Coupling Glacial Hydrology into a High-Order Numerical Ice Model

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1 Introduction

A new high-order flow-band model with coupled subglacial hydrology is used to explore the drainage of supraglacially-stored water through englacial fractures and assess the influence of this water on glacier dynamics. This work forms part of the Canadian contribution to IPY project GLACIODYN. The focus of this project is a study of the dynamics of the Belcher glacier located in the Canadian high arctic. The Belcher Glacier system is the major outlet of the Devon Island Ice Cap. This is a large, fast-flowing, tidewater glacier sharing similarities with many Greenland outlet glaciers.

2 Model Description

Our model is two dimensional being composed of one horizontal dimension, in the direction of the ice flow, and one vertical dimension through the ice column. We also include a flow-band adaption by having a parameterization of the width across the flowline.

The model incorporates a multilayer longitudinal stress scheme following [2] and [5]. The longitudinal stresses are expected to have an essential role at the Belcher especially near the terminus and where basal sliding is considerable.

As a means of validating our model we have conducted experiments that form part of the Ice-Sheet Model Intercomparison Project - High-Order Models (ISMIP-HOM) [6]. Results from one particular example, Experiment E: Haut Glacier d'Arolla, are presented here. This experiment provides a test for the velocity/stress solution of the non-linear force-balance equations. It uses the fixed geometry of Haut Glacier d'Arolla under isothermal conditions and simple basal boundary conditions. Results for surface horizontal velocity and basal shear stress are shown to be within the benchmark range.

The model has an evolving free surface by considering conservation of mass and can be thermomechanically coupled by solving an advective-diffusive heat equation. The coupling occurs through the temperature dependent flow-law parameter, as well as from internal friction from deformational heating. There is also the framework here for potential coupling to the hydrological system.

As this model is intended for a tidewater glacier a suite of basic options for calving has been installed. These include the water-depth relation [4], the flotation criterion [8], and a more recent rule based on crevasse formation [1].

The hydrology aspect of the model incorporates vertical fracture propagation and a subglacial drainage system. The drainage system will ultimately comprise 'slow'/distributed and 'fast'/channelized drainage networks. The hydrology model is taken from the subglacial water drainage component of [3]. This considers conservation of mass in a subglacial water sheet

$$\frac{\partial h^s}{\partial t} + \frac{\partial Q}{\partial x} = \frac{Q_G + u_b \tau_b}{\rho L} + M_b, \qquad Q = -\frac{K h^s}{\rho_w g} \frac{\partial \phi}{\partial x},$$

where h^s denotes the water sheet thickness, Q is a Darcian water flux, $\phi = P_w + \rho_w g b$ represents the fluid potential, and $K = K(h^s)$ the hydraulic conductivity. From this we determine the water pressure $P_w = P_i \left(\frac{h^s}{h^s_c}\right)^{7/2}$, where h^s_c is some critical water sheet thickness.

In order to mimic vertical englacial fracture propagation we employ the linear elastic fracture mechanics of [9].

The hydrology interacts with the ice dynamics through the basal interface. To model the basal sliding we use a Coulomb friction law as proposed and advocated by [7]. This law relates the basal drag, τ_b, to the basal velocity, u_b, as follows

$$\tau_b = C \left(\frac{u_b}{u_b + N^n \Lambda}\right)^{1/n} N, \qquad \Lambda = \frac{\lambda_{max} A}{m_{max}}$$

where $N = P_i - P_w$ is the effective pressure, λ_{max} a dimensional wavelength for the dominant bedrock bumps, m_{max} a typical bed slope, A and n are Glen's flow law parameters and C is a constant. This is a non-linear Robin-type boundary condition which cannot be solved independently but forms part of the solution to the ice-flow problem. This type of sliding law is favoured over the more standard power law formations which allow large basal stresses to develop at the bed for an arbitrary effective pressure.

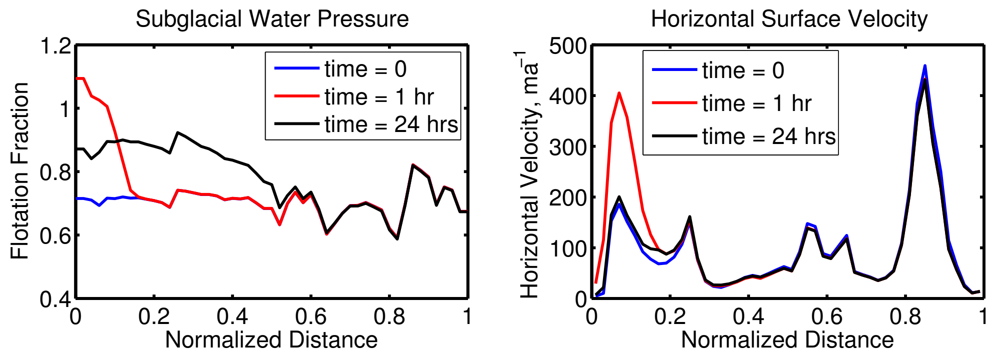
Using a two-dimensional model we assume that ice flows in an infinite plane; however, glacier flow is confined in a channel and thus is effected by lateral drag. We parameterize the lateral drag at the side walls and include this stress term in our force-balance equations.

$$\sigma_{xy} \approx -\frac{\nu(u - u_L)}{W} = C \left(\frac{u_L m_{max}}{u_L m_{max} + N_L^n \lambda_{max} A)}\right)^{1/n} N_L,$$

where u_L is the lateral sliding along the side walls. This sliding is computed by again applying the Coulomb friction law with the vertical distribution of effective pressure along the side walls, N_L.

3 A Drainage Scenario

An experiment to mimic the drainage of a supraglacial lake in an effort to understand the coupling between hydrology and ice dynamics is conducted. In this scenario we envisage supraglacial drainage into a crevasse forcing englacial fracture propagation, with high enough tensile stresses and water injection rates the fracture reaches the bed providing a surface to bed connection. Rapid drainage of a meltwater pond through this fracture occurs providing local water injection into the subglacial drainage system. We then monitor the transient response of water pressure and glacier flow speed, as seen in this figure.



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