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Simulations of the evolution and dynamics of the Antarctic Ice Sheet in past and future climates

Report of category 2 project funded by the ILTS Research Fund

Period 2009.04.01–2010.03.31 (FY 2009)

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Work report

Introduction

The Antarctic Ice Sheet is by far the largest single land ice body on the present-day Earth, with a total ice volume of $24.7 \times 10^6\,\mathrm{km}^3$ and in addition $0.7 \times 10^6\,\mathrm{km}^3$ of the attached ice shelves (Ross Ice Shelf, Filchner-Rønne Ice Shelf, Amery Ice Shelf and others). This corresponds to a sea level equivalent of about 56.6 m (Lemke et al. 2007). Recent results indicate that the Antarctic Ice Sheet shows a surprisingly strong reaction on global warming (Bindoff et al. 2007). The main contribution seems to be from West Antarctica, which goes along with an observed speed-up of ice streams and outlet glaciers like Pine Island Glacier.

This project aims at investigating the evolution and dynamics of the Antarctic Ice Sheet in changing climates in the past (glacial-interglacial cycles) and future (global warming scenarios). On the operational side, a key element is to develop the ice sheet model SICOPOLIS (http://sicopolis.greveweb.net/) into a high-resolution model for the Antarctic Ice Sheet which treats the grounded ice sheet, the ice shelves, the grounding lines and the calving fronts in a physically adequate, state-of-the-art fashion. Key scientific questions to be addressed with this integrated model are: (I.) What is the contribution of the Antarctic Ice Sheet to past sea level changes over glacial-interglacial cycles? (II.) What is the contribution of the Antarctic Ice Sheet to future sea level changes under global warming conditions? (III.) Can ice-dynamic processes lead to accelerated decay of the Antarctic Ice Sheet in the next decades and centuries? (IV.) Is there any evidence for instabilities of the West Antarctic Ice Sheet, triggered either (a) by natural climate variability in the past or (b) by global warming in the future? Results are intended to serve as input for the next (fifth) IPCC Assessment Report (AR5).

Data assimilation

The first step of the project work was to assemble a suitable set of SICOPOLIS input data for the present-day state of the Antarctic Ice Sheet, including its surrounding ice shelves. We used the set of common input data developed by the multi-model effort SeaRISE (Sea-level Response to Ice Sheet Evolution; http://oceans11.lanl.gov/trac/CISM/wiki/AssessmentGroup;

http://websrv.cs.umt.edu/isis/index.php/SeaRISE_Assessment) for that purpose. The relevant data for SICOPOLIS are the surface and basal topographies, the surface temperature, the precipitation rate and the geothermal heat flux. These data were interpolated on regular grids in the stereographic plane with 40, 20 and 10 km resolution. This work was mainly done by R. Greve. Support from international collaborator A. Humbert (Univ. Hamburg, Germany), who has gathered a lot of experience with similar problems, proved to be helpful.

Preliminary simulations of the Antarctic Ice Sheet

Preliminary simulations of the Antarctic Ice Sheet over the last four glacial-interglacial cycles were carried out. These simulations employed the 40-km resolution and the climatic forcing (surface temperature and precipitation as functions of space and time) as specified by Greve (2006), and ignored ice shelf dynamics for the time being. The simulations were not intended to produce any definite results, but served the purpose of testing and optimizing the ice sheet model. Nevertheless, the simulated changes in surface topography and surface velocity patterns proved useful in order to support findings by Iizuka et al. (2010) on past migration of the ice divide between the Shirase and Sôya drainage basins derived from chemical characteristics of marginal ice (Fig. 1).

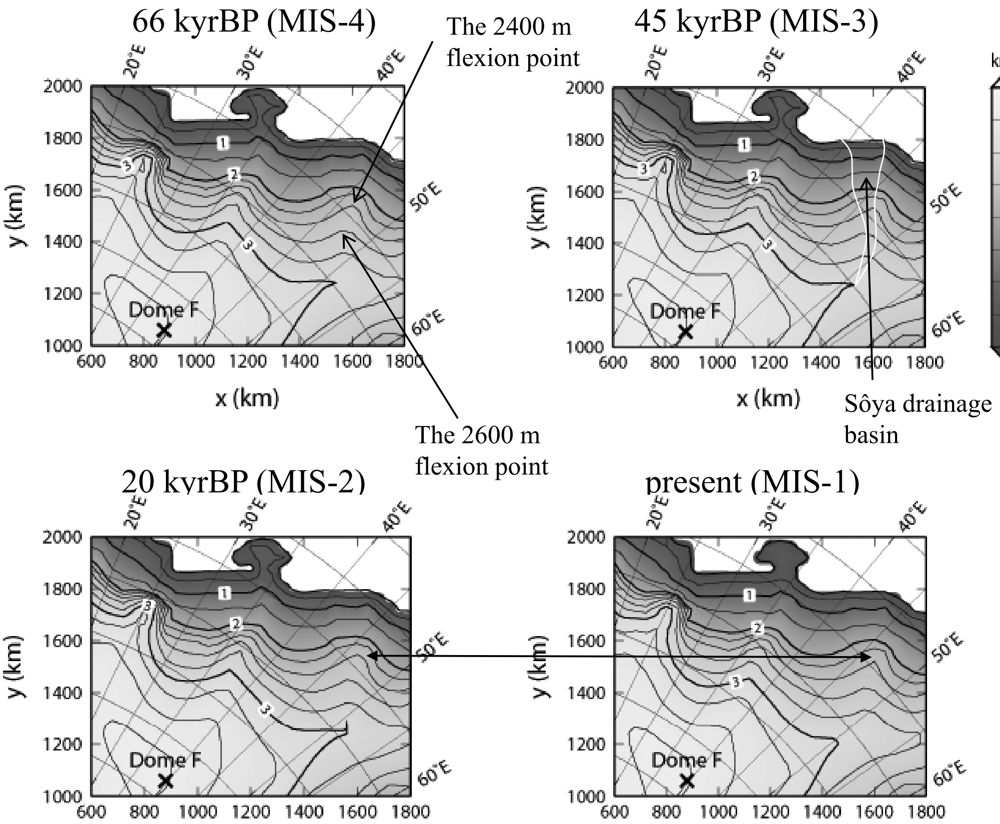

Figure 1: Snapshots of past surface elevations of the Antarctic ice sheet (66, 45, 20, and 0 kyr BP) calculated by SICOPOLIS. The arrow between the MIS-2 and present snapshots shows an example of the moving of flexion points, indicating past migration of the ice divide between the Shirase and Sôya drainage basins (Iizuka et al. 2010, Fig. 7).

Development of a solver for the shallow shelf approximation

The ice sheet model SICOPOLIS in the version 2.9, which had been available when this project started, did not contain ice shelf dynamics at all. Instead, ice shelves were simply cut off, and the ice flow across the grounding line assumed to calve immediately into the surrounding ocean. In order to improve this treatment, the doctoral student T. Sato, who started his doctorate in the Cryosphere Science Course of the Graduate School of Environmental Science at Hokkaido University, developed a finite difference algorithm for solving the shallow shelf field equations for the horizontal velocity field. The algorithm was verified successfully by comparison with the analytical solution for an ice shelf ramp (Greve and Blatter 2009). Stand-alone simulations for a simple, "academic" (ring-shaped) ice shelf geometry were run (Fig. 2), and integration of the algorithm into the ice sheet model SICOPOLIS was started. This work item benefitted from active exchange with domestic collaborators A. Abe-Ouchi (AORI, Univ. Tokyo), F. Saito (JAMSTEC), and international collaborator N. Kirchner (Univ. Stockholm, Sweden).

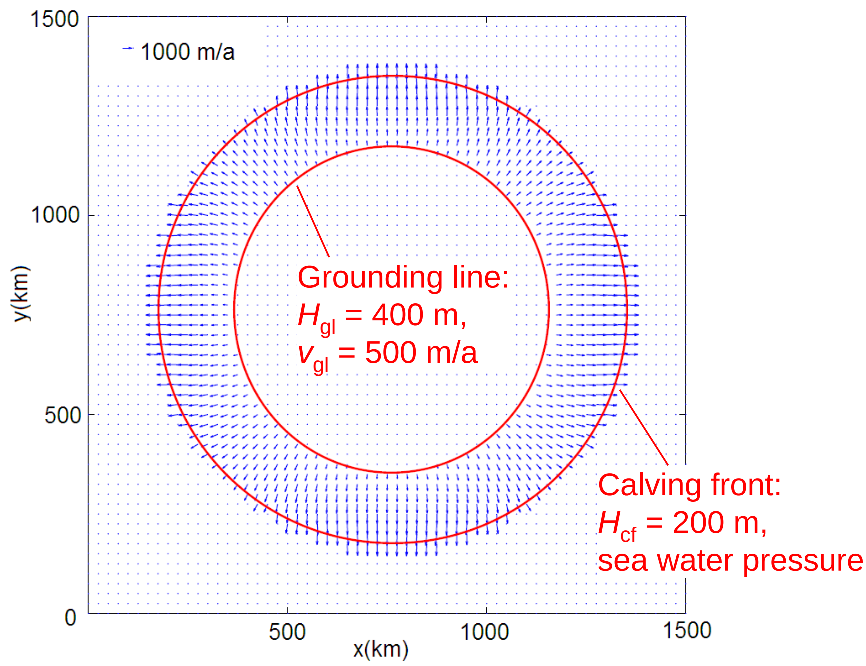

Figure 2: Computation of the horizontal velocity field of an annular ice shelf with prescribed geometry (width 200 km, thickness varying linearly from 400 m at the grounding line to 200 m at the calving front) and inflow velocity (500 m/a). Horizontal resolution $\Delta x = 25\,\mathrm{km}$.

Shallow shelf approximation in general curvilinear coordinates

A particular feature of the ice sheet model SICOPOLIS is that is solves all model equations in general curvilinear coordinates on the surface of the Earth (the only requirement is orthogonality). This allows to switch easily between different grids, such as the stereographic map plane, geographical coordinates (longitude/latitude) etc. While the formulation of the shallow ice approximation for grounded ice in these general coordinates is essentially straightforward, this turned out to be unexpectedly difficult for the shallow shelf approximation. We started from the full Stokes problem for ice flow, subjected it to a general coordinate transformation using Riemann metrics, and then derived the shallow shelf approximation by adopting the hydrostatic and plug flow approximations in the general coordinate system. The resulting set of equations was formulated in contravariant and mixed form. This work was mainly done by doctoral student T. Sato, supervised by R. Greve and S. Sugiyama.

Future work

This project will be continued in the FYs 2010-2013 (2010.04.01–2014.03.31), funded by a JSPS Grant-in-Aid (*kakenhi*) for Scientific Research (A). For this period, the following main works are planned:

- Full implementation of coupled ice-sheet/ice-shelf dynamics in SICOPOLIS.
- Investigation of ice-dynamic processes (grounding line dynamics, calving front dynamics, basal sliding) with the full Stokes model Elmer/Ice (http://www.csc.fi/elmer/), development of suitable parameterizations.
- Development of a higher-order algorithm for ice sheet dynamics in SICOPOLIS.
- Paleoclimatic simulations and model validation.
- Global warming simulations as part of the SeaRISE community effort.

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Publications in FY 2009

- Iizuka, Y., H. Miura, S. Iwasaki, H. Maemoku, T. Sawagaki, R. Greve, H. Satake, K. Sasa and Y. Matsushi. 2010. Evidence of past migration of the ice divide between the Shirase and Sôya drainage basins derived from chemical characteristics of the marginal ice in the Sôya drainage basin of East Antarctica. *J. Glaciol.*, **56** (197), 395–404.

Presentations in FY 2009 (presenter underlined)

- Greve, R.: Dynamic/thermodynamic modelling of ice sheets in changing climates. International Symposium *Frontiers of Low Temperature Science*, Hokkaido University Sustainability Weeks, Sapporo, Japan, 2009.11.09–10. [Invited talk.]
- Greve, R., T. Sato and T. Dunse: Implementation of ice shelf dynamics and marine ice dynamics in the ice sheet model SICOPOLIS. International Glaciological Conference *Ice and Climate Change: A View from the South*, Valdivia, Chile, 2010.02.01–03. [Invited talk.]
- Sato, T. and R. Greve: Implementation of large-scale ice shelf dynamics in the ice sheet model SICOPOLIS. AGU (American Geophysical Union) Fall Meeting, San Francisco, USA, 2009.12.14–18. [Poster presentation.]

Intellectual property rights

- Distribution of SICOPOLIS V3.0 pre-release 1 as free software under the terms of the GNU General Public License (2010.03.11).