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# 科学研究費補助金研究成果報告書

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研究課題名（和文）　氷床における氷の異方性と高速氷流、およびその気候変動との関係性

研究課題名（英文）　Induced anisotropy, fast ice flow and climate change in ice sheets

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研究成果の概要： This project dealt with two hot topics in current climatological research on ice sheets, *induced anisotropy* and *fast ice flow*, by means of numerical modelling. A new versatile, three-dimensional computer model "Elmer/Ice" for flowing ice masses was developed, which solves the full-Stokes equations. Within Elmer/Ice, induced anisotropy is described by the "CAFFE model". The CAFFE model was applied to the site of the EDML ice core at Kohnen Station in east Antarctica, for which the measured surface velocity and fabrics profile could be reproduced well. Elmer/Ice with the CAFFE model was applied to a 200 x 200 km window around the Dome Fuji ice core in central east Antarctica. The main findings of the simulations were: (i) the flow regime at Dome Fuji is a complex superposition of vertical compression, horizontal extension and bed-parallel shear; (ii) for a geothermal heat flux of 60 mW $m^{-2}$ the basal temperature at Dome Fuji reaches the pressure melting point; (iii) the fabric shows a weak single maximum at Dome Fuji; (iv) the basal age is smaller where the ice is thicker and larger where the ice is thinner. As a spin-off study, Elmer/Ice was also applied to the Gorshkov crater glacier at Ushkovsky volcano, Kamchatka, which is characterized by an unusually large aspect ratio and a very high geothermal heat flux. Simulations of the Greenland ice sheet were carried out with R. Greve's ice-sheet model SICOPOLIS. It was found that (i) the present-day North-East Greenland Ice Stream (NEGIS) shows basal sliding enhancement by the factor three compared to the surrounding, slowly flowing ice, and (ii) ice-dynamical processes (basal sliding accelerated by surface meltwater) can speed up the decay of the ice sheet significantly, but not catastrophically in the 21st century and beyond. Modelling with Elmer/Ice of the flow regime of the Antarctic drainage system from Dome Fuji to Shirase Glacier is still ongoing. One doctoral thesis (Mr. Hakime Seddik) and one master thesis (Ms. Shoko Otsu) were completed at Hokkaido University within this project.

交付額

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## １．研究開始当初の背景

Ice sheets are an important dynamic component of the Earth's climate system. Whereas the usual slow-flow conditions for ice, described as an isotropic power-law fluid, are reasonably well understood, the presence of induced anisotropy as well as fast ice flow (ice streams) pose a great challenge to realistic modelling efforts for ice sheets in changing climate conditions.

Since the 1990's, dynamic/thermodynamic modelling studies of ice sheets have experienced a major boost owing to the availability of powerful computers. By the time this project was proposed (October 2005), active groups, working on paleoclimatic as well as future scenarios, were at the Center for Climate System Research, University of Tokyo (Prof. A. Abe-Ouchi, Dr. F. Saito), the Free University of Brussels, Belgium (Dr. P. Huybrechts, Dr. F. Pattyn), the Department of Physics, University of Toronto, Canada (Prof. W. R. Peltier, Dr. L. Tarasov) and several other places. Most of the available models were based on the shallow-ice approximation, and full-Stokes-flow solvers had only been used for diagnostic studies of alpine glaciers.

Induced anisotropy had been studied theoretically and experimentally (lab tests) by working groups at the Department of Mechanical Engineering, Nagaoka University of Technology (Prof. N. Azuma), the Department of Mechanics, Darmstadt University of Technology, Germany (Prof. K. Hutter) and the Laboratory of Glaciology and Environmental Geophysics (LGGE), Grenoble, France (Prof. P. Duval, Dr. J. Meyssonier). However, consideration of induced anisotropy in three-dimensional modelling studies of ice sheets had never been done. The great importance of fast ice flow in ice sheets had drawn considerable attention in connection with the observed accelerated decay under global-warming conditions. For Greenland, accelerated basal sliding due to surface meltwater percolating to the ice base had been identified as a crucial process in this context, but detailed, three-dimensional modelling studies had not been carried out so far.

## ２．研究の目的

The two phenomena of induced anisotropy and fast ice flow, which are highly relevant in current climatological research on ice sheets, were targeted by means of numerical modelling. Both phenomena are crucial in understanding the dynamic response of the ice sheets of Antarctica and Greenland to past and future climate change.

A central point of the project was the development of a new, versatile computer model "Elmer/Ice" for the dynamics and thermodynamics of flowing ice masses (in cooperation with Dr. Thomas Zwinger, CSC – IT Center for Science in Espoo, Finland). Elmer/Ice solves the full-Stokes equations, which makes the model in principle applicable to all different types of flowing ice masses, including the vicinity of ice-sheet domes (important in conjunction with ice-core projects), ice streams, transition zones between ice-sheet, ice-stream and ice-shelf flow and also small glaciers. Induced anisotropy was implemented in the form of the CAFFE model (in cooperation with Dr. Luca Placidi, University of Rome "La Sapienza", Italy, and Dr. Olivier Gagliardini, LGGE Grenoble, France).

Modelling studies were carried out for the entire Greenland Ice Sheet (with a focus on the fast-flowing ice streams), the vicinity of Dome Fuji in the central East Antarctic Ice Sheet, the fast-flowing drainage system from Dome Fuji to Shirase Glacier and, as a spin-off study, for the Gorshkov crater glacier at Ushkovsky volcano, Kamchatka. For the ice-stream systems, the focus was on ice-sheet stability or instability in a future warming climate, whereas for the Dome-Fuji area, the focus was on induced anisotropy and consequences for ice-core dating.

## ３．研究の方法

Ice-sheet modelling is based on the dynamic/thermodynamic field equations and boundary conditions for the flow of polycrystalline ice. These equations are based on the continuum-mechanical balance equations of mass, momentum and energy plus constitutive equations for the ice deformation, heat conduction and internal energy. Typical three-dimensional ice-sheet models solve this coupled system of equations numerically by either finite-difference (FD) of finite-element (FE) methods, and compute the ice extent, thickness, flow velocity, temperature and age as functions of time for a prescribed period. External forcing is specified by the mean annual air temperature at the ice surface, the net surface mass balance (ice accumulation minus ablation), the global sea level and the geothermal heat flux entering the ice body from below.

For the studies of this project, two different models were used. SICOPOLIS (SImulation COde for POLythermal Ice Sheets, http://sicopolis.greveweb.net/) is an established FD model based on the shallow-ice approximation, that is, the momentum balance is simplified by only considering the hydrostatic pressure and shear stresses in horizontal planes. By contrast, the newly developed FE model Elmer/Ice solves the full-Stokes equations, that is, all stresses are retained in the momentum balance. Further, Elmer/Ice was coupled with the CAFFE model (Continuum-mechanical, Anisotropic Flow model, based on an anisotropic Flow Enhancement factor) in order to account for induced anisotropy. The price to pay for this sophistication is a much larger computational demand, so that in this project Elmer/Ice was used for diagnostic simulations which analyze the present state of an ice sheet, while time-dependent simulations were conducted with the computationally less demanding model SICOPOLIS.

４．研究成果

（１） The dynamic/thermodynamic ice-sheet model Elmer/Ice was developed successfully. Elmer/Ice is based on the open-source computational tool "Elmer" for multi-physics problems provided by the CSC – IT Center for Science in Espoo, Finland (http://www.csc.fi/elmer/), and, as already mentioned above, solves the full-Stokes equations, which makes it very versatile. Following the open-source philosophy, all new routines for Elmer/Ice have been made publicly available, thus constituting a lasting legacy of this project for the cryosphere science community worldwide.

（２） Based on earlier versions of anisotropic flow laws and fabric evolution equations by Dr. Luca Placidi, we developed a thermodynamically consistent form, termed the CAFFE model. The CAFFE model is an application of the theory of mixtures with continuous diversity for large, polycrystalline ice masses in which induced anisotropy cannot be neglected. The anisotropic response of the material is described by a simple anisotropic generalization of Glen's flow law based on a scalar anisotropic enhancement factor. The enhancement factor depends on the orientation mass density, which corresponds physically to the orientation distribution function (i.e., the fabric). The evolution of anisotropy is modelled by the evolution of the orientation mass density, which is governed by the balance of mass of the mixture with continuous diversity. [See the papers by Placidi et al. (2009) and Greve et al. (2009).]

（３） The CAFFE model was applied to the EPICA (European Project for Ice Coring in Antarctica) ice core at Kohnen Station, Dronning Maud Land, Antarctica (referred to in short as "EDML core"). A one-dimensional flow model for the site was devised, which includes the anisotropic flow law and the fabric evolution equation of the CAFFE model. Three different solution methods were employed, (i) computing the ice flow based on the flow law of the CAFFE model and the measured fabrics, (ii) solving the CAFFE fabric evolution equation under the simplifying assumption of transverse isotropy, and (iii) solving the unrestricted CAFFE fabric evolution equation. Method (i) demonstrated clearly the importance of the anisotropic fabric in the ice column for the flow velocity. The anisotropic enhancement factor produced with method (ii) agrees reasonably well with that of method (i), even though the measured fabric shows a girdle structure (which breaks the transverse isotropy) in large parts of the ice core. For method (iii), we found that the measured fabric is reproduced well by the model down to approximately 2100 m depth, and systematic deviations further down could be attributed to the disregard of migration recrystallization in the model. [See the paper by Seddik et al. (2008).]

（４） A three-dimensional modelling study was conducted for the vicinity (200 x 200 km domain) of Dome Fuji in the central East Antarctic Ice Sheet. For this study, the model Elmer/Ice was used, and induced anisotropy was treated by the CAFFE model. Since time-dependent simulations over glacial-interglacial cycles were not feasible due to the enormous computational demand, only steady-state simulations for present-day climate conditions and fixed geometry were carried out. The main findings were: (i) the flow regime at Dome Fuji is a complex superposition of vertical compression, horizontal extension and bed-parallel shear; (ii) for a geothermal heat flux of 60 $\mathrm{mW\,m^{-2}}$ the basal temperature at Dome Fuji reaches the pressure melting point (in agreement with observations) and the basal melting rate is ~ 1 $\mathrm{mm\,a^{-1}}$; (iii) the fabric shows a weak single maximum at Dome Fuji (weaker than observed, probably due to the disregard of migration recrystallization in the CAFFE model), which increases the age of the ice compared to an isotropic scenario; (iv) as a consequence of spatially variable basal melting conditions, and contrary to intuition, the basal age is smaller where the ice is thicker and larger where the ice is thinner. The latter result is of great relevance for the consideration of a future drill site in the area. [See Fig. 1 and the paper by Seddik et al. (2009).]

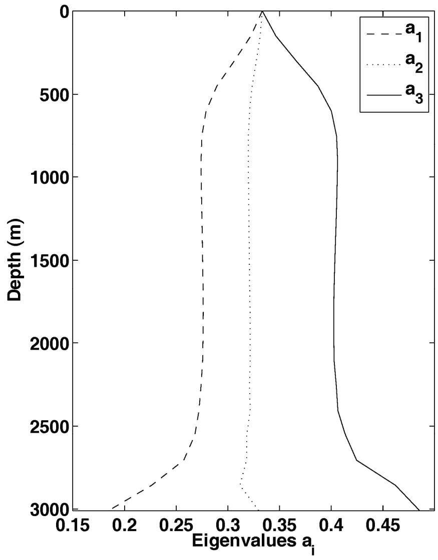


Fig. 1: Anisotropic steady-state simulation for the vicinity of Dome Fuji: Profiles of the eigenvalues $a_1$, $a_2$ and $a_3$ of the second-order orientation tensor at the Dome Fuji drill site (Seddik et al. 2009). At the surface, isotropic conditions with $a_1 = a_2 = a_3 = 1/3$ prevail. Further down, an elongated single maximum fabric with $a_1 < 1/3$, $a_2 \sim 1/3$, $a_3 > 1/3$ develops.

（5） In a spin-off study, Elmer/Ice was applied to the Gorshkov crater glacier in the summit caldera of Ushkovsky volcano, Kamchatka. This glacier is characterized by a large aspect ratio and special thermodynamic conditions at the bedrock caused by a locally enhanced and spatially strongly varying geothermal heat flux. Furthermore, large parts consist of firn rather than pure ice, which alters the rheological properties (viscosity, compressibility) of the glacier. Therefore, the Gorshkov crater glacier served as a good test for the asserted versatility of Elmer/Ice. By assuming steady-state conditions, the present-day velocity field, temperature field, basal melting rate and age distribution were simulated. We found that flow velocities are generally small (10's of centimeters per year). Horizontal and vertical velocities are of comparable magnitude, which shows that the shallow-ice approximation is not applicable. Owing to the spatially variable volcanic heat flux, the thermal regime at the ice base is cold in the deeper parts of the glacier and temperate in the shallower parts. The measured temperature profile and age horizons at the K2 borehole near the center of the glacier were reproduced quite well, and remaining discrepancies were attributed to transient (non-steady-state) conditions. Firn compressibility was identified as a crucial element for the simulations. [See the paper by Zwinger et al. (2007).]

（6） The dynamics of the Greenland Ice Sheet and its ice streams in response to climate change were simulated with the ice-sheet model SICOPOLIS. For this purpose, a high-resolution version of the shallow-ice model SICOPOLIS with a horizontal grid spacing of 10 km was set up.

In the first step, emphasis was put on one particular ice stream, namely the north-east Greenland ice stream (NEGIS). We assumed that the NEGIS area is characterized by enhanced basal sliding compared to the "normal", slowly-flowing areas of the ice sheet, and simulated the evolution of the ice sheet for the period from 250 ka ago until today, driven by a climatology reconstructed from a combination of present-day observations and GCM results for the past. By minimizing the misfit between simulated and observed ice thicknesses and surface velocities, we found that the present-day NEGIS shows basal sliding enhancement by a factor of approximately three. [See the paper by Greve and Otsu (2007)].

In the second step, simulations were carried out for several global-warming scenarios from the reference year 1990 until 2350. In particular, the impact of surface-meltwater-induced acceleration of basal sliding on the stability of the ice sheet was investigated. A parameterization for this acceleration effect was developed for which modelled and measured mass losses of the ice sheet in the early 21st century agree well. Simulation results suggest that (i) the ice sheet is generally very susceptible to global warming on time-scales of centuries, (ii) surface-meltwater-induced acceleration of basal sliding leads to a pronounced speed-up of ice streams and outlet glaciers, and (iii) this ice-dynamical effect accelerates the decay of the Greenland Ice Sheet as a whole significantly, but not catastrophically, in the 21st century and beyond. [See Fig. 2 and the papers by Greve (2008) and Greve and Sugiyama (2009).]

（7） The drainage system of the Antarctic Ice Sheet from Dome Fuji to Shirase Glacier was investigated with the model Elmer/Ice (without consideration of induced anisotropy) in order to characterize the three-dimensional flow regime and determine the relative contributions of slow ice-sheet flow and fast ice-stream/shelf flow. After optimization of the model domain and the finite-element mesh, the model successfully

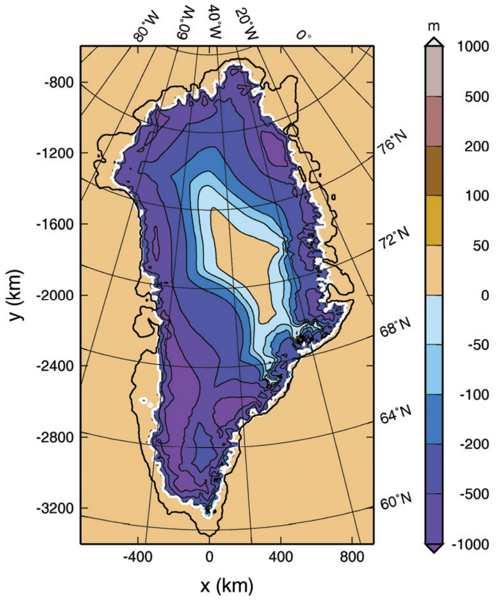


Fig. 2: Simulated thickness change of the Greenland Ice Sheet for the years 2350-1990 under a 1000-ppm stabilization scenario for atmospheric $CO_2$ [run #4 by Greve (2008) and Greve and Sugiyama (2009), including the melt-acc effect]. Brown colours mean no change or thickening, blue colours thinning. Thinning is most severe around the ice margin, whereas the interior ice sheet is less affected. The sea level equivalent of the ice loss 2350-1990 is 1.84 m.

reproduced the converging flow regime in the Shirase drainage basin. Computed surface flow speeds over- and underestimate the observations in the upper and lower reaches, respectively. Computed basal temperatures reach the pressure melting point at approximately 50% of the basin area, suggesting the important role of basal sliding in the Shirase drainage basin. This work is still ongoing, and a paper will be prepared later.

５．主な発表論文等
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