EISMINT

Ice sheet model intercomparison exercise phase two

Proposed simplified geometry experiments

Introduction

The experiments described here follow directly from those of the first phase of ice sheet model intercomparison [*Huybrechts et al.*, 1996]. As such they are intermediate between the benchmarking of the first phase and the complete ice sheet simulations of the other components of EISMINT phase two. They are necessary because EISMINT phase one did not directly address several aspects of ice sheet model performance, which may be important in interpreting the results of the phase two Antarctic and Greenland simulations. These aspects include:

1. full coupling between ice sheet temperature evolution and flow via temperature-dependent ice rheology;
2. temperature and form response times to stepped changes in boundary conditions (air temperature and surface accumulation rate);
3. divide migration rates in response to surface accumulation changes;
4. ice sheet response to simple, temperature-dependent sliding laws; and
5. ice sheet response to topographic variation.

In general, the tests proposed here attempt to simulate, using a simplified geometry, many of the features ice sheet modellers encounter when they work on 'real' ice sheets. It is anticipated that to arrive at a set of concensus results will be harder than was the case for the benchmark experiments.

General considerations

Only models which have both horizontal dimensions and calculate the temperature and velocity fields in the vertical are included in these experiments. The basic model set up is similar to the 'moving margin' benchmark of *Huybrechts et al.* [1996]. The principal difference is that all the experiments in phase two feature a temperature-dependent ice rheology. The most commonly used relationship between ice flow factor (A in Pa^{-3} s^{-1}) and temperature (T in K) is [*Paterson and Budd*, 1982]:

$$A\left(T^*\right) = a \exp\left(\frac{-Q}{RT^*}\right) \tag{1}$$

where T^* is temperature corrected for the dependence of melting point on pressure; a is a constant of proportionality; Q is the activation energy for ice creep; and R is the universal gas constant. No additional flow enhancement factor is used in these experiments.

As in the original benchmark, the ice accumulation/ablation rate (b in m yr^{-1}) is a function of geographical position (x and y in km) alone:

$$b(x,y) = \min\left[b_{max}, S_b\left(E - \sqrt{(x-\hat{x})^2 + (y-\hat{y})^2}\right)\right] \tag{2}$$

where b_{max} is the maximum accumulation rate; S_b the gradient of accumulation rate change with horizontal distance; and E is the distance from ($\hat{x}$,$\hat{y}$) at which accumulation rate is zero.

In contrast to the benchmark, the ice surface air temperature (T_a in K) is also a function of geographical position:

$$T_a(x,y) = T_{min} + S_T\sqrt{(x-\hat{x})^2 + (y-\hat{y})^2} \tag{3}$$

where T_{min} is the minimum surface air temperature and S_b the gradient of air temperature change with horizontal distance. This change is made in order to simplify the interpretation of model results (it removes the ice surface elevation - air temperature dependency).

A further change from the benchmark is the use of a 25 × 25 km horizontal grid (formerly 50 × 50 km). The model domain remains 1500 × 1500 km (61 × 61 grid cells). The choice of time step is, as before, left to the individual modeller. All experiments last for 200 kyr.

Table 1 provides a list of recommended ice sheet constants. As before, isotasy is omitted in all experiments.

Table 1 Constants used in the experiments.

Symbol	Constant	Value	Units
ρ	density of ice	910	kg m^{-3}
g	acceleration due to gravity	9.81	m s^{-2}
n	power in Glen's law	3	-
T_0	triple point of water	273.15	K
G	geothermal heat flux	-4.2×10^{-2}	W m^{-2}
k	thermal conductivity of ice	2.1	W m^{-1} K^{-1}
c	specific heat capacity of ice	2009	J kg^{-1} K^{-1}
Φ	dependence of melting on pressure	9.75×10^{-8}	K Pa^{-1}
L	latent heat capacity of ice	3.35×10^{5}	J kg^{-1}
R	gas constant	8.314	J mol^{-1} K^{-1}
	seconds per year	31556926	

It is recommended that modellers start this set of experiments by first reproducing their 'moving margin' benchmark runs. This should reduce the possibility of coding changes affecting the intercomparison's results.

Coupled response to stepped changes in boundary condition

This section is principally aimed at assessing the response times of thermally coupled ice sheets to stepped changes in their boundary conditions.

Experiment A

Use the following constants in the boundary condition equations (2) and (3):

$$\begin{aligned} b_{max} &= 0.5 \text{ m yr}^{-1} \\ S_b &= 10^{-2} \text{m yr}^{-1}\text{km}^{-1} \end{aligned}$$

$$\begin{aligned} E &= 450 \text{ km} \\ T_{min} &= 238.15 \text{ K} \\ S_T &= 1.67 \times 10^{-2} \text{K km}^{-1} \\ \hat{x} &= 750.0 \text{ km} \\ \hat{y} &= 750.0 \text{ km} \end{aligned}$$

Couple ice temperature and rheology using (1) with:

$$\begin{aligned} a &= 3.61 \times 10^{-13} \text{Pa}^{-3} \text{ s}^{-1} && \text{if T}^* < 263.15 \text{ K} \\ &= 1.73 \times 10^{3} \text{Pa}^{-3} \text{ s}^{-1} && \text{if T}^* \geq 263.15 \text{ K} \\ Q &= 6.0 \times 10^{4} \text{J mol}^{-1} && \text{if T}^* < 263.15 \text{ K} \\ &= 13.9 \times 10^{4} \text{J mol}^{-1} && \text{if T}^* \geq 263.15 \text{ K} \end{aligned}$$

Use a zero ice initial condition.

Experiment B

Using the final, steady-state ice sheet of Experiment A (t=200 kyr) as an initial condition, apply the following boundary condition constants:

$$T_{min} = 243.15 \text{ K}$$

Otherwise as Experiment A. This experiment assesses ice sheet response to a stepped 5 K warming.

Experiment C

Using the final, steady-state ice sheet of Experiment A (t=200 kyr) as an initial condition, apply the following boundary condition constants:

$$\begin{aligned} b_{max} &= 0.25 \text{ m yr}^{-1} \\ E &= 425 \text{ km} \end{aligned}$$

Otherwise as Experiment A. This experiment assesses ice sheet response to a stepped accumulation rate change. The change reduces the ‘plateau’ accumulation rate from 0.5 to 0.25 m yr^{-1} and also the area over which this maximum value operates. It will generate two types of change: change caused by the reduced ice sheet span and change caused by reduced accumulation rates.

Experiment D

Using the final, steady-state ice sheet of Experiment A (t=200 kyr) as an initial condition, apply the following boundary condition constants:

$$E = 425 \text{ km}$$

Otherwise as Experiment A. This experiment assesses ice sheet response to a stepped accumulation rate change. The change only reduces the area over which the maximum accumulation rate operates. It will therefore only lead to the changes caused by reduced ice sheet span, which contrasts with the two-fold changes of Experiment C.

Experiment E

Using the final, steady-state ice sheet of Experiment A (t=200 kyr) as an initial condition, apply the following boundary condition constants:

$$\begin{aligned}\hat{x} &= 850.0 \text{ km}\\ \hat{y} &= 850.0 \text{ km}\end{aligned}$$

Otherwise as Experiment A. This experiment assesses ice sheet response to a stepped migration of the air temperature/snow accumulation zonation. The centres of both distributions are moved 141 km in a 'north-westerly' direction. The equilibrium response should be the steady-state ice sheet of Experiment A shifted by (100 km, 100 km).

Experiment F

Repeat Experiment A (zero ice initial conditions) with the boundary condition constants:

$$T_{min} = 223.15 \text{ K}$$

Otherwise as Experiment A. This experiment investigates ice sheet temperatures in a cooler environment.

The incorporation of basal sliding

The section is aimed at assessing the response of ice sheet models to the incorporation of basal sliding. A linear sliding law is used:

$$\begin{aligned}u_i(h) &= -B\rho g H \frac{\partial(H+h)}{\partial i}\\ &\quad i = x, y\end{aligned} \tag{4}$$

where h refers to the ice sheet/bedrock boundary; H is ice thickness; g is gravity; ρ is ice density; and B is a free parameter in the various model experiments.

Experiment G

Repeat Experiment A with $B = 1 \times 10^{-3}$ m yr^{-1} Pa^{-1} in (4). This experiment assesses the effect of the sliding without coupling its distribution to that of basal pressure melting.

Experiment H

Repeat Experiment G with:

$$\begin{aligned}u_i(h) &= -B\rho g H \frac{\partial(H+h)}{\partial i} && \text{if } T(h) = T_{\text{pmp}}\\ u_i(h) &= 0 && \text{if } T(h) < T_{\text{pmp}}\end{aligned} \tag{5}$$

where T_{pmp} is the pressure melting point for ice. This experiment assesses the full effect of the sliding and its interaction with the distribution of basal temperature.

Topography

The final set of experiments introduce topography. Variations in ice thickness are expected to trigger many feedbacks within the ice sheet temperature - flow system.

Two types of topography are used. The data for these topographies will be provided in the form of three-column text files. The columns will be the points' x position in km, y position in km and bedrock elevation in m. The model domain will again be $0 \leq x \leq 1500$ km and $0 \leq y \leq 1500$ km with a 25×25 km grid (61×61 points) and isostasy calculations are not be included. These data files will be available from the homepage address given below.

The two topographies are shown in Figures 1 and 2. The first topography has a has a 200 km wide trough running from the domain's centre to one edge. The cross-section of the trough is based on a cosine function, whose amplitude varies from 0 at the domain's centre to 1000 m at the its edge. This data set attempts to simulate the large bedrock troughs often associated with glaciated areas. The second topography is s series of mounds with amplitude 500 m and based on superimposed cosine functions. This data set aims to represent a system of highland massifs and valleys.

Experiment I

Repeat Experiment A using the trough topography.

Experiment J

Repeat Experiment C using the trough topography and using the final, steady-state ice sheet of Experiment I (t=200 kyr) as an initial condition.

Experiment K

Repeat Experiment A using the mound topography.

Experiment L

Repeat Experiment C using the mound topography and using the final, steady-state ice sheet of Experiment K (t=200 kyr) as an initial condition.

Format of results

All results are to be submitted as column-based text files, using tabs or commas to space the columns. Three types of data set will be involved:

1. time series have two columns: time in kyr in the first and the actual data in the second. Times series for global (e.g., volume) and local data (e.g., basal temperature variation at a particular station) will be required.
2. plan-form data have three columns: x position in km in the first, y in the second (using the domain described above), and the actual data in the third. Plan-form data will be needed for several variables (e.g., thickness, horizontal ice flux and basal temperature) usually at the end of an experiment.
3. depth-profile data have two columns: height above bedrock in m in the first and the actual data in the second. Depth profiles will be required for the 3d-field variables (temperature and the velocity components) at selected stations.

The data should be real and use sufficient decimal places to resolve any variation within the data.

Please use the following file naming conventions:

1. three characters based on your name or group followed by an underscore (_);
2. the experiment's letter (one character) followed by another underscore;
3. a character indicating the data file type (**t** for time series, **p** for plan form and **d** for depth profile) followed by an underscore;
4. two characters indicating the variable from:

   tk - thickness in m

   tp - temperature (including basal) in K (not corrected for pressure melting point variation)

   uq - x component of vertically-integrated horizontal flux in $\text{m}^2\ \text{yr}^{-1}$

   vq - y component of vertically-integrated horizontal flux in $\text{m}^2\ \text{yr}^{-1}$

   af - flow coefficient A in $\text{Pa}^{-3}\ \text{s}^{-1}$: **in plan form**, give the weighted factor which appears in the ice continuity equation

   $$\frac{1}{H^{n+2}} \int_{h}^{H+h} \int_{h}^{H+h} A\left(T^{*}\right)(H+h-z)^{n}\, dz\, dz'$$

   otherwise, in depth profiles, give the coefficient that comes directly from 1

   wv - vertical velocity in m yr^{-1}

   uv - x component of horizontal velocity in m yr^{-1}

   vv - y component of horizontal velocity in m yr^{-1}

   vo - ice sheet volume in km^3

   ar - ice sheet area in km^2

   fr - fraction of ice sheet area at pressure melting point

   followed by an underscore; and
5. a single number indicating which station the time series or depth profile is for (see below).

An example based on my plan-form basal temperature data for Experiment F:

`ton_f_p_tp`

and for my time-series thickness data at point 3 for Experiment J:

`ton_j_t_tk_3`.

The data required for each run are:

plan form: thickness, basal temperature, horizontal flux (both components) and flow coefficient at 200 kyr (end of experiment);

global time series: volume, area and melt area fraction;

local time series: thickness, basal temperature at the stations (750 km, 750 km), (750, 1000) and (750, 1125) (stations 1 to 3 respectively); and

depth profiles: temperature, all velocity components and flow coefficient at the stations (750, 750), (750, 1000) and (750, 1125) at 200 kyr (stations 1 to 3 respectively).

The only exception to this is **Experiment E** where local time series and depth profiles are required at the stations (750, 750), (850, 850), (750, 1000) and (850, 1100) at 200 kyr (stations 1 to 4 respectively).

Results can be sent via email to the address given below. Hopefully, an anonymous ftp site will also be available. Depending on how well the intercomparison progresses, more data may be required.

Addresses

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References

Huybrechts, P., A. J. Payne and EISMINT intercomparison group, The EISMINT benchmarks for testing ice-sheet models, *Ann. Glaciol., 23*, 1996.

Paterson, W. S. B., and W. F. Budd, Flow parameters for ice sheet modelling, *Cold Reg. Sci. Technol., 6*, 175-177, 1982.

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