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Three-dimensional modelling of calving processes on Johnsons Glacier, Livingston Island, Antarctica

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Iceberg calving is an important mass loss mechanism from ice shelves and tidewater glaciers for many mid- and high-latitude glaciers and ice caps, yet the process is not well represented in prognostic models of ice dynamics. Benn and others (2007) proposed a calving criterion appropriate for both grounded and floating glacier tongues or ice shelves. This criterion assumes that the calving is triggered by the downward propagation of transverse surface crevasses, near the calving front, as a result of the extensional stress regime. The crevasse depth is calculated following Nye (1957), assuming that the base of a field of closely spaced crevasses lies at a depth where the longitudinal tensile strain rate tending to open the crevasse equals the creep closure resulting from the ice overburden pressure. Crevasses partially or totally filled with water will penetrate deeper, because of the contribution of water pressure to the opening of the crevasse. This criterion is readily incorporated into glacier and ice sheet models, but has not been fully validated with observations. We apply a three-dimensional extension of Benn and others' (2007) criterion, incorporated into a full-Stokes model of glacier dynamics, to estimate the current position of the calving front of Johnsons Glacier, Antarctica. We develop four experiments: (i) an straightforward three-dimensional extension of Benn and other's (2007) model; (2) an improvement to the latter that computes the tensile deviatoric stress opening the crevasse using the full-stress solution; (iii) a further improvement based on finding the depth at which the model-computed tensile deviatoric stress, considered as a function of depth, equals the ice overburden closure pressure; (iv) an experiment that adds, to the above, the effect of a threshold strain rate required for crevasses initiation. We found that the improvements considered in experiments (ii) and (iii) were necessary to reproduce accurately the observed calving front. Our modelling results also suggest that Johnsons Glacier has a polythermal structure, in contrast with the temperate structure suggested by earlier studies.

REFERENCES:

Benn, D.I., R.J. Hulton and R.H. Mottram. 2007a. Calving laws, sliding laws and the stability of tidewater glaciers. Ann. Glaciol., 46, 126-130.

Nye, J.F. 1957. The distribution of stress and velocity in glaciers and ice-sheets. Proc. Roy. Soc., Ser. A, 239(1216), 113-133.

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Contents

Motivation

The calving problem

Most used models:

- Water depth at front. Problems:
  - Highly empirical - distinct for different glaciers.
  - Does not describe the physical mechanism.
- Height above buoyancy. Problem:
  - Does not allow floating ice tongues/shelves.

Other models:

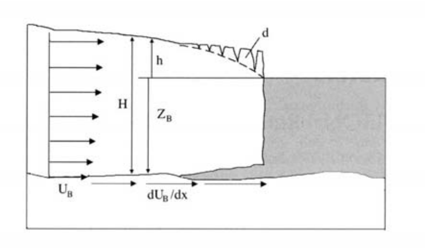
- Force imbalance at terminal ice cliffs.
- Undercutting by subaqueous melting.
- Torque arising from buoyant forces.

A recent model:

- Model of crevasse formation (Benn *et al.*, 2007).
  Advantages:
  - Strongly based on physics, allowing its use as pronostic model.
  - Allows the development of floating ice tongues.

Model of crevasse formation

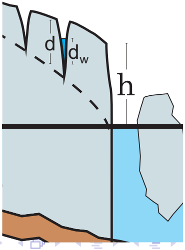
Basics. Benn *et al.* (2007)



$$x = L \text{ for } d(x) = h(x)$$

$$d = \frac{1}{\rho_i g}\left[2\left(\frac{\dot{\epsilon}_*}{A}\right)^{\frac{1}{n}} + (\rho_w g d_w)\right]$$

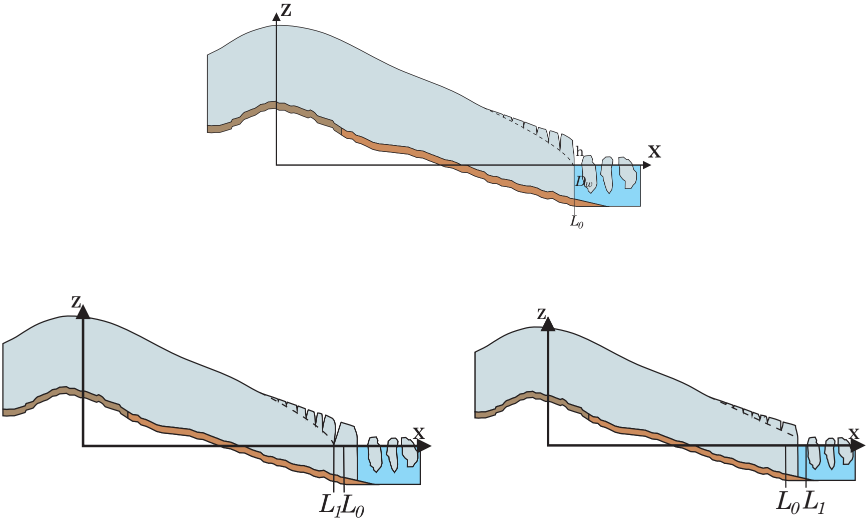
tensile stress = ice overburden pressure
(opening) (closing)



$$d_0 = \frac{2}{\rho_i g}\left(\frac{\dot{\epsilon}_*}{A}\right)^{\frac{1}{n}}$$

Model of crevasse formation

Glacier front evolution



Model of crevasse formation

Limitations and extension

Present limitations of crevasse formation model

- Bidimensional
- So far applied together with simple dynamical models:
  - Driving stress balanced by basal drag
  - Driving stress balanced by lateral drag
  - A combination of both

Our contribution

- 3D extension
- Application using a full-Stokes dynamical model
- Improved crevasse depth computation

3D calving model

Key aspects

- L becomes a function of x,y.
- $\dot{\epsilon}_*$ ($= \epsilon_{xx} = \frac{\partial u}{\partial x}$ in 2D model) now becomes strain rate along ice flow direction

$$\dot{\epsilon}_* \approx \frac{\|\mathbf{u}_2 - \mathbf{u}_1\|}{\|\mathbf{x}_2 - \mathbf{x}_1\|} .$$

- $\dot{\epsilon}_*$ determined from velocity field solution of a 3D full-Stokes model.
- Improved crevasse depth computation $\Rightarrow$ Experiments.

3D calving model

Experiments

Experiment 1. Benn's model

$$d_0 = \frac{2}{\rho_i g}\left(\frac{\dot{\epsilon}_*}{A}\right)^{\frac{1}{n}}$$

Without water

$$d = \frac{1}{\rho_i g}\left[2\left(\frac{\dot{\epsilon}_*}{A}\right)^{\frac{1}{n}} + (\rho_w g d_w)\right]$$

With water filling the crevasses

Experiment 2

Tensile deviatoric stress calculated directly from constitutive relation

$$d_0 = \frac{1}{\rho_i g} B \dot{\epsilon}_* \dot{\epsilon}^{\frac{1}{n}-1}$$

Experiment 3

Exp. 2 + Tensile deviatoric stress as a function of depth

Experiment 4

Exp. 3 + Introduce a 'yield strain rate'

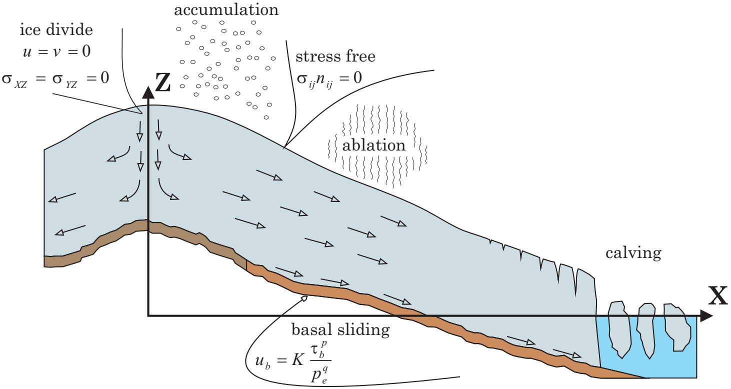
Dynamical model equations

$$\frac{\partial \sigma_{ij}}{\partial x_j} + \rho g_i = 0 \quad \text{conservation of linear momentum}$$

$$\frac{\partial u_i}{\partial x_i} = 0 \quad \text{conservation of mass}$$

$$\dot{\epsilon}_{ij} = A\tau^{n-1}\tau_{ij} \quad \text{constitutive relation}$$

Boundary conditions



Boundary conditions

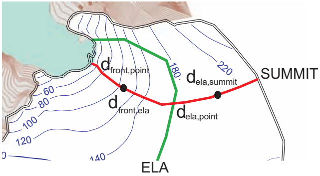
Basal sliding

Present implementation (1st approach)

$$u_b = -K \frac{(\rho g H)^p \, |\nabla h|^{p-1} \, \frac{\partial h}{\partial x}}{(\rho g H - \rho_w g H_w)^q},$$

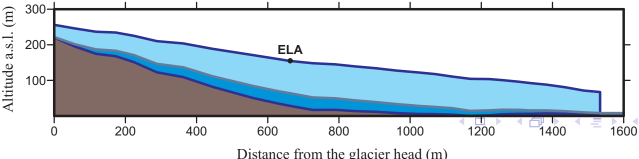
$$v_b = -K \frac{(\rho g H)^p \, |\nabla h|^{p-1} \, \frac{\partial h}{\partial y}}{(\rho g H - \rho_w g H_w)^q},$$

$$w_b = u_b \frac{\partial b}{\partial x} + v_b \frac{\partial b}{\partial y}$$



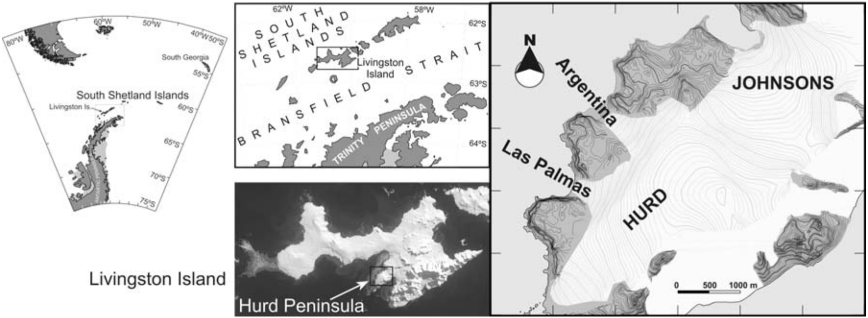
$$H_w^{ab} = C \frac{d_{front,point}}{d_{front,ela}} + abs(min(0, b))$$

$$H_w^{ac} = C(1 - \frac{d_{ela,point}}{d_{ela,summit}})$$



Application: Johnsons glacier

Location of Livingston Island and Hurd Peninsula, and surface map of Johnsons and Hurd glaciers (South Shetland Islands, Antartica).

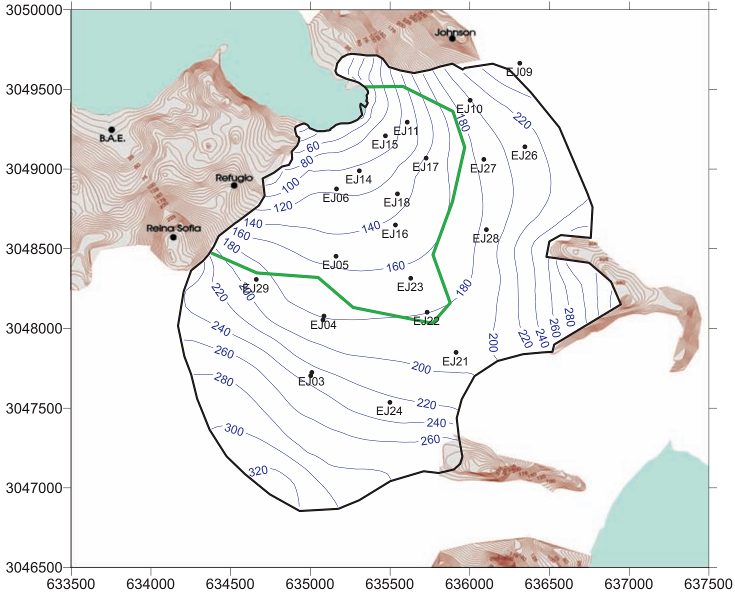


Limitations:

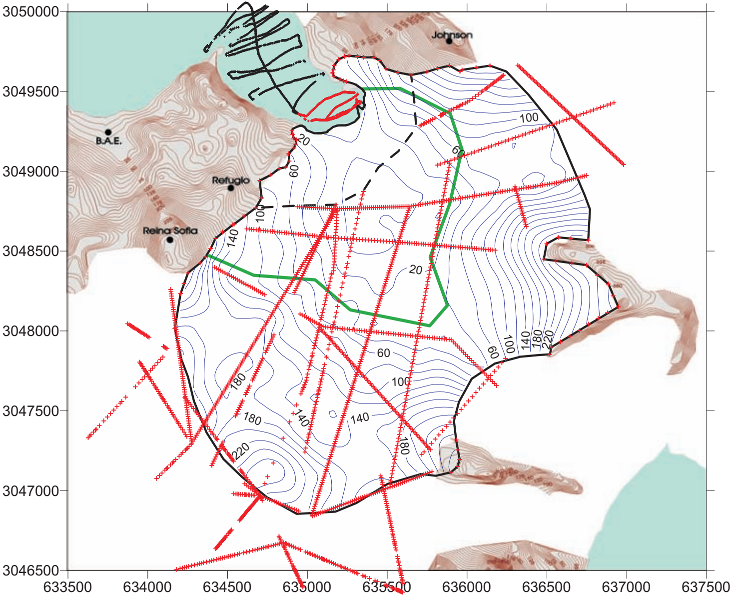
- Short time series of front position (5 yr.).
- Flat slope of seabed in proglacial area.
- Resulting in nearly constant front position.

⇒ Application restricted to estimating model-predicted front position.

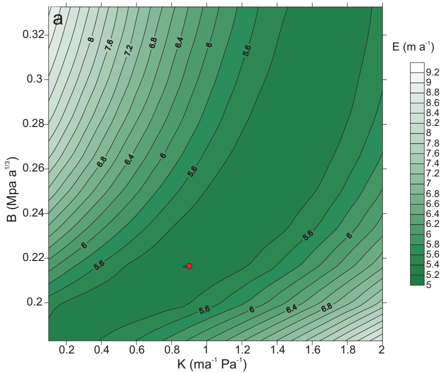
Surface topography and ELA

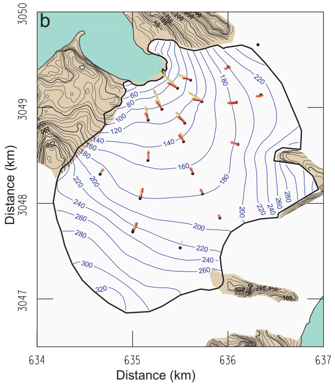


Radar profiles, bathymetry and subglacial relief map



Model parameters tuning. K uniform

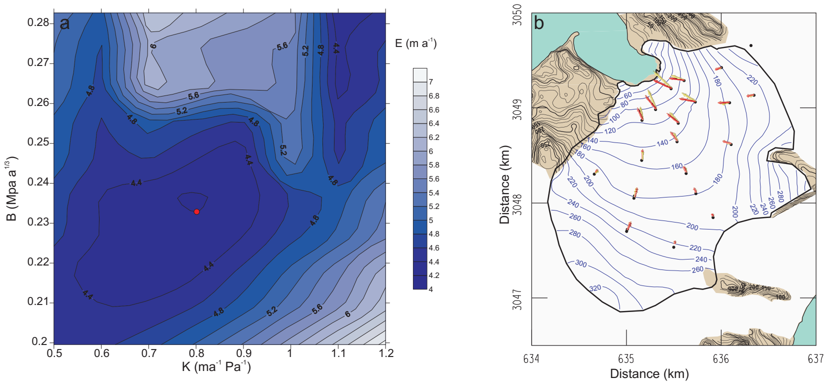




Not in good agreement with observations near the glacier front.

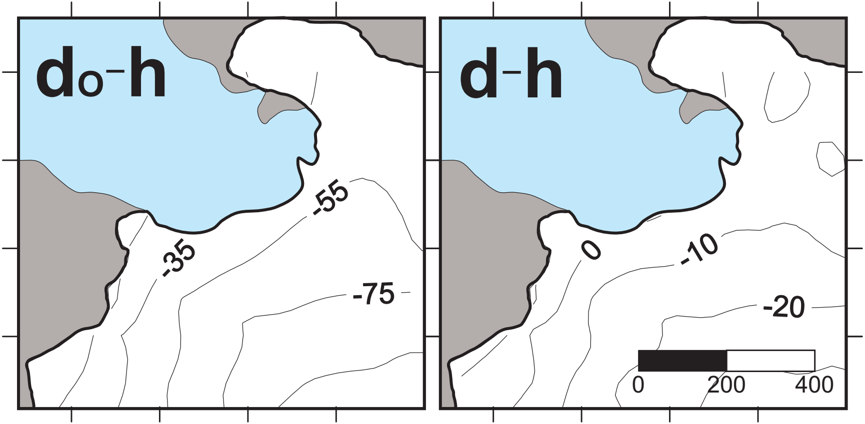
Model parameters tuning. Nonuniform K

- K weighted according to position (2 zones, nearly coincident with accumulation & ablation).
- Aimed at closer agreement between computed and observed velocities.



Much better agreement with observations near the glacier front.

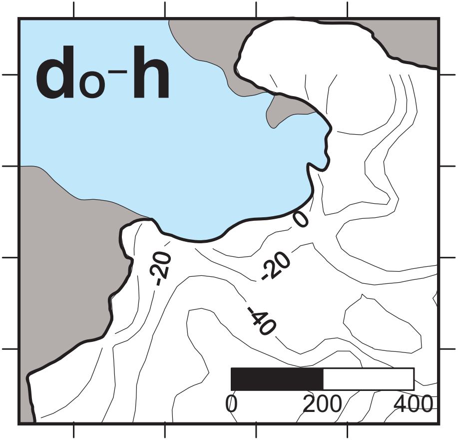
Predicted front position. Experiment 1



Water-free crevasses

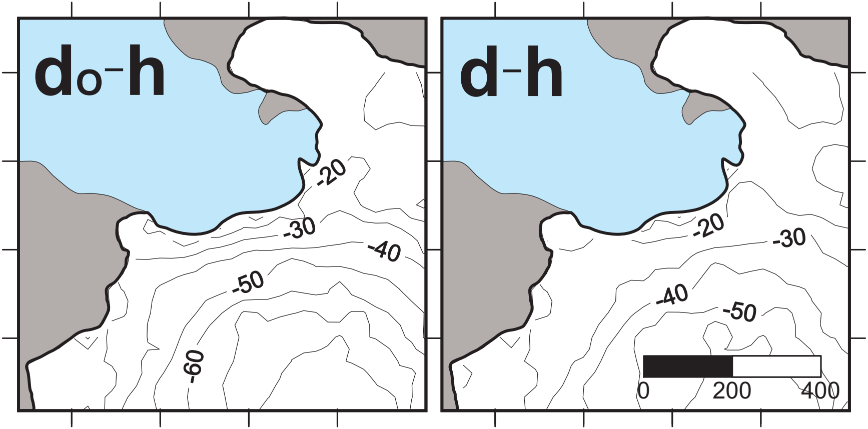
Water-filled crevasses ($d_w = H/2$)

Predicted front position. Experiment 2



Water-free crevasses

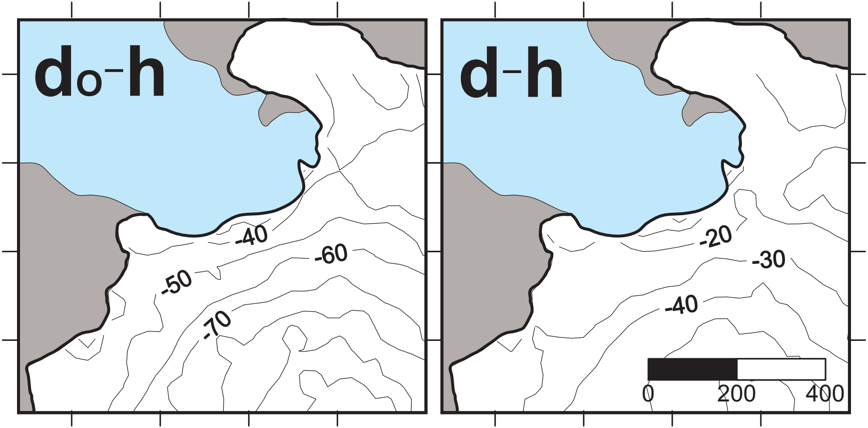
Predicted front position. Experiment 3



Water-free crevasses

Water-filled crevasses ($d_w = H/10$)

Predicted front position. Experiment 4



Water-free crevasses

Water-filled crevasses ($d_w = H/6$)

Conclusions and outlook

Conclusions

- Our three-dimensional extension of Benn's calving criterion, with Nye's formula, does not accurately reproduce the observed front position unless a large amount of water filling the near-front crevasses is hypothesized.

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- The modified criterion for crevasse depth, which computes the deviatoric longitudinal stress opening the crevasse using the full-stress solution, substantially improves the results. No water in crevasses is necessary. Crevasse depth slightly overestimated.

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- The model that considers the tensile deviatoric stress opening the crevasse as a function of depth provides the best fit to observations with a small amount of water filling the crevasses.

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- The modified criterion for crevasse depth, which computes the deviatoric longitudinal stress opening the crevasse using the full-stress solution, substantially improves the results. No water in crevasses is necessary. Crevasse depth slightly overestimated.
- The model that considers the tensile deviatoric stress opening the crevasse as a function of depth provides the best fit to observations with a small amount of water filling the crevasses.
- Introducing a 'yield strain rate'does not improve the fit to observations, unless a slightly larger amount of water is assumed. Such a yield strain rate is a physically plausible mechanism to overcome the fracture toughness of the ice.

Conclusions and outlook

Outlook

- Improving the representation of basal sliding.
  Some alternatives:
  - Improving the estimates of τ_b and H_w.
- Application of the calving model to a glacier with a good record of front positions (e.g. Hansbreen), allowing use of transient model in prognostic mode.


Thank you