Modelling the dynamics of tidewater outlet glaciers: approaches, issues and perspectives

Andreas Vieli,
University of Zürich, Switzerland

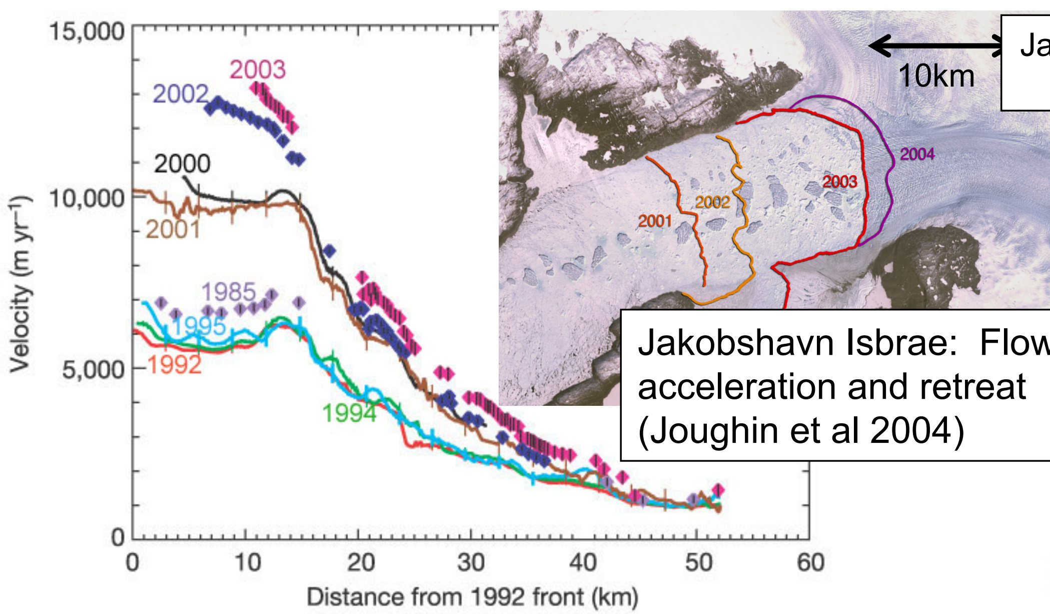
Thanks to Faezeh Nick,...

Introduction

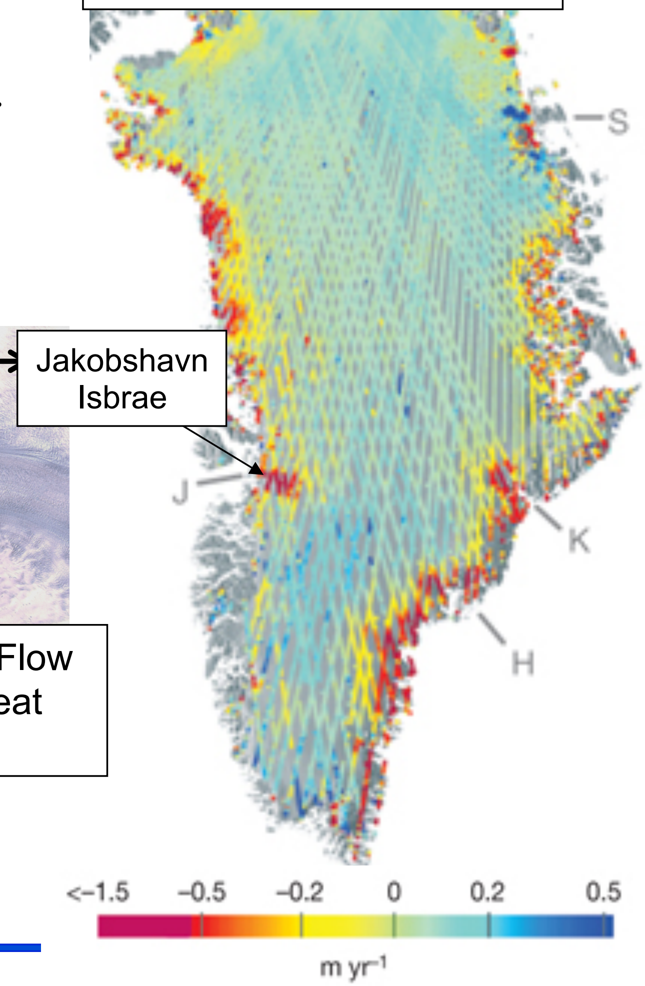
- Tidewater outlet glaciers
  - Retreat, acceleration and thinning

- Not reproduced/predicted by ice sheet models (IPCC 2007)

Surface elevation change in Greenland (Pritchard, Nature 2009)



Jakobshavn Isbrae: Flow acceleration and retreat (Joughin et al 2004)



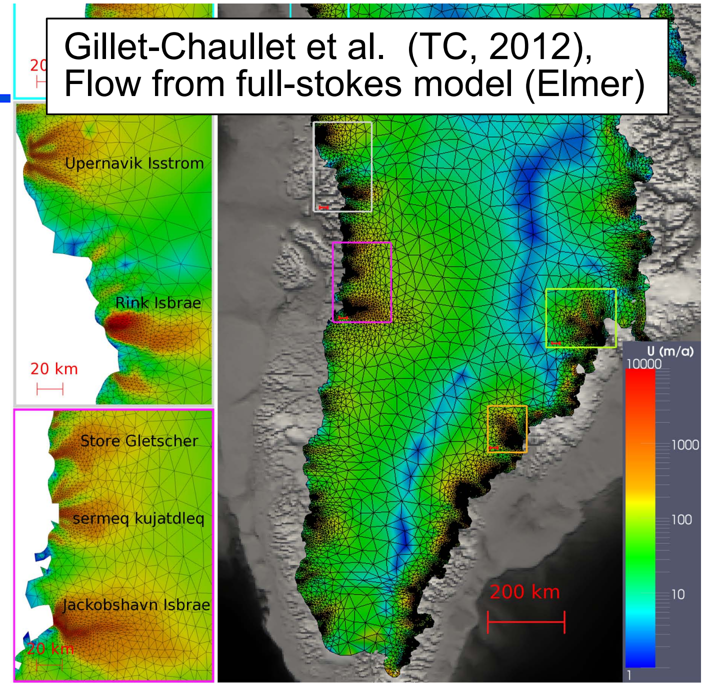
The modelling issue

Ice sheet models do well for:

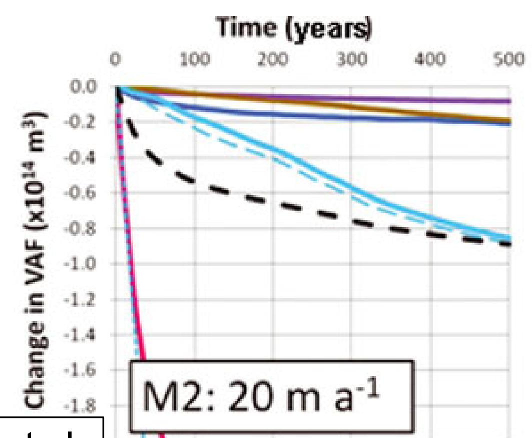
- Ice flow (SIA, higher order,…) ✓
- Surface evolution ✓
- Numerical methods (1D-3D, finite Differences/Elements,…) ✓
- Grounding line motion (✓)

But poor representation of processes at outlet-ocean boundary

- Spatial resolution: few km wide
- Calving/terminus dynamics: front fixed
- Forcing crude: e.g. indirect ocean melt
- Prescribed 'what if…' forcing scenarios (no retreat feedbacks)



Gillet-Chaullet et al. (TC, 2012), Flow from full-stokes model (Elmer)



Bindschadler et al. (2013) SeaRISE

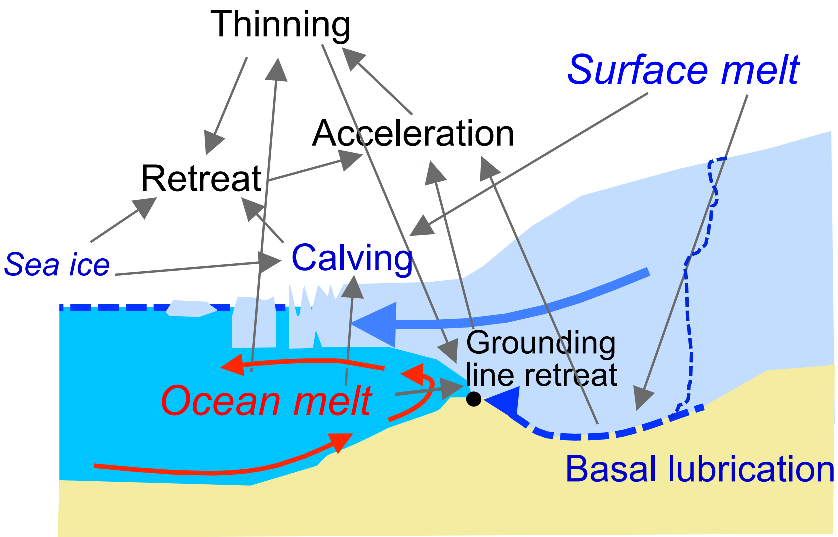
Models of tidewater outlet glacier dynamics

Ice sheet models IPCC/Sea-level

- Predictions (sea-level, IPCC)
- Ice sheet scale

Minimal fully dynamic outlet glacier model (1D, SSA,…)

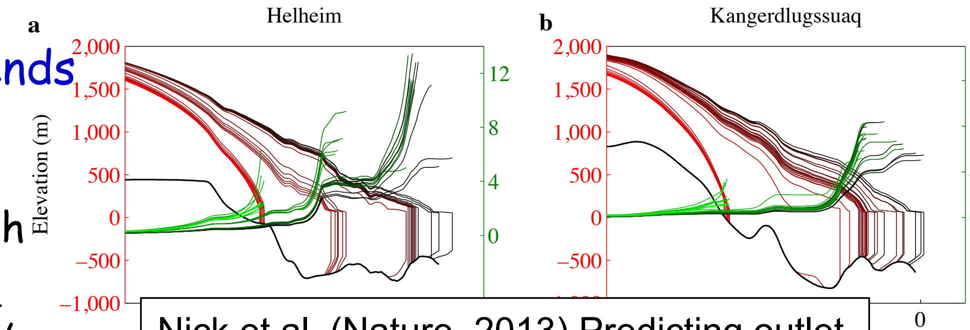
- Moving calving front
- Couple forcing to dynamic response
- Explore/illustrate dynamic feedbacks – modelling issues



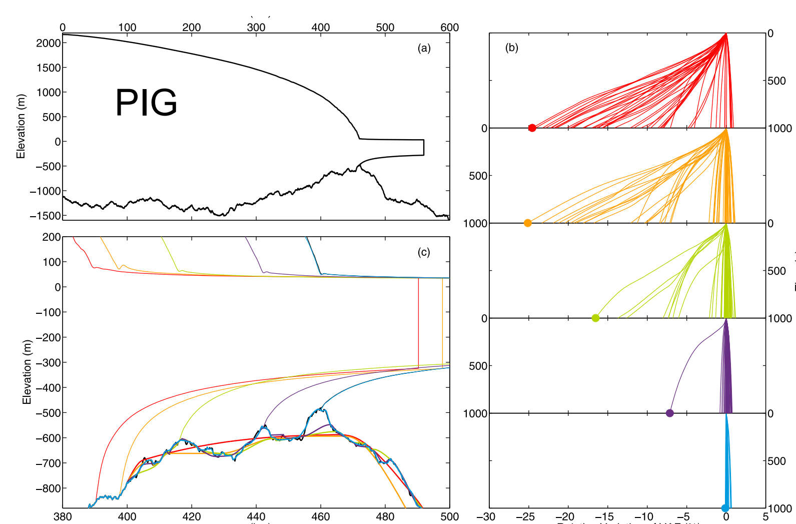
Sensitivity to fjord/trough geometry

- Retreat rate strongly depends on fjord/trough geometry
  - Water depth/Trough width
  - Non-linear with depth ($h^{\sim 4}$, Schoof 2007)
  - P_{eff}-sliding (Pfeffer, 2007)
- Threshold behaviour

- Variations/details of bed important (uncertainty)
- Requires high spatial model resolution (adaptive)



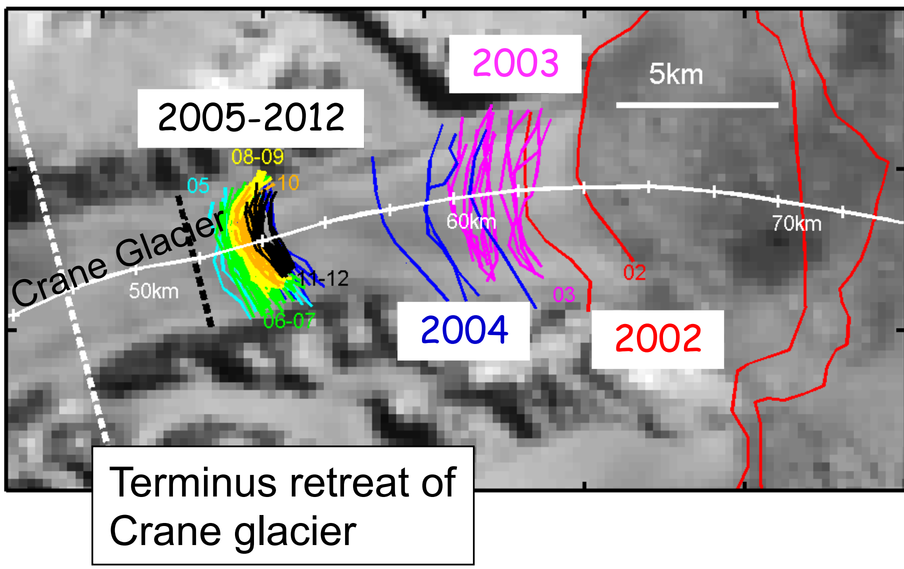
Nick et al. (Nature, 2013) Predicting outlet glacier retreat

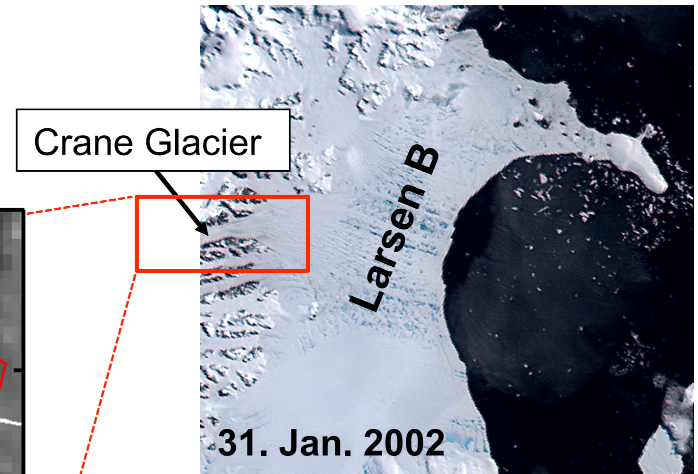


Durand et al. (GRL, 2011) Impact of bedrock description on modeling ice sheet dynamics

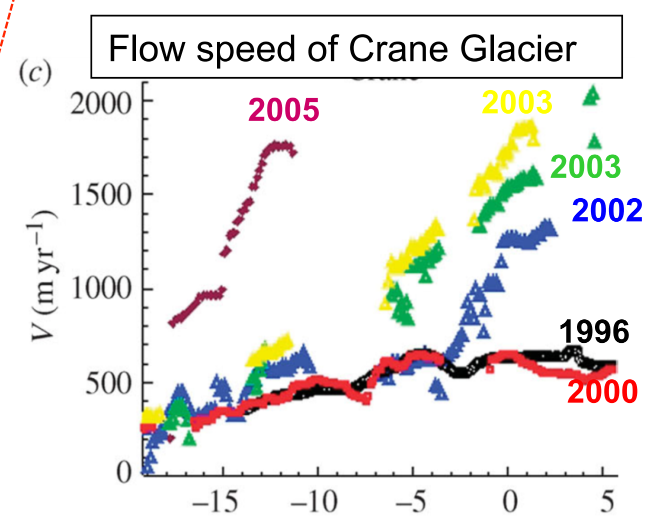
Terminus/upstream dynamics

- Experiment: collapse of Larsen B ice shelf 2002
- Effect on tributary glacier Crane





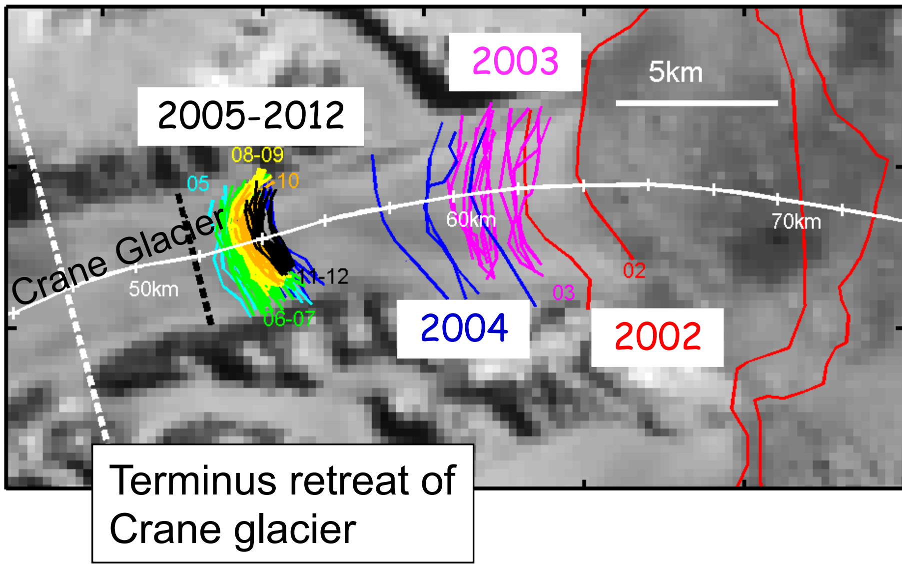
National Snow and Ice Data Center

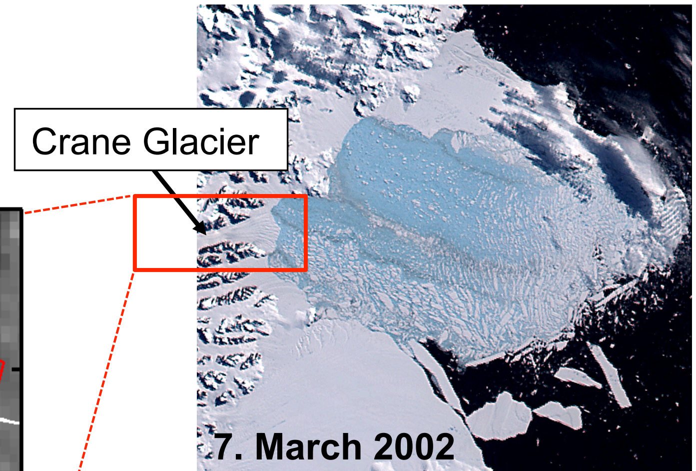


From Rignot et al. 2004/06

Terminus/upstream dynamics

- Experiment: collapse of Larsen B ice shelf 2002
- Effect on tributary glacier Crane





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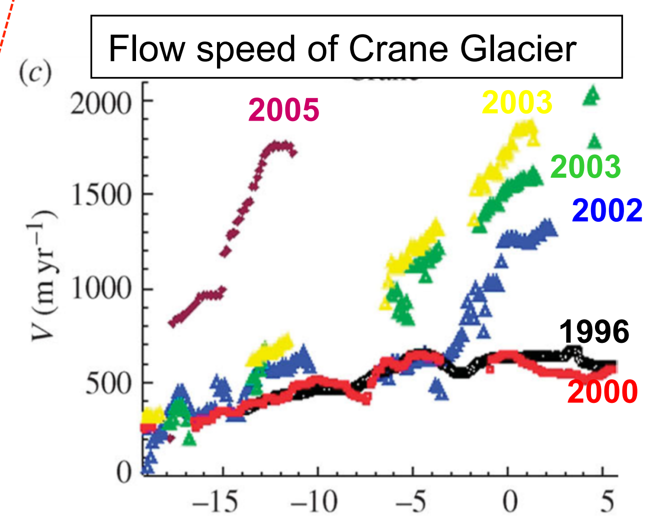
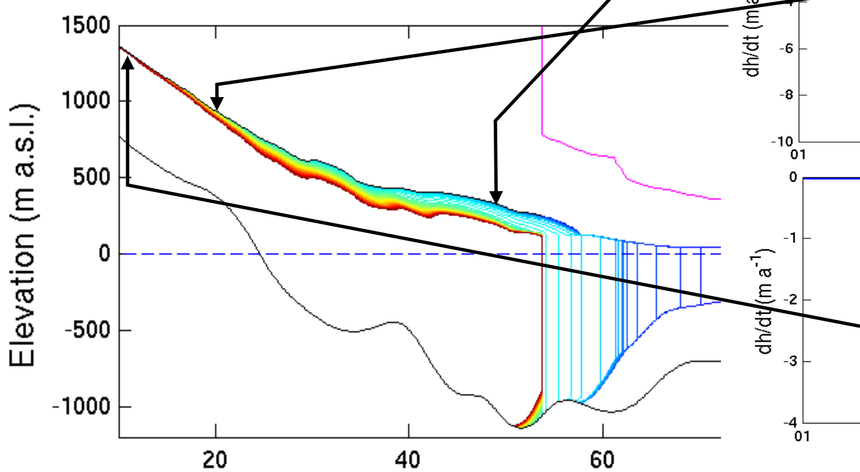


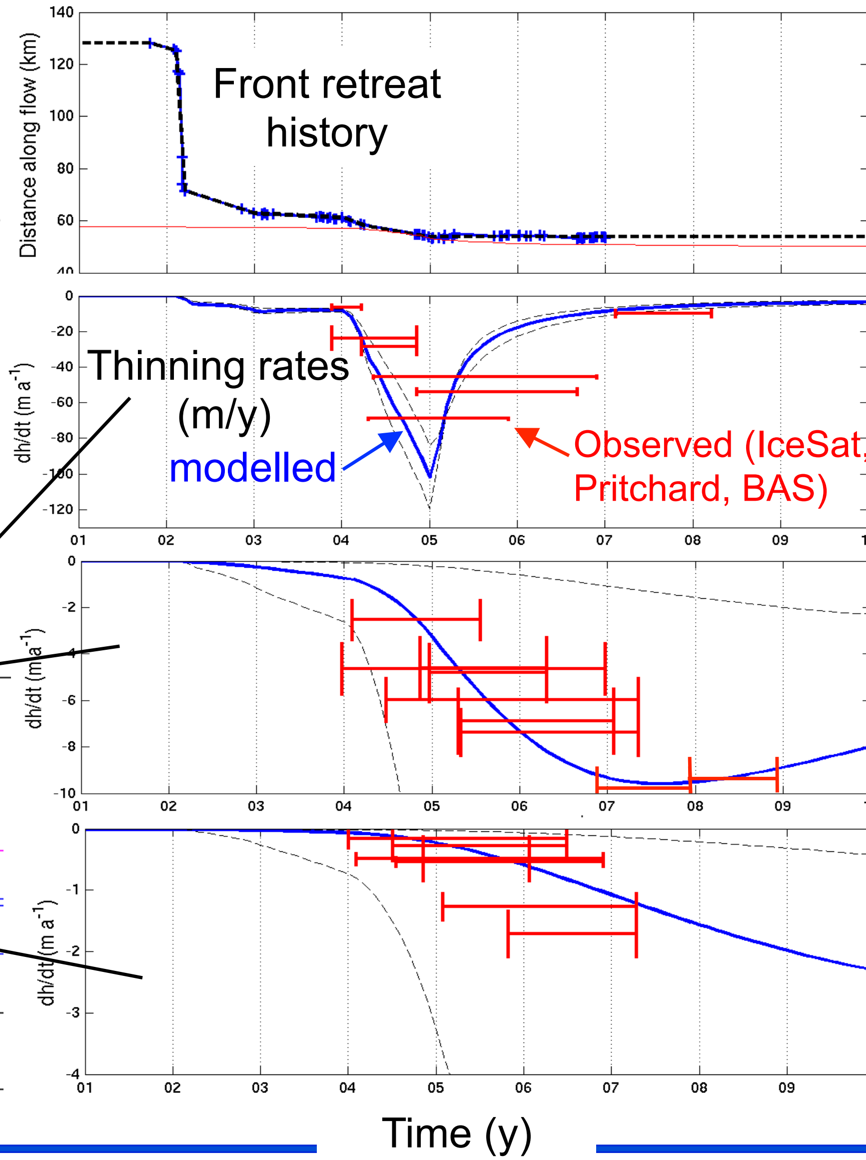
From Rignot et al. 2004/06

Modelling thinning

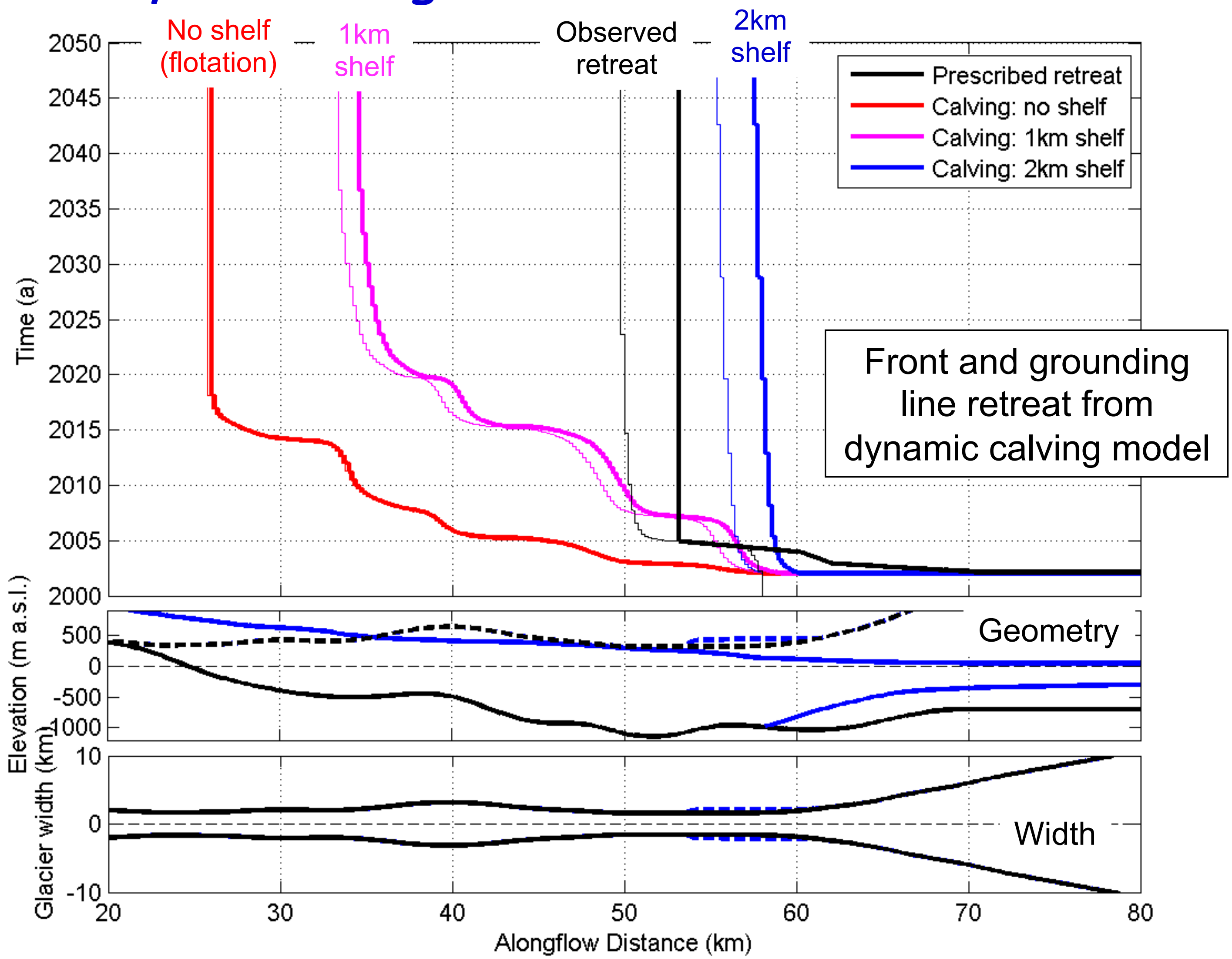
Experiment: prescribe retreat

- Upstream thinning/acceleration linked to terminus retreat
- Crucial: Calving retreat – buttressing feedback





Sensitivity to calving model I



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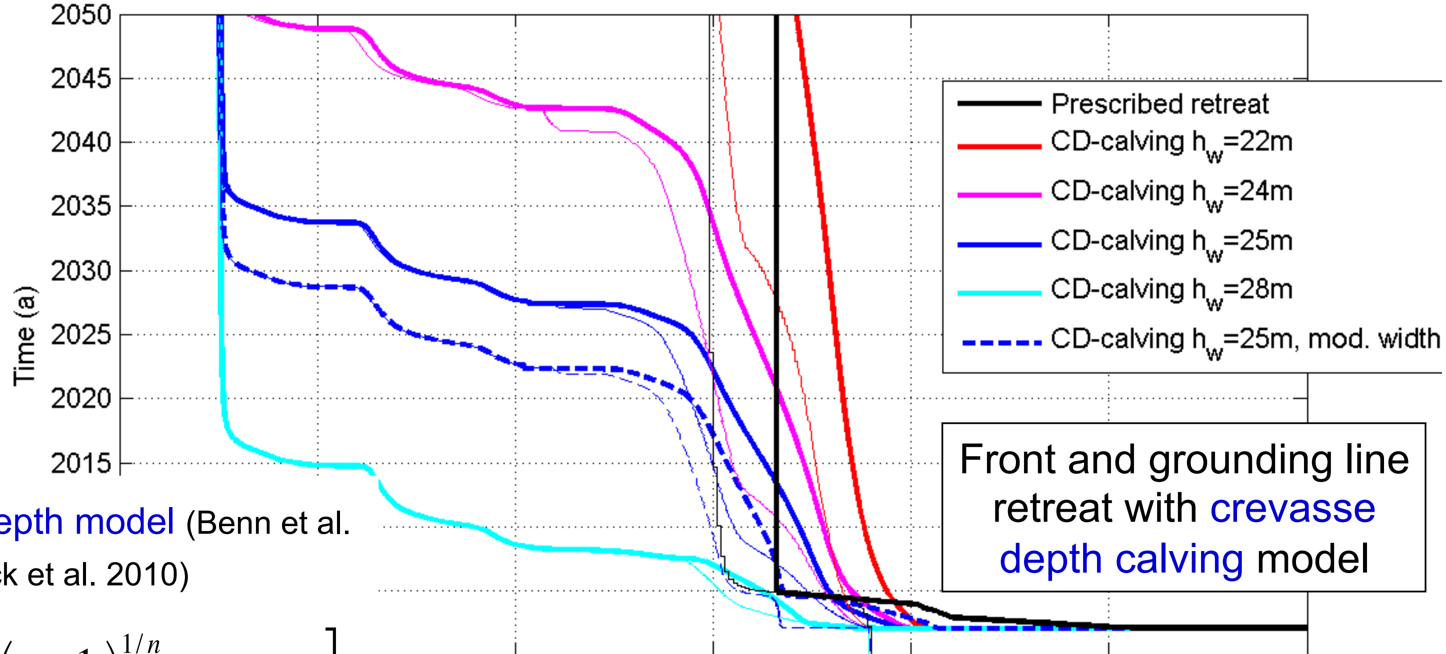
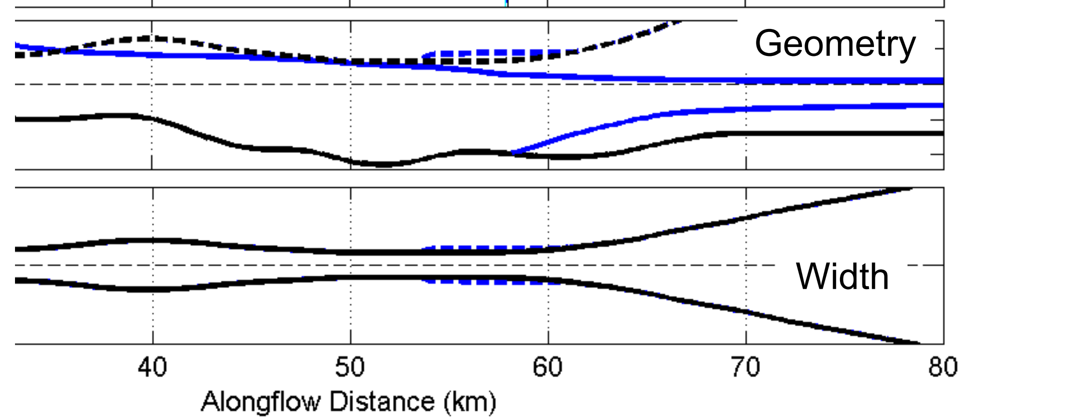
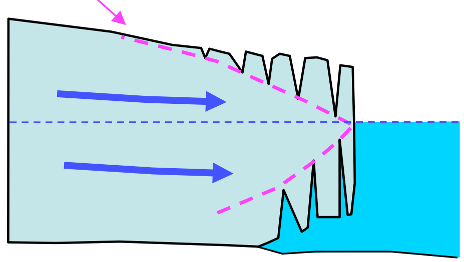
Sensitivity to calving model II





Crevasse depth model (Benn et al. 2007; Nick et al. 2010)

$$d = \frac{2}{g\rho_i}\left[\left(\varepsilon_{xx}\frac{1}{A}\right)^{1/n} + \rho_w g d_w\right]$$



Response to external forcing: ocean melt

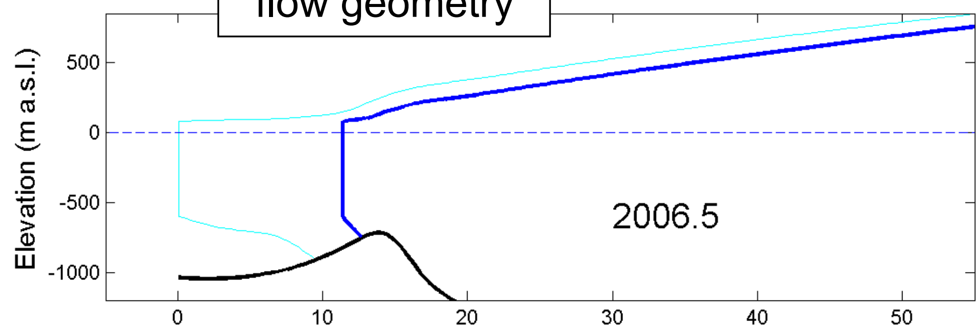
Jakobshavn Isbrae

- Ocean melt: m/d (Motyka 2010)

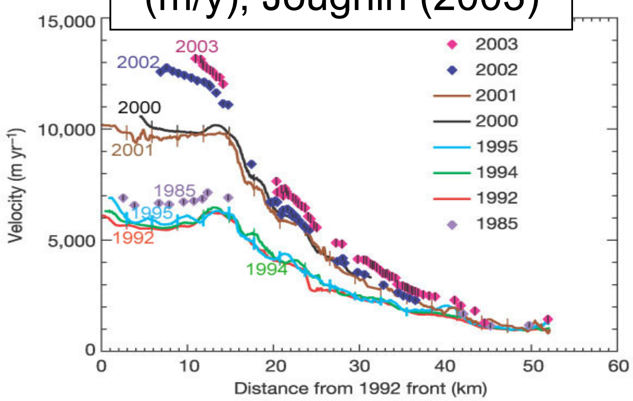
Experiment:

- after 1997 20% enhanced ocean melt
- seasonal pattern
- dynamic calving criteria

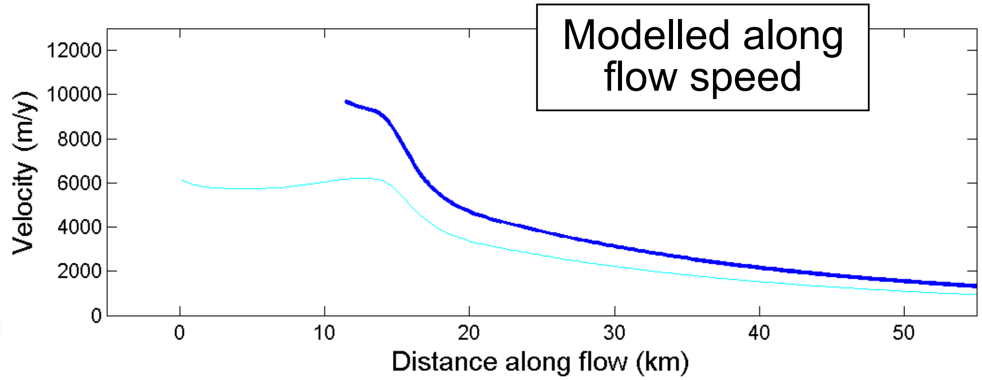
Modelled along flow geometry



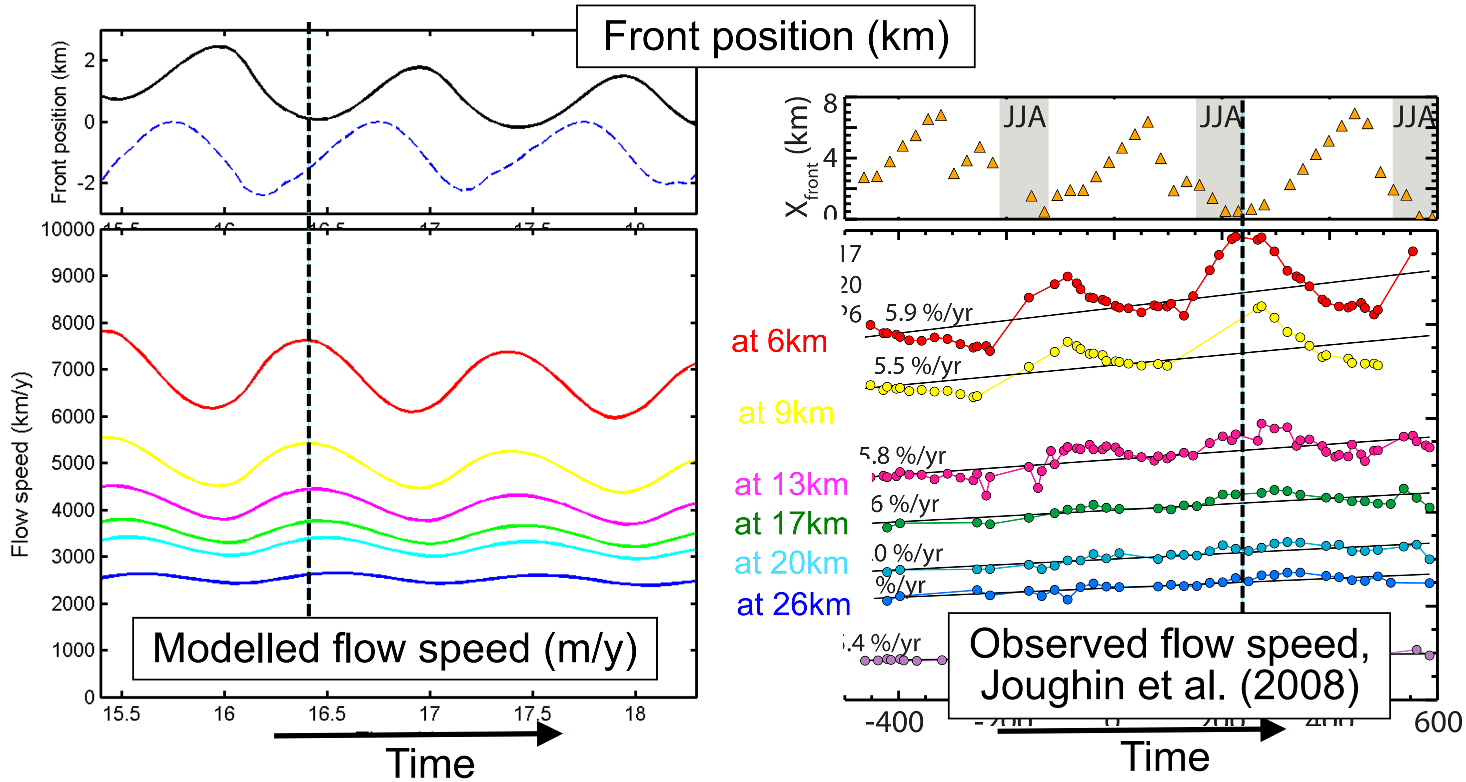
Observed flow speed (m/y), Joughin (2003)



Modelled along flow speed



Seasonal variations in flow speed

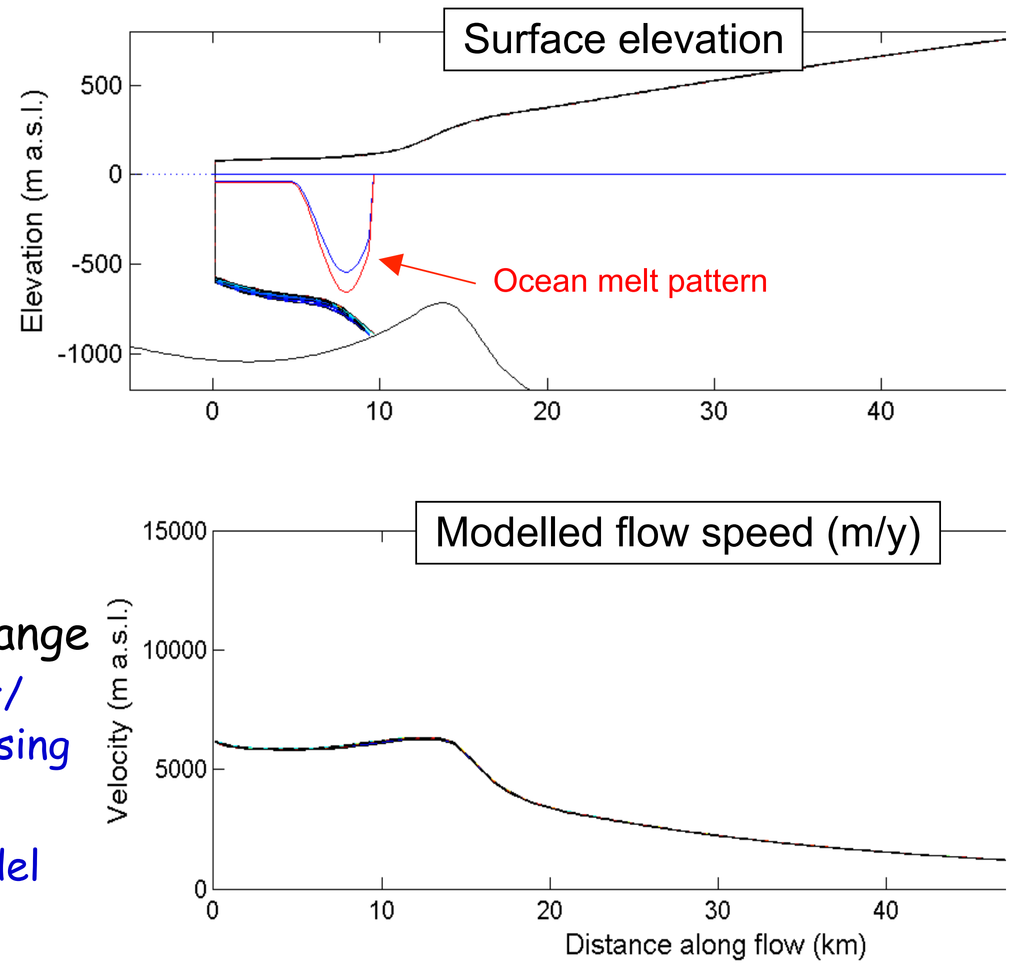


- Reproduce upstream variations in speed
- Changes from terminus

Ocean melt forcing

Experiment:

- 20% enhanced melt
- Fixed calving front



Trigger:

- Ocean melt

Mechanism for dynamic change

- Feedback between retreat/ calving and loss of buttressing
- Dependence on calving model

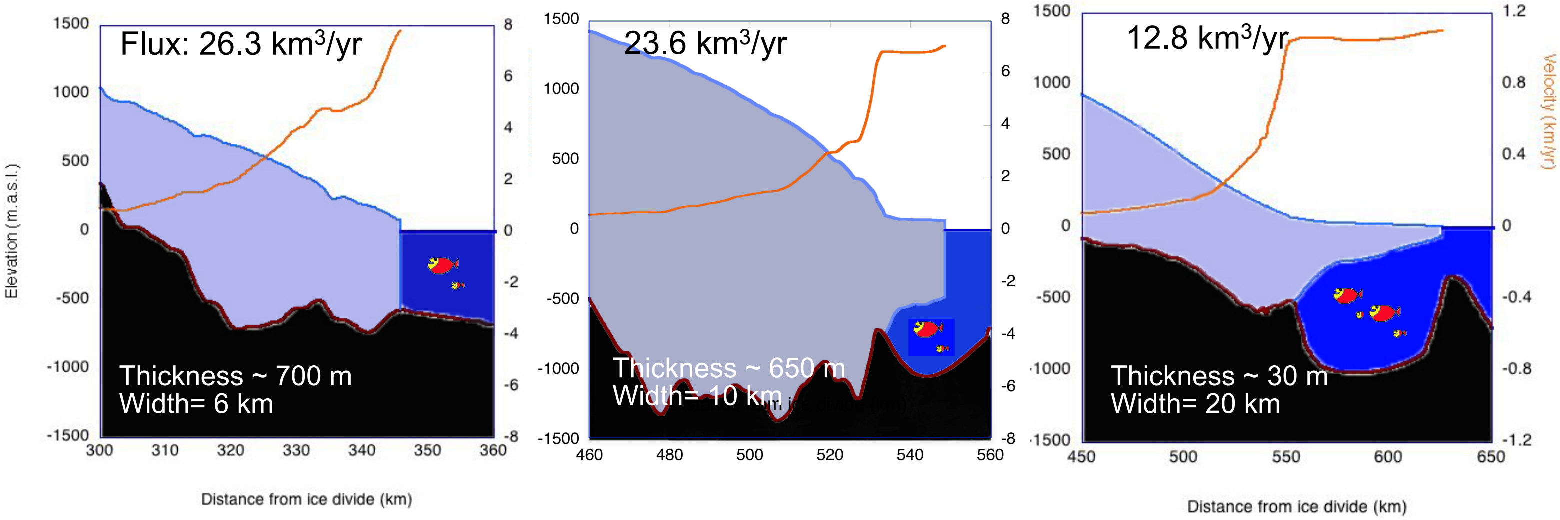
Sensitivity to forcing type

Modelling outlet glacier dynamics of 4 major outlets (Nick et al. Nature, 2013)

Helheim
- Sea-ice
- Air-temp

Jakobshavn
- Sea-ice
- Ocean melt

Petermann
- Ocean melt
- (Basal sliding)



Variable sensitivity to forcing

- depending on glaciers/terminus type/climate
- can change during retreat

Ocean melt forcing and calving

Grounded terminus (instead of floating)?

- Oversteepen/weaken calving front
  ➔ enhance calving

Numerical modelling issues

- Difficult to implement at vertical ice front
- Coupling of ocean melt to ice models

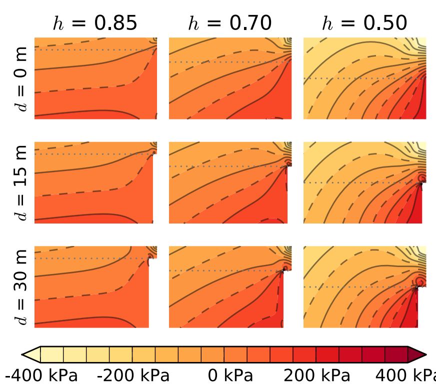
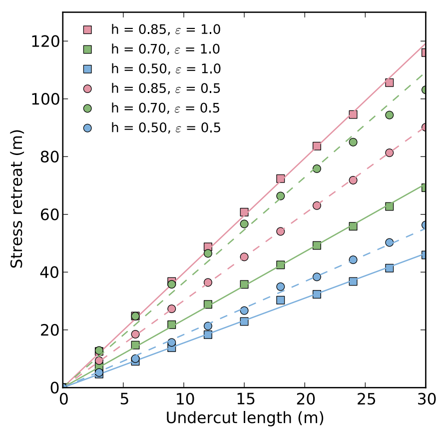
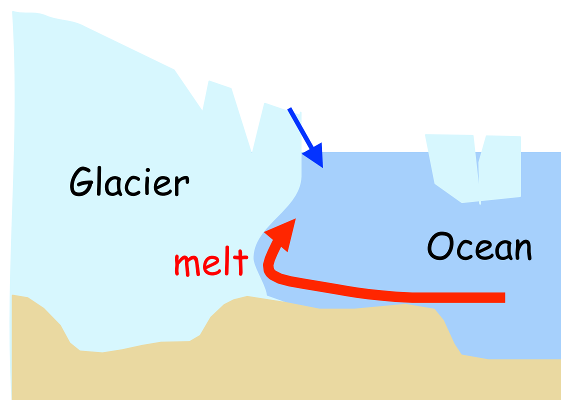


Fig. 2. Comparison of first principal Cauchy stresses, relative to hydrostatic pressure, for a variety of water depths and undercut

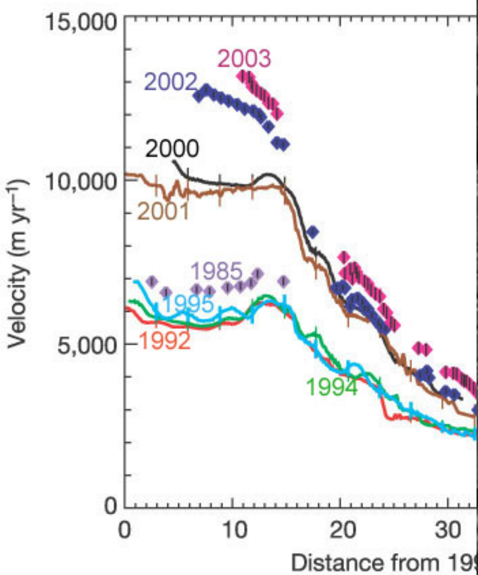


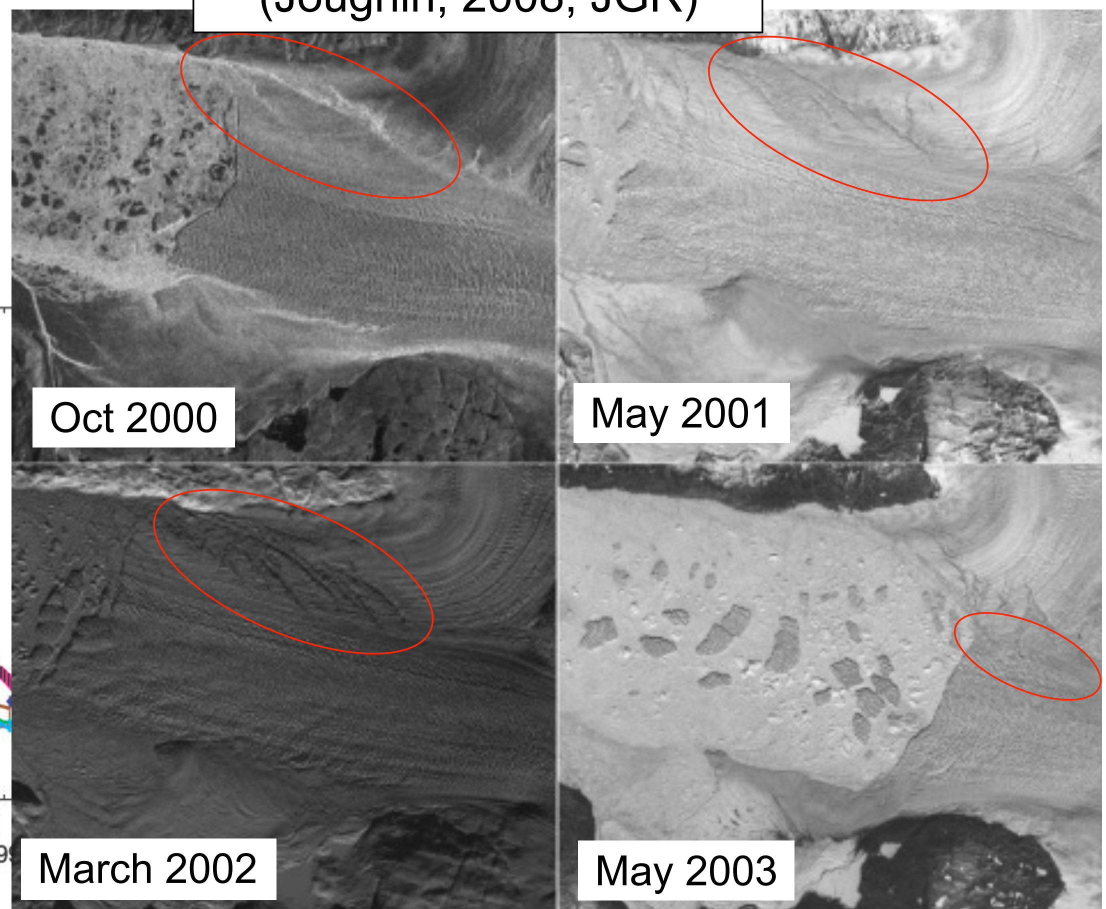


O'Leary and Christoffersen (TC, 2013) Calving on tidewater glaciers amplified by submarine frontal melting

Lateral shear weakening: Jakobshavn Isbrae

Disintegration of floating tongue at Jakobshavn (Joughin, 2008, JGR)



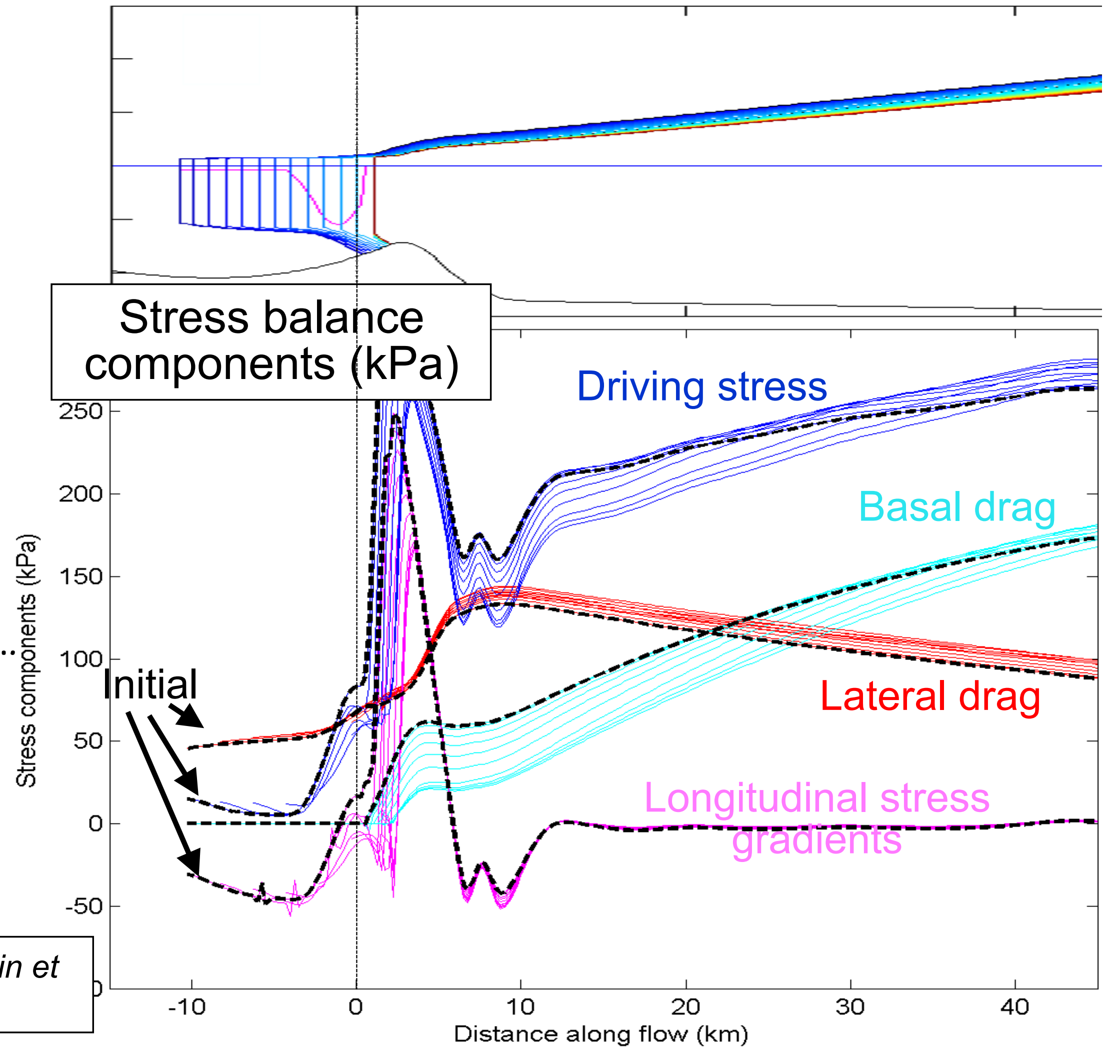


Lateral shear weakening Jakobshavn

Weakening of lateral shear margins

- Enhance acceleration
- Strain softening, fracture

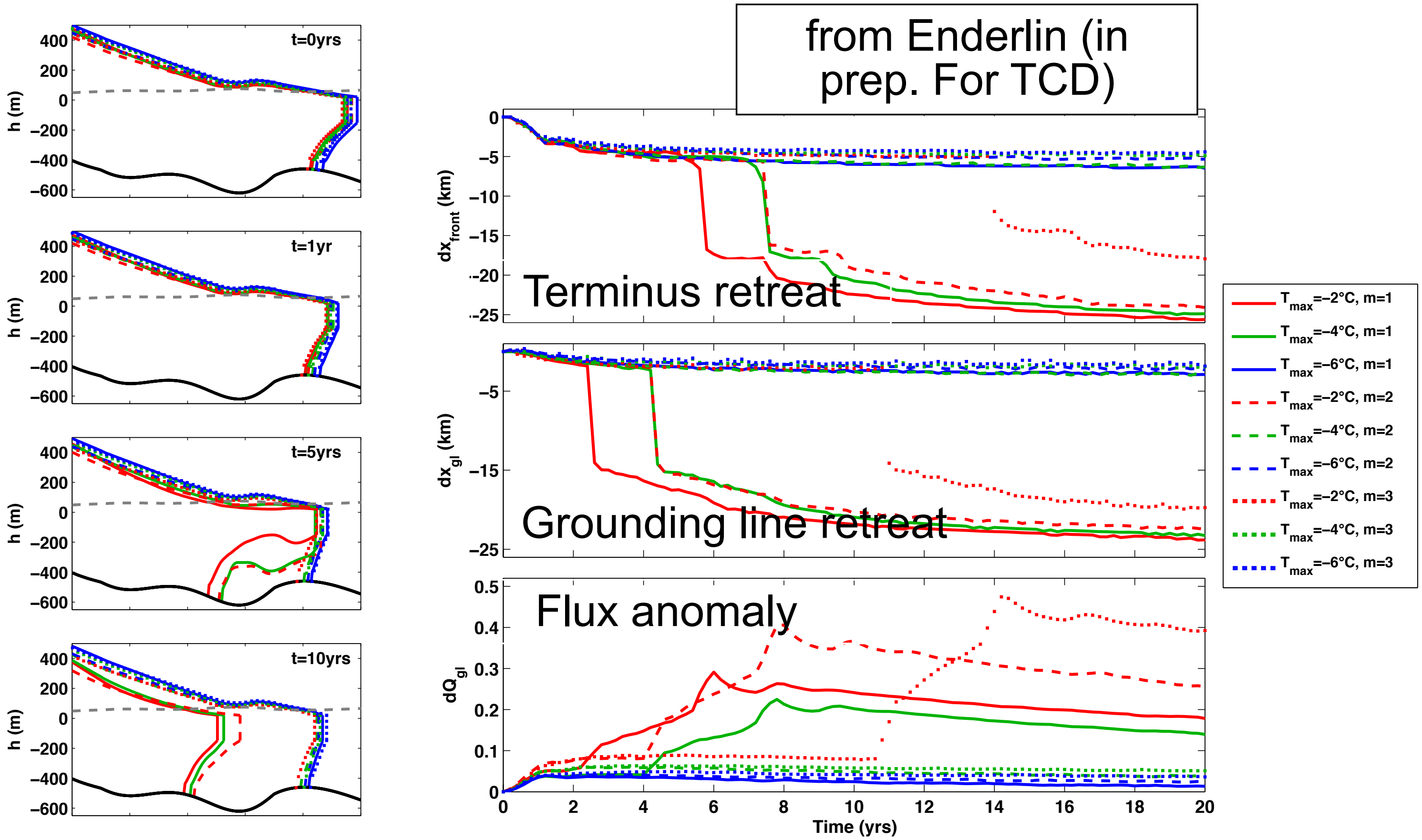
- Numerical models
  - narrow, subgrid,
  - data, (inversion),...
  - damage,...



See: Vieli and Nick, 2011; Joughin et al. 2012; VanderVeen, 2011

Sensitivity to ice rheology/sliding exponent

from Enderlin (in prep. For TCD)



- Sensitivty/uncertainty from internal parameters

Implications from modelling

- Terminus dynamics controls upstream dynamics (mass loss)
  - Upstream propagation: ok
  - Calving model crucial – robust/validation
- Forcing
  - Calving linked to forcing: ocean melt, air temp., sea-ice… (How?)
  - Not just ONE forcing important (terminus type/climate)
- High sensitive to fjord/trough geometry (bed/width)
  - Threshold/non-linear behaviour (predictions?)
  - Need accurate topography
- Lateral shear softening, rheology?
- Only 'simple' fully dynamic outlet glacier model (SSA, flowline,…)

How to improve models

Technical/numerical development

- Grid resolution, 1D to 3D
- Moving boundaries (calving front: resolution, adaptive grids,..)
- Flow approximation: higher-order, full stokes

Process representation

- Calving models (3D, damage, statistical,…)
- Coupling of calving to forcing (ocean melt models…)
- Initial conditions (transient?)

Validation/calibration: Benchmark data sets

- Geometry data (bed,…)
- Response and forcing data (e.g. ocean, …)
- Range of time scales: in particular long-term
- model-model intercomparison

Final thoughts

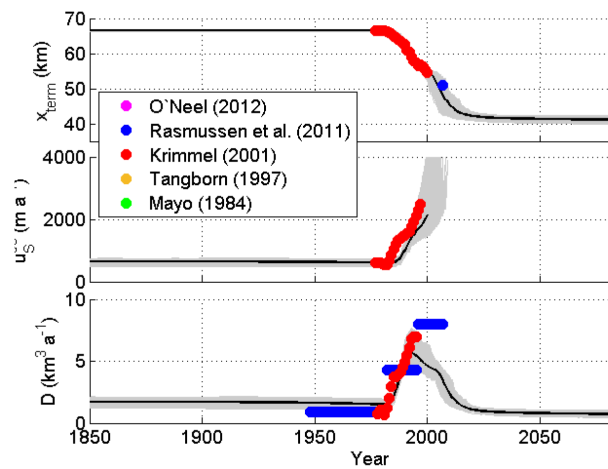
Rethink expectation on models

- Not predict exact timing of single retreat-event
- 'Average retreat trend' (ensemble of glaciers/responses, decades/ century)

Not just large Greenland ice-sheet outlets

- Smaller tidewater glaciers (Alaska, Svalbard,…)
- Extensive dataset - Benchmark data set
- Easier accessible

Apply models!!!

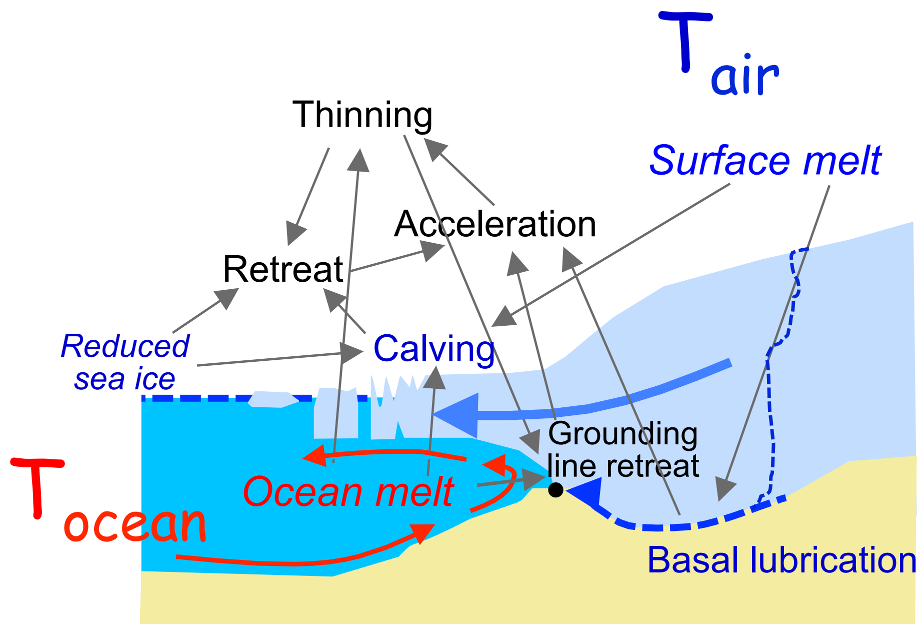


Colgan et al. (TC, 2012) Monte Carlo ice flow modeling projects a new stable configuration for Columbia Glacier, Alaska, c. 2020


Thank you

External forcing

- Surface melt
- Ocean melt
- Sea-ice



- Dynamic response coupled to forcing

Summary: terminus/upstream dynamics

- Terminus dynamics determines upstream dynamics
  - thinning, acceleration, mass loss
- Inland propagation ✓
- Strong dependence on calving model/parametrization
- Influence of channel topography

Ocean melt forcing and calving

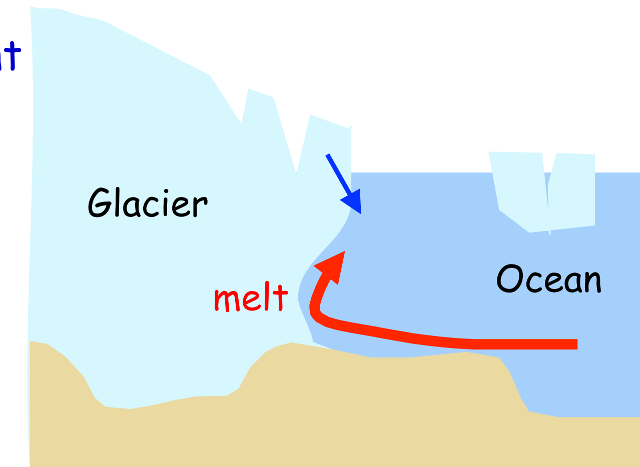
Grounded terminus (instead of floating)

- Oversteepen/weaken calving front
  ➔ enhance calving

Numerical modelling issues

- Ocean forcing records: temperature/ salinity
- Coupling of ocean melt to ice models
- Difficult to implement at vertical ice front

Hansbreen Svalbard
(Vieli et al 2002)



A minimal fully dynamic flowline model (1D)

- Dynamic treatment of calving: front position criteria –

Explore/illustrate

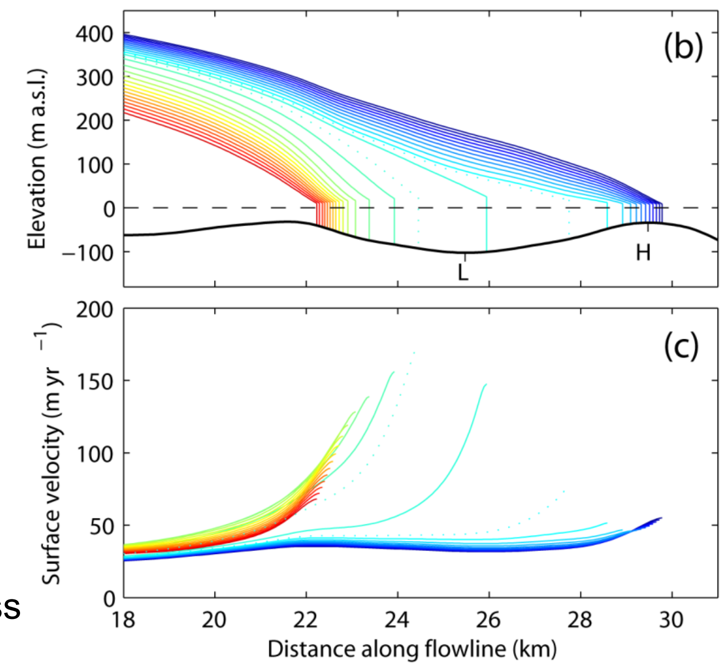
Mostly confined in trough/fjord: 1D-flowline/band

- Couple forcing to dynamic response
- Role of terminus dynamics/calving on upstream dynamics

- Basal, lateral and longitudinal stresses
- Moving grounding line/front – stretching grid

Boundary condition at terminus

$$\left.\frac{\partial u}{\partial x}\right|_{front} = A \cdot \left[\frac{1}{4}\rho_i g\left(1-\frac{\rho_i}{\rho_w}\right)\right]^n \cdot h_f^{\ n}$$



Stress balance

$$2\frac{\partial}{\partial x}h\nu\frac{\partial u}{\partial x} - \beta u^{1/m} - \frac{h}{W}\left(\frac{5u}{2AW}\right)^{\frac{1}{n}} = \rho_i g h\frac{\partial s}{\partial x}$$

Longitud. grad. | Basal | Lateral | Driving stress

External forcing: ocean melt

Experiment:

- prescribed ocean melt pattern
- 20% enhanced melt (+1°C)
- Dynamic calving criteria (crevasse depth model)