Modelling the response of ice sheets to climate change – the challenge of Antarctica

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Aim

Simulate response of Antarctic ice sheet to **recent** climate change and predict **future**

What is the forcing on the ice sheet?

Atmospheric variability?

Oceanic variability?

Direct of indirect?

Coupling between ice and environment

What physics govern the response of the ice sheet?

Stress transmission in ice masses and associated dynamics

Migration of the grounding line

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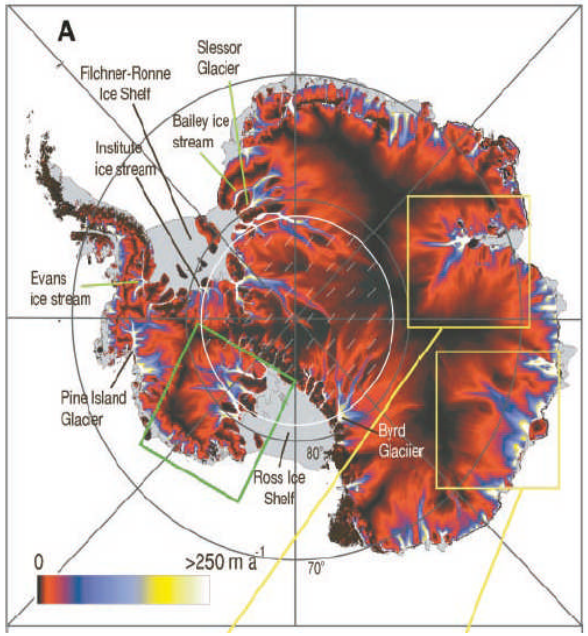
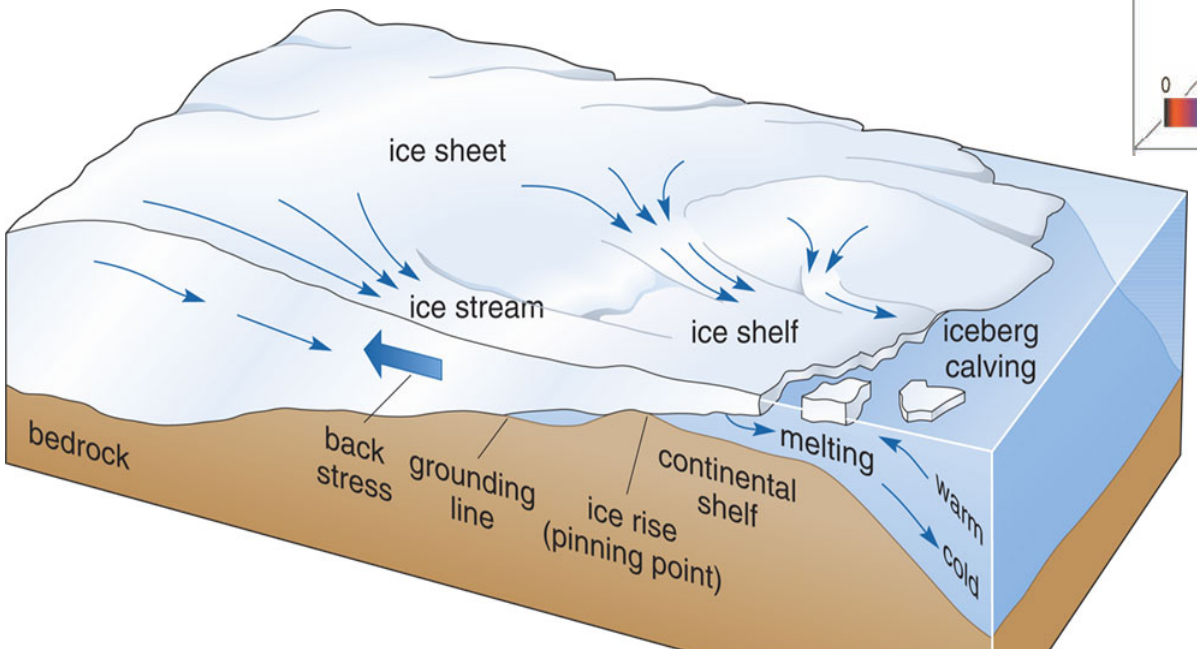
Components of an ice sheet

- slow-flowing interior (~10 m/yr)
- fast-flowing ice streams (>500 m/yr)
- floating ice shelves
- grounding line





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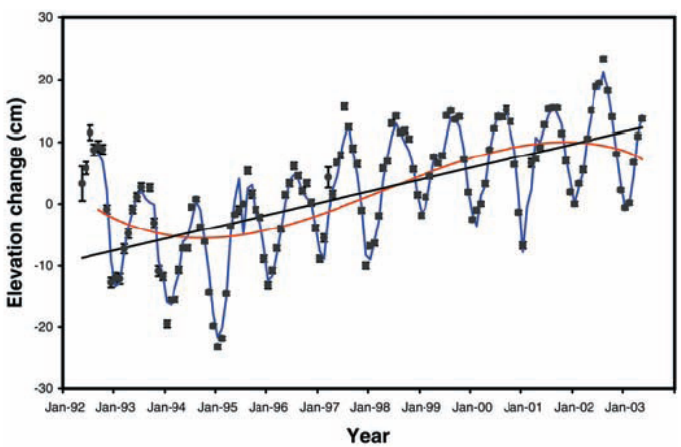
Antarctic mass balance

Wingham and others (2006) use ERS radar altimetry to determine change in surface elevation from 1992 to 2003.



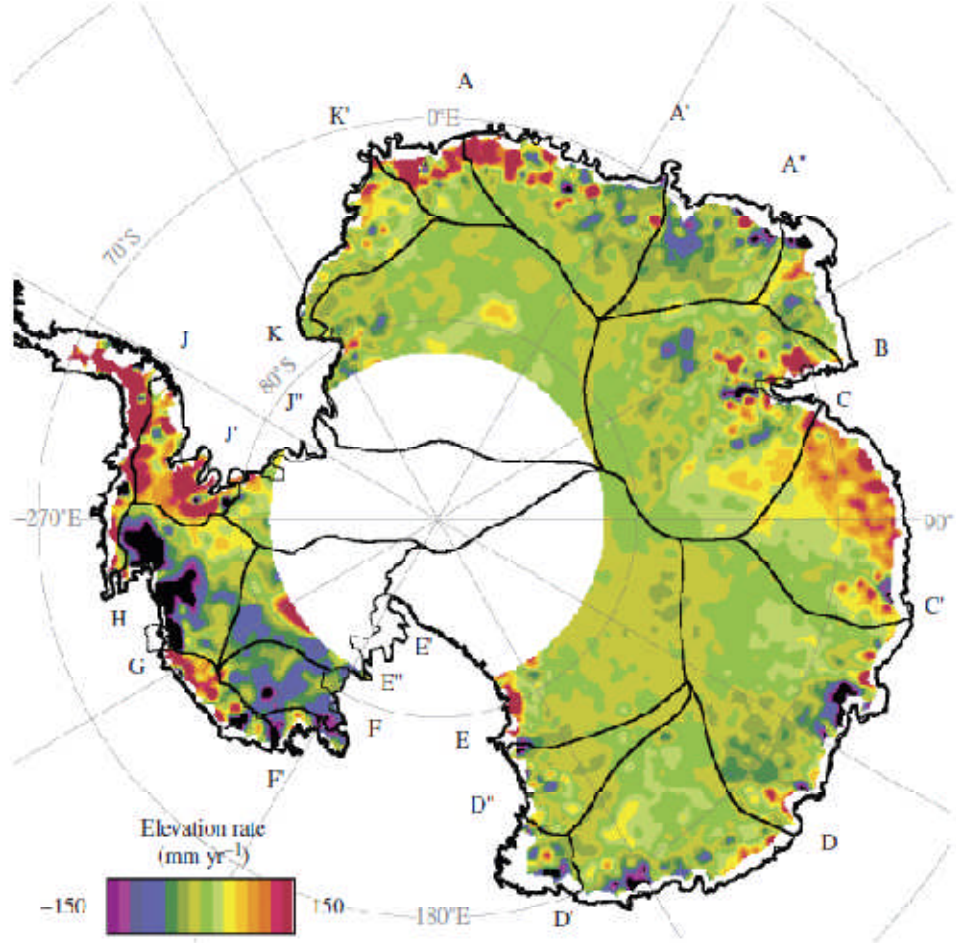


Figure 1. Rate of elevation change of the Antarctic ice sheet, 1992–2003, interpolated using a Gaussian filter of radius 50 km.

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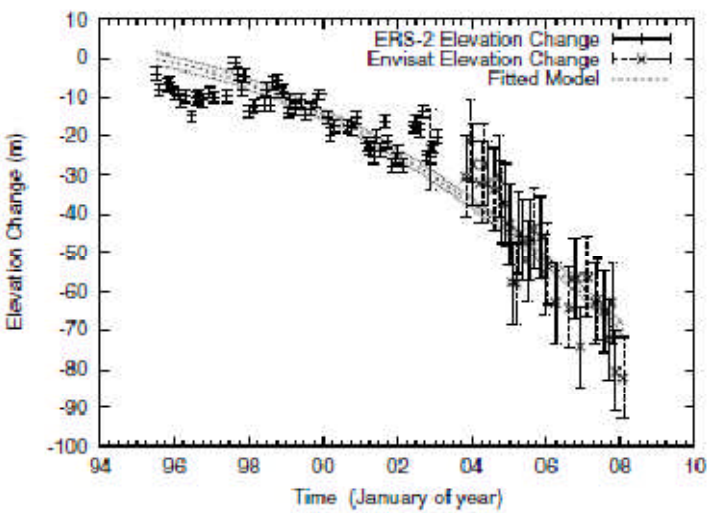
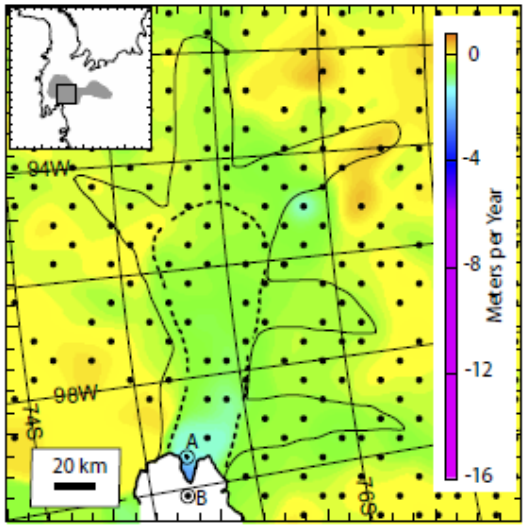
Amundsen Sea mass balance

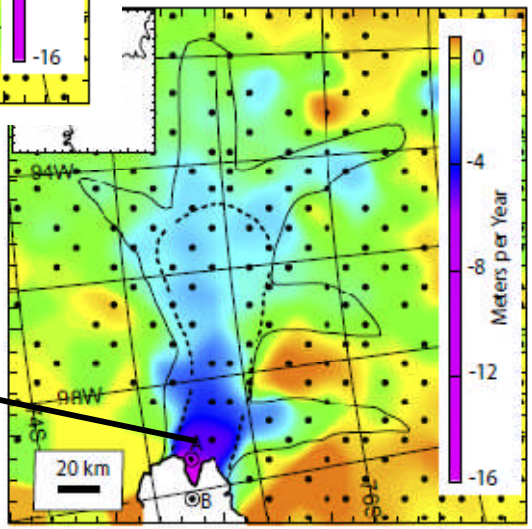
Wingham and others (2009) use cross-calibrated ERS-2 and ENVISAT radar altimetry to extend time series from 1995 to 2008.



1995



2006



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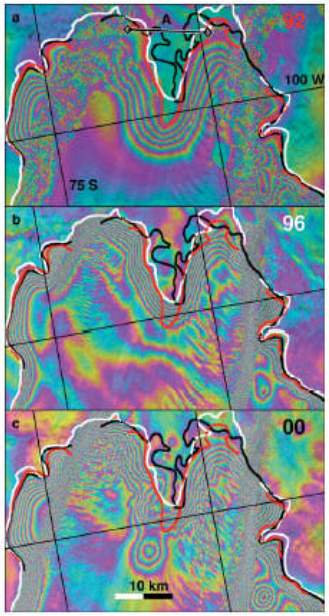
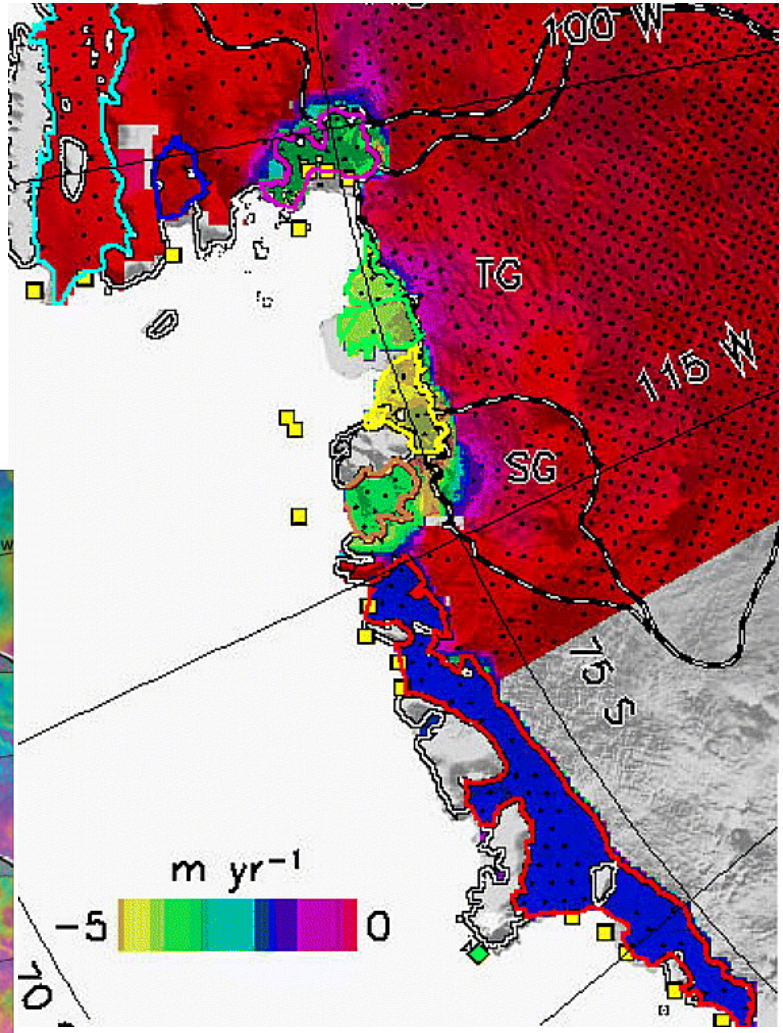
Forcing is thought to be oceanic

observations suggest that thinning of floating ice shelves is ubiquitous (~ 4 m/yr)

thinning results in retreat of the grounding line (as mapped by SAR interferometry)

pattern of thinning excludes atmospheric (snowfall) and internal dynamics





Shepherd and others (2004)

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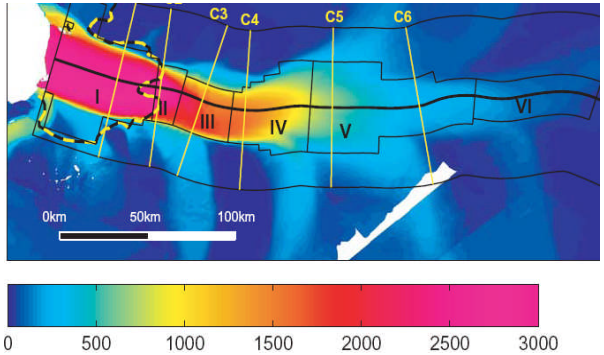
Coupling ice shelves to grounded ice

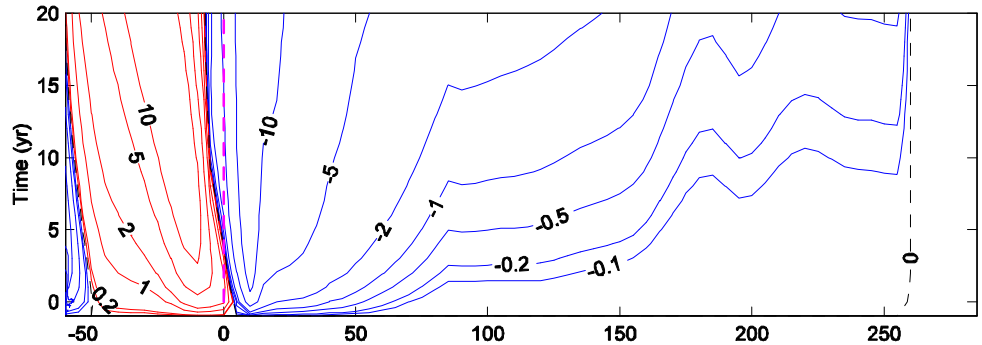


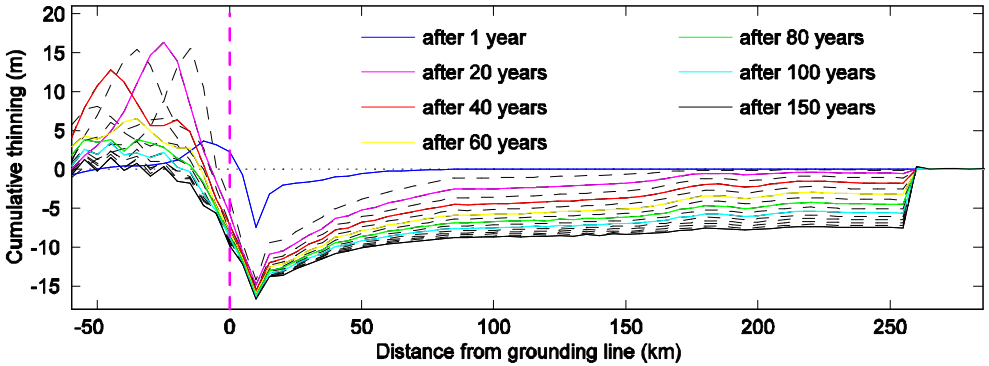
Payne and others (2004) showed how perturbations to ice shelf could be transmitted up the ice stream on decadal time scales

Two-fold mechanism of instantaneous stress release and diffusive response

Mechanism subsequently confirmed using field-based GPS by Scott and others (2008)

Grounding line fixed





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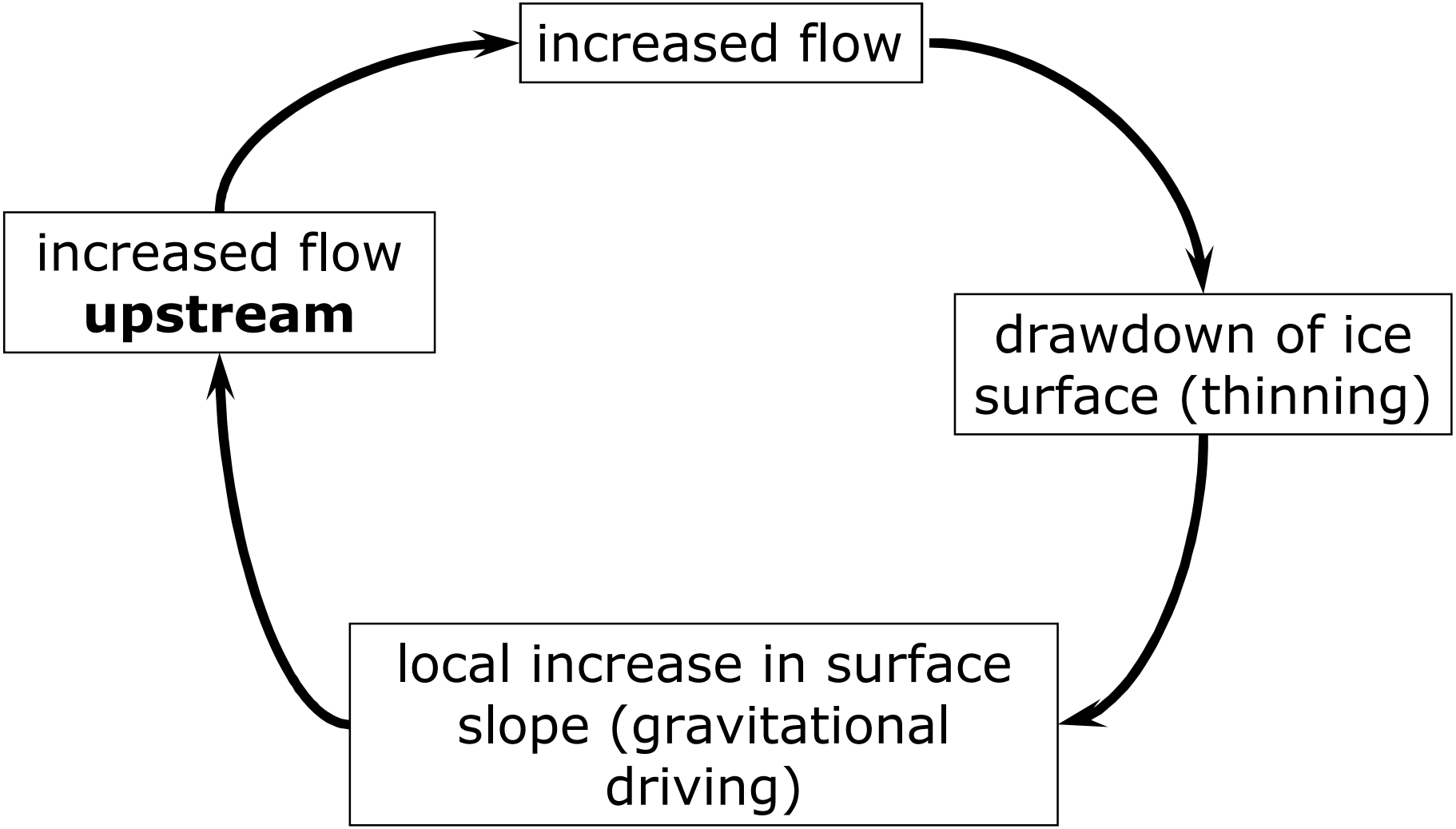
Mechanism



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Basic components of model

- stress solution
  - first-order approximation to shallow ice
  - no acceleration
  - hydrostatic balance assumed in vertical

$$2\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yy}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} = -\rho g \frac{\partial s}{\partial x}$$

$$2\frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{xx}}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yz}}{\partial z} = -\rho g \frac{\partial s}{\partial y}$$

normal stress deviators | shear stresses | gravitational driving

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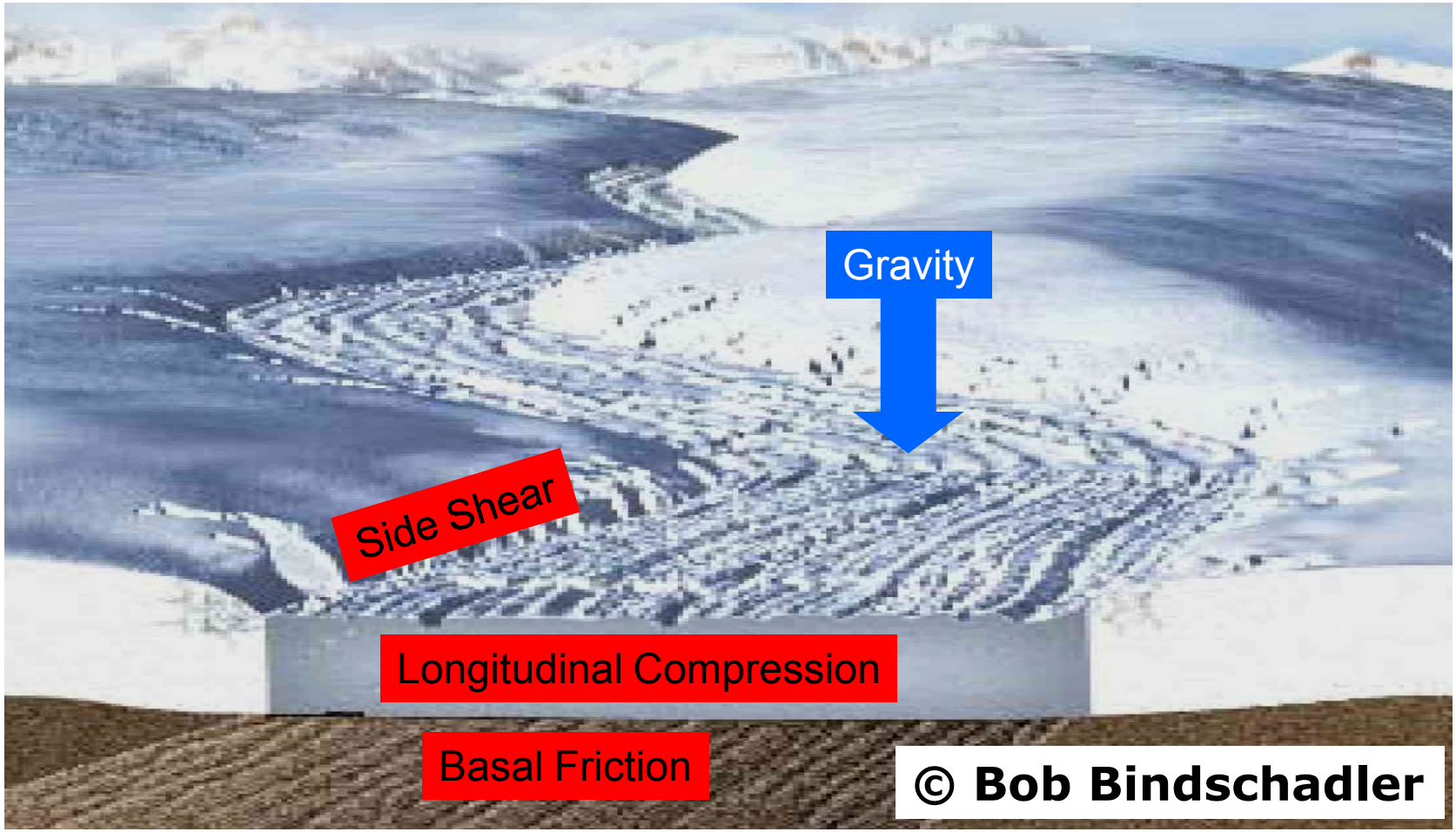
Glacier force balance



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General first-order model

- solve for horizontal velocities
- substitute for stresses using constitutive relation for ice (Glen's flow law)
- two 3d elliptical equations coupled through effective viscosity

$$2\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{yy}}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xz}}{\partial z}=-\rho g\frac{\partial s}{\partial x}$$

$$2\frac{\partial}{\partial x}f\frac{\partial u}{\partial x}+\frac{\partial}{\partial x}f\frac{\partial v}{\partial y}+$$

$$\frac{\partial}{\partial y}\frac{f}{2}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial z}\frac{f}{2}\frac{\partial u}{\partial z}=-\rho g\frac{\partial s}{\partial x}$$

$$f=\frac{1}{2}A^{-1/n}\left[\frac{\partial u}{\partial x}^2+\frac{\partial v}{\partial y}^2+\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)^2+\frac{1}{4}\left(\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2+\frac{\partial u}{\partial z}^2+\frac{\partial v}{\partial z}^2\right)\right]^{(1-n)/2n}$$

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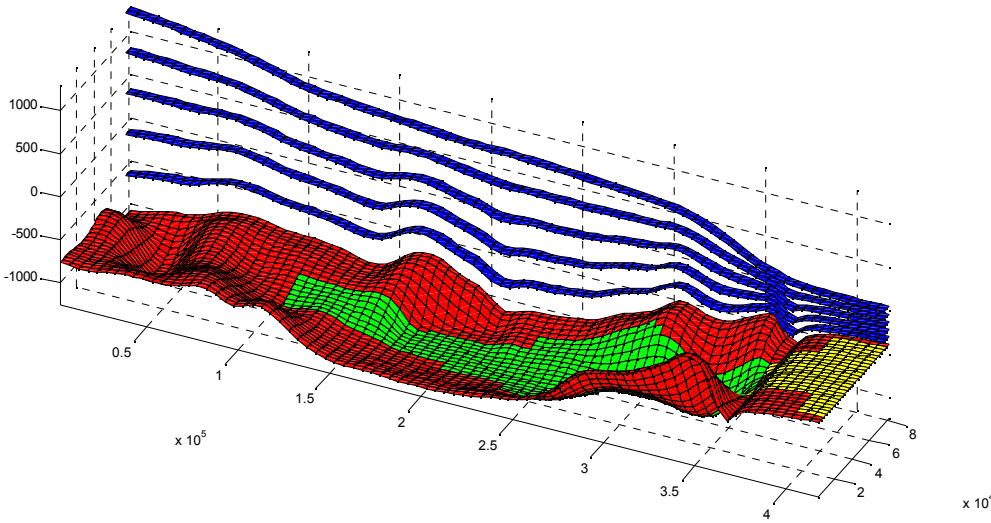
First-order model

- need to use stretched coordinates because of irregular geometry in vertical
- complicates each horizontal second derivative term requires (1 $\Rightarrow$ 5)
- roughly 40 terms in total



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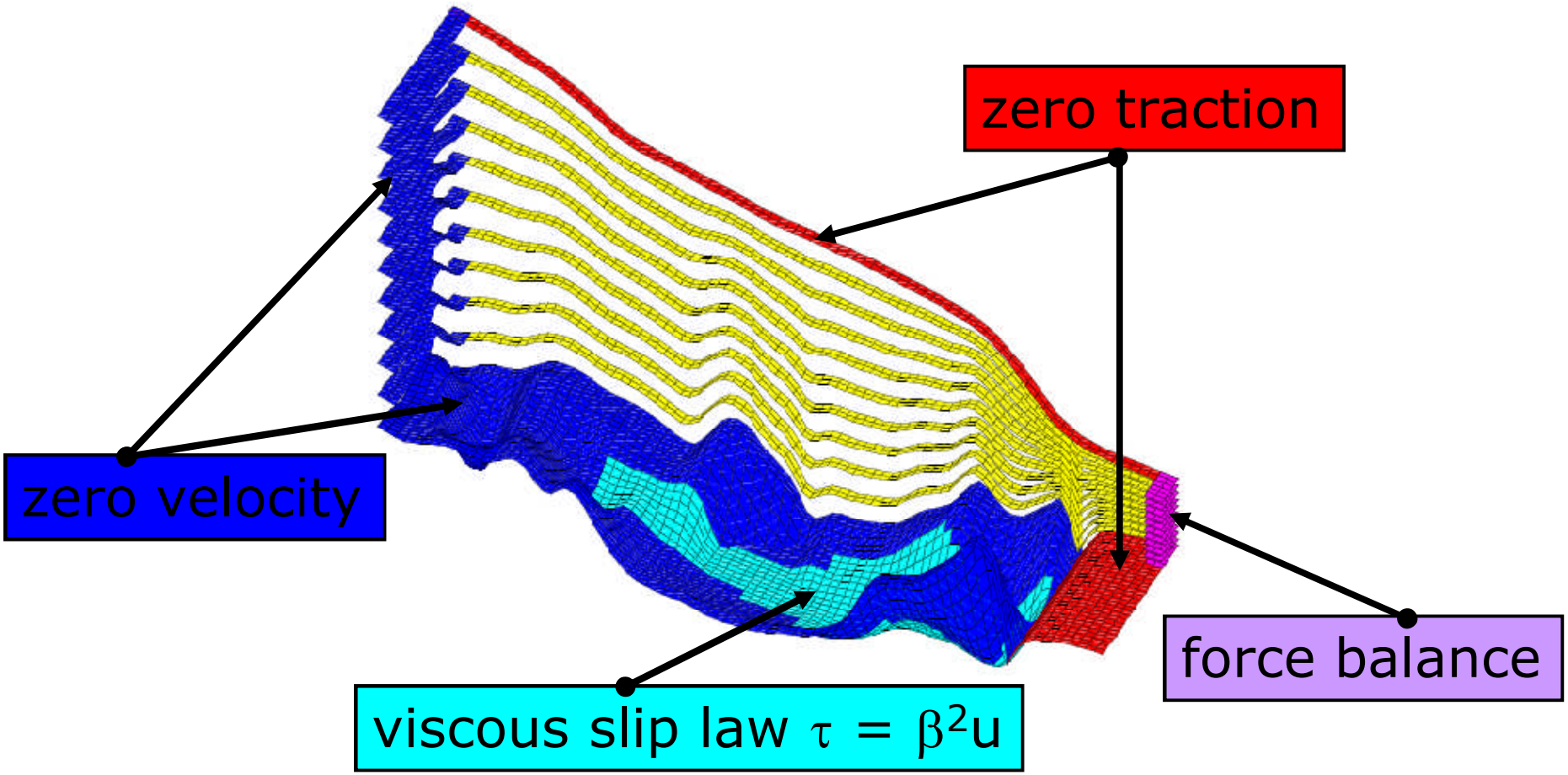
Model geometry and boundary conditions



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IPCC Assessments

4th AR (2007) provides sea-level estimates but explicitly excludes this type of process

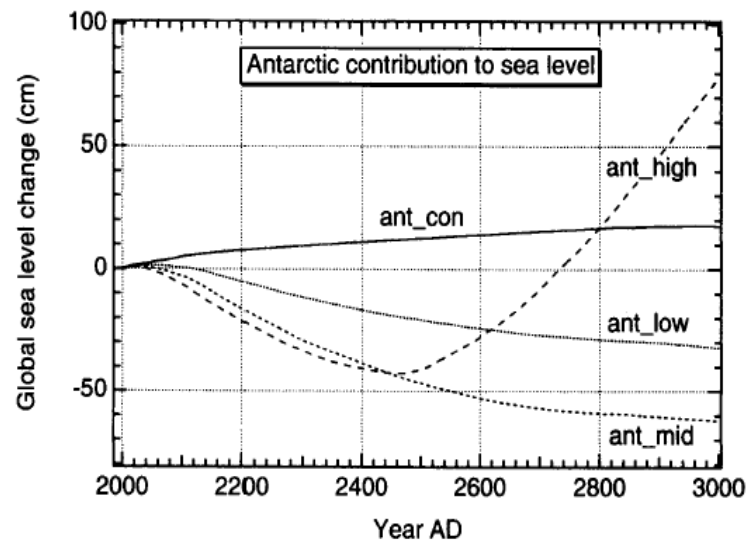
Previous coupled modelling only allows ice-atmosphere coupling

Huybrechts and de Wolde (1999) increased find precipitation in interior

However, only mechanism of mass loss was surface melt, which required warming of ~8 °C, which led to grounding-line retreat

Table SPM-3. Projected globally averaged surface warming and sea level rise at the end of the 21st century. {10.5, 10.6, Table 10.7}

Case	Temperature Change (°C at 2090-2099 relative to 1980-1999) [a]		Sea Level Rise (m at 2090-2099 relative to 1980-1999)
	Best estimate	*Likely* range	Model-based range excluding future rapid dynamical changes in ice flow
Constant Year 2000 concentrations [b]	0.6	0.3 – 0.9	NA
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59



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vertical shear stresses

gravitational driving

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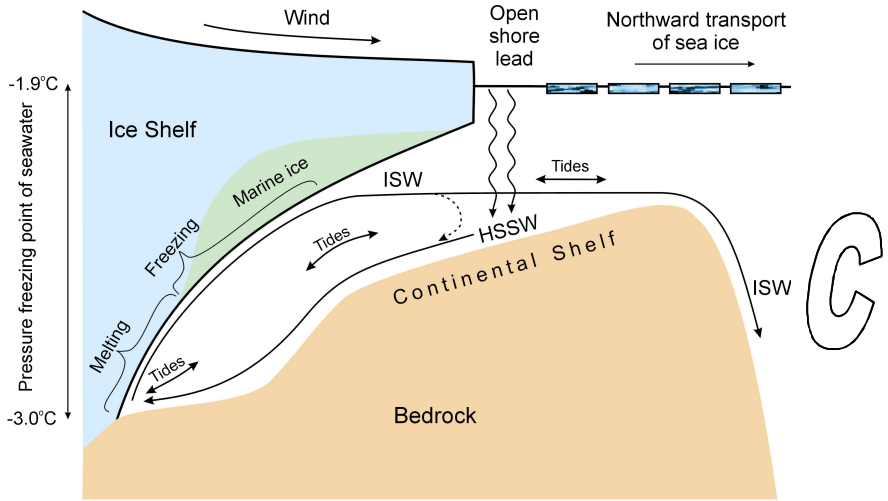
Coupling ice sheets to oceans



Climate change

Southern Ocean

A

Ice shelf ocean cavity

B

Floating ice shelf

C

Grounded ice sheet

Numerics of grounding line migration

HadCM3 and OCCAM

plume model

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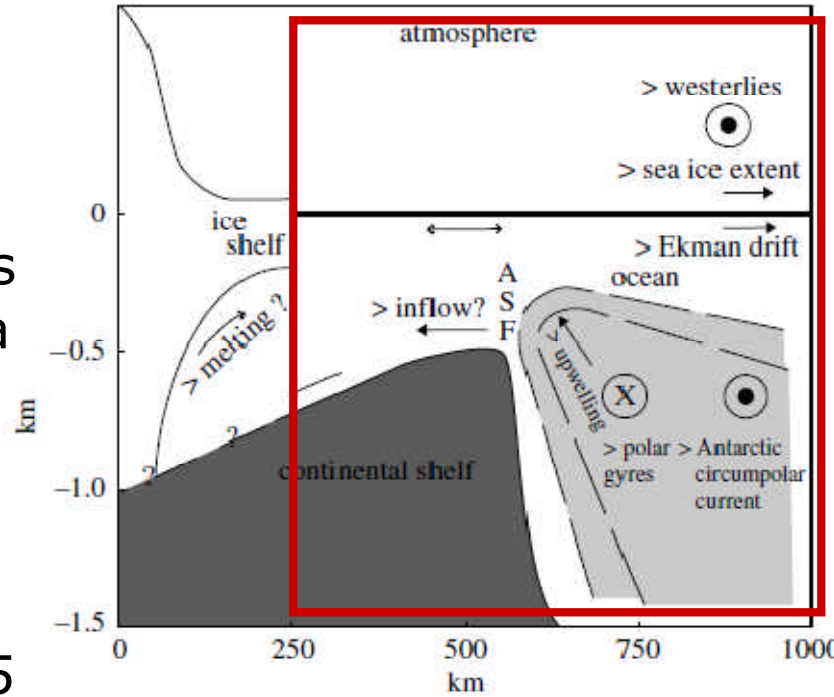
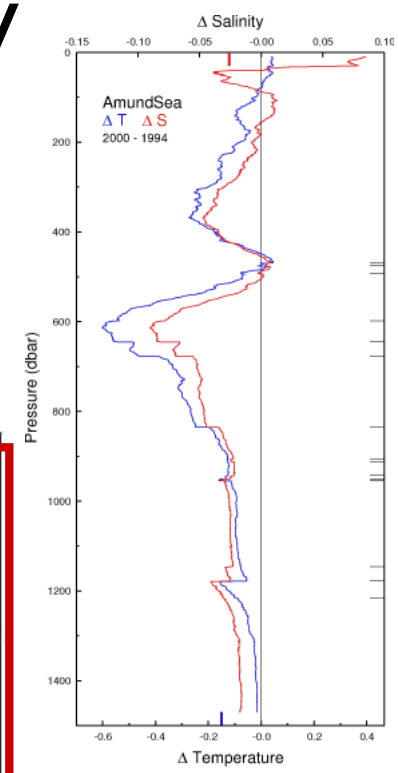
A. Modelled ocean variability

Key control thought to be upwelling of Circumpolar Deep Water (CDW) on to continental shelf at depth of ~500 m

NOT direct oceanic warming because this water mass is up to a century old

Only observations suggest that 1994 was warmer (by ~0.5 °C) than 2000





Jacobs 2006

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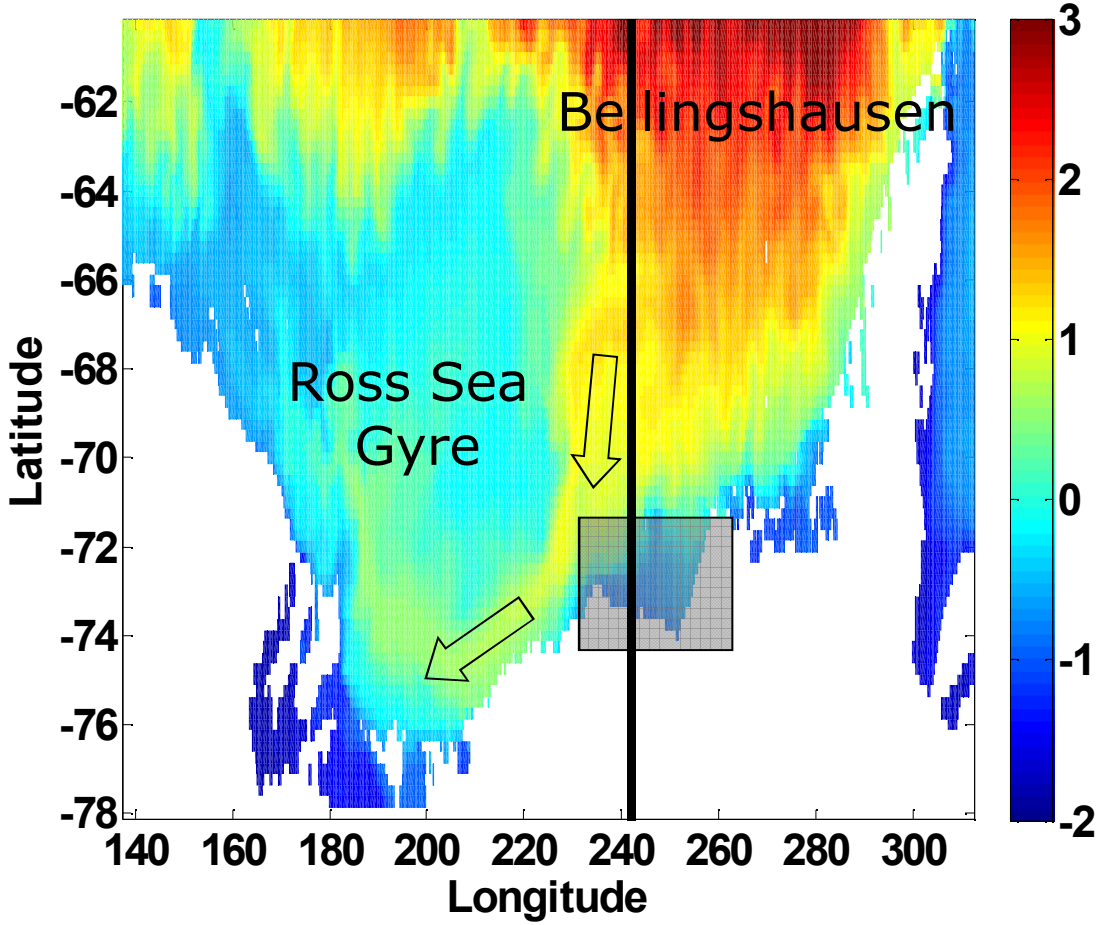
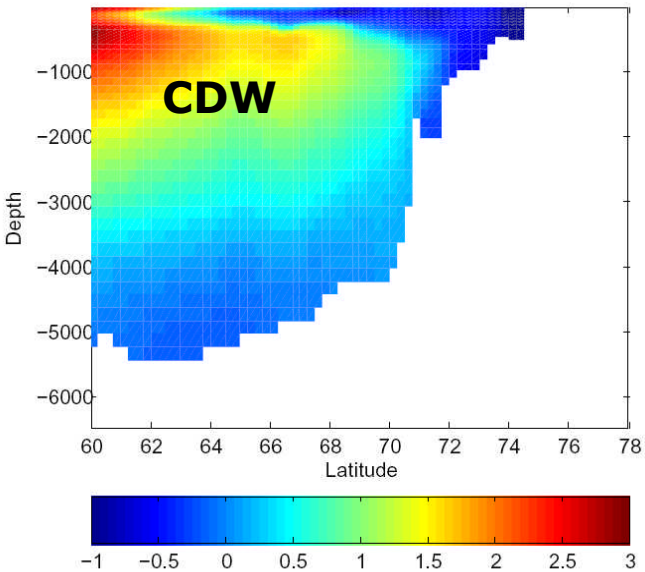
OCCAM coastal current system in area

Temperature (°C) between 500-1000 m depth





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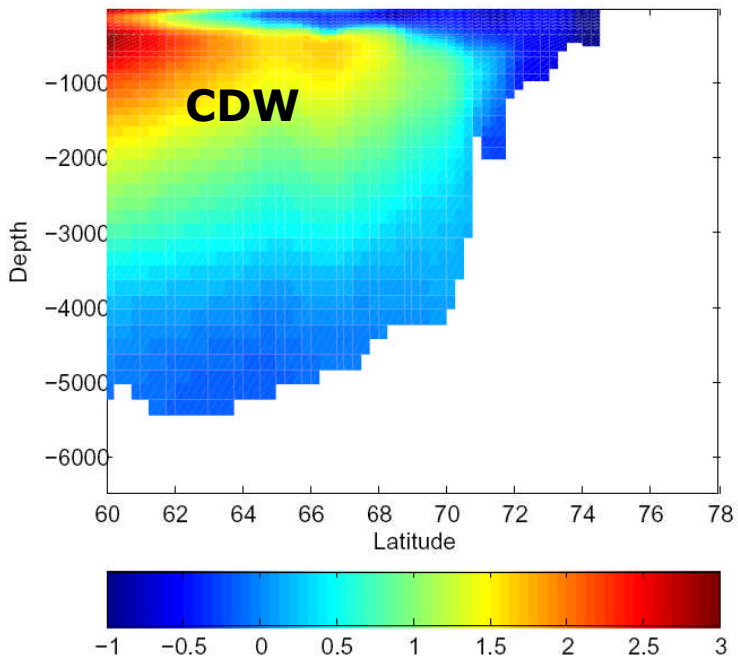
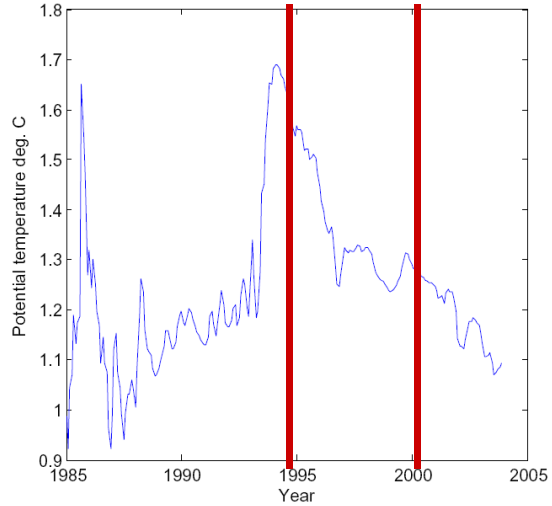
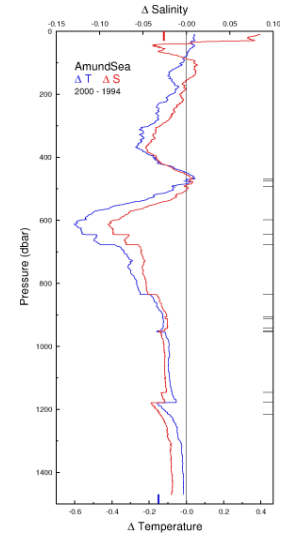
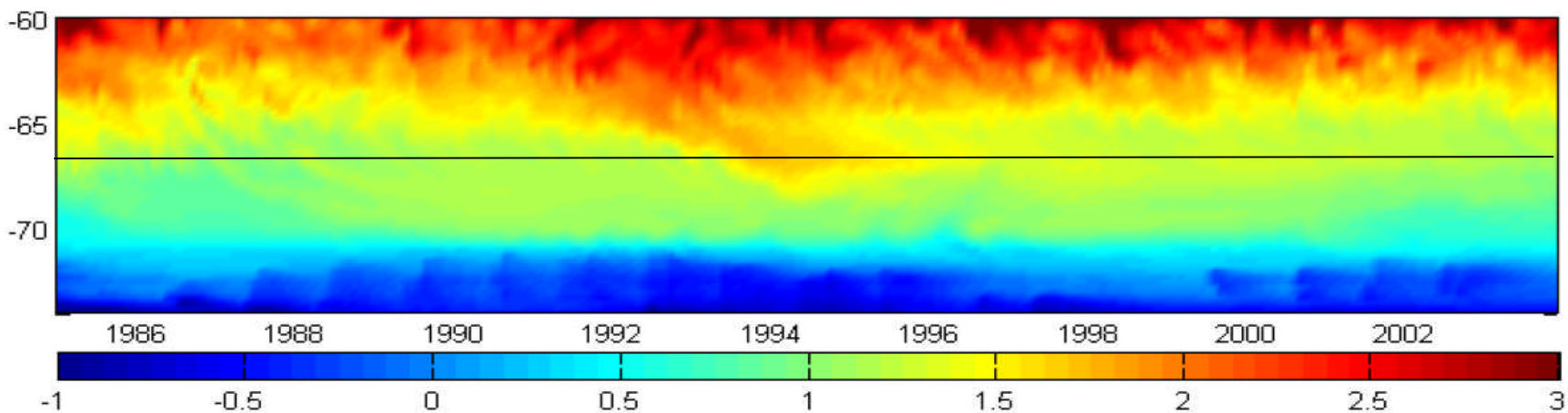






Max. water temperature as a function of latitude and date



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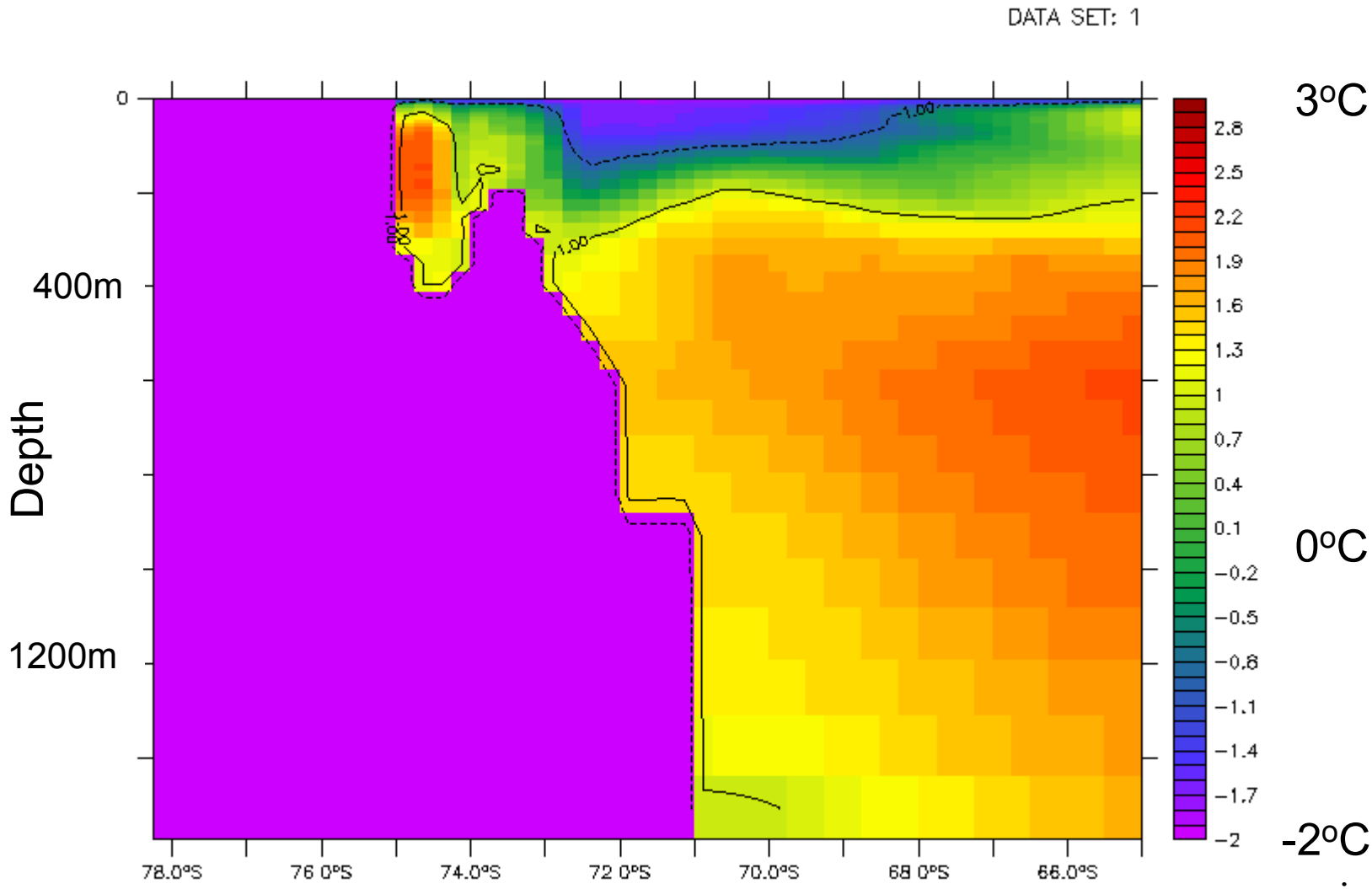
OCCAM potential temperature

Monthly means varying with depth and latitude from 1985-2003, in vicinity of Pine Island Glacier



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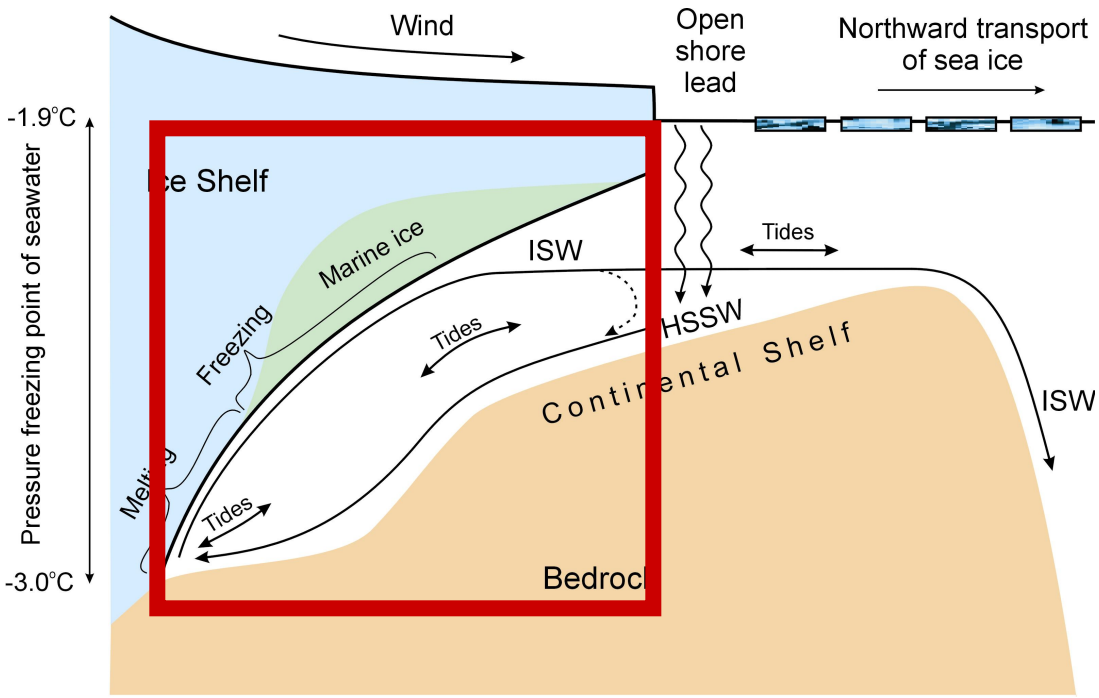
B. Coupling ocean to ice

Interaction of ocean and ice within cavity dominated by plume of buoyant, melt-rich water that flows along underside of shelf



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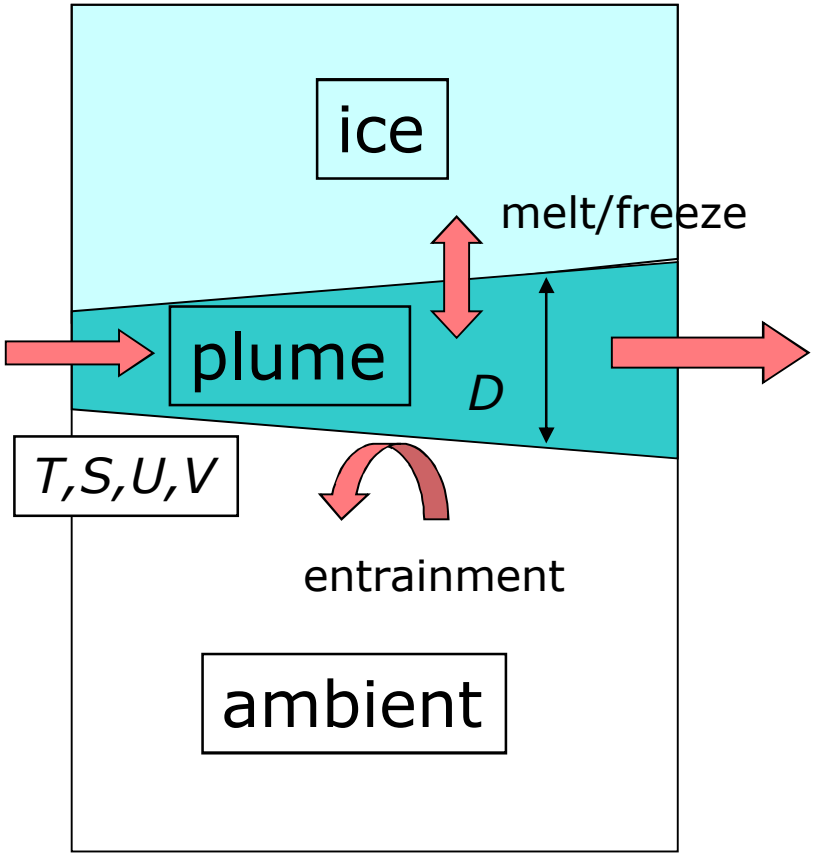
Numerical model

- vertically integrated, time dependent
- mass balance gives plume depth (D) incorporates melt and entrainment
- horizontal momentum balances (U and V) (Coriolis, lateral and surface drag, buoyancy etc included)
- temperature (T) and salinity (S) transport with lateral mixing
- linearized equation of state for density
- run to equilibrium in ~ 10 days



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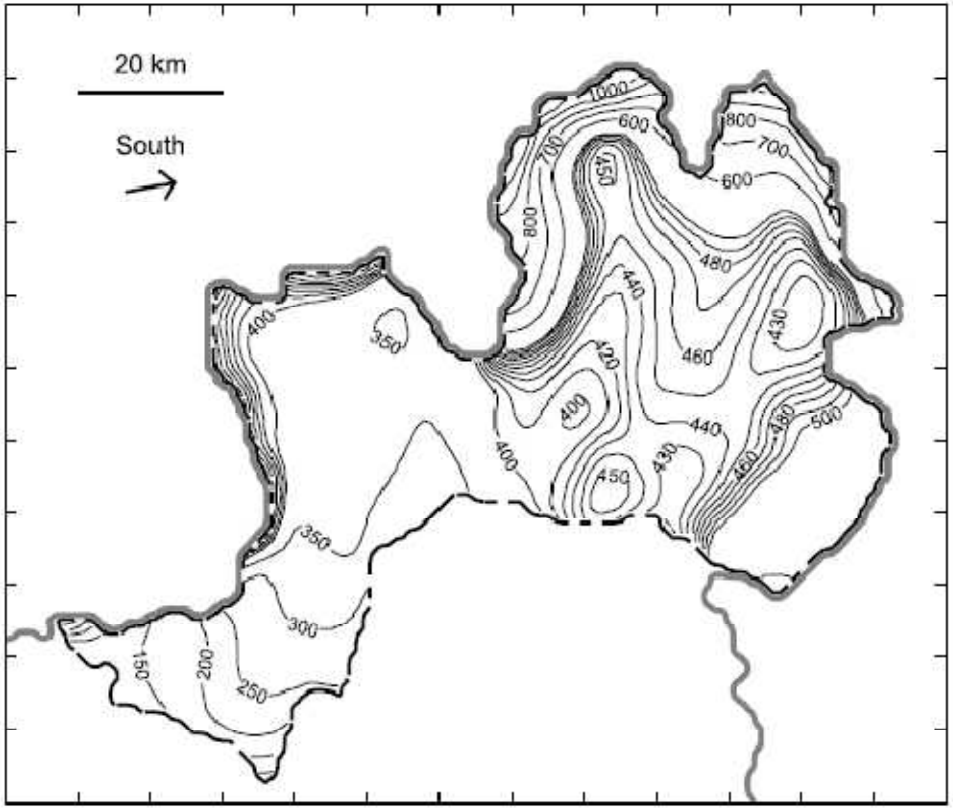
Shelf topography

- relationship between upper-surface elevation and thickness obtained from Corr and others (2001) flight lines
- relationship extend to whole ice shelf based on Bamber DEM
- grid resolution of 1 km

Depth of ice shelf base (m)



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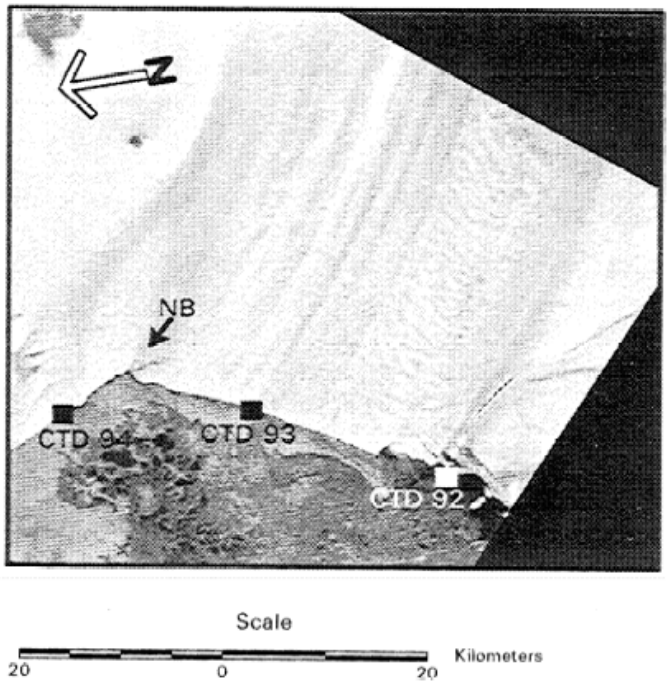
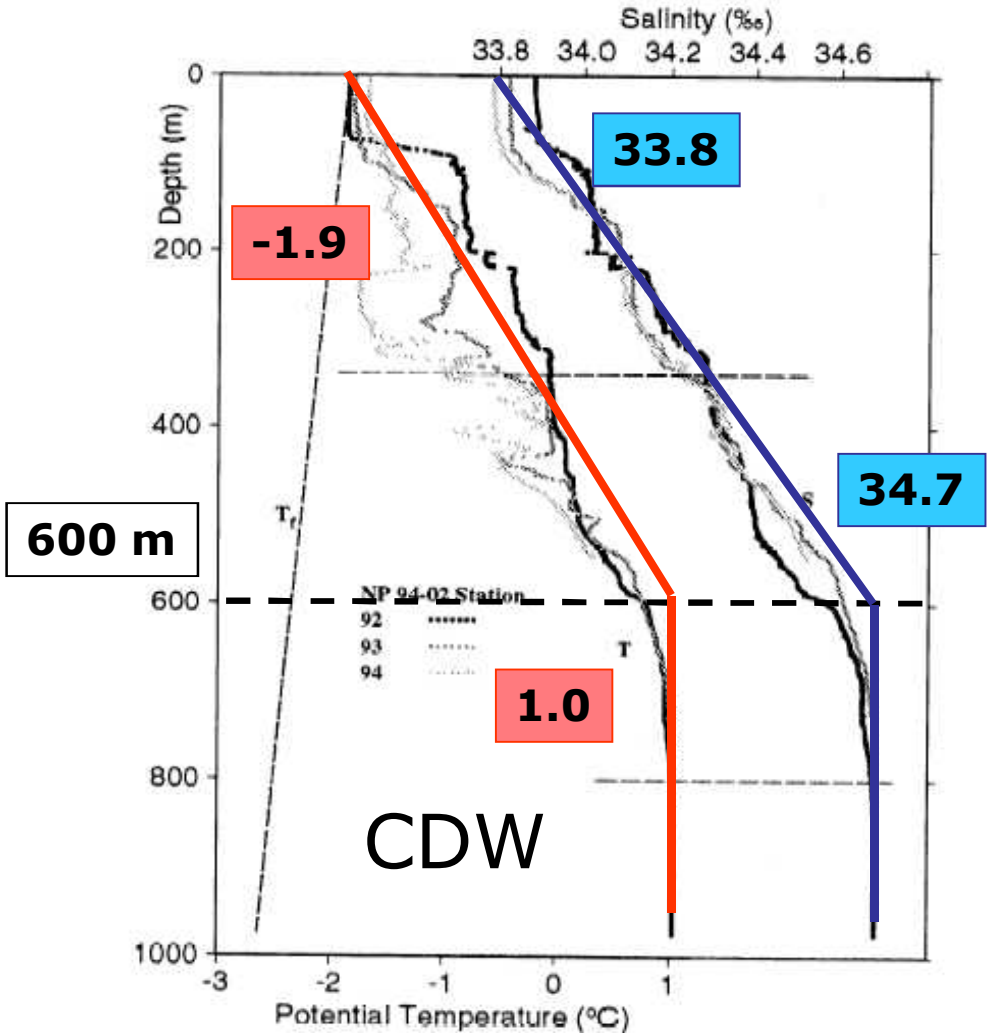
Entrainment of ambient water

- 1994 profiles of ambient temperature and salinity from Jacobs and others (1996)





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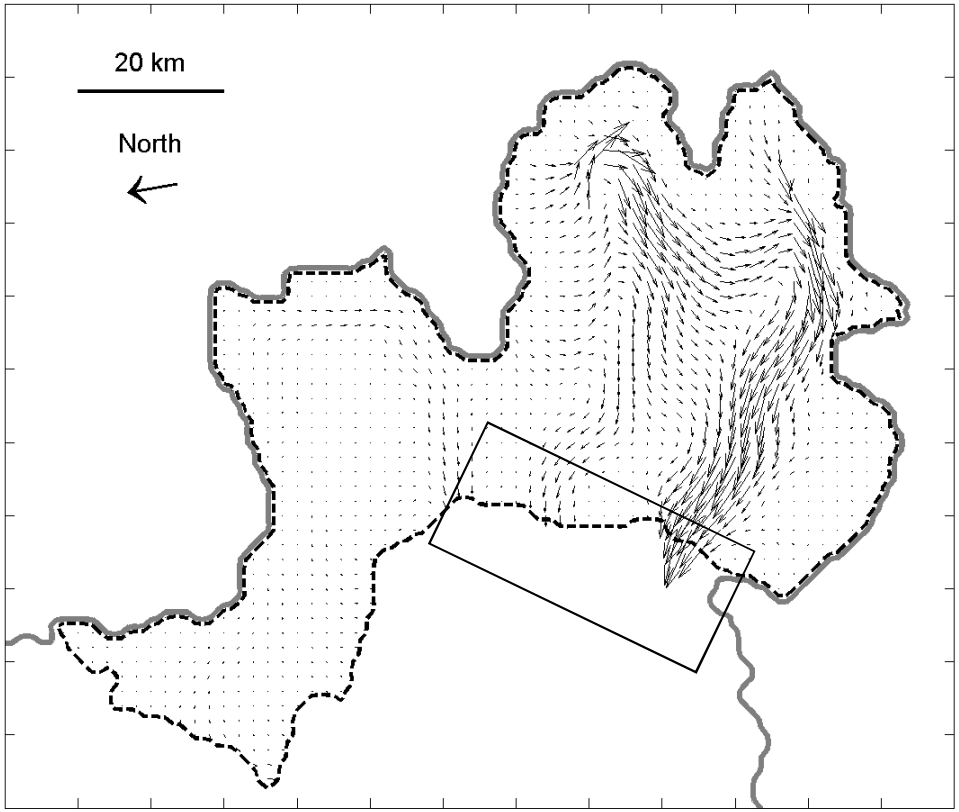
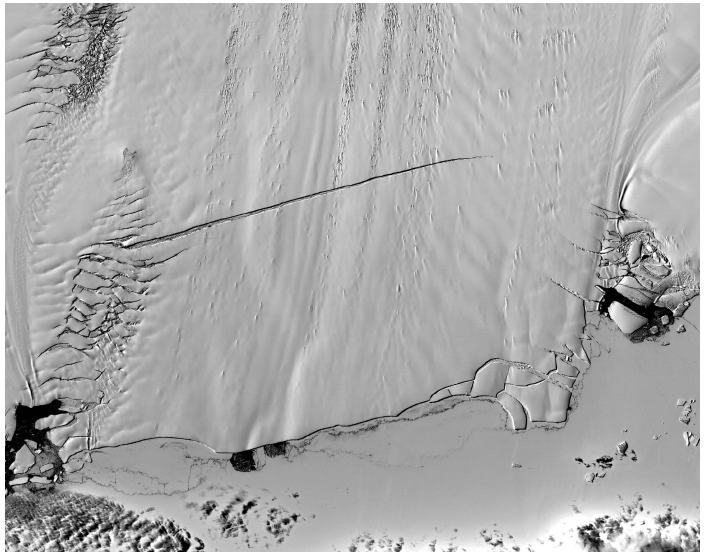
Path of plume





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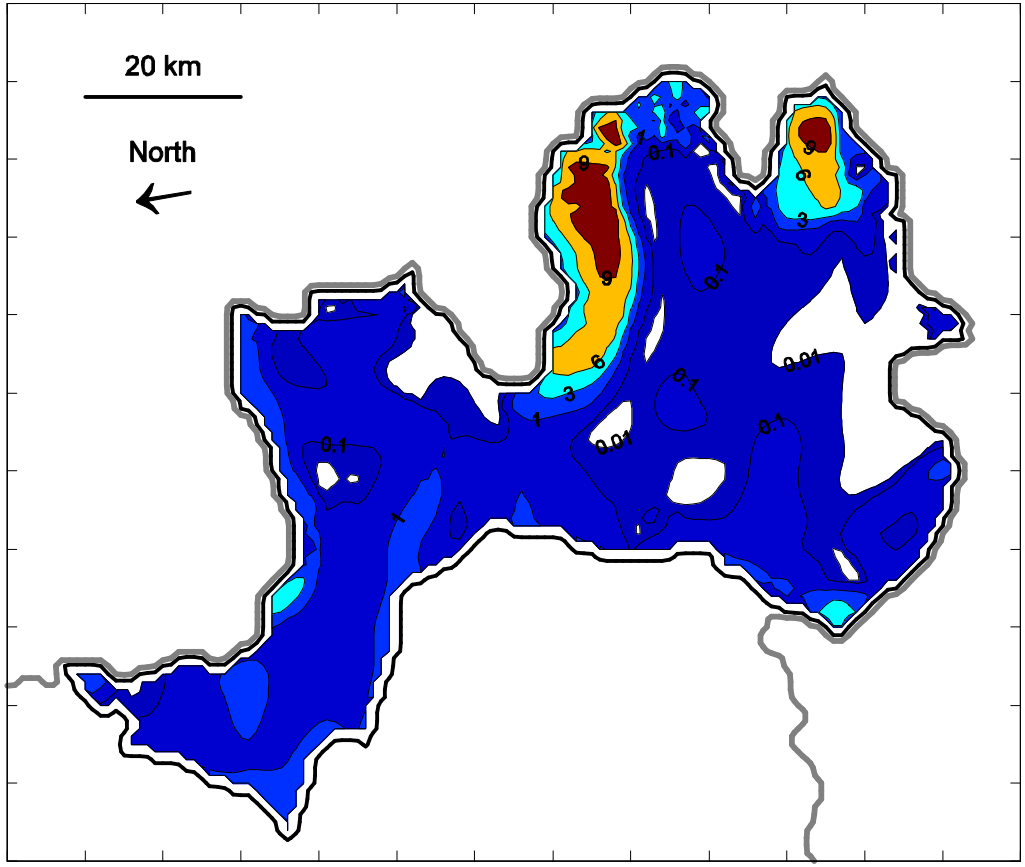
Mass balance

- entrainment comprises 99% of the mass input to the plume
- entrainment concentrated at depth close to the grounding line

Entrainment rates in km yr^{-1}



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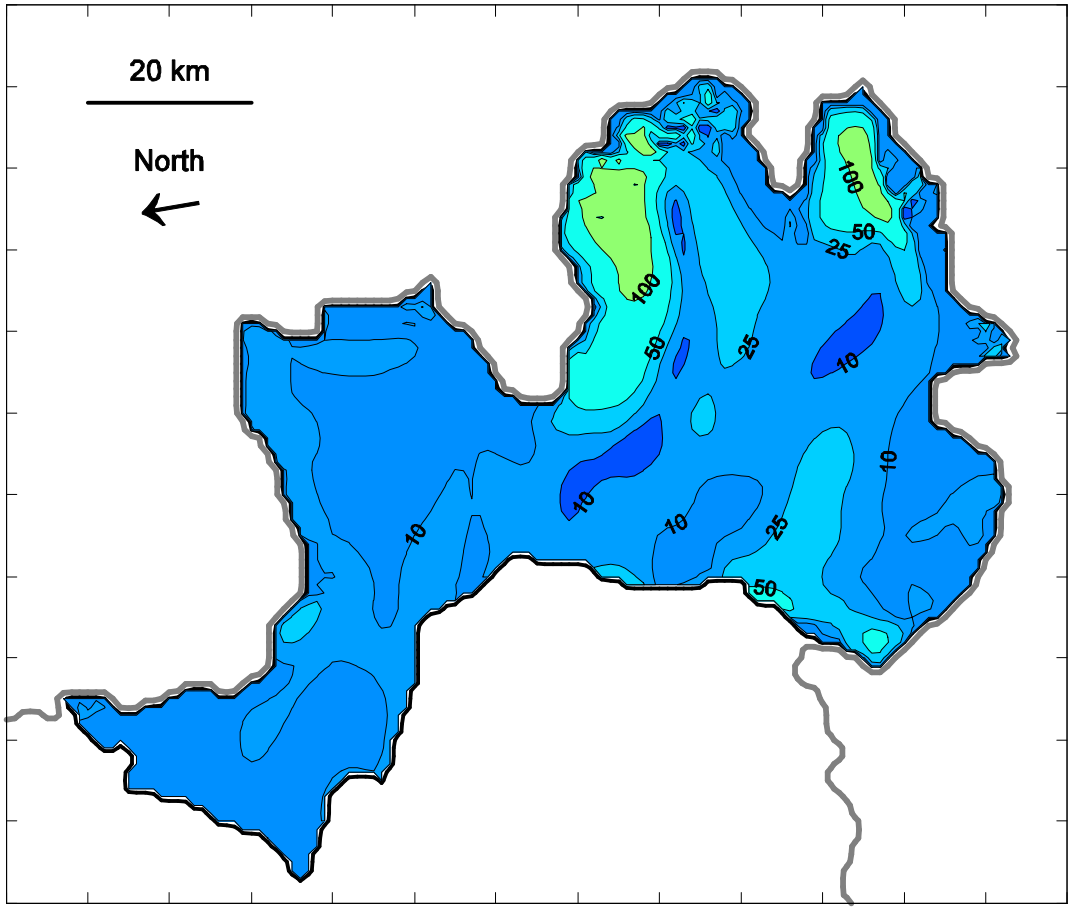
Mass balance

- very high melt rates predicted with 10 km of the grounding line
- secondary pattern governed by path of plume
- modelled tuned to reproduce mean melt rates obtain from ice-divergence calculations (see later)

Melt rates in m yr^{-1}



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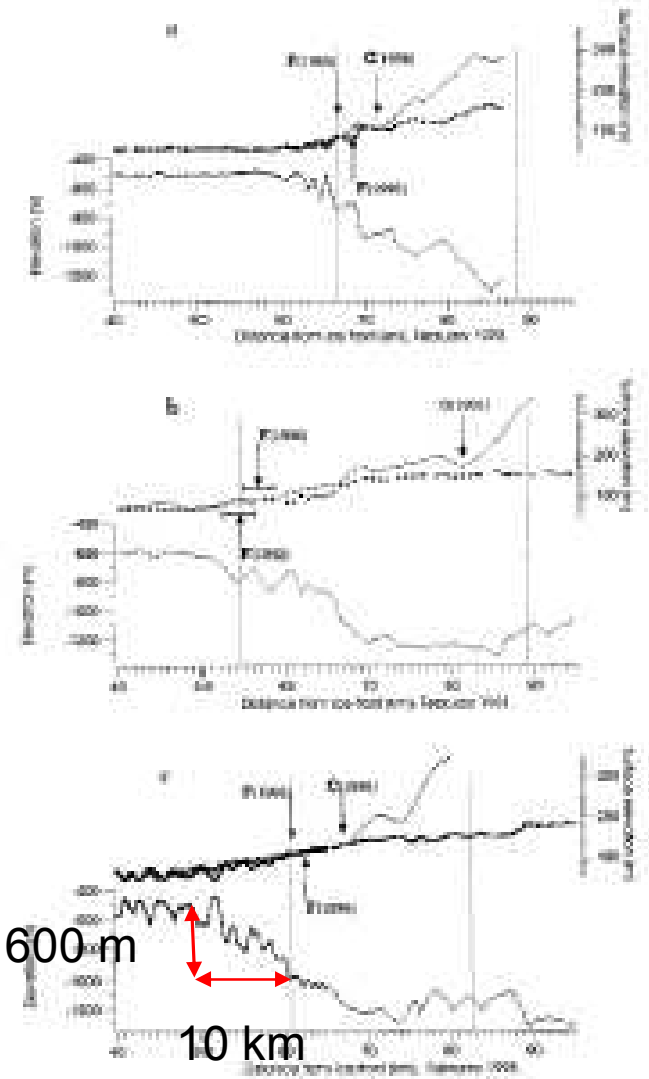
Quick estimate …

- assuming ice velocity of 2 km yr^{-1} gives transit time of 5 yrs for 10 km
- estimate melt rate based on thickness reduction in this time
- two 1988 BAS flight lines give melt rates of 83 and 120 m yr^{-1}



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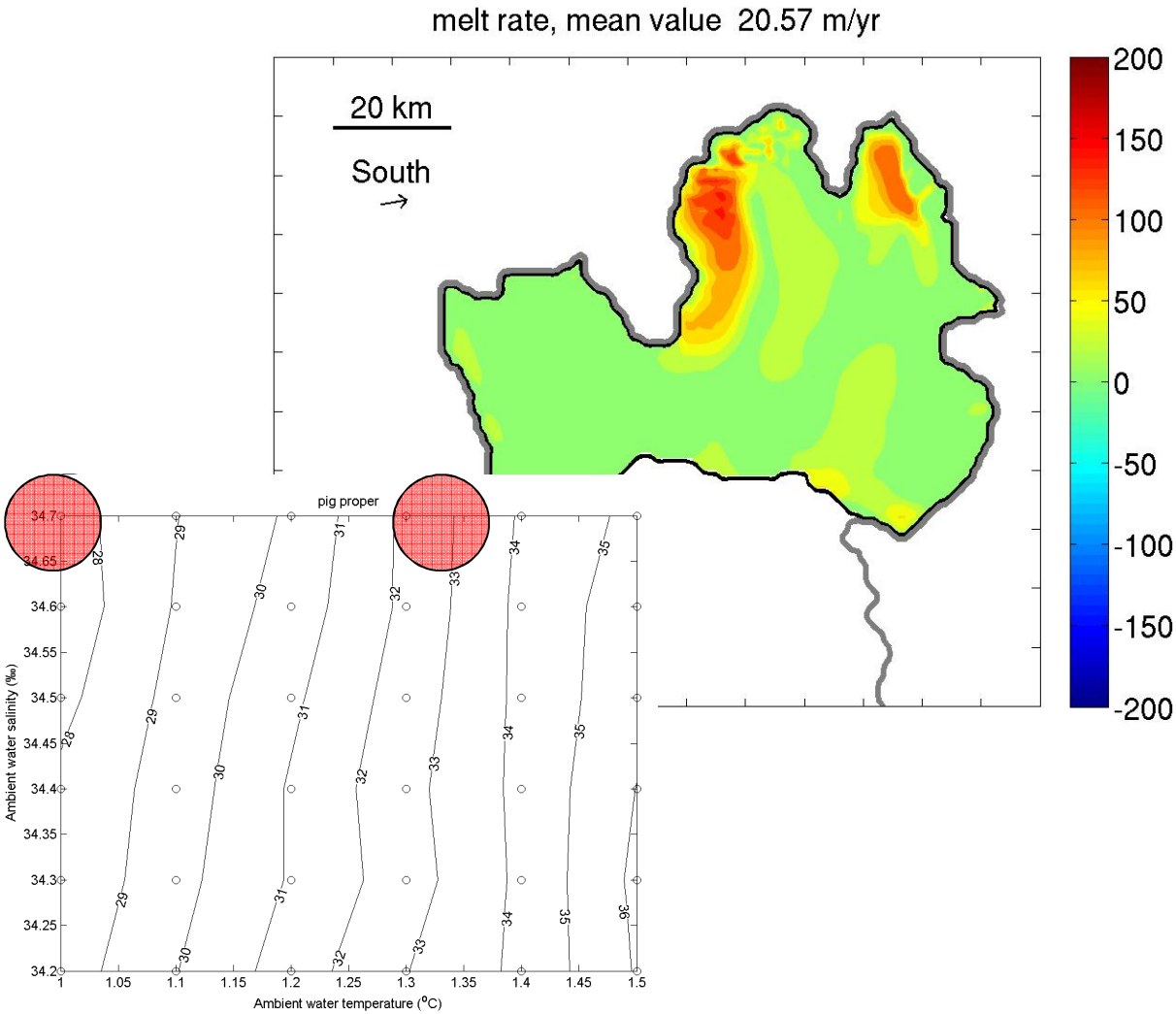
Perturbation of ambient water mass

- Pine Island ice shelf observed to be thinning at ~4 m yr^{-1} (Shepherd and others 2004)
- can estimate magnitude of warming needed to generate this change of melt
- ~0.3 °C is close to OCCAM and observed variability



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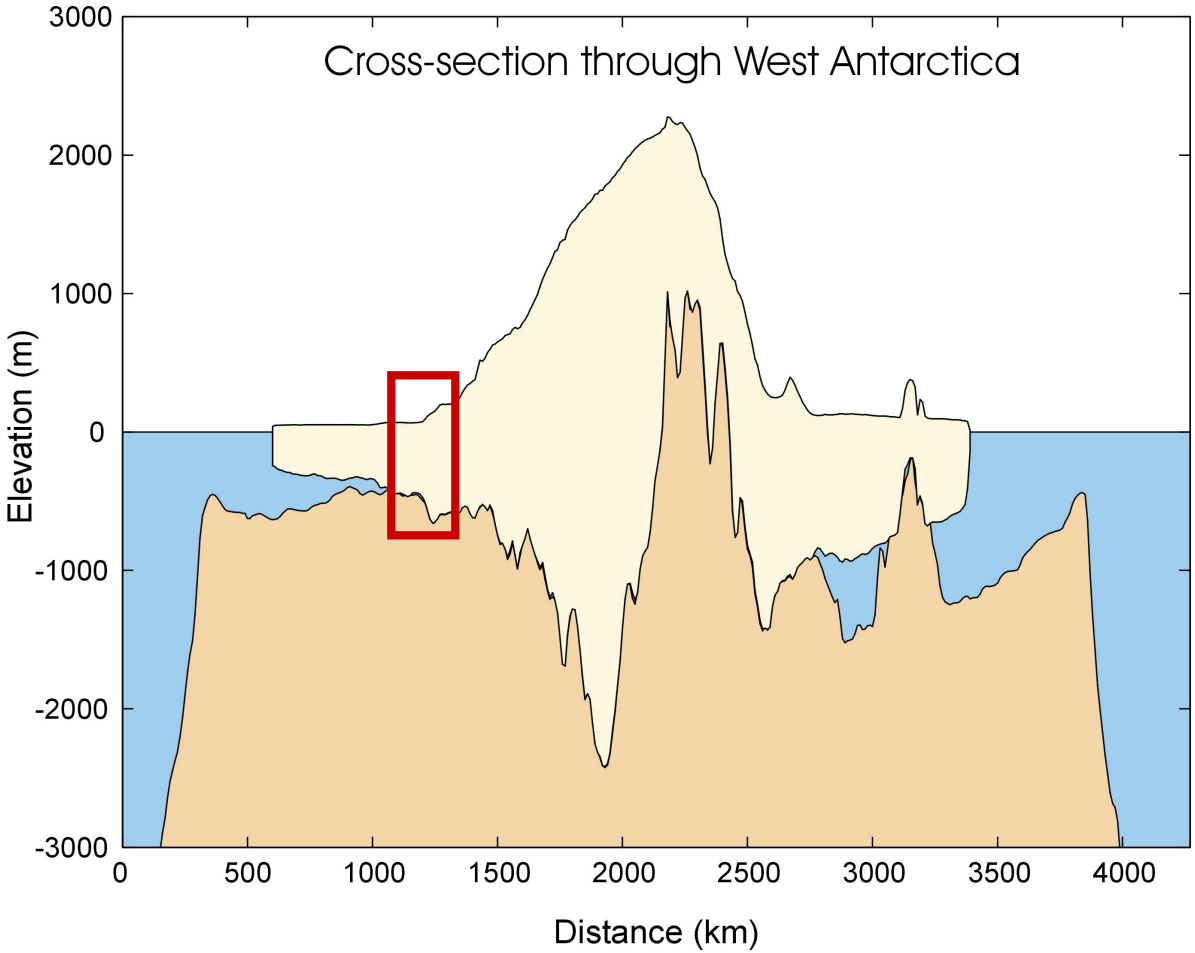
C. Numerical modelling of GL migration

Full effect of ocean warming can only be simulated if GL allowed to retreat

There are long-standing issues with the modelling this process

A robust numerical model has yet to be developed



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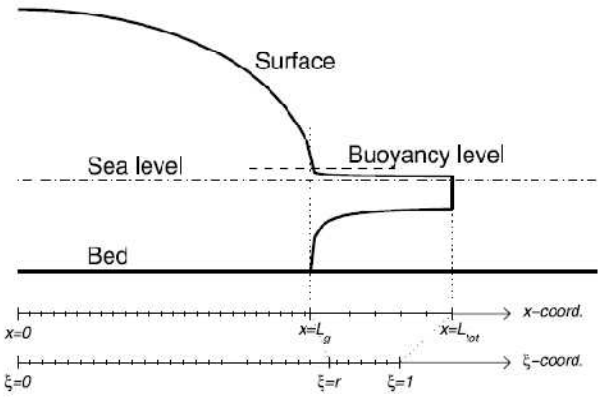
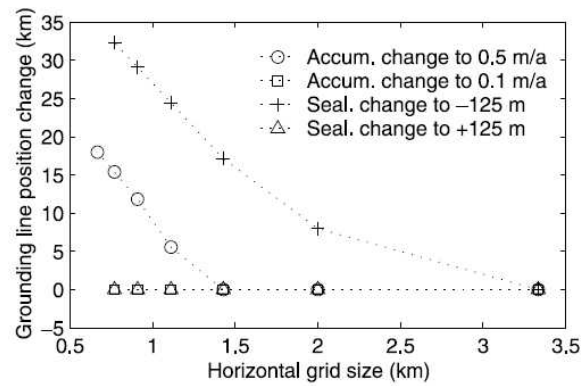
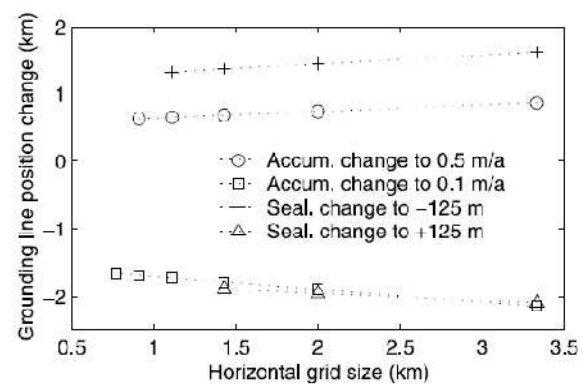
Issues

- work by Vieli and Payne (2005) showed that fixed grid can not model migration well
- in 1-d. a stretched coordinate systems works but difficulties in implementing in 2-d.
- grounding line affects both basal traction and gravitation driving (break in surface slope)
- recent theoretical advances (e.g., Schoof) suggest problem is at least solvable
- also issues associated with incorporating ice streams with width <50 km







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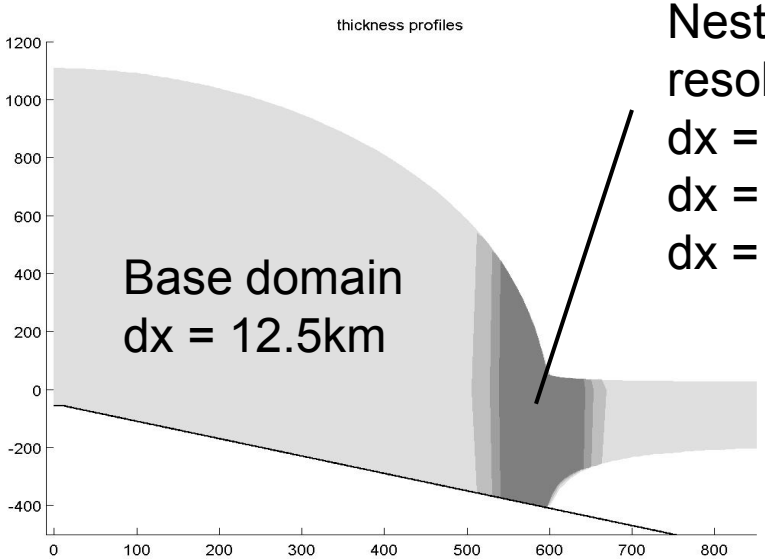
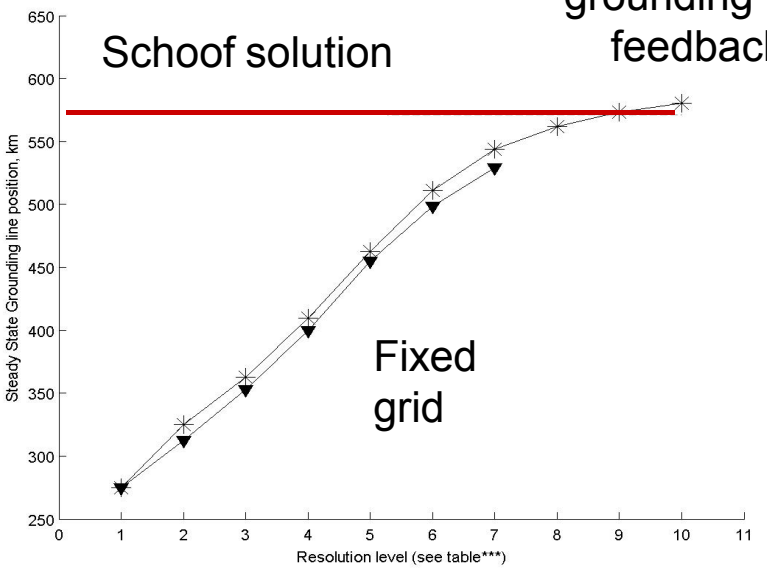
Adaptive Mesh Refinement



Nests, doubling resolution
dx = 6.3km,
dx = 3.1km,
dx = 1.6km etc…

Mesh refinement with grounding line feedback



12.5km 200m 25m

suggests grid at grounding line may still have to be < 1km

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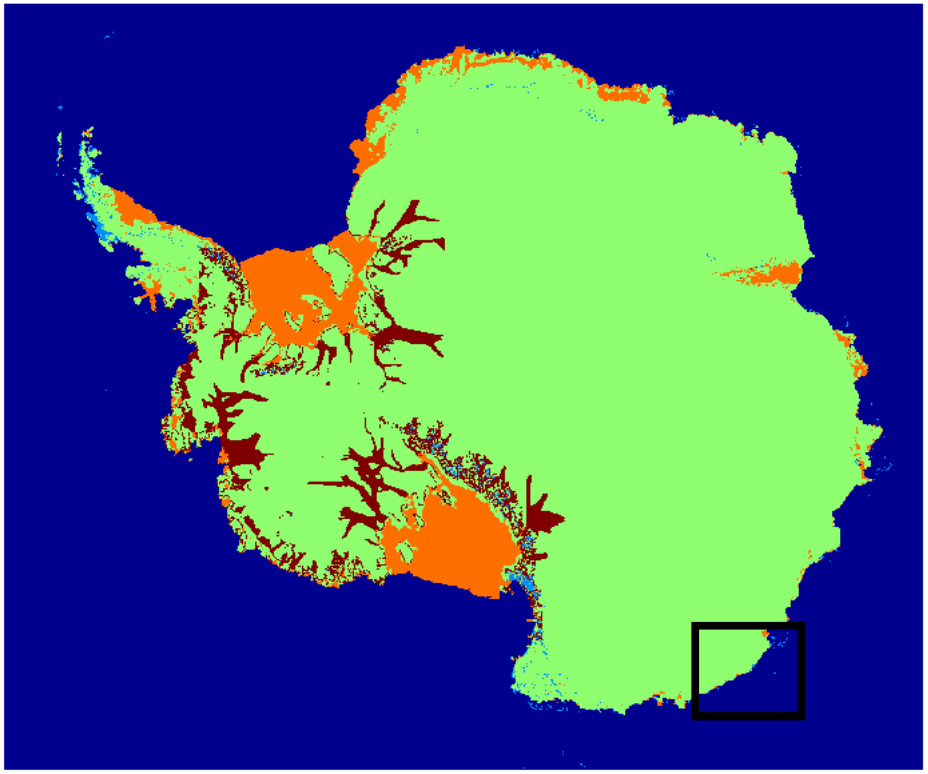
Nested grid

- need to solve 3d elliptical equations at each time step
- very computationally expensive
- can avoid some of this expense by using nested grids
- allow focus on ice streams and grounding lines



- 5 km BEDMAP dataset
- WAIS ice streams
- grounding line

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Summary

Simulate response of Antarctic ice sheet to **recent** climate change and predict **future**

What is the forcing on the ice sheet?

What physics govern the response of the ice sheet?

Oceanic variability? ✓

Atmospheric variability? ?

Direct of indirect?

Coupling between ice and ocean ✓

Stress transmission in ice masses and associated dynamics ✓

Role of basal processes ?

Migration of the grounding line ?

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