Report of the Third EISMINT Workshop on Model Intercomparison

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with contributions from:

Ayako Abe-Ouchi
Isabelle Marsiat
Frank Pattyn
Tony Payne
Catherine Ritz
Vincent Rommelaere

and the other participants

Grindelwald, Switzerland
25-27 September 1997

CONTENTS

1. SUMMARY

The Third EISMINT Workshop on Model Intercomparison was held in the SunStar Hotel in Grindelwald from Thursday September 27th to Saturday September 29th 1997. The principal objective of this meeting was to discuss the results of the final phase of the model intercomparison venture, where existing ice-flow models were compared under real-world situations and under much more challenging conditions than had been the case during previous workshops held in Brussels in 1993 and Bremerhaven in 1994.

A first planning meeting to prepare the Grindelwald workshop was organized in Brussels on 29-30 March 1996. This planning meeting was attended by Drs. Richard Hindmarsh, Doug MacAyeal, Catherine Ritz, Vincent Rommelaere, Tony Payne, Mikhail Verbitsky, and Philippe Huybrechts. We discussed which tests we considered most useful for the third phase of the venture, what suitable data would be available, and how the work could be practically organised. It was decided to define 5 intercomparison topics (Greenland models; Antarctic models; Ice-shelf models; Thermomechanical effects; and Grounding-line treatments), each of which would be taken care of by a coordinator. The respective coordinators (C. Ritz, T. Payne, and P. Huybrechts) first performed the experiments they designed themselves, and then produced a written description. All was put on the web in September 1996 (http://homepages.vub.ac.be/~phuybrec/eismint.html), and widely advertised, both directly to previous participants, as on the E-mail forum of the International Glaciological Society. These documents form part of this report.

Participants could directly load the experimental descriptions and the required datasets from the webpages set up in Brussels, with further links to sites in Grenoble and Southampton. Results of the tests were sollicited before May 1st 1997. During the summer of 1997, the respective topic coordinators collated and plotted with some student help all results for presentation in Grindelwald.

In total, 13 scientists participated in the various experiments, most of them in more than one topic. Almost all major ice-sheet and ice-shelf modeling groups were represented at the meeting, with a dominance of European groups, but also including several groups and individuals from Japan, the USA and Canada. The workshop was attended by 21 persons from 8 different countries, including 3 non-European.

The workshop itself took three days. The first day was entirely devoted to a plenary presentation and discussion of the model intercomparison results by topic coordinators. This was followed during the second morning by group discussions of model results per intercomparison topic, and a plenary presentation of conclusions by designated rapporteurs. Highlights of the intercomparison results and the minutes of the group discussions form the major part of this report, and summarise the main achievements of the workshop. It was agreed to write up the main results in three separate papers prepared by the respective topic coordinators and co-authored by the participants. These papers are to be submitted to the international literature within the next few months.

From the intercomparison results, it turned out that most of the Greenland models produced very similar results. As these models only dealt with grounded ice dynamics, this clearly indicated that the previous intercomparison tests concentrating on numerics and detecting errors in the various codes had borne fruit (topic 1). Two more or less complete Antarctic models dealing with the entire ice-sheet/ ice-shelf system were presented at the meeting. An interesting difference between these two models concerned the way the grounding zone is treated, which resulted in a different chronology of, in particular, the history of the last deglaciation in West Antarctica (topic 2). The two ice-shelf models participating in the ice-shelf tests behaved nearly identical, thereby confirming previous results from the Ross Ice Shelf benchmark (topic 3). Perhaps most interestingly, all thermomechanically coupled models were shown to exhibit the radial instabilities in basal temperature and ice flux first documented in papers by Tony Payne, confirming that these instabilities are probably not a mere product of the particular numerics employed by Tony in his prior work (topic 4). A concensus on how to deal with the marine ice-sheet problem and grounding-line dynamics, on the other hand, could not be established. All models behaved very differently, raising fundamental questions about the state of equilibrium and stability of the ice-sheet/ ice-shelf junction, and the reversibility of the process of grounding-line migration, which subjects deserve to be investigated more thoroughly in future work (topic 5).

The afternoon of the second day was devoted to an open talks session on recent developments in the field of ice-flow modeling. Talks were presented on topics like dealing with small-scale features such as outlet glaciers and ice streams, the grounding-line problem, numerical techniques, basal boundary conditions, and model applications to West Antarctica and the northern hemisphere ice sheets.

Taking advantage of the splendidly clear weather on the third day, the 'informal discussions' were continued on Jungfraujoch, where we hiked to the Mönchsjochhütte. The excellent views on Aletschgletscher and the surrounding mountains were very much appreciated.

In all, the general feeling was that the series of intercomparison workshops held between 1993 and 1997 have definitely pushed the art of ice sheet modelling a decisive step forward. It has enabled groups and individuals worldwide to further develop and improve their dynamic ice-flow codes. Several European groups are now in possession of upgraded models that have been thoroughly tested under a wide variety of boundary conditions. These models can therefore be considered as sufficiently reliable tools to better investigate ice sheets and their interaction with the climate system.

Brussels, 15 June 1998

Philippe Huybrechts

2. PROGRAMME

Thursday 25 September 1997

9:00 to 12:30 - Morning session

Plenary presentation and discussion of the model intercomparison results by topic coordinators

CATHERINE RITZ (Grenoble):
Greenland ice sheet models

PHILIPPE HUYBRECHTS (Brussels/ Bremerhaven):
Antarctic ice sheet models

12:30 to 14:00 - Lunch

14:00 to 18:00 - Afternoon session

Continuation of presentation and discussion of intercomparison results

CATHERINE RITZ (Grenoble):
Ice shelf models

PHILIPPE HUYBRECHTS (Brussels/ Bremerhaven):
Grounding-line treatments

TONY PAYNE (Southampton):
Topography/ basal sliding effects

Friday 26 September 1997

9:00 to 12:30 - Morning session

Group discussion of model results per intercomparison topic; Plenary presentation of conclusions;

THERMOMECHANICAL MODELS (Chairperson: ISABELLE MARSIAT)

GROUNDING-LINE TREATMENTS (Chairperson: FRANK PATTYN)

GREENLAND MODELS (Chairperson: AYAKO ABE-OUCHI)

Closing discussion.

12:30 to 14:00 - Lunch

14:00 to 18:00 - Afternoon session

Presentation of invited talks (about 30' each, including questions)

SHAWN MARSHALL (Vancouver):
A continuum mixture treatment of ice-stream thermomechanics and ice-stream coupling in a large-scale ice-sheet model.

NICK HULTON (Edinburgh):
High resolution modelling on the CRAY T3D: Part 1: Problems of moving to variable resolution.

MIKE MINETER (Edinburgh):
High resolution modelling on the CRAY T3D: Part 2: Parallel processing for ice sheet modellers.

LEV TARASOV (Toronto):
Coupled climate-thermomechanical modelling of the Northern Hemispheric ice sheets

CHRISTOPH MAYER (Bremerhaven):
The transition zone problem.

ANDREW FOWLER (Oxford):
Problems in the numerical computation of a simple ice sheet model including sliding and drainage.

ANDREW CLIFFE (East Anglia):
Numerical treatments of full steady ice sheet flow equations when bed slopes are unity.

TONY PAYNE (Southampton):
A model of the West Antarctic ice sheet.

Saturday 27 September 1997

Excursion to Jungfraujoch.

3. PARTICIPANTS

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4. INTERCOMPARISON WEBPAGES

General

Welcome to Phase II of the Model Intercomparison Activity, as organised within the framework of EISMINT (European Ice Sheet Modeling INiTiative). The objective of this activity is to test and compare existing numerical ice-sheet, ice-shelf, and glacier models as they are run by several groups worldwide, in order to narrow down uncertainties and to enable participating groups to upgrade their own models.

For Phase II, we have been working on a new series of experimental setups, aiming at comparing the performance of models under real-world situations and under much more challenging conditions than was the case during previous workshops held in Brussels (1993) and in Bremerhaven (1994).

Topics

We have now produced descriptions for 5 intercomparison topics, each of which will be coordinated by the person mentioned in brackets:

- **comparison of models applied to the Greenland ice sheet (Coordinator: Catherine Ritz, e-mail: catritz@glaciog.grenet.fr)**
- **comparison of models applied to the Antarctic ice sheet (Coordinator: Philippe Huybrechts, e-mail: phuybrec@vub.ac.be)**
- **comparison of ice-shelf models (Coordinator: Vincent Rommelaere, e-mail: vince@glaciog.grenet.fr)**
- **comparison tests involving thermomechanical coupling (Coordinator: Tony Payne, e-mail: A.J.Payne@soton.ac.uk)**
- **comparison of grounding-line treatments (Coordinator: Philippe Huybrechts, e-mail: phuybrec@vub.ac.be)**

How to participate

If you plan to participate in this venture, which is certain to push the art of ice-sheet modelling a further step ahead, please observe the following steps:

- load in the respective experimental set-up descriptions as indicated for each topic
- send a mail to Philippe Huybrechts and to the respective topic coordinator to let them know about your intentions to participate
- finalise the experiments and send the data to the respective coordinators **by May 1st, 1997**, at the very latest.

Each of you who have submitted results will be invited to attend a three-day workshop, to be organized in October 1997 in Grindelwald (Switzerland). This workshop will be devoted to discussing the results of the various experiments and will also have an open session for those of you who want to use the opportunity to report on their latest research. Important to note is that the expenses for this workshop (travel, lodging, meals) will be entirely covered by the European Science Foundation.

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Intercomparison of existing Greenland models

The required experimental setups and files are available on an anonymous ftp server at the LGGE (Laboratoire de Glaciologie et Geophysique de l'Environnement):

- ip number: 195.220.81.2 (alaska.ujf-grenoble.fr)
- user name: anonymous
- password: your e-mail address
- file: pub/EISMINT-INTERCOMP/GREENLAND/green-descr.ps

Please contact Catherine Ritz if there are any difficulties with the ftp-server.

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Intercomparison of existing Antarctic models

Philippe Huybrechts

The experiments aim at comparing steady state behaviour (with/ without a prescribed grounding line), and at comparing model behaviour during the glacial cycles and under enhanced greenhouse warming conditions. Compared to the other intercomparison tests (grounding-lines, ice shelves and Greenland), the important new feature is the evaluation of treatments for grounding-line migration in two horizontal dimensions.

The experiments first of all concern 3D time-dependent thermomechanical models with a coupled ice shelf, but part of the experiments can also be performed by models without thermomechanical coupling (vertically integrated models) or by models that only consider grounded ice-sheet flow.

The experimental description document is either available as as an rtf (Rich Text Format) file (recommended), or as a postscript file.

The experiments also require a number of data files. These are:

bed40eis.dat: bedrock elevation on 40 km grid
sur40eis.dat: surface elevation on 40 km grid
thi40eis.dat: ice thickness on 40 km grid
mask40eis.dat: mask on 40 km grid (1 = grounded ice; 0 = everything else)
forcanteis.dat: forcing data over last two glacial cycles (220 ky BP - present). first column = year; second column = SPECMAP sea-level; third column = Vostok temperature change.

Please contact me if there are any difficulties with obtaining the description document or the input files.

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Intercomparison of ice-shelf models

The required experimental setups and files are available on an anonymous ftp server at the LGGE (Laboratoire de Glaciologie et Geophysique de l'Environnement):

- ip number: 195.220.81.2 (alaska.ujf-grenoble.fr)
- user name: anonymous
- password: your e-mail address
- file: pub/EISMINT-INTERCOMP/ICE-SHELVES/ROSS/ross-descr.ps
  (for the Ross ice shelf comparison)
- file: pub/EISMINT-INTERCOMP/ICE-SHELVES/OTHER/shelf-descr.ps
  (for the other tests on the ice shelves)

Please contact Vincent Rommelaere if there are any difficulties with the ftp-server.

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Comparison of grounding-line treatments

Philippe Huybrechts

These experiments aim at comparing treatments of grounding-line migration and of the ice-sheet/ ice-shelf transition, both in steady state as in dynamic situations in response to sea-level variations and ice-thickness changes. They are for a schematic geometry and assume lateral symmetry, so that they can be performed by both 2-D and 3-D models.

The experimental description document is either available as a normal ASCII text file, as an rtf (Rich Text Format) file (recommended most), or as a postscript file.

Please contact me if there are any difficulties with obtaining the description document.

IMPORTANT REMARK: The description document has been modified in €6.3 (Role of basal sliding) on 23 April 1997. These changes are in the .rtf document, but not in the .ps and .txt documents, and have been sent around by E-mail. If you cannot access the .rtf document or have not received my mail on this subject, please contact me to obtain the updated information.

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<u>5. INTERCOMPARISON OF GREENLAND MODELS</u>

EISMINT INTERCOMPARISON EXPERIMENT

COMPARISON OF EXISTING GREENLAND MODELS

coordinator
Catherine Ritz

INTRODUCTION

The objective is to compare the different existing models when they are applied to a real ice sheet. There is a glaciological interest to see how the different models perform in real cases. Another purpose more linked to climate studies is to estimate the validity of the reconstructions the models can produce. The time scale of these reconstructions is either the last climatic cycle or the close future to investigate the effect of a global warming.

Compared to the schematic ice sheet used in the previous EISMINT intercomparison experiments, the Greenland ice sheet adds two important features :
- The bedrock is rough
- There is a mass balance-surface elevation feedback.

Moreover it is possible to compare the results with the present surface topography extension, surface slope, shape of contour lines.

TYPE OF MODELS

The models concerned by this intercomparison are those simulating the evolution with time of the ice sheet geometry and of the temperature and velocity fields within the ice. As there are now several 3D models with thermomechanical coupling we will focus on this type of model. However, models without thermomechanical coupling (vertically integrated) can also participate to the intercomparison.

The isostatic response should be modelled also, and the method chosen should be described. If the unloaded bedrock is necessary, we will assume that the present bedrock is in equilibrium with the present ice sheet (although this is not absolutely true).

Participants should provide information on their model in the file INFO.name (see result files)

EXPERIMENTS

We plan to compare the models for three simulations :

1) Steady state with present climatic conditions

The initial condition is given by the present surface and bedrock topography. The time needed to reach the equilibrium depends on the initial temperature field and on the models. For this steady state simulation it is better not to include the thermal conduction in the bedrock because it makes the equilibrium time longer. The simulation is stopped when the criterium of steady state is fulfilled. This criterium is a change in volume less than 0.01% in 10000 years. The simulated time necessary to reach such a steady state must be mentionned.

2) Evolution along the last climatic cycle

The initial ice sheet is the one obtained with the steady state simulation.

The forcing in temperature is derived from the GRIP ice core (Dansgard and al. 1993, see INPUT FILES). This ice core is supposed to go back to 250 000 years BP but it is now accepted that the deeper part of the ice core was affected by ice flow processes so it is not reliable for periods older than the previous interglacial. However it is a better representation of the temperature before the Eemian than a steady state. The temperature field at 130 000 years BP should then be more realistic. Consequently the simulation covers the last 250 kyr but the results will be significant only for the period 130 kyr to present. The models will be compared only on this period.

The temperature changes at GRIP can be derived from the $\delta^{18}O$ content,
$\Delta T = 1.5 (\delta^{18}O + 35.27)$

The GRIP file (sum89-92-ss09-50yr.stp) contains the 50 years averages of original series. It was provided by Sigfus Johnsen. The time scale ss09 is only slightly different from the ss08 that is on the server of the noaa (see input files). The isotopic record is the one used for the temperature calculations in Johnsen et al. (1995). The value -35.27 ‰ is the average for the last 50 years. We suppose that over these 50 years the temperature is the same as today. The ages are years before 1989.

Note that the temperature at GRIP is the result of the climatic processes and is not really a forcing. We propose this record to force the models because it is an easy method when using the degree day method as most models do. Some models may use a different method (EBM for example). Provided they can reconstruct the same temperature (or close) at GRIP they can participate to the intercomparison. People can also choose if the climatic forcing is spatially constant or changes for example with latitude and altitude.

The sea level change is derived from the SPECMAP curve (Imbrie et al. 1984, see INPUT FILES).
ΔSea level = -34.83 (δ^{18}O +1.93)

In order to compare the greenhouse experiment with a “standard” experiment the time integration of the climatic cycle run should be carried on for the next 500 years in the future with ΔT= 0 and Δsea level = 0.

3) Greenhouse warming.

The initial ice sheet is the one obtained for the present (1989) in the climatic cycle simulation. The simulation covers 500 years.

Temperature forcing: There are many projections of future climate but they often cover only one century. We choose to prescribe a scenario similar to the result of Manabe and Stouffer (1994) in the case of 2 x CO_2 (stabilisation simulations). This scenario covers 500 years and we depict it with two warming rates: Between 0 (start of the simulation) and 80 years, the temperature increases with the rate 0.035 °C/year (2.8 °C for 80 years). Between 80 and 500 years, the warming rate is 0.0017 °C/year (.714 °C for 420 years). The total temperature increase is 3.514 °C.

Sea level forcing: No change.

PARAMETERS

We consider two levels
Level 2: with a prescribed set of parameters
Level 3: with the preferred set of parameters for each model

The steady state experiment has to be performed twice with level 2 and level 3. The purpose of level 2 is to compare the models with exactly the same set of parameters and try to estimate the relative influence of the parameters and of the models themselves. The prescribed set of parameters is given in Table 1. If possible, for this level, ablation rate should be calculated with a degree day method.

TOPOGRAPHICAL AND METEOROLOGICAL DATA

Bedrock and surface (present) topography are those compiled by Anne Letréguilly (Letréguilly et al. 1991) on either a 20 km or 40 km grid in polar stereographic projection. For the surface elevation, the data set compiled by Ekholm (Ekholm and al. 1995) is more accurate, however there is no bedrock topography on the same grid . We thus prefered to use the Letréguilly's grid file that has already been used by several modelling groups (see also INPUT FILES).

Ellesmere Island. The surface and bedrock data set is not good on Ellesmere Island. This has no consequence for the steady state and the greenhouse simulations. For the climatic cycle simulation it is likely that the greenland and Ellesmere ice sheets merge when the sea level drop while there is almost no ablation. We want to focus on the Greenland ice sheet so we would like each modeller to prevent his Greenland ice sheet to merge with the Ellesmere one.

Some models are not in Cartesian plane grid but in latitude longitude one. In the grid files the latitude and longitude of each node are given so it is possible to reconstruct a new grid. People wanting to run their model in spherical coordinate should contact Catherine Ritz in order to find the best way to compare with the plane experiments.

Accumulation rates were compiled by Philippe Huybrechts from Ohmura and Reeh (1991), and are on the same grid as topography. WARNING : this map is already converted in ice equivalent (with density 910 kg m^{-3}).
Data of the surface temperature were compiled by Ohmura (Ohmura 1987) but are not on a grid. The following parameterisation gives a good fit to these data (Letréguilly, personnal communication):

Mean annual temperature **Ta** (in deg C)
Ta = 49.13 - 0.007992 * Z -0.7576 * latitude

where Z=max (Surface elevation, 20*(latitude-65))

Summer temperature **Ts**
Ts = 30.38 -0.006277 * (surface elevation) - 0.3262 * latitude

SUMMARY ON THE EXPERIMENTS

There are 4 experiments

The experiment names are :
SSL2 Steady state , prescribed set of parameters (table 1)
SSL3 Steady state , free set of parameters
CCL3 Climatic cycle simulation (free set of parameters)
GWL3 Greenhouse warming simulation (free set of parameters).

Table 1 Prescribed set of parameter for level 2

gravity	9.81 m s^{-2}
gas constant	8.314 J mol^{-1} K^{-1}
ice density	910 kg m^{-3}
mantle density	3300 kg m^{-3}
sea water density	1028 kg m^{-3}

Deformation law. Glen flow law $d_{ij} = f.a \exp(-Q/RT^*) \tau^{n-1} \tau_{ij}$

where d_{ij} is a strain-rate component, τ_{ij} is the corresponding stress component, τ is the effective shear stress, T* is the absolute temperature corrected for the dependence of melting point on pressure, Q is the activation energy and R is the gas constant.

exponent n=3
enhancement factor f =3
coefficient a and activation energy Q

$T^* < 263.15$ K a=1.14 10^{-5} Pa^{-3} yr^{-1} Q=60 kJ mol^{-1}
$T^* > 263.15$ K a= 5.47 10^{10} Pa^{-3} yr^{-1} Q=139 kJ mol^{-1}

No sliding

Thermal physical parameters

Geothermal flux :	50 mWm^{-2}
Triple point of water	273.15 K

ice

Thermal conductivity	2.1 W m^{-1} K^{-1}
Specific heat capacity	2009 J kg^{-1} K^{-1}
latent heat capacity	335 kJ kg^{-1}
Dependence of the pressure melting point on the depth	$T^* = 273.15 - 8.7\ 10^{-4}$ x depth (depth in meter)

bed

Thermal conductivity of the bed	3 W m^{-1} K^{-1}
Specific heat capacity for the bed	1000 J kg^{-1} K^{-1}

Ablation parameterisation *(degree day method)*

Positive degree day factor for ice	8 mm d^{-1} °C^{-1} (mm of water)
Positive degree day factor for snow	3 mm d^{-1} °C^{-1}

Superimposed ice : 60% of the melted snow refreezes
The annual cycle of temperature is expressed as a cosine function
Standard deviation of the daily temperature 5°C

Accumulation rate: the experiment with level 2 is a steady state experiment with present climatic condition. We assume that accumulation rate is the same as given in the input file (suaq).

INPUT FILES

The files are on the ftp anonymous of the LGGE in the directory:
pub/EISMINT-INTERCOMP/GREENLAND/INPUT-FILES

Topography

For each resolution the grids are given on the following format

1 file with the grid grid20-EISMINT or grid40-EISMINT

format

line 1 : nx ny resolution
line 2 : ' I J Latitude longitude'
line 3 ->end *for each node*

I (W-E or x direction)	column 1
J (S-N or y direction)	column 2
Latitude	column 3
Longitude	column 4

1 file with the topographical data : suaq20-EISMINT or suaq40-EISMINT

format:

line 1 : nx ny resolution
line 2 : ' S H B Accum'
line 3 -> end for each node

surface elevation	column 1
ice thickness	column 2
bedrock elevation	column 3
Accumulation rate	column 4

Climatic forcing

GRIP record : sum89-92-ss09-50yr.stp information in grip18O.readme
SPECMAP record specmap.017

The file for the sea-level forsing comes from the noaa server and can also been found there
ftp ftp.ngdc.noaa.gov or http:/www.ngdc.noaa.gov
The GRIP record has been provided by Sigfus Johnsen.

RESULTS

The result files must be put on the same ftp anonymous of the LGGE
directory pub/EISMINT-INTERCOMP/GREENLAND/RESULTS

Please send also an E-mail to catherine Ritz to warn that results have been sent.

Output format (in fortran)

* Surface and bedrock elevation, ice thickness and temperature should be in format (F9.3) time in format (I7) , position (I,J) in format (I3), and all the other variables in format (e12.5).
* At least one blanc between each column.
* If the model does not calculate a variable, please fill with the undefined value 999.999

There are several type of results: snapshots (horizontal fields and transect) and time dependent variables. Participants should also provide a file with information concerning their model (see info file)

Snapshots results

The snapshot results will give a picture of the ice sheet at given times
These times are the following.

Steady state simulation :
when the equilibrium is reached . snapshot name: T000

Climatic cycle simulation

time	snapshot name
-130 kyr	T130
-65 kyr	T065
-21 kyr	T021
-9 kyr	T009
present	T000

Greenhouse warming simulation

time		snapshot name
present	+ 50 years	T050
	+ 100	T100
	+ 500	T500

Horizontal 2d fields name **HF**

The format is the same as the gridded input data (surface, thickness, berock) except that there are more columns

format

line 1 : nx ny resolution

line 2 :

line 3 -> end for each node

Surface elevation (m)	column 1
ice thickness (m)	column 2
bed elevation (m)	column 3
basal temperature (°C difference with melting)	column 4
surface temperature (°C)	column 5
ablation rate (m/y ice equivalent)	column 6
accumulation rate (m/y ice equivalent)	column 7
velocity along x (m/y, vertically averaged)	column 8
velocity along y (m/y,vertically averaged)	column 9

Some people may want to give other fields (for example age of the ice at the bottom or depth of the transition glacial interglacial, thickness of the temperate basal layer .....). Then please contact Catherine Ritz so we can decide together which fields we add.

Vertical 2d fields on a E-W transect name **VF**

The transect is the closest to the GRIP location.

GRIP 72.58 N 37.64 W altitude 3238 m, thickness 3029 m

grid 20 km transect J=77

grid 40 km transect J=39

Format of the file

from I=1 to I=nx

from surface to bottom

x position (m, origin at I=0)	column 1
z position (m, origin at present sea level, upward)	column 2
Ux velocity (m/yr)	column 3
Uy velocity (m/yr)	column 4
Uz velocity (m/yr)	column 5
Temperature (°C,difference with the melting point)	column 6

Time dependent variables name **TV**

Every 100 years in the climatic cycle simulation (except for the “futur” period 0-500 years where it should be every 10 years)
Every 10 years in the Greenhouse warming simulation

Format of the file.

time (years, negative before present)	column 1
ice covered surface (m^2)	column 2
total ice volume (m^3)	column 3
mean accumulation rate over ice (m/y ice equivalent)	column 4
mean ablation rate over ice (m/y ice equivalent)	column 5
calving (m^3/y ice equivalent)	column 6
basal melting (m^3/y ice equivalent)	column 7
area with basal melting (m^2)	column 8
maximum surface elevation (m)	column 9
I position of the highest node	column 10
J position of the highest node	column 11

“over ice” and “ice covered” means the grid cells with a positive ice thickness and the grid cells that can receive ice flux from a neigbour. It is the case for example for the grid points on the boundary of the ice sheet (at least in the models where the boundary jumps from point to point).

Time dependent variables at GRIP name **GR**

This file is necessary only for the climatic cycle experiment.

time (years, negative before present)	column 1
surface elevation at GRIP (m)	column 2
ice thickness at GRIP (m)	column 3
basal temperature at GRIP real temperature (not corrected)	column 4
surface temperature at GRIP (°C)	column 5
accumulation rate at GRIP (m/y , ice equivalent)	column 6

closest point to GRIP
I=47 J=77 with the 20 km grid
I=24 J=39 with the 40 km grid

INFO file

The file can be either in ascii or in a postcript format
This file should include:
* reference where the model is described. If this paper is in press the authors should either give as many details as possibble in the info file or send a draft version.
* for the experiments with preferred set of parameters, all the parameters that are different from the prescribed ones.
* method for the numerical resolution of the mass conservation equation (type of spatial discretisation, staggered grids, ADI or other method ...)
* Thermomechanical coupling : which processes are included (advection, diffusion, strain heating, polythermal ice ...)
* Ablation parameterisation
* Accumulation rate parameterisation for different climatic conditions or/and ice sheet altitude
* Bedrock modelling: local or regional (lithosphere rigidity), diffusive or relaxed (asthenosphere).Is the drop of sea level taken into account ?
* Method for calving
* Other characteristic of the model ?

Names of the result files

"experiment name"//"type of result"//"time of snapshot (if necessary)"//.'name'

examples

SSL2HFT000.Doug
steady state,prescribed parameters,horizontal fields, snapshot at the end of the simulation, by Doug MacAyeal

CCL3VFT021.Catritz
Climatic cycle,free parameters,vertical field, time 21 k by Catherine Ritz

CCL3GR.Catritz
climatic cycle, free parameter, GRIP time dependent variable

GWL3TV.Tony
Greenhouse warming, free parameters, time dependent variables by Tony Payne

INFO.Philippe
Information on his model by Philippe Huybrechts.
If this file is postcript file then the name should be INFO-PS.name.
Participants can choose their extension name as long as there is no ambiguity with somebody else (please check with Catherine Ritz). The name can be in lower or upper case.

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directory /pub/EISMINT-INTERCOMP/GREENLAND

REFERENCES

Dansgaard W., Johnsen SJ, Clausen HB, Dahl-Jensen D, Gunderstrup NS, Hammer, CU, Hvidberg CS, Steffensen JP, Sveinbjörnsdottir AE, Jouzel J and Bond G (1993) Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature* 364: pp 218-220

Ekholm S, Forsberg R, Brozena JM (1995) Accuracy of Satellite altimeter elevations over the Greenland ice sheet. *J. Geophys. Res.* 100(2): pp 2687-2696.

Imbrie J, Hays J.D, Martinson D.G, McIntyre A., Mix A.C., Morley J.J, Pisias,N.G., Prell W.L. and Shackleton N.J. (1982) The orbital theory of Pleistocene climate: Support from a revised chronology f the marine delta18O record. in Berger, A.L. et al. (eds) : *Milankovitch and climate,* part I, NATO ASI series, p 269-305.

Johnsen S. J., Dahl-Jensen D., Dansgaard W. and Gundestrup N. (1995) Greenland paleotemperatures derived from GRIP bore hole temperature and ice core isotope profiles. *Tellus* **47B**, 624-629

Letreguilly A, Huybrechts P, Reeh N (1991) Steady state characteristics of the Greenland ice sheet under different climates. *J. glaciol.* 37(125): pp 149-157

Manabe S. and Stouffer R.J. (1994) Multiple century response of a coupled ocean-atmosphere model to an increase of atmospheric carbon dioxide. *J. Climate*, 7, 5-23.

Ohmura A (1987) New temperature distribution maps for Greenland Z. *Gletscherkd.*

Glazialgeol. 23(1): pp 1-45.

Ohmura A and Reeh N (1991) New precipitation and accumulation maps for Greenland. *J. Glaciol.* 37: pp 140-148.

Intercomparison of Greenland ice sheet models

Coordinator : Catherine Ritz

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1 Introduction

There is an increasing number of models able to simulate the evolution of large ice sheets in response to climatic changes. The most complete of these models are three-dimensional and time dependent. They include coupling between the velocity and temperature fields, basal sliding, isostatic response and some coupling with the atmospheric characteristics (precipitation, temperature). These models are rather complex and it is difficult to test them. Intercomparison experiments provide a useful tool to detect severe mistakes and to assess the uncertainty on the results.

Three levels of ice-sheet models intercomparison were identified (Huybrechts and al. 1996). At the first level, boundary conditions and as many physical processes as possible were fixed. At the second level, some freedom was given on the physical processes employed in the models. These two levels were investigated during the first EISMINT intercomparison experiment and the main results were that under these simple conditions most models agreed.

The third level consists in experiment on a real ice sheet with prescribed data sets for the bedrock topography, surface temperature and precipitation . We present here the intercomparison on the Greenland ice sheet. This experiment adds two important features compared to the previous intercomparisons : first the bedrock is rough, second there is a mass balance - surface elevation feedback. There is a glaciological interest to see how the different models perform when they include such processes. Another issue more related to climatic studies is to assess how accurate are the reconstructions of the Greenland ice sheet during the last climatic cycle or in the next future in response to global warming.

2 The experiment model set-up

see the text proposed to the participants (March 1997)

3 Participants

Nine models participated in this experiment all including thermo-mechanical coupling. The authors were asked to add their name as an extension of the files. It is this extension that will be used in the following text and figures. We summarize here the main characteristics of these models.

Author(s)	**Method**	**grid**	**extension**
Philippe Huybrechts	finite differences	20 km	PHILIPPE
Roderik Van De Wal	finite differences	20 km	ROD
Lev Tarasov	finite differences	20 km	LEV
Ralf Greve	finite differences	40 km	GREVE
Shawn Marshall	finite differences	40 km	SHAWN
Tony Payne	finite differences	40 km	TONY
C. Ritz, A. Fabre	finite differences	40 km	CATRITZ
James Fastook	finite elements	40 km	FASTOOK
Douglas MacAyeal	finite elements	varying triangles	DOUG

4 Results

There were a huge amount a results so we will select a few significant points and concentrate on the geometry (surface elevation, volume, area covered by ice).

4.1 Steady state experiments

When considering the large scale geometry of the simulated ice sheet, there are little differences between the models results (see figure 1, surface elevation maps). The main difference concerns the extension of the ice sheet and this seems to be related to the way ablation is parameterized. One interesting feature is that the maps of basal temperature are rather different indicating that the large scale geometry is not so sensitive to the basal temperature.

4.2 Climatic cycle experiment

4.2.1 Time dependent results

The extension of the ice sheet (ice area) is governed by two mechanisms : ablation rate and sea level changes that allow the ice sheet to extend further. Both mechanisms should lead to a larger ice sheet during the cold periods than during interglacial stage. Such a behaviour is indeed simulated by all the models (figure 2). However the difference in the amplitude of the change reaches (at least) a factor 3. This is striking during the Eemian with one model (GREVE) giving a very small ice sheet.

Concerning the maximum altitude, the models indicate that it is driven by the changes in precipitation. All the models assumed that precipitation was reduced during the cold ages. The maximum altitude is consequently slightly lower ($\approx$150 m) during these periods than during interglacials. There is an exception with the model of Greve because the reduction of the ice sheet during the Eemian is large enough to affect the central parts of the ice sheet.

The variations of ice volume are governed by ablation and precipitation rates that play opposite roles. Compared to interglacial periods, ablation rate is smaller during the cold periods leading to a larger ice sheet. On the other hand, precipitation is smaller, leading to a lower ice sheet. In the results obtained here, the ice volume shows almost the same type of variation as the ice covered area, indicating that ablation plays the dominant role.

Finally one can wonder why one model gives a so small ice sheet during the Eemian while the others do not. We suspect that the ablation is involved but this variable is rather difficult to interpret in the time dependent outputs and a more detailed study of the horizontal 2D fields (snapshots) is in process to study this point.

4.2.2 snapshots

We focus on two snapshots : present time (CCL3HFT000) and Eemian (CCL3HFT130).
The “present time” snapshot is the one obtained at the end of the climatic cycle simulation. It is supposed to reproduce as well as possible the present ice sheet topography and indeed all the models give a rather realistic ice sheet. The surface elevation maps are almost similar to those obtained with the steady state experiment except that the ice sheet is slightly higher (see figure 3). This result was expected because when taking into account the past climatic changes the present ice sheet still remembers the ice age. It has consequently a colder basal temperature than with steady climatic conditions leading to a reduced ice flow and a thicker ice sheet.

On figure (4), representing the modelled ice sheet during the Eemian period, we observe much more discrepancies between the results than with the other snapshots. As already mentioned, Ralf Greve simulates a very reduced ice sheet split into two parts. Shawn Marshall simulates an ice sheet similar to the present time one. The other results are intermediate.

It is interesting to note that all the authors are able to tune their model in order to obtain a present ice sheet quite comparable with the real one. However, there is a variety of possibilities to tune a model and the models themselves are not identical (although they are based on the same physical processes). Consequently they give very different simulated ice sheets during the Eemian. A first conclusion is that being able to reproduce the present ice sheet is not a proof that the reconstruction for the other periods is valid. The differences between the models indicate the uncertainty on the results of such type of simulation. Finally, it seems that the ablation process holds a dominant role.

4.3 Greenhouse warming

With the prescribed warming scenario for the next 500 years, all the models produce a decrease in ice volume ranging from 0.08 to 0.2 $10^{15} m^3$ in 500 years.

5 Conclusion

Almost all the groups working on this type of large scale models took part in the intercomparison. Some had already performed simulation on the Greenland ice sheet but for some others it was an opportunity to apply their model to this ice sheet. I hope that this experiment has been a stimulating exercise for everybody.
The main glaciological result (not unexpected) is that the evolution of the Greenland ice sheet strongly depends on the parameterization of its surface mass balance and this gives us direction for future research.
A paper is in preparation with the provisional title
“ Intercomparison of Greenland ice sheet models : A tool to assess the validity of past and future ice sheet reconstruction “

5.6. Minutes of the group discussion (Rapporteur: A. Abe-Ouchi)

Nine groups had submitted their results for the Greenland ice-sheet experiment. The model intercomparison was very useful not only to let the participants notice their careless mistakes or coding errors, but also to get a common picture on the sensitivity of the Greenland ice sheet.

The following items were discussed in the group discussion for the Greenland experiment:

(1) general conclusions were listed
(2) the possible source of discrepancy of the model results were listed
(3) the plan after the meeting was discussed.

(1) General conclusions

(1-1) By comparing the results with commonly defined mass-balance input and with freely chosen input, it was apparently seen that the mass balance governs the ice sheet geometry rather than the ice physics.

(1-2) Discrepancies of the volume change (LGM-present) during glacial cycles are governed by different treatments of the accumulation change, whereas the ablation difference affects the extent (LGM-present) of the ice sheet. Sea level affects both the volume and extent.

(1-3) There was a good agreement on Eemian ice sheet volume and extent, except for one model which might have had an error in the mass balance input.

(1-4) The discrepancies in the treatment of the cut-off of ice sheet at the sheet edge or calving process seem to affect the LGM ice sheet calculation and should be considered with great care.

(1-5) Regarding changes for Summit throughout the glacial cycle, the following features were listed:

The LGM ice sheet is lower and more stable than the present ice sheet, whereas the Eemian summit is higher in altitude and has higher variability. The mean value of the summit height varies amoung models as follows:

Eemian: 3300m plus minus 100m
LGM: 3150m plus minus 150m
Present: 3200m plus minus 100m

(1-6) On the shift of position of Summit, 20-40 km was observed which corresponds to 1 to 2 grid points in the models. The Eemian ice-sheet summit shifts towards the west by 20 to 40 km and the LGM ice-sheet towards the west by about 20km. For firm conclusions, higher resolution experiments are needed.

(2) Differences in the treatment of processes in the model

- coordinate system
- numerics
- isostasy
- mass balance input
    1. ablation degree day factor
    2. accumulation: the dependence on temperature and the way of deciding rain or snow.
- temperature input
- calving process (how do we cut off ice?)
- sliding (yes / no)
- enhancement factor

(3) Plan after the meeting

(3-1) A questionnaire will be sent out by Catherine Ritz after the meeting concerning the treatment of processes.
(3-2) Resubmission of results is allowed and requested if necessary.
(3-3) New experiments with GCM outputs for global warming scenarios can be proposed as next phase experiments.

Figure captions

Figure 5.1: Surface elevation maps obtained with the steady state experiment level 3 (SSL3)

Figure 5.2: Evolution of the area covered by ice along the climatic cycle with the experiments CCL2 (prescribed parameters) and CCL3 (preferred parameters)

Figure 5.3: Surface elevation maps obtained with the climatic cycle experiment (CCL3) for the time slice 'present time'

Figure 5.4: Surface elevation maps obtained with the climatic cycle experiment (CCL3) for the time slice '130 kyr BP (Eemian)'

Figure 5.1

Ice surface elevation (km) SSL3

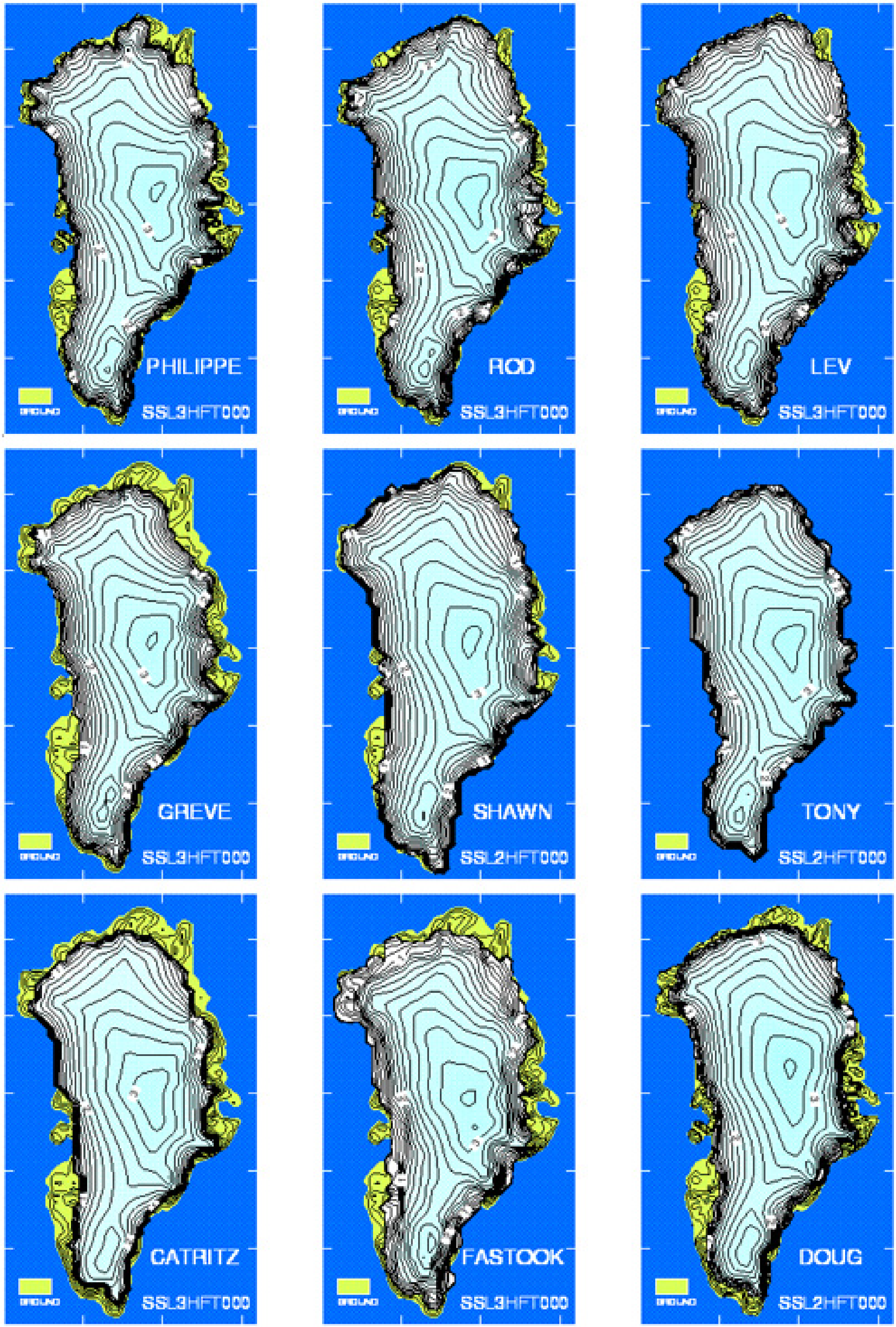
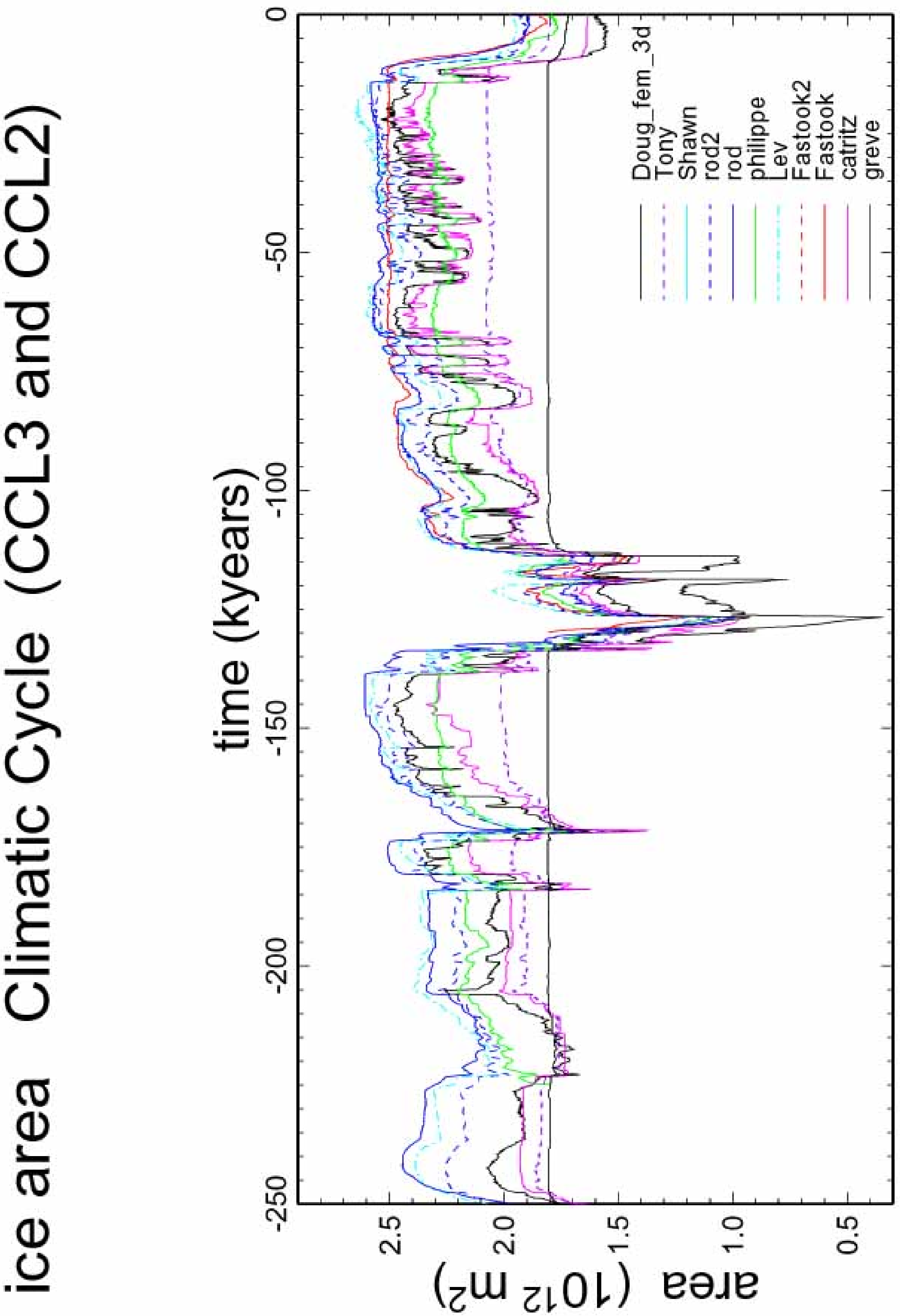


Figure 5.2



ice area Climatic Cycle (CCL3 and CCL2)
time (kyears)
area (10^{12} m^2)
-250
-200
-150
-100
-50
0
2.5
2.0
1.5
1.0
0.5
Doug_fem_3d
Tony
Shawn
rod2
rod
philippe
Lev
Fastook2
Fastook
catritz
greve

Figure 5.3

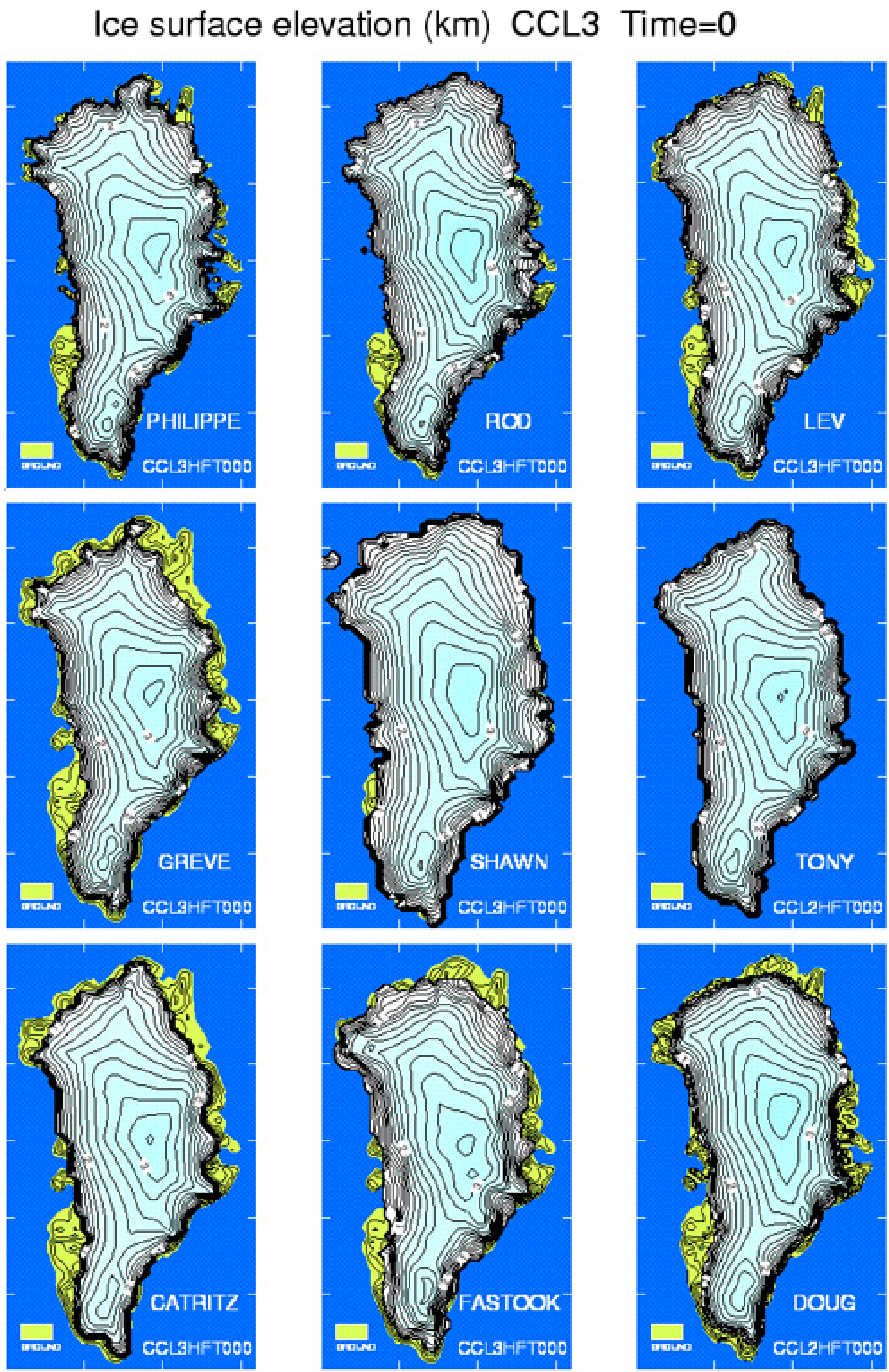
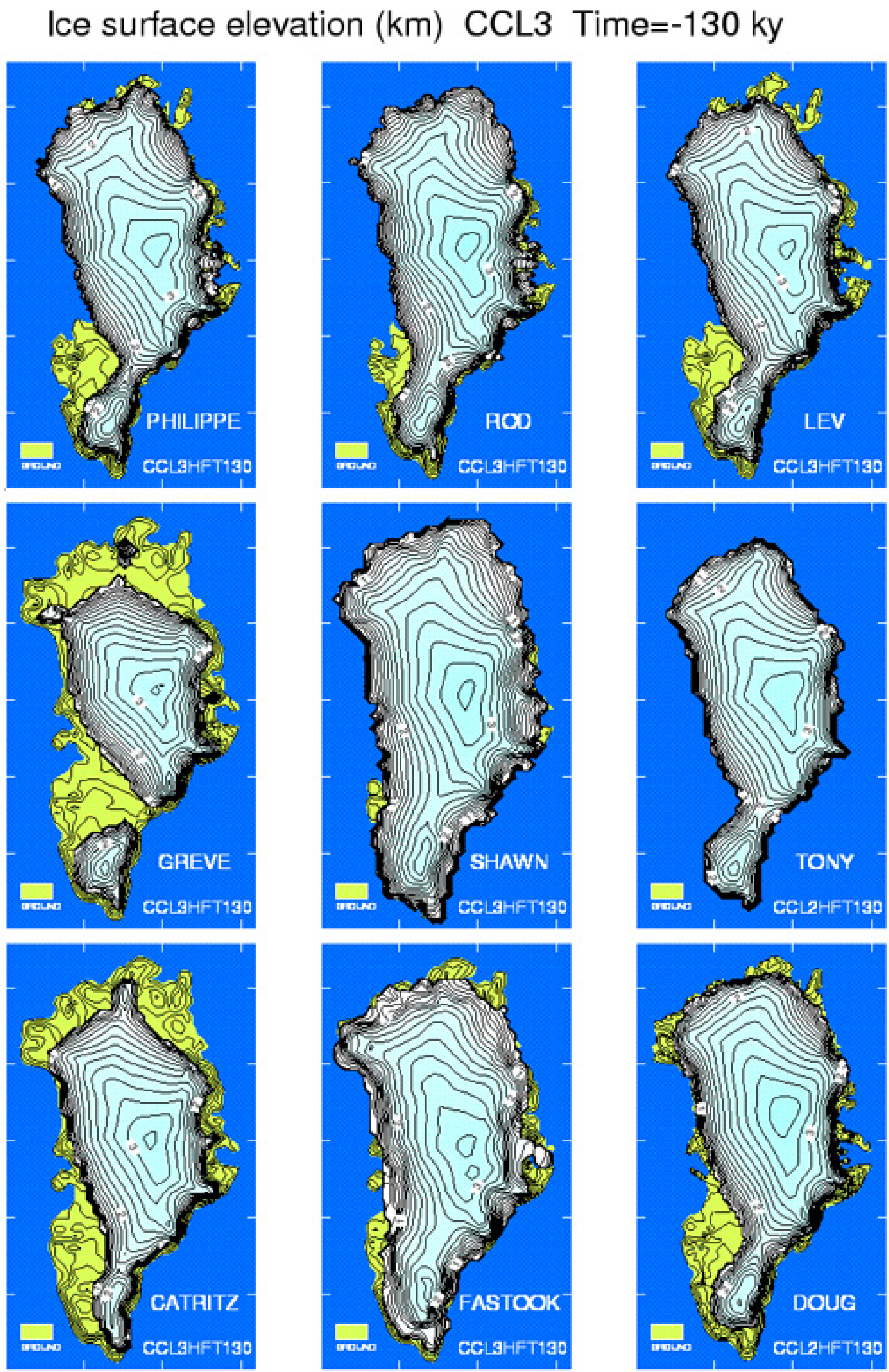

Ice surface elevation (km) CCL3 Time=0
PHILIPPE
CCL3HFT000
ROD
CCL3HFT000
LEV
CCL3HFT000
GREVE
CCL3HFT000
SHAWN
CCL3HFT000
TONY
CCL2HFT000
CATRITZ
CCL3HFT000
FASTOOK
CCL3HFT000
DOUG
CCL2HFT000

Figure 5.4


Ice surface elevation (km) CCL3 Time=-130 ky
PHILIPPE
CCL3HFT130
ROD
CCL3HFT130
LEV
CCL3HFT130
GREVE
CCL3HFT130
SHAWN
CCL3HFT130
TONY
CCL2HFT130
CATRITZ
CCL3HFT130
FASTOOK
CCL3HFT130
DOUG
CCL2HFT130

6. INTERCOMPARISON OF ANTARCTIC MODELS

EISMINT Phase II
Comparison of existing Antarctic models

Coordinator:
Philippe Huybrechts

1. Introduction

The objective is to compare existing models of the Antarctic ice sheet, and to find out how they perform under prescribed climatic and environmental forcings. Compared to the other intercomparison tests (grounding-lines, ice shelves and Greenland), the important new feature is the evaluation of treatments for grounding-line migration in the two horizontal dimensions.

The experiments aim at comparing steady state behaviour (with/ without a moving grounding line), and at comparing model behaviour during the glacial cycles and under enhanced greenhouse warming conditions.

Today, only one or two models exist that deal with the interaction between ice-sheet and ice-shelf flow in an explicit way, but most other models of the Antarctic ice sheet contain some or other ad-hoc treatment to find the position of the grounding line.

As such, the experiments first of all concern 3D time-dependent thermomechanical models with a coupled ice shelf, but part of the experiments can also be performed by models without thermomechanical coupling (vertically integrated) or by models that only consider grounded ice-sheet flow (with/ without a moving grounding line).

A preliminary version of this document was originally prepared by Michael Verbitsky.

2. The model domain

The model calculations are performed on a square grid that is laid out over a polar stereographic projection with standard parallel at 71°S, which coincides with the domain of the Drewry (1983) map folio. The grid is centred at the pole and comprises a 141 x 141 gridpoint matrix. The gridpoint distance is 40 km (Huybrechts, 1992). The following transformation formulas apply between geographical and map coordinates:

$$x = 2Rk\tan(\pi/4 + \phi/2)\sin\lambda$$
$$y = 2Rk\tan(\pi/4 + \phi/2)\cos\lambda$$

$$\phi = \arcsin(-\cos c)$$
$$\lambda = \arctan(x/y)$$
c = 2arctan ((x**2+y**2)**0.5/(2Rk))

$i = x/\Delta x + 71$ $\qquad\qquad$ $j = y/\Delta y + 71$

ϕ = latitude, negative in southern hemisphere

λ = longitude, increases clockwise

R = 6371221 m
k = 0.9728
Δx = 40000 m
Δy = 40000 m

3. Data

3.1. Geometric datasets (Huybrechts, 1992; 1993):

Bedrock elevation:	**bed40eis.dat**
Surface elevation:	**sur40eis.dat**
Ice thickness:	**thi40eis.dat**
Ice mask:	**mask40eis.dat**

<u>These files are written as follows:</u> <u>1st record:</u> title
<u>2nd record:</u> Fortran format to read one row
<u>record 3 to 2681:</u> data for 141 rows, written as 141 blocks consisting of the row number, which is followed by 18 records with data for the 141 columns.

<u>An easy way to read these data would be:</u>

```
      REAL DATA(NX,NY)
      CHARACTER*80,TITLE,FMT
      READ(1,1000)TITLE
      READ(1,1000)FMT
      DO 2000 J=1,NY
 2000 READ(1,FMT)KDUM,(DATA(I,J),I=1,NX)
 1000 FORMAT(A80)
```

where NX=141, NY=141.

3.2. Forcing during glacial cycles: **foranteis.dat**

This file contains 2201 records with forcing data over last two glacial cycles at a 100-year resolution (220 ky BP - present). First column = year; second column = SPECMAP sea-level (m); third column = Vostok temperature change (deg. C).

3.3. Surface temperature (Huybrechts, 1993) :

mean annual temperature Ta (in deg C):
Ta = 34.46 - 0.00914*Hsur -0.68775*latitude

summer temperature Ts (in deg. C):
Ts = 16.81 - 0.00692*Hsur - 0.27973*latitude

where Hsur is surface elevation and latitude is taken positive

3.4. Accumulation rate [m/y of ice equivalent], after Huybrechts and Oerlemans (1988):

M = 1.5 * 2**(Ta/10)

4. Experiments

We consider 4 different experiments:

<u>Level two:</u> the present-day control experiment with a fixed grounding line and a prescribed set of parameters

<u>Level three:</u> three experiments with the models as they are with a preferred set of parameters and degrees of freedom (present-day equilibrium, glacial cycle, response to enhanced greenhouse warming)

4.1. Control experiment: present-day equilibrium

The initial condition is given by the present surface and bedrock topography. For the first test (level two), the grounding line is fixed to its present condition by using the mask-file. There is no isostatic compensation of the bedrock, no bottom melting, no heat conduction in the bedrock and no basal sliding. The model is then relaxed to steady state with the prescribed set of parameters given in §5. The criterium for steady state is a change in total ice volume of less than 0.01% in 1000 years.

As the next step, use your preferred model with a preferred set of parameters and as many degrees of freedom as your model allows to simulate as closely as possible the present ice sheet, again in steady state.

4.2. Evolution during the last two glacial cycles

Use the data in forcanteis.dat to force sea-level and temperature and make a simulation over the last two glacial cycles. Initial condition is the one obtained with your preferred model under §4.1.

4.3. Response to enhanced greenhouse warming

The initial ice sheet is the present steady state obtained with your preferred model.

The temperature scenario is identical to the one imposed for the Greenland intercomparison experiments and covers 500 years: between 0 (start of the simulation) and 80 years, the temperature increases with the rate of 0.035 °C/year (2.8°C for 80 years). Between 80 and 500 years, the warming rate is 0.0017°C/year (.714 °C for 420 years). The total temperature increase is 3.514 °C. No sea-level forcing.

5. Model parameters

- Glen's flow law with exponent n = 3 :
  $\varepsilon_{ij} = m.a \exp(-Q/RT^*)\, \tau^2\, \tau'_{ij}$ with:
  - m = 5
  - $T^* < 263.15$ K a $= 1.14\ 10^{-5}$ $Pa^{-3}a^{-1}$ Q = 60 kJ mol^{-1}
  - $T^* > 263.15$ K a $= 5.47\ 10^{10}$ $Pa^{-3}a^{-1}$ Q = 139 kJ mol^{-1}

- gravity: 9.81 m s^{-2}
- ice density: 910 kg m^{-3}
- water density: 1028 kg m^{-3}
- conversion factor for seconds to year: 1 year = 31556926 seconds
- geothermal heat flux: 0.0546 W m^{-2}
- triple point of water: 273.15 K
- thermal conductivity: 2.1 W m^{-1} K^{-1}

- specific heat capacity: 2009 J kg^{-1} K^{-1}
- latent heat capacity: 335 kJ kg^{-1}
- dependence of the pressure melting point on depth: $T^* = 273.15 - 8.7 \times 10^{-4} \times$ depth

6. Format of results

All results are to be put on the anonymous ftp server at the Vrije Universiteit Brussel:

ftp.vub.ac.be (134.184.129.7)

on the directory: **/pub/exchange**

These files will only remain there for 10 days and file names are not visible, so please send an E-mail to Philippe Huybrechts to warn that data have been sent, together with a list of the file names.

There are several types of results: snapshots (horizontal fields and transect) and time dependent variables. Participants should also provide a file with information concerning their model: characteristics, model parameters, references, etc...

<u>File names are to be coded as follows:</u>

wwxxyyzz.name

where **ww** refers to the type of data:
hf = 2d horizontal field
ht = horizontal transect
ts = time series

where **xx** refers to the type of experiment:
cr = control run (prescribed set of parameters)
er = control run (preferred model)
gc = glacial cycle simulation (preferred model)
gw = greenhouse warming (preferred model)

where **yy** refers to the time:
t000 = steady state (cr/ er) or present (gc)
t125 = Eemian minimum (in area)
t060 = -60 ka
t016 = Last Glacial Maximum (in area)
t006 = -6 ka
t100 = +100 years
t500 = +500 years

where **zz** refers to the type of variable **(only hf)**:
se = surface elevation (m)
it = ice thickness (m)
be = bed elevation (m)
st = surface temperature (°C)
bt = basal temperature (relative to melting) (°C)
ac = surface mass balance (m/y ice equivalent)
vm=vertically averaged velocity magnitude (m/y)

and **name** has a length of maximally 5 characters based on your name or group

For example, the file **htert000.phil** contains my data for the horizontal transect of the control run with my preferred model in steady state.

In addition, the file **info.name** will contain the specific information on your model.

6.1. Horizontal fields

These files should be written in the same way as the input files, with the data written in format F10.4. Data are required for:

1. surface elevation (m)
2. ice thickness (m)
3. bed elevation (m)
4. surface temperature (°C)
5. basal temperature (relative to melting) (°C)
6. surface mass-balance
7. vertically averaged velocity magnitude (m/y)

<u>An appropriate way to write these files is:</u>

```
      REAL DATA(NX,NY)
      WRITE(1,1000)
      WRITE(1,1001)
      DO 100 J=1,NY
 100  WRITE(1,1002)J,(DATA(I,J),I=1,NX)
 1000 FORMAT('TITLE')
 1001 FORMAT('(I5,/,17(8F10.4,/),5F10.4)')
 1002 FORMAT(I5,/,17(8F10.4,/),5F10.4)
```

where NX=141, NY=141.

Outside the area of interest (e.g. in the ice shelf or ocean area) use the undefined value of **999.9999**

6.2. Horizontal transects

This is for a transect which cuts across the West Antarctic ice sheet, the Ross Ice Shelf and the East Antarctic ice sheet, for J=51.

Format of the file:

line 1: nz (# gridpoints in vertical direction)
line 2 ->142: from i=1 to i=141

i	column 1
surface elevation (m)	column 2
ice thickness (m)	column 3
bed elevation (m)	column 4
elevation of ice bottom (m)	column 5
surface temperature (°C)	column 6
surface mass balance (m/y i.e.)	column 7
vertically averaged velocity (m/y)	column 8

line 143 -> end: from i = 1,141
from surface to bottom

i	column 1	
z position (m)	column 2	
x-velocity (m/y)	column 3	
y-velocity (m/y)	column 4	
z-velocity (m/y)	column 5	
temperature (°C)	column 6	(relative to melting)

Columns are separated by at least one blanc.

6.3. Time-dependent files

Data every 100 years for the steady state runs and the glacial cycle simulations
Data every 10 years for the greenhouse warming scenarios

These files contain data in format: **(1x, f8.0, 3(1x,e14.6), 1x, f8.4, 2(1x, f7.4))**

1. time (years)
2. grounded ice area (m^2)
3. grounded ice volume (m^3)
4. area of grounded ice at pressure melting point (m^2)
5. mean basal temperature of grounded ice, relative to melting (°C)
6. mean accumulation rate over grounded ice (m/y ice equivalent)
7. mean ablation rate over grounded ice (if any) (m/y ice equivalent)

7. Addresses

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8. References

Drewry, D. (1983): Antarctic glaciological and geophysical folio. Scott Polar Research Institute (Cambridge).

Huybrechts Ph. and J. Oerlemans (1988): Evolution of the East Antarctic ice sheet: a numerical study of thermo-mechanical response patterns with changing climate, Annals of Glaciology 11, 52-59

Huybrechts, Ph. (1992): The Antarctic ice sheet and environmental change: a three- dimensional modelling study, Berichte zur Polarforschung 99, 241 p.

Huybrechts Ph. (1993): Glaciological modelling of the Late Cenozoic East Antarctic Ice Sheet: stability or dynamism?, Geografiska Annaler 75 A (4), 221-238.

6.1. Introduction

The major new feature and complication of modeling the Antarctic ice sheet is the coupling with an ice shelf, so that one needs to deal with grounding-line migration in an explicit way. Up to the Grindelwald meeting, only one such operational model existed, making a comparison rather restricted and perhaps not entirely worthwhile. However, prior to the meeting a second such model had been developed by the Grenoble group.

In the course of this activity, Antarctic models were tested under three situations, namely: (i) present-day steady-state behaviour, both with prescribed (Level 2) as under freely chosen parameters (Level 3), (ii) behaviour during the last two glacial cycles, and (iii) response to future climate warming on a 500-year time scale.

6.2. The experimental model set-up

see the preceding text proposed to the participants by Philippe Huybrechts (February 1997).

6.3. Participating models

All models are 3-D, and include thermomechanical coupling and bedrock adjustment.

Author	Type of model
S. Marshall (Vancouver)	no ice shelf, fixed grounding line no longitudinal stress 15 layers in vertical: 10%-5% ice thickness
R. Greve/ R. Calov (Darmstadt)	no ice shelf, fixed grounding line no longitudinal stress polythermal ice calculation 61 layers in vertical: 10%-1% ice thickness
C. Ritz/ V. Rommelaere (Grenoble)	flow calculated in three regions grounding zone is 'shelfy stream' moving grounding line 21 layers in vertical: 5% of ice thickness
P. Huybrechts (Brussels/ Bremerhaven)	flow calculated in three regions grounding zone treated as grounded ice moving grounding line 11 layers in vertical: 15%-2% ice thickness

These 4 models fall in two groups. The first two only deal with grounded ice and have a fixed grounded domain. The last two deal with the entire ice-sheet system consisting of grounded ice, ice shelf and a transition of some kind in between these two areas. The Huybrechts and Grenoble models are rather similar, except that the Grenoble model considers a linear rheology for the ice shelves (n=3 in Huybrechts model), and that both models have a different treatment of the transition zone around the grounding line. In the Huybrechts model, this zone is made up of one gridpoint, where all stresses are included in the effective stress of the flow law. In the Grenoble model, there is a special treatment for a shelfy stream, that is, for grounded ice that is treated as an ice shelf with low basal friction for all gridpoints that either border an ice shelf, have a low effective normal pressure, or a low basal shear stress. The latter treatment presents an important improvement over previous models.

Other differences between all 4 models concern the vertical layering, which influences the accuracy of the solution, in particular at the base. The Darmstadt model considers polythermal ice, and thus accounts for the effects of the intergranular water content on the flow properties of ice.

6.4. Results

6.4.1. Steady state experiments

The first experiment aimed at reproducing the present-day Antarctic ice sheet in steady state with prescribed parameters and datasets, and with a fixed grounding line (Level 2). From the results presented at the meeting, it could be seen that apparently no gross errors were made in implementing the model set-up by the various groups. Around 100000 years were required to obtain a stationary state. In all, most of the model results were quite similar, in particular for the Huybrechts and Grenoble models, which produced nearly identical fields. Apparent deviations included problems with the thermal fields in Wilkes Land in the Darmstadt model, where up to 50% of the vertical ice column was found to consist of temperate ice and also thickness was much lower. This behaviour was attributed to the neglect of basal sliding, which would lead to numerical instabilities at the base in their model. In the Marshall model, some problems appeared in the vertical transects (error in writing files, numerical instabilities?), see Figs. 6.1 and 6.2.

Introducing a free choice of parameters and a freely moving grounding line (Level 3), demonstrated that the Huybrechts and Grenoble models were able to produce a stationary West Antarctic ice sheet. Common to both models was also the recession of the grounding line along the most overdeepened outlet glaciers of the East Antarctic ice sheet, especially for the Ninis and Mertz glaciers. The Grenoble model also produced a flatter ice sheet in the Siple Coast area, which is more in accordance with the observations, and generally attributed to high basal sliding and/ or low basal traction.

A comparison between the Huybrechts model for Level 2 and Level 3 experiments also indicated that the grounding line position is not very much controlled by the surface climate.

6.4.2. Glacial cycle experiments

The models were respectively forced by the Vostok isotope temperature and the SPECMAP sea-level records over the last two glacial cycles. The evolution of ice volume is shown in Fig. 6.4. Time slices of surface elevation are presented as Figs. 6.5-6.7. Concentrating on the models which treat grounding-line migration (Huybrechts and Ritz/ Rommelaere) demonstrates that both models are able to reproduce a full cycle of growth and retreat, and produce a very similar maximum extent during the Last Glacial Maximum. The major difference between the two models, however, is that the Huybrechts model produces a larger amplitude cycle with a phase shift of about 5000 years compared to the Grenoble model. In the Grenoble model, the deglaciation already starts at 16 ky BP, whereas in the Huybrechts model this occurs after around 9 ky BP. Conclusive field evidence in support of either scenario, however, is lacking.

Another difference between both models are the large areas of low surface slopes and high velocities produced at times in the Grenoble model, and which is due to their specific treatment for a 'shelfy stream', or rather, a 'shelfy plate'.

6.4.3. Greenhouse warming experiments

All models produced a larger mass balance, and thus growth of grounded ice thickness. This effect was counteracted in the Grenoble model because of important grounding-line recession along the Siple Coast. Another point which also became clear is the important role played by viscosity changes of the ice shelf, and which are linked to temperature (Fig. 6.8).

6.5. Conclusion

From these experiments, it can be concluded that there are presently two more or less complete Antarctic models available. These two models produce many similar results, but also exhibit differences, most notably related to grounding-line migration in the Ross Sea sector of West Antarctica. The predominant effect of Antarctic ice sheet changes results from grounding-line changes, which affect all variables in the ice sheet. This effect is far larger than the inclusion of e.g. the polythermal ice calculation.

A concensus on the response of the Antarctic ice sheet to warmer climates could not be reached. The main uncertainty is due to the amount of grounding-line change and the mechanisms playing in ice shelf and grounding zone.

6.6. Figure captions

Figure 6.1: Basal temperatures for the control run, Level 2 specified model parameters (hfcrt000bt).

Figure 6.2: Vertical transect of temperature for the control run, Level 2 parameters (htcrt000.temp).

Figure 6.3: Vertically integrated horizontal velocities for the control run, Level 2 specified parameters (hfcrt000vm).

Figure 6.4: Grounded ice volume for the glacial cycle experiment (tsgc).

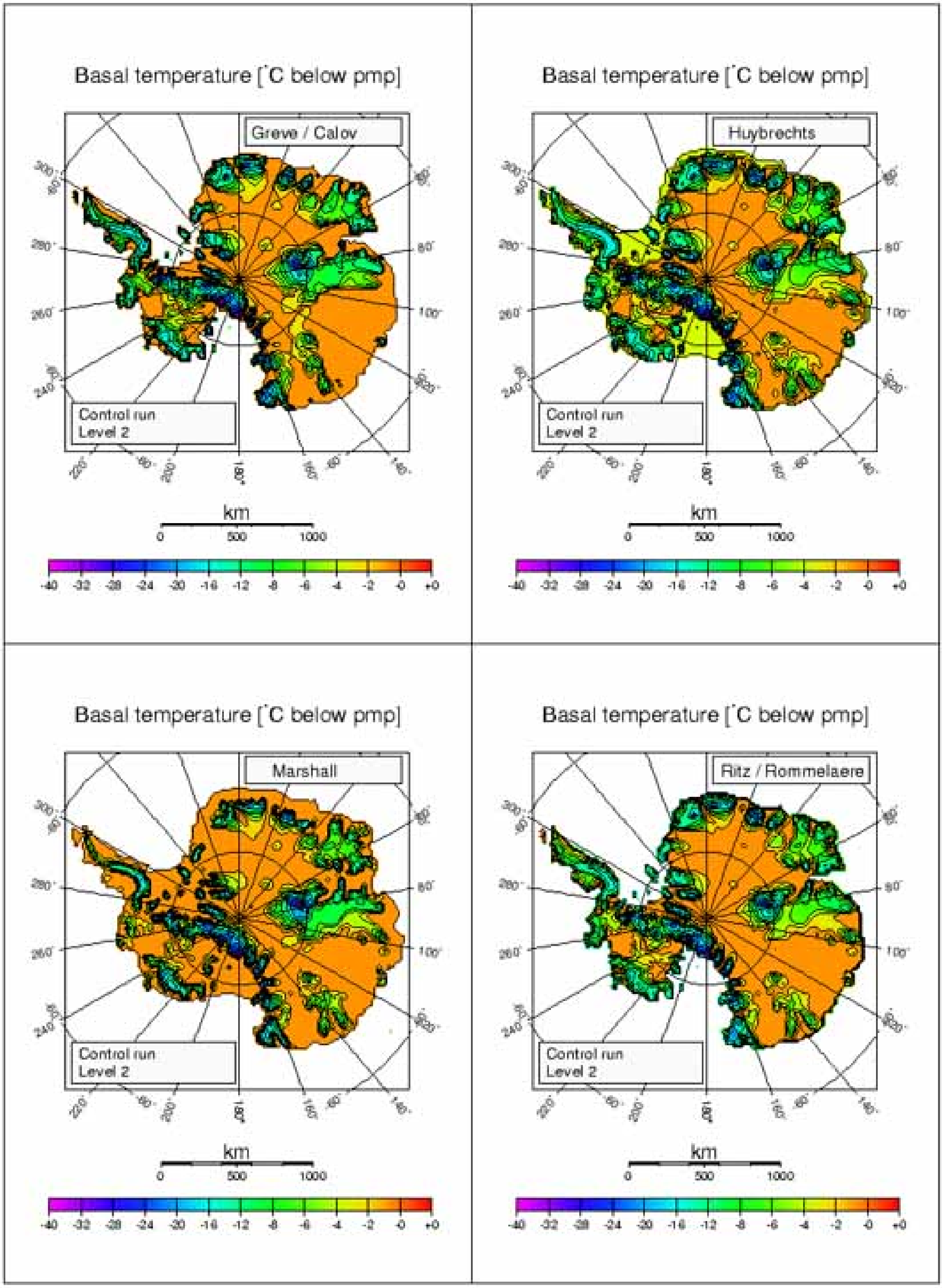
Figure 6.5: Surface elevation for the glacial cycle experiment, Eemian minimum (hfgct125se).

Figure 6.6: Surface elevation for the glacial cycle experiment, Last Glacial Maximum (hfgct016se).

Figure 6.7: Surface elevation for the glacial cycle experiment, Present-day (hfgct125se).

Figure 6.8: Grounded ice volume for the greenhouse warming experiment (tsgw).

Figure 6.1



Basal temperature [˚C below pmp]
Greve / Calov
Control run
Level 2
km
0 500 1000
-40 -32 -28 -24 -20 -16 -12 -8 -6 -4 -2 -0 +0
Basal temperature [˚C below pmp]
Huybrechts
Control run
Level 2
km
0 500 1000
-40 -32 -28 -24 -20 -16 -12 -8 -6 -4 -2 -0 +0
Basal temperature [˚C below pmp]
Marshall
Control run
Level 2
km
0 500 1000
-40 -32 -28 -24 -20 -16 -12 -8 -6 -4 -2 -0 +0
Basal temperature [˚C below pmp]
Ritz / Rommelaere
Control run
Level 2
km
0 500 1000
-40 -32 -28 -24 -20 -16 -12 -8 -6 -4 -2 -0 +0

Figure 6.2

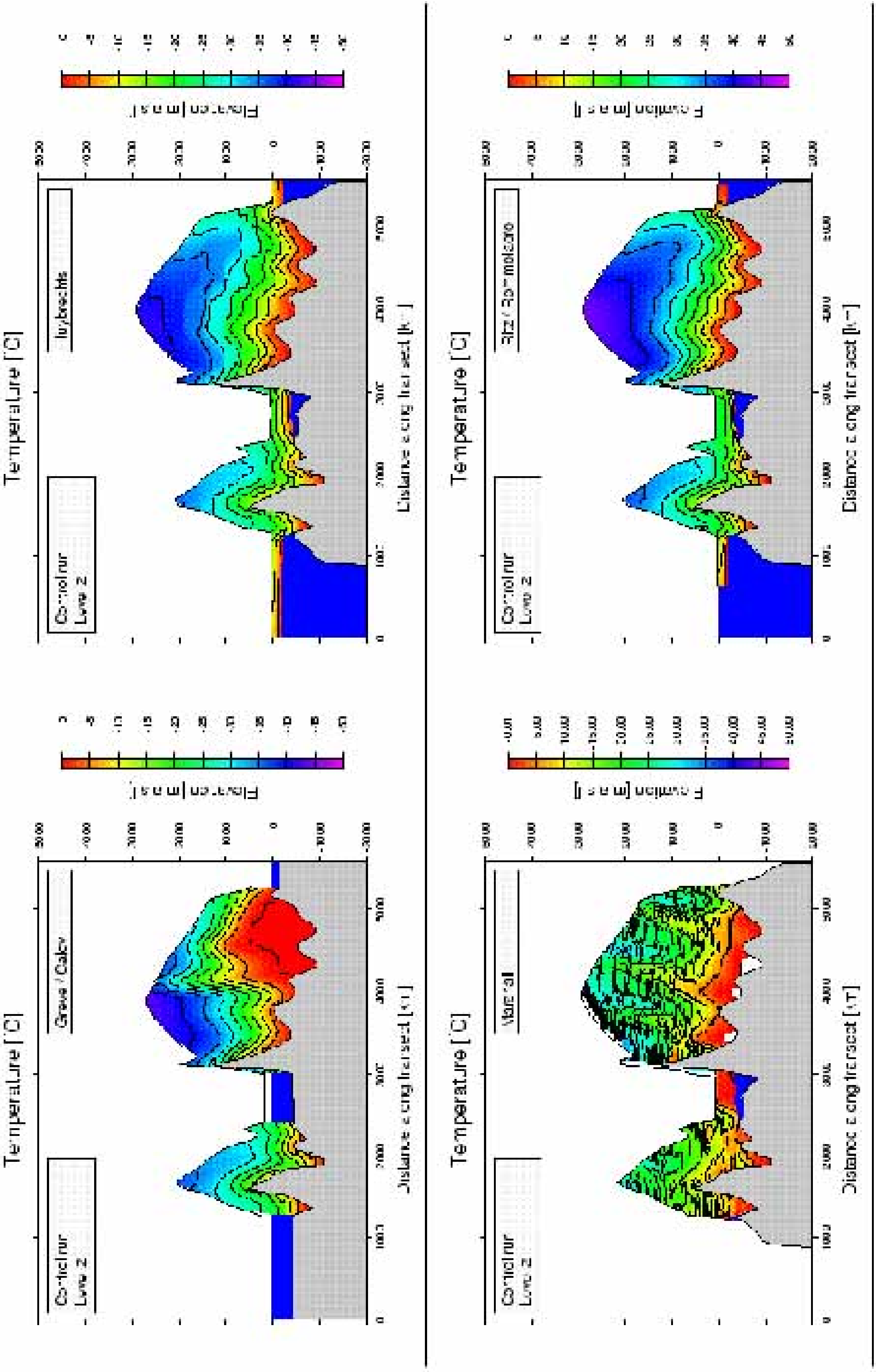
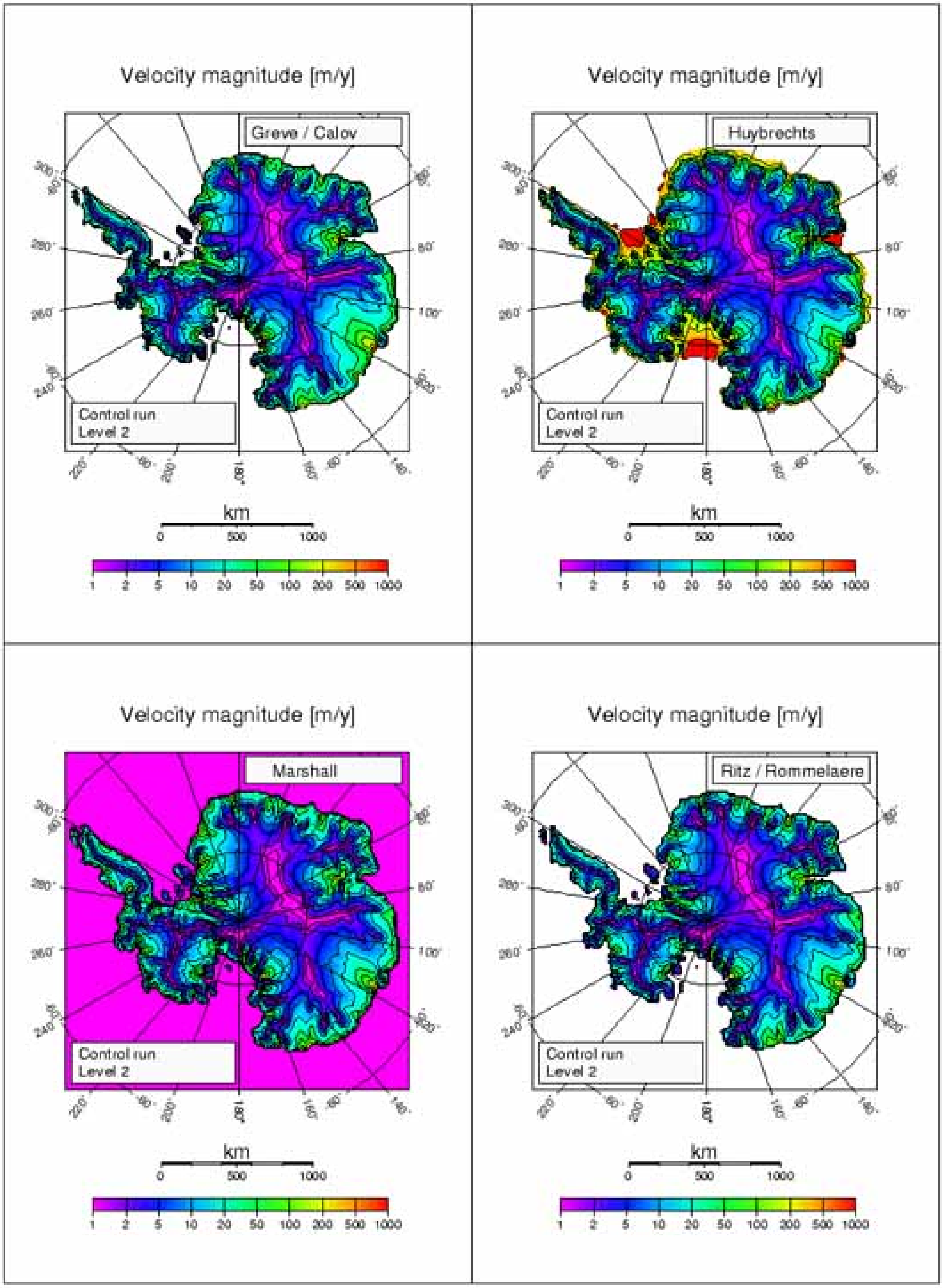
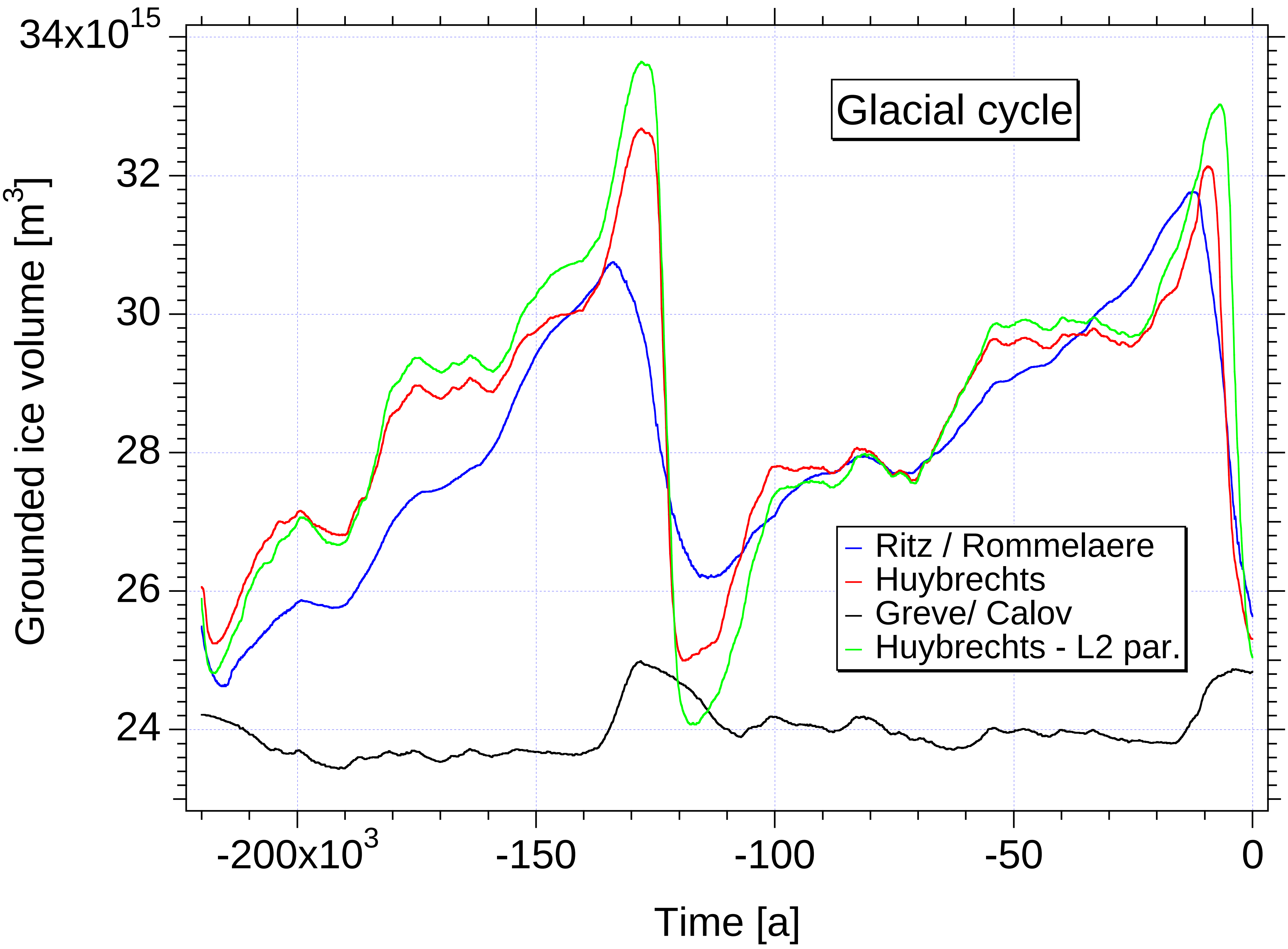


Figure 6.3


Velocity magnitude [m/y]
Greve / Calov
Control run
Level 2
Velocity magnitude [m/y]
Huybrechts
Control run
Level 2
Velocity magnitude [m/y]
Marshall
Control run
Level 2
Velocity magnitude [m/y]
Ritz / Rommelaere
Control run
Level 2
km
0
500
1000
1
2
5
10
20
50
100
200
500
1000



Glacial cycle
Ritz / Rommelaere
Huybrechts
Greve/ Calov
Huybrechts - L2 par.
Grounded ice volume [m^3]
34x10^15
32
30
28
26
24
Time [a]
-200x10^3
-150
-100
-50
0

Figure 6.4

Figure 6.5

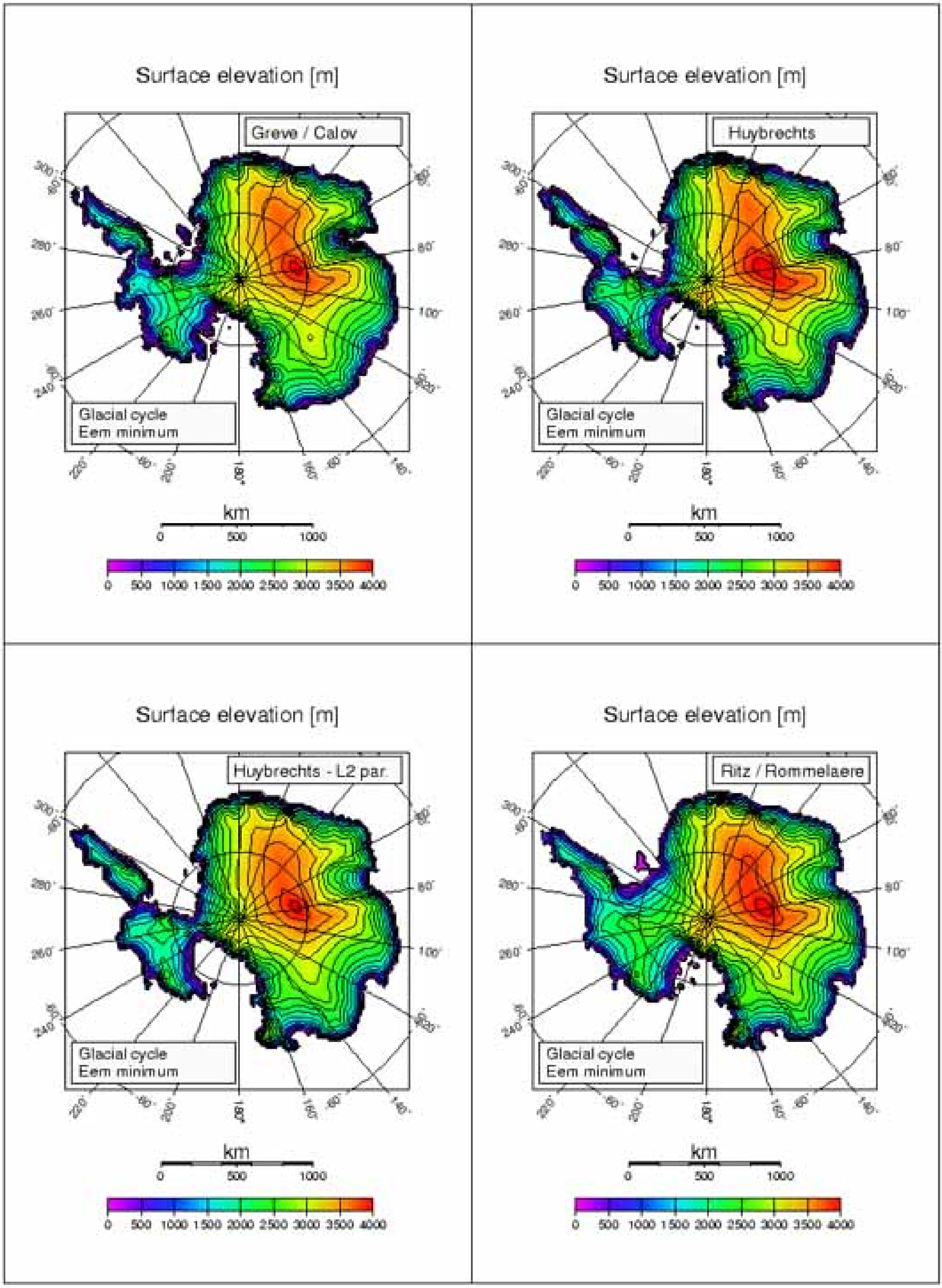

Surface elevation [m]
Greve / Calov
Glacial cycle
Eem minimum
km
0
500
1000
0
500
1000
1500
2000
2500
3000
3500
4000
Surface elevation [m]
Huybrechts
Glacial cycle
Eem minimum
Surface elevation [m]
Huybrechts - L2 par.
Glacial cycle
Eem minimum
Surface elevation [m]
Ritz / Rommelaere
Glacial cycle
Eem minimum

Figure 6.6

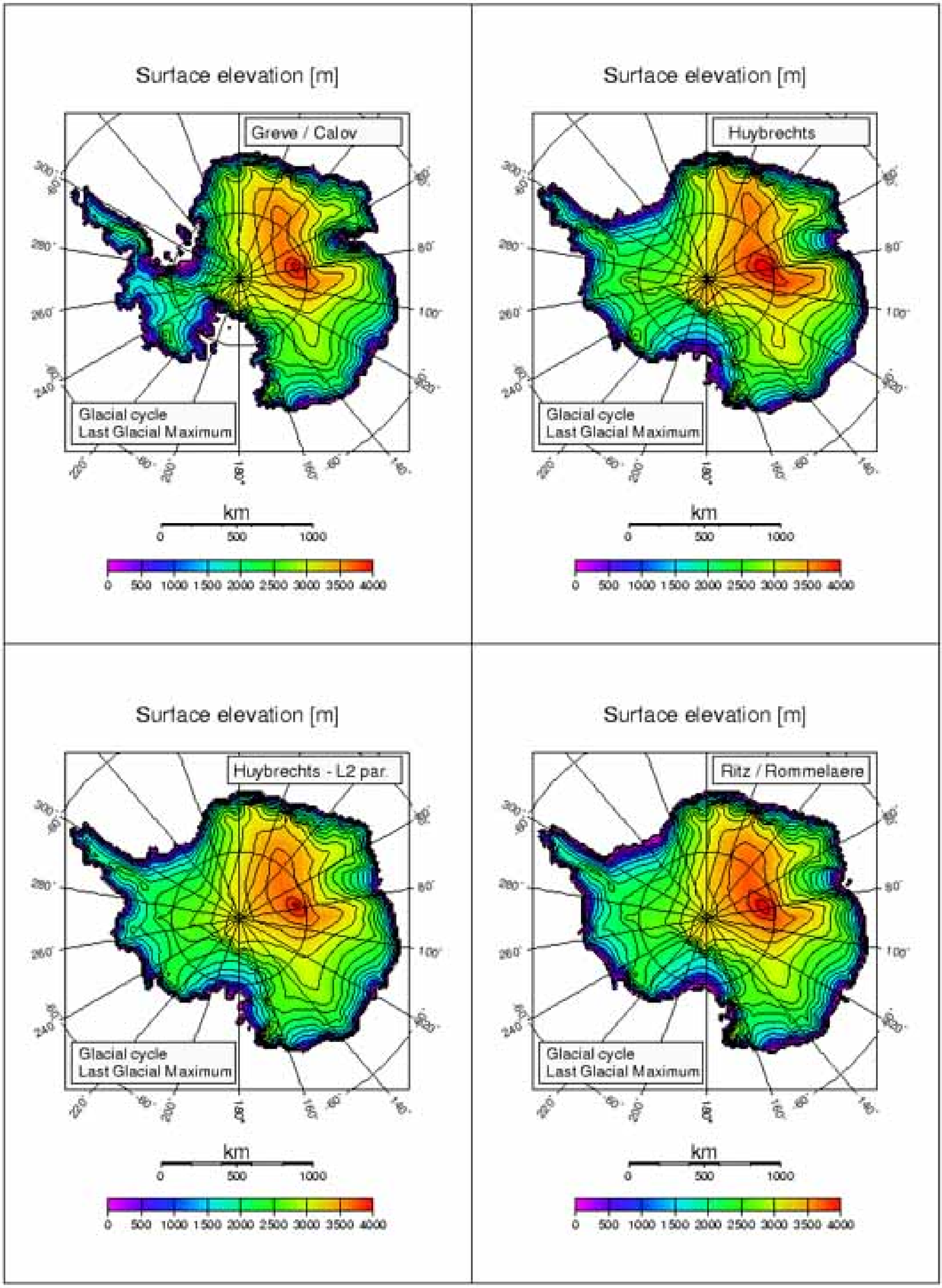
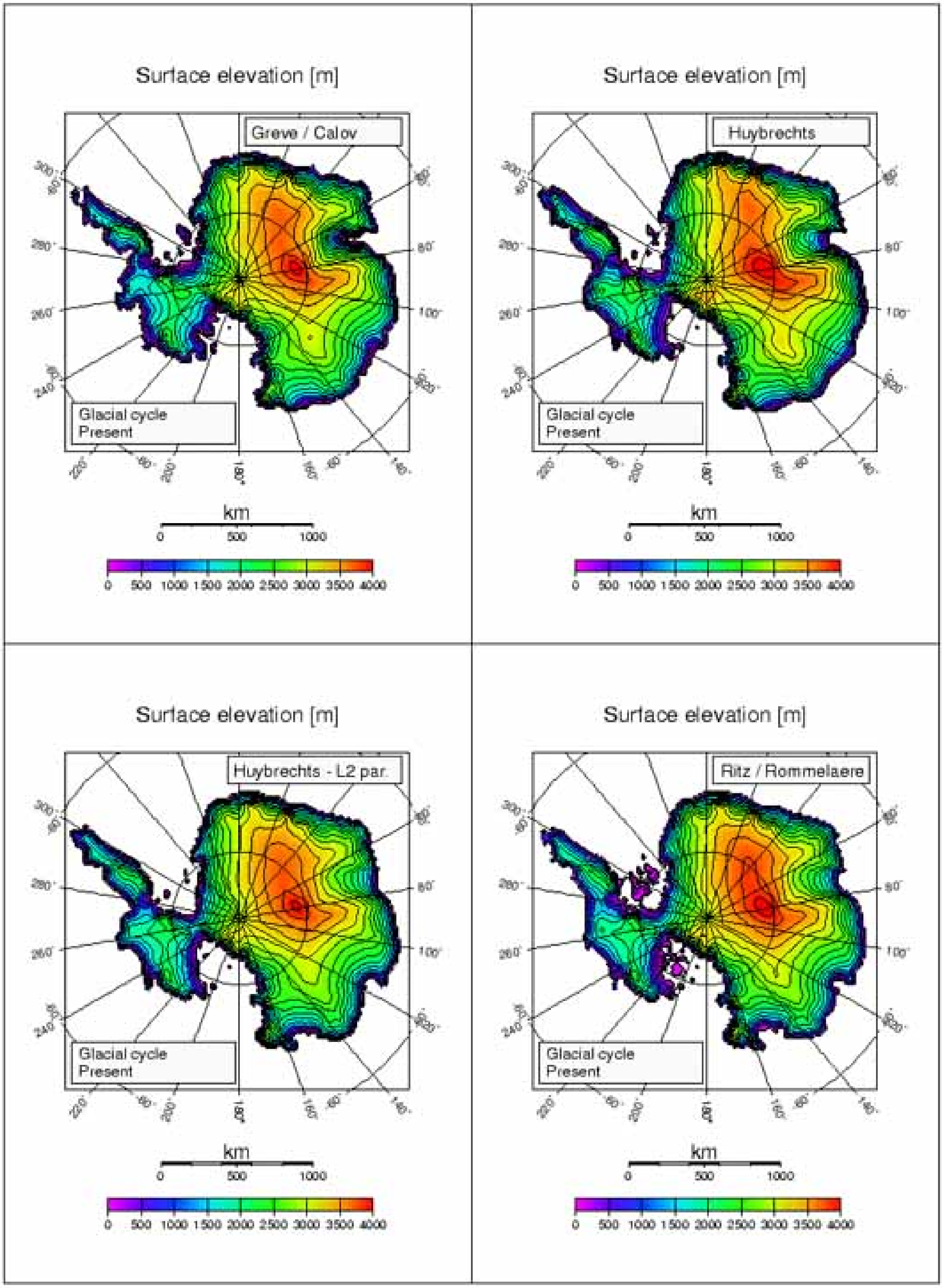

Surface elevation [m]
Greve / Calov
Glacial cycle
Last Glacial Maximum
km
0
500
1000
0
500
1000
1500
2000
2500
3000
3500
4000
Surface elevation [m]
Huybrechts
Glacial cycle
Last Glacial Maximum
km
0
500
1000
0
500
1000
1500
2000
2500
3000
3500
4000
Surface elevation [m]
Huybrechts - L2 par.
Glacial cycle
Last Glacial Maximum
km
0
500
1000
0
500
1000
1500
2000
2500
3000
3500
4000
Surface elevation [m]
Ritz / Rommelaere
Glacial cycle
Last Glacial Maximum
km
0
500
1000
0
500
1000
1500
2000
2500
3000
3500
4000

Figure 6.7


Surface elevation [m]
Greve / Calov
Glacial cycle
Present
km
0
500
1000
0
500
1000
1500
2000
2500
3000
3500
4000
Surface elevation [m]
Huybrechts
Glacial cycle
Present
Surface elevation [m]
Huybrechts - L2 par.
Glacial cycle
Present
Surface elevation [m]
Ritz / Rommelaere
Glacial cycle
Present

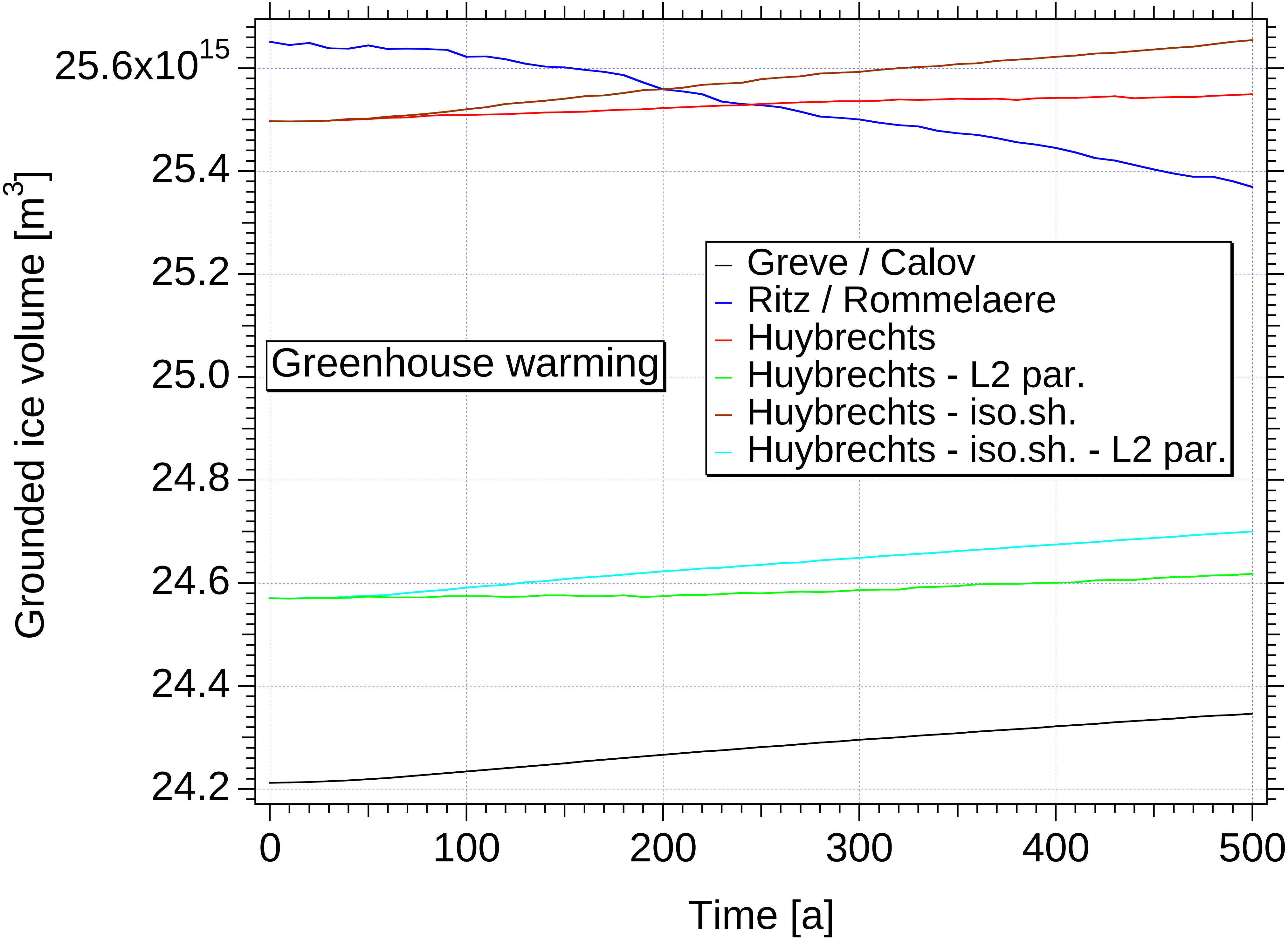

Grounded ice volume [m^3]
25.6x10^15
25.4
25.2
25.0
24.8
24.6
24.4
24.2
0
100
200
300
400
500
Time [a]
Greenhouse warming
Greve / Calov
Ritz / Rommelaere
Huybrechts
Huybrechts - L2 par.
Huybrechts - iso.sh.
Huybrechts - iso.sh. - L2 par.

Figure 6.8

7. INTERCOMPARISON OF ICE-SHELF MODELS

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ICE SHELF MODELS INTERCOMPARISON
SETUP OF THE EXPERIMENTS[1]

The tests proposed below were defined and discussed during an EISMINT workshop held in Brussels (March 29-30th). The purpose of these tests is not to give an overview of what can be done in ice-shelf modeling, but rather to fix benchmarks for future modeling attempts and to detect weakness in the approaches that are commonly used. The experiments may be somewhat restrictive and may not be appropriate for all kinds of model. All suggestions to improve this setup are of course welcome.

I - Tests on ideal geometry

This part is designed to check (whenever possible, meaning when an analytical solution is available) and to compare the results of different models in simplified conditions. The thread of these tests is to simulate the response of an ice-shelf due to a fluctuating ice-stream discharge.

1- Mass conservation

a) tests 1-2

As far as I know, all ice-shelf models treat the Stokes' equations and the ice mass conservation independently (basically ice-shelf models have two governing equations instead of one for grounded ice sheet models). The following test is a classical means to see how accurate is the advection scheme (or mass conservation scheme, in our case). Let's consider a square ice shelf with a fixed velocity field. An ice-stream is fluctuating at a boundary of the domain and we want to check whether or not our conservation scheme is able to propagate the signal of the ice-stream along the ice shelf.

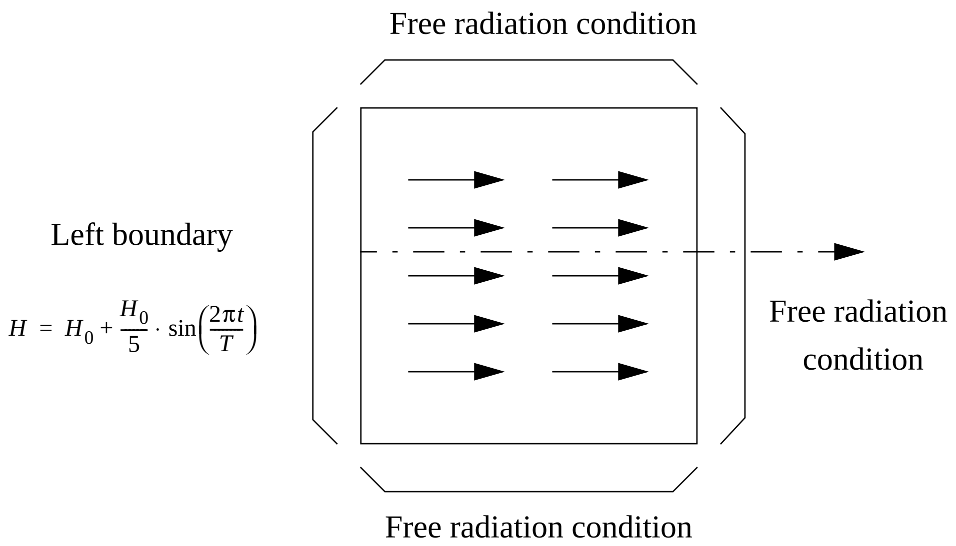
parameters of run 1
- L=200km (length and width of the ice-shelf).
- velocity field: $(u_0, 0)$ with u_0=400m/a
- initial thickness field: H_0 = 500m
- period of fluctuation: T=200 years
- let the system evolve during 500 years (=2.5T)
- numerical resolution: (FD: 41x41 gridpoints or an equivalent number of nodes for FE).

1. This is an evolving document. An updated version (postscript file) can be accessed by anonymous ftp on alaska.grenet.fr (130.190.75.2) in the /pub/EISMINT2 directory.

- time step: user's choice, but it has to be less than dx/u_0; a value of 10 years should be accurate.

<u>parameters</u> of run 2:

The same as in the previous run, but with a resolution of 81x81 gridpoints (or its equivalent in terms of number of nodes). A time step of 5 years is recommended.



NB1: this is a one-dimensional problem which can also be performed to test a flow-line model.

NB2: The analytical solution (wave propagation equation) is: $H(x, y) = H_0 + \frac{H_0}{5} \cdot \sin\left(\frac{2\pi}{T} \cdot \left(t - \frac{x}{u_0}\right)\right)$

<u>b) tests 3-4</u>

In two dimensions, problems with the numerical treatment of conservation laws may arise when fluxes are not perpendicularly to a grid cell. Tests 3 and 4 are formally identical to test 1 and 2 but with a rotation of the numerical domain.

<u>parameters</u> of run 3:

- initial thickness field: constant thickness of 500m.
- velocity field (u_1,v_1), with $u_1 = 160 \cdot \sqrt{5}$ m/a and $u_1 = 80 \cdot \sqrt{5}$ m/a.
- period of fluctuation: T=200 years
- let the system evolve during 500 years (=2.5T)
- numerical resolution: (FD: 41x41 gridpoints or an equivalent number of nodes for FE).
- recommended time step: 10 years.

<u>parameters</u> of run 4:

The same as in the previous runs but with a higher resolution (81x81 gridpoints or equivalent number of nodes)

recommended time step: 5 years.

<u>c) format of the results</u>

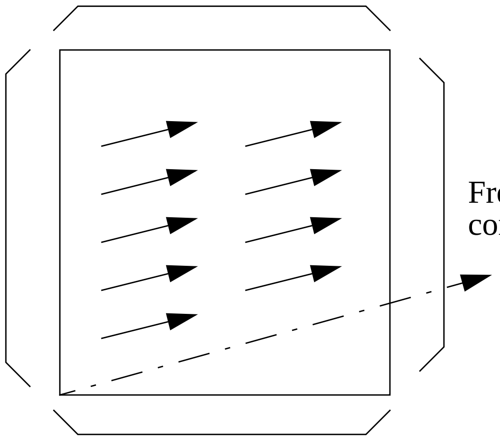
For each run, I would like the participant to provide me the following files:

✔ adv$n$c.$name: where $n is the test number (from 1 to 4), $c is a character you may have to use if you test several schemes and $name is the participant's name.

Free radiation condition

Left boundary

$$H = H_0 + \frac{H_0}{5} \cdot \sin\left(\frac{2\pi}{T} \cdot \left(t - \frac{y}{v_1}\right)\right)$$



Free radiation condition

Low boundary $$H = H_0 + \frac{H_0}{5} \cdot \sin\left(\frac{2\pi}{T} \cdot \left(t - \frac{x}{u_1}\right)\right)$$

<u>examples:</u> - adv1a.vince for the first algorithm used by Vince to solve test 1.
- adv3p.pamela for the sixteenth algorithm used by Pamela to solve test 3.

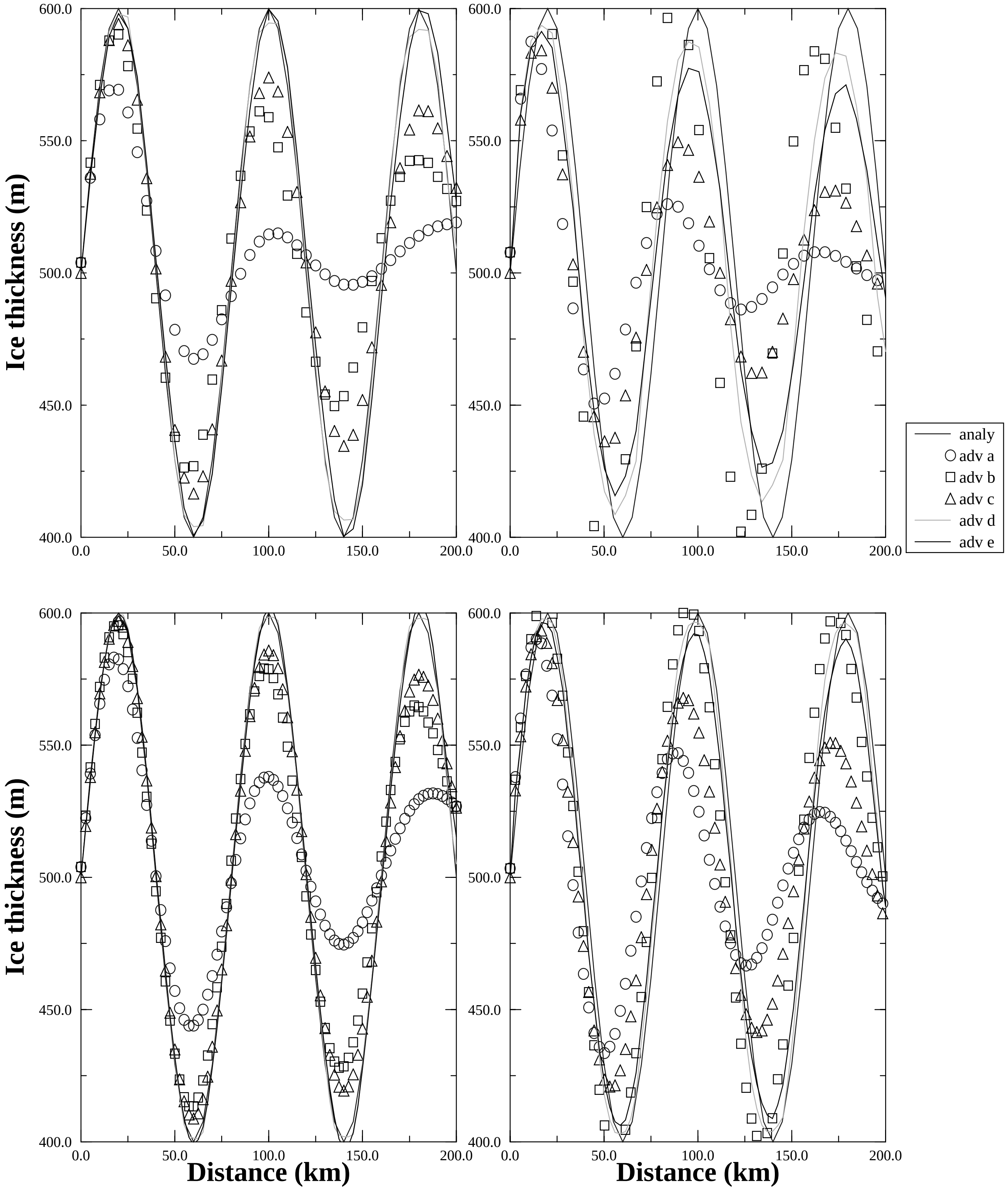
This file should contain data in two columns, without any separator (such as : or ;) in between. The first column contains the x-coordinates in km, the second contains the ice thickness in meters. The x-coordinates and thickness are taken along a cross section in the direction of the wave propagation. For test 1 and test 2, pick the gridpoints x-coordinates in the middle of the numerical domain (i=21 for FD). For test 3 and test 4, pick the x-coordinates (and the thickness values) along a line 2j-i=1 (the X-axis, on which the thickness values have to be taken, is represented by the dashed-dotted arrow on the figures)

✔ A short note of explanation on the different algorithms which were used: which one seems to be the best, why such algorithm is not suited to the problem, and conclusions about the scheme and the resolution which should be used for the «fluctuating ice stream problem».

✔ A summary of the performance of each algorithm. The best would probably be to provide the number of floating operations required by each scheme, but I don't know how to do this on my HP. So, A list of CPU time and on what kind of machine will be enough. This is just designed to have an idea on the «limits» of each algorithm.

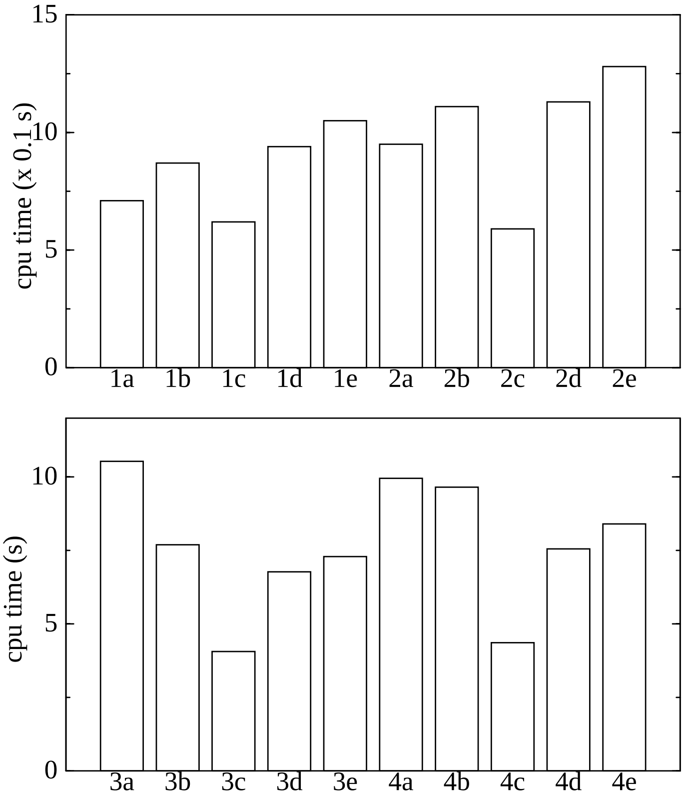
<u>d) preliminary results</u>

I performed these tests and plotted the results (compared to the analytical solution) on the following pages. The surprising thing, which came to me, is that the schemes (a and b) I was using were not able to reproduce the analytical solution (although I'm convinced that they are sufficient



Ice thickness (m)
Distance (km)
analy
adv a
adv b
adv c
adv d
adv e

when we only want to treat the steady state problem). This surprise was for me the opportunity to test three other schemes. At least two of them (run d and e) are much better reproducing the analytical solution. The results of test 3 and 4 suggest that scheme d with a high resolution is the most adapted to the problem. (And thus the conservation scheme I'm going to use for the next parts).



2- Diagnostic equations

This is the second type of governing equations in an ice-shelf model. In this part, we try to compute the depth averaged velocity field from a prescribed ice thickness field and prescribed boundary conditions. The ice-shelf we shall study has the same dimensions as in the previous part.

a) test 1-2

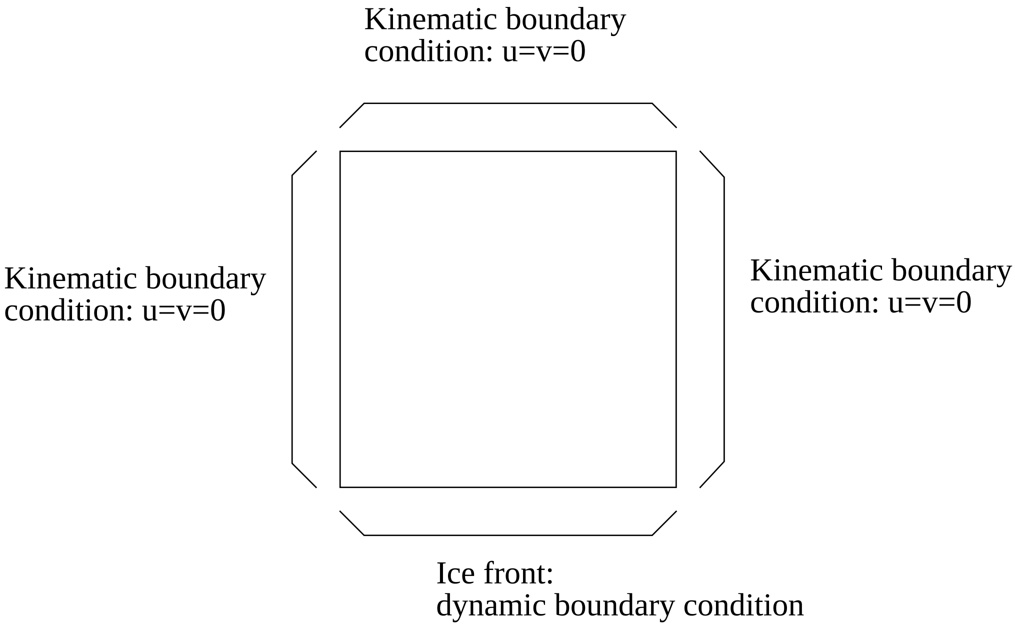
First, we shall ignore the rheological properties of ice and we shall consider ice as a newtonian viscous fluid (constant viscosity).

<u>parameters:</u>

- ice density: 917 kg/m3.
- sea water density: 1028 kg/m3.
- gravity acceleration: g=9.81 m.s^{-2}.
- initial ice thickness field: 500m.
- ice viscosity : 25 MPa.a (order of magnitude of what is observed on the Ross Ice Shelf)
- resolution: 41 by 41 for test 1, 81 by 81 for test 2

<u>NB</u>: I don't think there is any analytical solution to this problem. However, the symetry of the

results can be checked.



b) test 3-4

Same geometry, same resolution, same boundary conditions, but ice is now considered as an isotropic material following Glen's flow law.

<u>parameters:</u>

- ice viscosity: $\eta = \frac{A_T^{-\frac{1}{3}}}{2 \cdot \dot{\varepsilon}^{\frac{2}{3}}}$ with $A_T=5.7\mathrm{x}10^{-18}$ $Pa^{-3}a^{-1}$ (corresponding to an isotherm ice-shelf at 253K).

ε is the second invariant of the strain rate tensor.

<u>*c) test 5-6*</u>

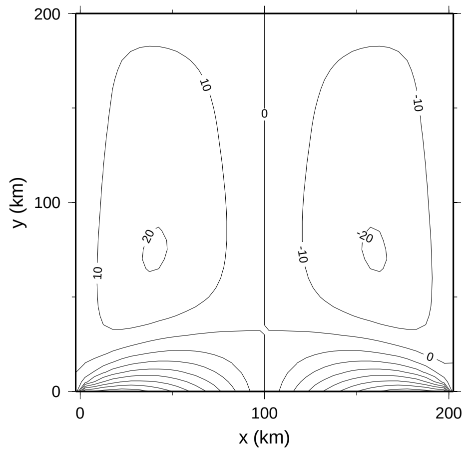
In the previous run, the upper boundary condition is changed to account for an ice stream entering the ice-shelf. The x-velocity u is unchanged (equal to 0 everywhere on the upper boundary). The upper boundary condition for y-velocity becomes the following:

$$v(x, (y = L)) = v_{max} \cdot \left(\left[\frac{x - x_m}{x_w} \right]^2 - 1 \right) \cdot Heav\left(1 - \left[\frac{x - x_m}{x_w} \right]^2 \right)$$

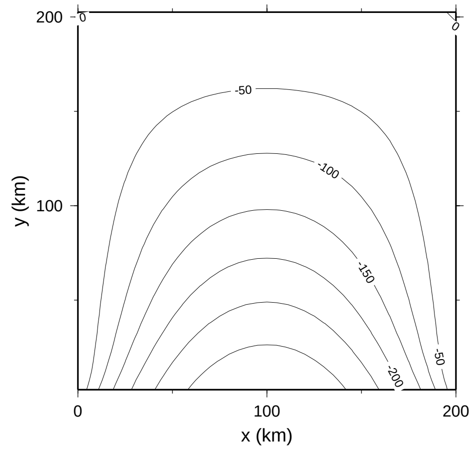
where Heav is the Heaviside (or «step») function, x_w is the half-width of the ice-stream and x_m the coordinate of its center. Note that v has to be negative.

<u>parameters:</u>

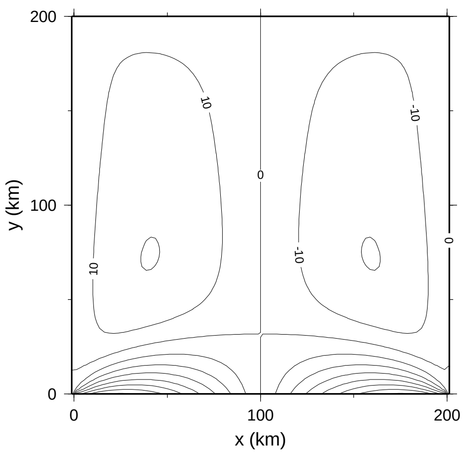
- v_{max} = 400 m/a
- x_m = 100 km
- x_w = 25 km



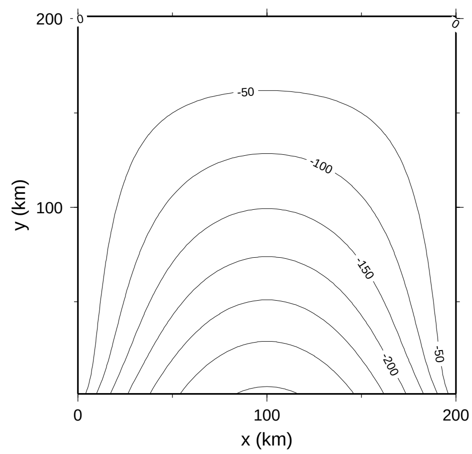
Horizontal x-velocity (u) in m/a - test 1



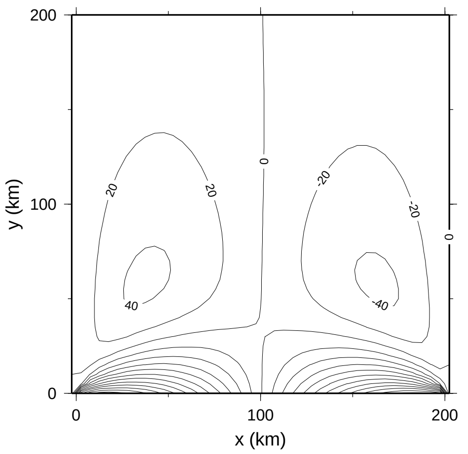
Horizontal y-velocity (v) in m/a - test 1



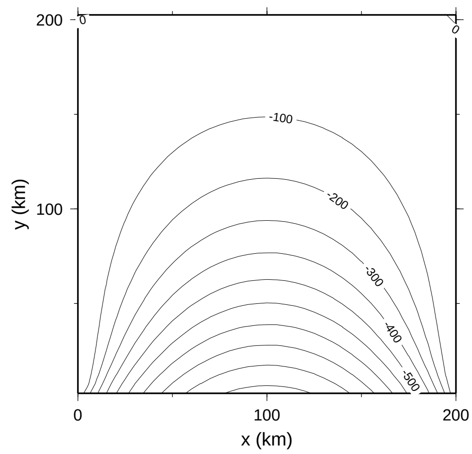
Horizontal x-velocity (u) in m/a - test 2



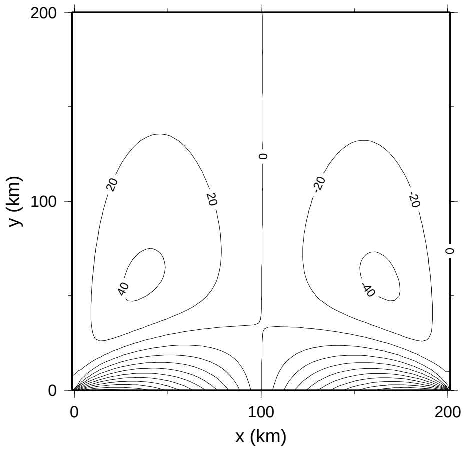
Horizontal y-velocity (v) in m/a - test 2



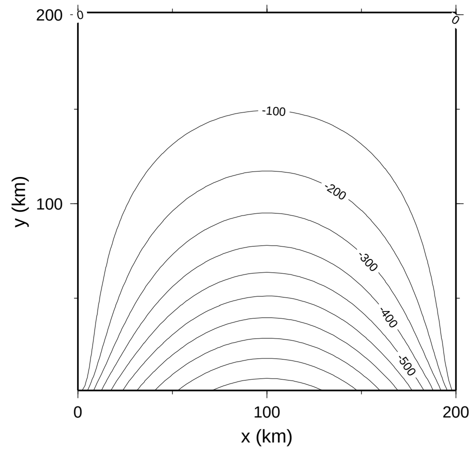
Horizontal x-velocity (u) in m/a - test 3



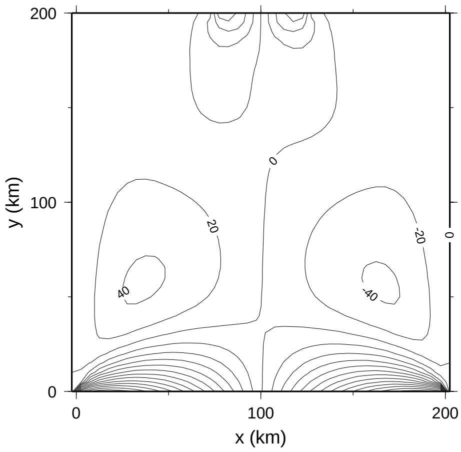
Horizontal y-velocity (v) in m/a - test 3



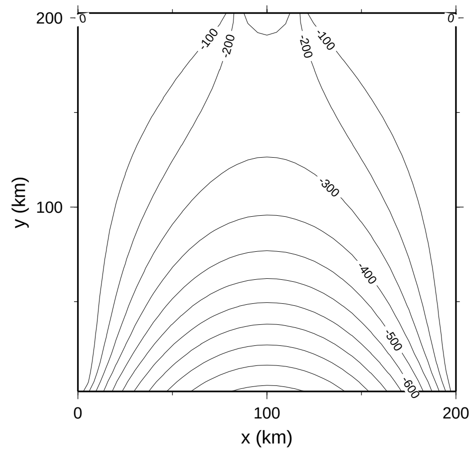
Horizontal x-velocity (u) in m/a - test 4



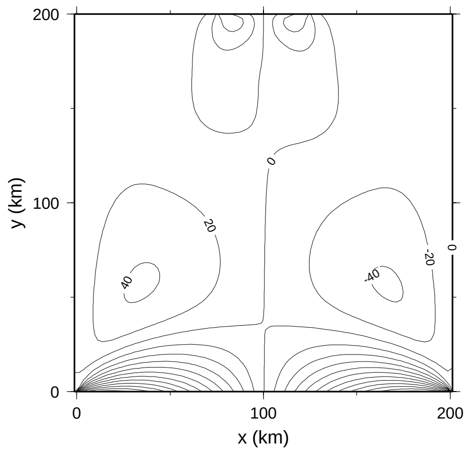
Horizontal y-velocity (v) in m/a - test 4



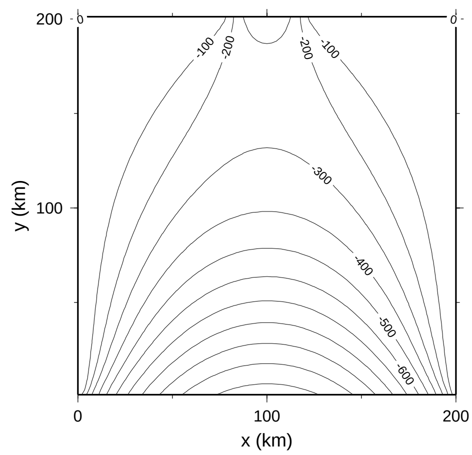
Horizontal x-velocity (u) in m/a - test 5



Horizontal y-velocity (v) in m/a - test 5



Horizontal x-velocity (u) in m/a - test 6



Horizontal y-velocity (v) in m/a - test 6 *d) results*

For each run, I would like the participant to provide me the following files:

✔ dia$n$c.$name: where $n is the test number (from 1 to 6), $c is a character you may have to use if you test several schemes and $name is the participant's name. This file contains data in four columns (without any separator such as : or ;): x-coordinates (km), y-coordinates (km), x-velocity component (m/a)and y-velocity component (m/a).

✔ A short note of explanation on the different algorithms which were used: is it a direct or indirect (e.g. iterative) method of resolution, which scheme seems to be the best, why such algorithm is not suited to the problem, and conclusions about the scheme and the resolution which should be used for the «fluctuating ice stream problem».

✔ A summary of the performance of each algorithm.

3- Coupled model of ice-shelf flow

a) test 1

With the parameters defined in run 5-6 in the previous part (diagnostic equations), let the system evolve and reach asteady state (5000 years). The accumulation rate is set to a constant value of 0.2 m/a (ice equivalent).

b) test 2: fluctuating ice stream problem

From the steady state obtained above, make the ice-stream fluctuate by changing the maximum velocity of the ice-stream with time (1000 years evolution):

$$v_{max} = 400 + 100 \cdot \sin\left(\frac{2\pi}{T} \cdot t\right)$$

v_{max} is in m/year

c) back-force

I would like the participants to define, according to them, what is the global force (in N) which restrain the ice-shelf in its embayement. The evolution of this «back-force» (whatever it is) should then be computed at each time step to provide an estimation of the ice-shelf response to changing conditions of an ice-stream - test 2 - (Is this response linear with changes in the ice-stream dynamics? Can we expect some kind of «hysteresis» in the back-force?).

d) results

✔ - std.$name: file in five columns: x-coordinates (km), y-coordinates, x-velocity component (m/a), y-velocity component and ice thickness of the ice-shelf in steady state.

✔ - flct$t.$name: $t is a number varying from 1 to 7. Files in three columns: y-coordi-

nates, y-velocity component on the center line and ice thickness on this center line at different times.
$t=1: 200 years, $t=2: 500 years, $t=3: 600 years, $t=4: 700 years, $t=5: 800 years, $t=6: 900 years, $t=7: 1000 years.

✔ - bck.$name: file in two columns: time (in years, a time step of 20 years would be fine) and «global back-force» (in N) for the fluctuating ice stream problem.

II- Ross Ice Shelf experiment

a) experiment

A dataset of the present (1979) configuration of the Ross Ice Shelf is available for finite elements, as well as for finite differences. The finite difference version may be accessed by anonymous ftp on alaska.grenet.fr in the /pub/EISMINT-INTERCOMP/ICE-SHELVES/ROSS/ directory. The finite element version can be asked to Doug MacAyeal (drm7@midway.uchicago.edu).
I also join a file (visco.ross) which contains what is, according to me, the present effective viscosity of the Ross Ice Shelf.

I would like the participant to perform a time-evolution experiment with the Ross Ice Shelf geometry for the next 200 years. No plausible scenario (changes in temperature, accumulation rates, ice stream discharges, ice viscosity...) is given here and the participant will have to propose one (present configuration, output from 3D Antarctic model, IPCC inspired scenario, ...). This experiment is thus highly subjective, but some special trends may come out of the results.

b) results

✔ - a short note of explanation on the scenario you used.

✔ - ross.$name: file in five columns containing the x-coordinate, y-coordinate, ice thickness (m), x-velocity (m/a), y-velocity (m/a).

7.1. Introduction

Building further on the Ross Ice Shelf benchmark (MacAyeal et al., 1996), the purpose of this series of tests was to detect weaknesses in the approaches that are commonly used. The experiments aimed at investigating mass conservation, an optimal scheme for the advection terms, accurate determination of the diagnostic velocity field, and on coupled modeling of ice-shelf flow and ice thickness evolution. Tests included a rotation of the numerical domain, a fluctuating ice-stream problem and the calculation of 'back-stress'.

7.2. The experimental model set-up

see the preceding text proposed to the participants by Vincent Rommelaere (February 1996).

7.3. Participating models

Author	Numerical method
V. Rommelaere, C. Ritz	Finite difference, conjugate gradient algorithm
P. Huybrechts	Finite difference, local point relaxation

7.4. Main results

Only two ice-shelf models participated in this series of tests. Both models solved exactly the same equations, but differed in their numeric treatment. It turned out that both models produced almost exactly the same results, and thus succesfully passed the demanding experiments designed by V. Rommelaere. For that reason, it is not necessary to repeat the results here, as they are already contained in the experimental setup. This result further confirms the good agreement between both models obtained for the Ross Ice Shelf benchmark.

7.5. Reference

MacAyeal, D.R., V. Rommelaere, P. Huybrechts, C.L. Hulbe, J. Determann, and C. Ritz (1996): An ice-shelf model test based on the Ross Ice Shelf, Antarctica, Annals of Glaciology 23, 46-51.

8. INTERCOMPARISON OF THERMOMECHANICAL EFFECTS

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 $\mathrm{Pa}^{-3}\ \mathrm{s}^{-1}$) 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 $\times$ 25 km horizontal grid (formerly 50 $\times$ 50 km). The model domain remains 1500 $\times$ 1500 km (61 $\times$ 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 $\times$ 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 $\times$ 10^{-8}	K Pa^{-1}
L	latent heat capacity of ice	3.35 $\times$ 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:

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

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 $\mathrm{m}^2\ \mathrm{yr}^{-1}$

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

   af - flow coefficient A in $\mathrm{Pa}^{-3}\ \mathrm{s}^{-1}$: **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 $\mathrm{m\ yr}^{-1}$

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

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

   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

Postal address:

Tony Payne
Department of Geography,
University of Southampton,
Highfield,
Southampton SO17 1BJ, U.K.

Telephone numbers:

phone: +44 1703 593823
fax: +44 1703 593729

Email address:

`ajp2@soton.ac.uk`
or
`A.J.Payne@soton.ac.uk`

WWW homepage:

`www.soton.ac.uk/~ajp2/eismint2`

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.

Tony Payne
February 25, 1997

Figure 1 Trough topography contoured every 75 m

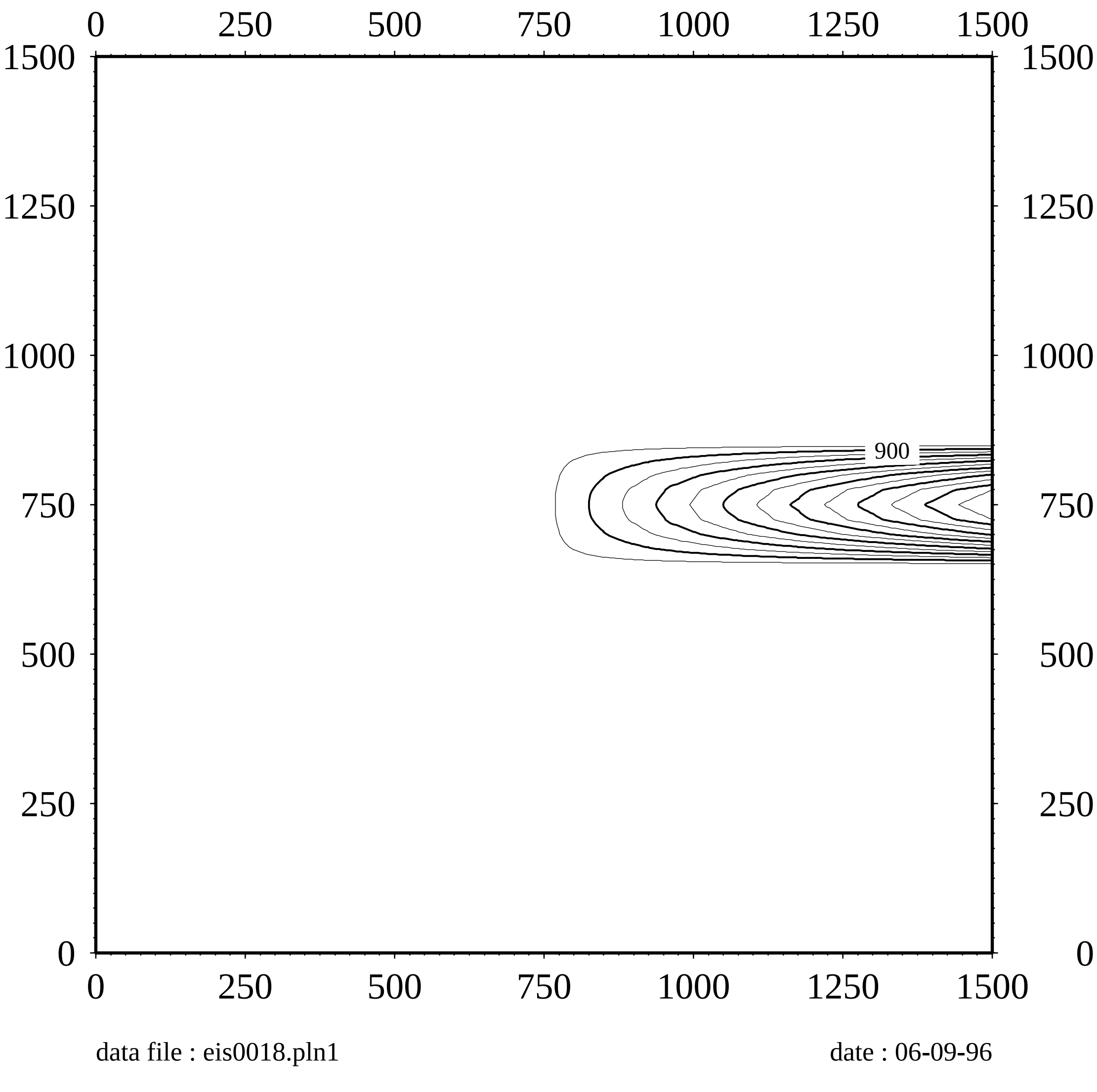
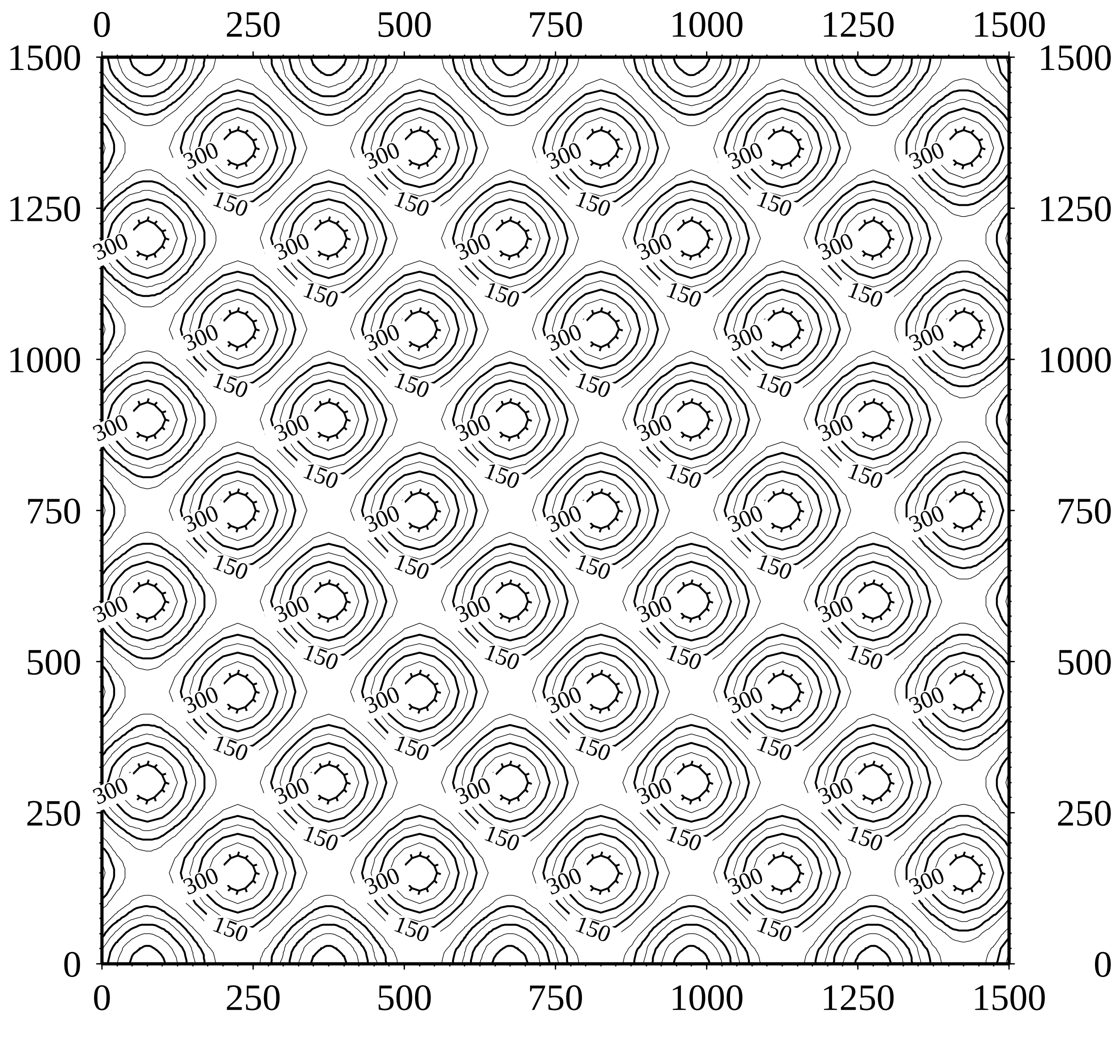


Figure 2 Mound topography contoured every 75 m



data file : eis0020.pln1

date : 06-09-96

8.1 Introduction

The experiments proposed followed directly from those of the first phase of the ice sheet model intercomparison (Huybrechts et al., 1996), but differed slightly in its aim. The aim of Huybrechts et al. (1996) was to provide a benchmark to aid in the development of new ice sheet model codes, while the aim of the present experiments is to highlight some of the problems associated with coupling ice temperature and flow modelling.

8.2. The experimental model set-up

see the preceding text proposed to the participants by Tony Payne (February 1997).

8.3. Participating models

Only models which have both horizontal dimensions and calculate the temperature and velocity fields in the vertical were included in this benchmark. Before the Grindelwald meeting, eight groups had responded and sent their results to Tony Payne. Thanks to Tony's work, all the results had been made available in an comparable form on a web site although remaining anonymous, allowing the contributors to both check for errors in their implementation of the experiments and focus thought on some the behaviour exhibited by the models before the Grindelwald meeting. This greatly helped to reduce the effects of misunderstood experiments set-ups and models bugs, many groups having had time to submit corrected results before the meeting. The results were presented in anonymous format.

Group	Author
Darmstadt	R. Greve
Maine	J.L. Fastook
Southampton	A.J. Payne
Brussels/ Bremerhaven	P. Huybrechts
Tokyo	A. Abe-Ouchi and S. Fuyuki
Reading/ Darmstadt	I. Marsiat and R. Calov
Vancouver	S.J. Marshall
Grenoble	C. Ritz

8.4. Highlights of the results

The most interesting/puzzling results came from experiments A and F. Experiment A, was similar to the moving margin experiments of Phase 1 but featured the thermomechanical coupling and removed the dependence of air temperature on surface elevation. The F experiment was similar to A but with air temperature uniformly 15K lower. In both experiments, ice volume and ice area show a reasonable degree of agreement between groups (Table 8.1). However, results related to the thermal component of the models vary widely, in particular the fractional area at melting point. In contrast to the moving margin experiment of EISMINT Phase one, there is evidence of instability in the predicted flow and in experiment A, three models show a non-radial pattern in their basal temperature, flow coefficient and horizontal fluxes (Fig. 8.1). In experiment F, featuring a colder climate (divide temperature is now -50C as opposed to -35C), the instability is present in all results except in one group whose results are markedly different from the other models (Table 8.2; Fig. 8.2). The area affected by the instability is far greater than in experiment A.

A series of four experiments were performed at assessing the response of the modelled ice sheet to various changes in climate. There was a general consensus between the results, with most models showing the same type of variations at a similar time scale in the ice volume, ice thicknesses and non melting ice temperatures. In experiment B, where a step warming (5 K) was imposed on the steady state of the experiment A ice sheet, all groups predicted a thinning response to the warming, an increase of the melt area, and very similar time series of the thickness and non melting basal temperature. Reduction in accumulation rate (both the maximum accumulation rate and the positive accumulation area were reduced) led to a global thinning of the ice sheet with a decrease of the melt area (exp.C). The smaller ice sheets were more stable than in experiments A and F. When changes in accumulation were only applied to the accumulation area (reduction of the area over which the maximum accumulation rate operates) but not the rates, all groups predicted less thinning from observed in expt. C, with little change in melt area, small changes in individual basal temperatures and a general tendency to reach equilibrium more rapidly. The last of the four experiments investigated divide migration in response to a 141 km north-westerly shift in the climate divide. The modelled ice sheets migrated to the new spatial equilibrium in around 60 kyr, with temperatures and thicknesses of the new equilibrium ice sheet very similar to that in A; the few differences being attributed to slightly different spatial form of the instabilities.

A series of two experiments were performed at assessing the response of ice sheet models to the incorporation of basal sliding; the first assessing the effect of the sliding without coupling its distribution to that of basal pressure melting (the sliding is a function of basal shear stress only and occurs irrespective of the thermal state of the basal ice); the second assessing the full effect of the sliding and its interaction with the distribution of basal temperature (the sliding is a function of basal shear stress and occur only when the basal ice is melting). In the first case, the results show more consistency than those in experiment A, the stability problems which haunted experiment A not being present. In the second case the stability problems of Experiments A and F were observed in virtually all models, with variability in melt area,and to a lesser extent in ice thickness and volume, throughout the entire run.

The final set of experiments introduced topography. Variations in ice thickness are expected to trigger many feedbacks within the ice sheet temperature - flow system. Two types of topography were used. The first topography had a 200 km wide trough running from the domain's centre to one edge, attempting to simulate the large bedrock troughs often associated with glaciated areas. The second topography was a serie of mounds aiming to representing a system of highland massifs and valleys. Most of the models showed a fair degree of agreement. Generally, the trough allowed enhanced flow which affects the ice thickness distribution, not affecting the divide position. Transect results of the models in the mounds topography were in particularly good agreement (Fig. 8.3), the various feedbacks generated by the uneven topography did not enhance the differences between models.

8.5. Summary of the results

Although there is a general consensus between the models for simulating ice volume and thicknesses, variables related to the thermodynamics, such as basal temperature, melting basal area, local ice flux magnitude, etc.. show a wider scatter. Two key features arise from these results. First, experiments B to E allow us to characterize the magnitude, direction and time scale for various changes in atmospheric boundary condition. This may be of interest in interpreting ice core data and understanding the basics mechanisms of ice sheet - climate interactions with coupled models. There is a fair degree of agreement between our models on this. Second, Experiments A, F, G and H highlight the instability which the coupling of temperature to flow introduces. All models show this instability to some extent and it would be useful to agree on the mechanisms involved, whether they are realistic or not and if it may compromise the ability of ice sheet models to predict unstable events.

8.6. Minutes of the group discussion (Rapporteur: I. Marsiat)

As expected from the results described above, most of the discussions focused on the instabilities appearing in experiments A and F. Is this instability purely numerical or has it a physical reality ? Is it induced by the numerics when trying to solve a circular ice sheet problem on a square grid, but the mechanism by which the instability propagates being close to physical instabilities encountered in real ice sheets ? Why is the instability more important when the climate is colder ? Is this instability visible in the Greenland and Antarctic experiments ? If the instability is real, is the system still predictable ? Do we want to eliminate the instability ?

These questions have not been answered but some proposals have been made to solve the problem. Mathematicians conducting theoretical work such as linear stability analysis could help to reduce the effects of the numerics in generating the instability. New experiments have been proposed such as : (i) changing the Arrhenius relation to a smoother one, (ii) using spherical coordinates, (iii) changing the geometry of the problem, (iv) starting with initial conditions other than the no-ice condition. Dependence on horizontal and vertical resolution and numerical schemes used in the models should also be evaluated.

The most spectacular intervention was done by Andrew Fowler and its "Fairy Liquid" experiment (due to the only use of washing powder in the Sunstar Hotel, the latter was perfectly replaced with ketchup). When a glob of ketchup is flattened between two perfectly uniform glass plates, it spreads in a perfectly radial pattern. When the two plates are then moved apart, the ketchup retracts forming non radial patterns, like twigs. This is explained by the penetration of relatively non viscous liquid (the air) in a more viscous liquid (the ketchup). As when an ice sheet recedes, relatively "warm" and less viscous ice of the margins penetrates into the cold and more viscous ice of the centre of the ice sheet. The twigs observed in the experiments were very similar to some instability features observed in the A and F experiments.

It was then proposed that we should aim at publishing some or all of these results in a "Warning bell paper" highlighting the problems associated with coupled thermomechanical models and providing a benchmark for future modelling work. The creation of a database gathering the results of the different models, accessible only by those who contributed was also proposed.

8.7. Reference

Huybrechts, P., A.J. Payne, and the EISMINT Intercomparison Group (1996): The EISMINT benchmarks for testing ice-sheet models, Annals of Glaciology 23, 1-12.

8.8. Table and figure captions

Table 8.1: Key variables at the end of Experiment A.

Table 8.2: Key variables at the end of Experiment F.

Figure 8.1: Basal temperature at the end of the run in K (Experiment A).

Figure 8.2: Basal temperature at the end of the run in K (Experiment F).

Figure 8.3: Ice thickness at the end of the run in m (Experiment K).

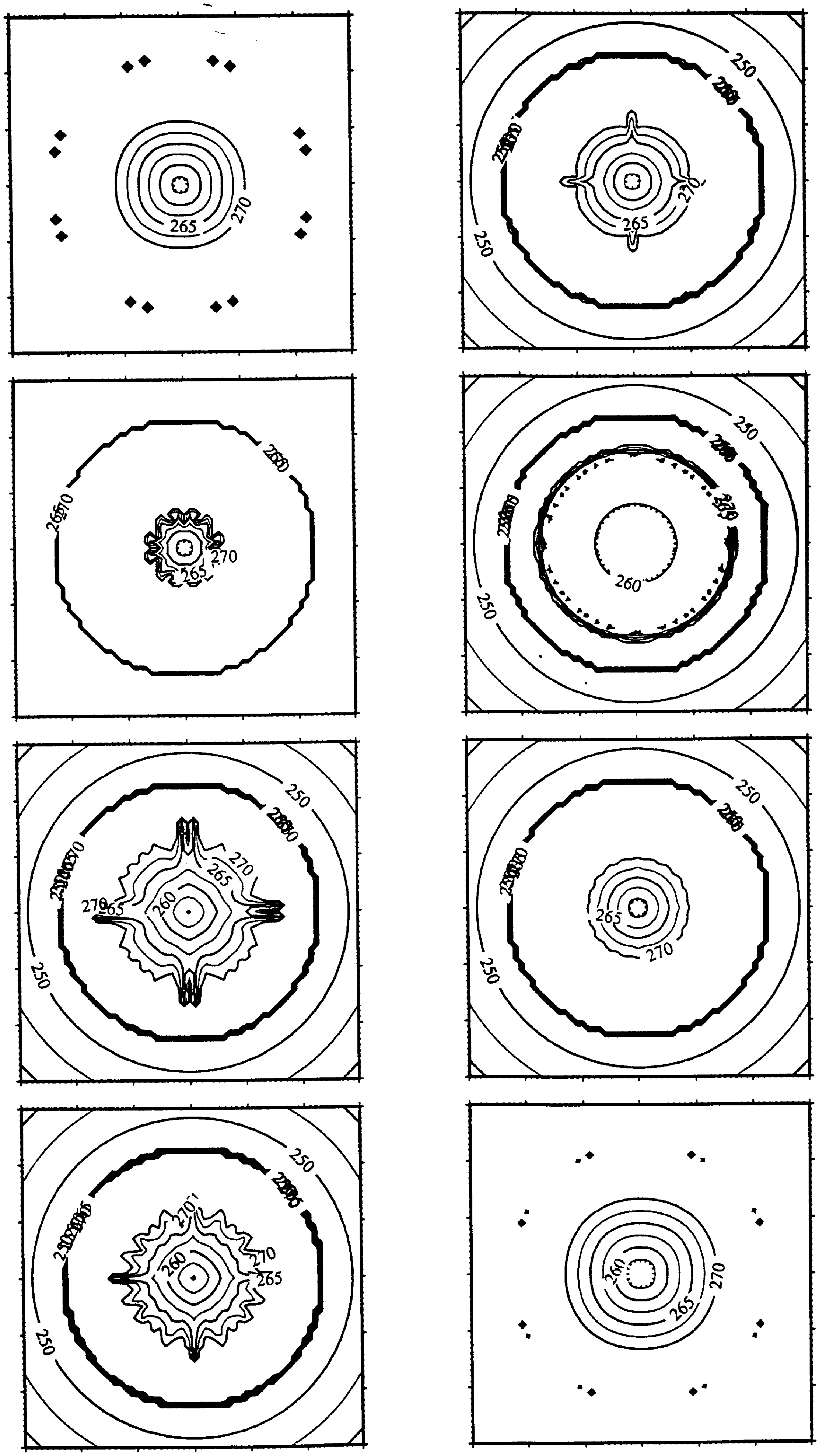
Experiment A - global

Group	Volume $\times 10^6$ km^3	Area $\times 10^6$ km^2	Melt Fraction
Z	2.068	1.031	0.699
Y	2.111	1.031	0.587
X	2.060	1.031	0.632
V	2.107	1.031	0.375
U	2.167	1.031	0.934
T	**2.596**	**1.098**	**0.430**
S	2.134	1.031	0.667
R	2.147	1.031	0.779
mean	2.113	1.031	0.668
range	0.099	0.000	0.504

Table 8.1

Figure 8.1

Temp. expt A



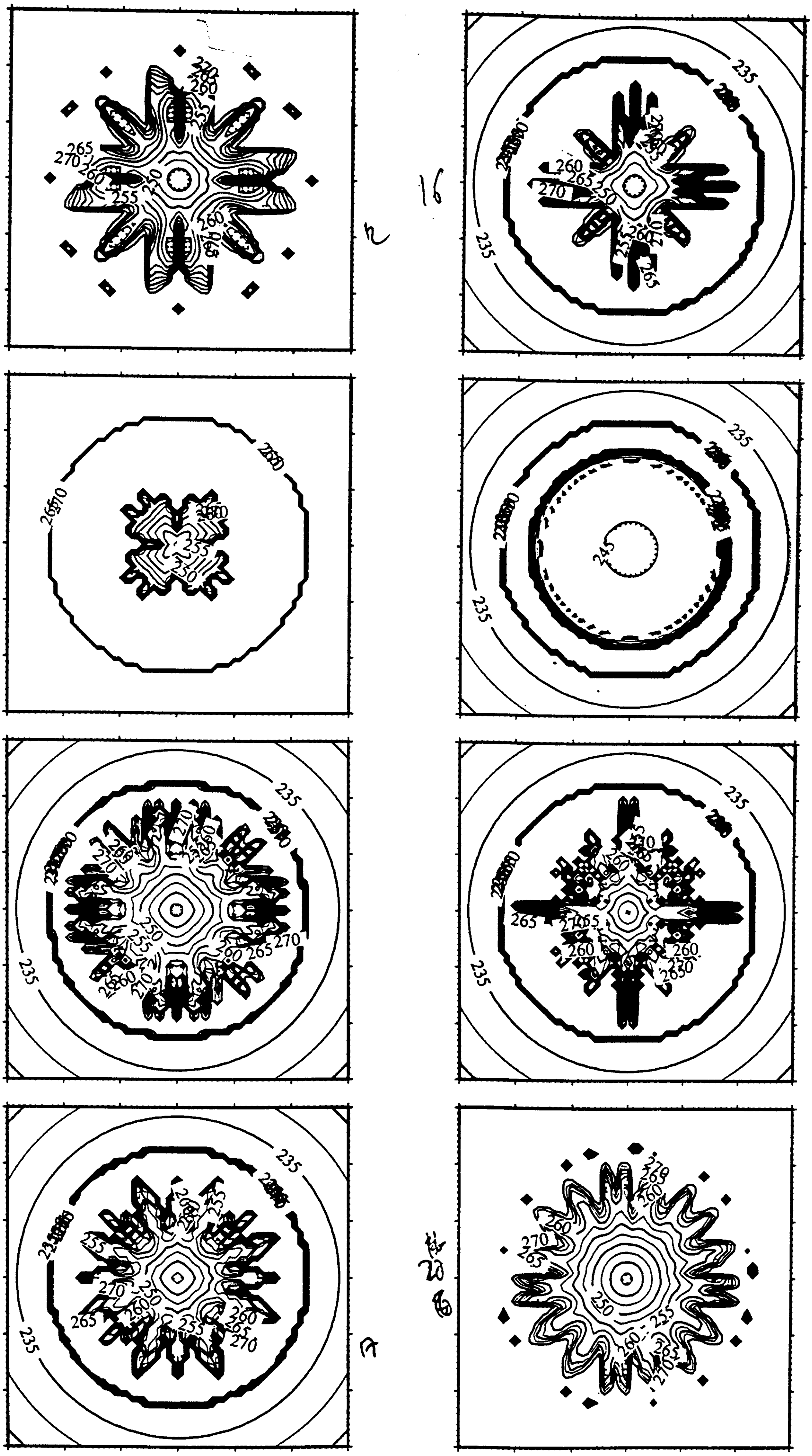
Experiment F - global

Group	Volume $\times 10^6$ km^3	Melt Fraction
Z	2.283	0.569
Y	2.378	0.323
X	2.290	0.422
V	2.277	0.310
U	2.354	0.864
S	2.353	0.397
R	2.333	0.747
mean	2.325	0.519
range	0.101	0.554

Table 8.2

Temp, expt F

Figure 8.2



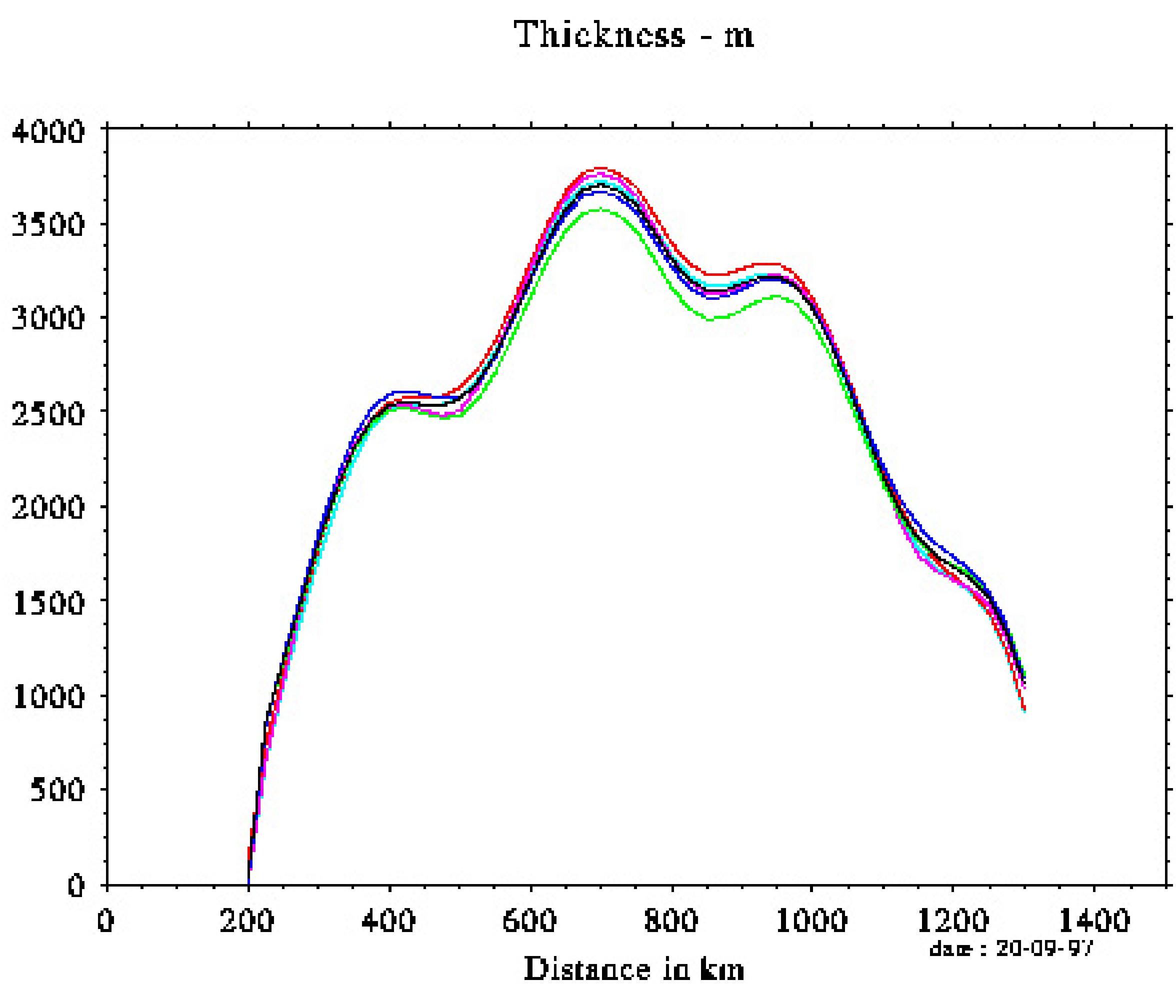

Thickness - m
4000
3500
3000
2500
2000
1500
1000
500
0
0
200
400
600
800
1000
1200
1400
date : 20-09-97
Distance in km

Figure 8.3

9. INTERCOMPARISON OF GROUNDING-LINE TREATMENTS

EISMINT
Comparison of grounding-line treatments

Coordinator:
Philippe Huybrechts

1. Introduction

The grounding-line separates the grounded ice zone from the floating ice zone, which each have their distinct flow regime. Some distance away from this grounding zone, either in the ice shelf or in the ice sheet, ice flow is reasonably well understood and there is some concensus as to which simplifications can be made in the stress equilibrium, either to have flow dominated by shearing in horizontal planes, most of it at the base, or to have flow by lateral shearing and longitudinal stretching, as in the ice shelf. This fundamental difference between the two flow regimes seems to suggest the existence of a transition zone where all stress components are important and none of the usual simplifications can be made. It also raises the problem of the width of such a transition zone, if any, which is moreover likely to be strongly influenced by the occurrence of basal sliding or the development of ice streams. On the other hand, it has also been suggested that the details of the stress and strain conditions at the grounding line would be unimportant for modeling grounding-line migration, as the inland flow would be little influenced by conditions in the ice shelf, and grounding-line migration is above all controlled by conditions of hydrostatic equilibrium in the grounding area.

Whatever the case, grounding-line migration and the coupling of ice-sheet flow with ice-shelf flow can rightly be considered as one of those 'grand unsolved modeling problems', which is nevertheless of prime importance because it is the predominant mechanism by which the Antarctic ice sheet changes its dimensions, and by which the Quaternary ice sheets of the northern hemisphere were able to expand over shallow sea-beds during glacial times, in particular in the Arctic Basin. Furthermore, similar mechanisms may also play in a tidewater or calving glacier environment.

The experiments described below aim at comparing treatments of grounding-line migration and of the ice-sheet/ ice-shelf transition, both in a steady state as in dynamic situations in response to sea-level variations and ice-thickness changes. It is anticipated that the proposed experiments will shed more light on problems of:

- mass conservation across the grounding zone
- surface profile of the ice-sheet/ ice-shelf transition
- width of a transition zone, if any

- degree of simplification possible in numerical models
- the state of equilibrium of the grounding line (neutral/ stable/unstable)

2. Type of models

These experiments have been designed for a schematic geometry and assume lateral symmetry, so that they can be performed by both 2-D and 3-D models. The ideal model should be able to solve the flow over the entire domain, and have a freely moving grounding line which obeys hydrostatic equilibrium. However, it is not strictly necessary for the models to explicitly include ice-shelf flow; any treatment of grounding-line migration is welcomed to the exercise. Other models only solve for the flow field, but do not include a freely evolving geometry. These models are also welcomed and should only preform the steady state experiments, and if necessary, use the analytical form to obtain the ice-sheet geometry (Nye-Vialov; Van der Veen)

3. Model setup

The basic model setup considers a flowband of 51 points in the x-direction and a horizontal grid spacing of 2 km (NX=51, DX=2000 m), with an unspecified width in the transverse y-direction (one gridpoint for flowline models, minimum 3 gridpoints for 3-D or 2-D vertically integrated models). The latter models should consider full symmetry in the y-direction; output is only required for the central flowline. The bed is a down sloping plane with slope of -5×10^{-3} in the x-direction with an elevation of -250 m at the upstream boundary and an elevation of -750 m at the downslope boundary. i=1 for the upstream end (ice divide) and i=51 for the downstream end (ice shelf front).

Modelers are free to make whatever simplifications to the stress equations in any of the flow regimes (ice sheet, grounding zone, ice shelf) in whatever way they deem most appropriate, but should use the same physical parameters and flow law over the entire model domain. They should also exclude isostasy, basal sliding (in the standard series of experiments), and thermomechanical coupling.

4. Model parameters

- Glen's flow law with exponent n = 3 and a pre-exponential flow law parameter corresponding to a temperature of about -10° C.:
  $\varepsilon_{ij} = A_0 \tau^2 \tau'_{ij}$ with $A_0 = 1 \times 10^{-18}$ $Pa^{-3} year^{-1}$
- gravity: 9.81 ms^{-2}
- ice density: 910 kgm^{-3}

- water density: 1028 kgm^{-3}
- conversion factor for seconds to year: 1 year = 31556926 seconds

5. Boundary conditions

Boundary conditions on the flow are to be taken for an ice divide (zero surface gradient; ice thickness is a free variable) at the upstream end, and for a uniaxial spreading ice shelf at the downstream end. Models which do not include an ice shelf explicitly should choose appropriate boundary conditions at the grounding line. Sea level elevation is initially set at 0 m. The accumulation rate is fixed at 0.3 m/year over the entire model domain. There is no bottom melting.

6. Experiments

6.1. Steady state experiment

To arrive at a steady state, first define the grounding line to lie at the gridpoint i=26, i.e. i=26 is the last grounded gridpoint, and i=27 is the first floating gridpoint. This means that the ice thickness at i=26 cannot be less than 565 m. Then build up an ice sheet/ice shelf system while holding the position of the grounding line fixed at this location and subsequently run to a steady state. The criterium for steady state is a change in total ice volume of less than 0.1% in 1000 years. Initial conditions can either be a uniform slab of ice thickness of 565 m or an analytical solution for both the ice sheet and ice shelf to save time. The next step is to relax the fixed grounding line and have the position of the grounding line determined from the floatation condition. Pursue the calculations until a final steady state sets in. A first important test is to find out whether the grounding line remains at the same location. Preliminary calculations suggest that this is indeed the case and that the appropriate ice thickness for the given span and material constants is around 1600 m at the ice divide.

6.2. Sensitivity to stepped changes in boundary conditions

Starting from the steady state obtained in 6.1, do 4 stepped sensitivity experiments, which consider a freely generated geometry and grounding line position:

- sea level -125 m
- sea level +125 m
- accumulation rate of 0.1 m/year
- accumulation rate of 0.5 m/year

Run these experiments to a steady state

Secondly, starting from the respective steady states, reset the sea-level and accumulation forcing again to their standard values and run to steady state. This gives a total of 8 sensitivity experiments.

6.3. Role of basal sliding

Repeat all experiments described above by including basal sliding. Therefore, use a relation of Weertman-type, corrected for the effect of subglacial water pressure:

- sliding velocity = 2 x 10^{-13} N^{-3} year $^{-1}$ m^{8} x (basal shear stress)^{3}/(height above buoyancy)
- height above buoyancy = ice thickness + (water density/ ice density) x (bed elevation - sea level stand)
- Put a lower limit of 1 m on height above bouyancy to avoid devision by zero.

7. Format of results

All results are to be submitted, preferably by E-mail, as column-based text files. Two sets of data files are involved, one for the steady states (20 in total), and another one for the time-dependency of the runs. File names are to be coded as follows:

wwxxyyzz.name

where **ww** refers to the type of data: ss = steady state
ts = time series

where **xx** refers to the type of experiment: re = reference run
ls = sea level -125 m
hs = sea level +125 m
la = accumulation rate 0.1 m/year
ha = accumulation rate 0.5 m/year

where **yy** refers to the initial state: st = starting from the reference or initial state
pe = starting from the perturbed state

where **zz** refers to basal sliding or not: bs = basal sliding included nb = basal sliding excluded

and **name** has a length of maximally 5 characters based on your name or group

For example, the file **sslapenb.phil** contains my data for the steady state sensitivity experiment excluding basal sliding, in which the accumulation rate is reset from the perturbed value of 0.1 m/year to the standard value of 0.3 m/year.

7.1 Steady state files

These contain 7 columns in format **(5(1x,f8.2),2(1x,e14.6))** with the following data:

1. distance from ice divide (in km), i.e. from 0 to 100
2. ice thickness (m)
3. surface elevation (m)
4. vertically integrated ice velocity (m/year)
5. velocity at ice-sheet base (m/ year)
6. flux (in m^2/year, this is the product of columns 2 and 3)
7. vertically averaged horizontal strain rate (du/dx; in $year^{-1}$)

Length is 51 lines

7.2 Time-dependent files

These contain 6 columns in format **(1x,f8.0,1x,e14.6,1x,i2,3(1x,f8.2))** with the following data:

1. time at an interval of 250 years
2. area of grounded ice transect (m^2)
3. position of last grounded grid point
4. thickness at ice divide (m)
5. vertically integrated velocity at gridpoint i=21 (m/year)
6. vertically integrated velocity at gridpoint i=31 (m/year)

Length depends on the time needed to reach equilibrium.

8. Adresses

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9.1 Introduction

The experiments addressed the marine ice-sheet problem in a series of two-dimensional (flowline) tests of a schematic nature. Points of interest included the width of the transition zone (if any), the stability of the ice-sheet/ ice-shelf junction, the role of basal sliding, the reversibility of grounding-line migration, and more in general, the 'best way' to model it. Additional questions included mass-conservation across the grounding zone, and the degree of sophistication possible in numerical models.

9.2. The experimental model set-up

see the preceding text proposed to the participants by Philippe Huybrechts (April 1997).

9.3. Participating models

Author	Type of model
C. Mayer (Bremerhaven)	complete Stokes solution in 3-D glaciostatic equilibrium in vertical flow regimes determined by basal traction
F. Pattyn I (Brussels)	vertically integrated 'diffusive' ice sheet coupled with numerical ice shelf model longitudinal stress in effective stress
F. Pattyn II (Brussels)	full 2-D stress solution in ice sheet/ shelf
K. van der Veen (Ohio)	vertically integrated 'diffusive' ice sheet no longitudinal stress equilibrium ice shelf of one point no ice-sheet/ ice-shelf interaction
P. Huybrechts (Brussels/ Bremerhaven)	flowband model derived from Ant. model separate flow treatment in ice sheet/ shelf grounding line treated as grounded ice full flow calculation in ice shelf flow coupling through continuity

9.4. Summary of the results

Three series of tests were performed. First of all, a reference state was defined and its stability properties investigated. Then, two series of sensitivity tests were performed in which sea-level and accumulation rate were respectively raised and lowered, and both time-dependent and final steady state behaviour were examined.

9.4.1. Reference experiment

A first test was to find out whether it was at all possible for the models to produce a stationary ice sheet, which could then serve as a reference in further sensitivity tests. To do that, the grounding line was first held fixed at the midpoint, and the models were relaxed to a steady state, whereafter this restriction was lifted and the position of the grounding line was derived from hydrostatic equilibrium. It turned out that all models were able to successfully pass this first test, both with and without basal sliding (Fig. 9.1). The only exception was the Mayer model, which produced a different height-to-width ratio (wrong set-up, different flow parameter?).

It is of course difficult to prefer one model over another, however, there exists one test: in steady state, the mass flux should be linear with distance with a slope equal to the accumulation rate (Fig. 9.2). Some models, however, produced small wiggles indicative of numerical problems.

9.4.2. Sea-level experiments

In this series of experiments, an impulse change of sea level was imposed, both positive and negative (±125 m), followed by a reset after steady conditions were achieved. This produced very surprising results. As expected, lowering sea-level produced an advance of the grounding line to preserve hydrostatic equilibrium. However, the amount of sea-level advance differed widely among the models (Fig. 9.3). The same applied to the time-dependent behaviour: in some models the grounding line instantaneously jumped to the gridpoint corresponding to the impulse change of sea level, and did not move anymore. Other models exhibited dynamic behaviour, in the sense that the grounding line continued to advance after the initial migration until a new steady state was achieved, with a typical response time scale of 5000 years.

When resetting the grounding line to the reference state, another curious thing happened: none of the models produced grounding-line retreat, nor were able to reproduce the initial state again. This indicates hysteresis. Actually, the suspicion was aroused that for the prescribed model set-up, grounding-line migration due to a sea-level lowering would be an irreversible process: the thickness at the grounding line would in all cases adjust to the span of the grounded ice sheet. The longer the ice sheet, the thicker the ice sheet at the margin, and the further down the slope of the continental platform it could achieve a steady state. Another reason for the observed behaviour could be the dyssemetric profile of the 'height above buoyancy' in the vicinity of the grounding line. Because of the steep slopes near to the grounding line at the ice-sheet side, it would need a much stronger sea-level rise than a sea-level lowering to produce a grounding-line shift over the same distance. Inclusion of basal sliding was found to increase the sensitivity in all models.

9.4.3. Accumulation rate experiments

The prescribed accumulation changes (a change of ± 0.2 m / a) produced less grounding-line migration than the prescribed sea-level changes. Lowering accumulation rates hardly caused grounding-line retreat, whereas increasing accumulation rates produced a little advance. Resetting the accumulation rate to the reference value did not cause a reversal of the grounding line to the original position. Also here it was found that basal sliding increased the sensitivity. The reason is apparently that the inclusion of basal sliding decreases the surface slopes in the vicinity of the grounding line.

9.4.4. Conclusions

A summary of the steady-state positions of the grounding-line in all experiments is shown in Figs. 9.4 and 9.5. The main conclusions are:

- There is no consensus on the results

- There is no consensus on how the grounding line should be best modelled.

- All models are able to reach a stable solution

- It is unclear whether these results are indicative of neutral equilibrium

- Grounding-line migration seems to be an irreversible process, at least under the prescribed model set-up.

- Basal sliding enhances sensitivity to changes in boundary conditions.

9.5. Minutes of the discussion (Rapporteur: F. Pattyn)

Five models contributed to the grounding line experiments, each with a different level of physical sophistication, and - apparently - with different numerical solution schemes. From the experiments it was shown that all models behaved differently with respect to changing boundary conditions. For instance, when boundary conditions were stepwise changed, some models reacted to this change with a grounding line migration, while others did not. However, when boundary conditions were afterwards reset to their initial value, no grounding line movement was detected in all models. This behaviour arose the question if a neutral equilibrium of the grounding line could be assumed or not.

A. Fowler remarked that a 2 km horizontal resolution in the model setup was perhaps too coarse to catch the transition zone. He proposed to perform calculations at a resulution of 100 - 200 m locally near the grounding line, and to insert the result into a coarser (2 km) model. C. Mayer replied that both from his model simulations and observations in Antarctica, the transition zone was wide enough and thus well represented in the present model setup.

Another point regarded the switching boundary conditions from a grounded ice sheet to a floating ice tongue. In the grounded ice sheet, basal velocities are zero, while at the grounding line this no-slip condition changes abruptly into zero basal shear. One needs to be careful for singularity. Introducing basal sliding (as is done in half of the experiments) might eventually remove this risk.

The major aim of the grounding line experiments should be to analyze the grounding line area in such a way that numerical models can jump over it instead of being strangled by too much numerics. This point is perhaps the missing link between those who try to define the problem and those who try to solve it numerically.

No consensus was reached on how numerical models react or should react near the grounding line in response to changing boundary conditions of sea level and surface mass balance changes. It is furthermore impossible to find out whether the differences in behaviour are due to (i) the physical description of the model or (ii) the numercial solution scheme. P. Huybrechts pointed out that not all models are capable of conserving mass accross the grounding line. We therefore agreed that if we would like to compare differences in models regarding their physical background, the numerical schemes in the models should be altered so that they become mass conservative along the whole flow line.

A new line of experiments should consist of:

- Repeating the former experiments but with mass conserving numerical schemes

- Carrying out the same experiments but at different levels of horizontal and vertical resolution (1 km and even higher resolution).

9.6. Figure captions

Figure 9.1: Ice-sheet/ ice-shelf geometry in the reference experiment without basal sliding (ssrestnb). All models are able to freely generate the initial position of the grounding line.

Figure 9.2: Mass flux in the reference experiment without basal sliding (ssrestnb). The theoretical mass flux is a straight line with a slope equal to the accumulation rate.

Figure 9.3: Ice-sheet/ ice-shelf geometry and position of grounding line in the experiment where sea-level was stepwise lowered by 125 m (sslsstnb). All models behave differently.

Figure 9.4: Solution diagram for all runs without basal sliding. The three successive points respectively correspond to the reference state (left point), the steady state after the perturbation was applied as indicated (middle point), and the steady state after the boundary conditions (either sea level or accumulation rate) were reset to their reference conditions (right point).

Figure 9.5: Solution diagram for all runs including basal sliding. Inclusion of basal sliding makes the system more dynamic.

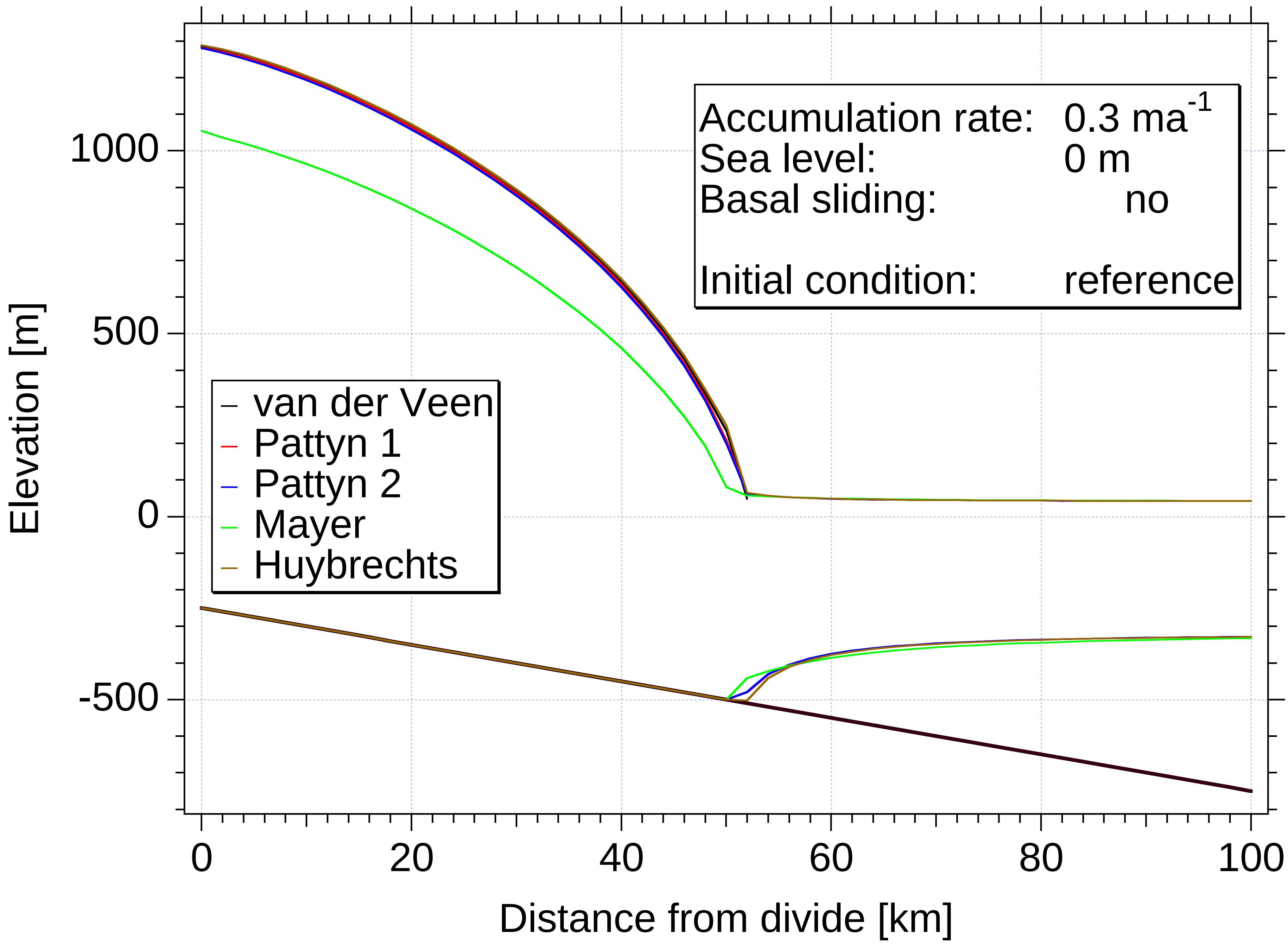

Accumulation rate: 0.3 ma^-1
Sea level: 0 m
Basal sliding: no
Initial condition: reference
van der Veen
Pattyn 1
Pattyn 2
Mayer
Huybrechts
Elevation [m]
1000
500
0
-500
0
20
40
60
80
100
Distance from divide [km]

Figure 9.1

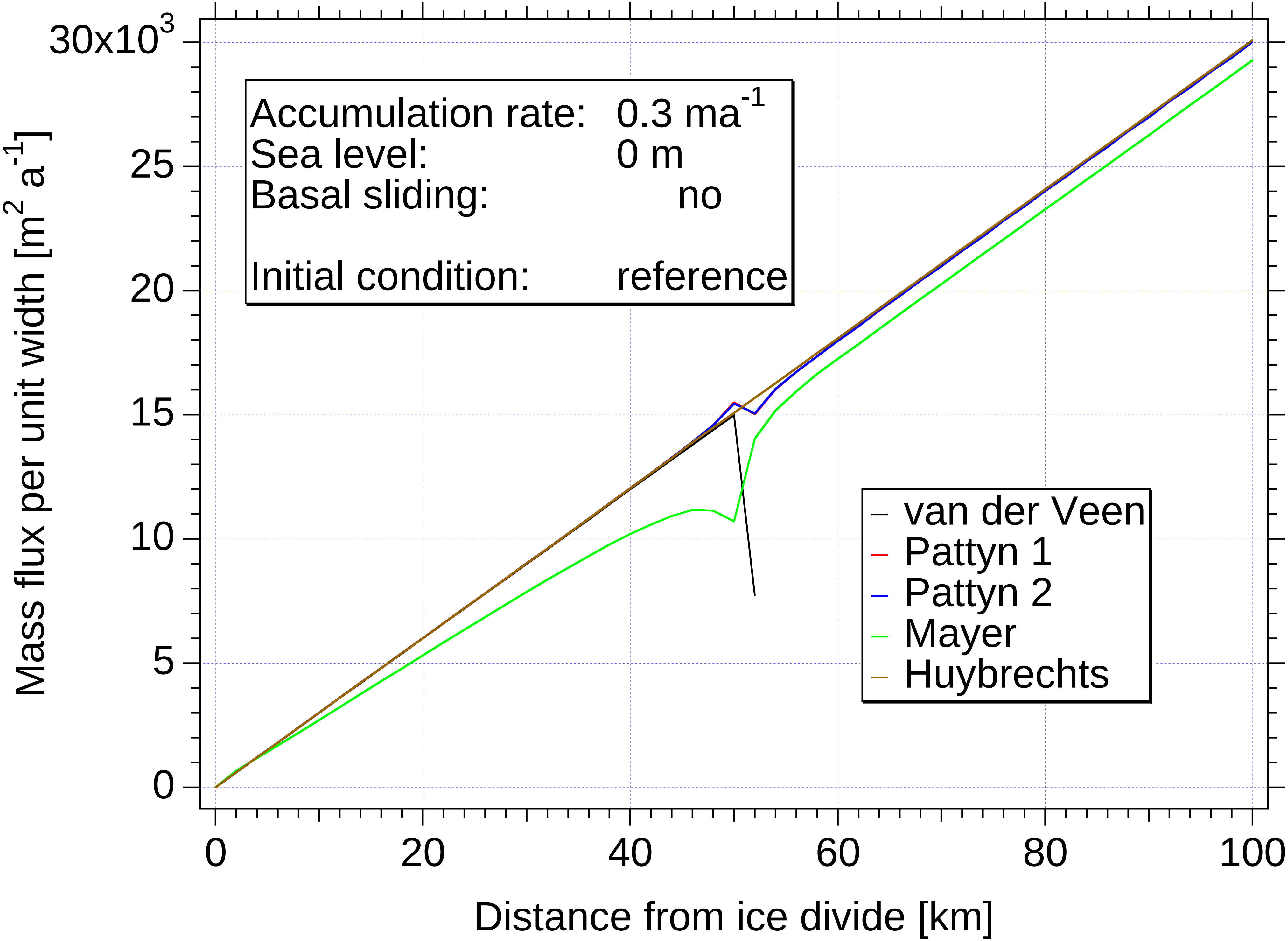
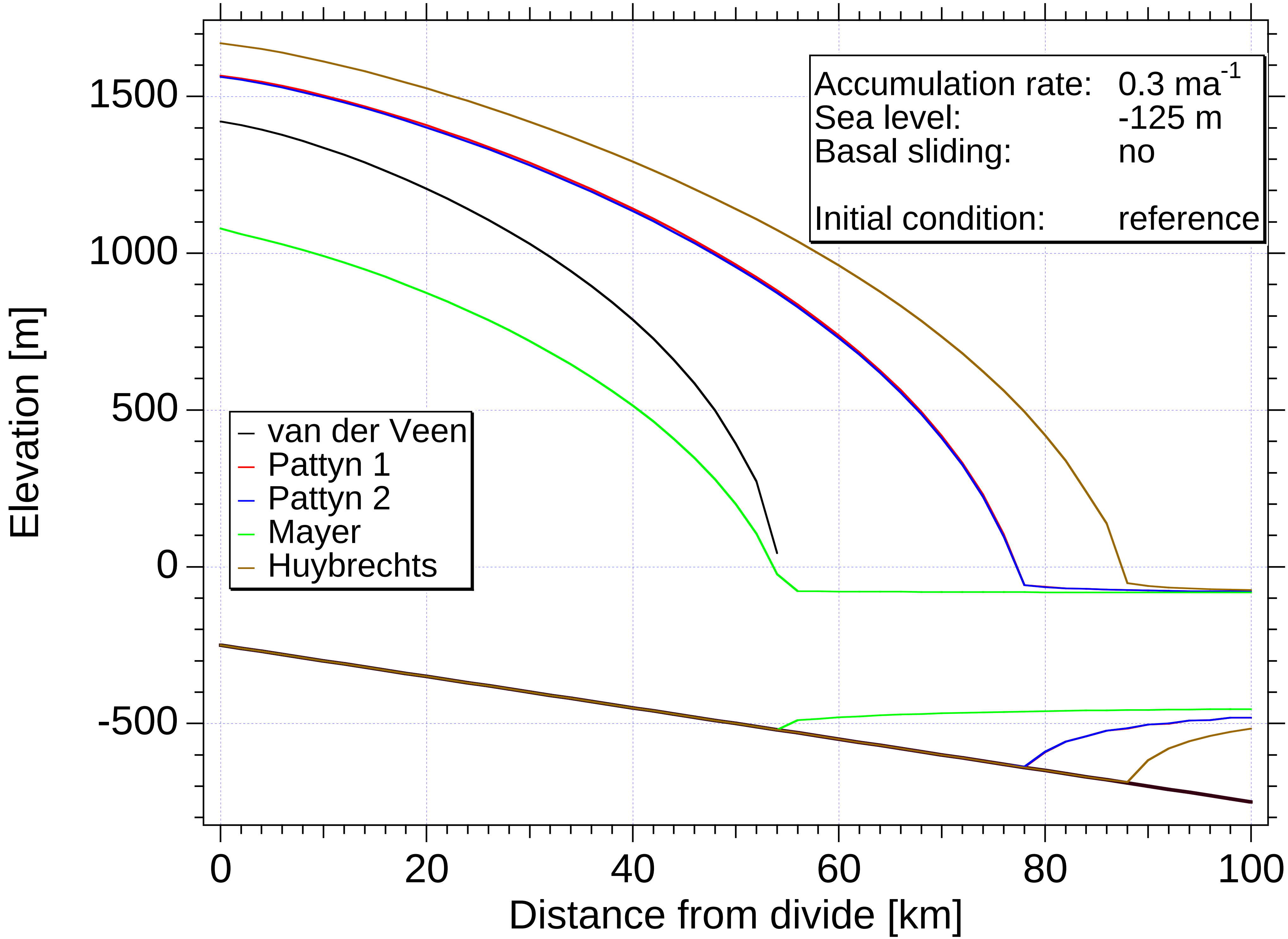

Accumulation rate: 0.3 ma^-1
Sea level: 0 m
Basal sliding: no
Initial condition: reference
van der Veen
Pattyn 1
Pattyn 2
Mayer
Huybrechts
30x10^3
25
20
15
10
5
0
0
20
40
60
80
100
Mass flux per unit width [m^2 a^-1]
Distance from ice divide [km]

Figure 9.2



Accumulation rate: 0.3 ma-1
Sea level: -125 m
Basal sliding: no
Initial condition: reference
van der Veen
Pattyn 1
Pattyn 2
Mayer
Huybrechts
Elevation [m]
Distance from divide [km]
1500
1000
500
0
-500
0
20
40
60
80
100

Figure 9.3

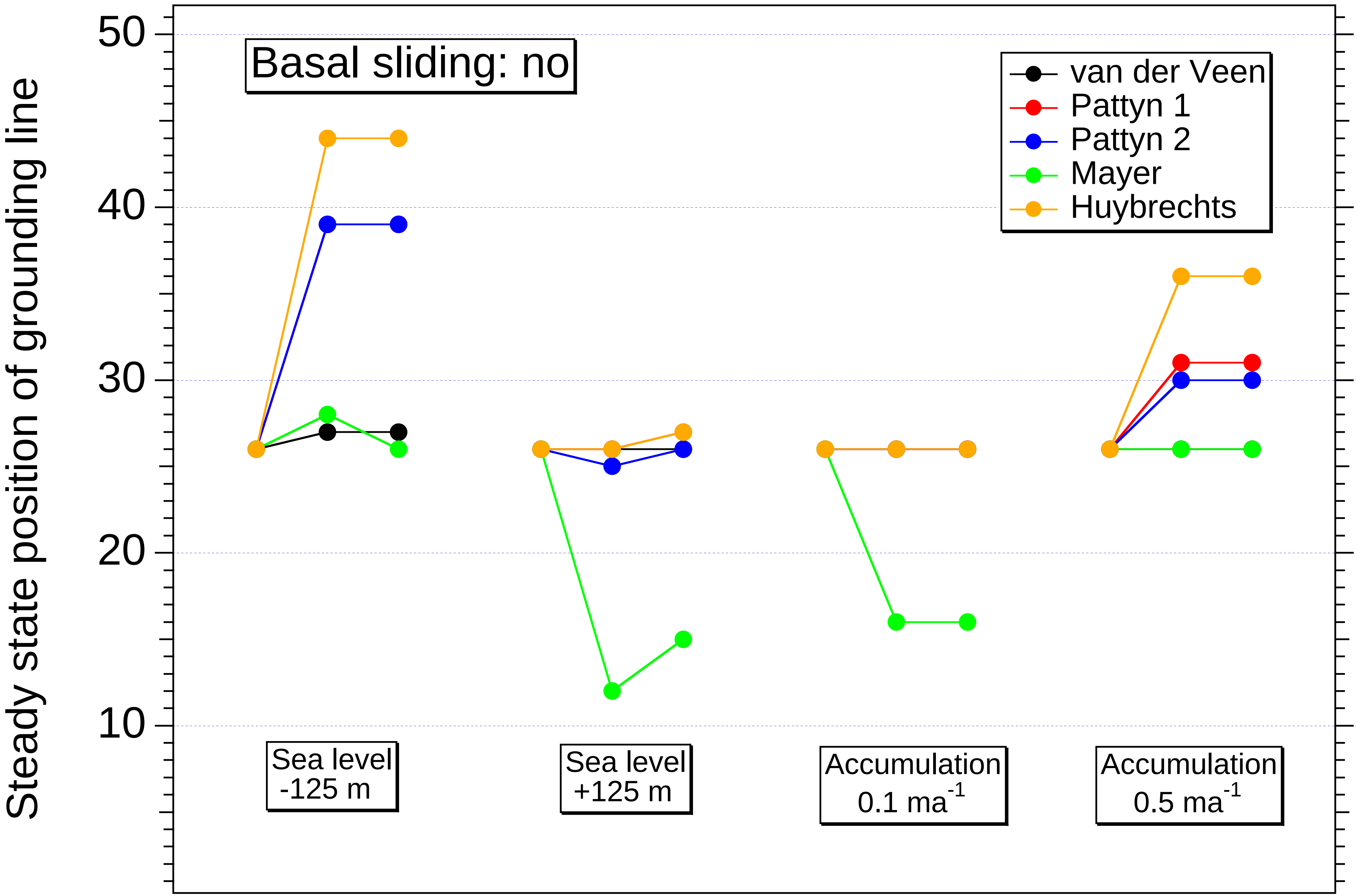

Steady state position of grounding line
50
40
30
20
10
Basal sliding: no
van der Veen
Pattyn 1
Pattyn 2
Mayer
Huybrechts
Sea level
-125 m
Sea level
+125 m
Accumulation
0.1 ma-1
Accumulation
0.5 ma-1

Figure 9.4

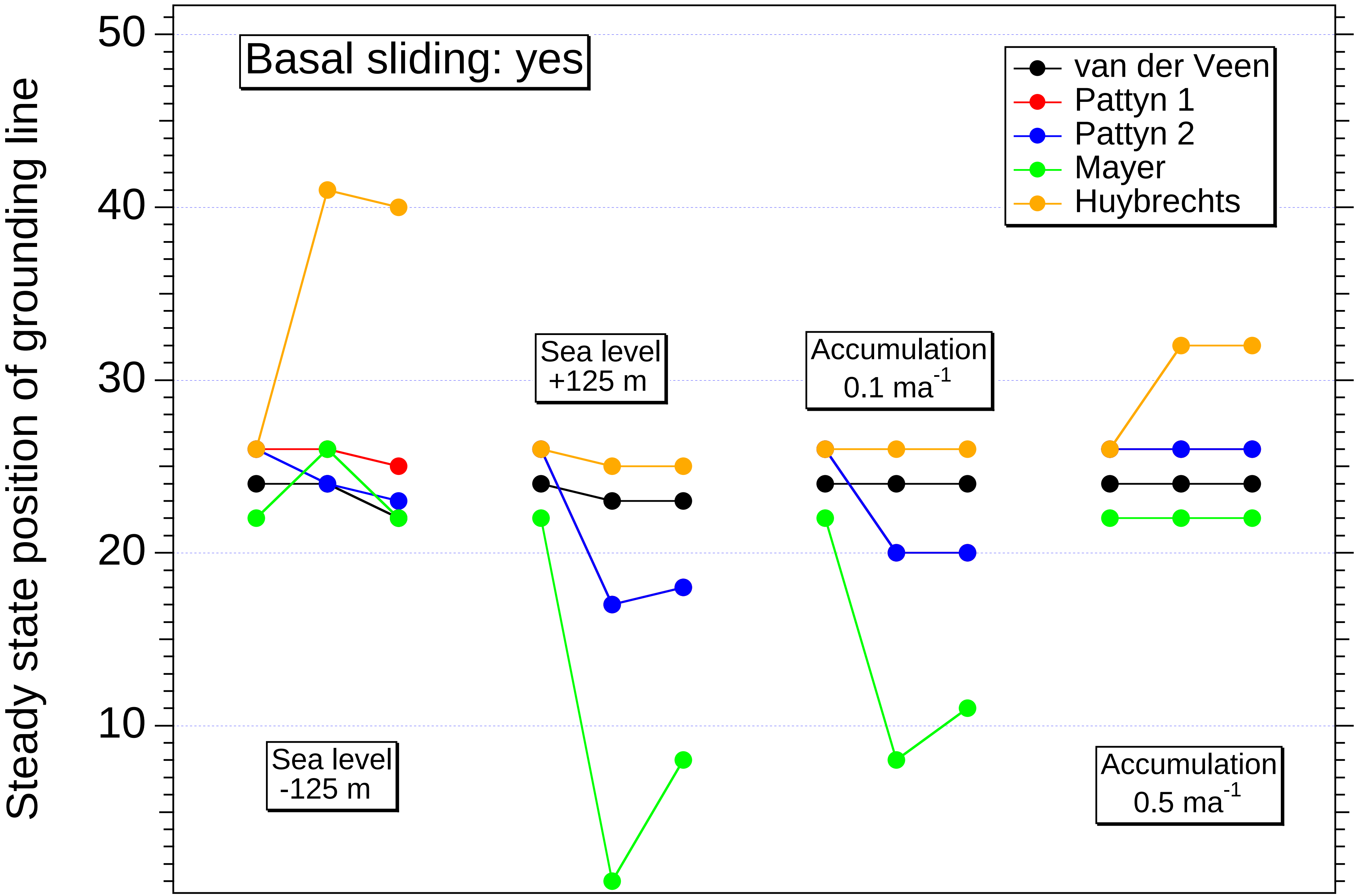

Basal sliding: yes
van der Veen
Pattyn 1
Pattyn 2
Mayer
Huybrechts
Sea level
-125 m
Sea level
+125 m
Accumulation
0.1 ma^-1
Accumulation
0.5 ma^-1
Steady state position of grounding line
50
40
30
20
10

Figure 9.5