

# ice2sea MISMIP<sup>3D</sup> intercomparison experiments

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## Note

Changes with respect to the previous description of experiments are shown in bold.

## 1 Description of prognostic experiments

### 1.1 Standard experiment – Stnd

The standard experiment is comparable to the MISMIP experiment, but with a different slope and origin. There are no lateral variations in  $y$ . The aim of this experiment is to verify the model with analytical solutions from Schoof (2007). The result of the run should give similar results as for the flow line case, since this is an extruded version of it. The bedrock elevation is defined by a sloping plane in the flow ( $x$ ) direction:

$$b = -100 - x \tag{1}$$

where  $b$  (m) is the bedrock elevation (positive above sea level) and  $x$  is the horizontal coordinate in the flow direction (in km). The standard parameters are similar to those of MISMIP and summarized in Table 1.

**The basic value for accumulation rate is  $\dot{a} = 0.5$ , but due to an error in the model experiment description file v1, experiments are now carried out for  $\dot{a} = 0.5$  and  $0.3 \text{ m a}^{-1}$ , respectively, where the value of  $0.5$  is considered the standard value.** Sliding is described by a power law linking basal shear stress  $\tau_b$  to sliding velocity  $u_b$ :  $\tau_b = C|u_b|^{m-1}u_b$ , with  $C$  and  $m$  constant.

#### 1.1.1 Domain size and boundary conditions

The domain is taken rectangular with  $x$  (flow direction) stretching from 0 to 800 km and  $y$  (transverse direction) from 0 to +50 km (Figure 1) on which the ice sheet is grown.

Flow parameter	$A$	$10^{-25} \text{ Pa}^{-3} \text{ s}^{-1}$
Seconds per year		$3600 \times 24 \times 365 \text{ s a}^{-1}$
Gravitational acceleration	$g$	$9.8 \text{ m s}^{-2}$
Ice density	$\rho$	$900 \text{ kg m}^{-3}$
Water density	$\rho_w$	$1000 \text{ kg m}^{-3}$
Glen index	$n$	3
Specific mass balance	$\dot{a}$	$0.5 / 0.3 \text{ m a}^{-1}$
Sliding rate	$C$	$10^7 \text{ Pa m}^{-1/3} \text{ s}^{1/3}$
Sliding coefficient	$m$	$\frac{1}{3}$

Table 1: MISMIP<sup>3D</sup> constants.

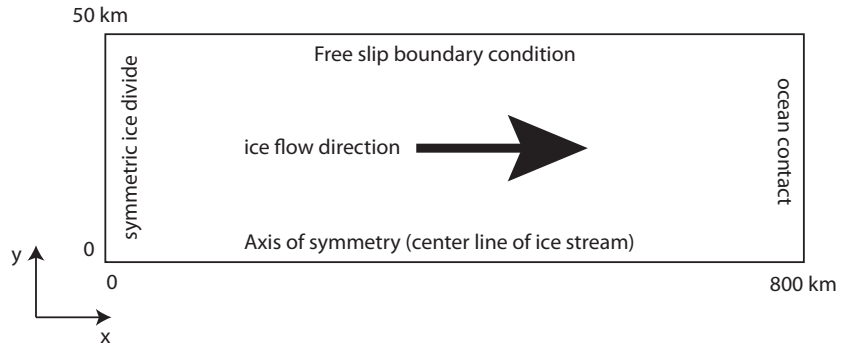


Figure 1: MISMIP<sup>3D</sup> domain.

Boundary conditions are a symmetric ice divide at  $x = 0$ , so that  $\frac{\partial h}{\partial x} = \frac{\partial z_s}{\partial x} = 0$ , where  $h$  is the ice thickness (m),  $z_s = z_b + h$  is the surface elevation and  $z_b$  is the lower boundary of the ice sheet ( $z_b = b$  when the ice sheet is grounded). In view of the initial bedrock topography, growing an ice sheet on this domain automatically guarantees the presence of an ice shelf at the downstream part. Therefore, at the ocean boundary of the ice shelf ( $x=800$  km), the outward pressure is partially balanced by the hydrostatic sea water pressure.

Two different lateral boundary conditions are applied. At  $y=50$  km, we have a free-slip boundary condition, resulting from a plane strain condition. Since we consider a symmetrical ice stream, a symmetry axis is introduced at  $y=0$  km, which gives the other lateral boundary condition. Therefore, only half a stream is simulated which considerably reduces the computer resources.<sup>1</sup> Boundary conditions are graphically depicted in Figure 1.

### 1.1.2 Stnd run

Starting from the initial setup (or an extrusive version of the flowline case), run the model under the appropriate boundary conditions and parameter settings until a steady state is reached. Numerical parameters, such as grid size, time step and integration period are to be chosen by each modeler, as long as the results are comprehensive and (as) independent (as possible) of the chosen grid size and time step. Figure 2 displays the resulting geometry (run here with a finite-difference shallow-shelf model, with  $(\Delta x, \Delta y) = 2.5$  km).

## 1.2 Basal sliding perturbation I – P75S

This experiment starts from the geometry obtained from *Stnd*. A basal sliding perturbation is introduced, precisely at the grounding line, centered on the axis of symmetry (at  $y=0$  km). It is therefore important to determine the position of the grounding line as accurate as possible. The sliding perturbation is defined by a Gaussian bump, i.e.

$$C^* = C \left[ 1 - a \exp \left( -\frac{(x - x_b)^2}{2x_c^2} - \frac{(y - y_b)^2}{2y_c^2} \right) \right] \quad (2)$$

where  $C^*$  is the perturbed basal sliding coefficient,  $a=0.75$  is the perturbation amplitude (a perturbation of 75%),  $x_b$  is the precise position of the grounding line at  $y=0$  km obtained from *Stnd*,  $y_b = 0$  km,  $x_c=150$  km, and  $y_c=10$  km. These parameters determine the spatial extension of the Gaussian perturbation.

Applying this perturbation to the basal sliding function, the model is run forward in time for 100 years. The perturbation will result in a general grounding line advance of approximately 20–25 km on the axis of symmetry and a thinning

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<sup>1</sup>The symmetry axis implies that  $\frac{\partial h}{\partial y} = \frac{\partial z_s}{\partial y} = \frac{\partial b}{\partial y} = 0$ , similar to the ice divide. Models that have a difficulty to impose a symmetry axis can model the domain from  $y = -50$  to  $+50$  km and apply a free-slip boundary condition at either side. They then output only half of the ice sheet.

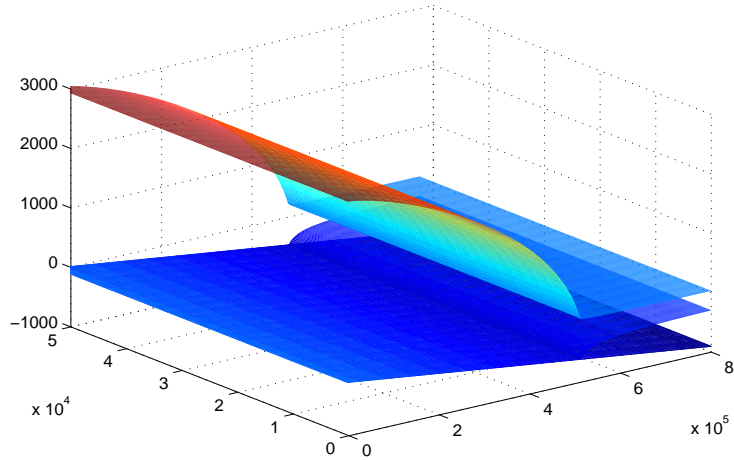


Figure 2: MISIMP<sup>3D</sup> initial setup: result of Stnd.

of the grounded ice sheet. An example of such a grounding line change is given in Figure 3.

### 1.3 Basal sliding perturbation II – P10S

Similar as the previous experiment, but with a perturbation amplitude of  $a=0.10$ . The reason for this experiment is that when the grounding line is too curved, as is the case with P75S, the advance leads to compression. This invalidates the assumptions used in Schoof (2007).

### 1.4 Test of reversibility – P75R and P10R

Based on the work by Schoof (2007), we know that for an ice sheet resting on a linearly sloping bedrock, a perturbation in flow parameters (such as basal sliding) is reversible. This experiment aims at proving this for the numerical model solution. Starting from the configuration obtained in the prognostic experiment P75S/P10S (perturbation after 100 years), remove the perturbation  $C^*$  and apply the original  $C$ . Let the model run in steady state or at least long enough so that the grounding line is not moving anymore. The resulting configuration should be equal to the original setup obtained with Stnd.

### 1.5 Other tests

Other tests with respect to basal melting and buttressing will follow and will be described in subsequent versions of this document. Whenever they will be ready, they will be posted on the website.

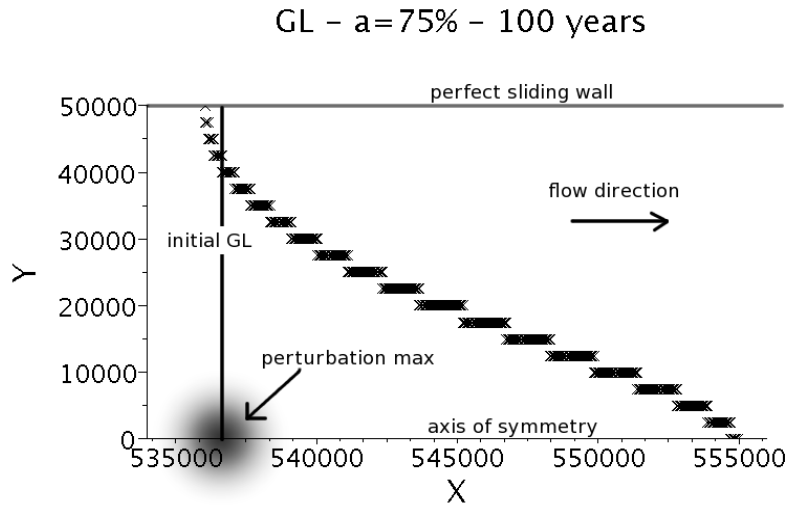


Figure 3: MISMIP<sup>3D</sup> P75S: plot of initial grounding line corresponding to *Stnd* (line) and the grounding line position across the ice stream due to the perturbation after 100 years (crosses). Experiment carried out with *Elmer/Ice*.

## 2 Description of diagnostic experiments

The aim of the diagnostic experiment is to directly test the numerical models approximating the Stokes equations with a high-resolution full Stokes Model (*Elmer/Ice*).

### 2.1 Diagnostic basal sliding perturbation – P75D and P10D

We start from a P75S/P10S solution produced with *Elmer/Ice*, which does not necessarily correspond to the perturbed solution produced by any other numerical ice sheet model. How to access the input files is described in Section 3. For this *Elmer/Ice* geometry, defined by  $h$ ,  $b$ , and  $z_b$ , compute the corresponding velocity field in a diagnostic fashion (no computation of  $\frac{\partial h}{\partial t}$ ). For the basal sliding perturbation (Eq. 2), the precise initial grounding line position in this experiment equals  $x_b = 537078$  m. The input files can be downloaded from the website (*Elmer75D.dat* and *Elmer10D.dat*).

## 3 Input and output files

### 3.1 *Elmer/Ice* input file for diagnostic experiment

The *Elmer/Ice* input file gives enough information on the geometry of the perturbation experiment produced with this model. Since results are on an unstructured grid, each modeler should adapt this geometry to his/her own needs. How-

Experiment	# files
Stnd	2
P75S	$2 \times 100$
P10S	$2 \times 100$
P75R	$2 \times 100 + 2$
P10R	$2 \times 100 + 2$
P75D	2
P10D	2

Table 2: Number of output files per experiment.

ever, for fixed grid models, a simple Matlab script to interpolate the Elmer/Ice data on a regularly-spaced grid is given in Appendix B.

The input file is an ASCII file containing 5 columns providing the geometry. The structure is  $x$ ,  $y$ ,  $h$ ,  $z_b$  (all in m), and MASK (having a value of 1, -1, 0, corresponding to nodes that are grounded, floated or the grounding line, respectively). The bedrock elevation  $b$  can be determined directly from (1).

### 3.2 Output files

Each experiment will give rise to sets of two output files, one output file covering the whole domain, similar to the input file described above, and one file describing parameters along the grounding line. All files are ASCII and either tabular-limited or space-limited. CSV (Comma Separated Values) or any other format are not accepted.

With exception of the standard experiment **Stnd**, which only outputs 2 files, output files are given every year, i.e.  $100 \times 2$  files. For the reversibility experiment another set of files is added for the steady state case. Diagnostic experiments also result in one set of two files (see Table 2).

#### 3.2.1 Whole domain output file

The first output file is an ASCII file containing 13 columns, of which only the first four provide the geometry. The structure is  $x$  (1),  $y$  (2),  $h$  (3),  $z_b$  (4) (all in m), MASK (5) (1 for grounded ice, 0 for grounding line, -1 for ice shelf),  $v_x(b)$  (6),  $v_y(b)$  (7),  $v_z(b)$  (8) (the three components of the basal velocity field, in  $\text{m a}^{-1}$ ),  $v_x(s)$  (9),  $v_y(s)$  (10),  $v_z(s)$  (11) (the three components of the surface velocity field, in  $\text{m a}^{-1}$ ),<sup>2</sup>  $\frac{\partial z_b}{\partial t}$  (12),  $\frac{\partial z_s}{\partial t}$  (13) (the imbalance rate at the base and the surface, respectively).

<sup>2</sup>Vertically integrated models fill up the columns with repeated values of the vertical mean velocity.

### 3.2.2 Grounding line output file

The second output file concerns variables along the grounding line. For models that interpolate a grounding line position between grid points, all variables should be mapped (interpolated) onto the grounding line. The output file contains a list of variables corresponding to positions  $x$ ,  $y$ . The file has 11 columns, i.e.,  $x_g$  (1),  $y_g$  (2) (the position of the grounding line in m),  $h_g$  (3), ice thickness at the grounding line,  $u_b$  (4),  $v_b$  (5) (horizontal velocity components at the base),  $u_s$  (6),  $v_s$  (7) (horizontal velocity components at the surface), and  $\bar{u}$  (8),  $\bar{v}$  (9) (vertical mean horizontal velocity components).

Columns 10 and 11 should contain the buttressing factor  $\theta$  (10) and the **tangential traction** across the grounding line (11), calculated at the grounding line. More details on the calculation of these parameters is given in Appendix A.

### 3.3 File naming

The general format of the output files is an alpha-numeric string of the following format: NNNxMMMMOOOy.dat, where:

**NNN**: is a three-letter acronym of the modeler composed of the first letter of the first name and the first two letters of the last name.

**x**: the model number (each modeler may have several models to submit)

**MMMM**: experiment type: Stnd, P75S, P75D, P75R, etc.

**OOO**: time slice: either a number between 001 and 100 or 'sst' for the steady state output files or the diagnostic experiments.

**y**: output file type: 'a' for the whole domain output file and 'b' for the grounding line file.

#### 3.3.1 Examples

- FPA1P75Dssta.dat: Whole domain output file from Frank Pattyn (model 1) for experiment P75D
- GDU1P10S051b.dat: Grounding line output file from Gael Durand (model 1) for experiment P10S at  $t=51$  years

## References

Schoof, C., 2007. Ice sheet grounding line dynamics: Steady states, stability and hysteresis. *J. Geophys. Res.* 112 (F03S28), doi:10.1029/2006JF000664.

## A Stresses at the grounding line

It is worth understanding how the different ways of solving the mechanical equations in the grounding line vertical boundary layer affect the results, and we request participant to provide sufficient information to relate their calculations to the Schoof (2007) formula.

The tenth column should contain  $\theta$  calculated at the grounding line. For models which explicitly use the Schoof formula within the numerical scheme, we ask them to report  $\theta$  as used in their numerical schemes. In the description of the model they should describe how they compute  $\theta$ . For formulations which do not use  $\theta$  directly in a formula, they should report  $\theta$  as ratio of the normal stress  $\sigma_{nn}$  across the grounding line to the unbuttressed normal stress  $\frac{1}{4}(1 - \rho_i/\rho_w)\rho_i gH$ .

In the eleventh column those who can compute it should present the **tangential traction** across the grounding line. If it is not computed, insert -9999.

A more complete prescription is given below.

### A.1 Explicit boundary layer

Report  $\theta$  as used in the Schoof (2007) equation (29) in their schemes. Report tangential traction  $\Sigma_t$  (see definition below) if they are able to.

### A.2 Full Stokes and Blatter/Pattyn

Define a tensor

$$\Sigma = \begin{bmatrix} 2\bar{\tau}_{xx} + \bar{\tau}_{yy} & \bar{\tau}_{xy} \\ \bar{\tau}_{xy} & \bar{\tau}_{xx} + 2\bar{\tau}_{yy} \end{bmatrix}$$

and at grounding line report  $\theta$  and  $\Sigma_t$  according to

$$\begin{aligned} \theta &= \Sigma_n / \left( \frac{1}{2} (1 - \rho_i/\rho_w) \rho_i gH \right) \\ \Sigma_n &= \mathbf{n} \cdot \Sigma \mathbf{n}, \\ \Sigma_t &= \mathbf{t} \cdot \Sigma \mathbf{n}, \end{aligned}$$

where  $\mathbf{n}$  and  $\mathbf{t}$  are the normal and tangential vectors in the  $xy$  plane.

### A.3 Vertically integrated approximations, implicit boundary layer

Define a tensor

$$\Sigma = \begin{bmatrix} 2\tau_{xx} + \tau_{yy} & \tau_{xy} \\ \tau_{xy} & \tau_{xx} + 2\tau_{yy} \end{bmatrix}$$

and at grounding line report  $\theta$  and  $\Sigma_t$  according to

$$\begin{aligned} \theta &= \Sigma_n / \left( \frac{1}{2} (1 - \rho_i/\rho_w) \rho_i gH \right) \\ \Sigma_n &= \mathbf{n} \cdot \Sigma \mathbf{n}, \\ \Sigma_t &= \mathbf{t} \cdot \Sigma \mathbf{n}, \end{aligned}$$



where  $\mathbf{n}$  and  $\mathbf{t}$  are the normal and tangential vectors in the  $xy$  plane.

## B Matlab script

The Matlab script below interpolates the unstructured Elmer/Ice data on a regularly spaced grid, defined by ( $\text{imax}$ ,  $\text{jmax}$ ), the number of grid points in  $y$  and  $x$  and  $\text{delta}$ , the grid size.

```
clear all;
close all;

% Loading data
A=load('Elmer75D.dat');
B= sortrows(A,[2 1]);
x0=B(:,1);
y0=B(:,2);
h0=B(:,3);
hb0=B(:,4);

% Interpolation on new grid
imax=21; % grid points in transverse direction
jmax=321; % grid points in flow direction (x)
delta=2500;
Li=(imax-1)*delta; % domain size
Lj=(jmax-1)*delta;
[X,Y] = meshgrid(0:delta:Lj,0:delta:Li);

cnt=0;
for i=1:imax
    for j=1:length(B)/imax
        cnt=cnt+1;
        x(j)=x0(cnt);
        y(j)=y0(cnt);
        hb1(j)=hb0(cnt);
        h1(j)=h0(cnt);
    end
    for j=1:jmax
        h(i,j) = interp1(x,h1,X(i,j));
        hb(i,j) = interp1(x,hb1,X(i,j));
    end
end
```