Form 8／様式 8
（外特 2008）

JSPS POSTDOCTORAL FELLOWSHIP
FOR FOREIGN RESEARCHERS

Research Report

1. Name: Hakime Seddik **(ID No.: P08861)**

Nationality: France

Host Institution: Institute of Low Temperature Science.

Host Researcher: Ralf Greve

2. Title of Research in Japan: Simulation of rapid dynamical changes of the Greenland ice sheet in response to global warming

3. Fellowship Period: From 2008/10/15 To 2010/10/14

4. Research background:

The proposed research focuses on the simulation of the Greenland ice sheet dynamics using a three-dimensional thermo-mechanically coupled full-Stokes model. The general goal of the study is to better assess the impact of global warming on Greenland dynamics. We are particularly aiming to investigate the potential acceleration of already fast flowing ice streams and its consequence on global sea level rise.

5. Research methodology:

For the realization of this project, we have developed a model of the entire Greenland ice sheet, which implements the full-Stokes equations for the ice dynamics. The thermo-mechanically coupled flow model (Elmer/Ice) was implemented with the finite-element method using the open source finite-element package Elmer (www.csc.fi/elmer). The finite-element mesh was creates using an anisotropic mesh adaptation scheme and contains 200k+ elements and 122k+ nodes.

6. Research implementation and results:

For the purpose of investigating the consequence in global sea level of the evolution of the Greenland ice sheet with changing climate, we have implemented with our model the four principal experiments defined in the SeaRise assessment project as follows:

- Experiment C1_E0: Constant climate run beginning at present (the epoch 2004-1-1 0:0:0) and running for 100 years holding the climate constant to the present climate.
- Experiment C1_E1: Similar to C1_E0 but with increased basal lubrication assumed. This is implemented by halving the basal drag everywhere in the domain.
- Experiment C2_E0: AR4 climate control run. The experiment starts with the present-day condition, but the climate forcing was derived from an ensemble average of 18 of the AR4 models run from the period 2004-2098 under the A1b emission scenario.
- Experiment C2_E1: Similar to C2_E0 but with increased basal lubrication.

Using the same experiments, our model is also compared to the model SICOPOLIS which is based on the shallow ice approximation.

The principal results are shown in Figure 1. Figure 1a shows the ice volume evolution (in meter Sea Level Equivalent) of the Greenland ice sheet over 100 years. The ice sheet reacts distinctly to the imposed scenario but our model shows that for a forcing with constant climate (C1_E0), the ice sheet is growing. The same experiment but with increased basal lubrication (C1_E1) shows similarly an increase of the ice volume but smaller than the initial control run, that is, the increased basal lubrication lead to a volume loss of 0.02 m SLE. The response to the direct global warming (AR4 climate) shows a stronger response than the ice dynamical scenario of increased basal lubrication. Relative to the constant climate control run (C1_E0), the global warming forcing (C2_E0) leads to volume losses of ~0.10 m SLE and the global warming scenario plus basal lubrication leads to volume losses of ~0.15 m SLE.

Figure 1b shows the ice volume evolution predicted by the model SICOPOLIS which is based on the shallow ice approximation. For all experiments, the sensitivity of SICOPOLIS is significantly higher than of Elmer/Ice. The most visible difference is the loss of volume predicted by SICOPOLIS for experiments C1_E0 and C1_E1 whereas the Stokes model predicted a volume gain. Besides the fundamental difference of the physics used to model the ice flow employed in the models, an explanation of this difference is of course not easily available at the moment. However, because of the initial conditions being produced by SICOPOLIS, the initial shock during the experiment is certainly higher in the case of the Stokes model. This can explain the different response, particularly for the experiments (C1_E0 and C1_E1) where the ice dynamics is the major process in the ice sheet evolution.

Besides these observations, it is interesting to note that the difference between the control runs (C1_E0 - C2_E0) are almost identical between models, 0.10 m SLE for Elmer/Ice, 0.08 m SLE for SICOPOLIS. This shows that the reaction to different types of forcing is consistent between models. The results presented here represent the first simulation of the evolution of the Greenland ice sheet under changing climate using a full-Stokes model and therefore it is a significant achievement in this research field.

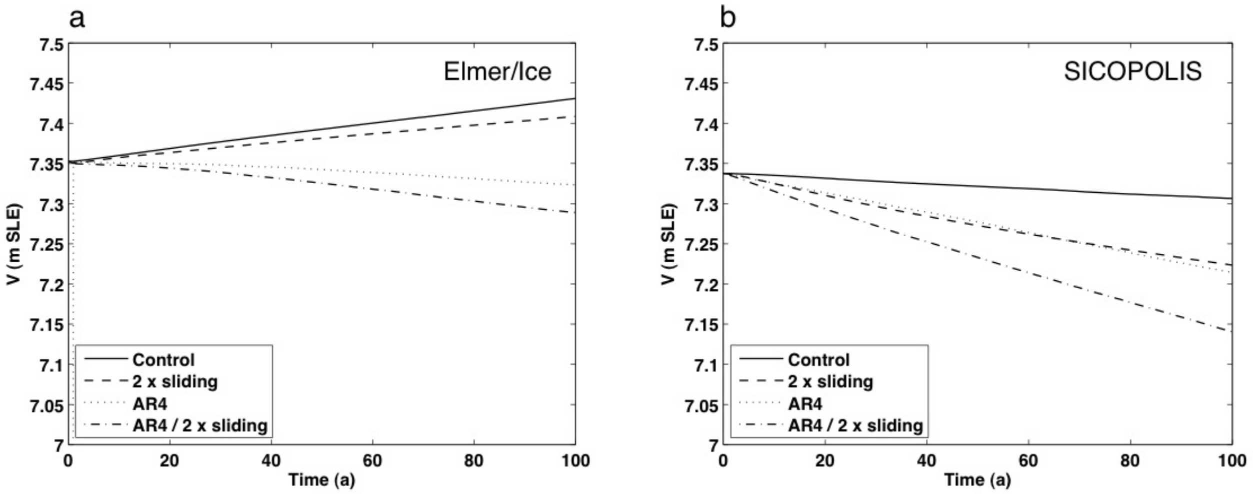

Fig. 1. Ice volume, V, changes simulated with (a) Elmer/Ice and (b) SICOPOLIS for experiments C1_E0 (control), C1_E1 (2 x sliding), C2_E0 (AR4) and C2_E1 (AR4 / 2 x sliding).

7. International exchange achieved through the research:

During my tenure, I have developed a more active research collaboration with the CSC-IT Center for Science in Finland. After my fellowship ended, I have secured a new position at the Institute of Low Temperature Science. I am now involved in a new project as Post-Doctorate researcher for a total of three years. The new project is a direct continuation of what I have achieved during my tenure and my new experience in innovative ice sheets modeling will be used during the new project.

8. Major publications of research results

The results are now being prepared for submission to the SeaRise assessment project (http://websrv.cs.umt.edu/isis/index.php/SeaRISE_Assessment).

Sapporo, Japan
November 2010 *Hakime Seddik*

Note:
1. This form must be submitted to TEI along with your host researcher's Form 9 within one month of the end of your fellowship tenure.
2. Please keep the length of your report within 3 pages.

Form 9／様式 9
（外特 2008）

平成 22 年 11 月 10 日

研　究　報　告　書

受入研究者
所属・職：　北海道大学・教授

氏　　名：　Ralf GREVE　　　　　　　(印)

日本学術振興会外国人特別研究員の採用期間中の研究について下記のとおり報告します。

記

１．外国人特別研究員　国籍・氏名・ID No.

フランス・Hakime SEDDIK

（**ID No.: P**　08821　　）

２．研究課題名

地球温暖化に応じてのグリーンランドの氷床の急速で動的な変化のシミュレーション

（英訳）　Simulation of rapid dynamical changes of the Greenland ice sheet in response to global warming

３．採用期間

平成２０年１０月１５日　～　２２年１０月１４日

（　２４か月間　）

４．研究の背景

The Greenland Ice Sheet is the second-largest land ice mass on the present-day earth, and its volume amounts to approx. 7.3 m SLE (metres of sea level equivalent). The overall mass balance is probably negative; however, the exact amount of the imbalance is not very well constrained. Surface melting will increase strongly with rising surface temperatures, which makes the ice sheet very susceptible to global warming. In addition, recent observations led to strong concerns that ice-dynamical processes (basal sliding accelerated by surface meltwater, speed-up of ice streams and outlet glaciers) may greatly accelerate the decay.

The scientific community has reacted to the need for improved predictions of sea level rise from ice sheet models. Coordinated research projects have been launched, such as the European-led ice2sea programme funded by the European Union Framework-7 scheme (http://www.ice2sea.eu/), or the US-led, community-organised SeaRISE effort (Sea-level Response to Ice Sheet Evolution; http://websrv.cs.umt.edu/isis/index.php/SeaRISE_Assessment, http://oceans11.lanl.gov/trac/CISM/wiki/AssessmentGroup). The Japanese ice sheet modelling community is committed to contribute to both ice2sea and SeaRISE as part of several research projects.

５．研究の方法

In this study, the postdoctoral fellow Dr. Hakime Seddik set up the model Elmer/Ice, which is based on the open-source finite element software package Elmer (http://www.csc.fi/elmer) and solves the full Stokes equations for glacial flow (e.g., Greve and Blatter, *Dynamics of Ice Sheets and Glaciers,* Springer, 2009), for the Greenland Ice Sheet. In the first step, a finite element mesh with a spatially constant resolution of 10 km was created, and steady-state simulations for the present-day dynamical and thermodynamical state of the Greenland Ice Sheet were carried out. Since the constant resolution does not make full use of the potential of the finite element method, the next step was to set up a finite element mesh with a highly refined resolution around the ice margin, in particular in the critical areas of the major ice streams (Jakobshavn Ice Stream, North-East Greenland Ice Stream, Kangerdlugssuaq and Helheim Glaciers). Simulations with this mesh are computationally much more demanding, and therefore suitable parallelisation techniques based on Open MPI were implemented.

Thermomechanically coupled test simulations for present-day steady-state conditions were conducted with the refined mesh. They served the double purpose of (i) testing methods to obtain numerically stable and accurate solutions, and (ii) providing initial conditions for transient (time-dependent) simulations on the response of the Greenland Ice Sheet to future global warming conditions. Alternatively, simulations with the simpler shallow ice model SICOPOLIS (SImulation COde for POLythermal Ice Sheets; http://sicopolis.greveweb.net/) over the last glacial/interglacial cycle (125,000 years) until today were carried out in order to obtain initial conditions that are close to the observed state of the present-day ice sheet. While the latter approach is based on simplified dynamic/thermodynamic model equations (the shallow ice approximation; e.g., Greve and Blatter 2009), it has the advantage that the climatic history of the ice sheet is more appropriately reflected in the simulated present-day ice sheet. Therefore, we decided to use the output of this type of simulation as initial conditions for the global warming simulations.

The purpose of the SeaRISE effort is to predict the likely range of the contribution of the Greenland and Antarctic Ice Sheets to sea level rise over the next 100's of years under global warming conditions. This is achieved by designing and executing a set of numerical experiments employing a wide range of ice sheet models. For the future climate simulations with Elmer/Ice, we used the four different SeaRISE specifications for the Greenland Ice Sheet:

- Experiment C1_E0: Constant climate control run; beginning at present (reference year 2004) and running for up to 500 years holding the climate steady to the present climate.
- Experiment C1_E1: Like C1_E0 (constant climate forcing), but doubled basal sliding assumed (a simple implementation of a purely ice-dynamical acceleration).
- Experiment C2_E0: AR4 climate control run; the climatic forcing is derived from an ensemble average from 18 of the AR4 models, run for the period 2004-2098 under the A1B emission scenario; beyond 2098 the climate persists to the end of the run up to 500 years into the future. [AR4: IPCC Fourth Assessment Report]
- Experiment C2_E1: Like C2_E0 (AR4 climate forcing), but with doubled basal sliding.

Due to computational limitations, we ran the four experiments only for 100 years into the future (2004-2103). For comparison, the experiments were also run with the above-mentioned shallow ice model SICOPOLIS.

６．研究実施の状況とその成果

備考：　研究内容と成果について、専門外の人にも理解してもらえるよう可能な限り平易な説明としてください。また、論文が主な学術誌に掲載された場合、その学術分野で極めて顕著な業績を得た場合、特許の出願その他本事業を通じて得られた成果がある場合はできるだけ具体的に記入してください。

Stable results could be obtained with both the full Stokes model Elmer/Ice and the shallow ice model SICOPOLIS for all four experiments. The control run C1_E0 with Elmer/Ice produces an ice volume gain of ~ 8 cm SLE during the 100 years of model time, while the same run with SICOPOLIS produces an ice volume loss of ~ 3 cm SLE. This difference, and in particular the stronger reaction of the Elmer/Ice run, results from the fact that the initial conditions were generated with SICOPOLIS (see above), so that the Elmer/Ice run accommodates the sudden switch in the representation of the ice dynamics from shallow ice to full Stokes.

In order to remove this effect largely, it is reasonable to discuss the results of the three other experiments (C1_E1, C2_E0, C2_E1) relative to the control run C1_E0 ("experiment minus control approach"). After 100 years of model time, the ice volume losses are as follows:

Elmer/Ice:	C1_E1 (2 x basal sliding) – C1_E0 (control)	~ 2 cm SLE
	C2_E0 (AR4 climate) – C1_E0 (control)	~ 10 cm SLE
	C2_E0 (AR4 climate and 2 x basal sliding) – C1_E0 (control)	~ 15 cm SLE

SICOPOLIS:	C1_E1 (2 x basal sliding) – C1_E0 (control)	~ 7.5 cm SLE
	C2_E0 (AR4 climate) – C1_E0 (control)	~ 8 cm SLE
	C2_E0 (AR4 climate and 2 x basal sliding) – C1_E0 (control)	~ 17 cm SLE

It is interesting to note that the sensitivities of Elmer/Ice and SICOPOLIS are very similar for the AR4 climate run C2_E0, while the sensitivity of Elmer/Ice is about 3 times smaller than that of SICOPOLIS for the 2 x basal sliding run C1_E1. The former finding is as expected because the representation of the surface mass balance is the same in both models, and the ice sheet reacts to the imposed global warming scenario (AR4 climate) mainly by a change of the surface mass balance (more surface melting). The associated changes of ice sheet dynamics are quite small. By contrast, the reaction to the 2 x basal sliding scenario is purely dynamical (accelerated ice flow), and the representation of ice dynamics as well as the resolution of fast-flowing ice streams and outlet glaciers are more sophisticated in Elmer/Ice than in SICOPOLIS. The factor 3 difference in sensitivity highlights the relevance of these improvements, and it is "good news" for concerns about rapid, dynamically induced ice sheet decay that Elmer/Ice shows a *lower* sensitivity then SICOPOLIS.

The simulations with Elmer/Ice discussed above can be considered a milestone in ice sheet modelling. For the first time, transient, thermomechanically coupled simulations have been conducted for an entire ice sheet with a full Stokes solver. Further work in this direction will hopefully lead to more robust predictions of ice sheet contributions to sea level rise.

The results of the four SeaRISE experiments are currently being prepared for submission to the SeaRISE coordinators. This is not trivial because the data on the irregularly spaced finite element mesh of Elmer/Ice must be interpolated to the regular grid required by SeaRISE, and the task could not be finished within the fellowship period. However, we expect to be able to deliver within this month (November 2010). The results will be part of a common publication of the SeaRISE contributors, and we are also preparing a separate publication that focuses on the novel full Stokes approach with Elmer/Ice.

７．本事業を通じて得られた国際交流上の成果

備考：　以下のような事例がある場合に具体的な例とともに記入してください。

（例）

研究員の来日により、海外の○□大学との研究交流がより活発になった。

採用期間終了後、研究員は、（国内又は国外）○□大学において常勤の職を得た。

採用期間終了後、研究員は、母国に帰国してからも日本との研究交流について○△の役割を担っている。

研究員の滞在により、若手研究者の国際化の観点が高まった。

During the two-year fellowship of Dr. Seddik, the bonds between the working groups of the Laboratory of Glaciology and Environmental Geophysics (LGGE) in Grenoble, France, the CSC – IT Center for Science in Espoo, Finland, and the Glacier and Ice Sheet Research Group of myself (R. Greve) at the Institute of Low Temperature Science (ILTS), Hokkaido University, have strengthened significantly. We have established a very active collaboration on "frontier" ice sheet modelling, including high-resolution full Stokes solvers and adaptive meshes, and we are going to continue it in the future.

Dr. Seddik has been working well, demonstrated great commitment and enthusiasm, and he is now an established player in the international and domestic ice sheet modelling community. I was very happy that I could offer him a full-time follow-up position as a researcher within a new project funded by JSPS [Scientific Research (A), "Simulation of the evolution and dynamics of the Antarctic Ice Sheet in past and future climates"], so that he can continue working on related problems in the next years.

（注）必ず様式８及び様式９を併せて採用期間終了後１か月以内に TEI あて提出してください。

本報告書は３頁にまとめてくださるようお願いいたします。なお、研究員本人には基本的に同じような内容を様式８（Form 8: Research Report）として英語で作成いただきます。