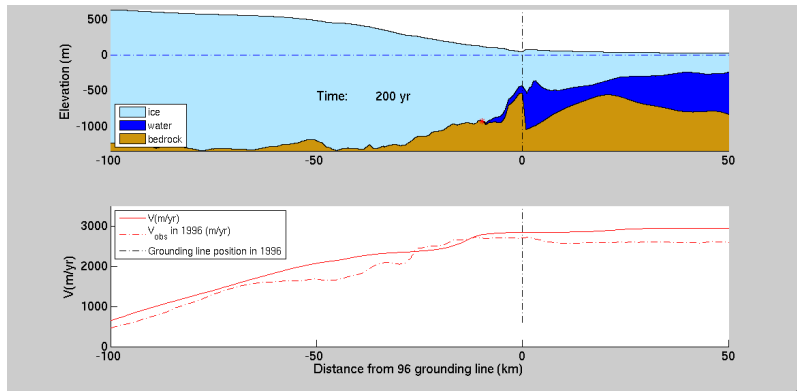
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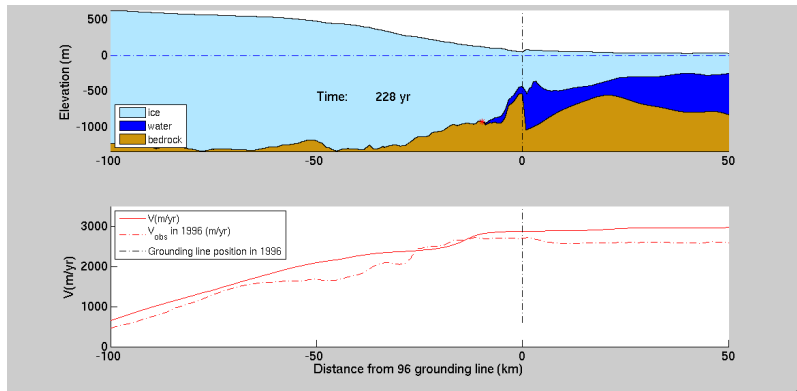
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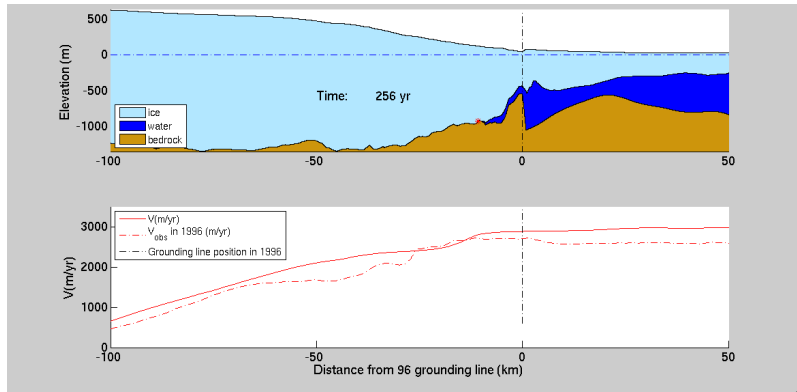
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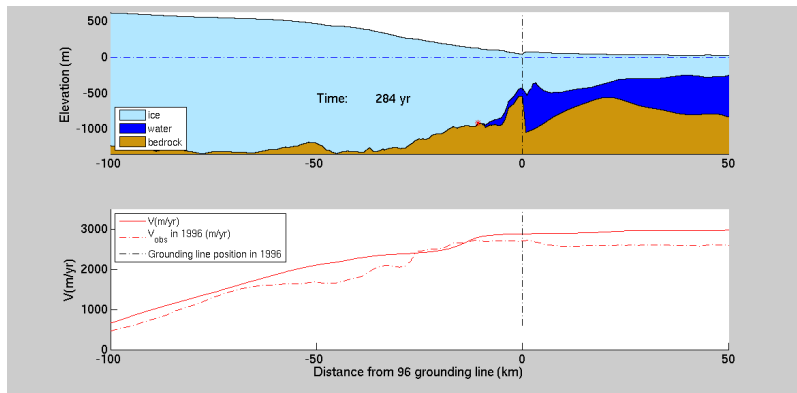
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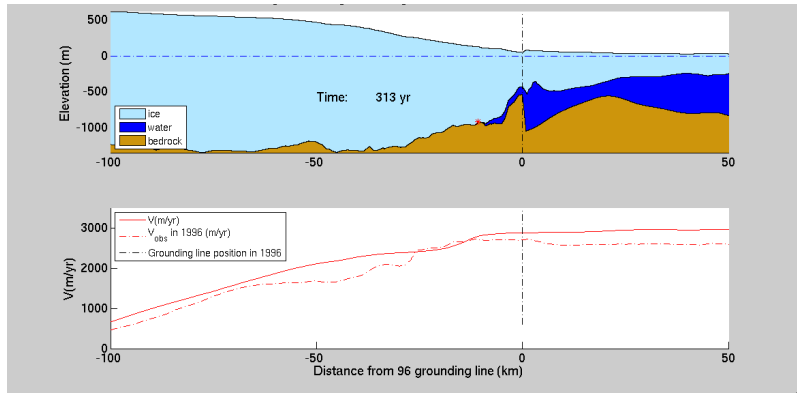
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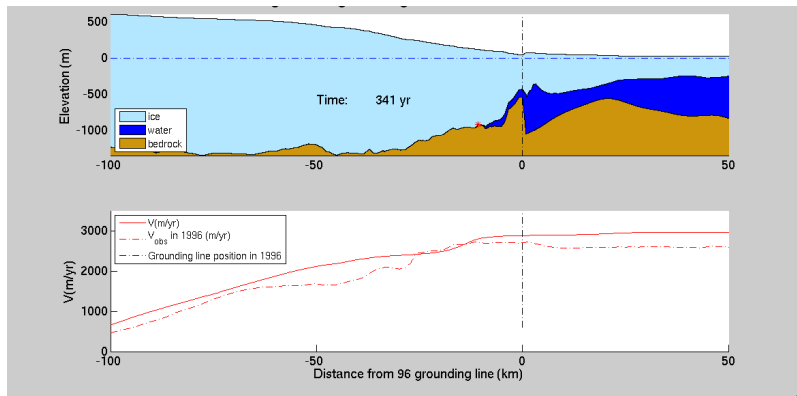
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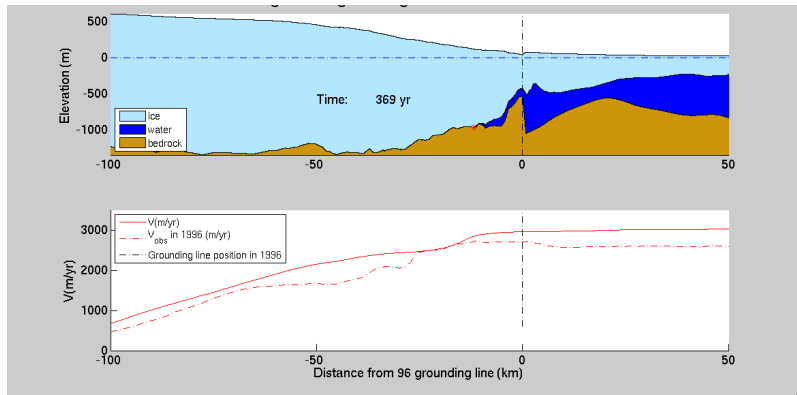
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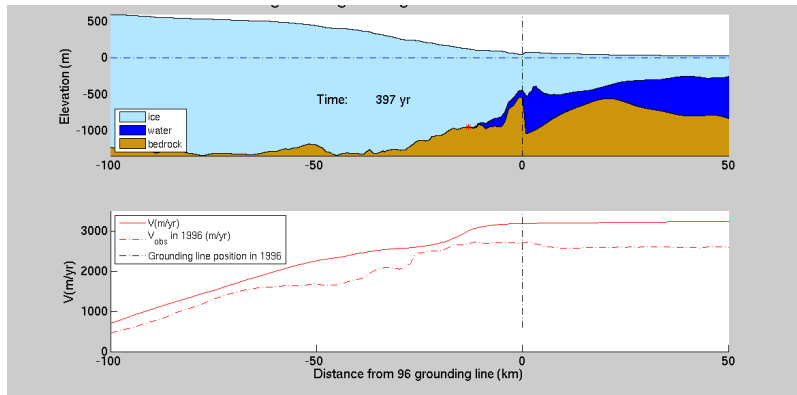
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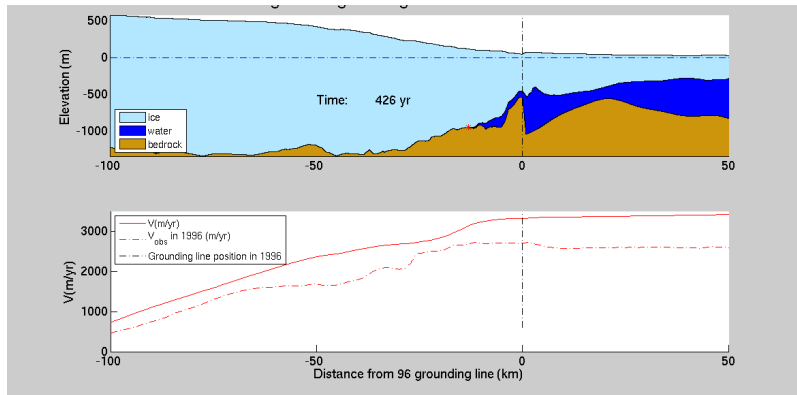
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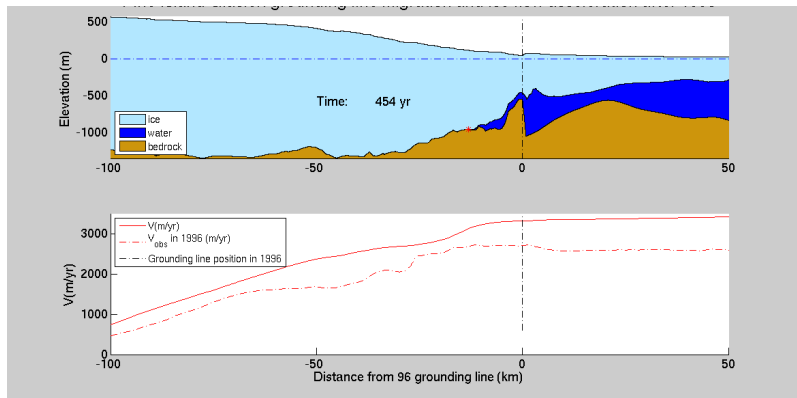
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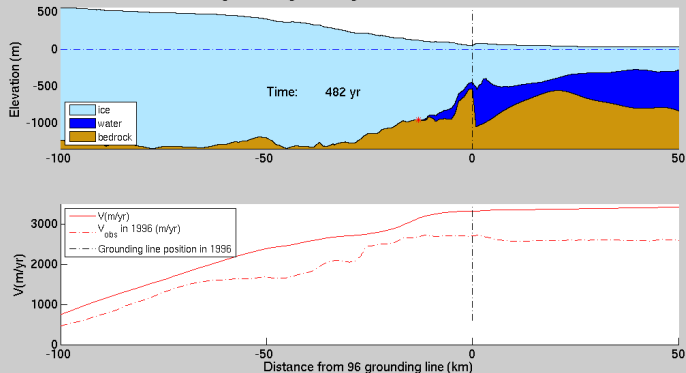
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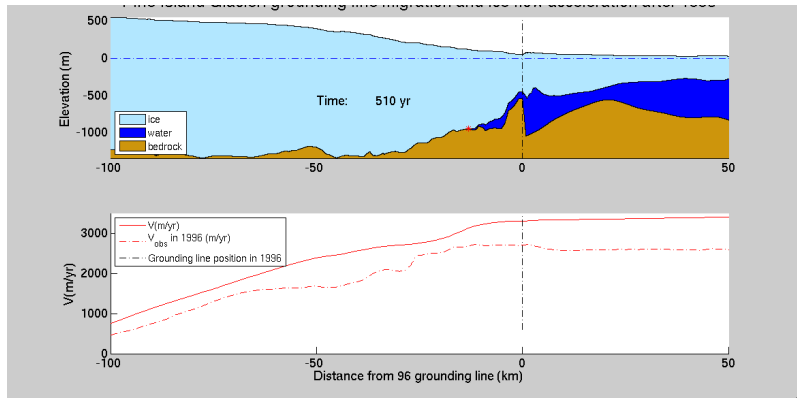
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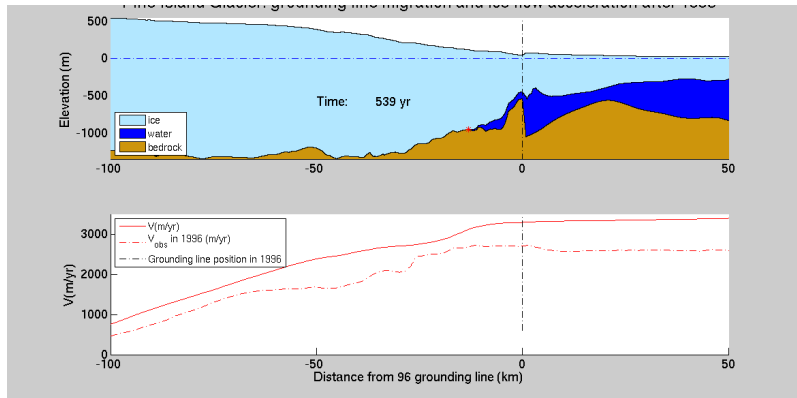
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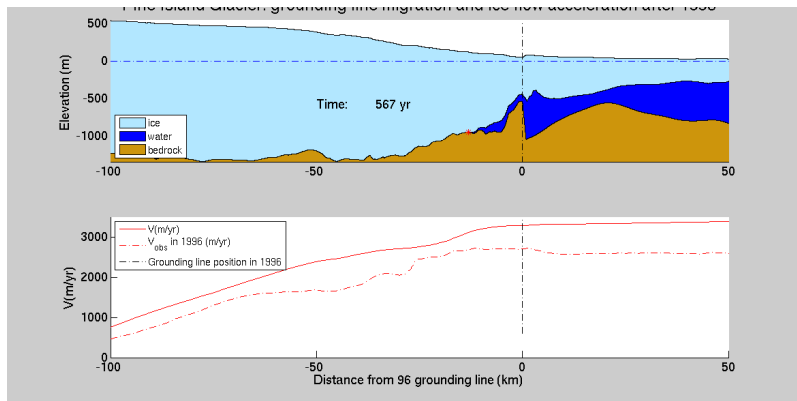
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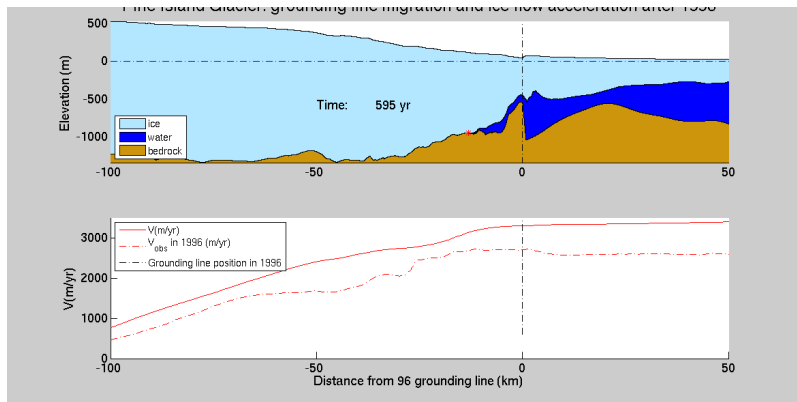
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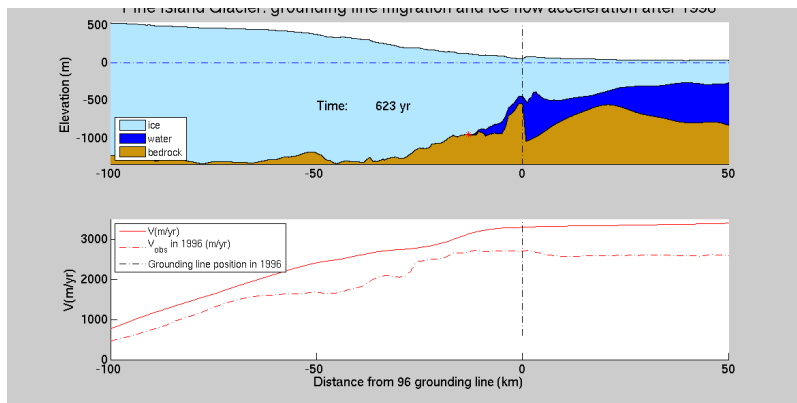
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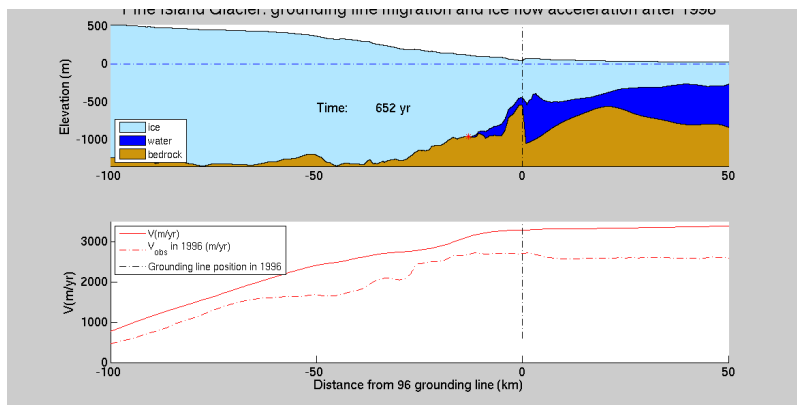
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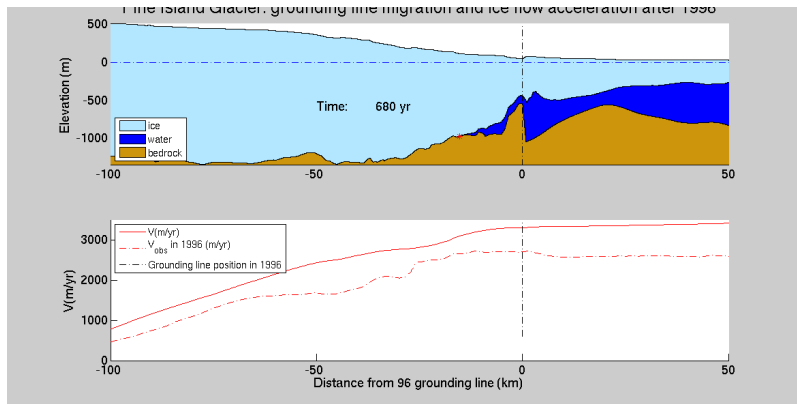
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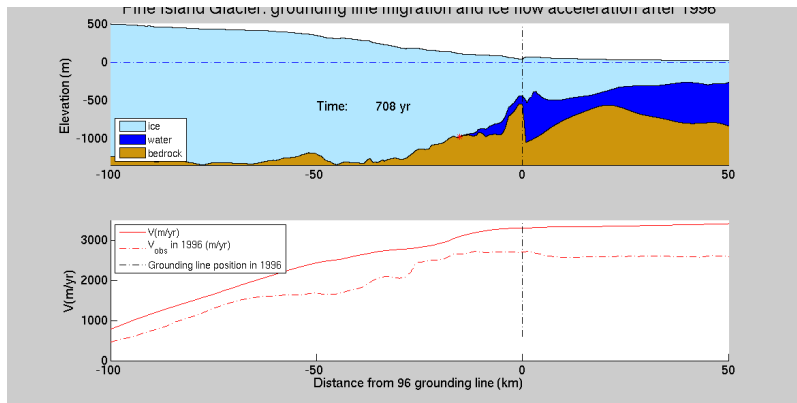
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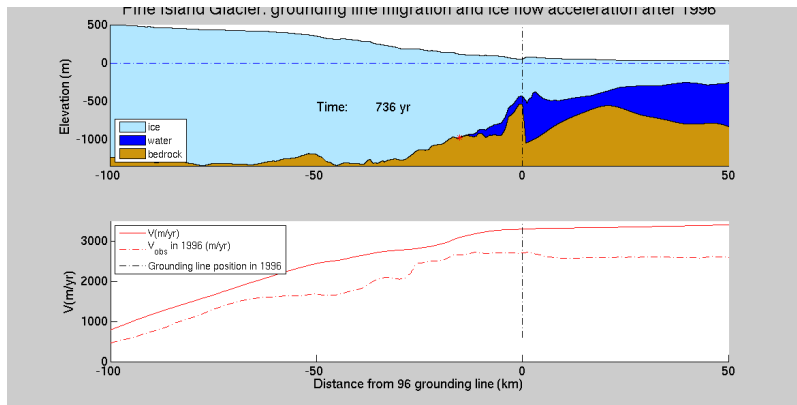
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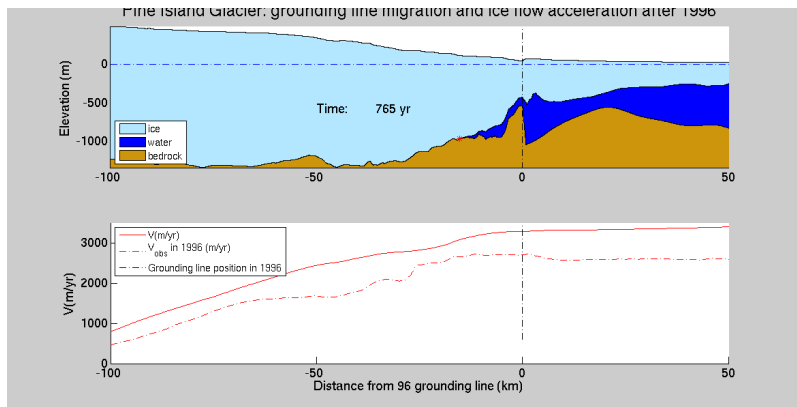
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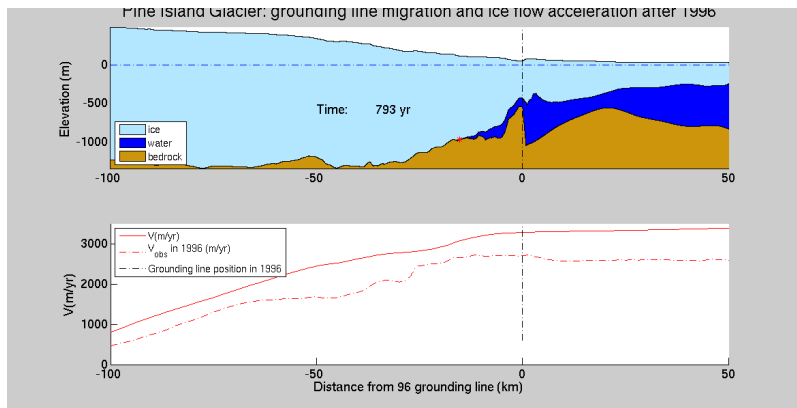
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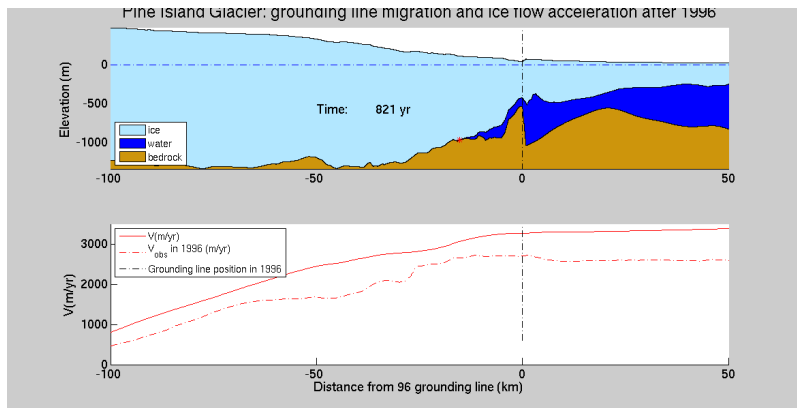
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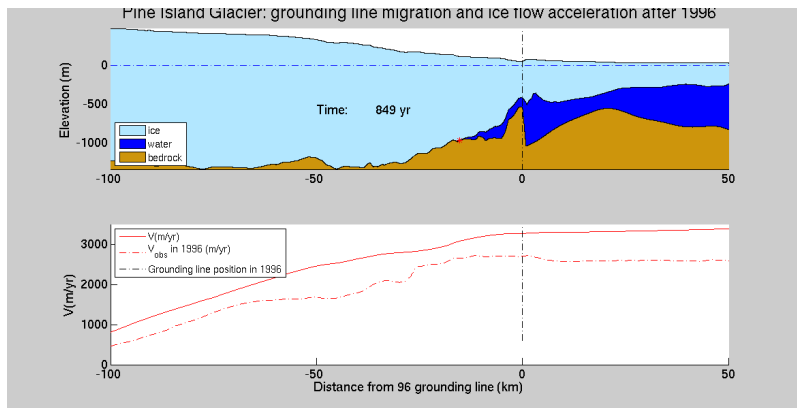
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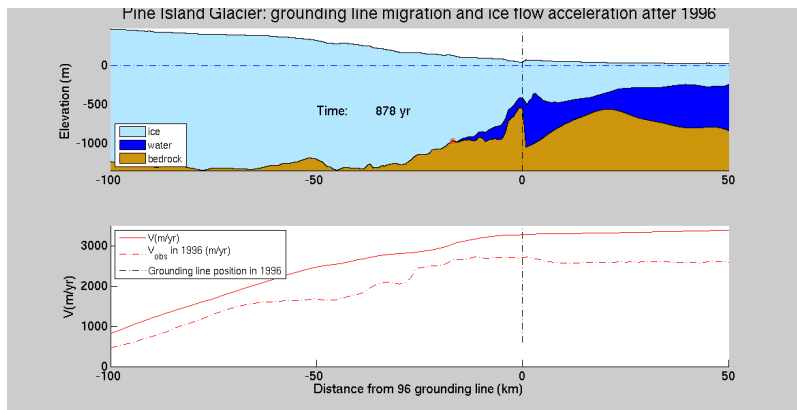
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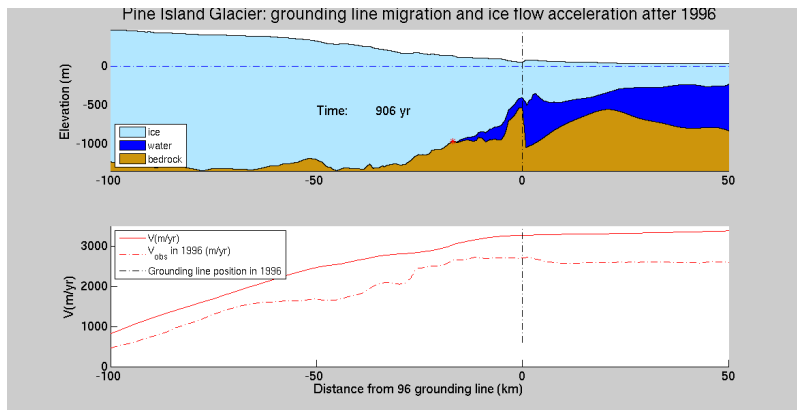
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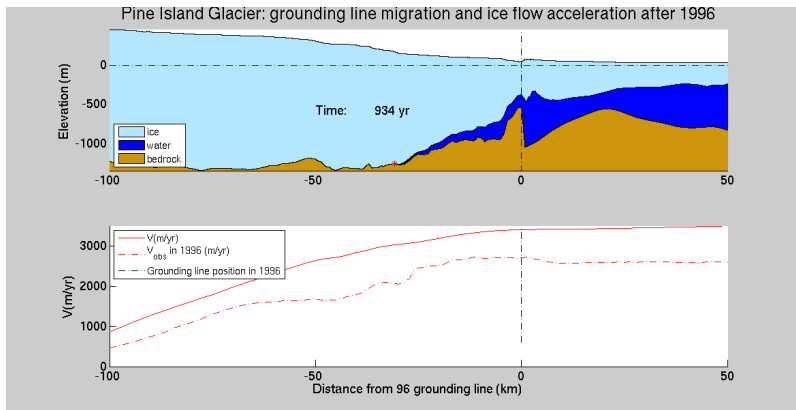
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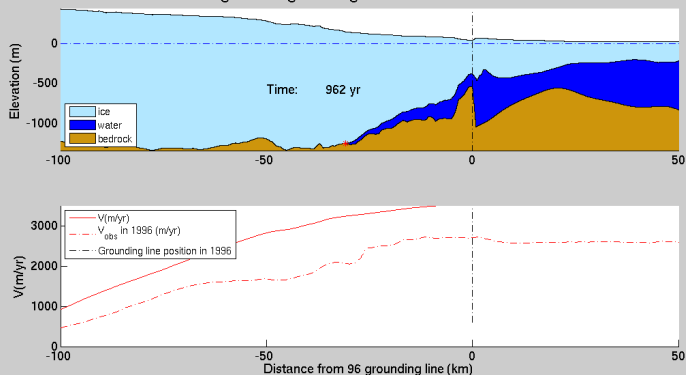
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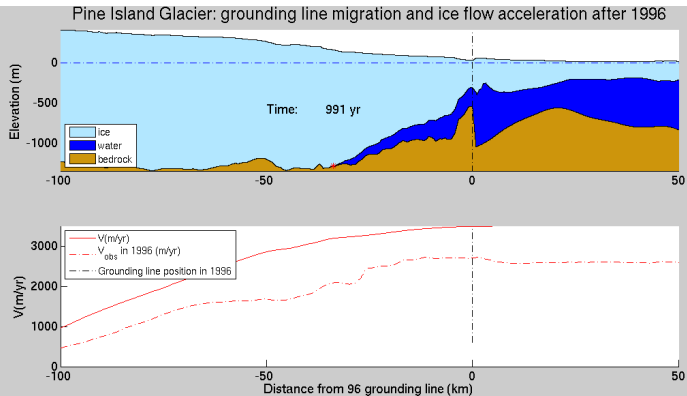
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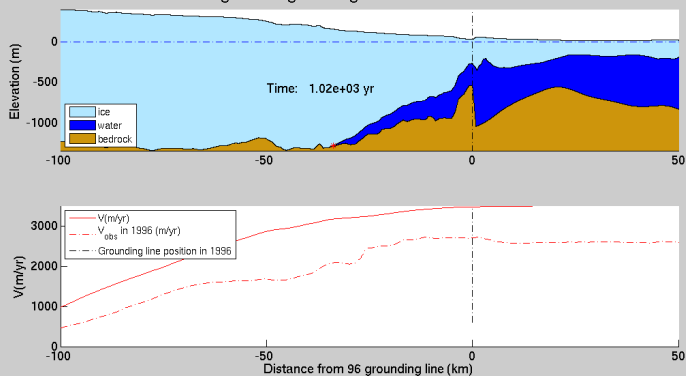
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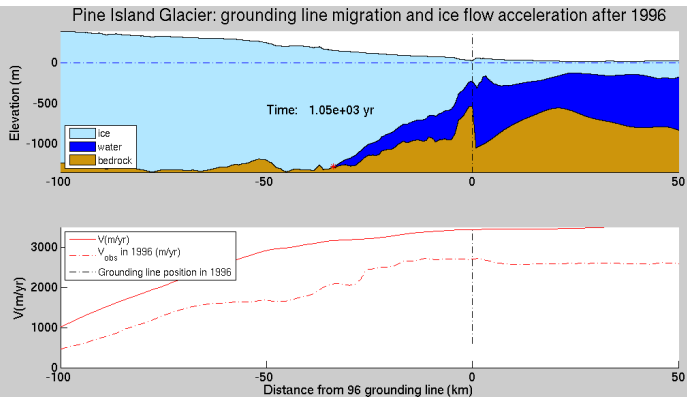
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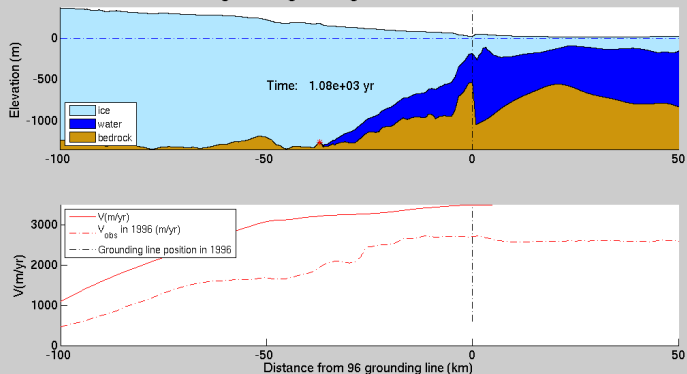
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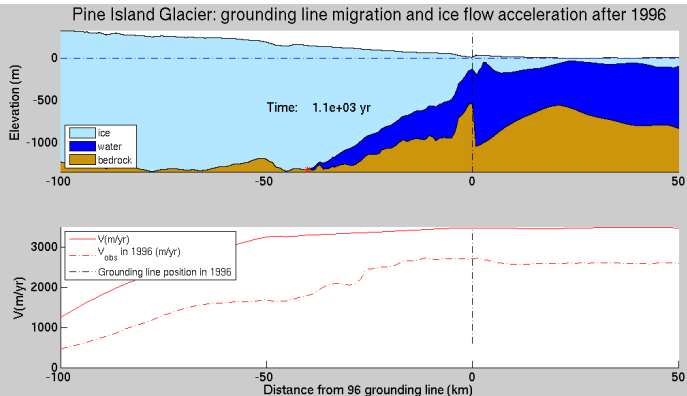
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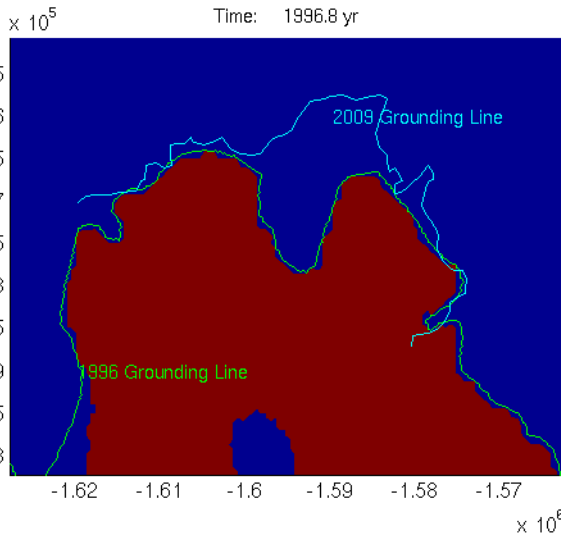
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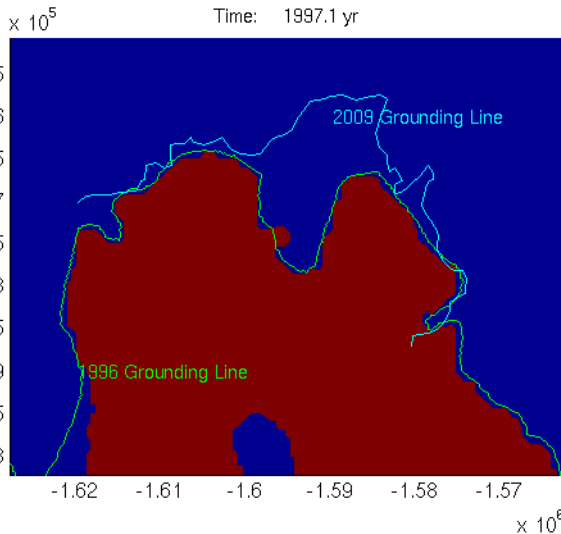
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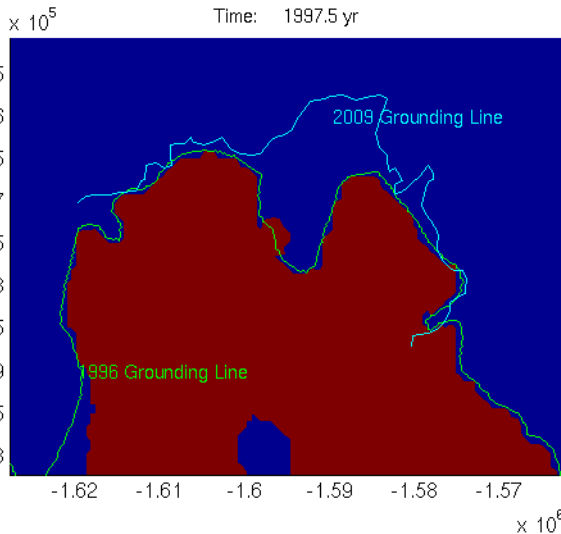
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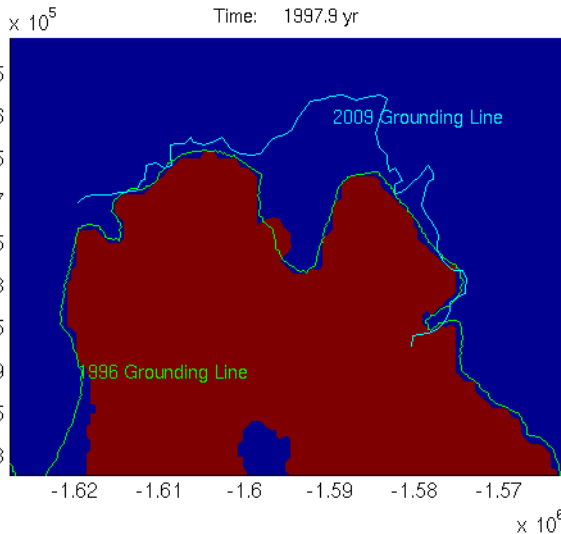
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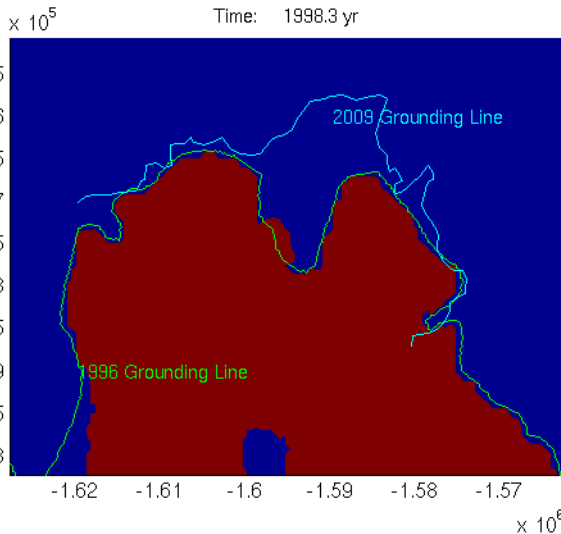
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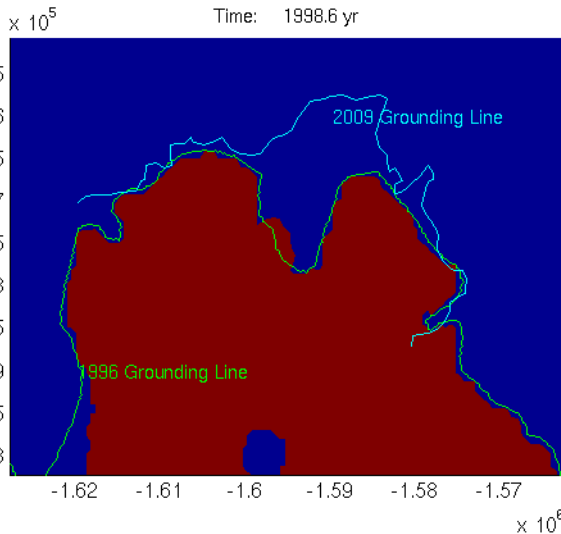
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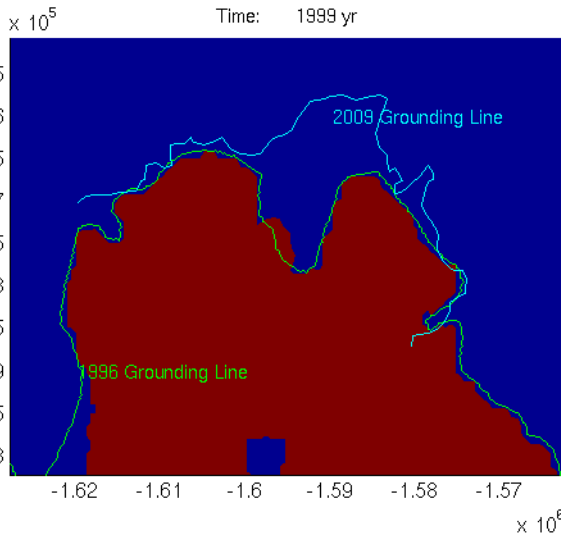
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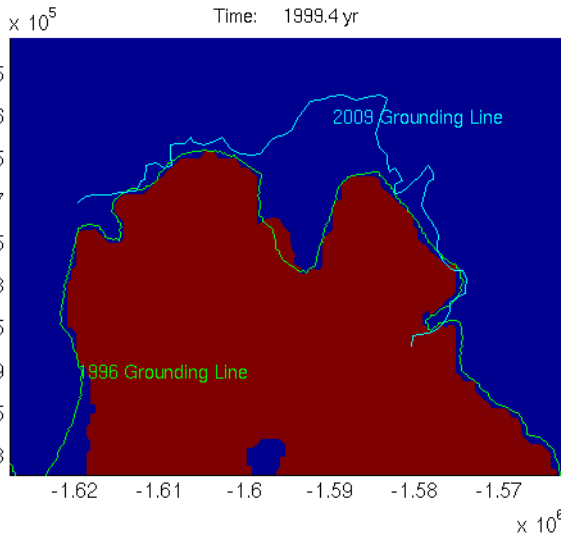
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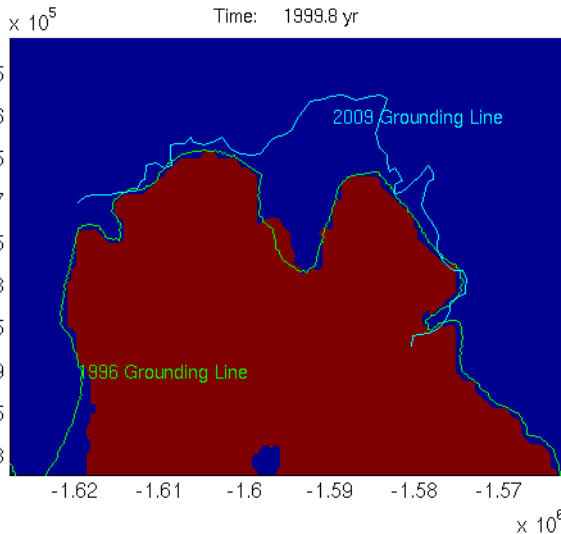
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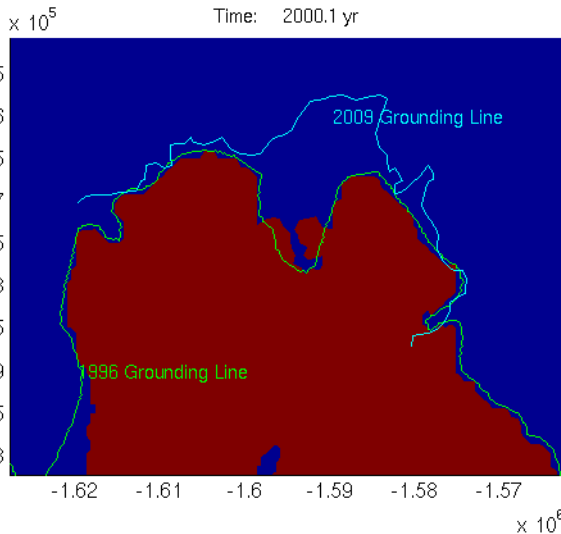
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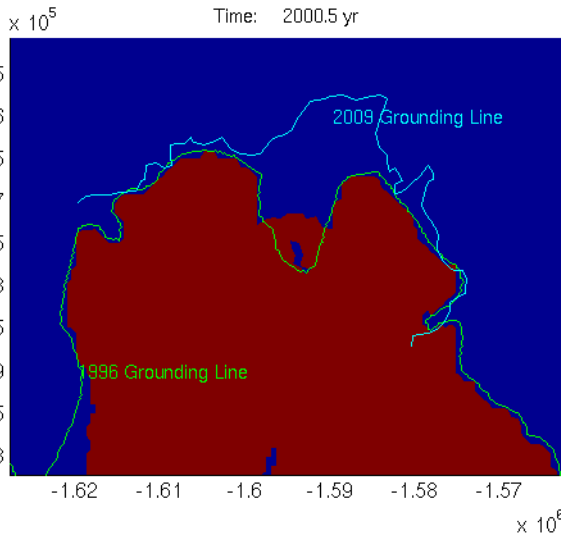
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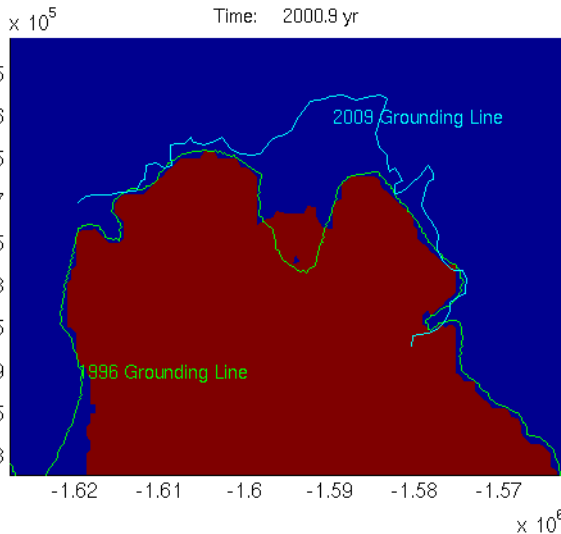
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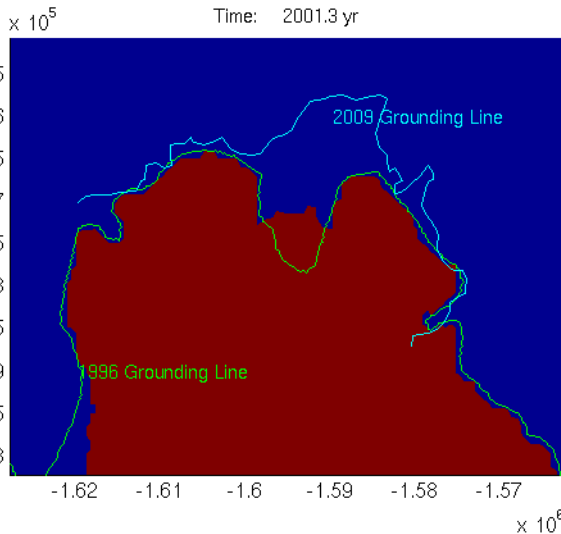
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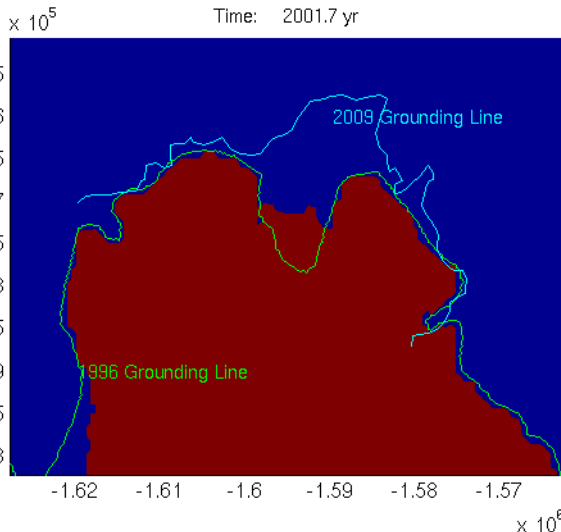
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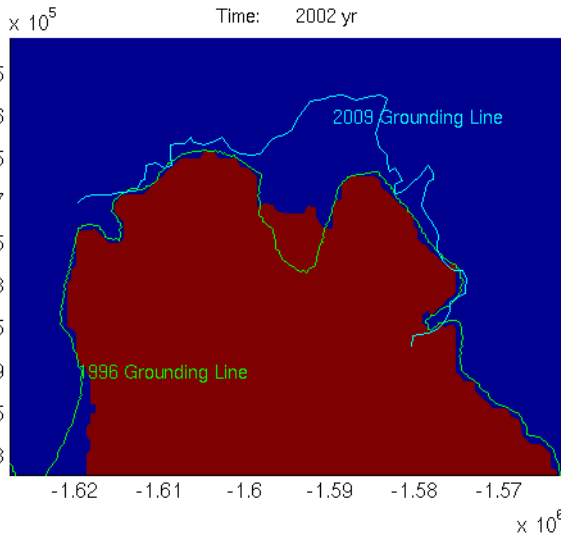
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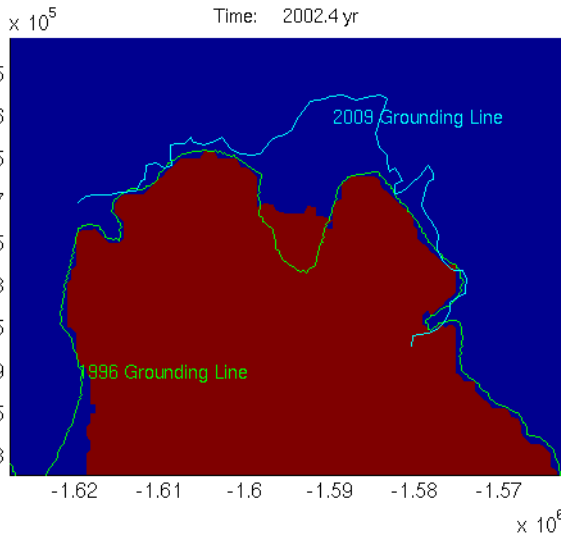
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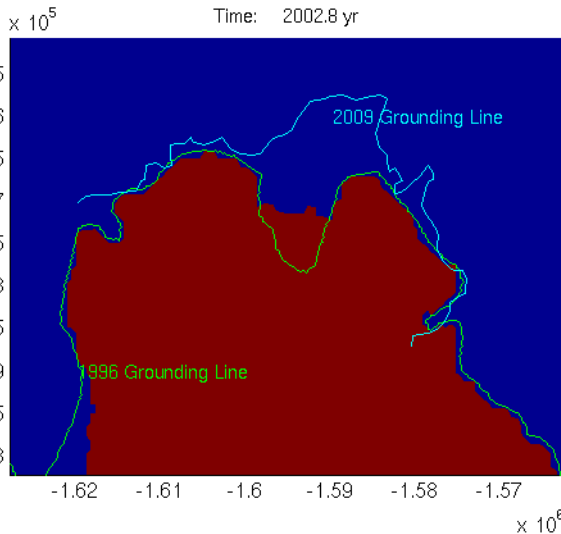
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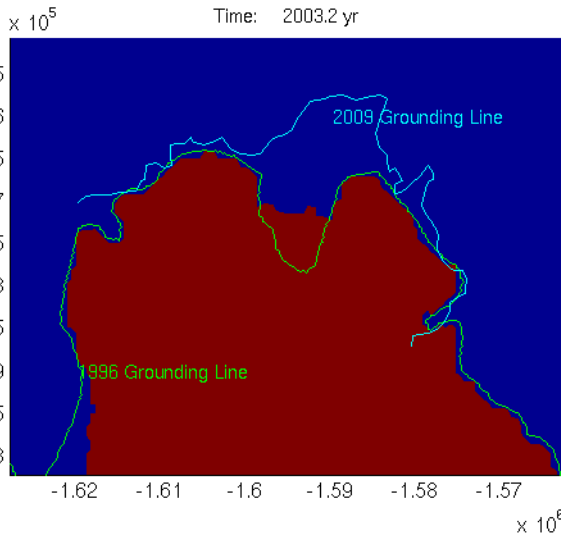
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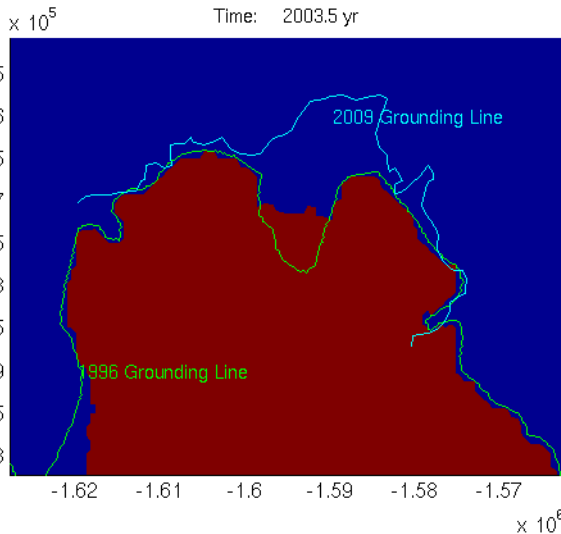
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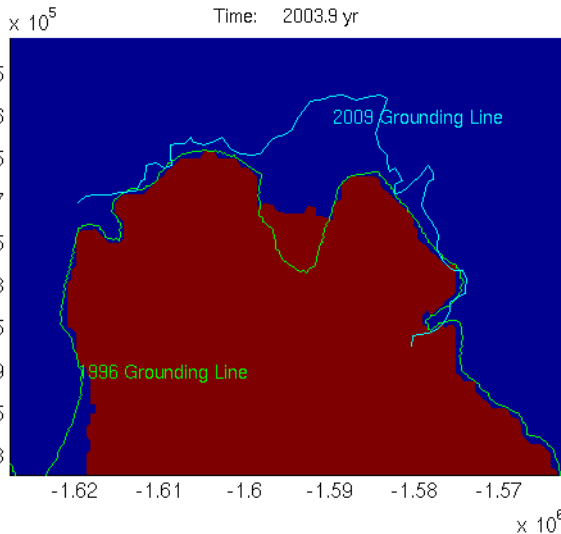
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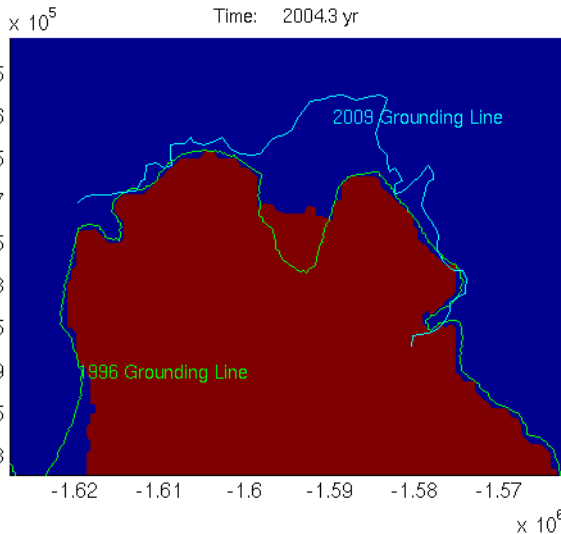
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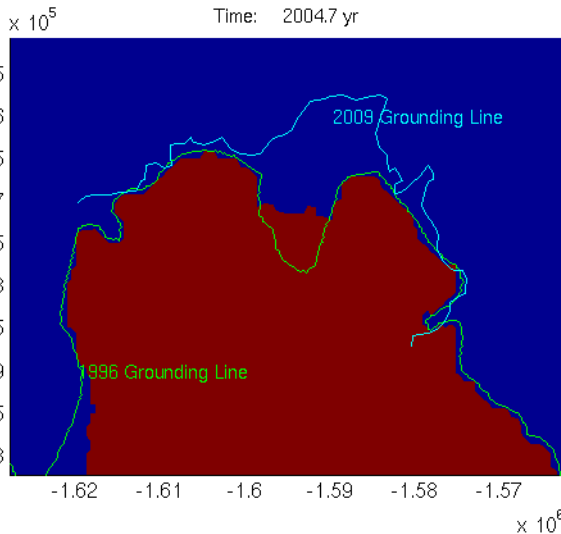
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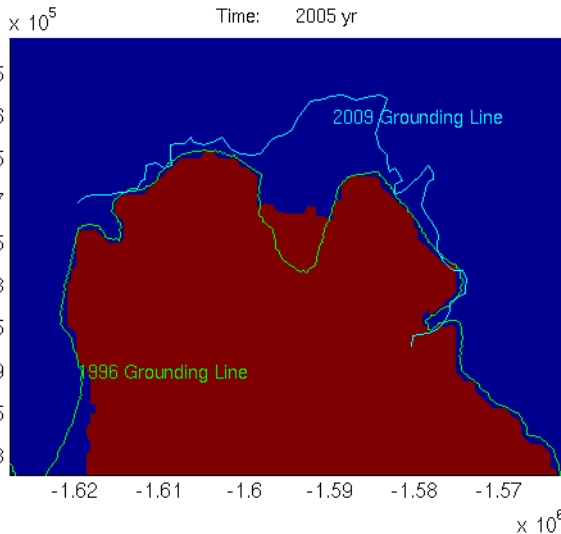
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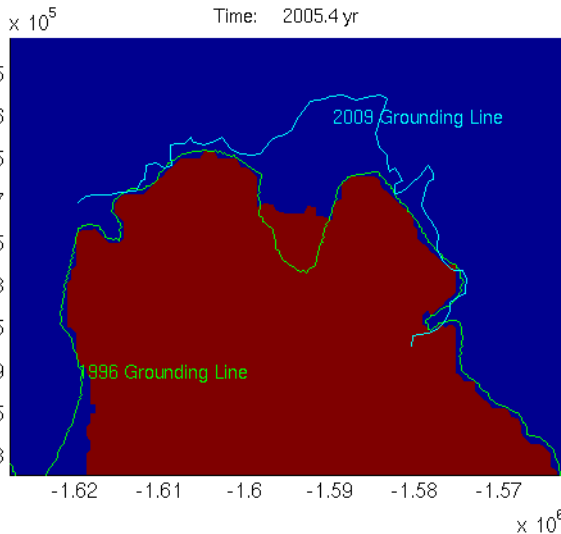
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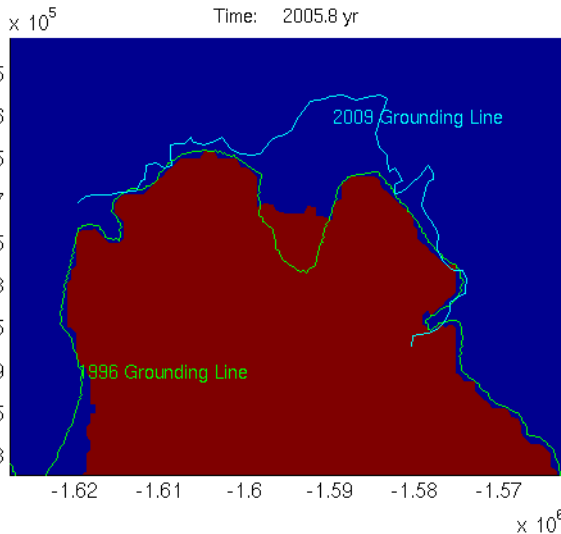
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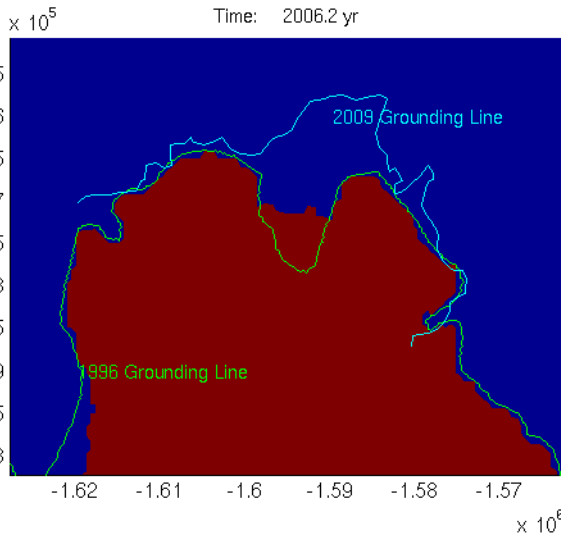
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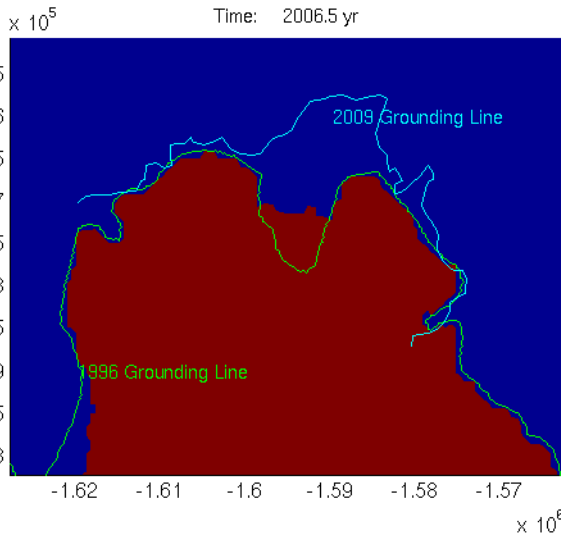
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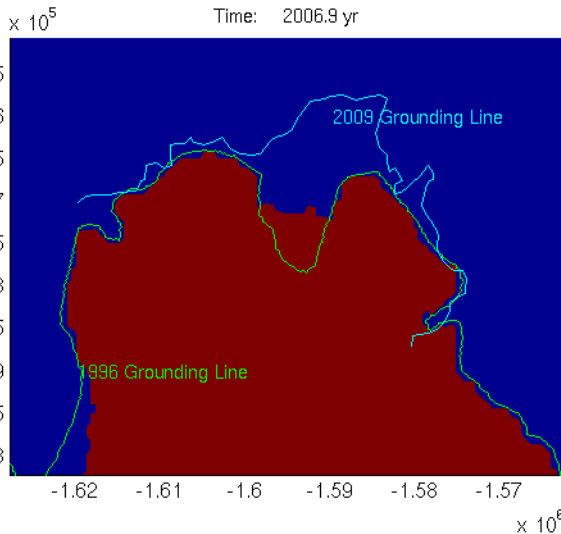
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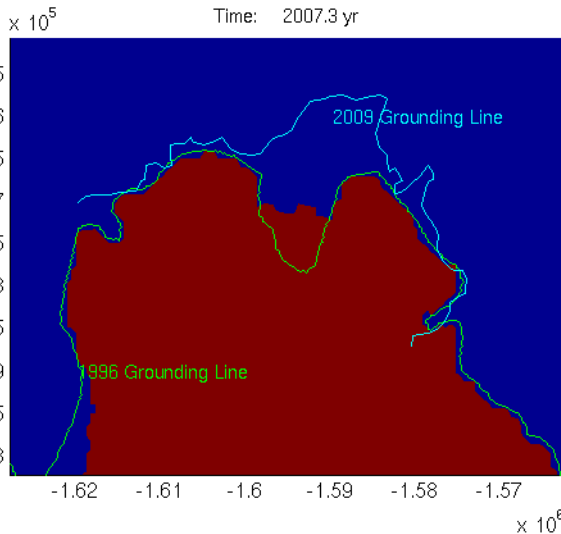
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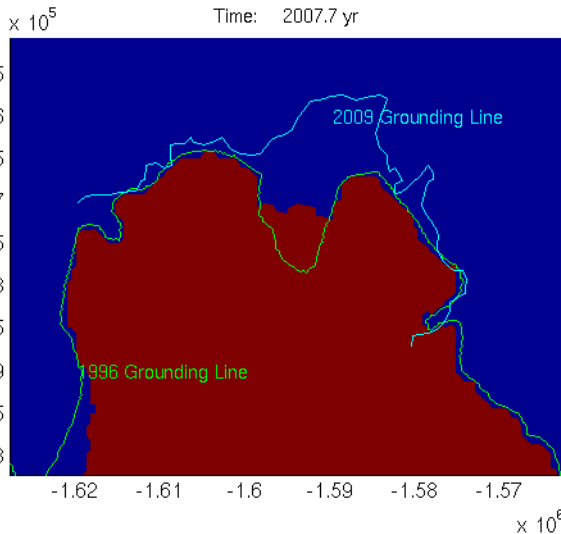
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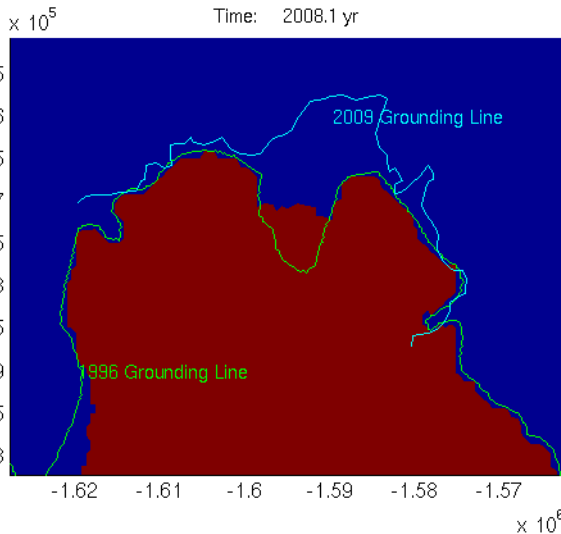
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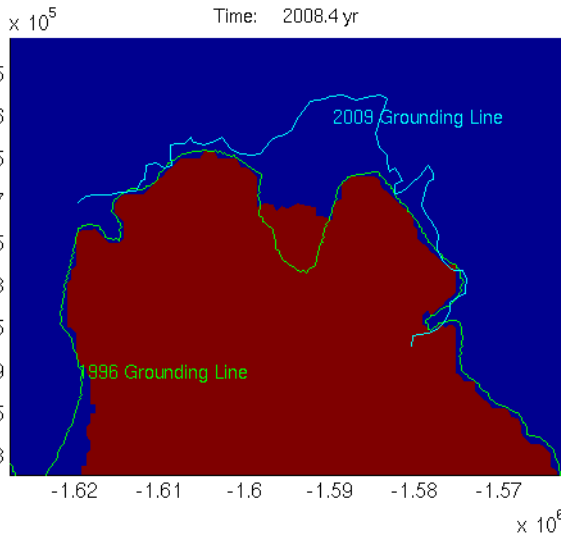
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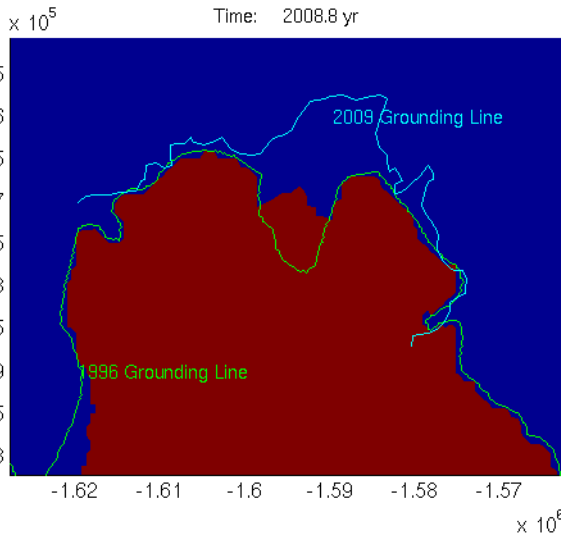
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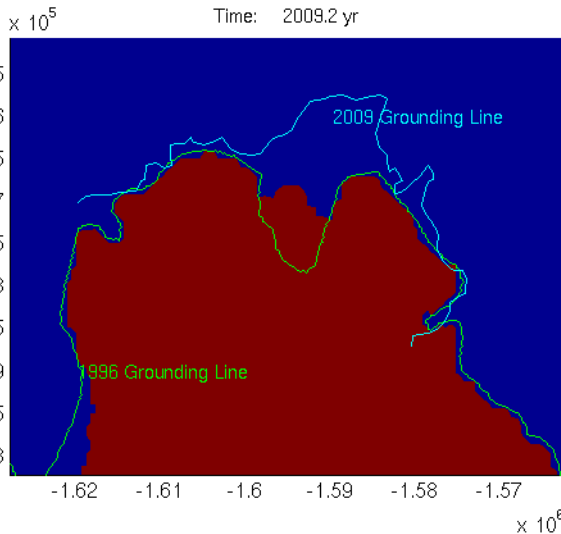
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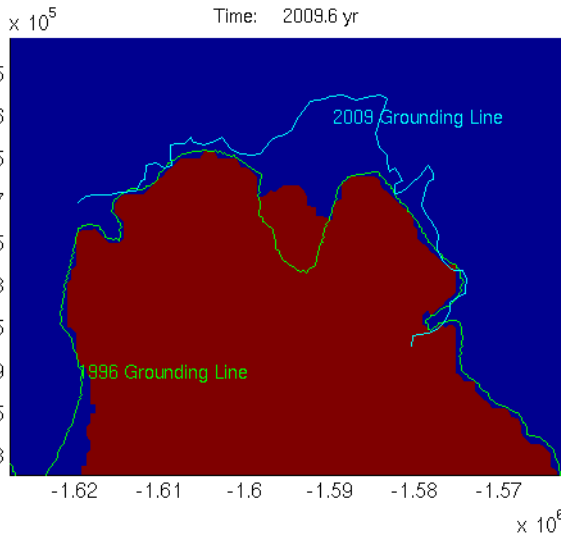
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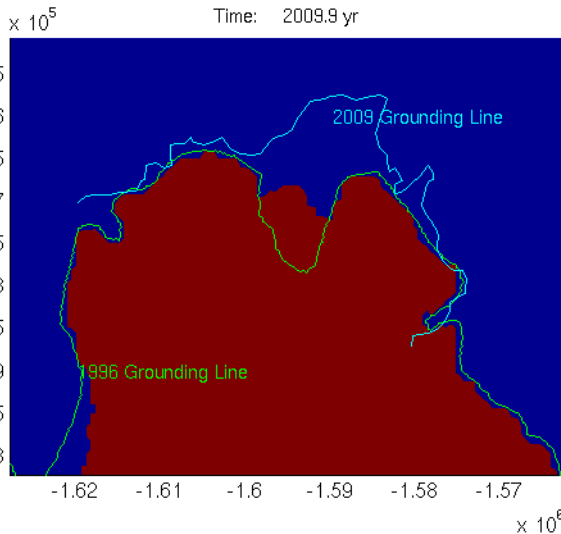
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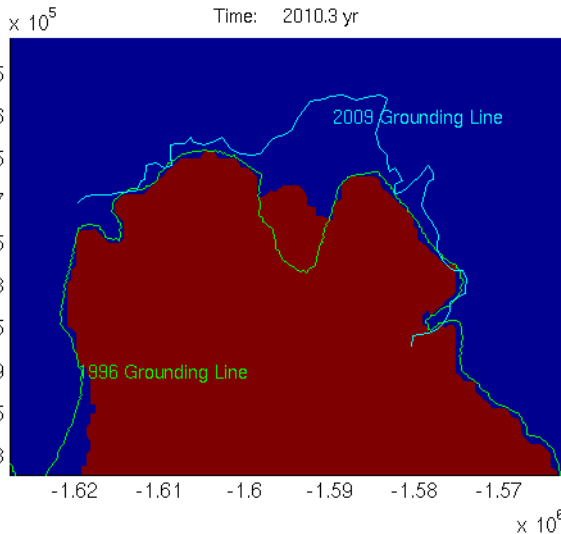
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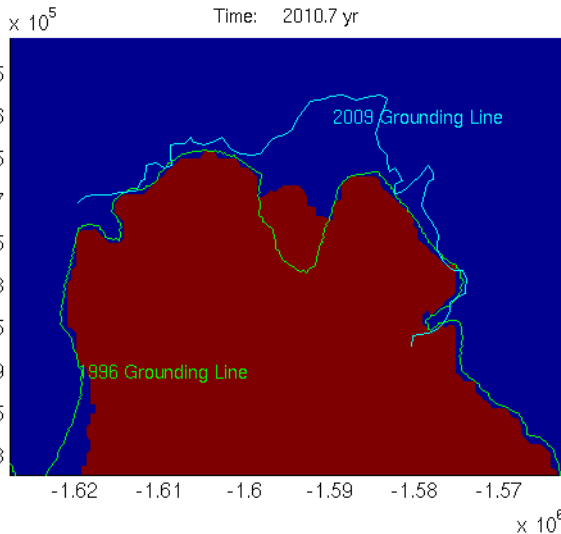
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[Le Brocq et al., 2009]: the evolution of the water-film thickness ( $w$ ) is given by:

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

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.

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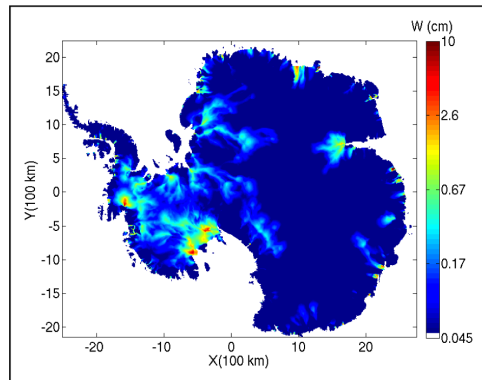
## Conclusions

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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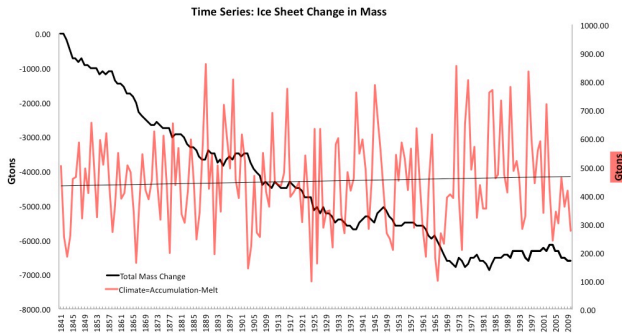
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ISSM now capable of transient forcing at the surface, using SMB time series (Schelegel et al., 2012, in revision).



In addition, new PDD model contributed by Kevin Le Morzadec.

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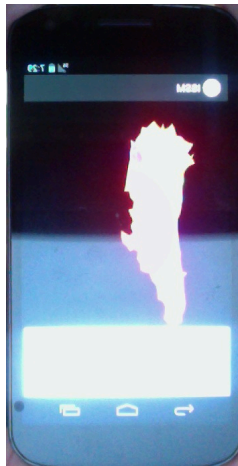
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- Python now supported as a new scientific toolkit.
- Windows XP64/Vista 64 supported in serial mode. Working towards parallel port. Packaging supported.
- Android support to run ISSM native.



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- Ice anisotropy not included (ice fabrics)
- Ice considered isotropic
- Cold ice model used in thermal model
- No polythermal ice
- Moving grounding line based on hydrostatic equilibrium
- Not implemented for full-Stokes (based on contact mechanics)
- Ice front and margins fixed in time, no calving law
- Calving rate equal to ice velocity

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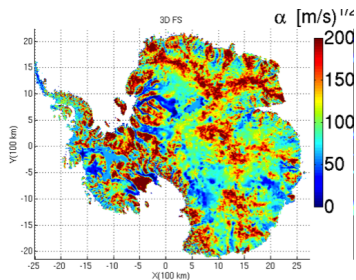
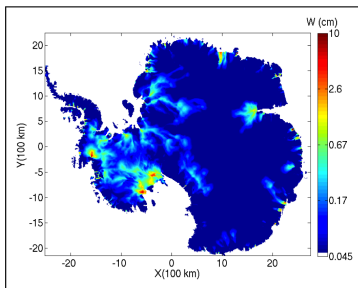
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- Basal friction fixed in time
  - Hydrology not coupled to basal friction
  - Sub-glacial hydrology only
- No englacial hydrology



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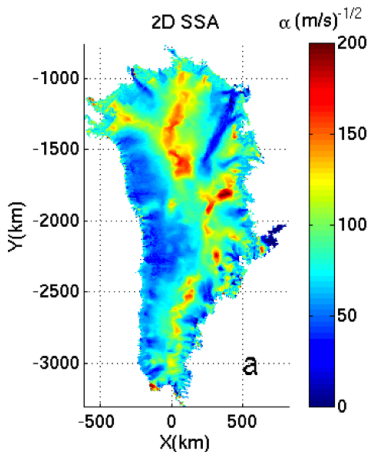
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Inversions limited to:

- Ice rheology
- Basal friction
- Ice thickness consistency with velocities

→ Assimilation for a given time

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Two way coupling to Atmosphere not implemented.

No surface model for atmospheric coupling. This will probably remain on the Atmospheric side.

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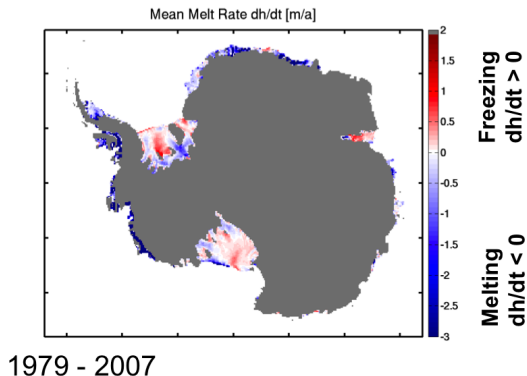
## Conclusions

## Ice/ocean interactions

Interaction between ice and ocean not included

- Melting rates under ice shelved prescribed
- Sea level fixed at  $z = 0$

→ ECCO3 project to couple ocean and ice models



Schodlok et al., submitted

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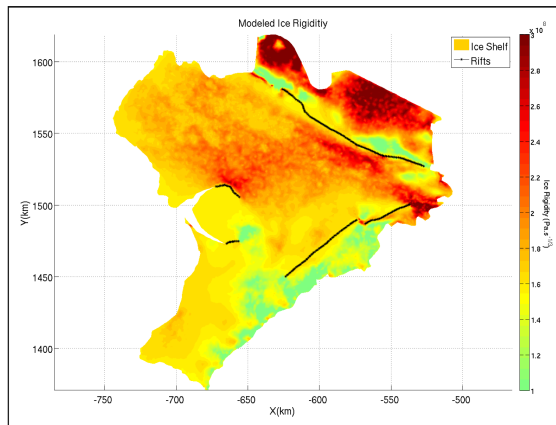
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- Post-glacial rebound: efforts to couple with PGR Model from Ivins et al, 1993.
- Rift propagation. Ongoing dvpt to include transient damage propagation.





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- Only triangle (2D) and prismatic (3D) elements
- No quadrangle elements
- Only P1 (piecewise linear nodal functions)
- No quadratic or higher-order interpolations
- Direct solver used for full-Stokes model
- No scalable solver (iterative solver). Ongoing work by Feras Habbal for scalable solvers using PETSc.

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- 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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## Capabilities

## Bibliography III

## Introduction

## Capabilities

Diagnostic Models  
Inversion  
Parallel Computing  
Rifting/Faulting  
Higher-order, Full-Stokes  
Anisotropic Adaptation  
Prognostic Models  
Thermal Analysis  
Sensitivity Analysis  
Ice Thickness Assimilation  
3D Hydrostatic Grounding  
Line Migration  
Hydrology  
Ice/Atmosphere Interaction  
Diverse software developments.

## What ISSM cannot do

Ice flow models  
Basal conditions  
Inversion and data assimilation  
Ice/atmosphere interactions  
Ice/ocean interactions  
Other capabilities  
Numerics

## Conclusions



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## Capabilities

## Bibliography IV

## Introduction

## Capabilities

Diagnostic Models

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Rifting/Faulting

Higher-order, Full-Stokes

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## What ISSM cannot do

Ice flow models

Basal conditions

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Thanks!

