Modelling of surface to basal hydrology across the Russell Glacier Catchment

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Effective pressure at the ice-bed interface governs glacier sliding.

The non-linear relationship between surface meltwater and glacier speedup is not credibly captured by current models.

This is needed to reduce uncertainties in glacier and ice sheet contributions to sea level.

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Ice-flow Model (Pimentel et al., *JGR*, 2010)

- **Higher-order stresses**: 1st-order approximation of the Stokes equation (Blatter, 1995; Pattyn, 2002), includes longitudinal stress gradients

- **Flow-band**: 2-D flowline model with flow-unit width parameter

- **Lateral Drag**: lateral shear stress parameterization, includes sliding at the side walls and glacier basin shape

- **Coulomb friction law**: basal sliding rule (Schoof, 2005)
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A mixed subglacial drainage network which includes dynamic switching between drainage components (Flowers, 2008)

- **Distributed**
  - macroporous water sheet
  - low capacity and efficiency
  - characteristic of winter

- **Channelized**
  - ice-walled conduits
  - high capacity and efficiency
  - characteristic of summer

- **Uplift**
  - When large amounts of water impinge on the glacier bed high water pressures are generated and cause flexure of the overlying ice
  - This uplift effect is modelled by treating the glacier as a uniform static beam
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Subglacial Hydrology Model

Distributed System

Channelized System

macroporous water sheet
low capacity
low efficiency
typical of winter

ice-walled conduit
high capacity
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typical of summer

A Test Case

An idealized mountain glacier

1. Glacier profile
   - Elevation vs. Distance downglacier, km

2. Seasonal and diurnal cycle
   - Temperature vs. Day of year
Conduit cross-sectional area, m$^2$

Subglacial water pressure, flotation fraction

Distance downglacier, km

Time, days

Conduit cross-sectional area, m$^2$

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Distance downglacier, km

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Pimentel

Glacio-Hydrodynamic Modelling
Model captures seasonal and diurnal cycles as well as the spring-transition.

Such features have been well observed in Alpine glacier system (e.g. Haut Glacier d’Arolla).

Increasing evidence of similar behaviour on Arctic glaciers, including Russell (e.g. Bartholomew, 2010).

Suggesting a unified treatment of basal processes across a range of scales.
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Supraglacial Lake Drainage Event

- Das et al. Science, 2008
- Supraglacial lake of volume 0.044 km$^3$
- Drains through 980 m of ice in 1.4 h
- 1.2 m of vertical uplift and 0.8 m of horizontal displacement
- Rapid response followed by subsidence and deceleration over 24 hrs

Supraglacial lake on Belcher Glacier, Devon Island Ice Cap. Photo by A. Garner.
Pre-existing channel network needed to dissipate flood response as quickly as observed

“Regular” seasonal melt as well as lake tapping events condition subglacial system

Model limitations - multi-directional flow of flood water

Other processes - horizontal turbulent hydraulic fracture for basal crack propagation (Tsai & Rice, *JGR*, 2010)

Supraglacial lake drainage events a regular occurrence within the Russell Glacier Catchment
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Numerical Model

- Ice Dynamics
- Basal Sliding
- Subglacial Hydrology
- Other Hydrology Components
Ice Dynamics Model (Pattyn, 2008)

A 3-D transient higher-order/full-Stokes ice-flow model

Image taken from Frank Pattyn’s homepage
The hydrology will be coupled to the ice mechanics by use of a Coulomb friction law (Schoof, 2005)

This is a pressure dependent sliding rule utilizing the spatial and temporal variations in basal water pressure from the hydrology model.

Overcomes problem of standard sliding laws that allow arbitrarily large basal shear stresses regardless of effective pressure.

Implemented as a non-linear Robin-type boundary condition which cannot be solved independently but forms part of the solution to the ice-flow problem.
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\[ \tau_b = C \left( \frac{u_b}{u_b + N^n \Lambda} \right)^{1/n} N, \quad \Lambda = \frac{\lambda_{max} A}{m_{max}} \]
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Subglacial Model (Schoof, *Nature*, 2010)

- A unified treatment of linked cavities and channels
- 2-D planform network of conduits
- Switching between drainage components within a spatially extended drainage catchment

\[
\frac{\partial S_{ij}}{\partial t} = c_1 Q_{ij} \Psi_{ij} + u_b h - c_2 N^n_{ij} S_{ij}
\]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(S)</td>
<td>conduit cross-sectional area</td>
</tr>
<tr>
<td>(Q)</td>
<td>water discharge</td>
</tr>
<tr>
<td>(N)</td>
<td>effective pressure</td>
</tr>
<tr>
<td>(\Psi)</td>
<td>hydraulic gradient</td>
</tr>
<tr>
<td>(u_b)</td>
<td>basal sliding speed</td>
</tr>
<tr>
<td>(h)</td>
<td>bedrock bump</td>
</tr>
<tr>
<td>(c_1, c_2, c_3, \alpha)</td>
<td>constants</td>
</tr>
</tbody>
</table>
Images taken from Schoof, *Nature*, 2010

Glacio-Hydrodynamic Modelling
Other Hydrology Components

- **Supraglacial** hydrology
- **Englacial** storage and transport
- **Groundwater** flow

Data

- Surface and Bed Topography (DEM)
- Automatic Weather Station (AWS) data used to obtain spatial and temporal melt variability
- Surface Velocities - from kGPS and remotely-sensed observations
- Basal reflectance - indicators of stick-slip zones
- Seismics - to ascertain bed properties
- Observations of englacial storage and surface-to-bed transition times
- Supraglacial lake/moulin locations, volumes and drainage times
• Glacier catchment response to variable inputs of melt (seasonal, diurnal and lake tapping events)
• Influence of englacial storage and surface-to-bed transition times
• How does ice-flow and subglacial processes interact to produce temporal and spatial patterns in basal decoupling
• Dynamic response to basal boundary layer stress distribution
• Compare 2009 and 2010 melt seasons
• Russell glacier catchment under future climate projections
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