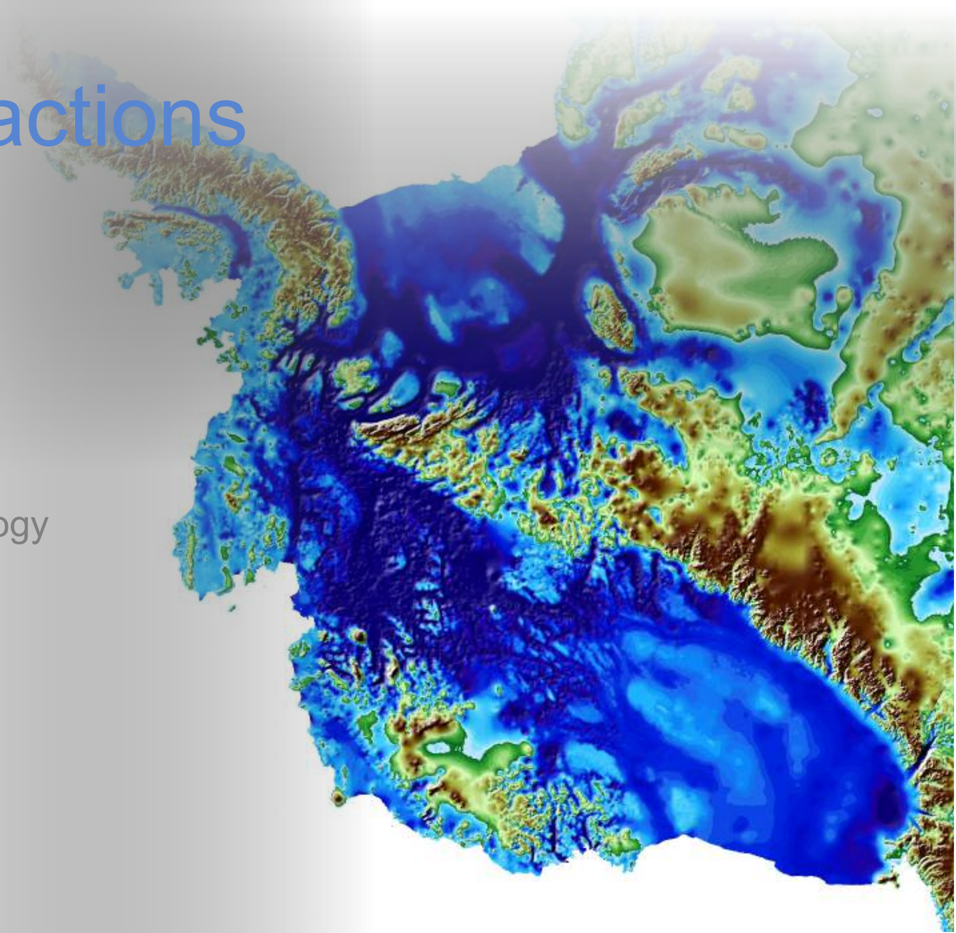
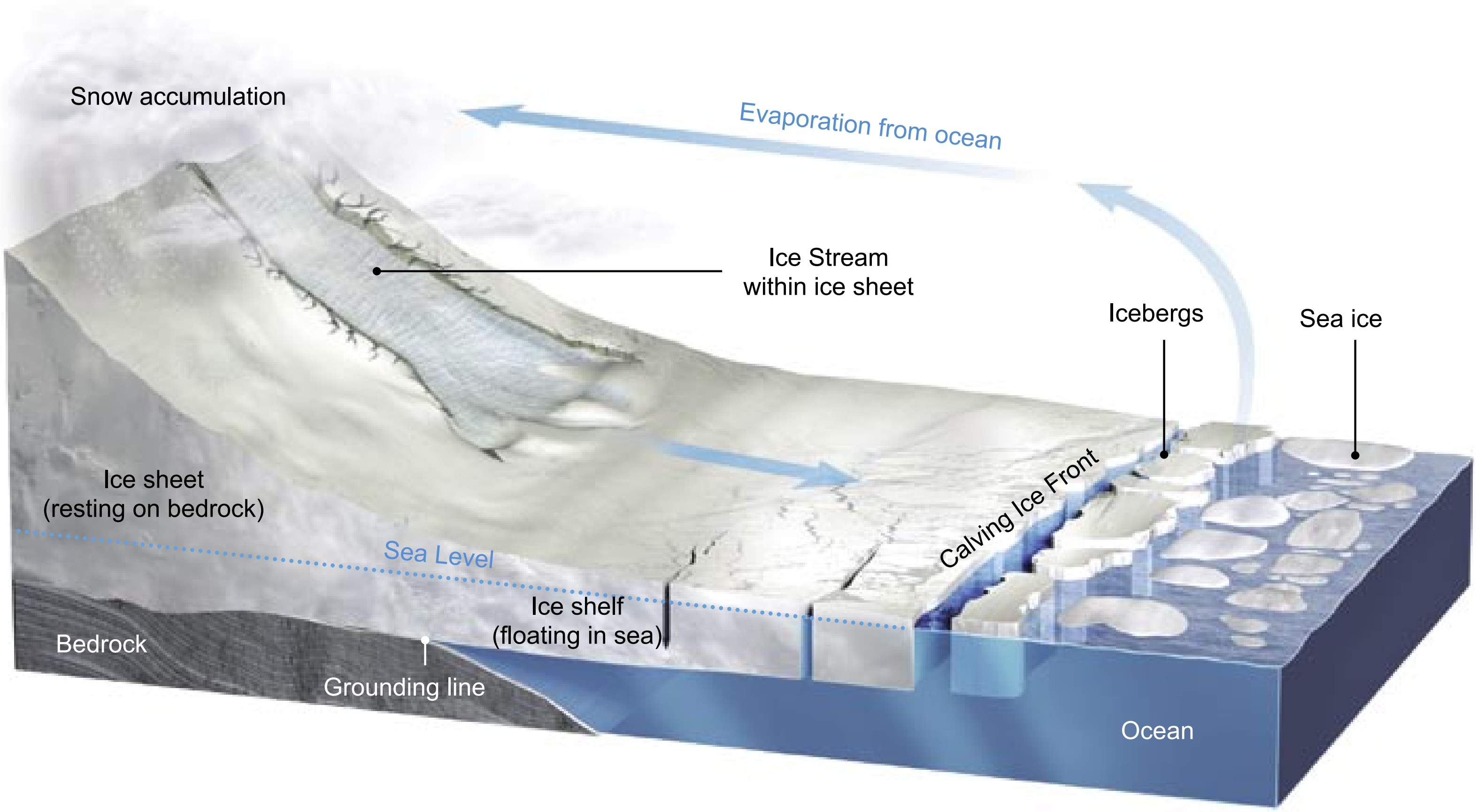
Modeling ice/ocean interactions



Hélène SEROUSSI

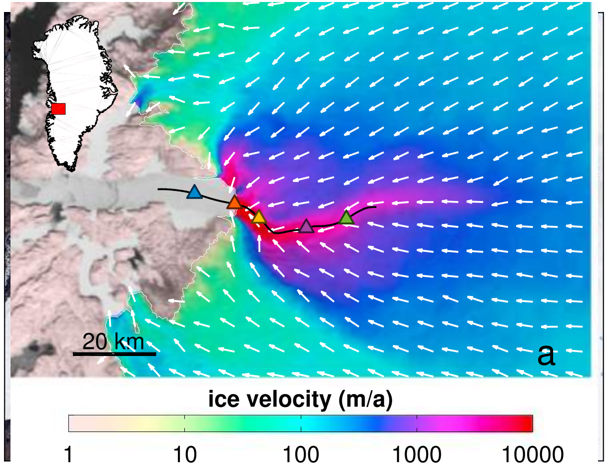
Jet Propulsion Laboratory - California Institute of Technology

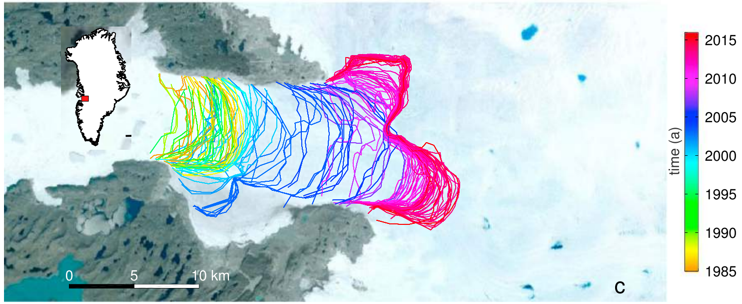
Introduction: ice sheets



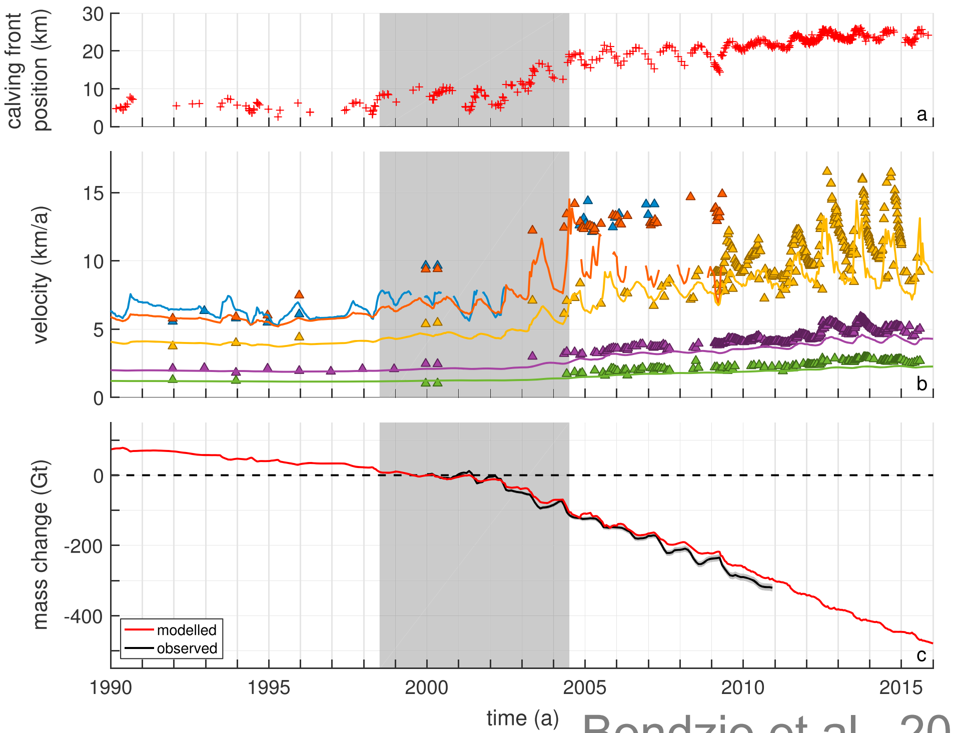
Jakobshavn Isbrae, West Greenland

Ice front retreat and glacier acceleration





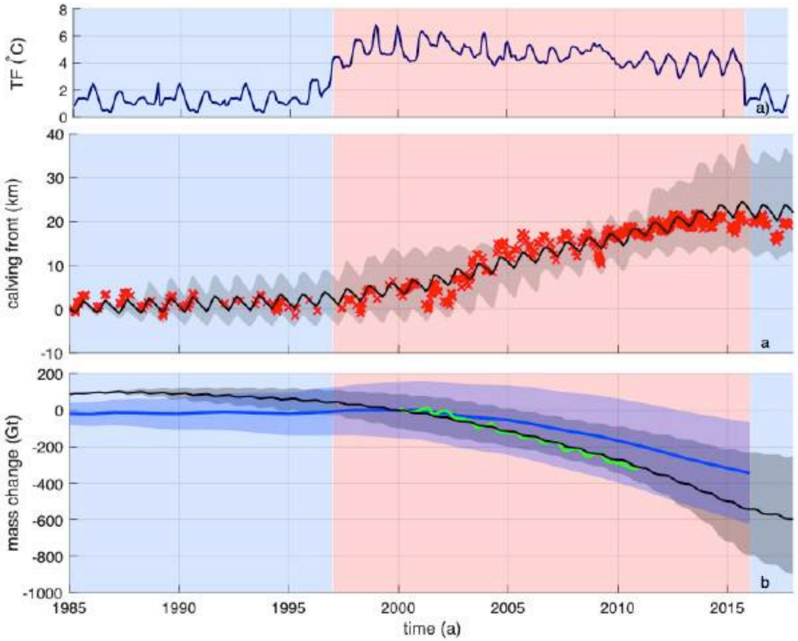
Modeled forced with ice front position



Bondzio et al., 2017

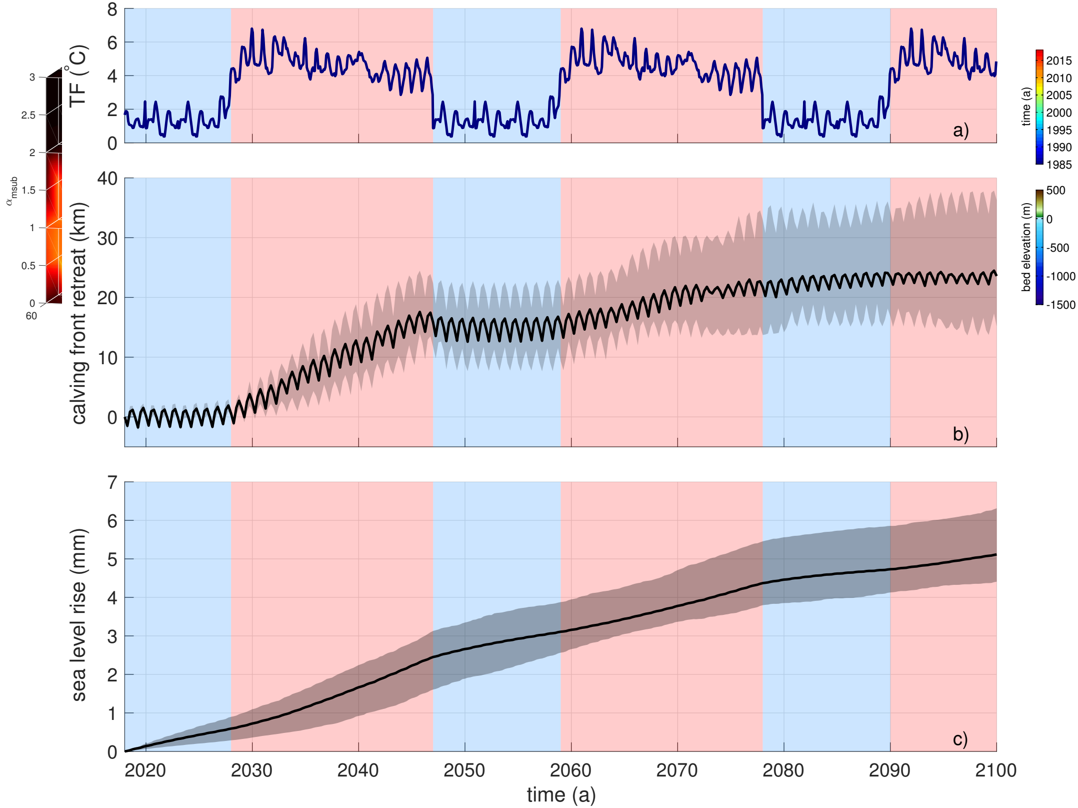
Jakobshavn Isbrae, West Greenland

Simulated ice front migration

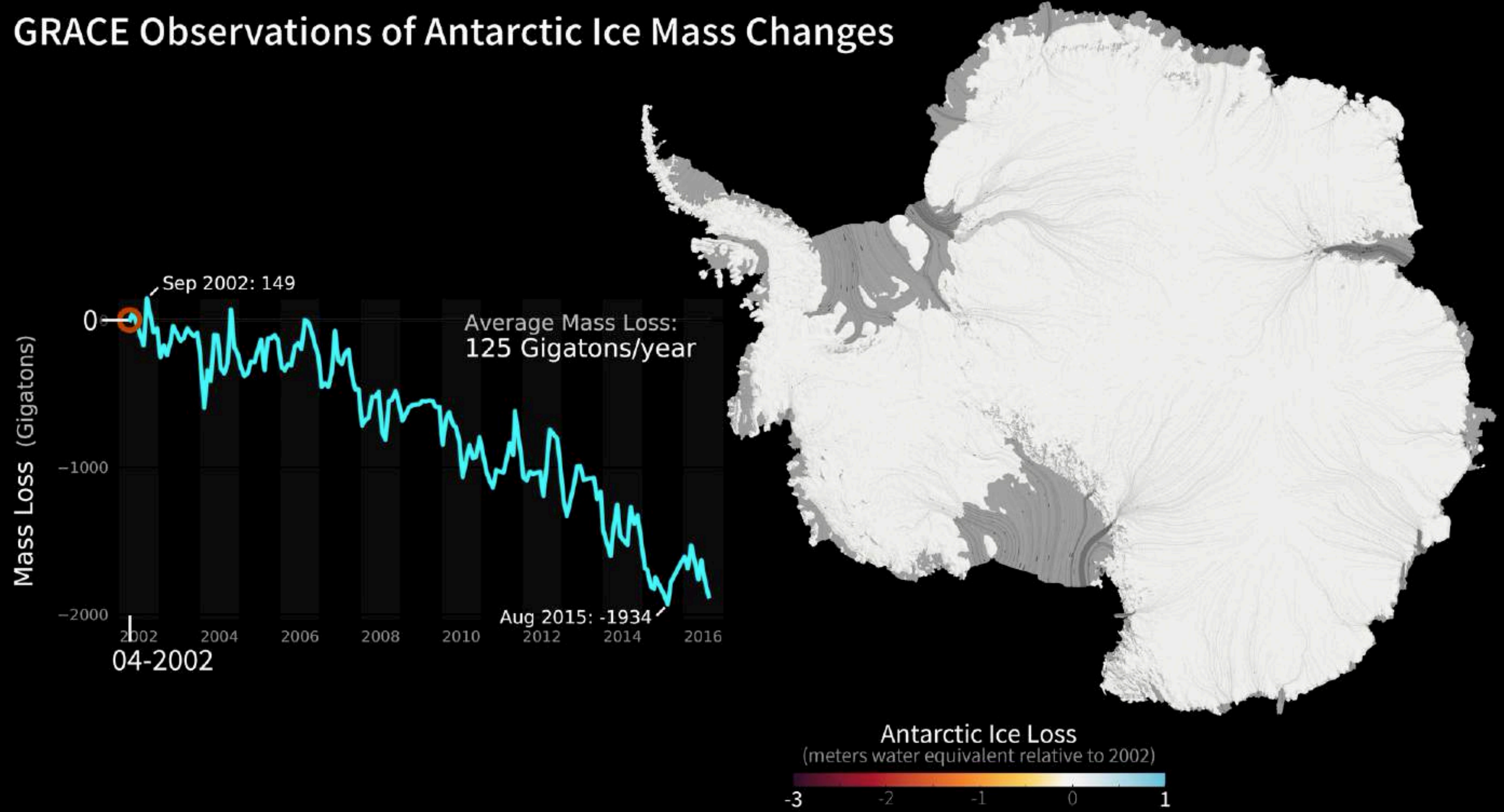


Bondzio et al., 2018

Ensemble for unknow parameters



GRACE Observations of Antarctic Ice Mass Changes



Outline

1. Modeling ice sheets and ice shelves
2. Ice shelves around Antarctica
3. Modeling ice shelf melt
4. Coupling ice and ocean models
5. Can we parameterize ice shelf melt?

Mass conservation

Continuity equation:

$$\frac{D\rho}{Dt} + \rho \, \nabla \cdot \mathbf{v} = 0$$

Incompressibility: a continuum is said to be incompressible if its density remains unchanged during motion

$$\frac{D\rho}{Dt} = 0$$

Mass balance of incompressible fluids:

$$\nabla \cdot \mathbf{v} = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0$$

Mass conservation

Incompressibility:

$$\nabla \cdot \mathbf{v} = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0$$

Surface evolution:

$$\frac{\partial s}{\partial t} + v_x(s)\frac{\partial s}{\partial x} + v_y(s)\frac{\partial s}{\partial y} - v_z(s) = \dot{M}_s$$

$$\frac{\partial b}{\partial t} + v_x(b)\frac{\partial b}{\partial x} + v_y(b)\frac{\partial b}{\partial y} - v_z(b) = \dot{M}_b$$

- s glacier surface elevation (m)
- b glacier base elevation (m)
- $\dot{M}_s$ surface mass balance (m/s ice equivalent, positive when accumulation)
- $\dot{M}_b$ basal mass balance (m/s ice equivalent, positive when melting)

Energy balance

Conservation of energy: $$\rho \frac{D}{Dt}(cT) = \nabla \cdot k_{th} \nabla T + \mathbf{\Phi}$$

- T ice temperature (K)
- c ice thermal conductivity (W/m/K)
- k_{th} ice heat capacity (J/K/kg)
- $\mathbf{\Phi} = \boldsymbol{\sigma} : \varepsilon$ deformational heating (W)

Ice energy balance:

$$\frac{\partial T}{\partial t} = -\mathbf{v} \cdot \nabla T + \frac{k_{th}}{\rho c} \Delta T + \frac{\mathbf{\Phi}}{\rho c}$$

Phase change included by capturing cold/temperate transition or using enthalpy formulations

Momentum balance

Conservation of momentum: $\rho\left(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v}\right) = \nabla\cdot\boldsymbol{\sigma} + \rho\mathbf{g} - 2\rho\Omega\times\mathbf{v}$

$$St\,\frac{\partial v^*}{\partial t^*} + (v^*\cdot\nabla^*)v^* = \frac{1}{Re}\frac{1}{\rho^*}\nabla^*\cdot\sigma^* + \frac{1}{Fr}g^* - \frac{1}{Ro}\,\Omega^*\times v^*$$

Variable	Glacier	Ice sheet	Ice stream
V_0	10^{-6}	10^{-5}	10^{-4}
G_0	10	10	10
R_0	10^4	10^6	10^5
Ω_0	10^{-4}	10^{-4}	10^{-4}
σ_0	10^5	10^5	10^5
ρ_0	10^3	10^3	10^3
T_0	R_0/V_0	R_0/V_0	R_0/V_0
St	1	1	1
Re	10^{-14}	10^{-12}	10^{-10}
Fr	10^{-17}	10^{-17}	10^{-14}
Ro	10^{-6}	10^{-7}	10^{-7}

$$St = \frac{R_0}{T_0 V_0}$$

$$Re = \frac{\rho_0 V_0^2}{\sigma_0}$$

$$Fr = \frac{V_0^2}{R_0 G_0}$$

$$Ro = \frac{V_0}{2\Omega_0 R_0}$$

Stokes flow: $\nabla\cdot\boldsymbol{\sigma} + \rho\mathbf{g} = 0$

Momentum balance

Incompressible viscous fluid: $\boldsymbol{\sigma}' = 2\mu\boldsymbol{\varepsilon}$

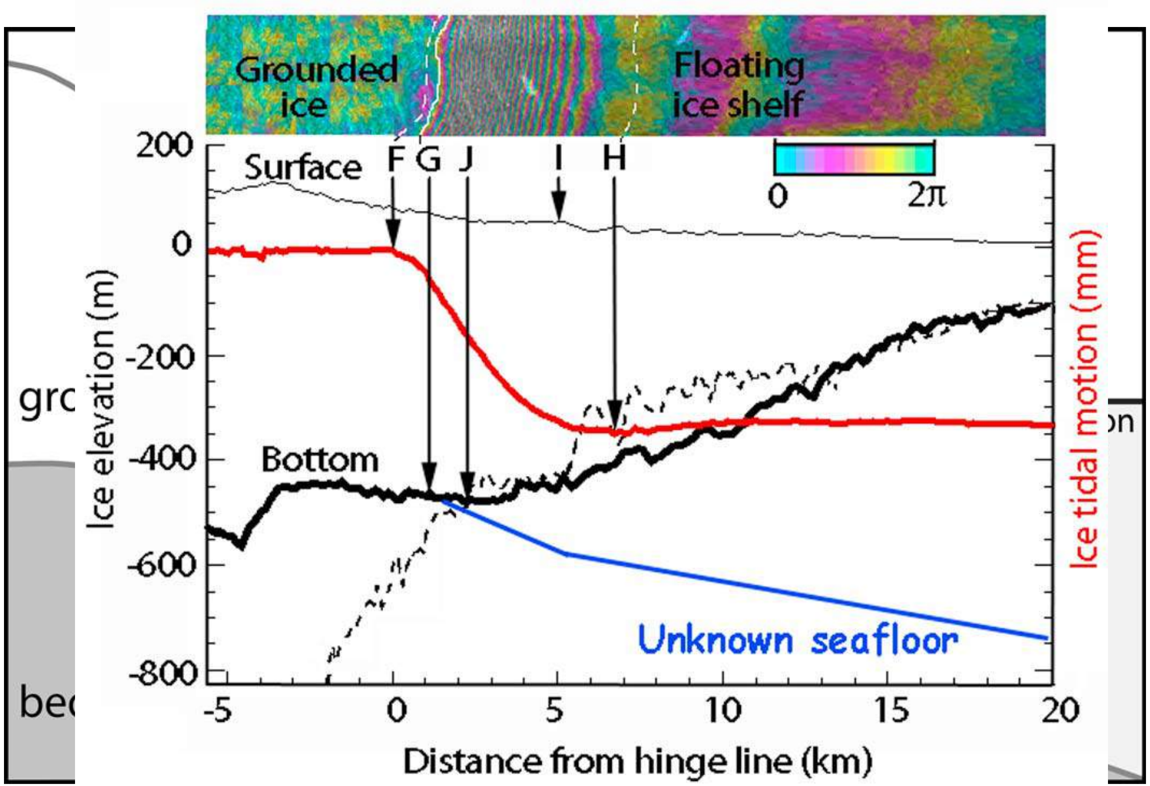
Glen's flow law (1955): $$\mu = \frac{B}{2\dot{\varepsilon}_e^{1-1/n}}$$

Boundary conditions:

- Ice/air interface: free surface $\boldsymbol{\sigma} \cdot \boldsymbol{n} \simeq 0$
- Ice/ocean interface: water pressure $\boldsymbol{\sigma} \cdot \boldsymbol{n} = P_w \boldsymbol{n}$
- Ice/bedrock interface: $$\left(\boldsymbol{\sigma} \cdot \boldsymbol{n} + \alpha^2 \mathbf{v}\right)_{||} = \mathbf{0}$$ $$\mathbf{v} \cdot \mathbf{n} = -\dot{M}_b n_z$$

Shallow aspect ratio: Shallow ice approximations (shallow ice and shallow shelf) to separate horizontal and vertical motion

Grounding line or grounding zone?



F: landward limit of ice flexure from tidal movement
G: limit of ice floatation (grounding line)
I_b: break-in slope
I_m: local elevation minimum
H: seaward limit of ice flexure from tidal movement

Rignot et al., 2019

Grounding line migration

Contact problem

- Full-Stokes stress balance
- Boundary condition:
  Ice/bedrock if:

$$z_b(x,t) = b(x) \quad \text{and} \quad -\sigma_{nn}|_b > p_w(z_b,t)\,,$$

Ice/water if:

$$z_b(x,t) > b(x)\,,$$

$$\text{or} \quad z_b(x,t) = b(x) \quad \text{and} \quad -\sigma_{nn}|_b \leq p_w(z_b,t)\,,$$

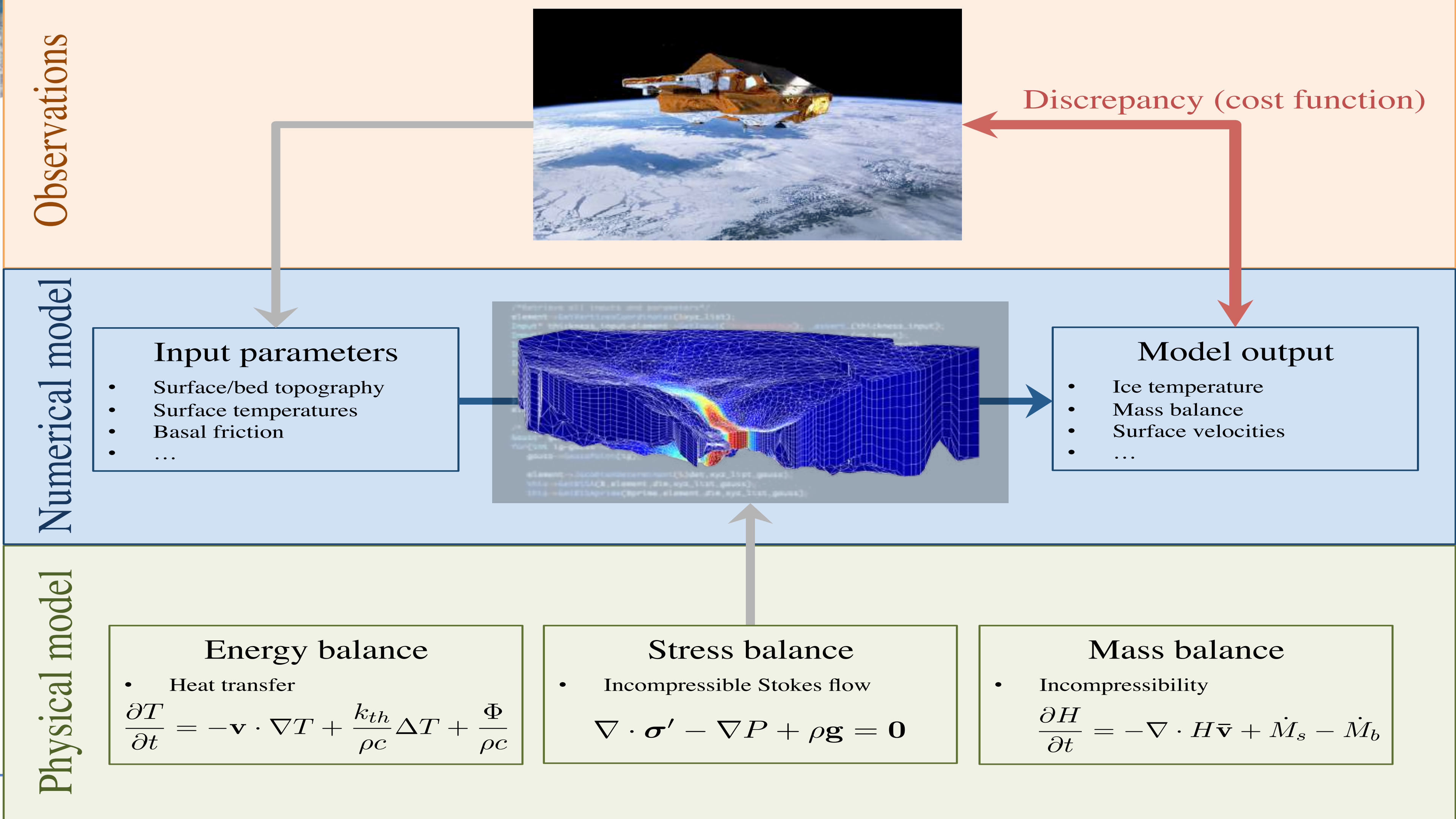
Hydrostatic assumption

- Simplified stress balance
- Hydrostatic condition:
  Hydrostatic thickness:

$$H_f = -\frac{\rho_w}{\rho_i} r, \quad r < 0,$$

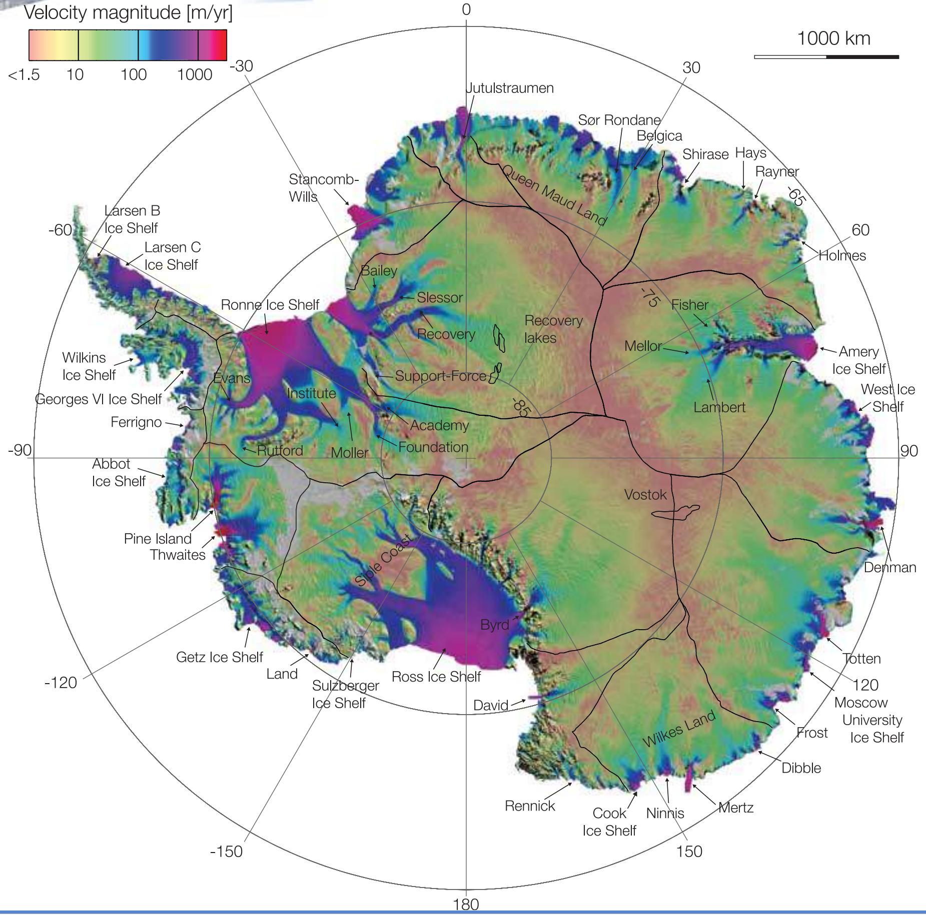
$$\begin{aligned} H &> H_f \quad \text{ice is grounded,} \\ H &= H_f \quad \text{grounding line position,} \\ H &< H_f \quad \text{ice is floating.} \end{aligned}$$

- Very high resolution required in the grounding line area

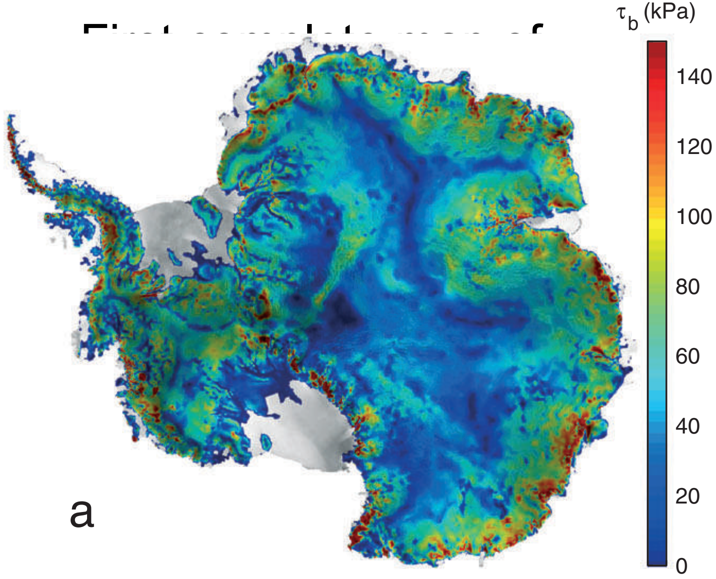


Observations
Discrepancy (cost function)
Numerical model
Input parameters
Surface/bed topography
Surface temperatures
Basal friction
...
Model output
Ice temperature
Mass balance
Surface velocities
...
Physical model
Energy balance
Heat transfer
$\frac{\partial T}{\partial t} = -\mathbf{v} \cdot \nabla T + \frac{k_{th}}{\rho c} \Delta T + \frac{\Phi}{\rho c}$
Stress balance
Incompressible Stokes flow
$\nabla \cdot \boldsymbol{\sigma}' - \nabla P + \rho \mathbf{g} = \mathbf{0}$
Mass balance
Incompressibility
$\frac{\partial H}{\partial t} = -\nabla \cdot H \bar{\mathbf{v}} + \dot{M}_s - \dot{M}_b$

Antarctic ice flow



Basal friction



Morlighem et al., 2013

Rignot et al., 2011

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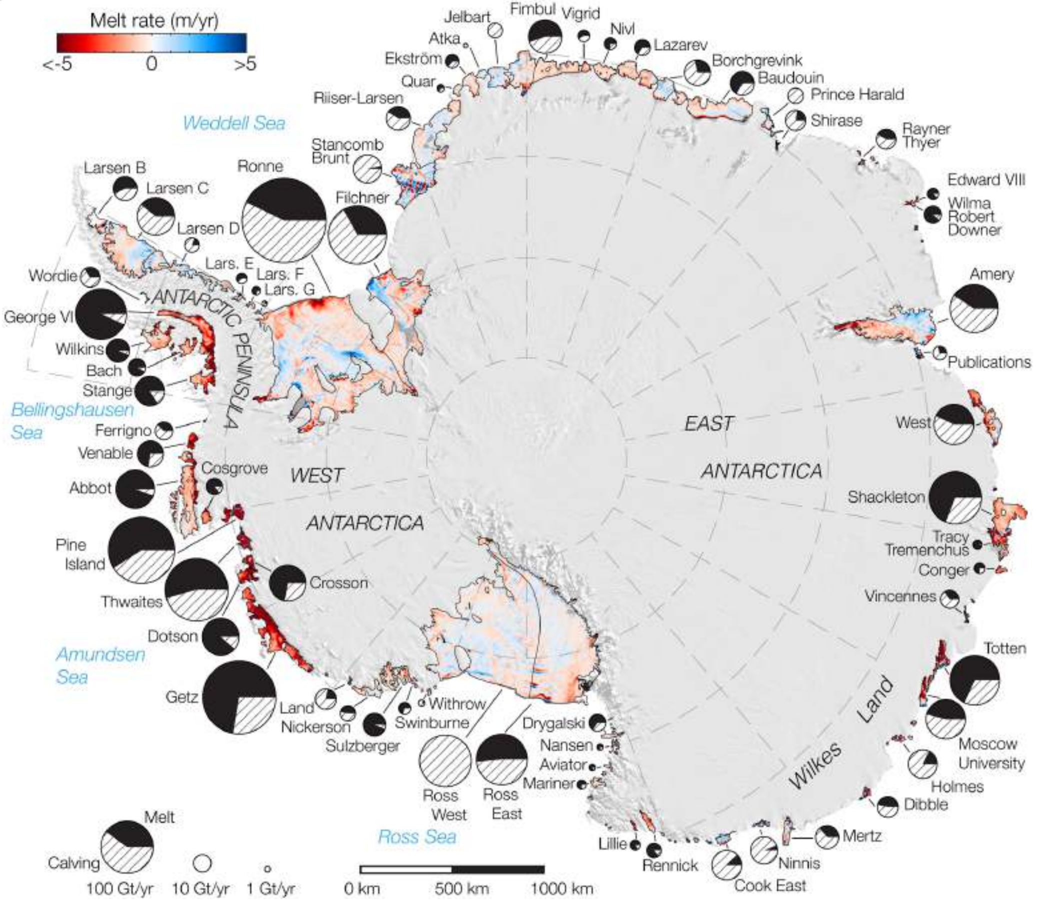
Ice shelves around Antarctica



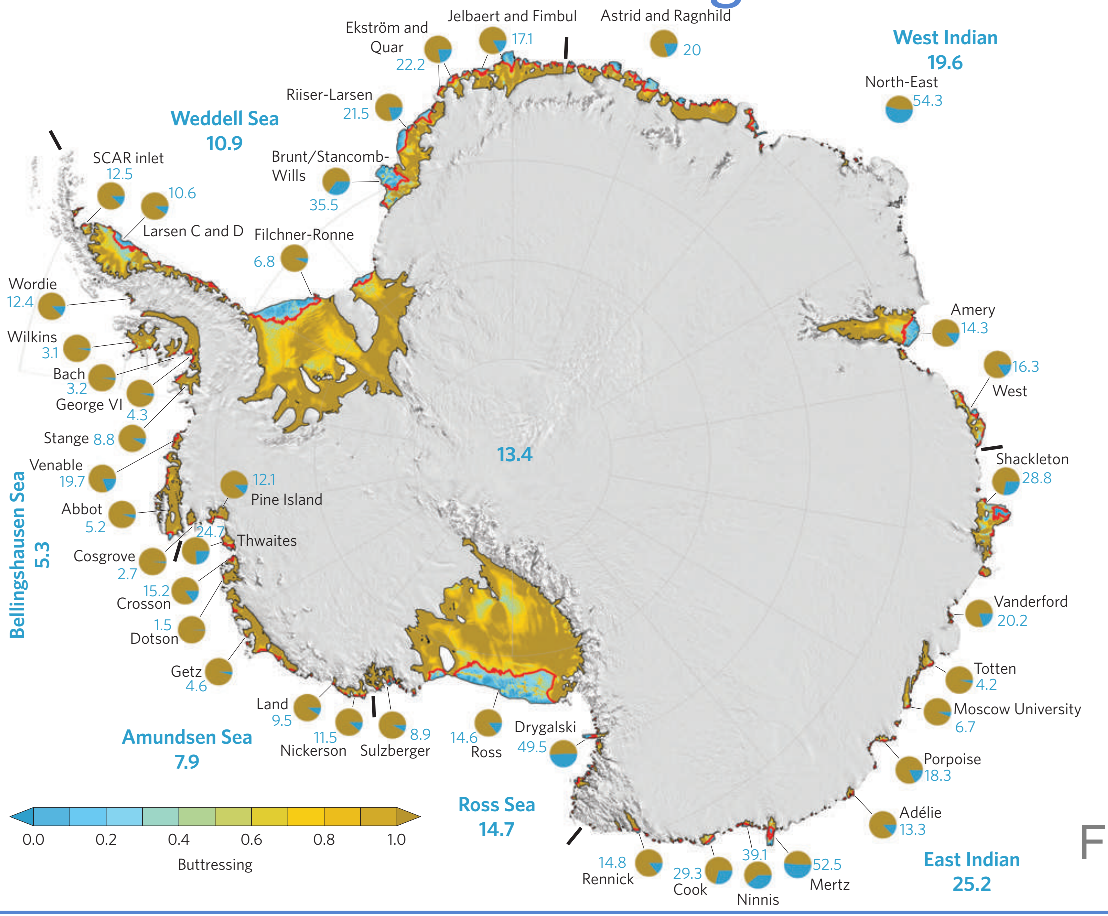
- Limited direct observations
- Melt rate estimates:

$$\frac{\partial H}{\partial t} + \nabla \cdot H\bar{\mathbf{v}} = \dot{M}_s - \dot{M}_b$$

- Equal contribution of calving and melting (∼1300 Gt/yr)
- Similar results in Depoorter et al. (2013)
- Variety of ice shelves (size, melt rate, calving rate, …)

Rignot et al., 2013

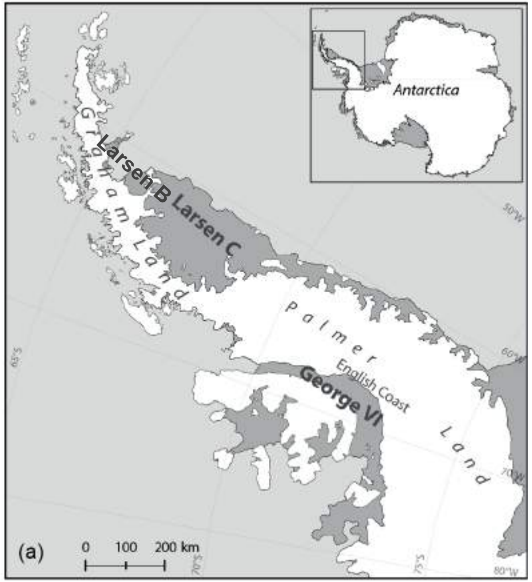
Ice shelf buttressing

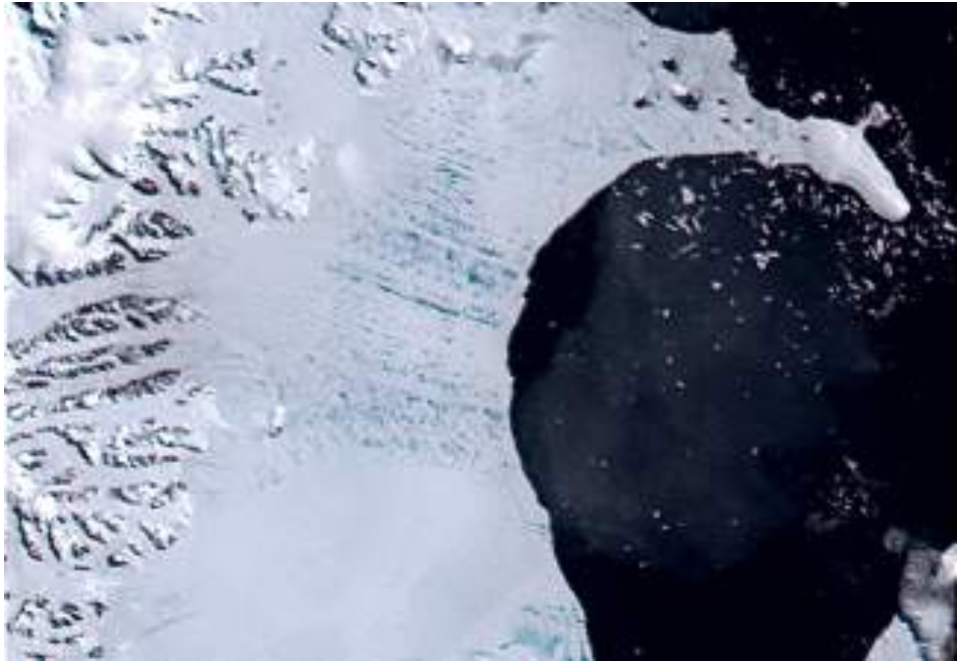


Fuerst et al., 2016

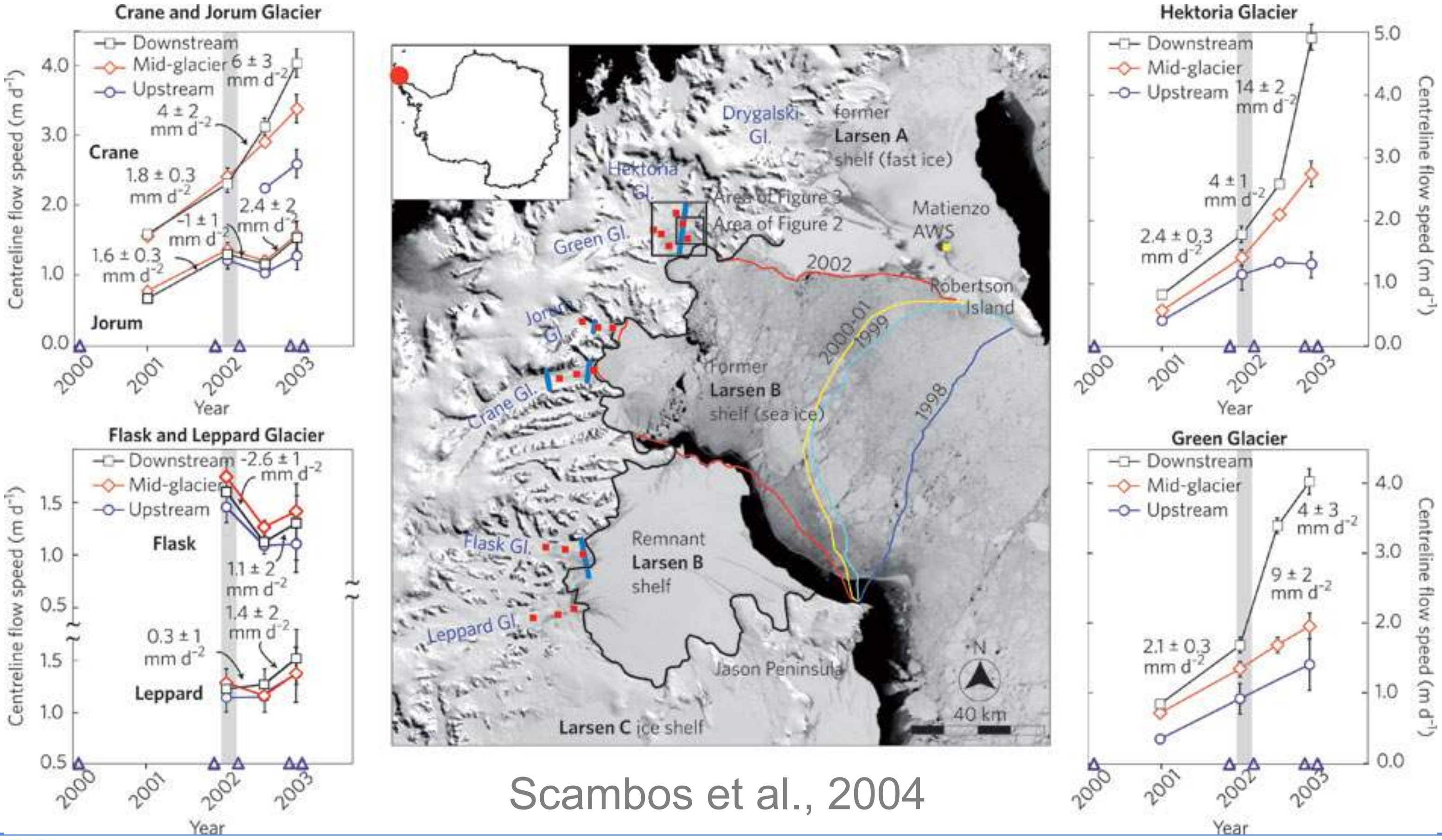
Larsen B breakup: a natural experiment

Larsen B break-up in 2002





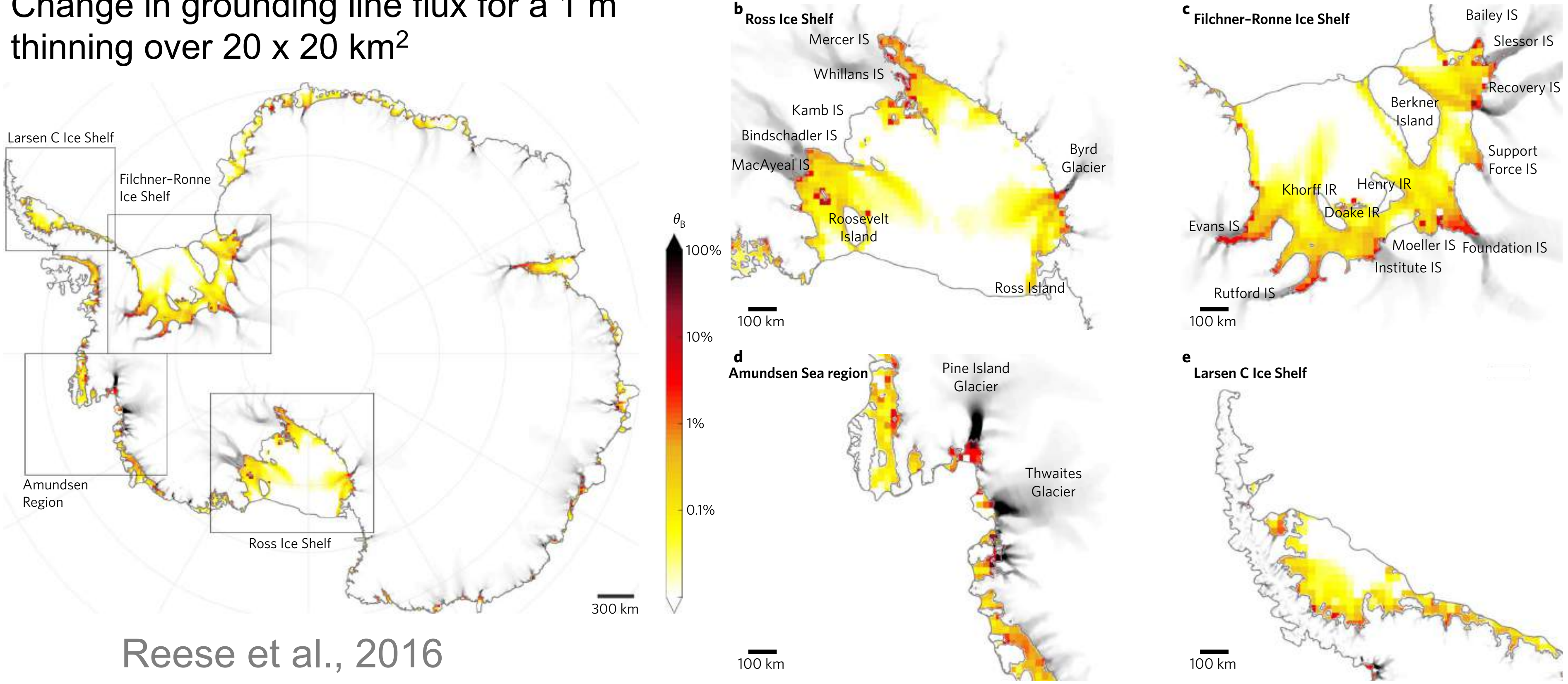
Larsen B breakup: a natural experiment



Scambos et al., 2004

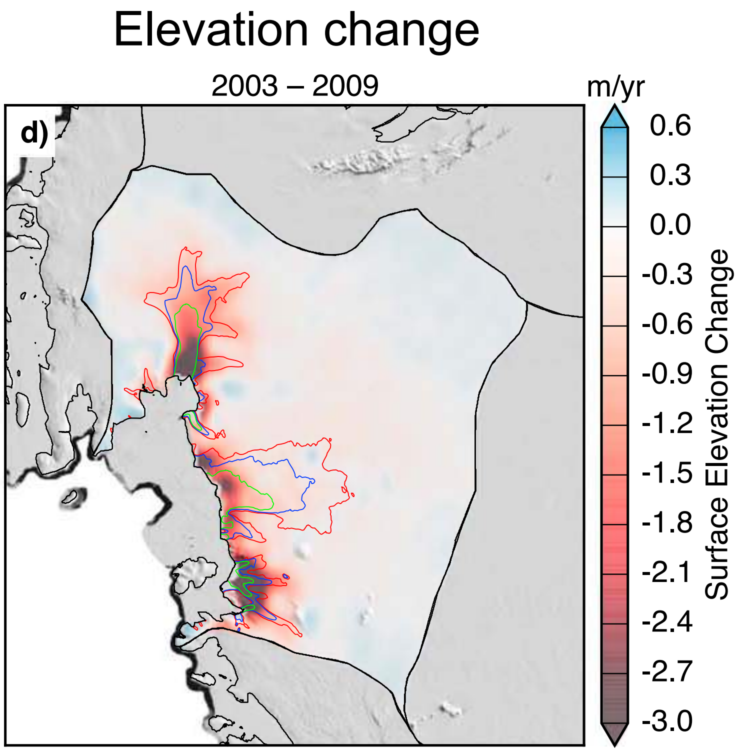
Impact of ice shelf melt

Change in grounding line flux for a 1 m thinning over 20 x 20 km^2

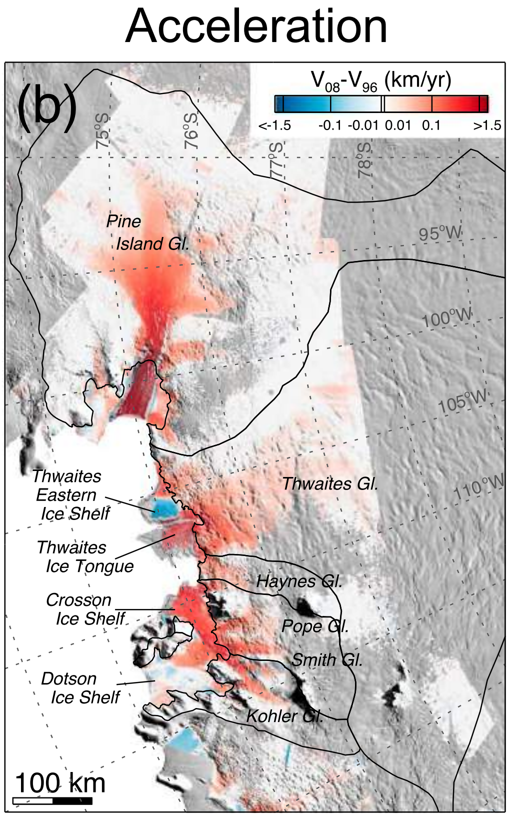


Reese et al., 2016

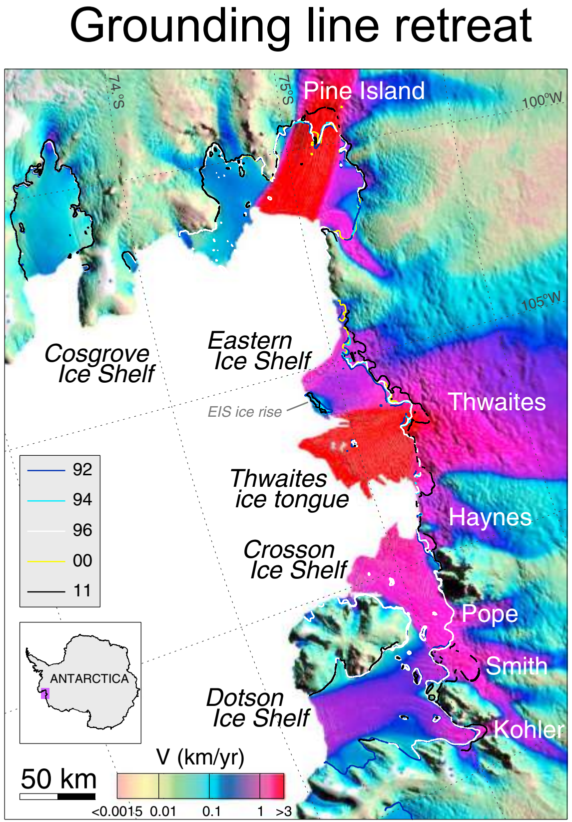
Observed changes in the Amundsen Sea



Sutterley et al., 2014



Mouginot et al., 2014



Rignot et al., 2014

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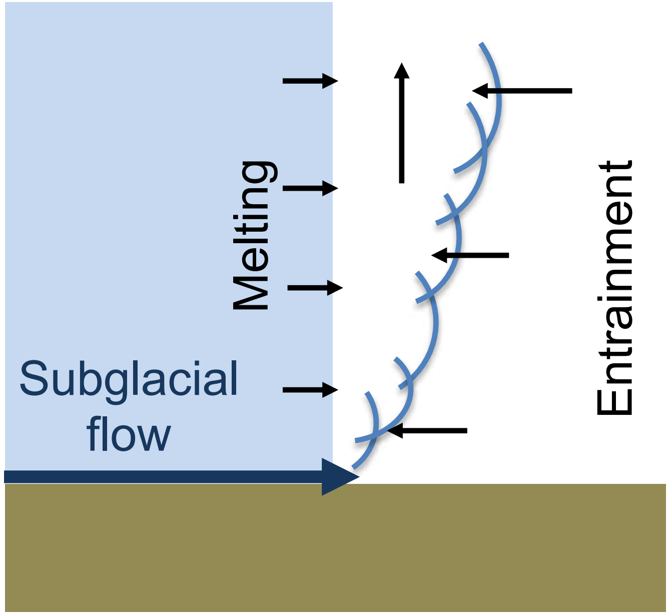
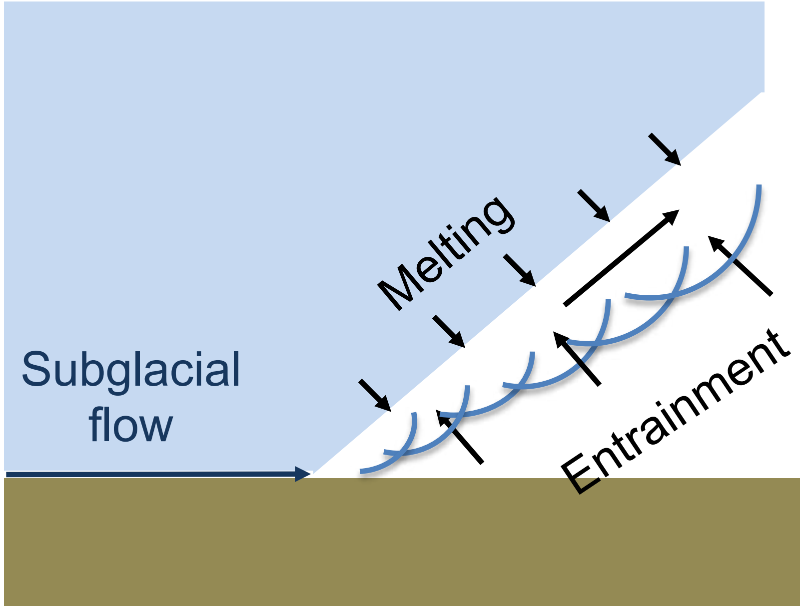
Ice/ocean interactions

Greenland tidewater glacier



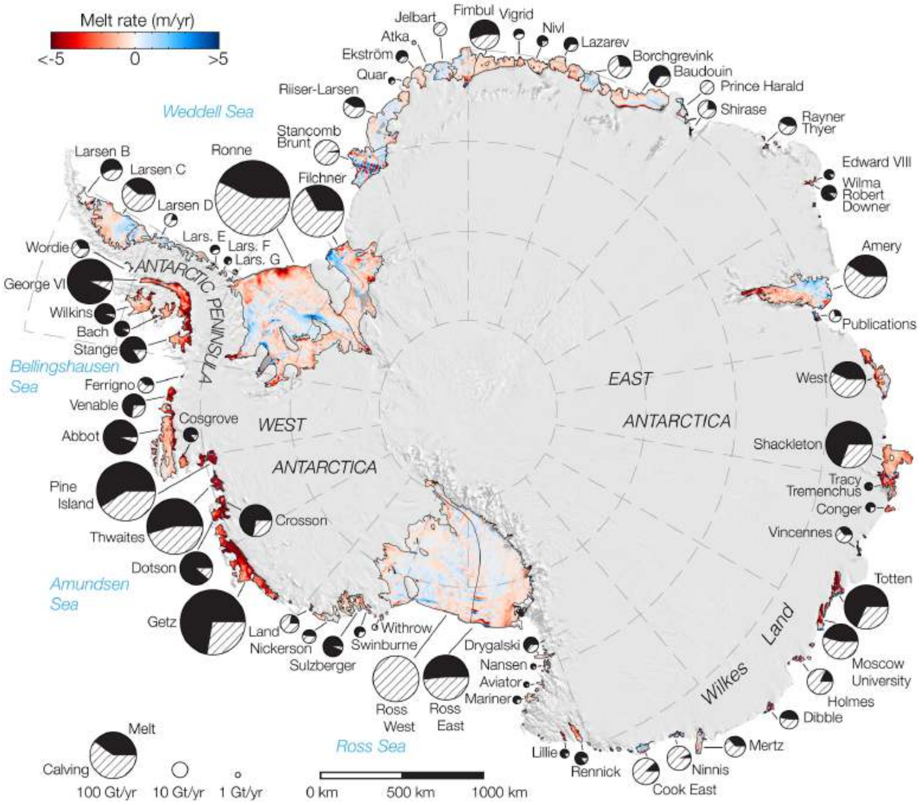
- Near vertical face
- Large amount of subglacial runoff with strong seasonal signal
- Small systems (1 kms)

Antarctic Ice shelf

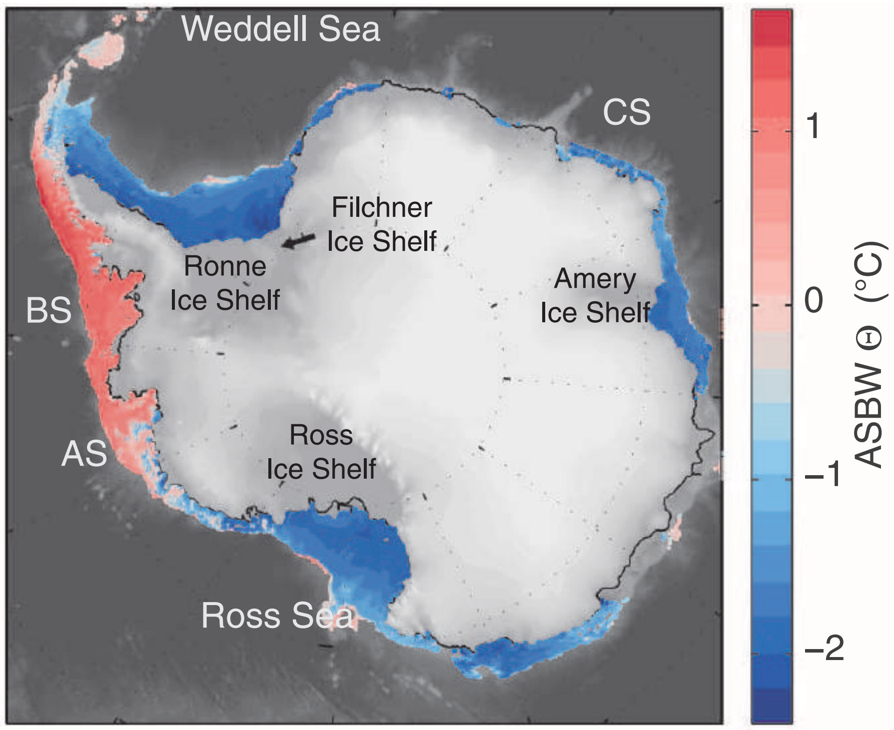


- Near horizontal face
- Limited amount of subglacial runoff with no seasonal signal
- Large systems (100 kms)

Southern Ocean

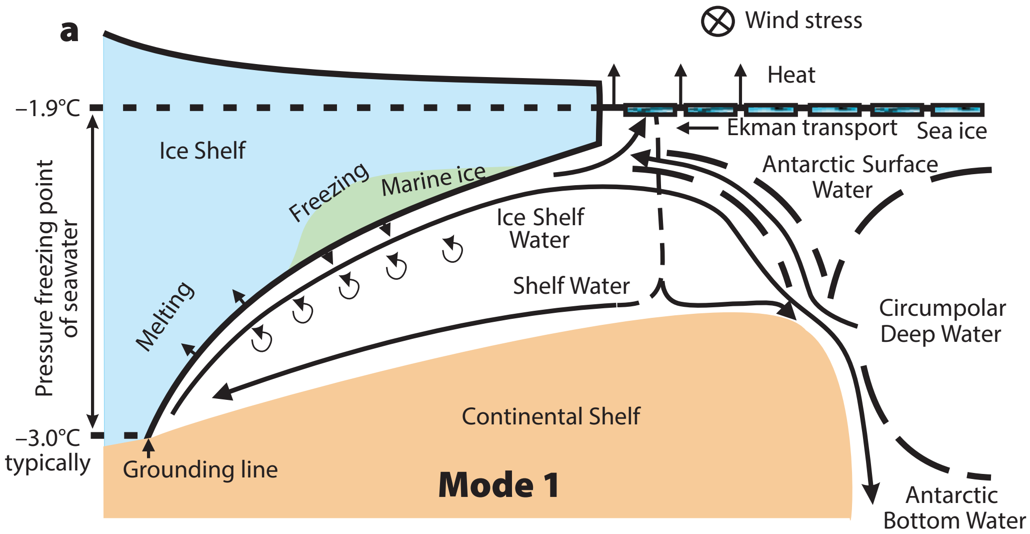


Rignot et al., 2013



Schmidtko et al., 2014

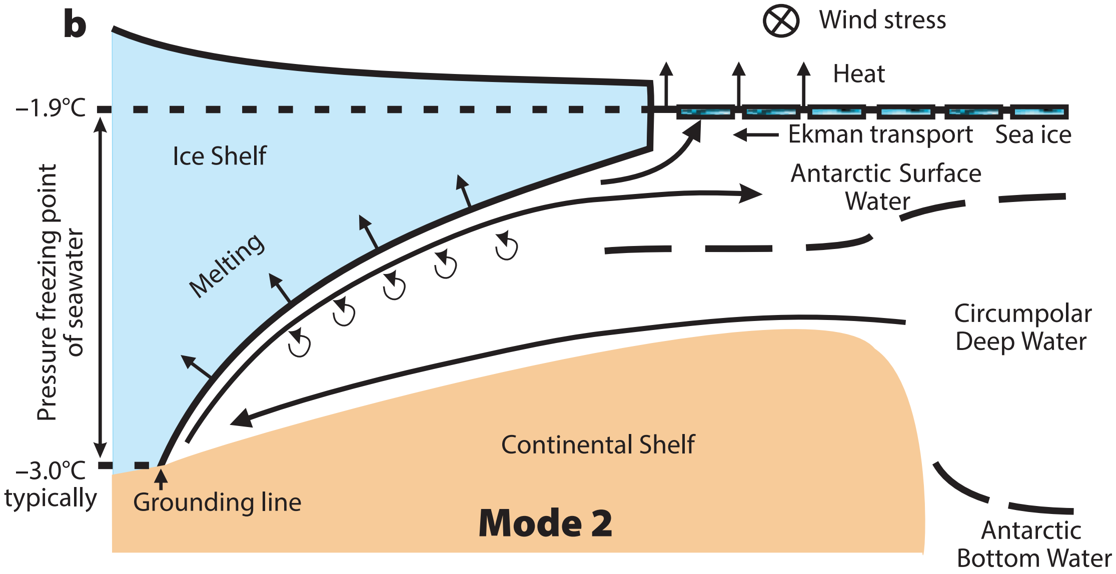
Cold ice shelves



- Dense Shelf Water dominates in sub-ice cavity
- Shelf Water has temperature close to the surface freezing point
- Brine rejection during sea ice growth
- Pressure dependence of the freezing point so melt at depth
- Refreezing occurs as water produced by melting becomes supercooled as it rises
- Ross/Weddell Sea

Jenkins et al., 2016

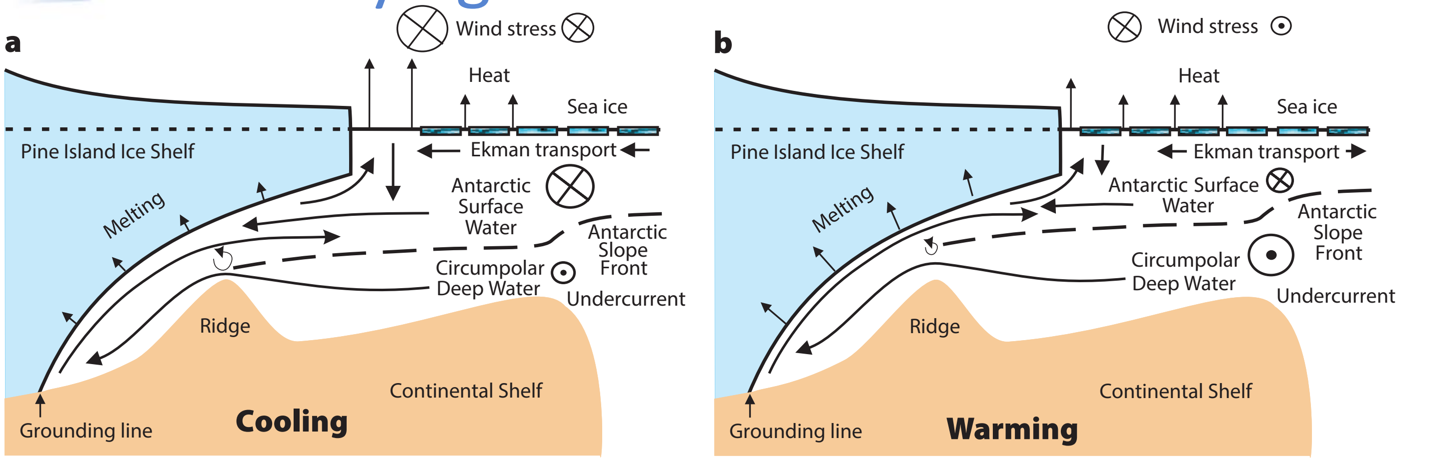
Warm ice shelves

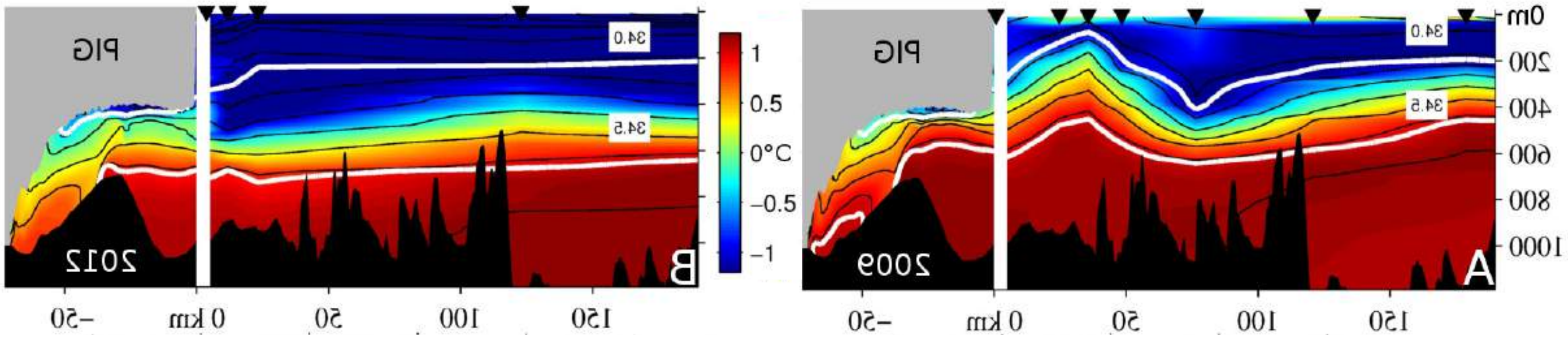


Jenkins et al., 2016

- No Shelf Water
- Circumpolar Deep Water densest water on the shelf
- Circumpolar Deep Water around 3°C above the surface freezing
- Rapid melting
- No refreezing
- Amundsen/Bellingshausen Seas

Varying ocean conditions





Dutrieux et al., 2014

Ice shelf melt from an ocean model

Three equations model (Jenkins et al., 2010)

- Heat balance at the phase change interface

$$\rho_i m L_i = \rho_i c_i \kappa_i \left.\frac{\partial T_i}{\partial z}\right|_b - \rho_w c_w \gamma_T \left(T_f - T_w\right)$$

- Freezing point of sea water

$$T_f = aS_b + b + cz_b$$

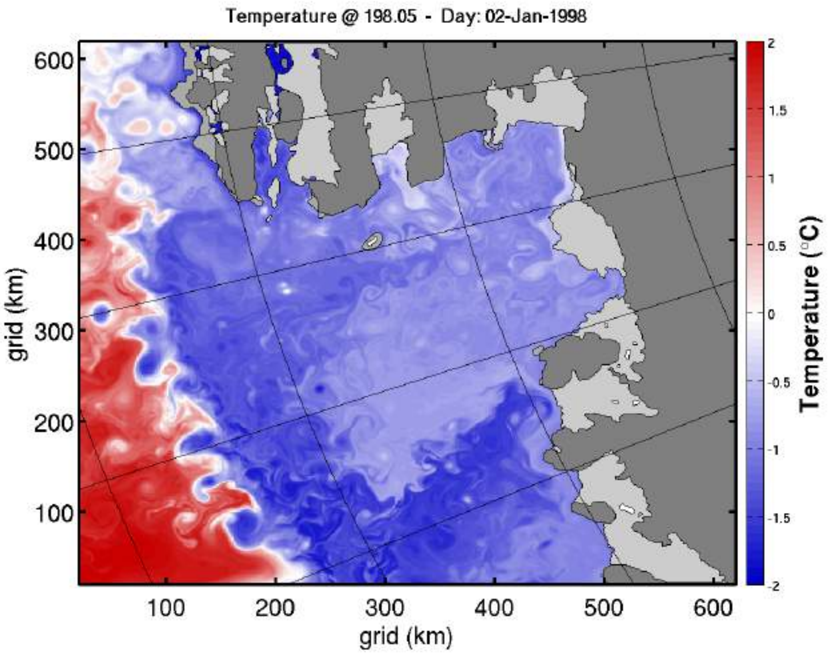
- Salt balance at the phase change interface

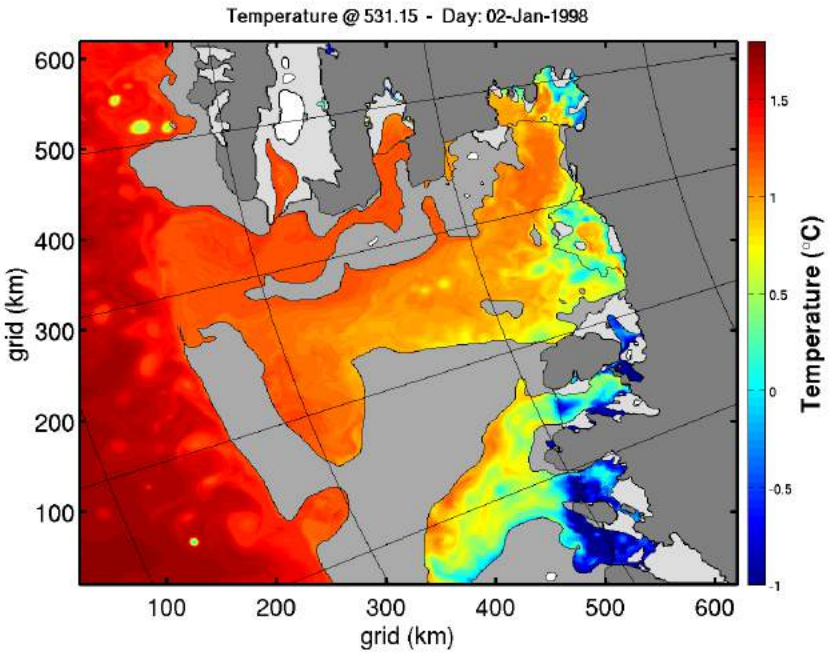
$$\rho_i m \left(S_b - S_i\right) = -\rho_w \gamma_S \left(S_b - S_w\right)$$

- Velocity dependent heat and salt exchange coefficients

$$\gamma_T = \Gamma_T \sqrt{C_d \left(u_b^2 + u_{tide}^2\right)} \qquad \gamma_S = \Gamma_S \sqrt{C_d \left(u_b^2 + u_{tide}^2\right)}$$

Ocean circulation

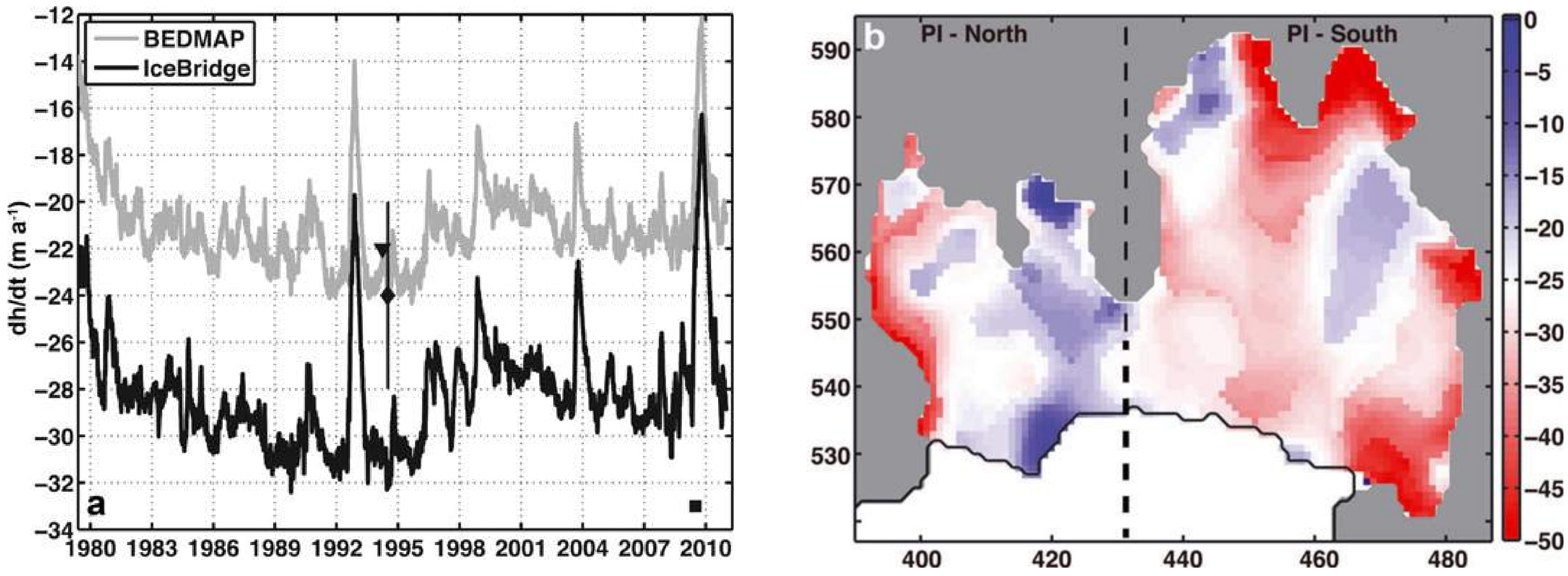




Schodlok et al., 2012

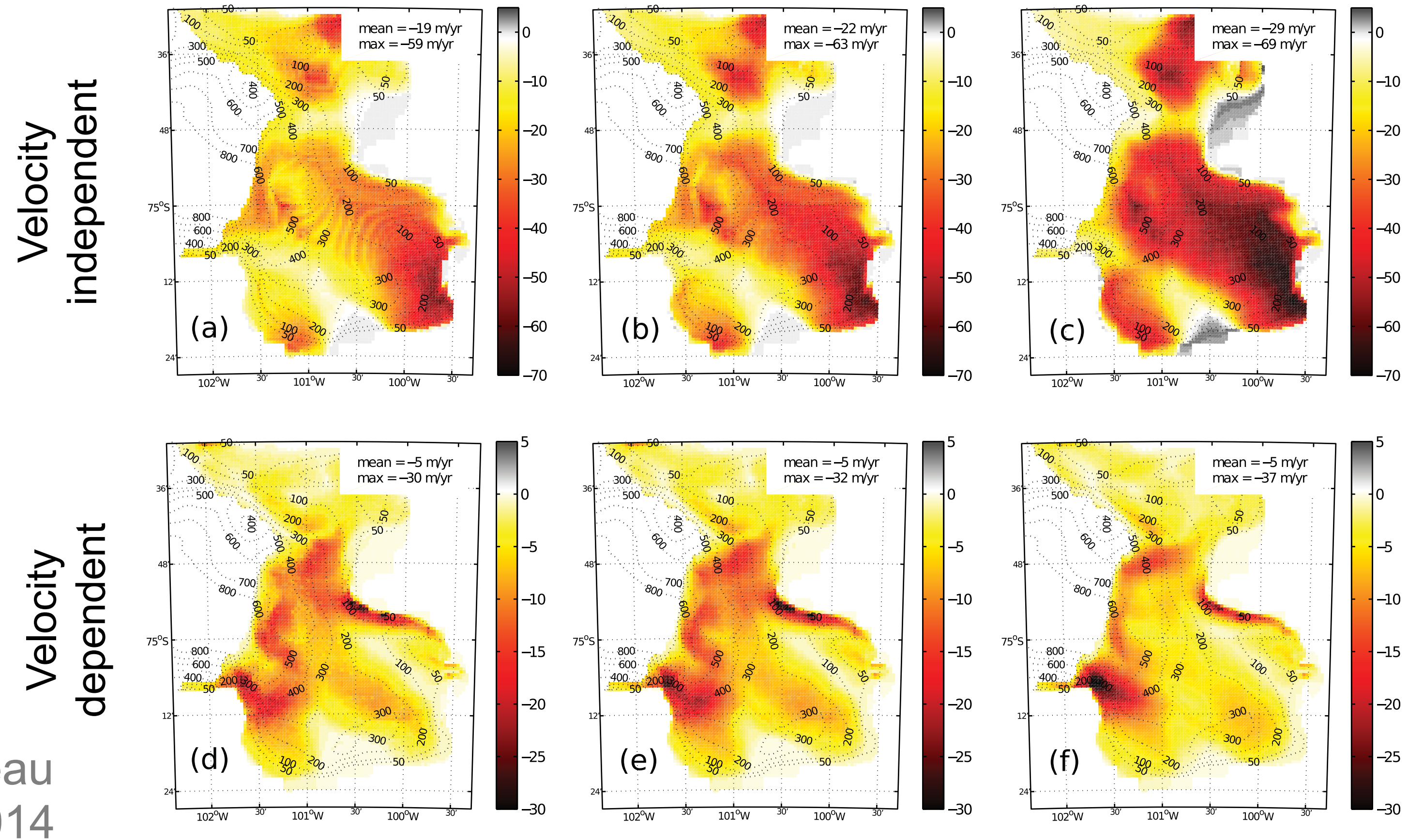
Varying ocean conditions

Melt spatially and temporally variable: example of Pine Island ice shelf



Schodlok et al., 2012

Impact of unknow coefficients



Dansereau et al., 2014

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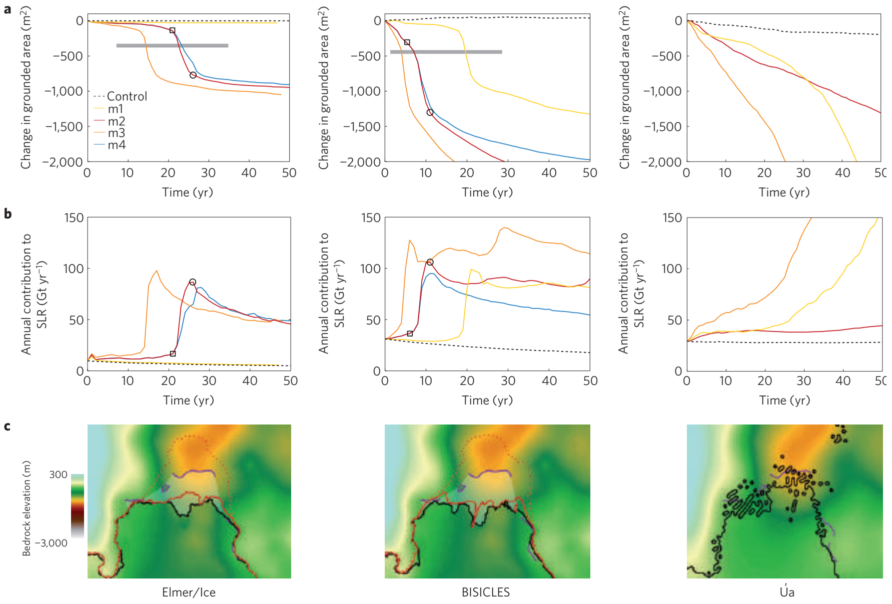
Need for coupled ice/ocean model ?

Ice dynamics sensitive to ocean melting

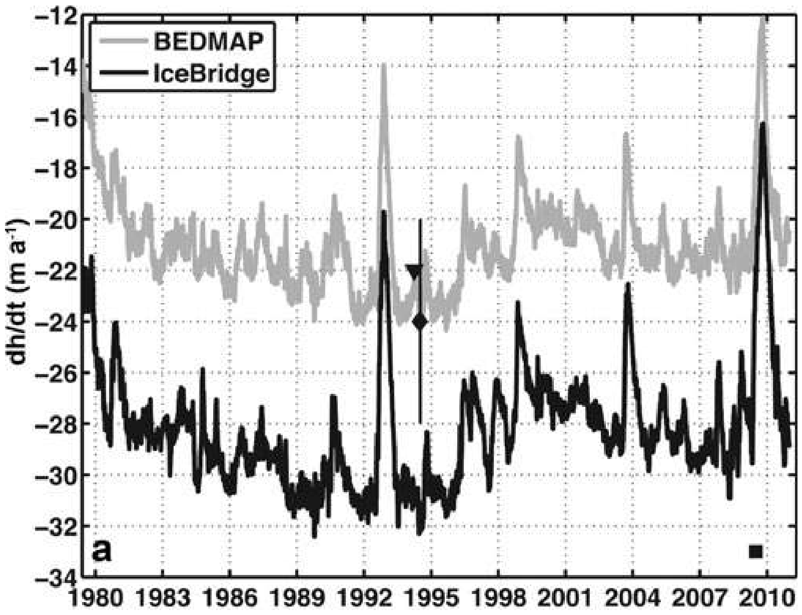
(Joughin et al.,2012, 2014; Favier et al., 2014; Seroussi et al., 2014)



Favier et al., 2014

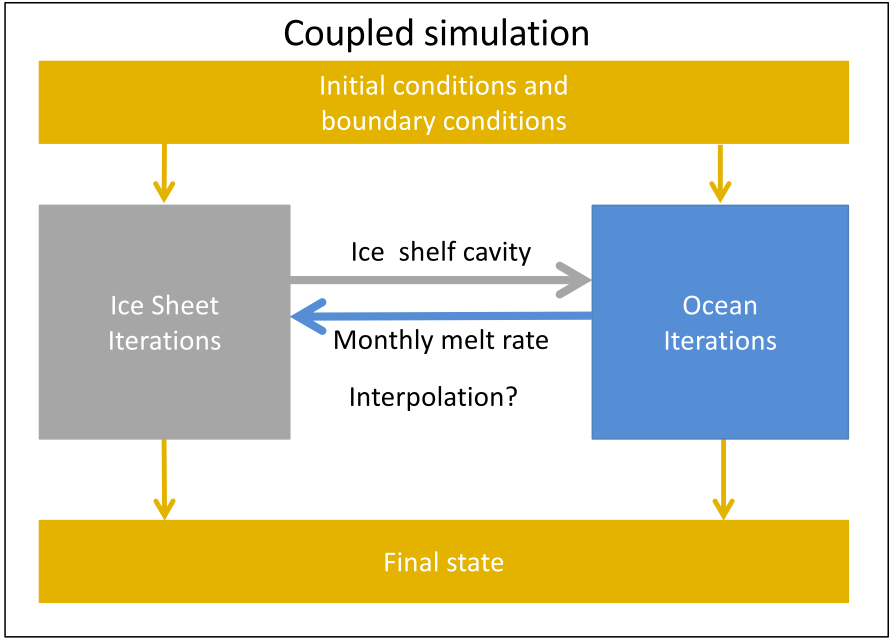
Basal melting sensitive to cavity shape

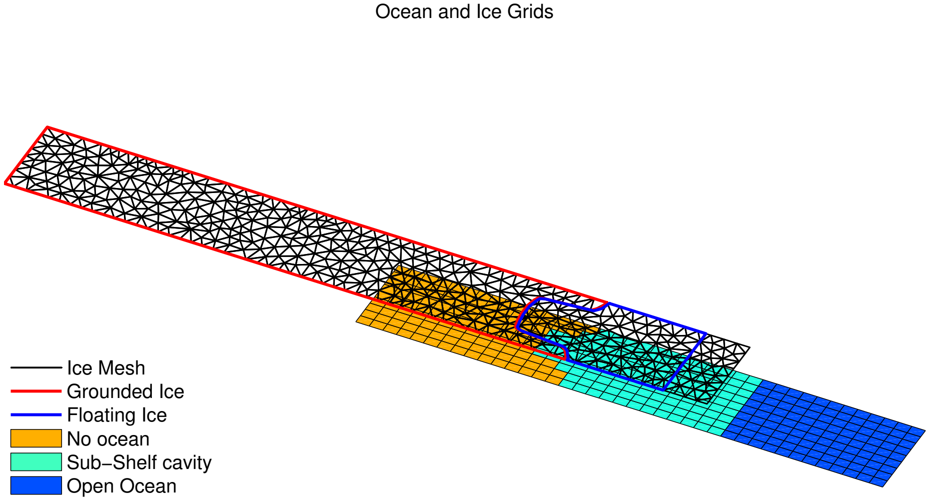
(Goldberg et al., 2012; Schodlok et al., 2012)



Schodlok et al., 2012

Coupled ice/ocean simulations

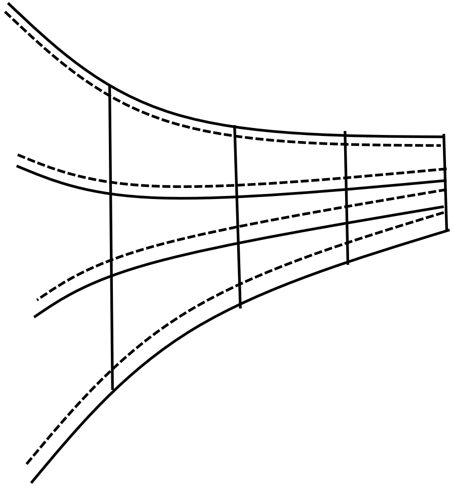


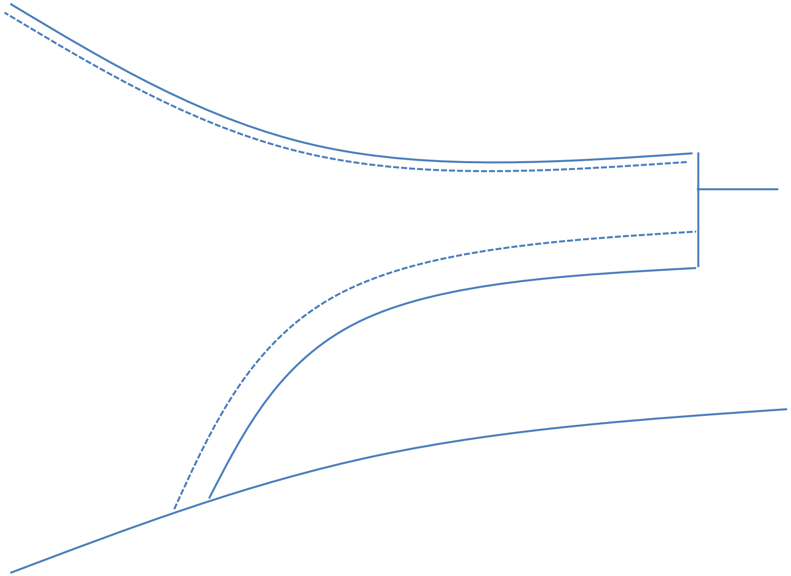


- Interpolation between grids
- Timescales
- Evolution of modeled domain

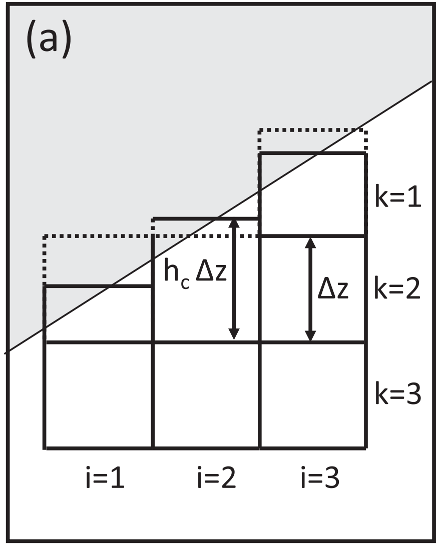
Evolving ice and ocean domain

Ice domain:
- ALE
- Horizontal layers follow topography





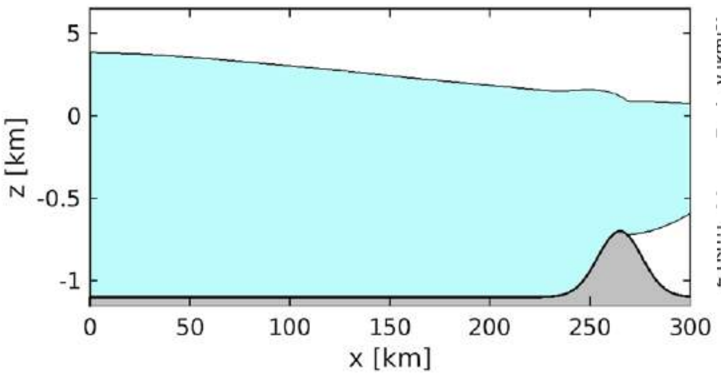
Ocean domain:
- Fixed grid
- Remeshing
- Add/remove cells

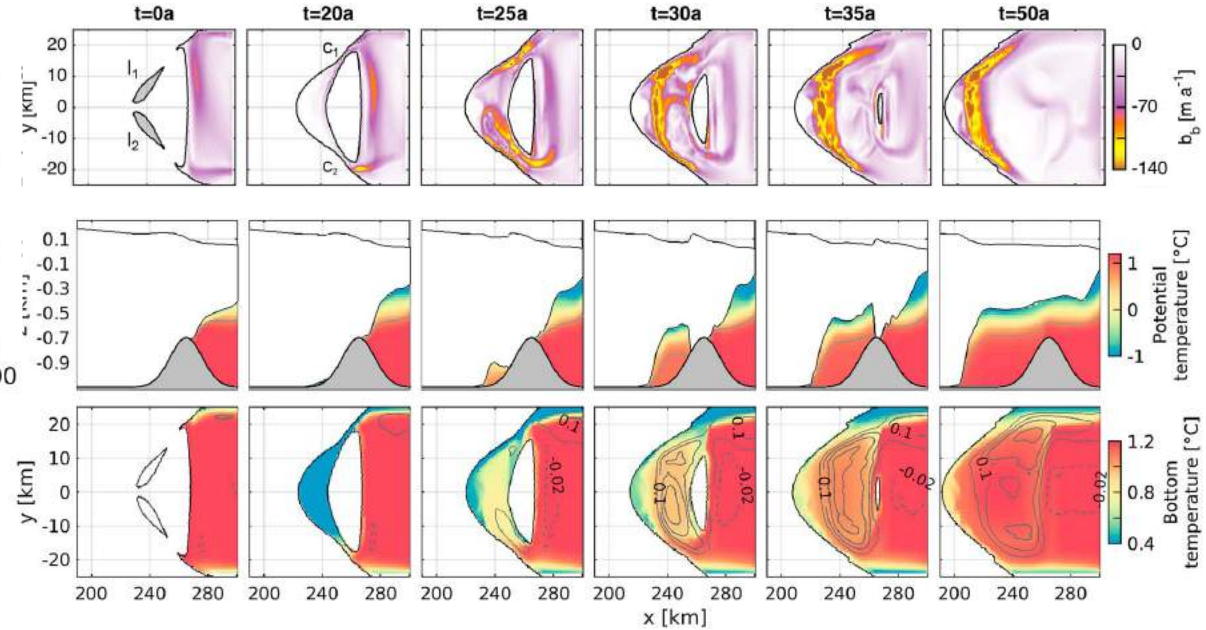


Goldberg et al., 2018

Idealized case of Pine Island Glacier

Complex grounding line retreat from a seabed ridge





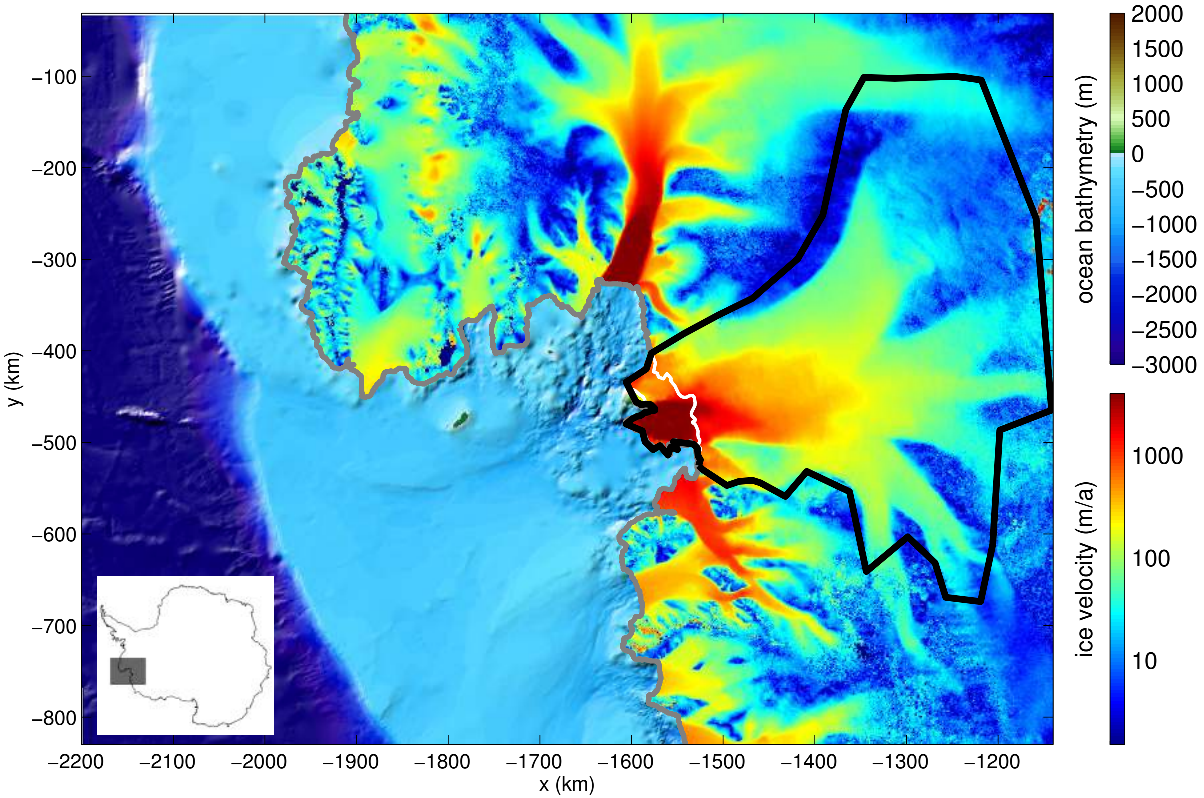
De Rydt and Gudmundsson, 2016

Simulation of Thwaites Glacier

ISSM-MITgcm simulations:
- 50 year simulations
- 1 month coupling
- 500 m resolution at GL
(sub-element parameterization)
- 2 km ocean model
- 5 year spin-up of ocean with fixed cavity shape

Experiments:
- 1992 forcing (ECCO)
- 1992 + 0.5°C forcing
- Uncoupled

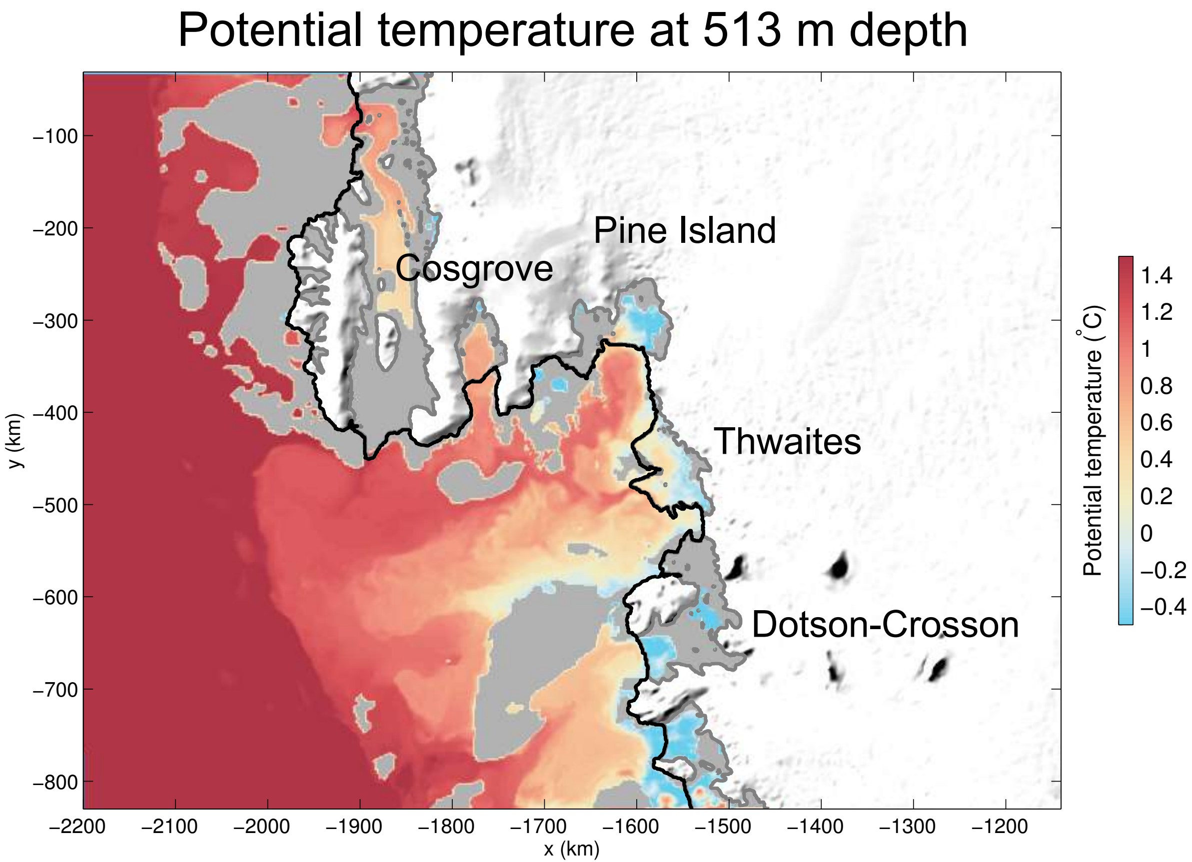
Seroussi et al., 2017



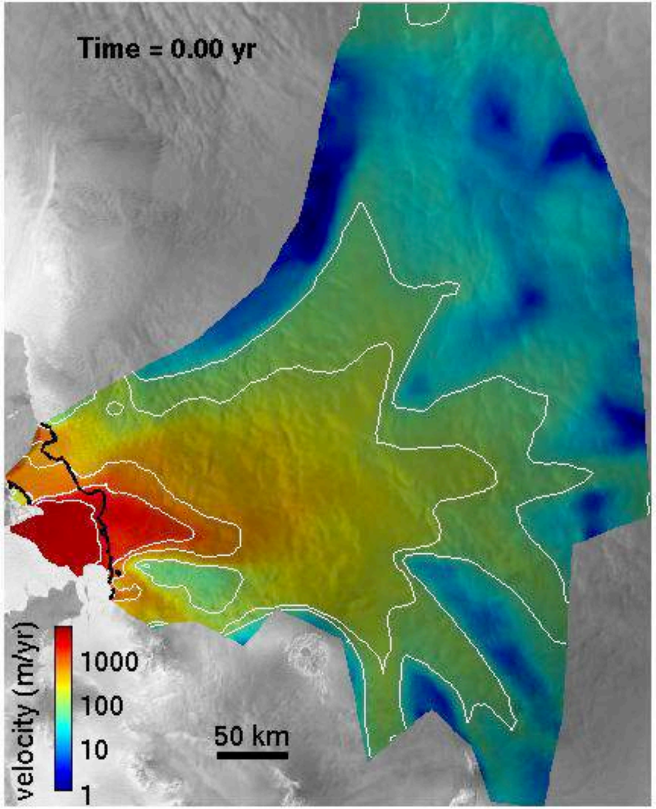
Ocean circulation

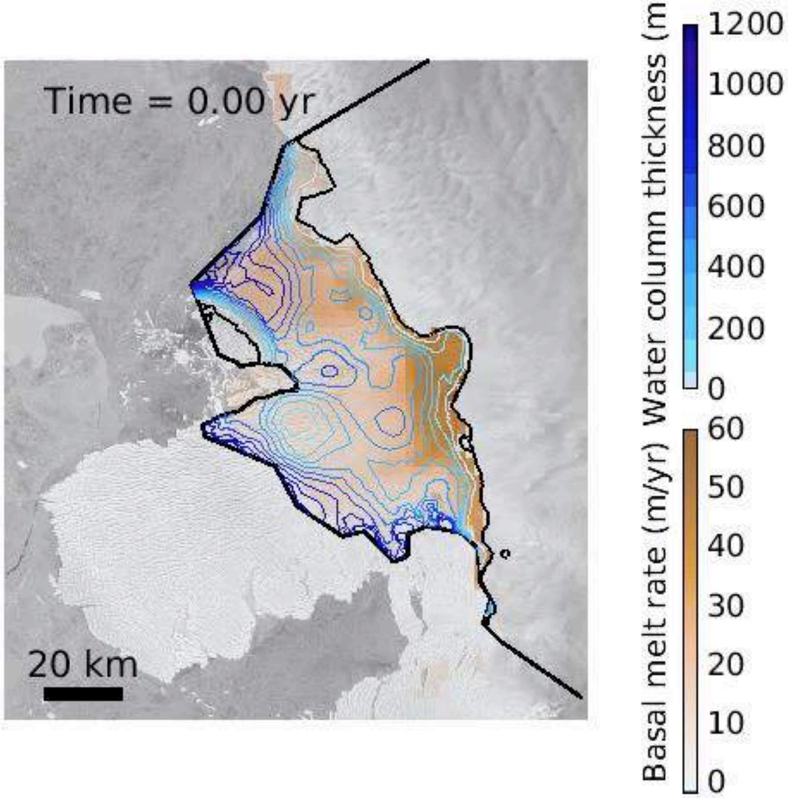
Simulated melt rates:

- Pine Island: 88 Gt/yr
- Thwaites: 81 Gt/yr
- Cosgrove: 37 Gt/yr
- Dotson/Crosson: 24Gt/yr



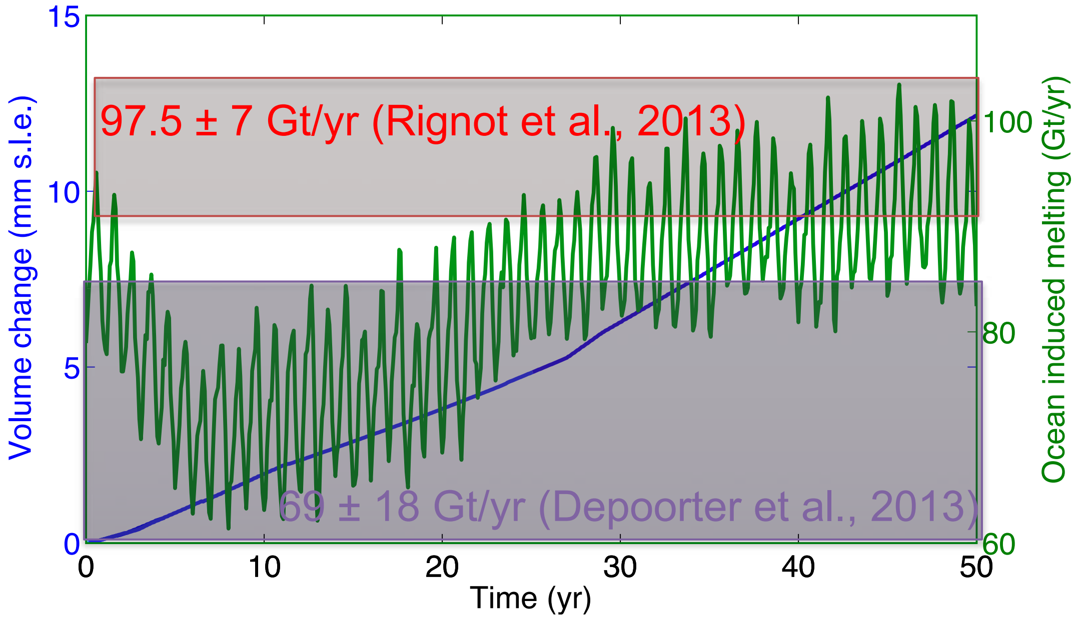
Evolution of Thwaites Glacier



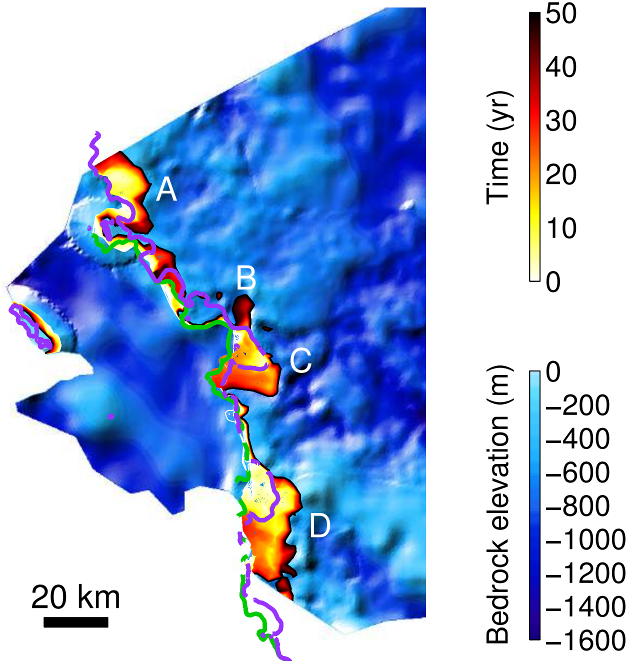


Comparison with observations

Ice shelf melt

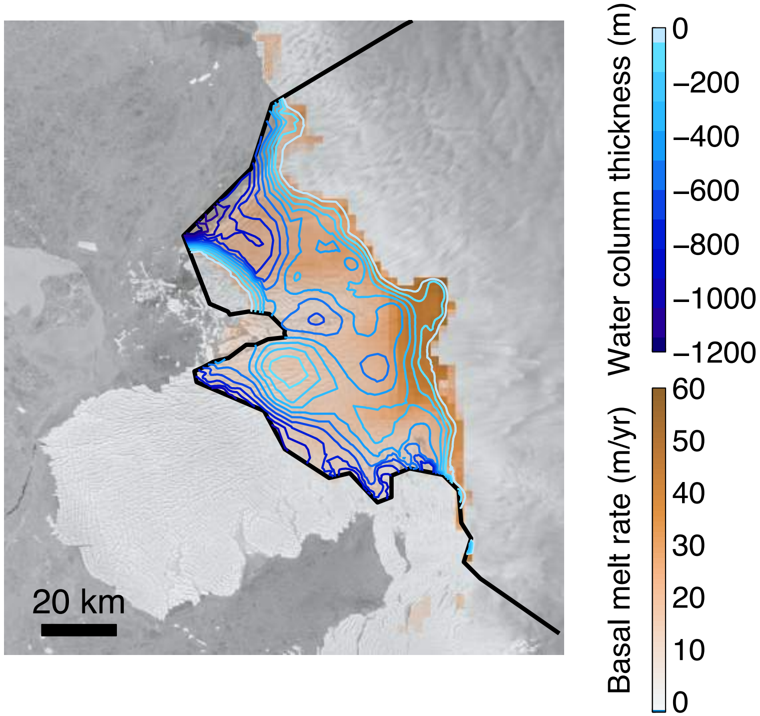


Grounding line

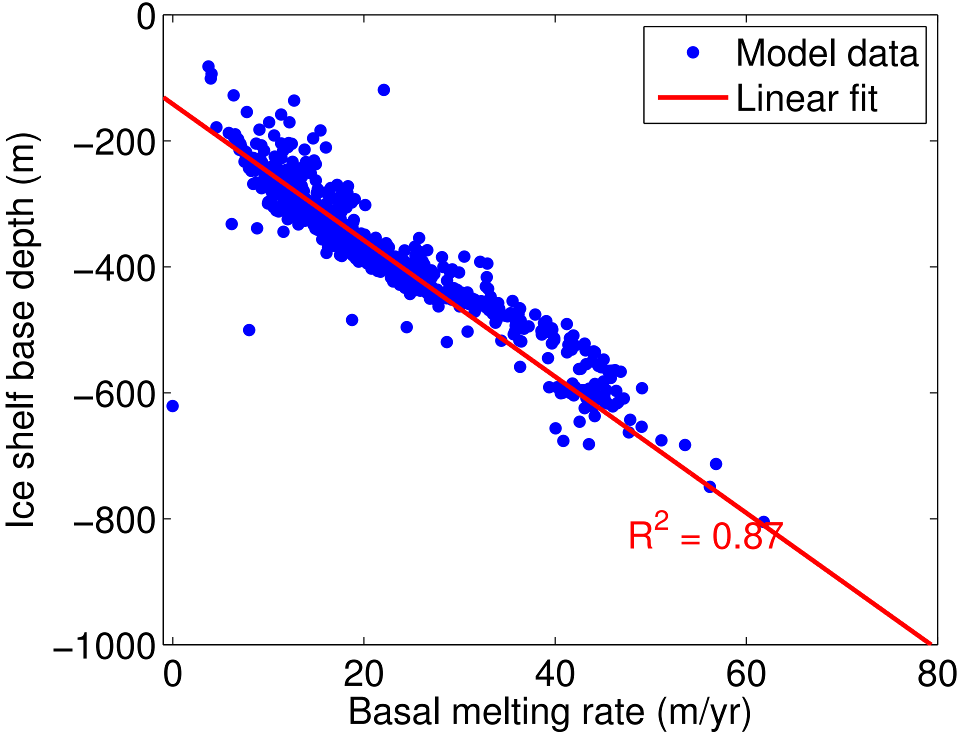


Comparison with parameterized melt

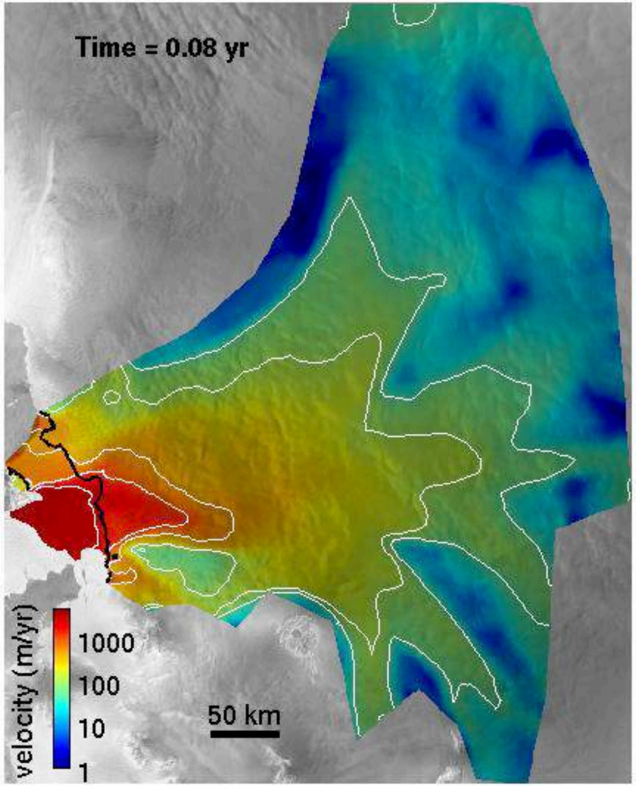
Initial melt

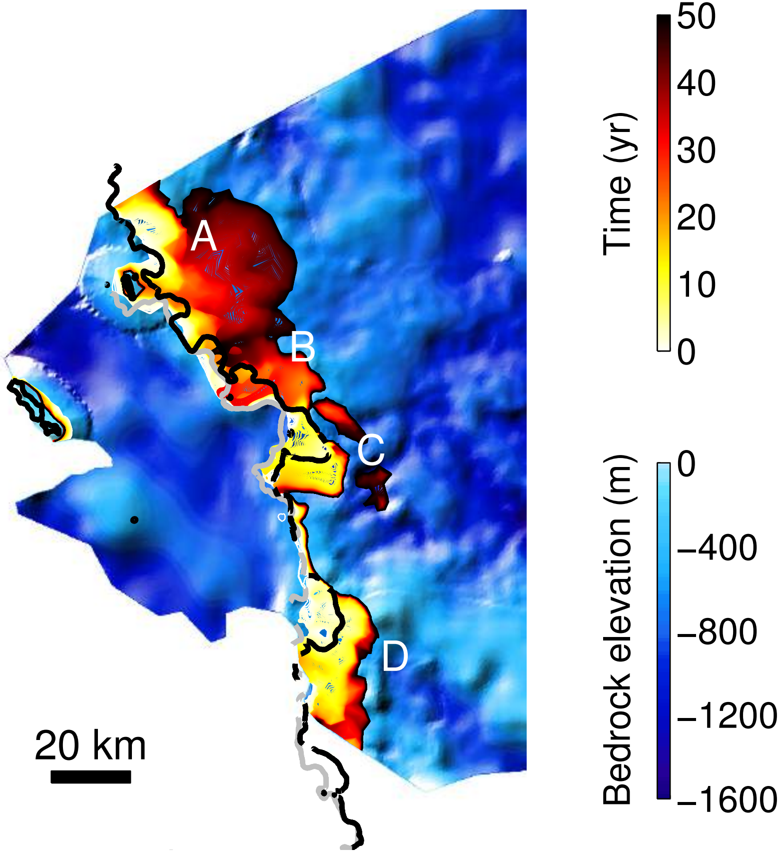


Melt parameterization

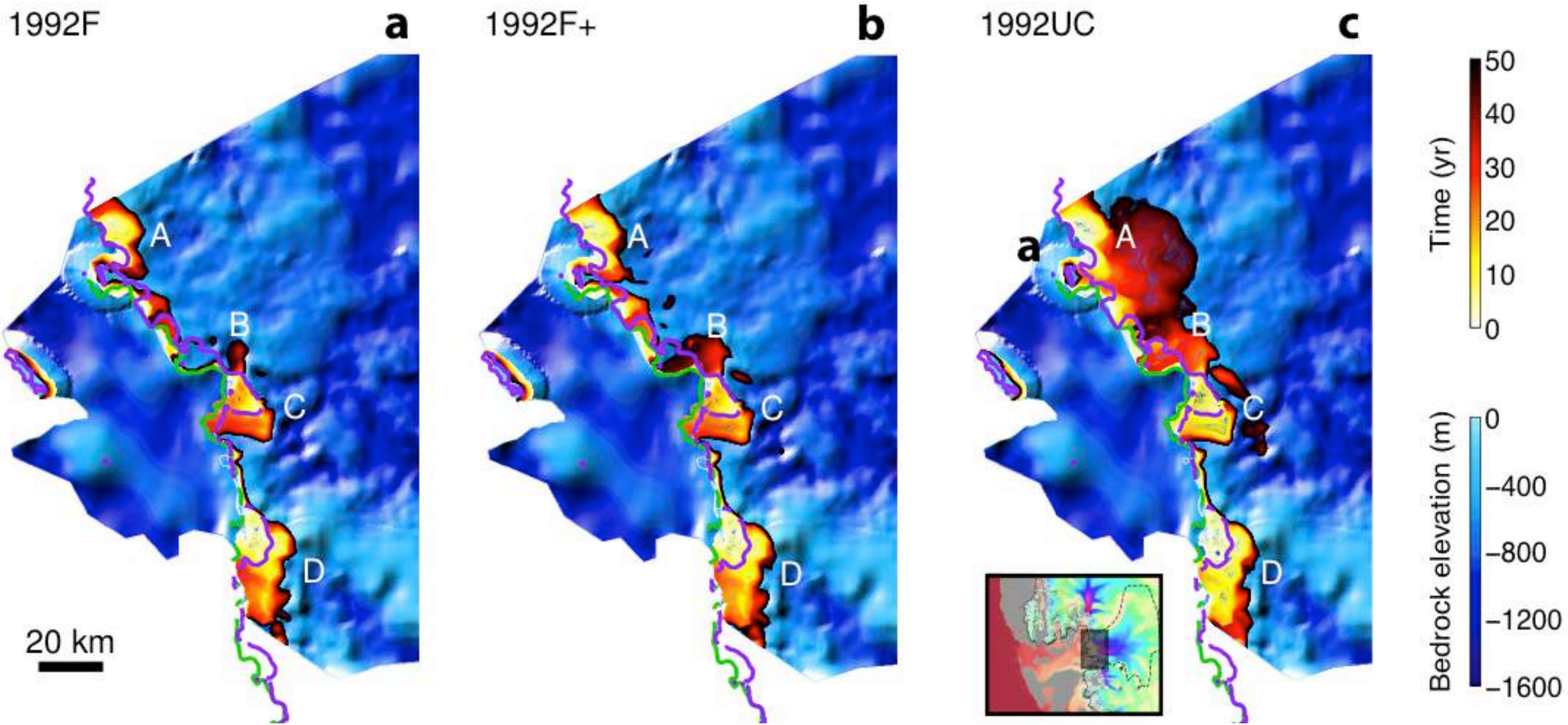


Uncoupled simulation (1992UC)





Grounding line evolution



Outline

1. Modeling ice sheets and ice shelves
2. Ice shelves around Antarctica
3. Modeling ice shelf melt
4. Coupling ice and ocean models
5. Can we parameterize ice shelf melt?

Parameterizations of ocean conditions

- Depth parameterization

- Quadratic local dependence on thermal forcing

$$\dot{m} = \gamma_T \left(\frac{\rho_w c_{po}}{\rho_i L_i} \right)^2 (T_o - T_f)^2$$

Holland et al. 2008

- Quadratic local/non local dependence on thermal forcing

$$\dot{m} = \gamma_T \left(\frac{\rho_w c_{po}}{\rho_i L_i} \right)^2 \langle T_o - T_f \rangle (T_o - T_f)$$

Favier et al. GMDD 2019

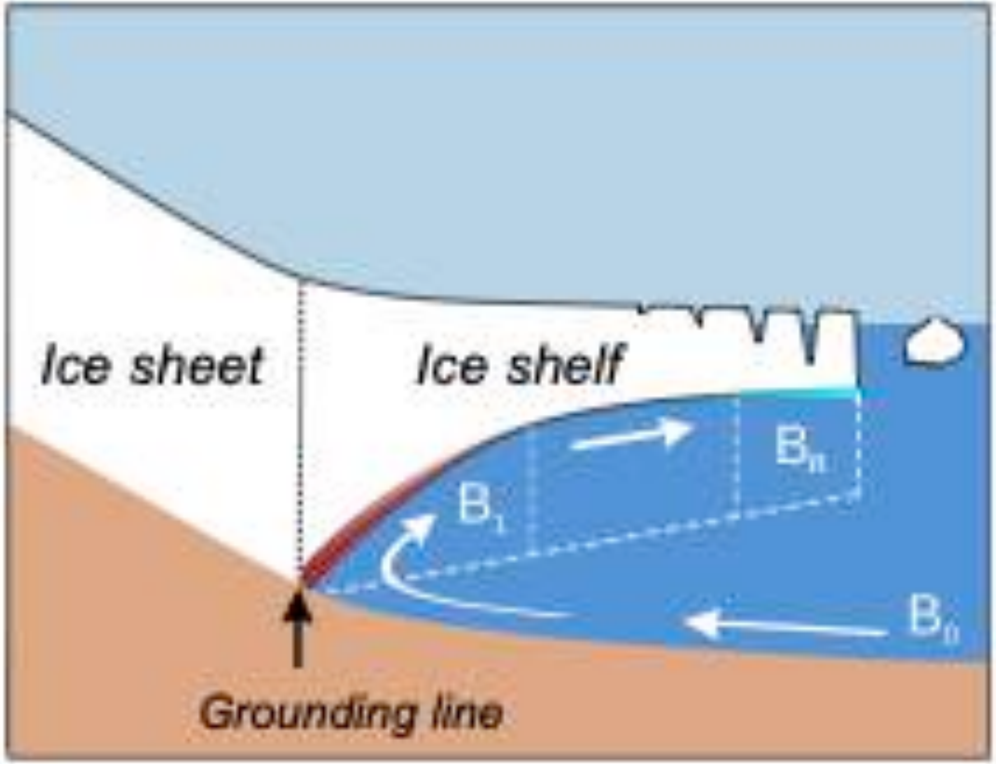
- PICO (Potsdam Ice-shelf Cavity mOdel): Box model

Reese et al. 2017

- PICOp (PICO + plume model)

Pelle et al. 2019

PICO



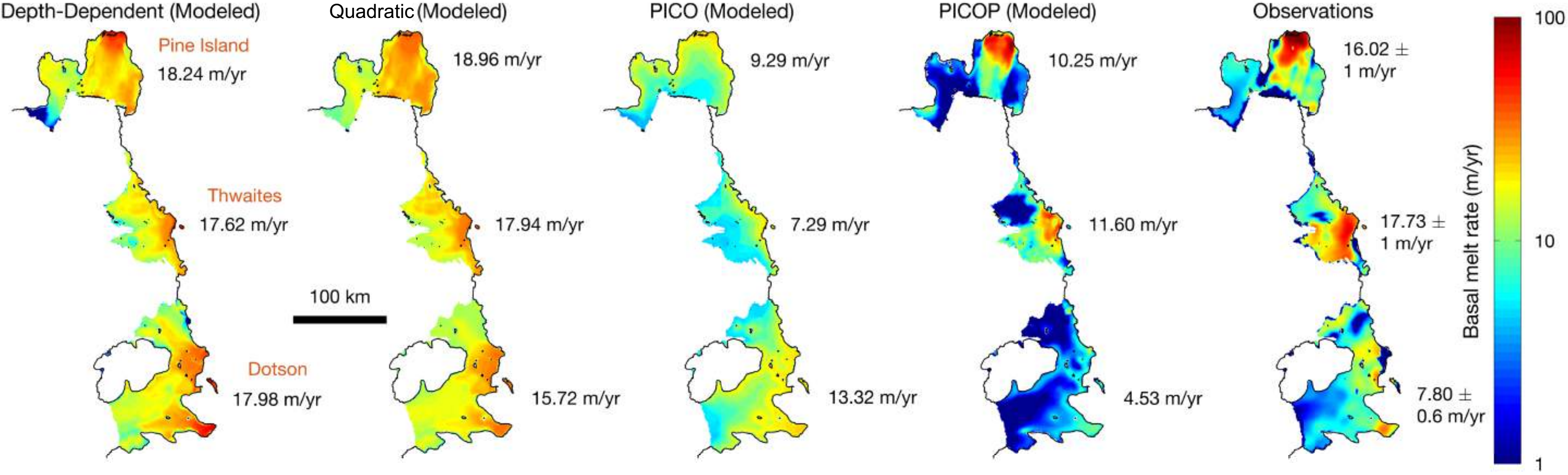
Reese et al., 2018

$$q\left(T_{k-1}-T_k\right)-A_k m_k \frac{\rho_i}{\rho_w}\frac{L}{c_p} = 0$$

$$q\left(S_{k-1}-S_k\right)-A_k m_k S_k = 0$$

- T_k Temperature of B_k
- A_k box surface area
- m_k melt rate of B_k
- $q = C\left(\rho_0-\rho_1\right)$ strength of the overturning circulation

Comparison of ice shelf melt rates



Summary

- Ice is a laminar viscous incompressible material
- Ice/ocean interactions are driving most of the dynamic changes observed in the Amundsen Sea (and elsewhere)
- Coupled ice-ocean model:
    - produce more realistic estimates of glacier retreat rates than ice model driven by parameterized melt
    - limited observations to constrain and validate models
- Ice sheets starting to be included in Earth System models mostly for ice/atmosphere coupling, not ocean (need ocean cavities)


Questions ?