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.
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 incorporates 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

\[ P = \sigma'_{xx} + \sigma'_{yy} - \rho_i g (s - \bar{z}) \]

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

- test the velocity/stress solution of the non-linear force-balance equations
- use fixed geometry
- no-slip basal b.c.
- isothermal
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The blue lines show results from the high-order intercomparison models (Pattyn et al., 2008).
**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.
Toy Experiments

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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:** \( u_c = \bar{u}_T - \frac{\partial L}{\partial t} \)

\( \bar{u}_T \) - vertically averaged velocity at terminus

\( L \) - glacier length

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**Surface Profiles**

**Glacier Length**

**Km/Year**

**Time, years**

**Calving Rate, \( u_c \)**

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**Fracture in Ice Flow Model**
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

Taken from van der Veen, 2007

- ice fracture toughness = 100 kPa
- tensile stress = 43 kPa
- ice thickness = 1123 m
- water injection = 1 m/hr
- time to reach bed = 43 days
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).
Future Work

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