Fracture Propagation in a High-order Ice-flow Model

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Aims

- develop a sophisticated hydrologically coupled model of ice dynamics in large outlet Arctic glaciers
- include high-order stresses (longitudinal stretching and lateral shearing) which play an essential role in the dynamics especially near the margins and when basal sliding is considerable
- incorporate glaciohydraulic processes that link surface conditions with basal processes

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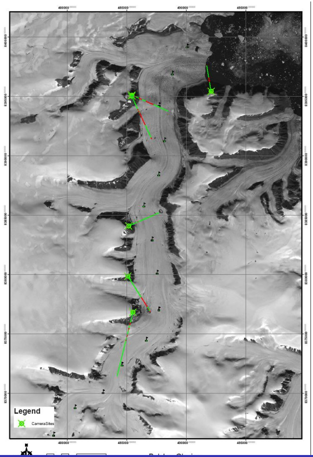
IPY Project: Belcher Glacier on Devon Island

Sharing similarities with many Greenland outlet glaciers, this is a large, fast-flowing, tidewater glacier.

The Belcher Glacier System on the Devon Island Ice Cap



Model Overview

- **Flow-band**
  One horizontal dimension (in the direction of the ice flow), one vertical dimension, and a parameterization of the width across the flowline.

- **Mass balance, evolving surface**

$$\frac{\partial h}{\partial t} = -\frac{1}{W}\frac{\partial(\bar{u}hW)}{\partial x} + M,$$

h	is the ice thickness
t	is time
W	represents the flowline width
$\bar{u}$	denotes the vertically averaged horizontal velocity
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High-order stress components

- The model incoporates a multilayer longitudinal stress scheme following (Blatter, 1995) and (Pattyn, 2002)
- The vertical normal stress is assumed to be hydrostatic

$$\frac{\partial \sigma_{zz}}{\partial z} = \rho_i g$$

with the pressure (the sum of the normal stresses) departing from the hydrostatic pressure by the longitudinal deviatoric stress $P = \sigma'_{xx} + \sigma'_{yy} - \rho_i g(s - z)$

- Unlike the full stress solution the pressure doesn't include the integrated horizontal gradient in vertical shear stress

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- **Thermomechanically coupled**
  - Solve an advective-diffusive heat equation
  - Temperature dependent flow-law parameter, as well as coupling from internal friction from deformational heating
- **Sliding and Calving rules**
  - Options for sliding: no-slip, power-laws, Coulomb friction law
  - Options for calving: water-depth relation, floatation criterion, crevasse formation
- **Coupled hydrology (in progress)**
  - Vertical fracture propagation
  - Englacial and subglacial components
  - Track energy exchange between water and ice

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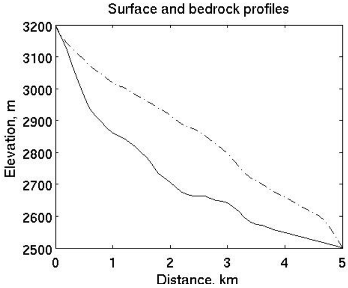
Model performance has been compared with

- benchmark solutions using model intercomparison exercises
- analytical solutions under simplifying assumptions

ISMIP-HOM Experiment E: Haut Glacier d'Arolla



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- use fixed geometry
- no-slip basal b.c.
- isothermal

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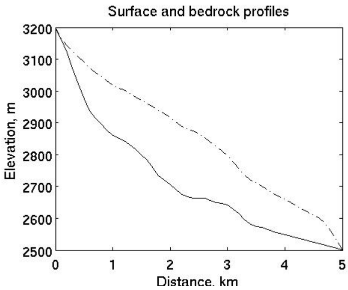

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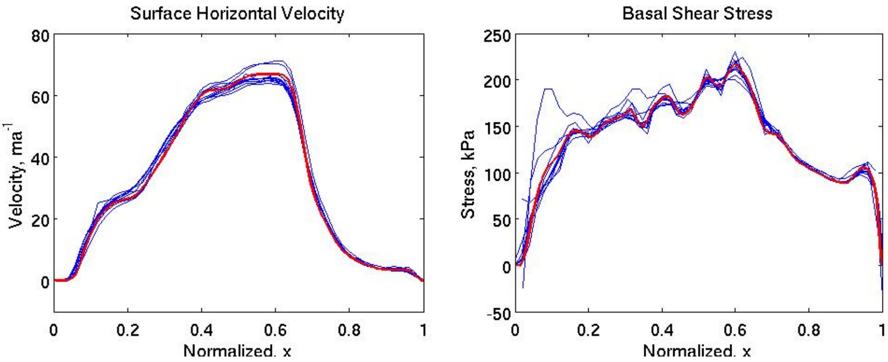
Model Comparison



The blue lines show results from the high-order intercomparison models (Pattyn et al., 2008).

Toy Experiments

Experiment I: Calving

An experiment is tried to test the advance and retreat of a marine glacier.

Experiment II: Fracture Propagation

An experiment is tried to mimic the drainage of a supraglacial lake through fracture propagation to the bed.

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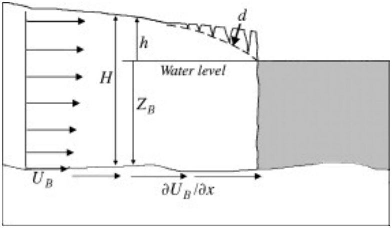
Experiment I: Calving

- Calving criterion is based on crevasse formation (Benn et al., 2007)
- Assumes calving is triggered by the downward propagation of transverse surface crevasses
- These crevasses open in response to down-glacier variations in flow speed (longitudinal strain rates)

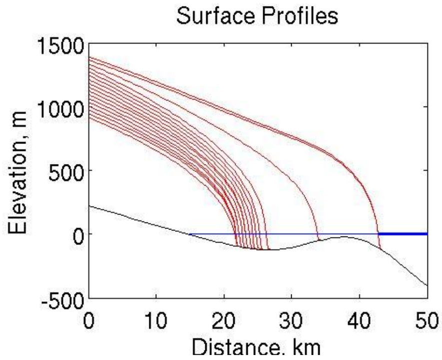


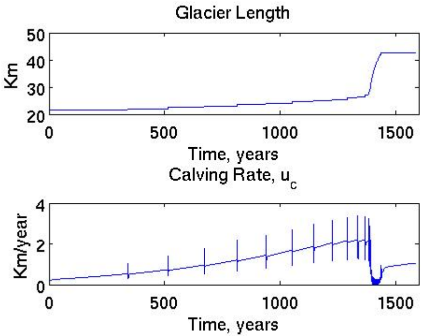
Taken from Benn et al., 2007

Tidewater Outlet Glacier

Calving rate: $u_c = \overline{u}_T - \frac{\partial L}{\partial t}$

L	glacier length
$\overline{u}_T$	vertically averaged velocity at terminus

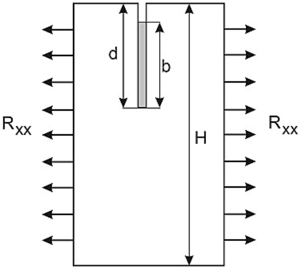




Experiment II: Fracture Propagation

- **Observations**
  Surface meltwater has been observed through water-driven fracture propagation to reach the bed (Das et al., 2008)
- **Importance**
  This hydromechanical process creates a mechanism for the rapid response of ice flow to climate change
- **Theoretical Basis**
  Linear elastic fracture mechanics (van der Veen, 2007).

Fracture Propagation



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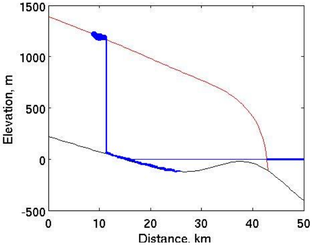

ice fracture toughness = 100 kPa
tensile stress = 43 kPa
ice thickness = 1123 m
water injection = 1 $\mathrm{m/hr}$
time to reach bed = 43 days

Future Work

- Model moulin formation generated by concentrated flow paths and frictional heating, simulate surface uplift caused by the sudden drainage of meltwater ponds, assess glacier speed-up as a result of increased lubrication, and monitor the closure of fractures because of refreezing.
- Simulations of Belcher using field data for model inputs (e.g. glacier geometry from GPS and radar surveys; mass balance from long-term measurements; supraglacial discharge from field observations) and for model verification (e.g. GPS-derived ice-surface velocities).

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Questions?