Ocean-Ice Interactions: A Cryospheric Perspective

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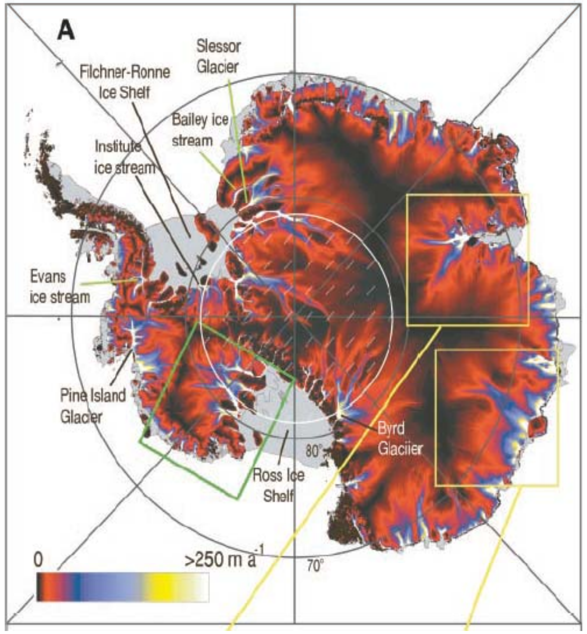
Steph Cornford, Rupert Gladstone and Dan Martin (LLNL)

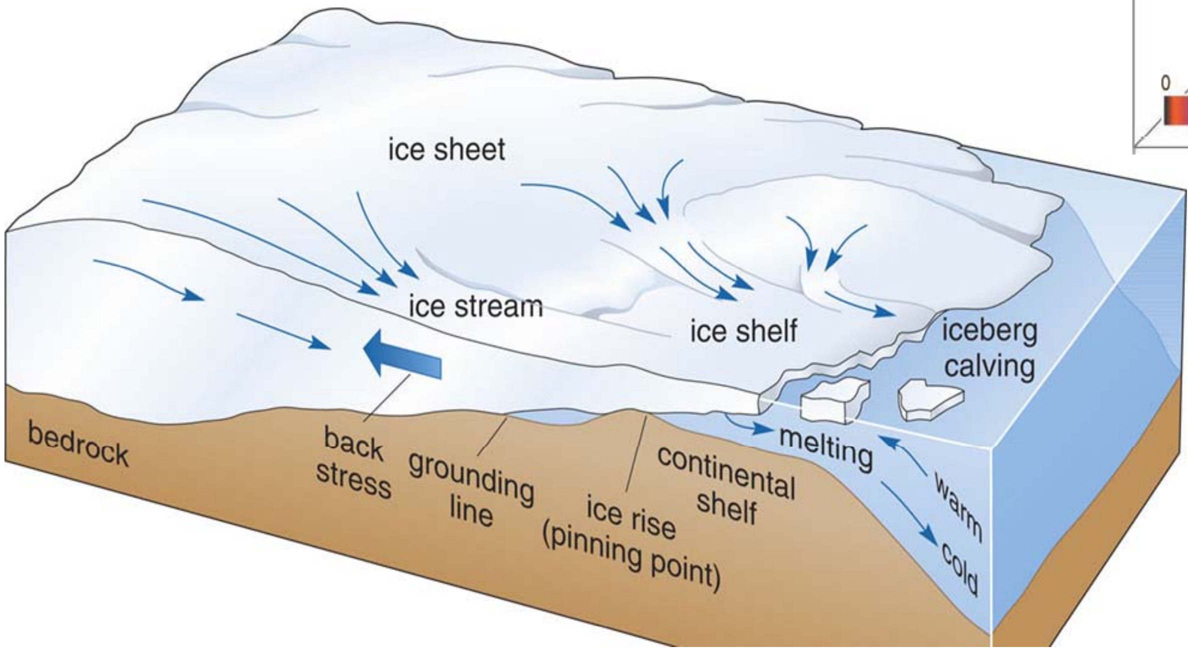
Outline

- Evidence of cryospheric response to oceans
- The Marine Ice Sheet Instability
- Flowline modelling of Pine Island Glacier
- Development and testing of an adaptive mesh model and application to PIG
- Application to West Antarctica: initialization and climate forcing

Components of an ice sheet

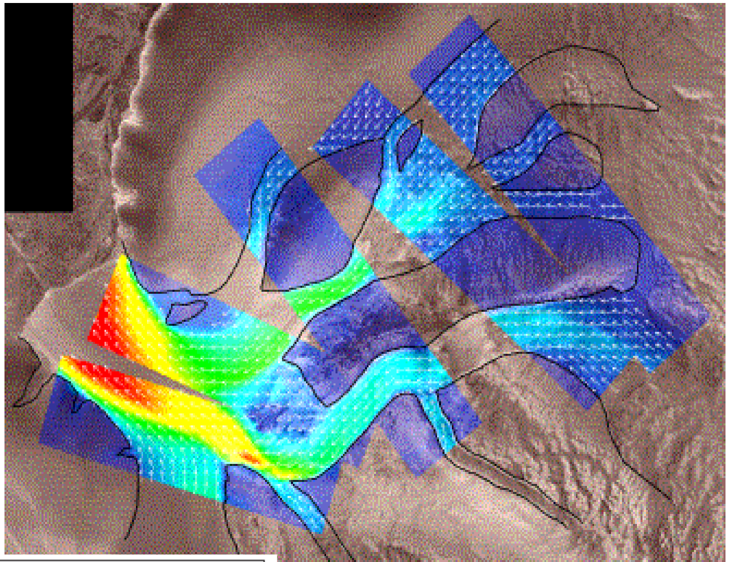
- slow-flowing interior (~10 m/yr)
- fast-flowing ice streams (>500 m/yr)
- floating ice shelves
- grounding line

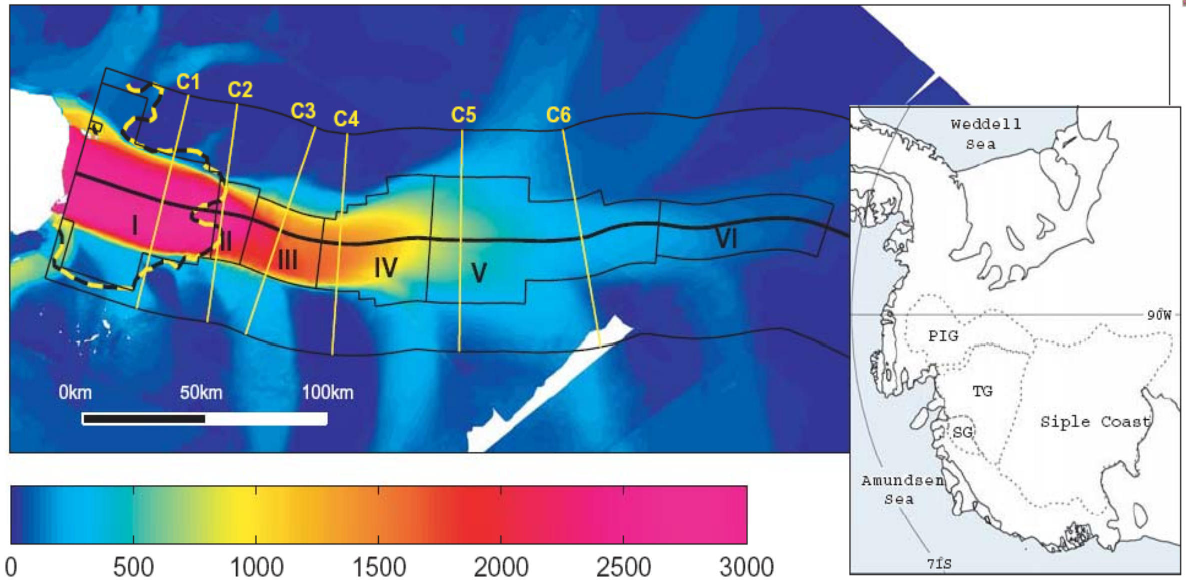


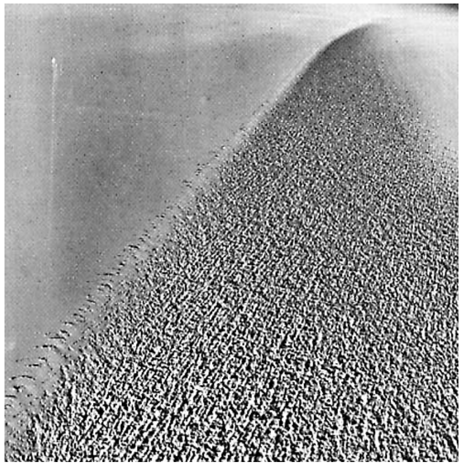


Ice streams and outlet glaciers

- sections of fast flowing ice ~50 km wide
- now thought to be crucial in dynamics of ice sheets

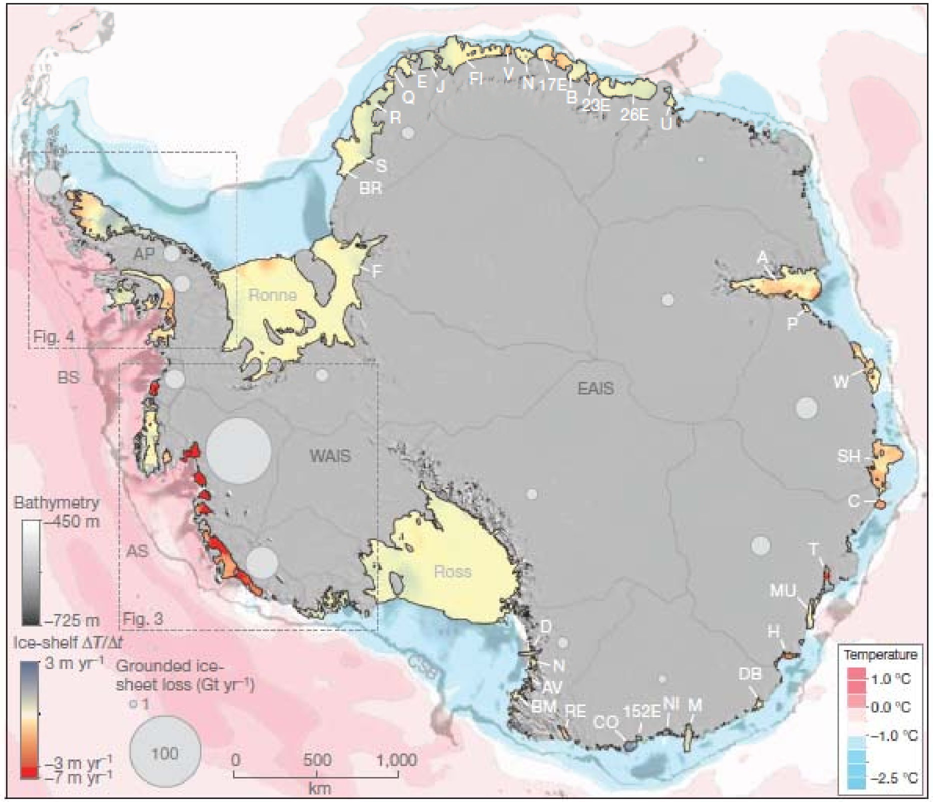


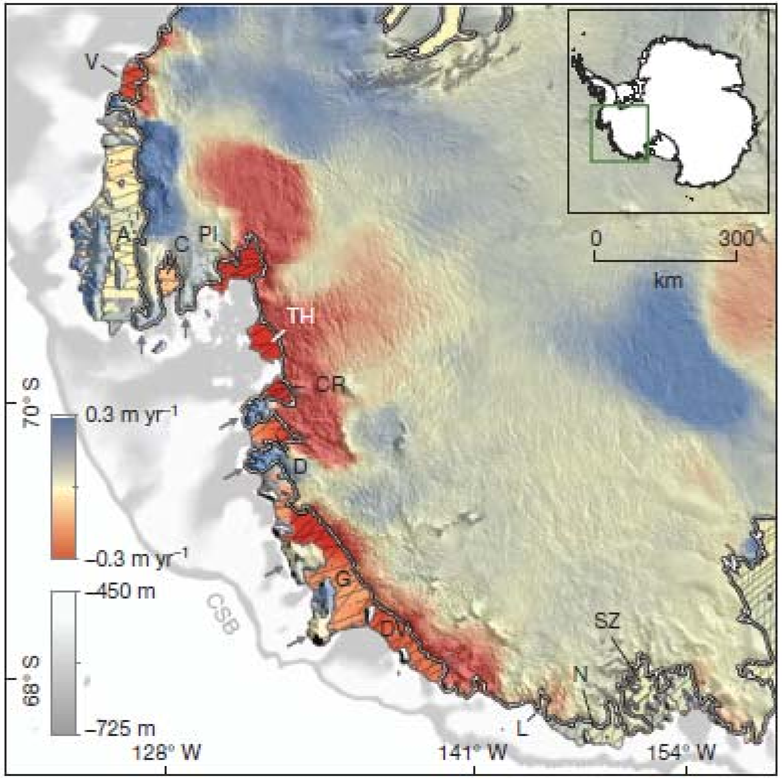




Antarctic ice-sheet loss driven by basal melting of ice shelves

H. D. Pritchard[1], S. R. M. Ligtenberg[2], H. A. Fricker[3], D. G. Vaughan[1], M. R. van den Broeke[2] & L. Padman[4]

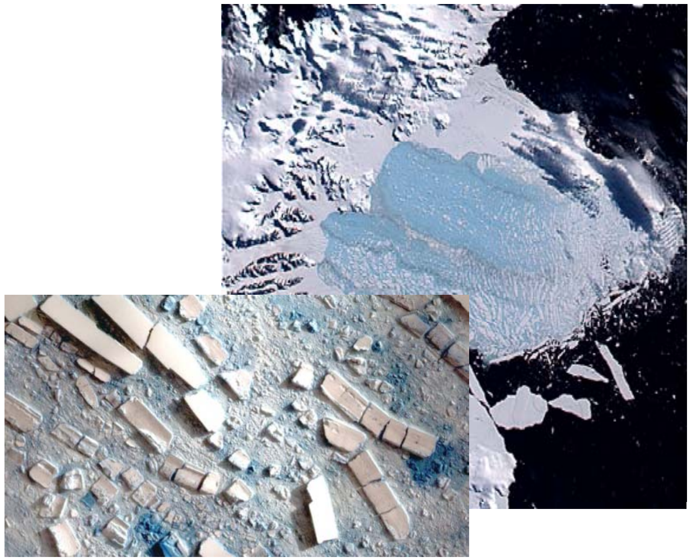


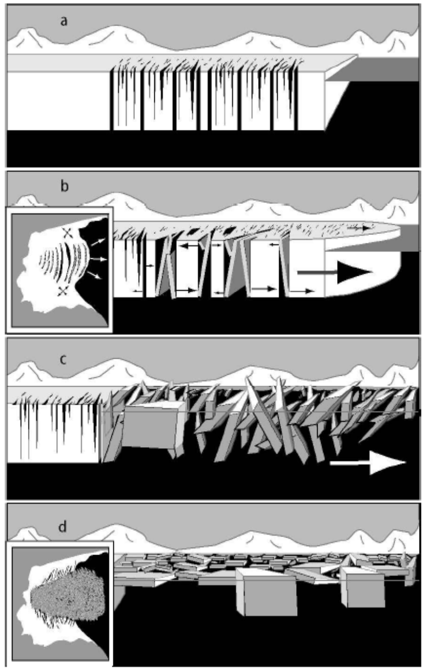


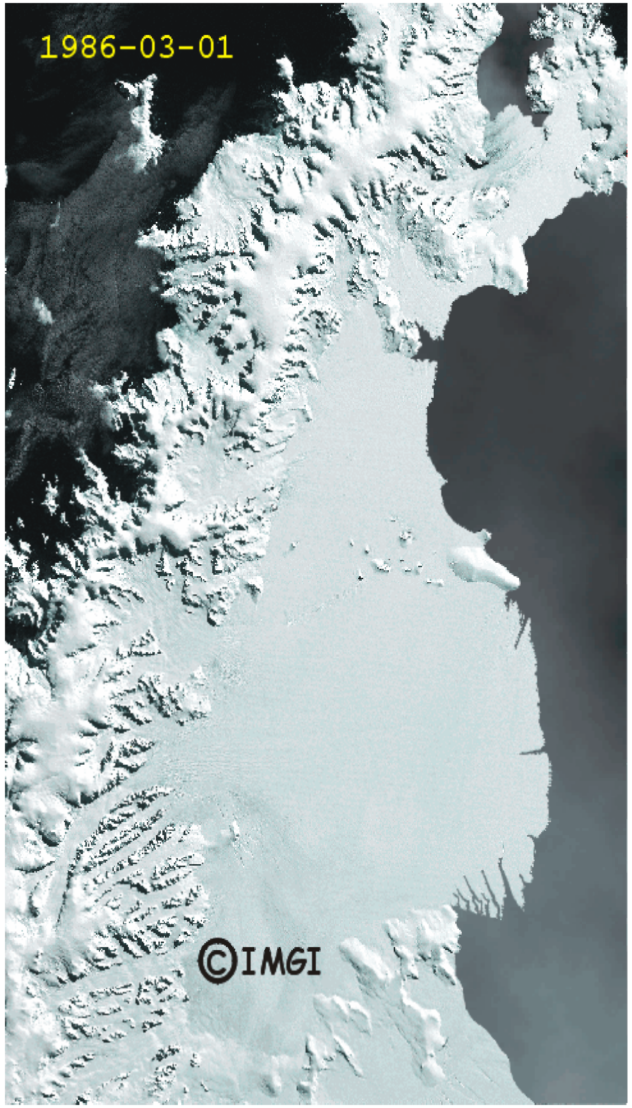
Larsen ice shelves

- collapse of ice shelf A in 1995 and B in 2002
- meltwater-driven fracture understood

MacAyeal and others 2003

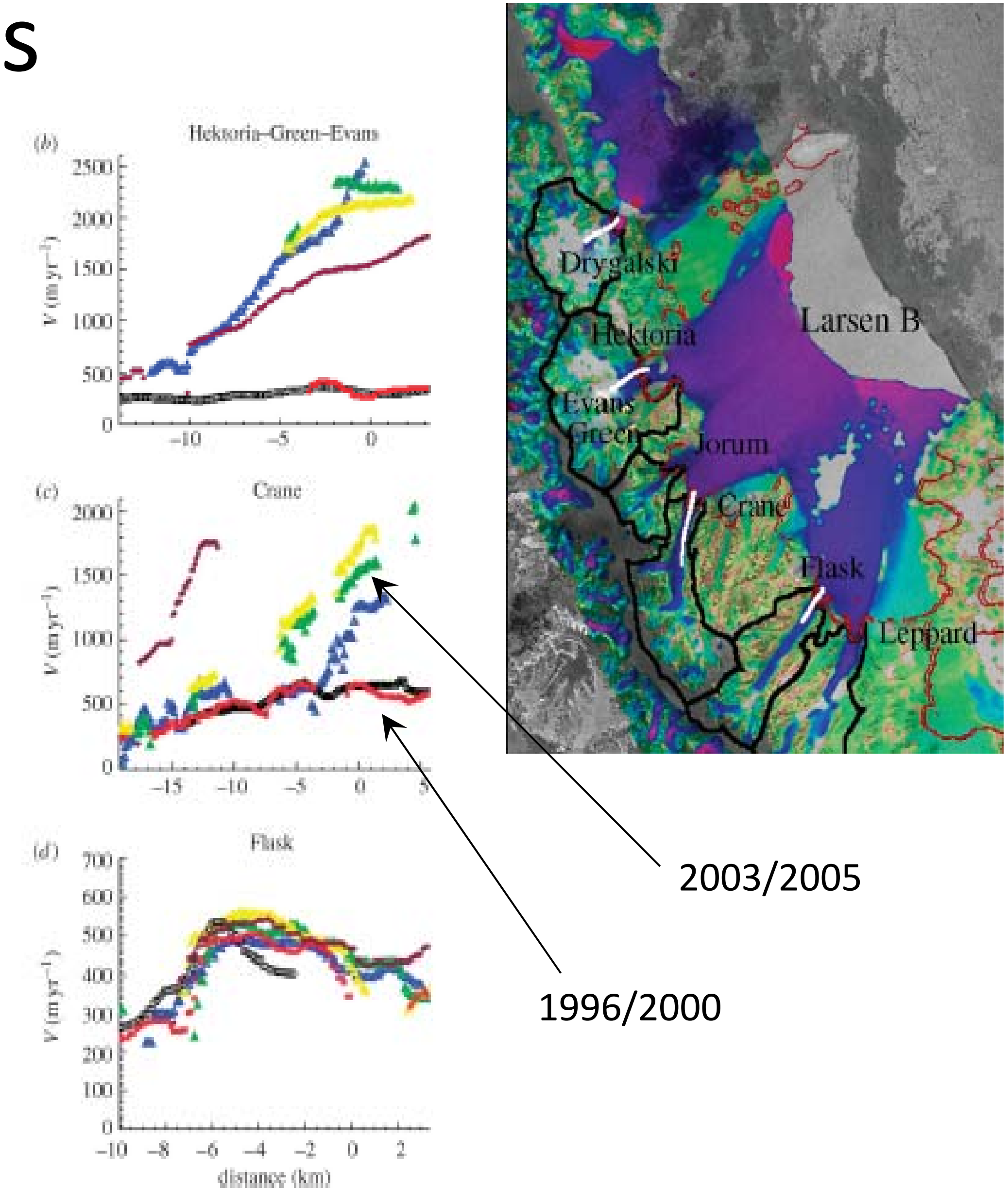






Larsen ice shelves

- minimal direct effect, however glaciers accelerated after collapse
- natural experiment testing link between floating and grounded ice

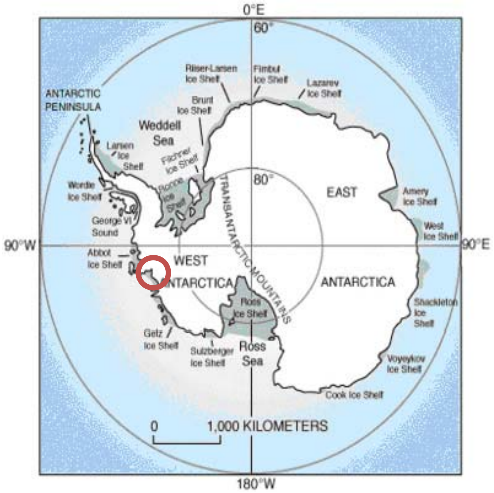


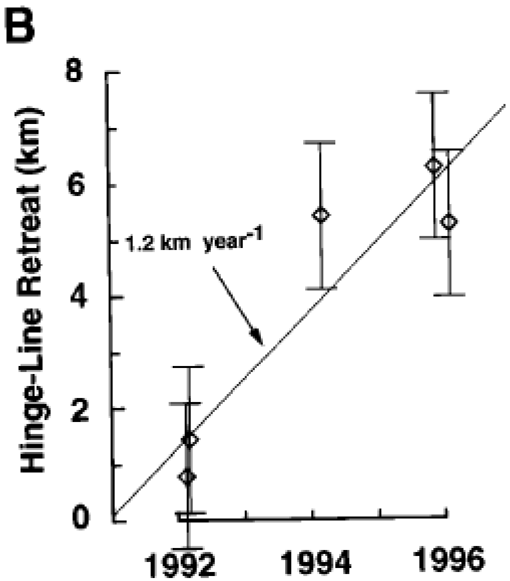
Rignot 2004
Scambos and others 2004

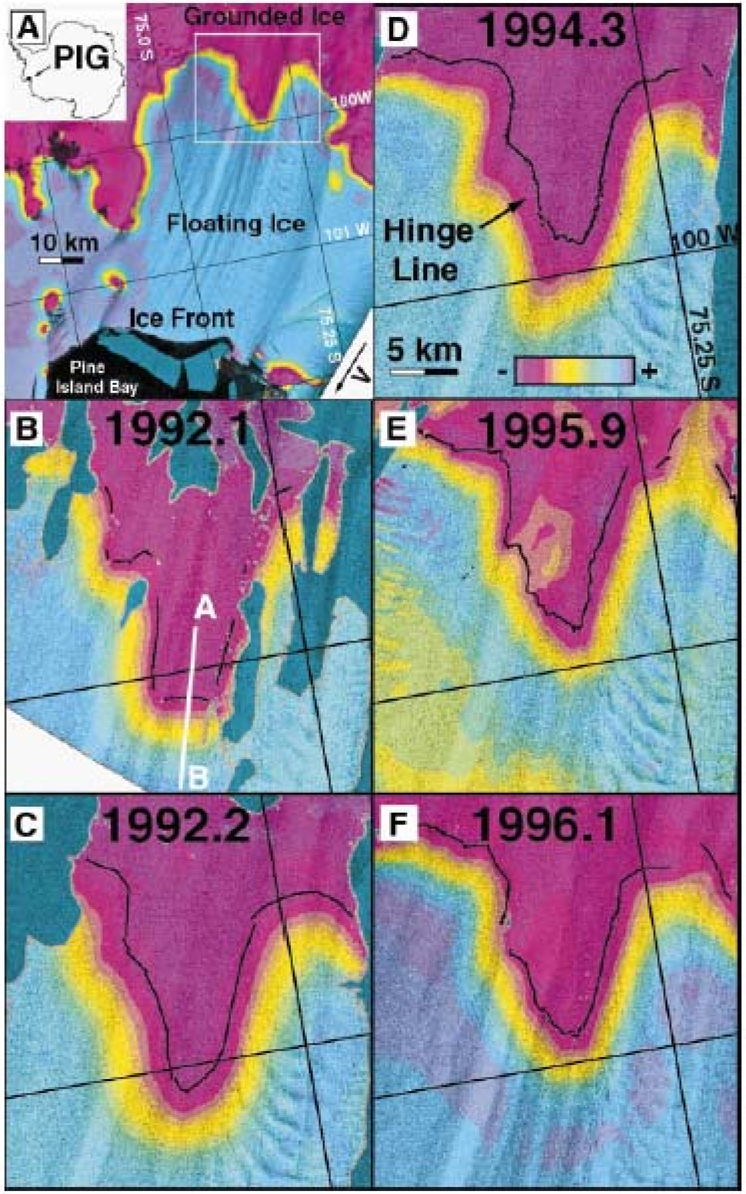
Grounding line retreat

Fast Recession of a West Antarctic Glacier

E. J. Rignot

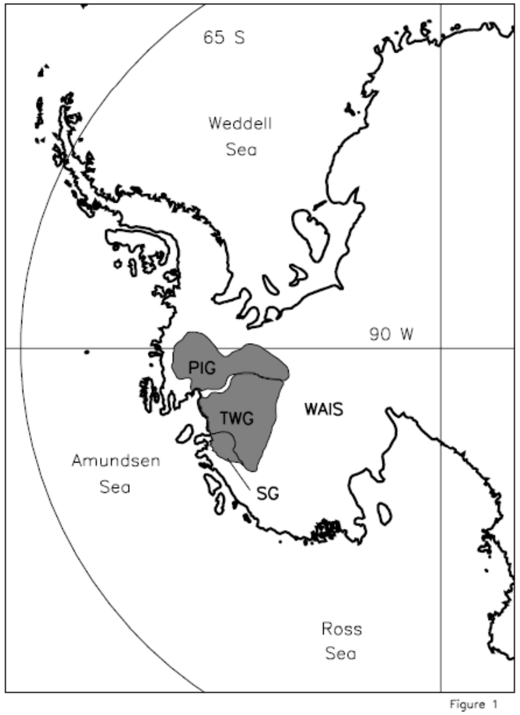


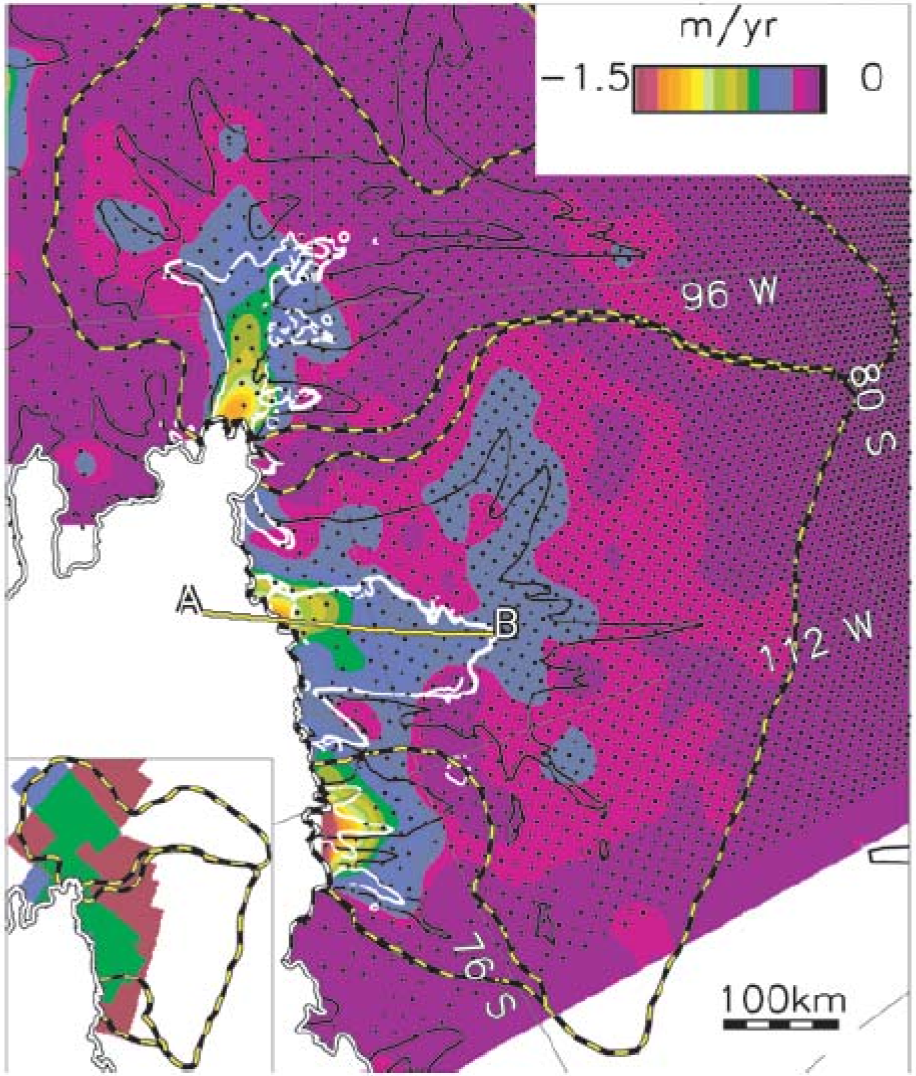




Inland thinning of the Amundsen Sea sector, West Antarctica

Andrew Shepherd, Duncan J. Wingham, and Justin A. D. Mansley



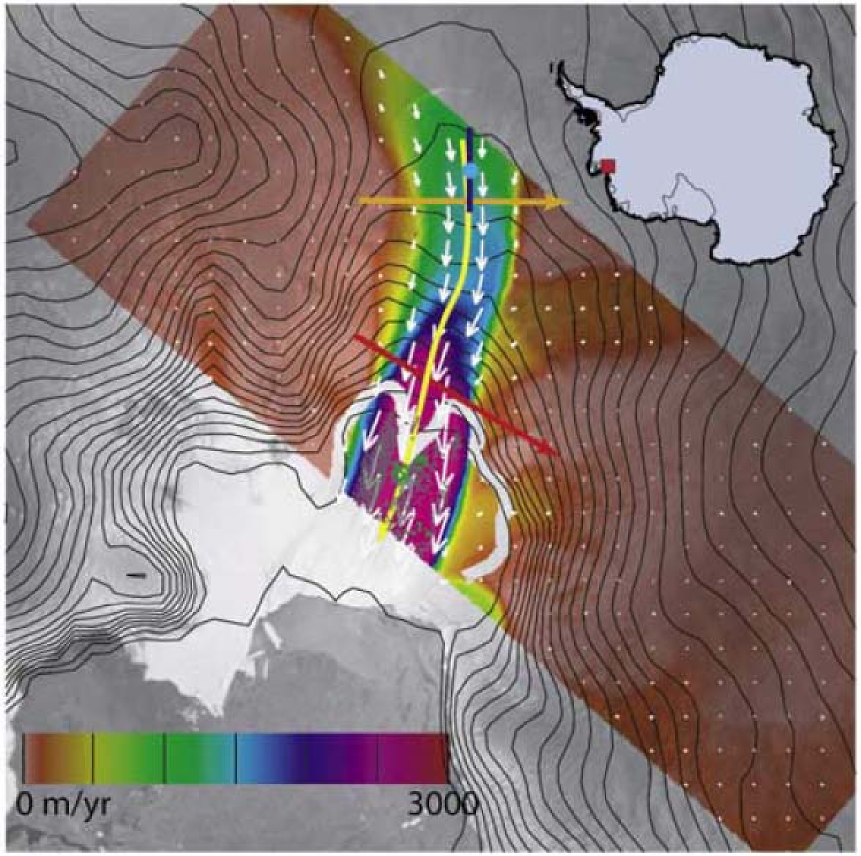


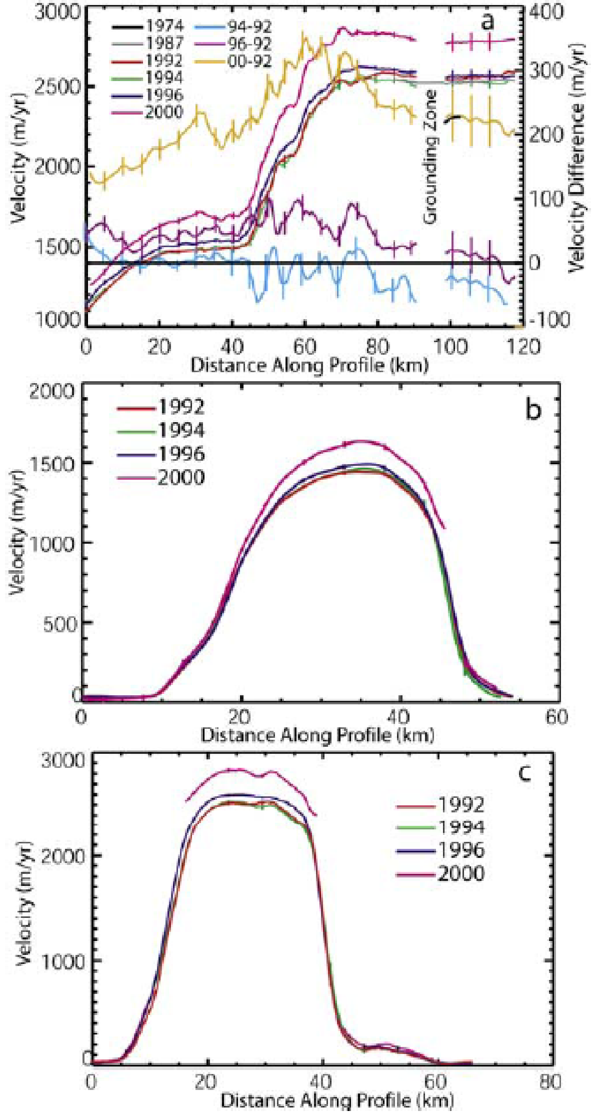
Links GL retreat to mass loss

Suggests that mass loss is limited to ice streams

Timing of Recent Accelerations of Pine Island Glacier, Antarctica

Ian Joughin,[1] Eric Rignot,[1] Christine E. Rosanova,[2] Baerbel K. Lucchitta,[3] and Jennifer Bohlander[4]





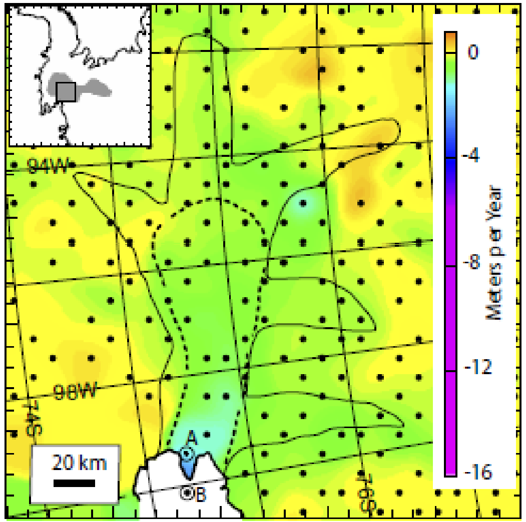
Thinning is caused by increased ice flow

Accelerating response

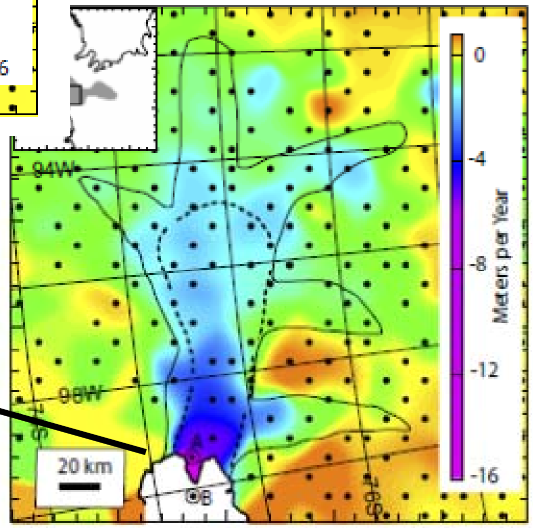
Wingham and others (2009) use cross-calibrated ERS-2 and ENVISAT radar altimetry to extend time series from 1995 to 2008

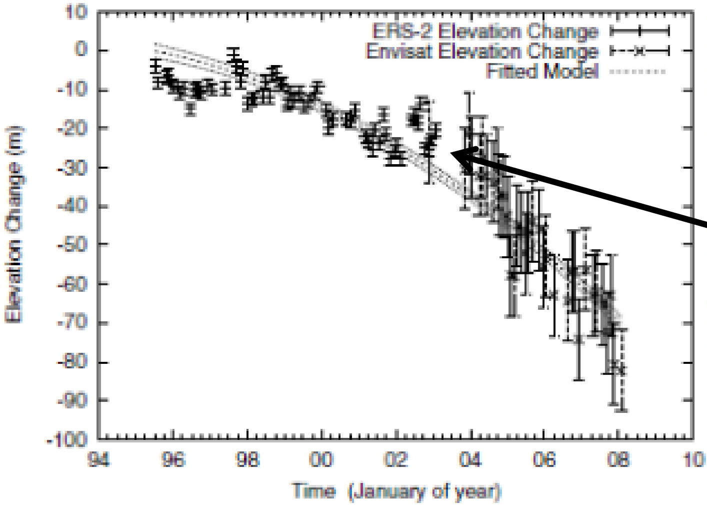
thinning rates increased fourfold

1995



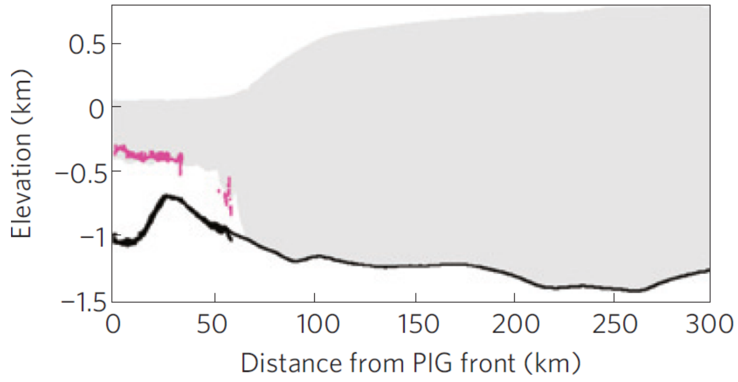
2006



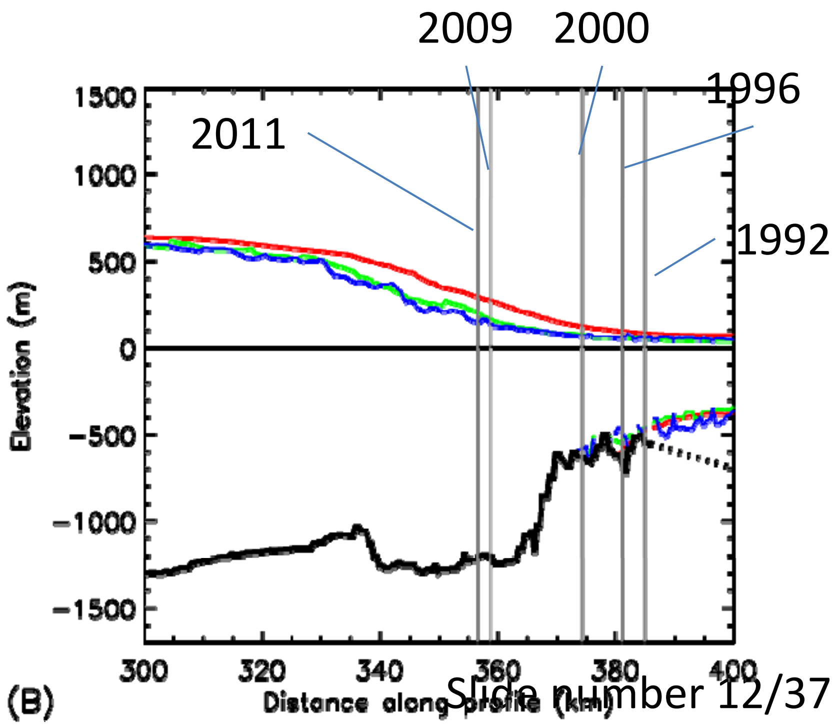


Accelerating response

- Jenkins and others (2010) identify a bedrock ridge under the ice shelf ~40 km from the current grounding line
- observed GL retreat rates consistent with GL occupying ridge in mid 1990s
- Retreat has been consistent since 1990s and accelerated through 2000s - 0.95 ±0.09 km/yr with peak 2.8 ± 0.7 km/yr



Jenkins and others 2010



Park and others (2013)

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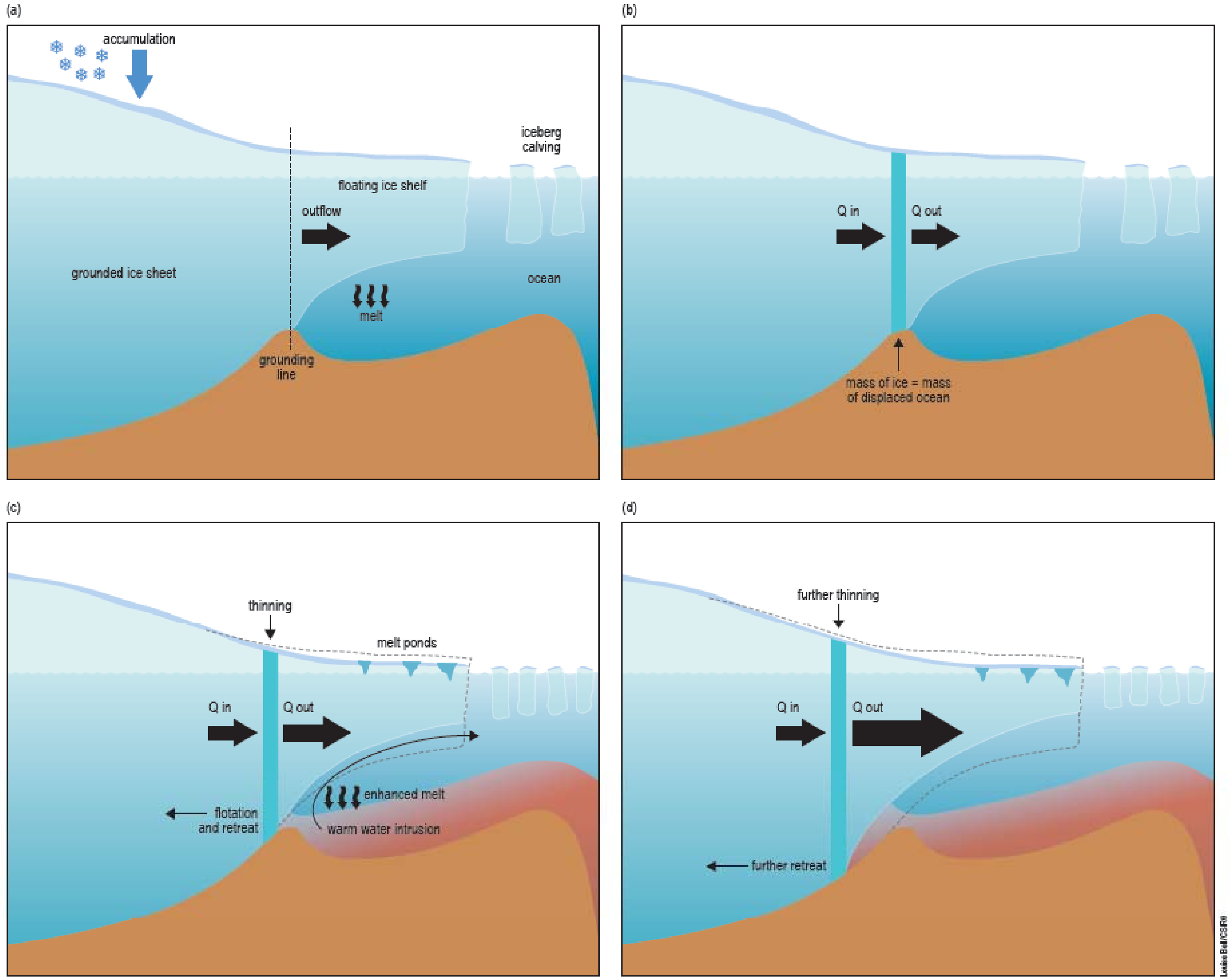
Marine ice-sheet instability



West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster

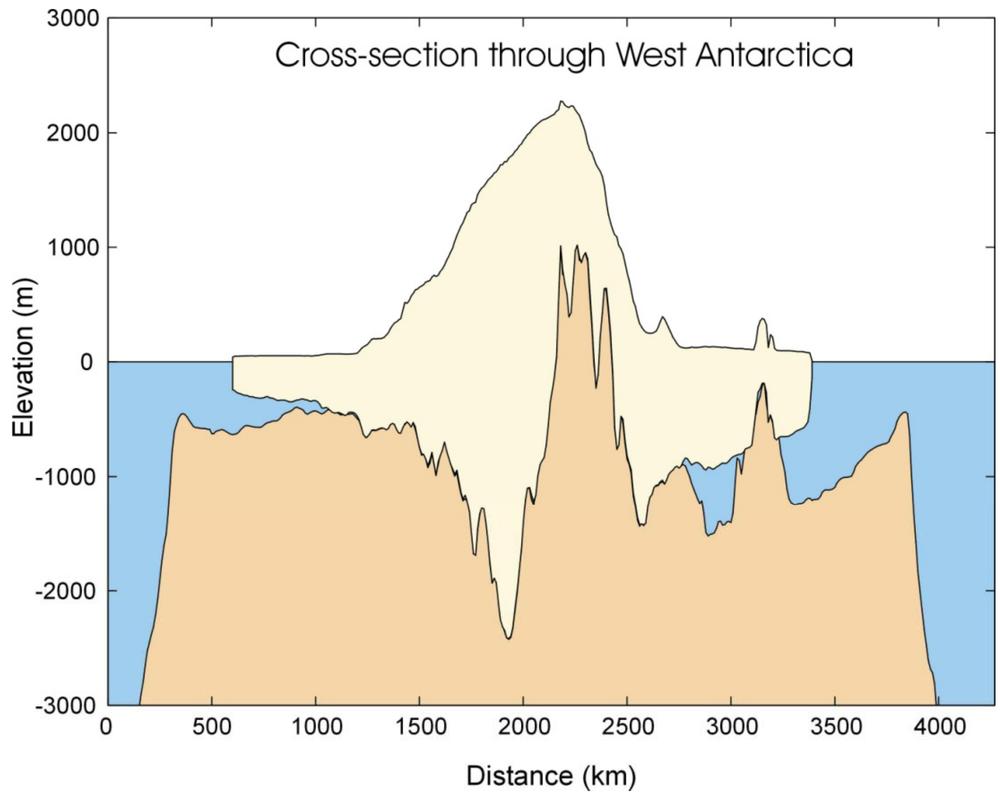
J. H. Mercer

Nature Vol. 271 26 January 1978

The Weak Underbelly of the West Antarctic Ice-Sheet

J. Glac. 1981

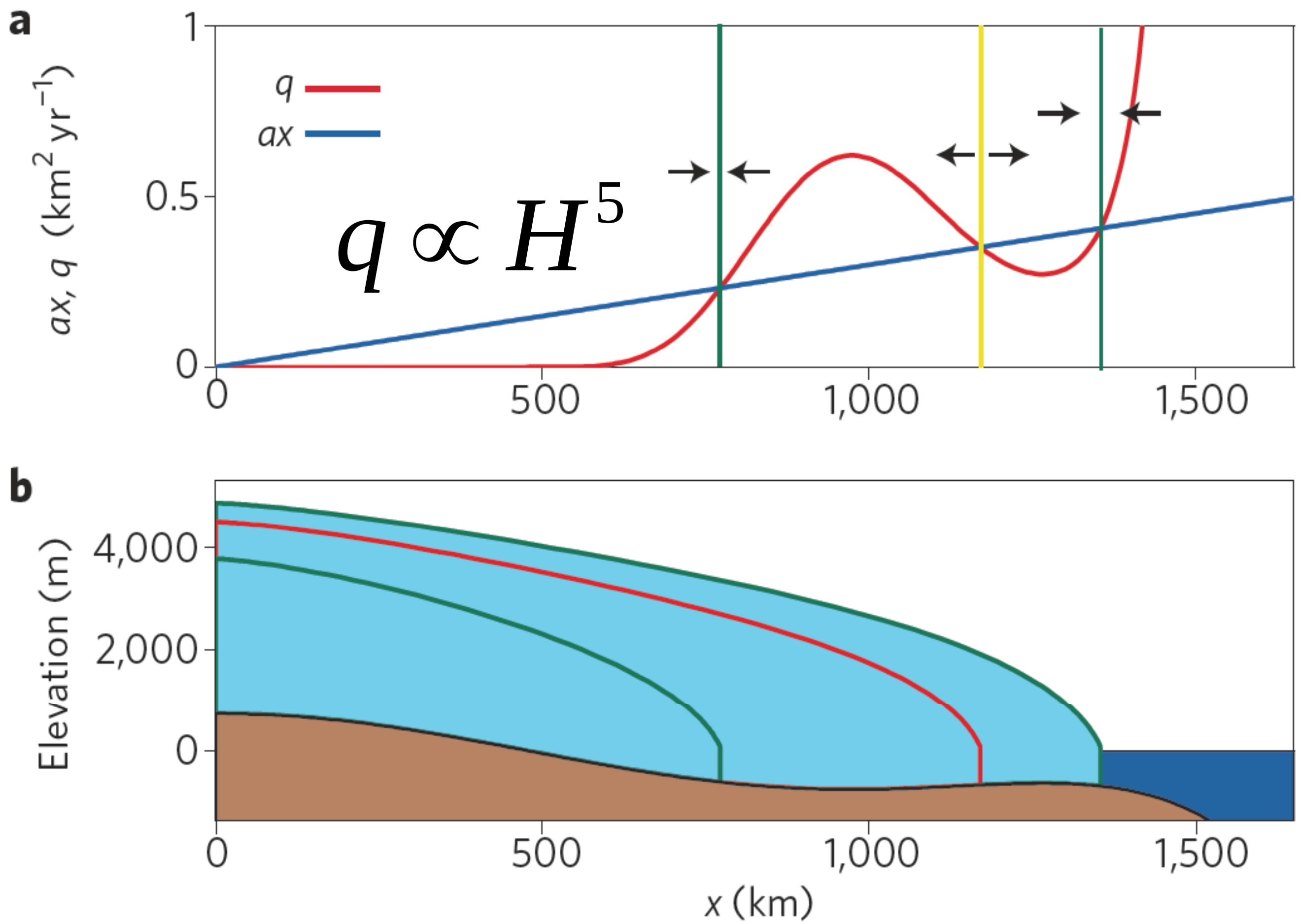
Terence J. Hughes
University of Maine - Main, terry.hughes@maine.edu



Ice sheet grounding line dynamics: Steady states, stability, and hysteresis

Christian Schoof[1]

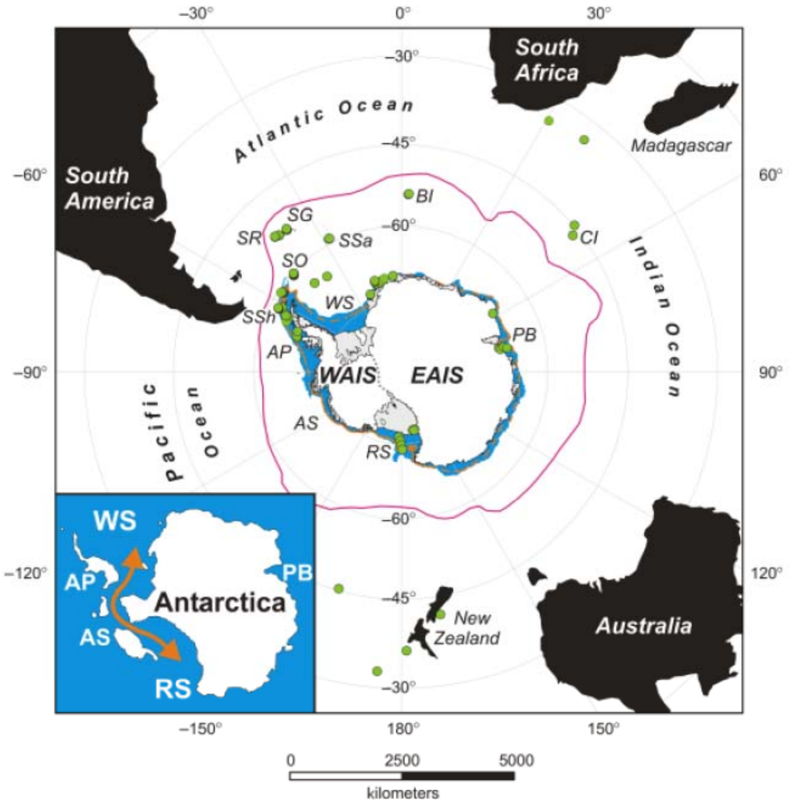
flux across GL sharply increasing function of thickness – basic ingredient for marine ice sheet instability



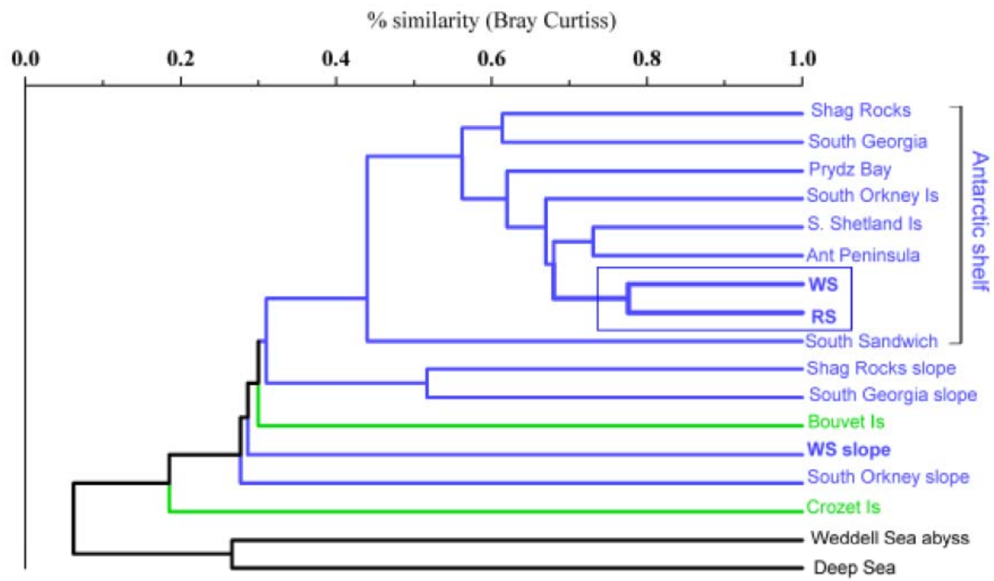
$$q \propto H^5$$

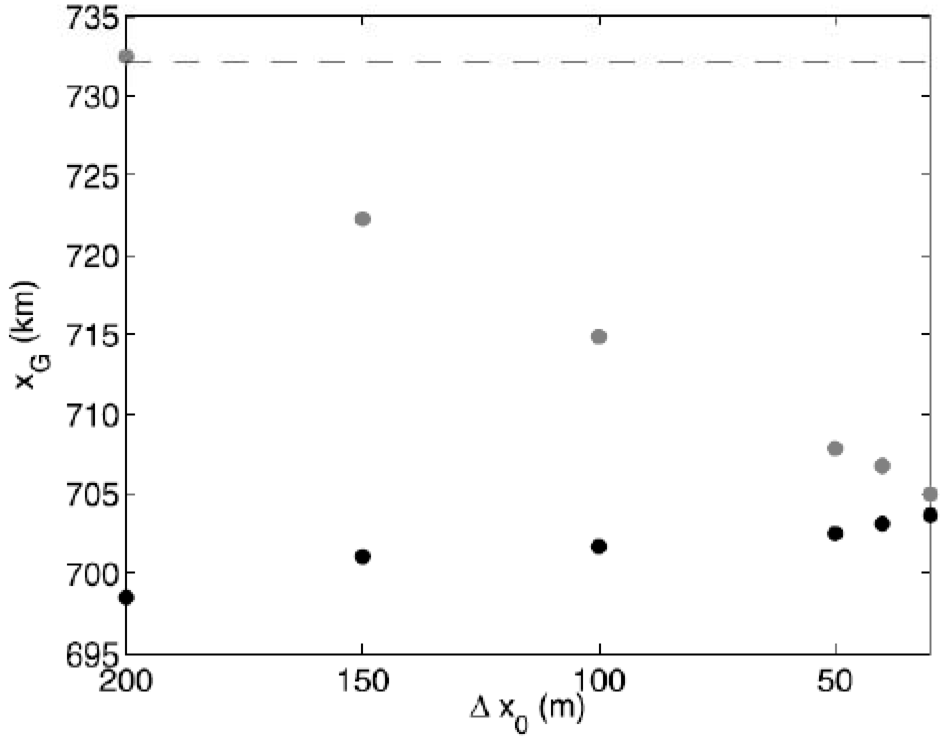
Faunal evidence for a late quaternary trans-Antarctic seaway

DAVID K. A. BARNES and CLAUS-DIETER HILLENBRAND
British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK



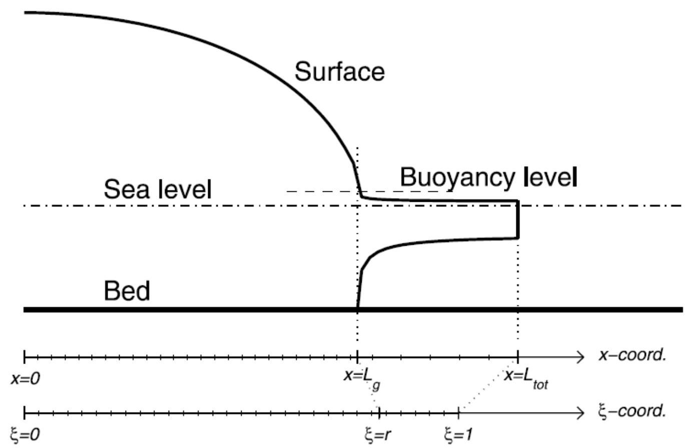
Genomics of bryozoans (sedentary organisms)





Evolution of the steady grounding line position as a function of the horizontal mesh extension. Black circles (gray circles) represent results obtained for simulations on the outward (return) path. Dashed line depicts results obtained by boundary layer theory (Durand et al., 2009)

- Durand et al., 2009, JGR
- Significant deviation from boundary layer theory
- No physical neutral equilibrium



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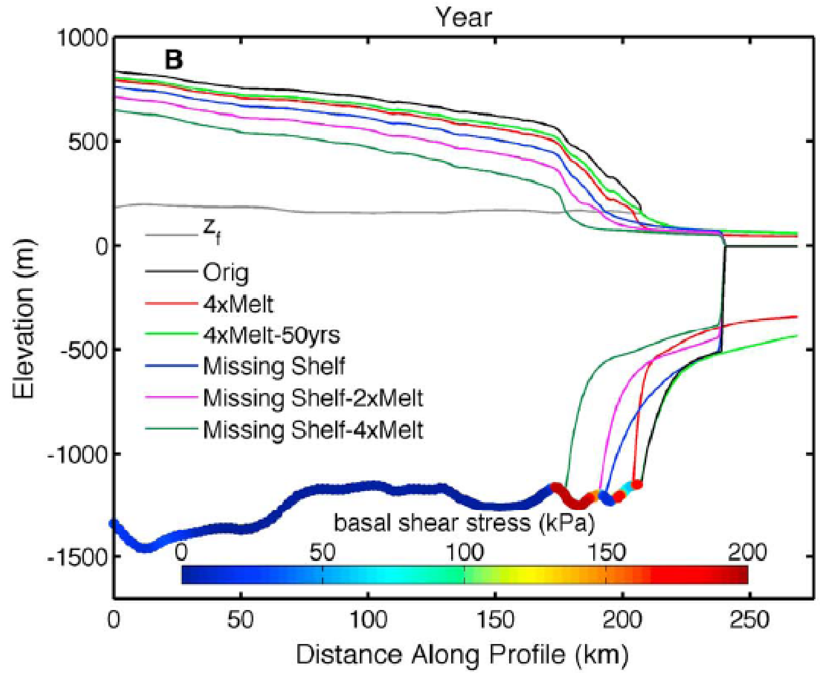
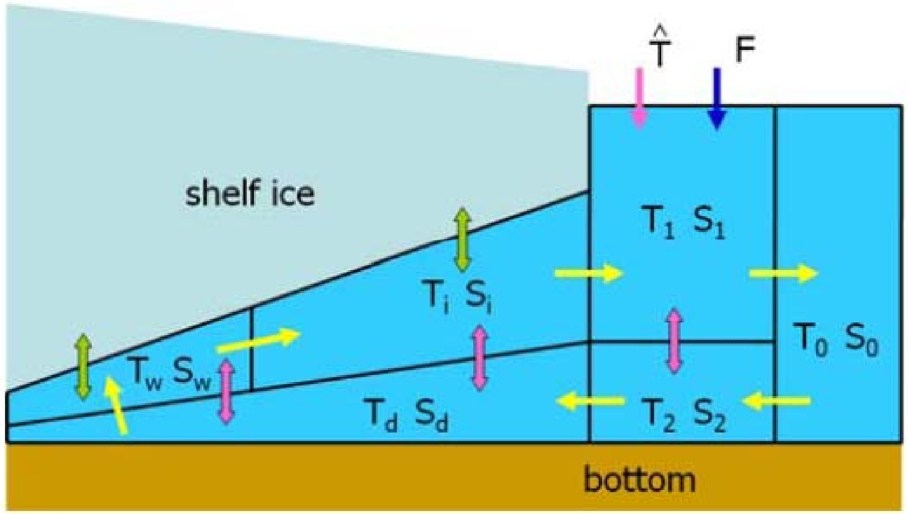
Flowline modelling of PIG

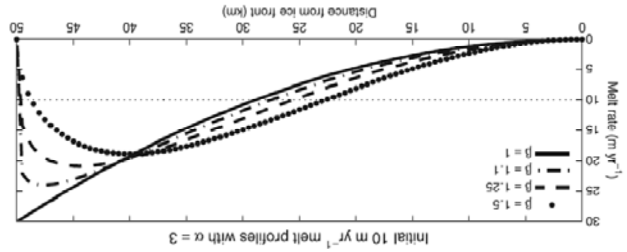
- Aim to use simple model of PIG to investigate behaviour from 1900 to 2200
- The model is cheap to run so that fine resolution is not an issue
- Also means 1000s experiments are possible so that can use ensembles to assess effects of parameter uncertainty
- Joughin et al (2010) use a 2-d. version of the model and find limited GL retreat



Melt model

- Box model of sub-shelf processes used to generate mean melt rates (Olbers and Hellmer 2010)
- Temperature and salinity conserved; 3-equation melt model; fluxes found as a function of density differences
- Means in two sub-shelf boxes used to constrain empirical relation developed by Walker and others (2008)
- Generates high melt rates close to GL as suggested by observations





Varying inputs/parameters

Minimax Latin Hypercube sampling was used to obtain 5000 combinations of these inputs (i.e. we ran an ensemble of 5000 simulations)

A = rate factor (a measure of how easily deformable the ice is, determined by temperature).

Two parameters jointly determine the "surface" mass balance profile (includes a contribution from tributaries).

Two parameters determine the profile of basal traction coefficient.

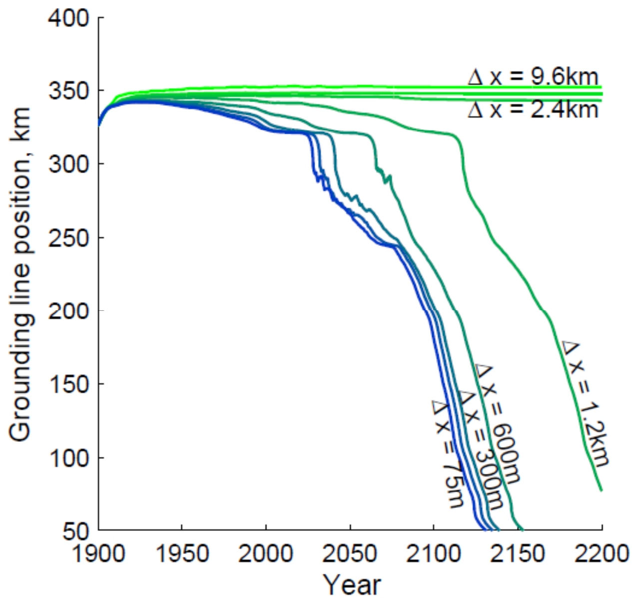
A lateral drag parameterisation is used with channel width W

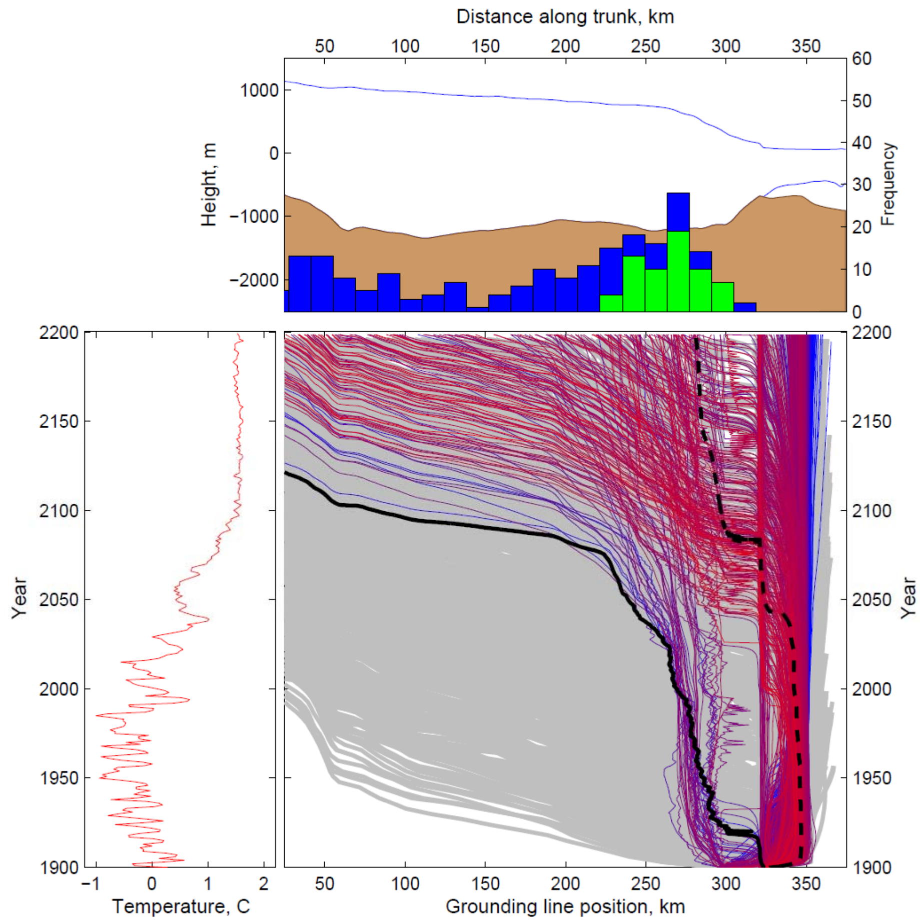
One parameter allows the initial (year 1900) thickness profile to vary

Input name	Units	Min. value	Max. value
A	$Pa^{-3}\ yr^{-1}$	3.1×10^{-18}	1.7×10^{-16}
C_{MB1}	$m\ yr^{-1}$	0.5	5.0
C_{MB2}	-	0	1
$C_{\beta^2 1}$	$Pa\ s\ m^{-1}$	1×10^{8}	5×10^{9}
$C_{\beta^2 2}$	$Pa\ s\ m^{-1}$	0	1×10^{10}
W	km	30	70
C_H	-	0.9	1.3

Results

- Likelihood proceedure to accept or reject members based on fit to observed thinning, grounding line positions and velocity
- Grey are rejected; blue to red reduced discrepancy





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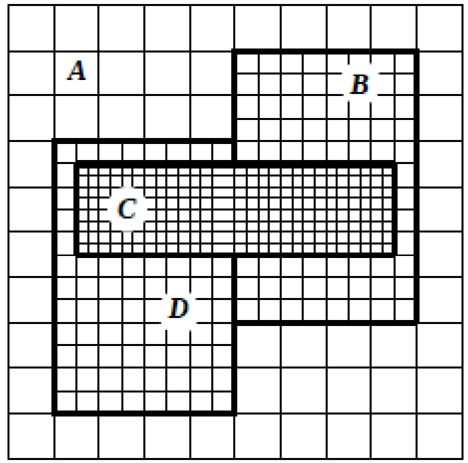
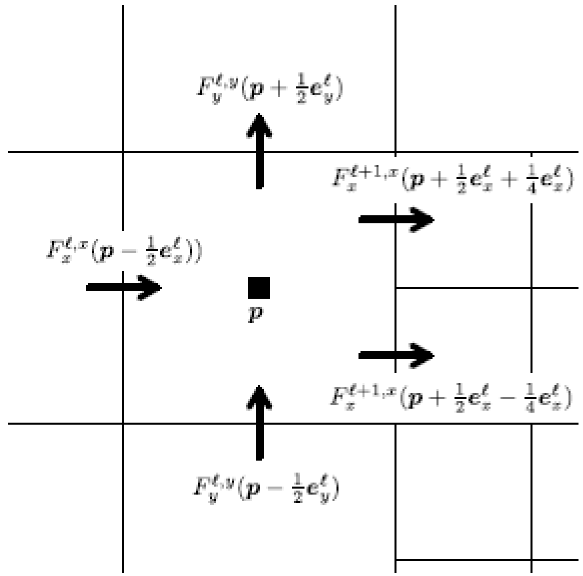
Bisicles ice sheet model

- Specifically designed for GL problems
- Based on CHOMBO adaptive-mesh refinement developed by Lawrence Livermore National Lab.
- Uses a vertically-integrated form of the stress equations proposed by Schoof and Hindmarsh (2010) known as L1L2
- Includes all stress terms but is vertically integrated
- CHOMBO ensures conservation between grids and offers massive parallelization



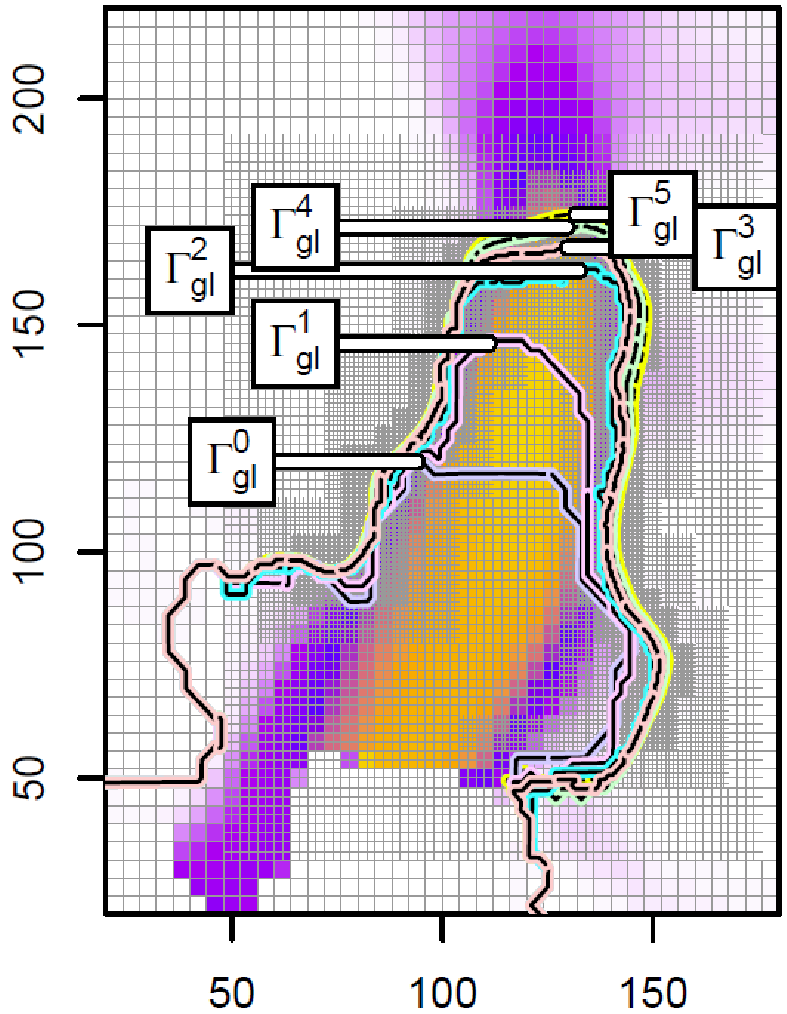
(a) Example block-structured mesh



(b) Fluxes at a coarse-fine interface

BISICLES

- Trial application to Pine Island Glacier
- Simulation using reasonable melt increase of 50 m/yr
- Results dependent on resolution from single level (5km) to six levels (~150 m)
- Confirms need for sub-km resolution



Colours refer to velocity

See movies

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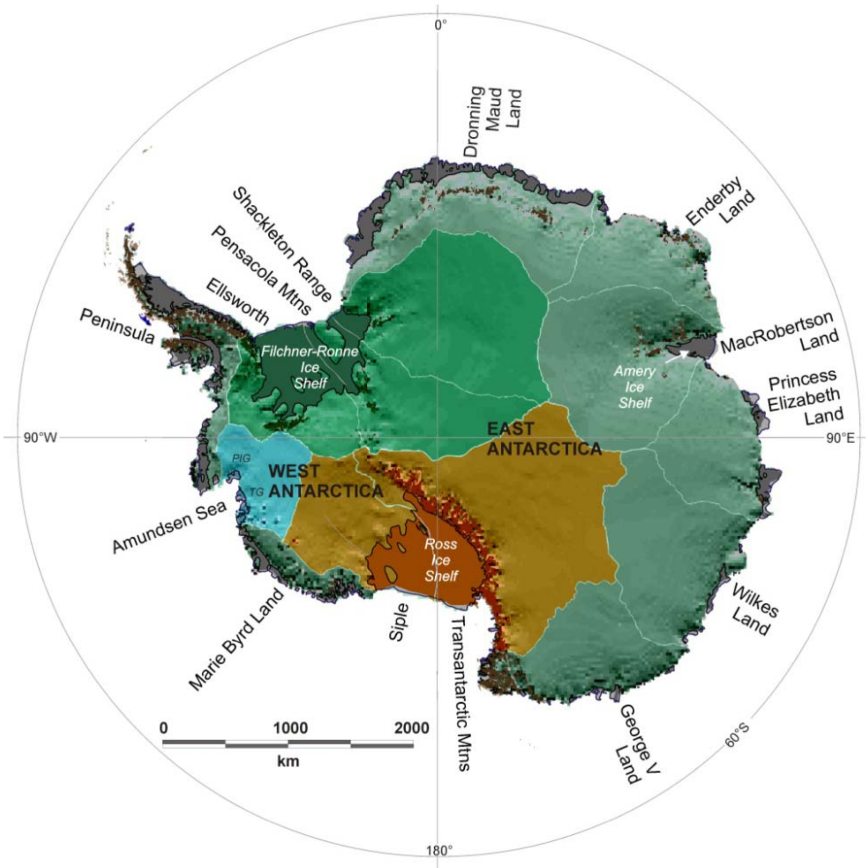
Experimental design

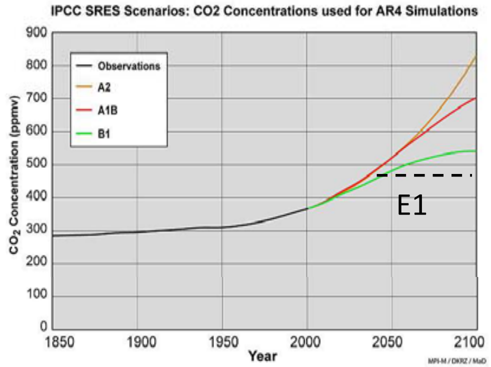
- Coupled problem but no such coupled model exists
- Use a chain of models from global AOGCMs $\rightarrow$ regional ocean and atmosphere models $\rightarrow$ ice sheet model
- Connelly and Bracewell (2007) show HadCM3 and ECHAM5 to do well for Antarctica
- Consider only West Antarctica



Experimental design

SRES scenarios A1B and E1 with AOGCMS

HadCM3 | ECHAM5



Snowfall - regional atmospheric modelling

- RACMO2 (Utrecht)
- LMDZ4 (Grenoble)

Melt - regional ocean modelling

- BRIOS (AWI)
- FESOM (AWI)

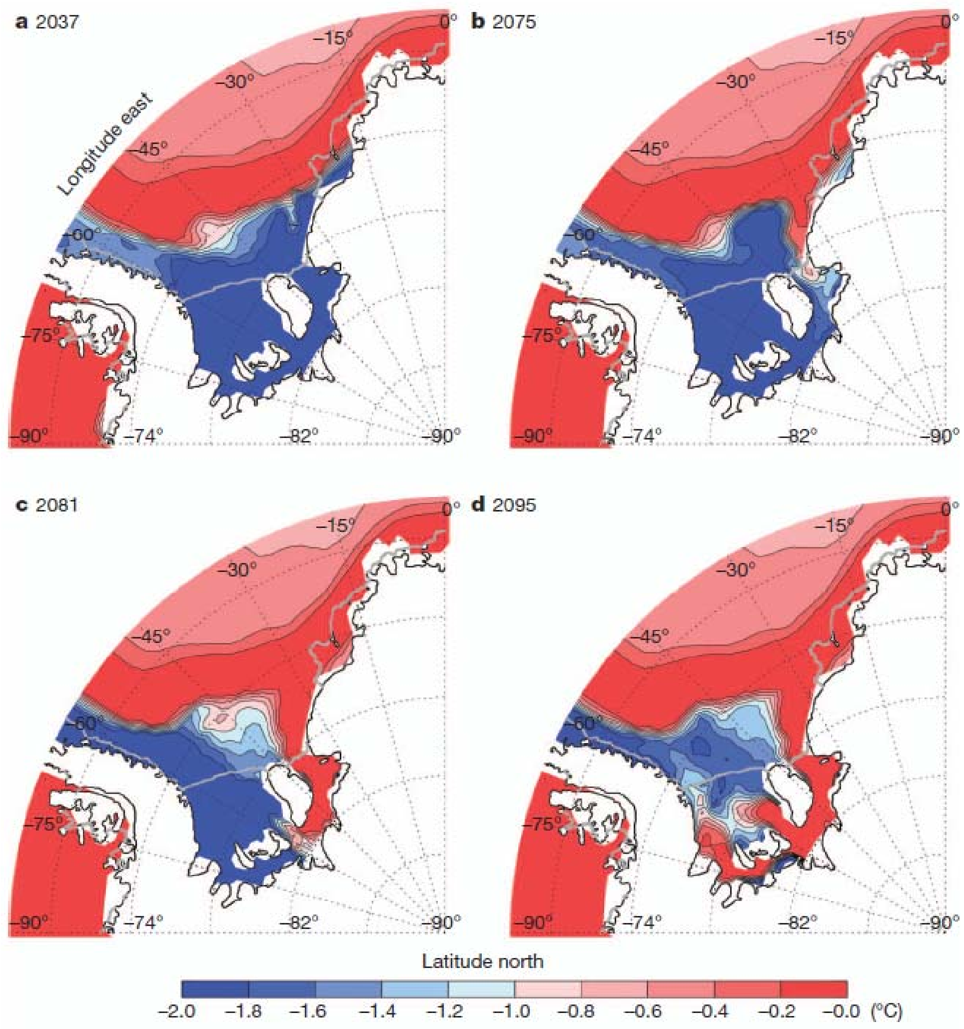
Anomalies against 1980 to 1989

BISICLES ice sheet model

Twenty-first-century warming of a large Antarctic ice-shelf cavity by a redirected coastal current

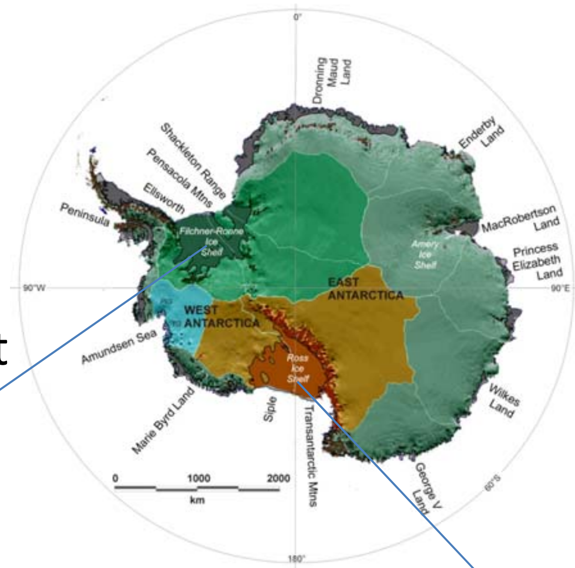
Hartmut H. Hellmer[1], Frank Kauker[1], Ralph Timmermann[1], Jürgen Determann[1] & Jamie Rae[2]

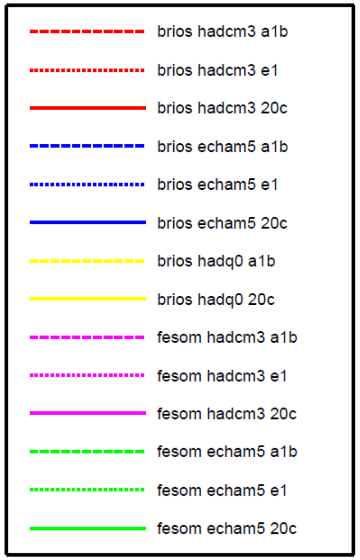
Regional Southern Ocean model forced using AOGCM output.

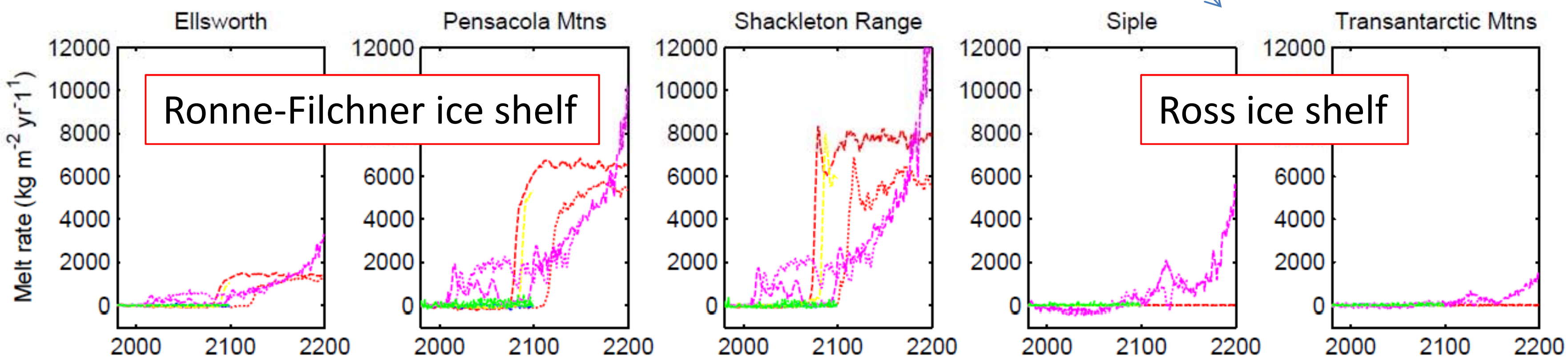


Ocean forcing – major ice shelves

- Warm water intrusion reported by Hellmer and others (2012) for BRIOS also in FESOM for Ronne-Filchner
- Leads to 10-20 fold increase in melt
- Similar phenomenon for Ross ice shelf after 2100 (FESOM only)

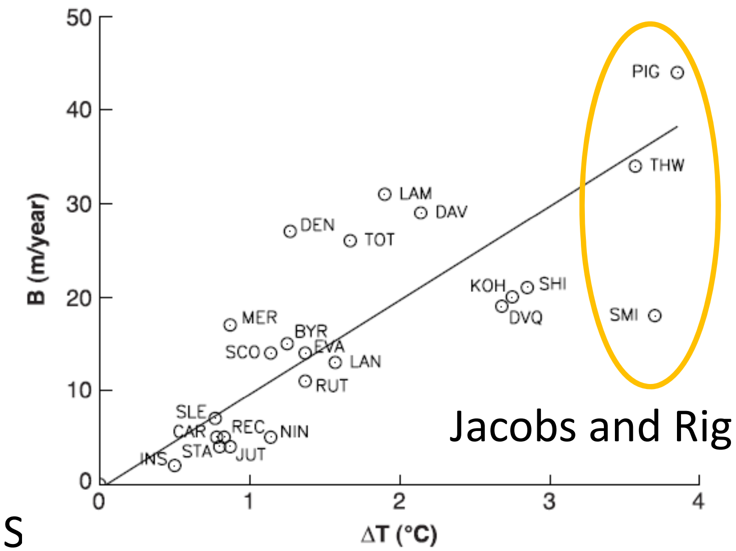




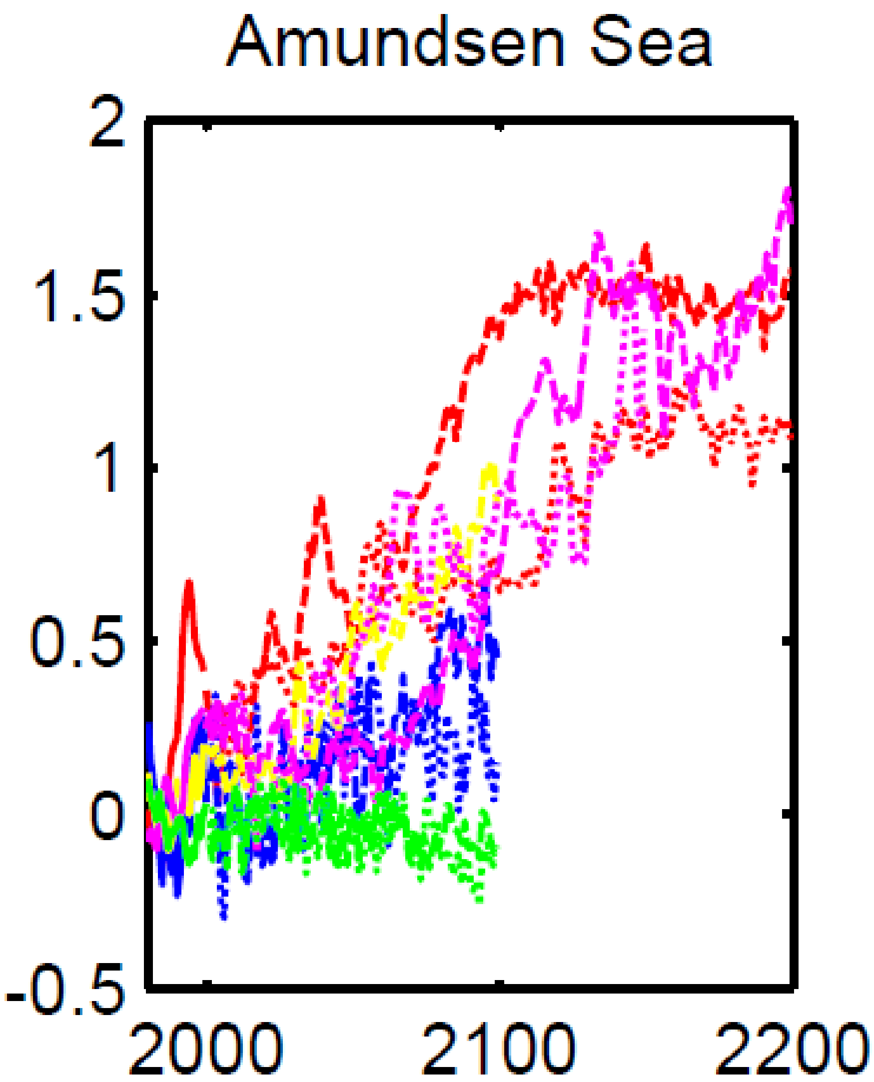


Ocean forcing – smaller ice shelves

- FESOM and BRIOS do not represent smaller shelves well
- Use index of coastal warming and convert to melt anomaly using empirical relation (e.g., Jacobs and Rignot 2002)
- Warming of 1 to 2 °C or 10-20 m/yr



Jacobs and Rignot 2002



Results

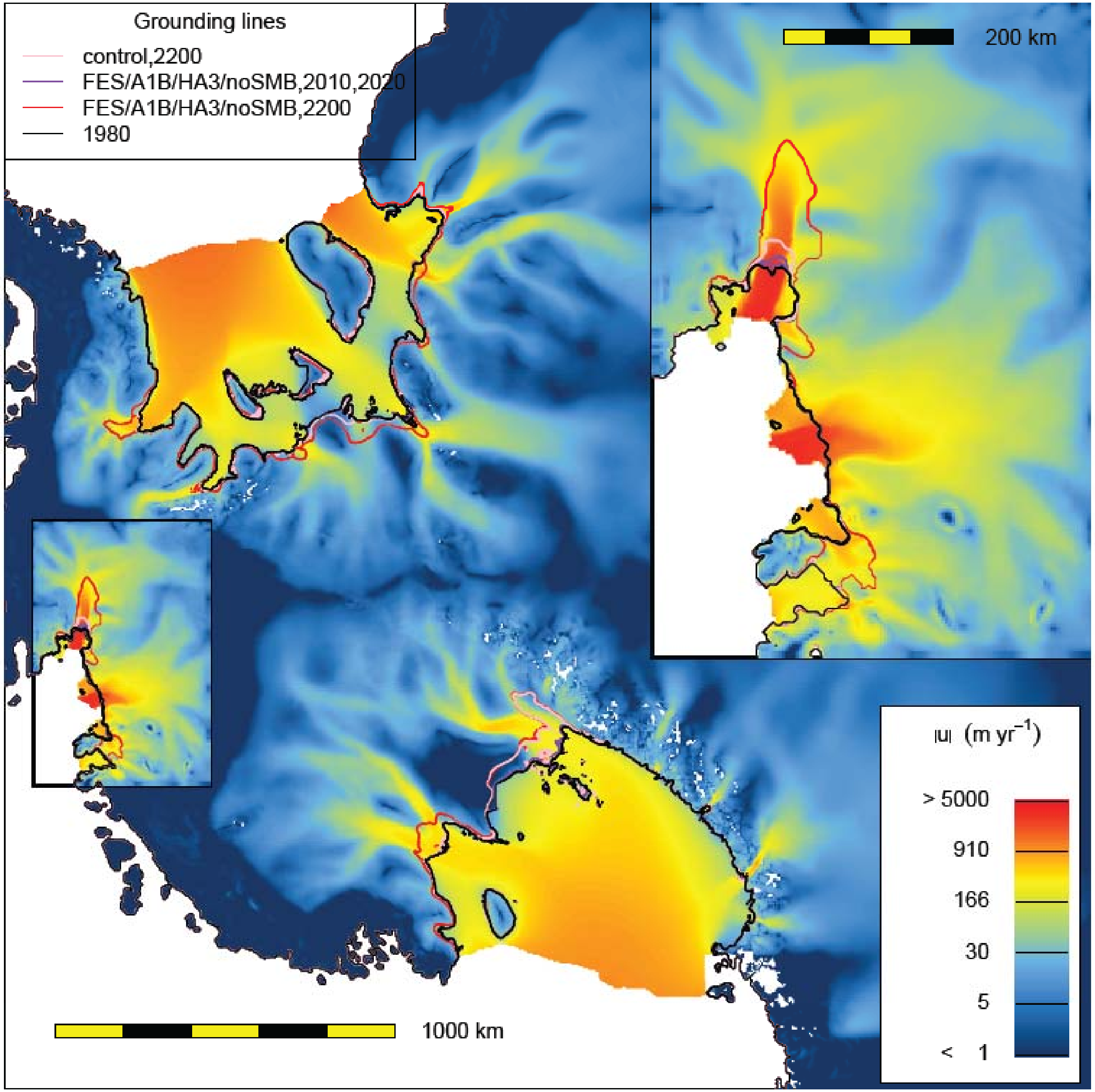
Background is the initial velocity field

KEY -

1980 ground line

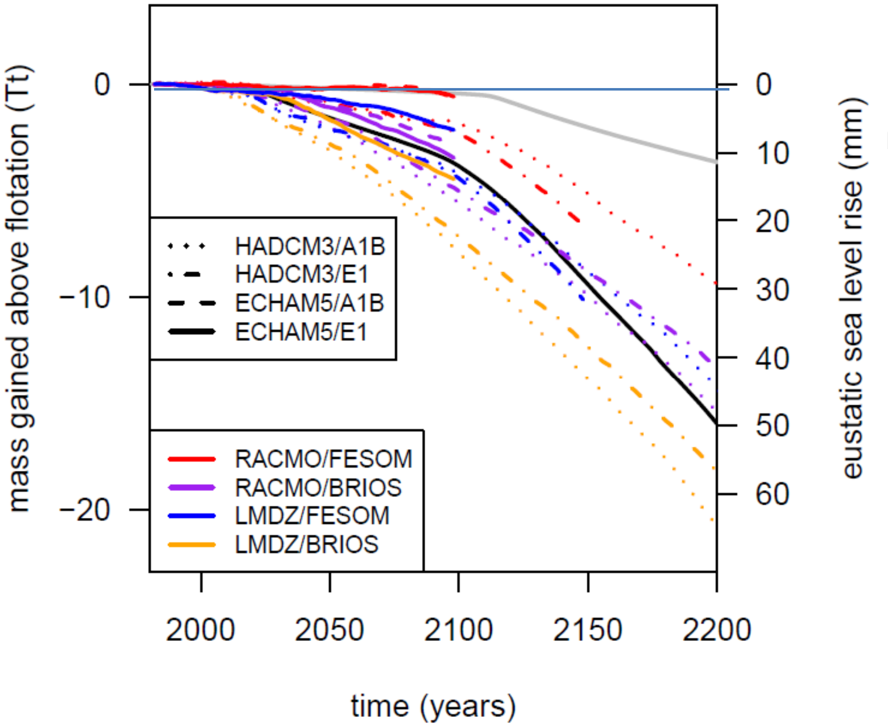
Worst case by 2200

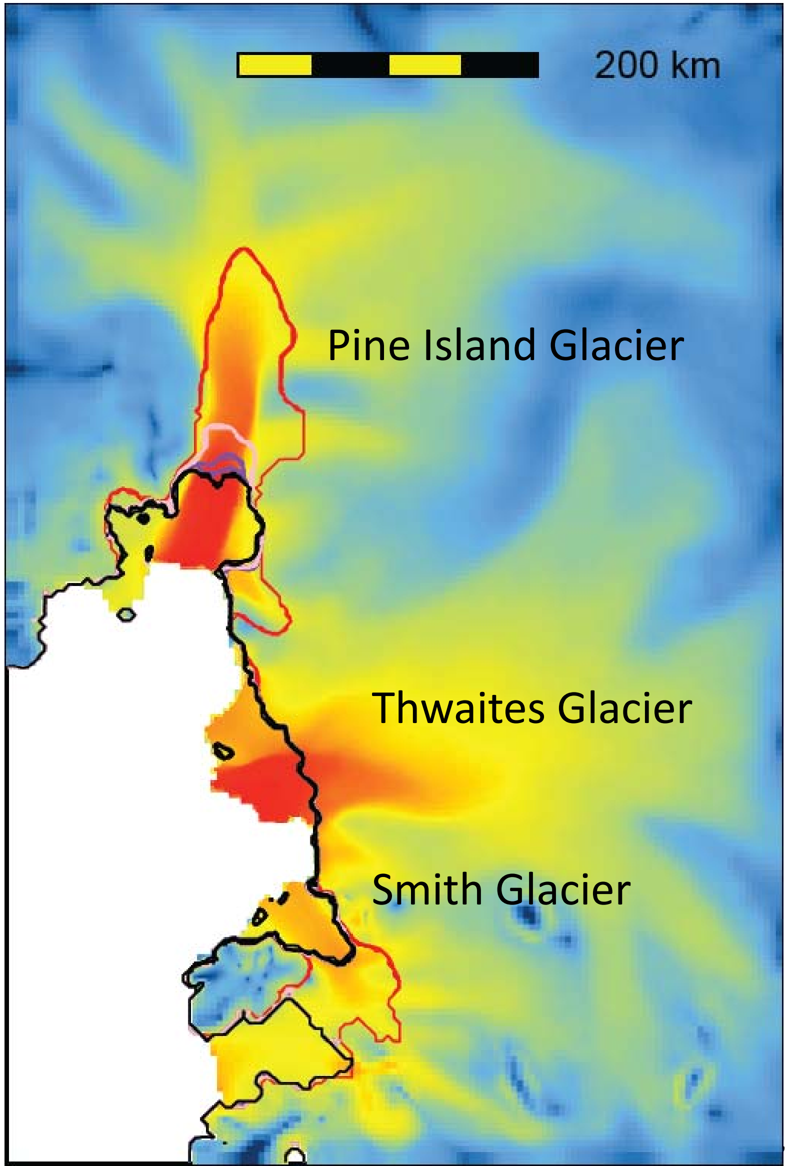
Control (no anomalies) shows some drift



Amundsen Sea and Pine Island

- Deglaciation of Pine Island Glacier and Smith Glaciers
- Thwaites shows no retreat related to lack of buttressing?
- Similar to recent GL observations





See movies

Summary

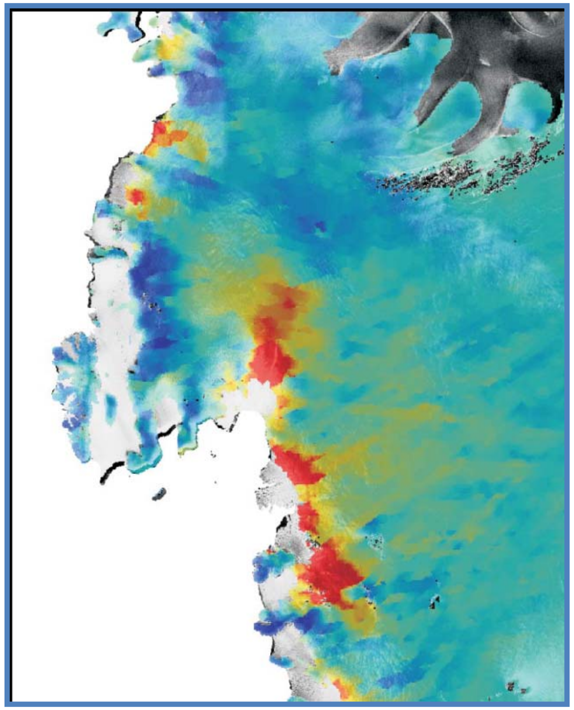
- Increased outflow is enough to compensate increased snowfall
- Sea level rise is predicted as -5 to 80 mm by 2200 depending on forcing (i.e., small)
- Sea level rise is limited because
  - GL retreat occurs late in the model run (c.f. ocean forcing)
  - Areas that retreat do not have much ice above buoyancy (so little effect or SLR) and/or
  - Large retreat limited to narrow channels (e.g., Pine Island)
- Sea level rise appears to continue to increase beyond 2200
- Omits East Antarctica
- Fuller estimate requires coupling to regional ocean model

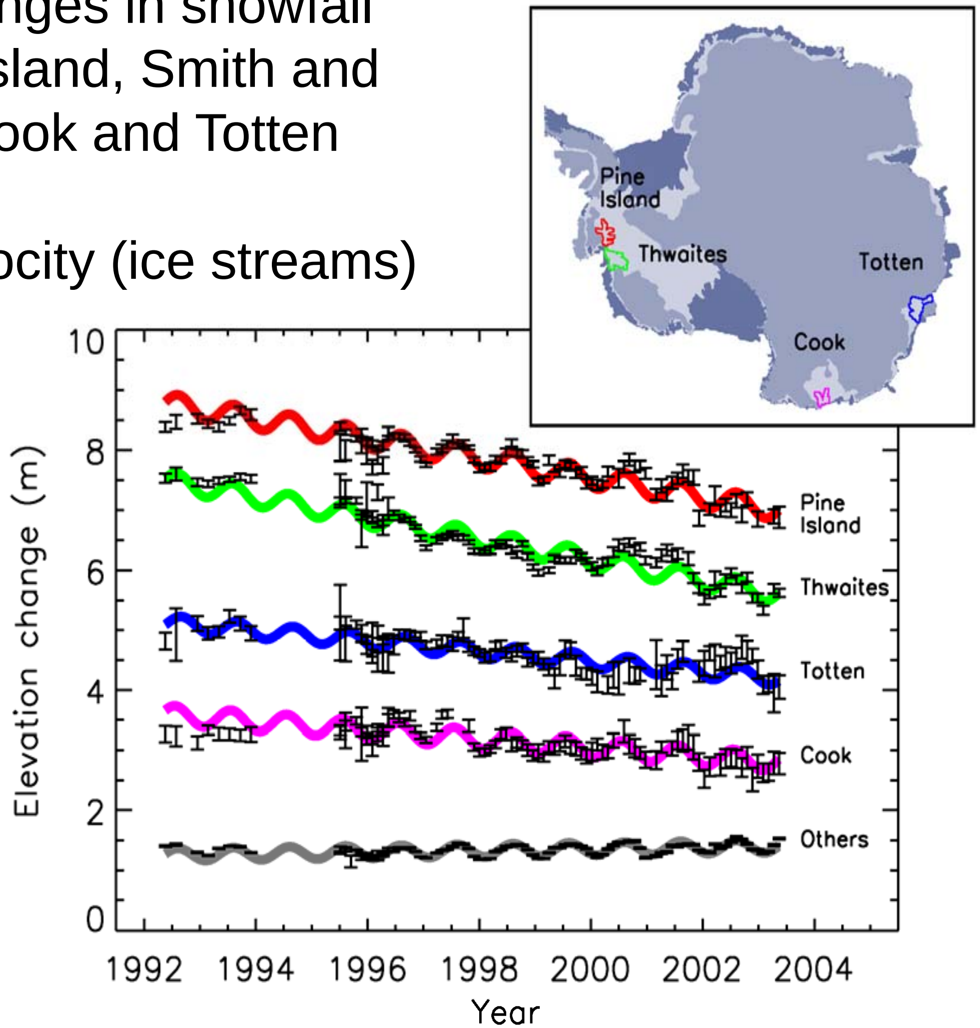
Antarctic mass balance

- interior thickening related to changes in snowfall
- coastal thinning in WAIS (Pine Island, Smith and Thwaites Glaciers) and EAIS (Cook and Totten Glaciers)
- close correspondence to ice velocity (ice streams)

Shepherd and Wingham 2007

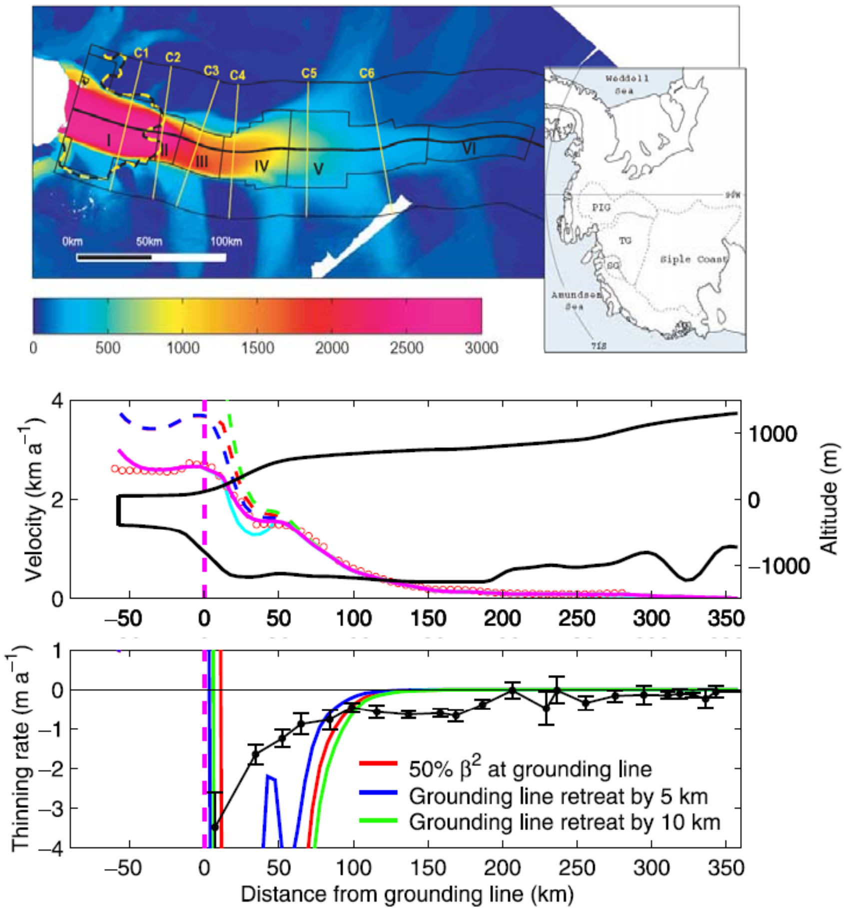
Pritchard and others 2009



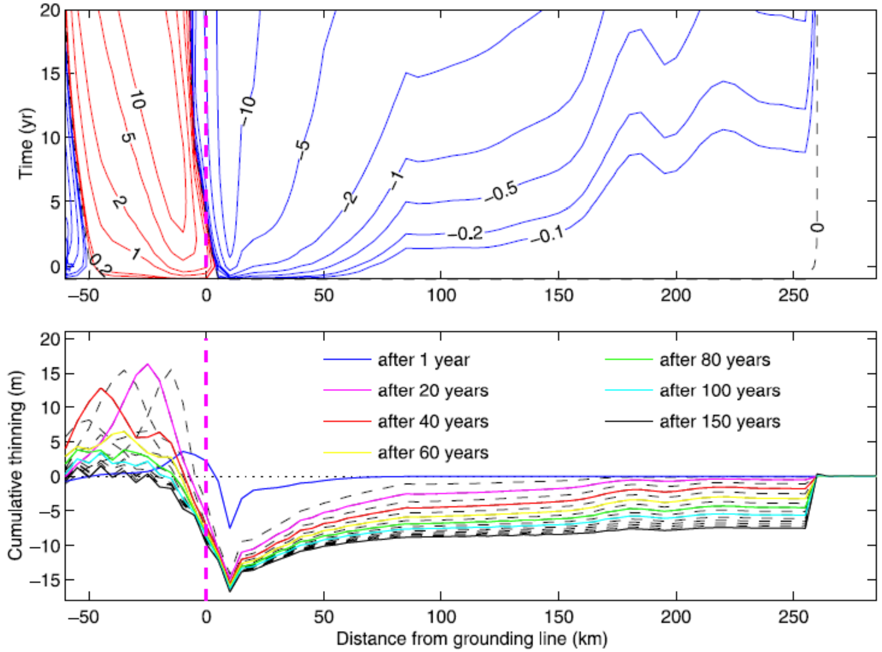


Recent dramatic thinning of largest West Antarctic ice stream triggered by oceans

Antony J. Payne,[1] Andreas Vieli,[1] Andrew P. Shepherd,[2] Duncan J. Wingham,[3] and Eric Rignot[4]



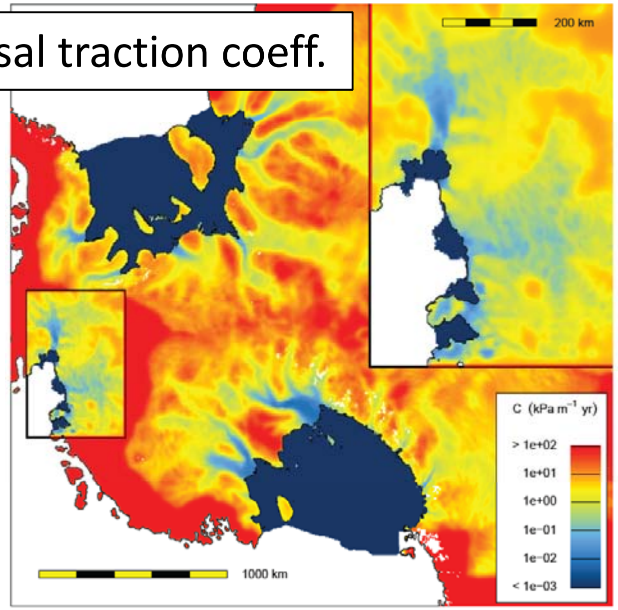
Demonstrated that GL retreat, flow acceleration and thinning all linked and caused by increased ice shelf melt



Initial conditions

- Observed ice sheet geometry
- Use methods based on Lagrange multipliers to find ice viscocity and basal traction consistent with observed velocities
- Evolve ice sheet for 50 years to allow noise to relax away
- **Employ 3 levels of refinement from 5 km to 612 m**

Derived basal traction coeff.



Derived rheology factor