Research Networking Programmes

Short Visit Grant ☐ **or Exchange Visit Grant** ☒

(please tick the relevant box)

Scientific Report

The scientific report (WORD or PDF file – maximum of eight A4 pages) should be submitted online within one month of the event. It will be published on the ESF website.

Proposal Title :

Ice dynamics of fast flow at ice/bed interface - basal process investigation in large-scale ice dynamic model

Application Reference N°: 4738

1) Purpose of the visit

Continuing with the numerical simulation on Austfonna ice cap, Svalbard with a full Stokes ice dynamical model, Elmer/Ice, started at Arctic Center, Rovaniemi, Finland, I aim to achieve a better understanding on mechanisms at the ice/bed interface triggering the recent speed-up events in Basin 3. One way towards the final goal refers to the coupling between a hydrology model and a ice dynamical model which takes account the feedbacks given by basal hydrology system and may explain both seasonal acceleration and inter-annual acceleration of the outlet glacier in Basin 3 locating at southeastern Austfonna.

By visiting the glaciology group led by Prof. Matti in Helsinki University I can get more knowledge and guidances on studying large scale land ice in Arctic region. Also another important purpose of visiting Helsinki is to get scientific collaboration and technical assistance from the developers and advanced user community of Elmer/Ice dynamics model through working directly and closely with A.P. Thomas Zwinger at CSC IT Center, Espoo.

2) Description of the work carried out during the visit

Two main numerical experiments have been carried out during the visit. Firstly, we use a 3 dimensional coupled hydrological-ice dynamic model to simulate the basal hydrology system and ice flow in Basin 3, Austfonna with initiation of topographic data from a Digital Elevation Model (DEM), model constrains surface velocity data from satellites and climatic forcing from Regional Climate Model (RCM). Secondly, a recent developed Discrete Particle Model (DPM) by CSC is used to investigate the shear zones in the fast flow region in order to find potential crevasses to direct surface melt water to the basal hydrology system.

2.1 Coupled hydrological-ice dynamic model

The ice dynamical model, Elmer/Ice, is a 3 dimensional finite element model which solves the Stokes equation and implements ice rheology by Glen's flow law (Gagliardini et al., 2013).

The hydrological model switches from inefficient drainage system (IDS) to efficient drainage system using a dual continuum porous equivalent approach, in which both components are treated as sediment layers with different parameterization and water head is calculated according to mass conservation and Darcy's law (de Fleurian et al., 2014). It is implemented in Elmer/Ice as solvers and by a water-pressure dependent sliding law being able to be coupled with ice dynamics.

A preliminary study is carried out to investigate the seasonal evolution of basal hydrology system from inefficient to efficient system in one year time scale. We find out that the distribution of water source flux highly effects the development of the efficient system. However, due to the drawback that the efficient drainage component in its current state does not account for channel closure and also the fact that we are more interested in inter-annual speed-up we only adopted the inefficient component of the hydrological model when doing coupled simulations.

A 3D unstructured mesh (Fig.1) is generated with open source software Gmsh (Geuzaine and Remacle, 2009) with a finest horizontal resolution 250m and extruded vertically to 10 layers imprinting surface and bed rock elevation.

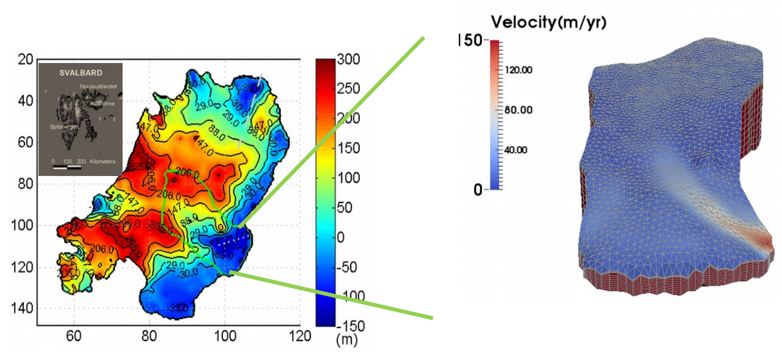

Figure 1. Basal topography of Austfonna with elevation contours is given by the DEM from Norwegian Polar Institute. Basin3 is outlined in solid green(left); And unstructured '3D' mesh with finestresolution of 250m showing the observedl surface velocity in 1995 (Dowdeswell et al., 2008)(right).

2.1.2 Coupling boundary conditions

Upper boundary are treated as stress-free surfaces. Surface Mass Balance (SMB) enters the kinematic boundary condition at the upper surface as climatic forcing.

The coupling between the hydrological model and the ice dynamical model at the bedrock boundary is achieved by solving the relation between the effective pressure N computed from the water pressure in IDS, the mean basal drag τ_b, and the basal velocity u_b in a simplified Coulomb-type friction law:

$$\tau_b = C \cdot N \left[\frac{\chi \cdot u_b^{-n}}{(1+\chi)} \right]^{\frac{1}{n}} \cdot u_b \qquad (1)$$

with

$$\chi = \frac{u_b}{C^n \cdot N^n \cdot A_s} \qquad (2)$$

where C, the post-peak decrease exponent is equal to 1; n, the exponent in Glen's flow law is equal to 3 and A_s is the friction coefficient.

2.1.3 Initialization

Before doing the coupled hydrological-ice dynamic simulation, a basal friction coefficient field β along with ice temperature (Fig. 2) need to be provided from the ice dynamical simulation first. β is derived by solving an inverse problem using Adjoint method (MacAyeal., 1992) to minimize the difference between modeled velocity and velocity data taken from InSAR observations acquired during the year 1995 (Dowdeswell et al., 2008), in which β is a parameter in a linear sliding law :

$$\tau_b = \beta \cdot u_b \qquad (3).$$

Then the obtained β is plugged into the thermo-mechanically coupled model for a steady state simulation to get the temperature field. This temperature field is fed back into the inverse problem calculation. This iteration is carried out several times until the cost function value of the inverse problem stays stable without dramatic changes and the change of temperature field of two sequential thermo-mechanically coupled simulation is small. A_s (Fig.2) is then calculated from β by matching Eq. (3) with Eq. (1) and (2).

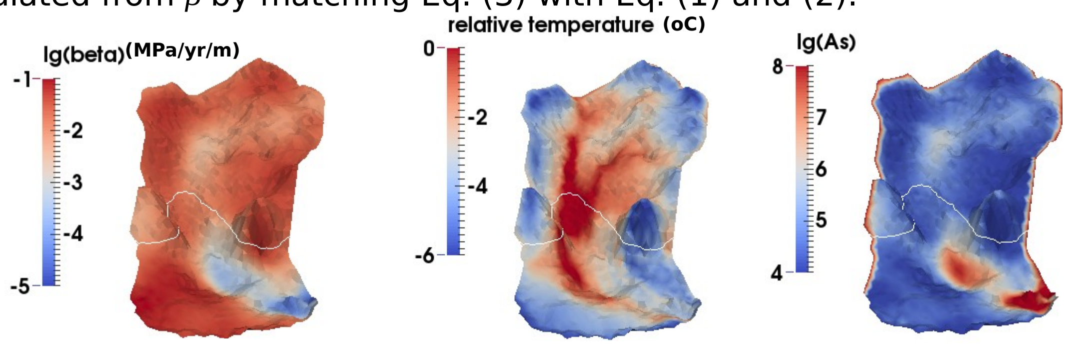

Figure 2. The base-10 logarithm of β, temperature relative to pressure melting point and the base-10 logarithm of A_s field at the bed of the ice body. The white line shows the water line below which the bed rock is under ocean.

Restarting from the step of the iteration between data assimilation and thermo-mechanical correction we run the coupled hydrological-ice dynamic model for three years with daily time steps to eliminate high frequency variations in ice thinning (or thickening) rate by relaxing the free surface, which are caused by artifacts of interpolation, mismatch between the time at which the geometry and velocity were observed and other input data errors. The 1990-1999 mean annual SMB from RCM HIRHAM is used as a force at the upper surface boundary.
After the relaxation in order to obtain a forcing that complies with the 1995 geometry for all following simulations a synthetic SMB (SMB_{syn}) is calculated according to the mass flux (section 2.1.3) :

$$u \cdot \frac{\partial h}{\partial x} + v \cdot \frac{\partial h}{\partial y} - w = -SMB_{syn} \qquad (4)$$

where *h* is the ice thickness; *x and y are* the distance in *x and y* direction respectively; *u, v* and *w* are the velocity components in *x y and z* direction respectively. SMB_{syn} is input as climatic forcing at the upper surface boundary in all targeted simulations.

2.1.4 Experiment set-up

Three sensitivity experiments with different water source flux input, a control experiment (t_{ctr}) with zero melt water input and several extrem scenario experiments have been set up in order to investigate to what extent the magnitude and distribution of water source effect basal hydrology and ice flow.
These three experiments are:
t_M, the input water source is only basal melt rate (Fig. 3 left) calculated from friction heating and geothermal heat flux at areas of the bedrock where the temperature is above pressure melting point;
$t_{M/DR}$, the input water source consists of basal melt rate and annual surface run-off flux time series from HIRHAM (Fig. 3 middle), applying the assumtion that all surface run-off reaches the bedrock where in the model they are imposed distributed water source;
$t_{M/CR}$, the input water source consists basal melt rate and fluxes that have the same magnitude as the total HIRHAM annual surface run-off flux time series in Basin 3 but distribute at a radom narrow channel across the sub-glacial 'bay' lies underneath the current sea level (Fig. 3 right).
In some extreme scenario experiments we use a input basal melt rate and fluxes that have 10(t_{ex10}), 50(t_{ex50}), 100(t_{ex100}) and 150(t_{ex150}) times the total HIRHAM annual surface run-off flux time series across the whole Basin 3 area (e.g. 0.00012 m/s, 0.00063 m/s, 0.0012 m/s and 0.0019 m/s in the year 2011, respectively) but distribute it in the area where the bedrock is below sea level.

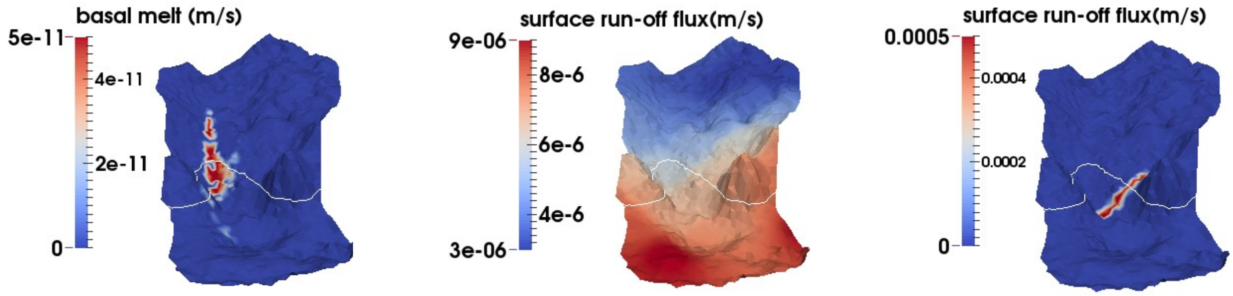

Figure 3. Different water source: basal melt water (left), surface run-off field of the year 2011 from HIRHAM (middle) and surface run-off distributed in the narrow channel(right).White line is the water line below which the bed rock is under ocean.

All the experiments are run for 22 years corresponding to the 22 HIRHAM run-off flux fields from 1990 to 2011.

2.2 Discrete Particle Model

In the DPM, the ice body is made of discrete elastic particles (DEPs). The massless bonding elastic beams between DEPs can break and induce brittle behavior when loading stress reaches the point for fracture (Åström et al., 2013).

The simulation with DPM is a preliminary test to investigate the development and propagation of crevasses at the surface and in the ice body in order to direct surface melt water into the basal hydrology system in the coupled hydrological-ice dynamic model simulations.

2.2.1 Experiment set-up

The geometry data (surface and bed elevation) are input from Elmer/Ice on a squared mesh with 40m resolution (Fig. 4). The friction coefficient distribution (β) obtained by the inverse method within the finite element continuum model was used to derive a corresponding sliding coefficient distribution for the DPM (Fig.4)

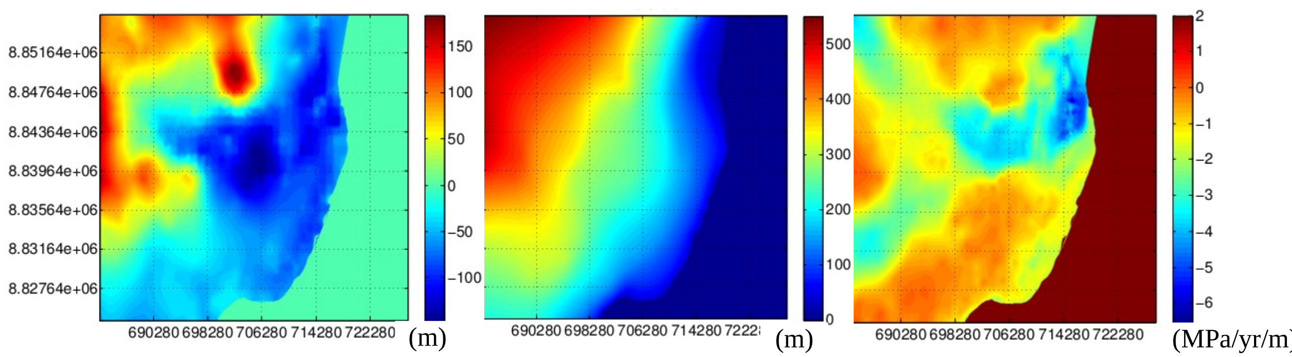

Figure 4. The bed (left) and surface (middle) elevation field as well as lg(β) distribution (right).

3) Description of the main results obtained

Figure 5 shows the basal velocity difference between several selected experiments and t_{ctr} in the end of the simulation. Results of the sensitivity experiments are all present there. Here we restrict the presentation to the result from t_{ex50} because the difference of t_{ex10} is similar with the sensitive experiments and t_{ex100} and t_{ex150} did not converge during the simulation.

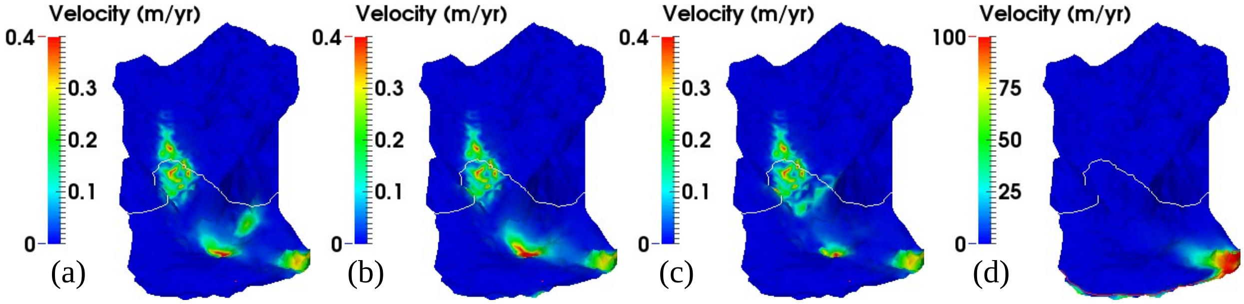

Figure 5. Basal velocity difference between (a) t_M ; (b)$t_{M/DR}$; (c) $t_{M/CR}$ and (d)t_{ex10} and the control (t_{ctr}) in the end of the simulation. The red line indicates the area below which the effictive pressure is below 0.White line is the water line below which the bed rock is under ocean.

The fast flow region in all experiments has accelerated in 22 years including the control experiment (velocity in the fastest area is about doubled). It may be because that the Coulomb friction coefficient (A_s) is calculated from a friction coefficient resulting from a linear sliding law in which a functional dependence on the effective pressure in not included. After coupling to a hydrological model effictive pressure gets reduced by a finite water pressure. However, only t_{ex50} experienced dramatic acceleration in the fast flow region comparing to t_{ctr}. There are only minor velocity differences between t_{ctr} and other sensitive experiments.

Quantitively speaking, run-off data within this model setup does not appear to be a good representation of water source besides basal melt. We may need to think about other water source such as water produced by hydrothermal mechanism. By looking at the region where effective pressure is equal to or below zero (Fig. 5) we notice that the ice flow can dramaticly accelerate only when large parts of the ice front becomes detached from the bedrock by water that tremendously reducing the basal drag.

It seems that IDS is not efficient enough to re-distribute water in a time scale of 22 years. Maybe a more efficient system (en-glacial or sub-glacial) is needed to re-distribute the water to where the overburnden ice normal stress is small so that the ice body becomes afloat in a relativly short time scale.

4) Future collaboration with host institution (if applicable)

Collaboration with Helsinki Univ. and CSC will continue on:

1. Couple DPM with Elmer/Ice to investigate the distribution of surface melt water to basal hydrology system through englacial fractures;
2. Tuning parameters for the hydrology model aiming to capture the recent speed-up event in Basin 3.

5) Projected publications / articles resulting or to result from the grant *(ESF must be acknowledged in publications resulting from the grantee's work in relation with the grant)*

A numerical study on speed-up events in Basin 3, Austfonna, Svalbard using a coupled hydrological-ice dynamic model. Planned to be submitted to The Cryosphere.

6) Other comments (if any)

Reference

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