博　士（環境科学）　セディック　ハキム

学 位 論 文 題 名

A full-Stokes finite-element model for the vicinity of Dome Fuji with flow-induced ice anisotropy and fabric evolution

（氷床流動による氷の異方性と構造変化を考慮した
フルストークス有限要素法モデルの構築と、
南極氷床・ドームふじ近傍への適用）

学位論文内容の要旨

A three-dimensional, thermo-mechanically coupled flow model with induced anisotropy has been developed and applied to the vicinity of Dome Fuji, Antarctica, the site of a recent Japanese deep ice drilling project. The model implements the full-Stokes equations for the ice dynamics, and the system is solved with the finite-element method (FEM) using the open source multi-physics package Elmer (http://www.csc.fi/elmer/). The model is therefore referred to as "Elmer/Ice".

The finite-element mesh for the computational domain has been created with two topographic data-sets, (i) high resolution data in a 60 x 60 km area around Dome Fuji, and (ii) lower resolution data obtained from the SICOPOLIS grid (Greve, pers. comm. 2006), based on the RAMPDEM V2 and BEDMAP data-sets for the entire Antarctic ice sheet. The high resolution data around the Dome Fuji station have been merged to the lower-resolution data to create a single domain of 200 x 200 km size. The resolution of the mesh is ~ 20 km near the boundaries, and it is gradually refined up to 500 m towards the position of the borehole located in the center of the domain. This procedure has been carried out in order to keep the lateral boundaries sufficiently far away from the dome, so that shallow-ice stresses can be prescribed there. At the base, no-slip conditions and a geothermal heat flux are employed, and at the surface, stress-free conditions and a spatially constant temperature are prescribed.

A Continuum-mechanical, Anisotropic Flow model, based on an anisotropic Flow Enhancement factor ("CAFFE model") is used for taking into account flow-induced anisotropy in ice. The flow law is implemented in Elmer/Ice by means of second and fourth order orientation tensors that describe the c-axis orientation of the fabric. Similarly, the fabric evolution equation is written in terms of the evolution of the second order tensor, and it is solved inside Elmer/Ice with a Discontinuous Galerkin method using Picard type iterations for the non-linearity. Since the fabric evolution equation also depends on the fourth order orientation tensor, the IBOF (Invariant-Based Optimal Fitting) closure function is used for the computation of its components from the solution of the second orientation.

The main questions addressed by the simulations carried out in this thesis are (i) what is the local flow field in the vicinity of Dome Fuji, (ii) how is the flow field affected by the anisotropic fabric, and (iii) what are the consequences for the interpretation of the climatological proxy data of the Dome Fuji ice core. The results are therefore relevant for the reconstruction of the paleoclimatic variability in East Antarctica, which is an important clue for understanding possible future climate changes on Earth. Further, the improved modelling of ice dynamics by solving the full-Stokes equations and including anisotropy is an important step towards simulating rapid dynamical changes which may destabilize the terrestrial ice sheets and lead to a potentially dangerous rate of sea level rise in a warming environment.

Two types of simulation have been carried out: steady-state isotropic and steady-state anisotropic. The model has computed the ice dynamics at the Dome Fuji and the distribution of the temperature at the ice base has been determined. With the computed melting conditions, the distribution of the age has been assessed. The resulting computed age has shown surprising results due to the location of old ice where the ice is thinner. The anisotropic simulation has shown the effect of ice anisotropy on ice dynamics (ice flow) and on the age. The model predicts old ice in comparison to isotropic conditions, however the complexity of recrystallization processes at the bottom of the Dome Fuji ice core associated with dome migration processes does not permit the exact modeling of the fabric and age at the borehole.

学位論文審査の要旨

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In the doctoral thesis of the candidate, a three-dimensional, thermo-mechanically coupled ice flow model with induced anisotropy has been developed and applied to the vicinity of Dome Fuji, Antarctica, the site of a recent Japanese deep ice drilling project. The model, referred to as "Elmer/Ice", implements the full-Stokes equations for the ice dynamics, and the system is solved with the finite-element method (FEM). The newly developed Continuum-mechanical, Anisotropic Flow model, based on an anisotropic Flow Enhancement factor ("CAFFE model") is used for taking into account flow-induced anisotropy in ice. The CAFFE model is validated by a simple, one-dimensional application to the EDML ice core, Antarctica, for which the observed fabric can be reproduced well. The CAFFE model is then implemented in Elmer/Ice by using second and fourth order orientation tensors that describe the c-axis orientation of the fabric. The finite-element mesh is set up for a 200 x 200 km window around Dome Fuji, and steady-state simulations for present-day climate conditions are carried out. The main findings of the study are:

- The ice flow points radially away from the dome, following essentially the steepest surface slope, and reaches maximum speeds of about 1.4 m a^{-1} in the 200 x 200 km domain. A significant influence of the bedrock topography does not become evident.
- The fabric shows a weak single maximum at the site of the Dome Fuji ice core. This is roughly in agreement with preliminary, unpublished measurements, which indicate a somewhat stronger single maximum in the near-basal parts, though. Reasons for the discrepancy are likely summit migration in the past and/or migration recrystallization, which are not accounted for in the model.
- The basal temperature reaches the pressure melting point at the drill-site, in agreement with observations. This leads to basal melting of the order of a millimeter per year, which limits the age of the near-basal ice.
- As a consequence of spatially variable basal melting conditions, and contrary to intuition, the near-basal age is smaller where the ice is thicker and larger where the ice is thinner. This result is of great practical relevance for the consideration of a future drill-site in the area.

The five members of the examination committee agreed that the thesis of the candidate constitutes a milestone in the field of ice-sheet modelling. Three-dimensional full-Stokes simulations are at the forefront of current research, and the combination with a model for induced anisotropy has never been carried out before. Beyond the direct implications for the Dome Fuji ice core project described above, the developed methods are highly useful for simulating possible rapid dynamical changes which may destabilize the terrestrial ice sheets and lead to a potentially dangerous rate of sea level rise in a warming environment. Also, flow simulations for smaller glaciers can benefit greatly.

During the three years of the study, the candidate has cooperated actively with researchers from four different countries (Japan, Italy, Finland, France), including two six-week stays at the CSC – Scientific Computing Ltd. (Espoo, Finland) and the LGGE (Grenoble, France). This highlights the strong linking to the international scientific community he has established. Further, the results have been presented at national (Seppyougakkai Akita 2006 and Toyama 2007) and international (AGU Fall Meeting 2007, San Francisco, USA; PICR-2 Sapporo 2007) conferences, and publications in international, peer-reviewed scientific journals are on the way.

In the meeting following the examination on February 1, 2008 (Fri), it was unanimously concluded by the five members of the examination committee that the candidate's thesis, as well as his performance in the examination, has met the demands to the full satisfaction, and that the candidate is to be conferred the degree of Doctor of Environmental Science [博士 (環境科学)].