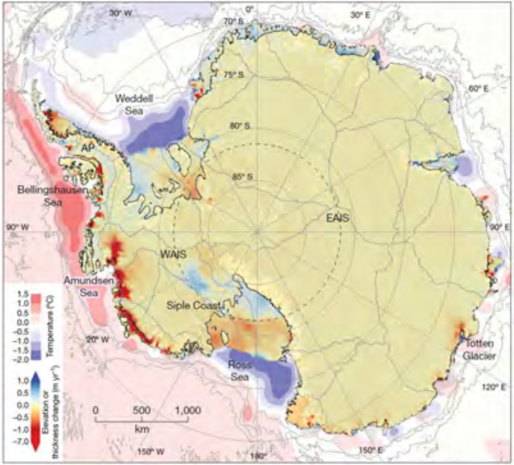
Bottlenecks in Antarctic ice-sheet modelling

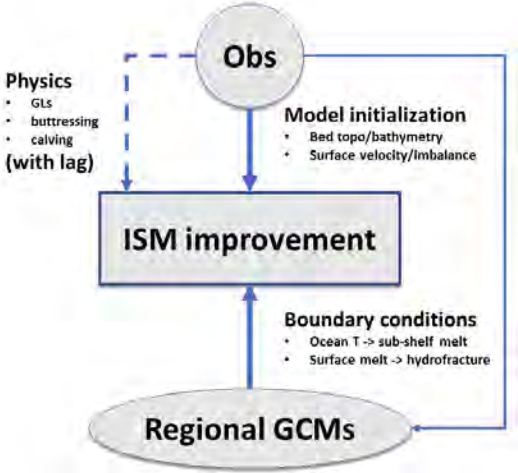
Frank Pattyn

Laboratoire de Glaciologie, Université libre de Bruxelles (ULB)

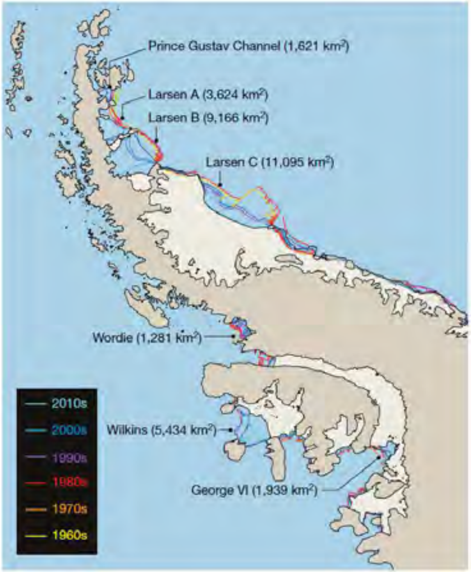
The Future of Earth System Modeling: Polar Climates, November 28-30, 2018, Caltech

EOS THE EXCELLENCE OF SCIENCE
fnrs fwo
ULB

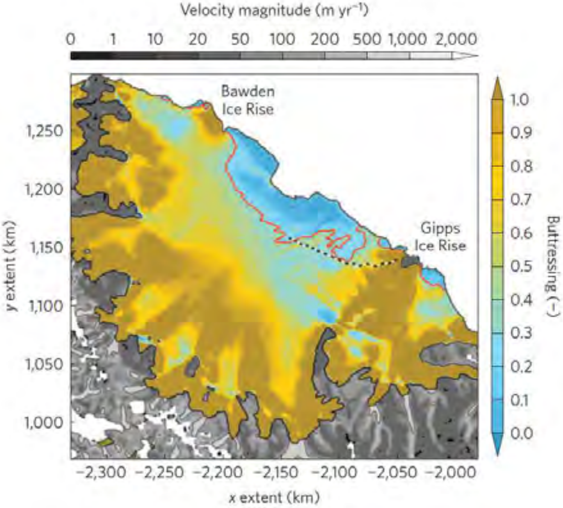




Shepherd et al. (2018)

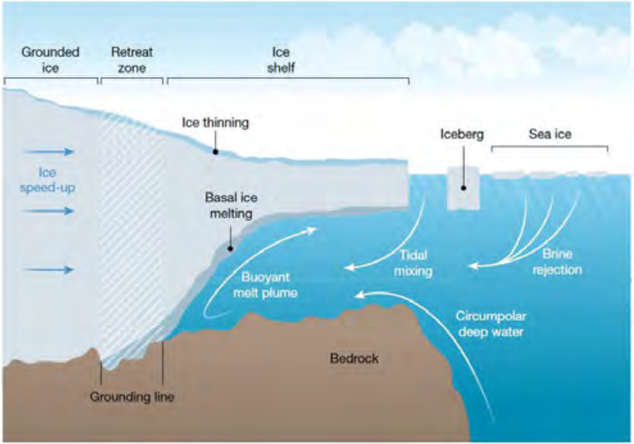


Shepherd et al. (2018)



Fuerst et al. (2016)

Marine ice sheet instability (MISI)



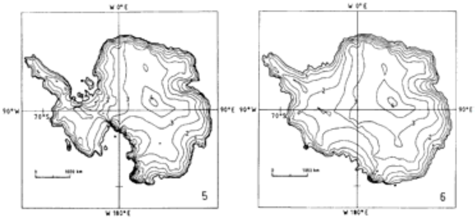
Shepherd et al. (2018)

- Weertman (1974) – Thomas and Bentley (1978)
- Ice discharge across GL should increase with h
- Ice sheet on upsloping (retrograde) bedrock: slight retreat $\rightarrow$ increase in h $\rightarrow$ increase in flux (positive feedback)

Ice-sheet modelling: from diffusive to advective

Fig. 3 *a*, Antarctic ice cover today, and *b*, after a 5–10 °C warming.

Mercer (1978)



Huybrechts (1990)

- MISI identified as potential destabilization in the 1970s
- Early 1990s: Ice sheet modelling emerged from paleo studies
- Ice sheets as a diffusive thermomechanical system interacting with climate on long time scales
- European Ice Sheet Modelling Intercomparison (EISMINT): tests on thermomechanical ice sheet models (Huybrechts et al., 1996; Payne et al., 2000)

From shallow-ice to full-Stokes: *stiff* equations

- **Conservation of mass**

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \nabla \cdot (\mathbf{v}\rho) = 0 \Rightarrow \nabla \cdot \mathbf{v} = 0$$

- **Conservation of linear momentum**

$$\rho \frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = \nabla \cdot \boldsymbol{\sigma} - \rho \mathbf{g} \Rightarrow \nabla \cdot \boldsymbol{\sigma} = \rho \mathbf{g}$$

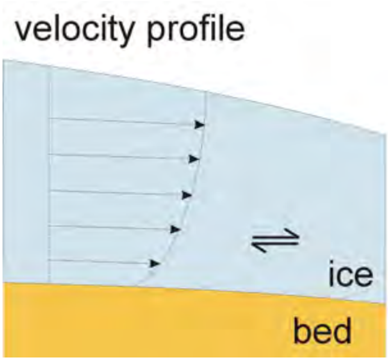
- **Conservation of energy**

$$\rho c \left[\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T \right] = \nabla \cdot (k \nabla T) - \frac{1}{2} \mathrm{trace}(\boldsymbol{\tau} \dot{\varepsilon})$$

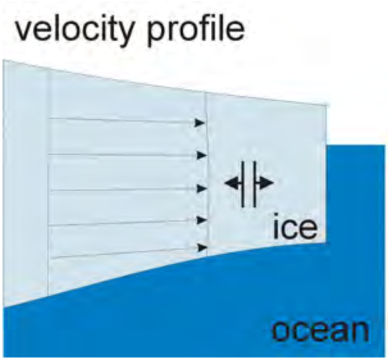
- A **constitutive equation** relates stress to strain

$$\boldsymbol{\tau} = 2\eta \dot{\varepsilon} \, , \, \eta = \frac{1}{2} A^{-1/n} \dot{\varepsilon}_e^{(1-n)/n}$$

Approximations to the Stokes equations



Ice sheet: vertical shearing
Shallow-Ice Approximation (SIA)



Ice shelf: longitudinal stretching
Shallow-Shelf Approximation (SSA)

Transition zones: all stresses equally important: full Stokes, HOM, Hybrid models

Grounding lines: not only a Stokes problem

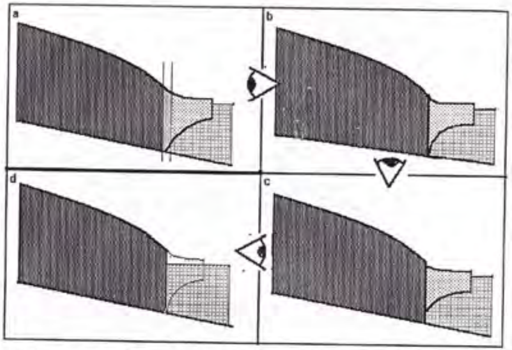
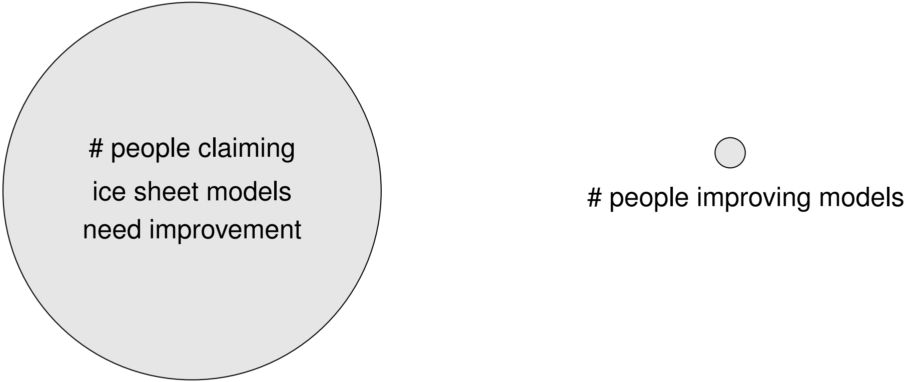


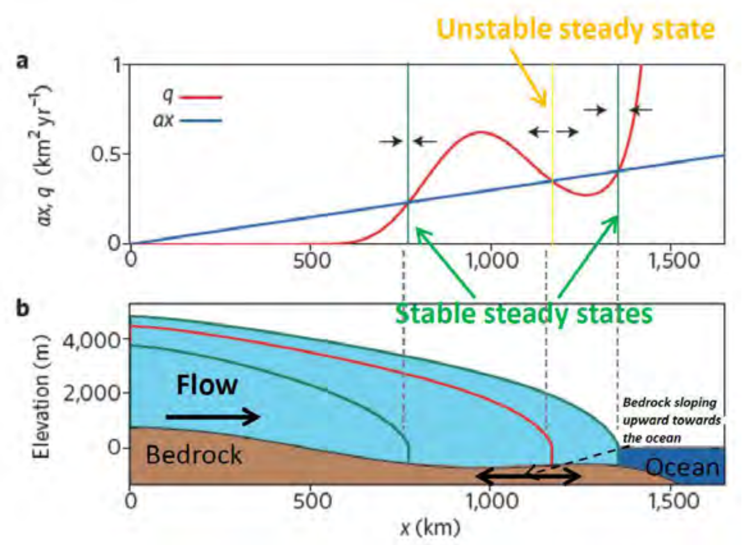
Figure 2: *Illustration of the reduction of the marine ice sheet problem. Step (a) to (b) shows the reduction of the full Stokes problem to regions where the sheet and the shelf mechanical approximations hold. The mechanical boundary layer need not be modelled because it is passive. We do not expect the thickness to be continuous, but we will in general not need to consider this because high slopes in the shelf at the grounding line will lead to a kinematical jump (step (b)- (c)). Where there is no passive grounding of the shelf, the marine ice sheet can be modelled as being shelfless (step (c)-(d)).*

- **Hindmarsh (1996)**: Passive role of ice shelves – neutral equilibrium for grounding lines (GL)
- **Vieli & Payne (2005)**: GL response highly dependent on spatial resolution
- **Pattyn et al. (2006)**: neutral equilibrium function of width of transition zone
- **Gladstone et al. (2010)**: further progress on interpolations around grounding lines

Dynamical processes related to ice flow not included in current models but suggested by recent observations could increase the vulnerability of the ice sheets to warming, increasing future sea level rise. Understanding of these processes is limited and there is no consensus on their magnitude. (***IPCC, AR4, 2007***)



Mathematical proof for MISI

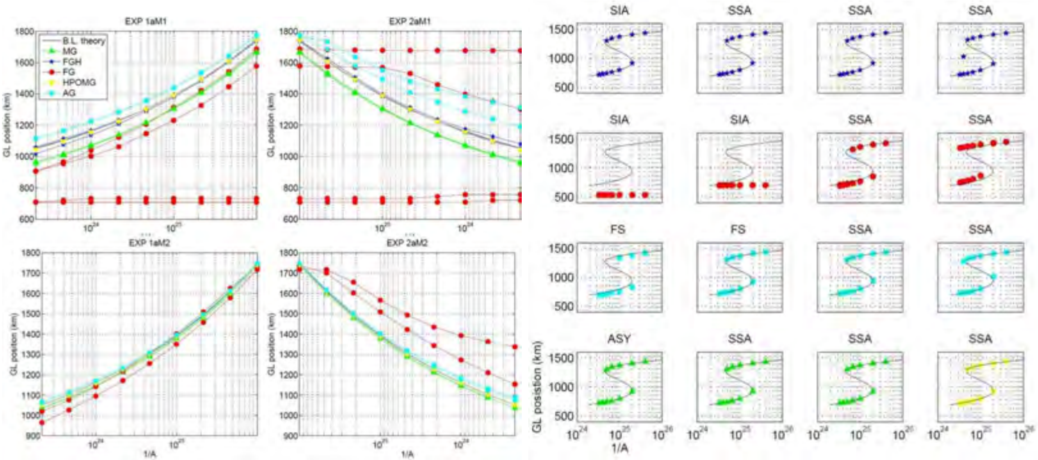


- Schoof (2006, 2007) qualitatively confirms Weertman (1974); Thomas and Bentley (1978)
- **GL is free boundary problem**: two independent conditions at moving boundary (one of which is flotation criterion)

$$\frac{\partial h}{\partial t} = \dot{a} - \frac{\partial (uh)}{\partial x} = 0$$

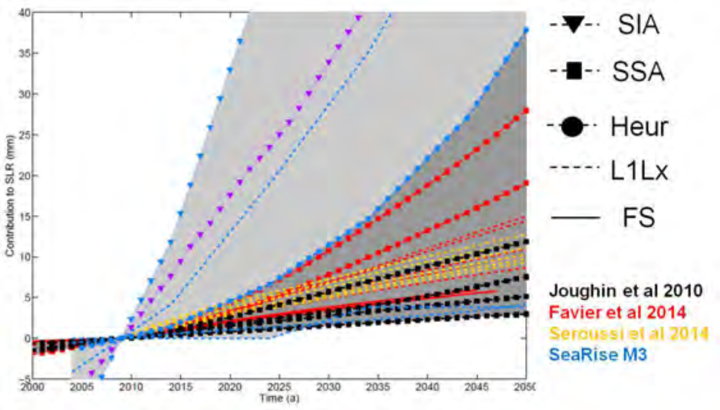
$$\Rightarrow q = \dot{a}x$$

MISMIP: unique GL positions and hysteresis

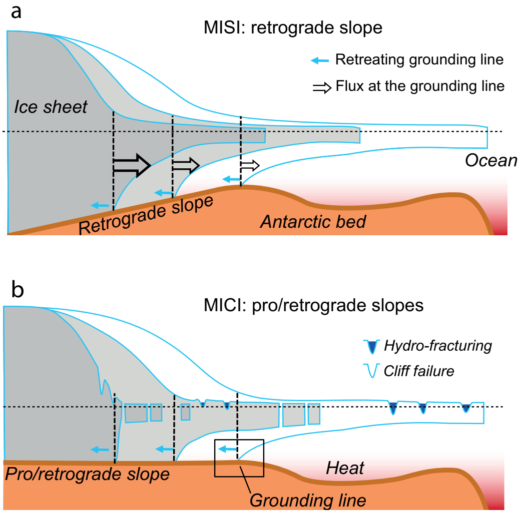


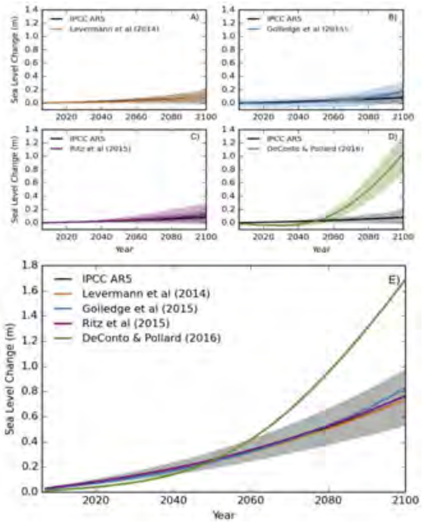
Pattyn et al. (2012)

Model improvements lead to reduced uncertainty (PIG)



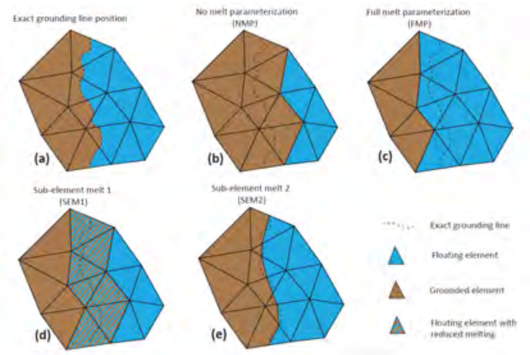
Durand and Pattyn (2015): Better understanding of GL behaviour led to reduced uncertainties in model response to forcing since AR5 (Pine Island Glacier)

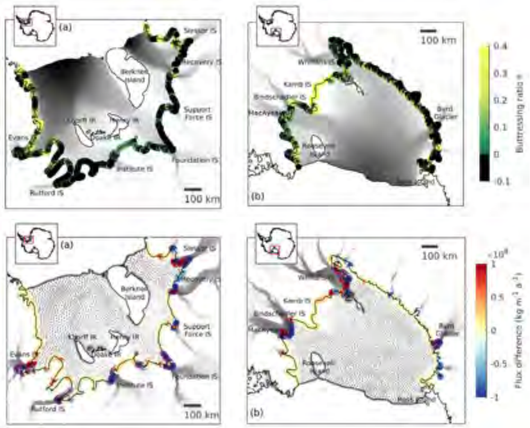




Difference between MISI (Marine Ice Sheet Instability) and MICI (Marine Ice Cliff Instability). MICI results in high-end SLR but is atmosphere-driven (not ocean); Pattyn et al. (2018); Vermeersen et al. (2018)

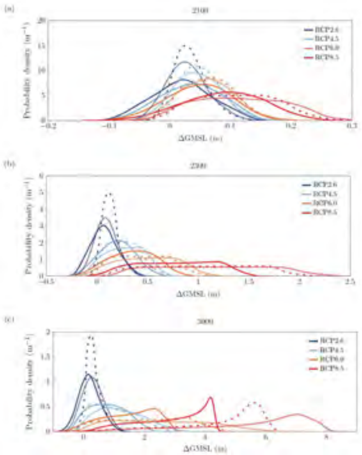
Numerical uncertainties

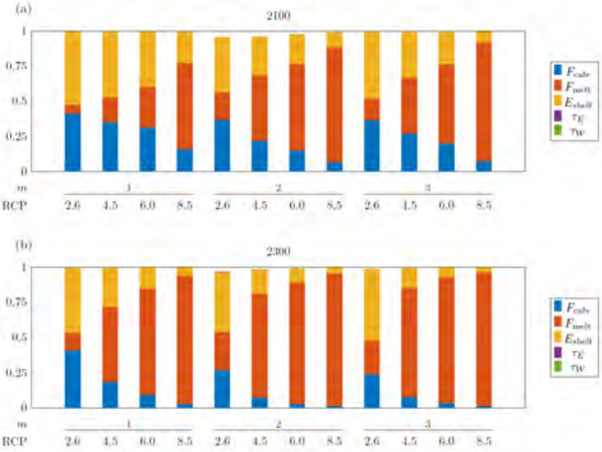




Seroussi and Morlighem (2018): Significant overestimation of the rate of GL retreat when melt is smeared out across the GL.
Reese et al (2018): Parametrization of buttressing may yield unphysical results (only diagnostic test).

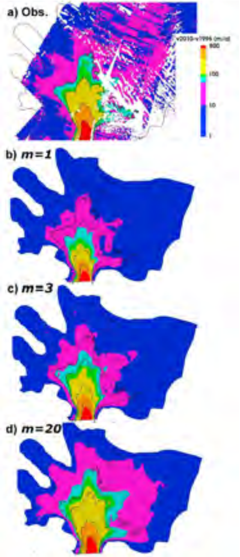
Physical parameter uncertainty

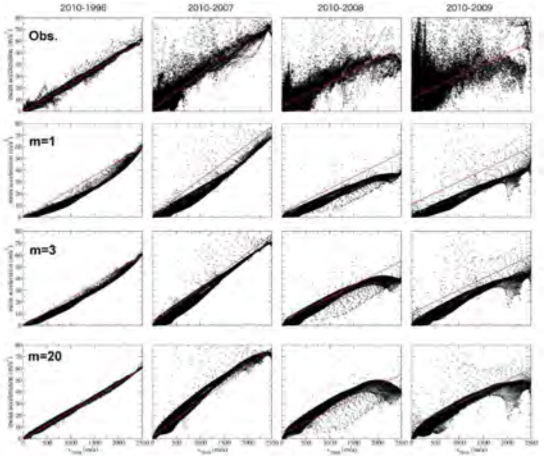




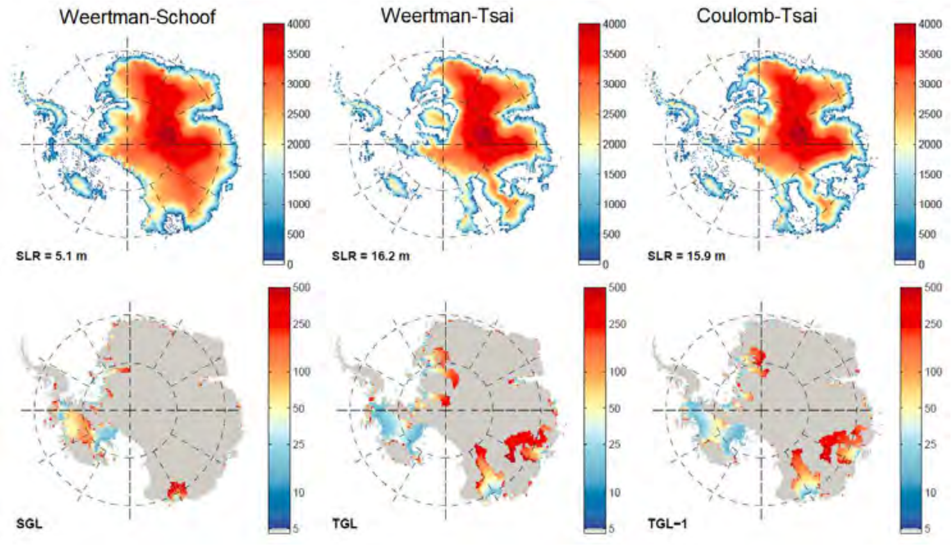
Bulthuis et al. (subm.): f.ETISh + emulators: Large sensitivity in response to basal conditions and the way sub-shelf melt relates to ocean conditions; complex PDFs

Improvements on model initialization



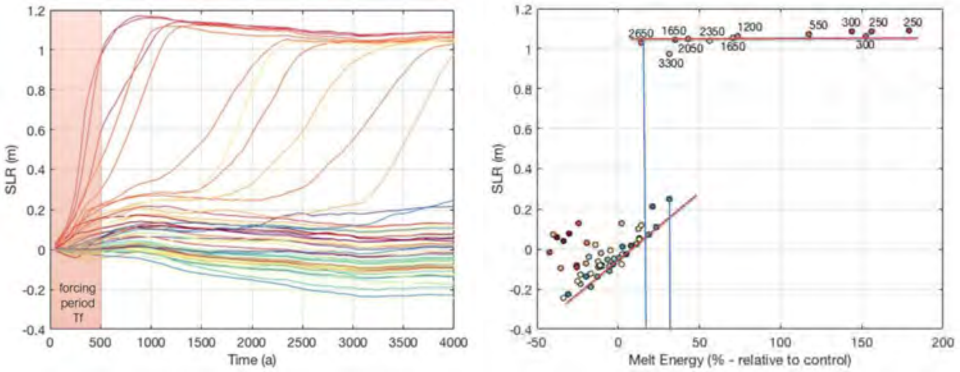


- Model initialization with observed surface velocities (assimilation)
- Test basal sliding law for best fit of observed changes in velocity (Gillet-Chaulet et al., 2016)
- PIG: plastic sliding law (m=5)



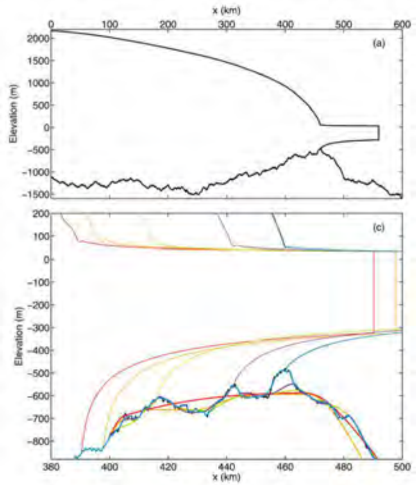
Pattyn (2017): abuk experiment: GL retreat rates are highly dependent on basal processes.

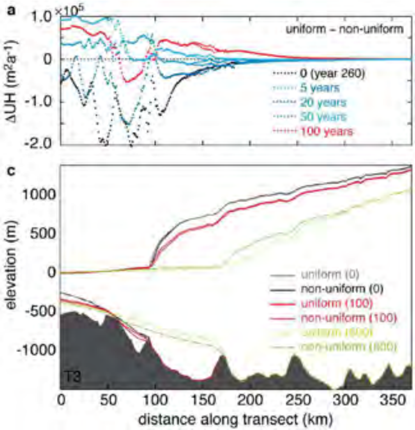
Tipping points of the Antarctic ice sheet



Applied forcing for restricted time periods (<500 year) — analysis of ice sheet response (ASE) on multi-millennial time scales. Some MISIs engage after >2500 years — >30% increase in melt energy irrevocably leads to MISI (Durand, Sun, Pattyn)

Effect of bedrock resolution





Durand et al. (2009); Waibel et al. (2018)

- Data collection and archiving (bed elevation, ice thickness, bathymetry) is essential for improving ISMs
- Gridded products are not always the most appropriate given adaptive grids/unstructured meshing

Conclusions

- **Paradigm shift** in ice sheet modelling from slow diffusive system to rapid (unstable) system and improved understanding of marine ice-sheet mechanics
- **Spread in response** still due to (i) uncertainties in boundary conditions and potential feedbacks; (ii) increased number of ice-sheet models; (iii) numerical uncertainties in models; (iv) bedrock/bathymetry uncertainties
- **MISMIPs** have a positive effect on model development:
  - Model ‘sorting’ based on how GL is represented becomes possible, reducing uncertainties present in SeaRISE
  - MISMIP tests are however not inclusive (lack of validation)
  - Further MISMIPs are on their way (MISMIP+, MISOMIP, InitMIP, ABUMIP, ...)
  - InitMIP: demonstrated importance of model initialization (data assimilation versus paleo-spinup)
- Short-term response remains hampered by these structural uncertainties, hampering **validation and hindcasting** of ISMs for short time predictions/projections