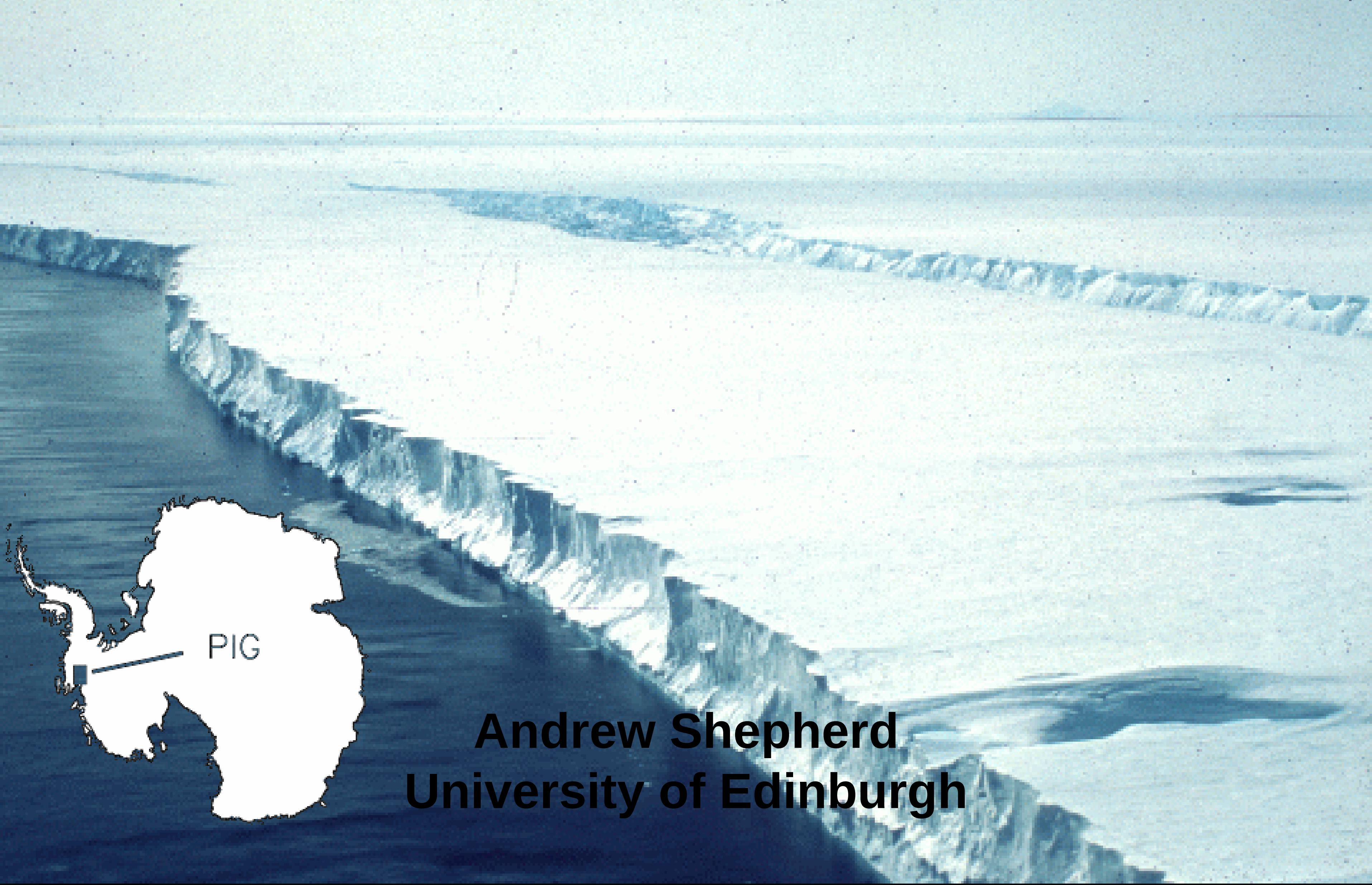
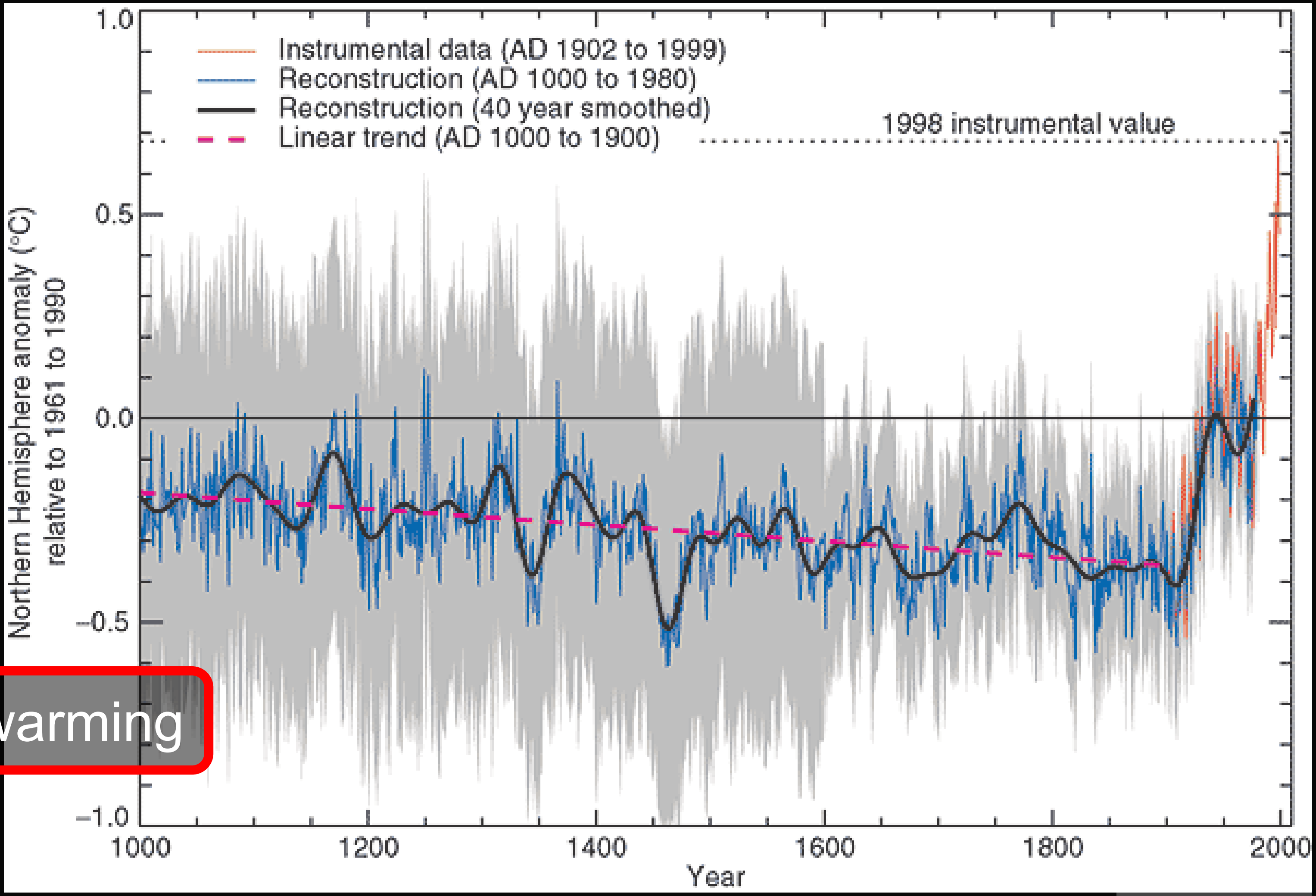
Pine Island Glacier – did we solve it?



Andrew Shepherd
University of Edinburgh

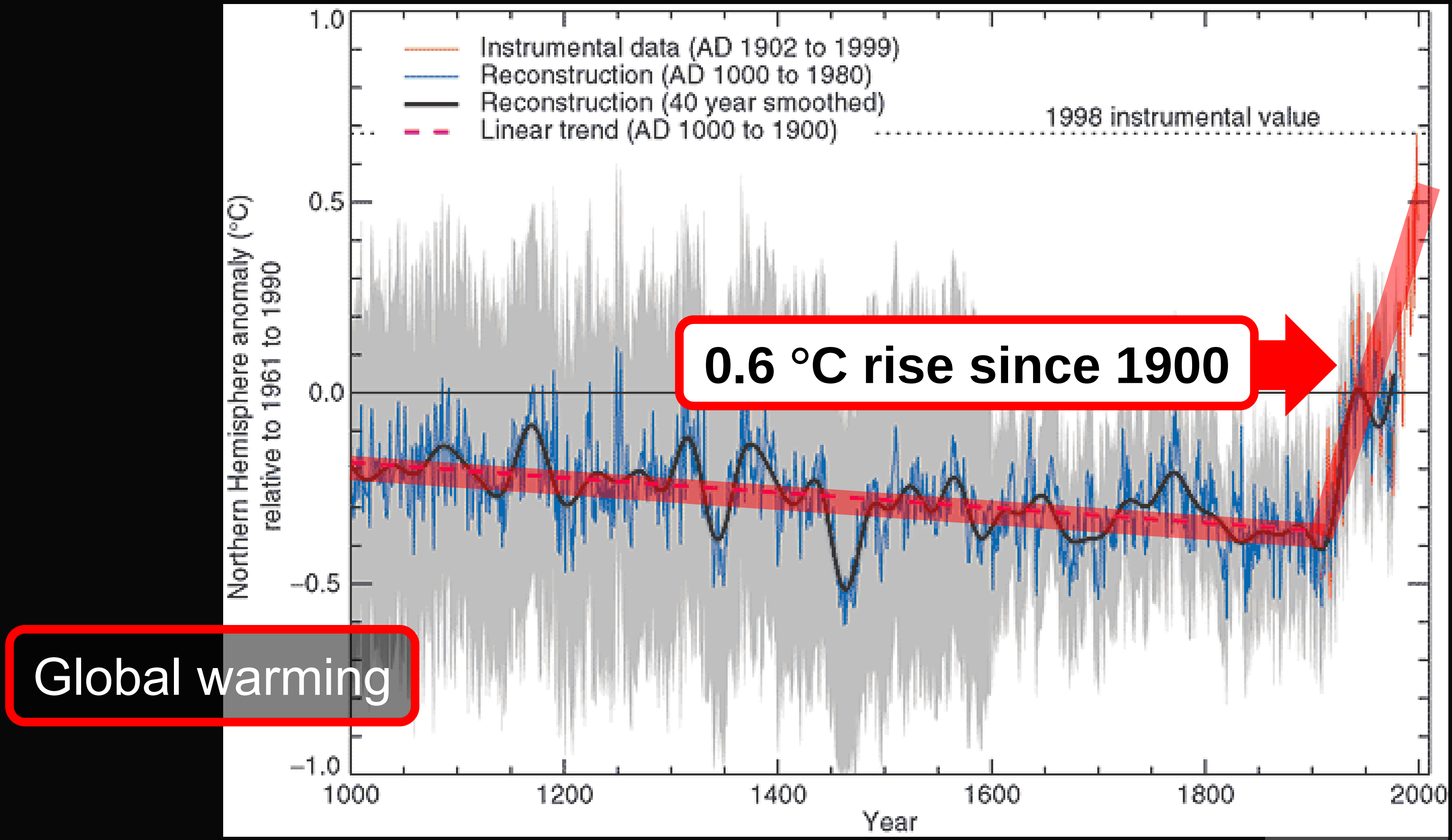
- IPCC Assessment reports (1990, 1995, 2001)



Global warming

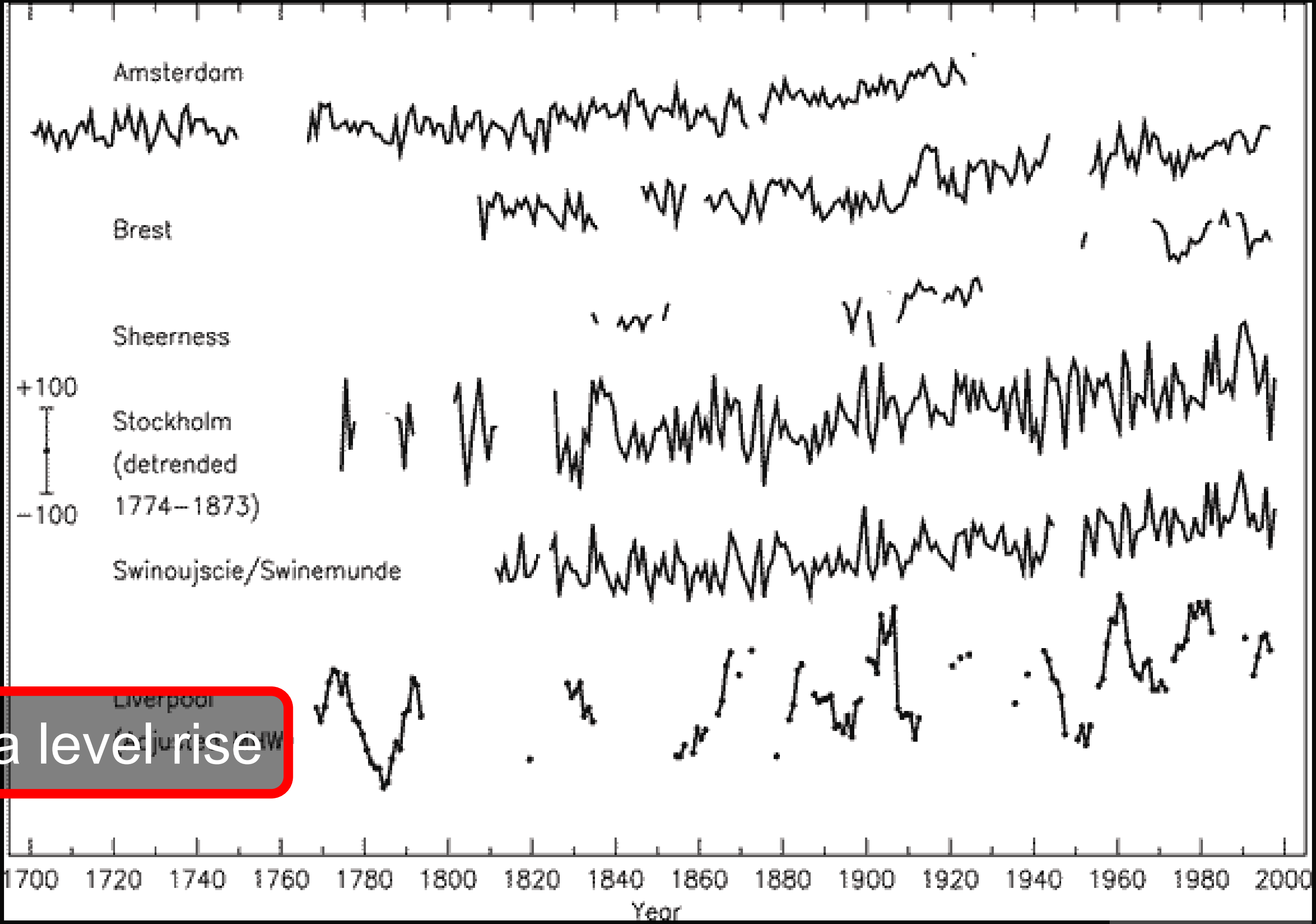
IPCC, 2001

- IPCC Assessment reports (1990, 1995, 2001)



IPCC, 2001

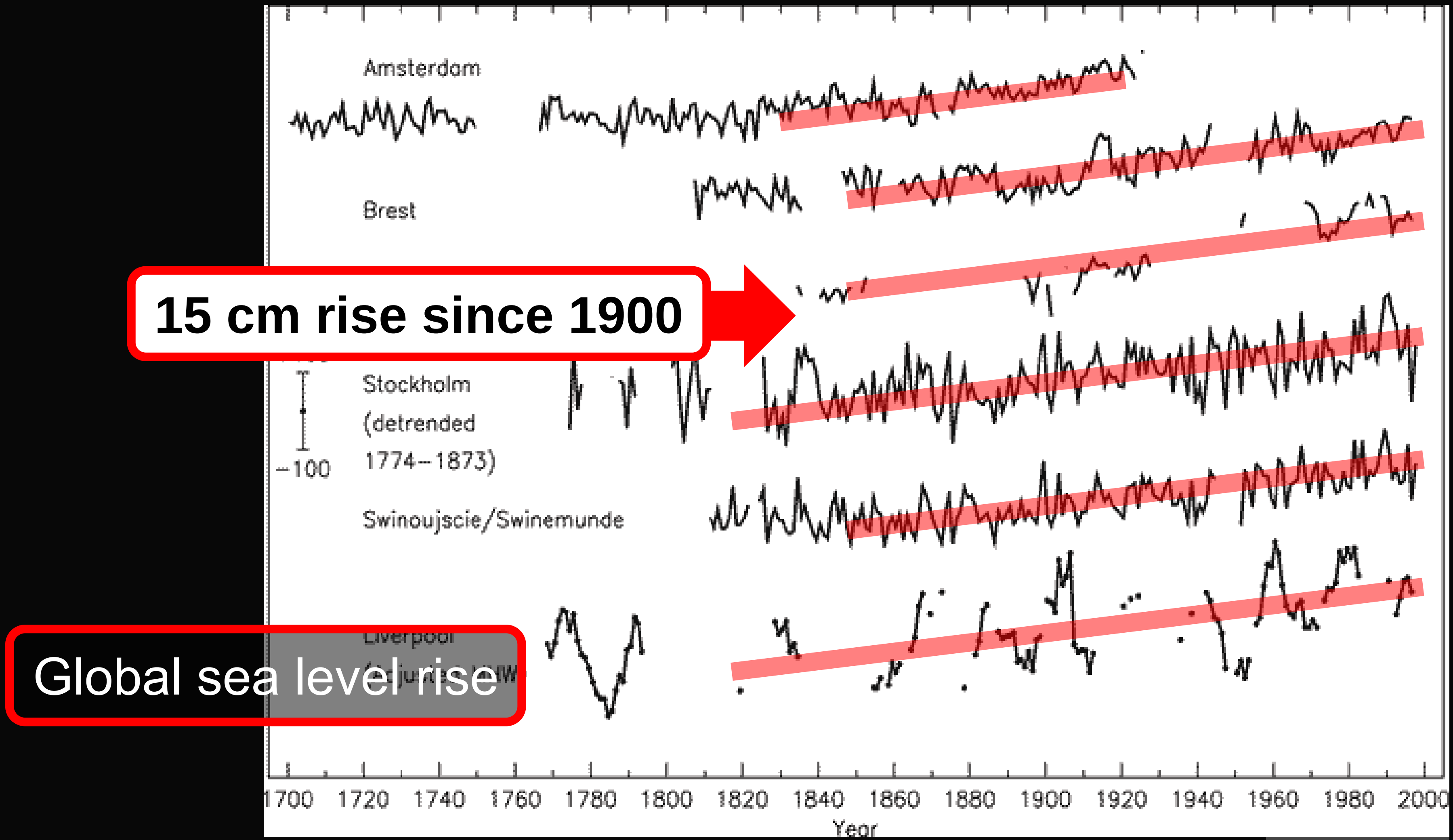
- IPCC Assessment reports (1990, 1995, 2001)



Global sea level rise

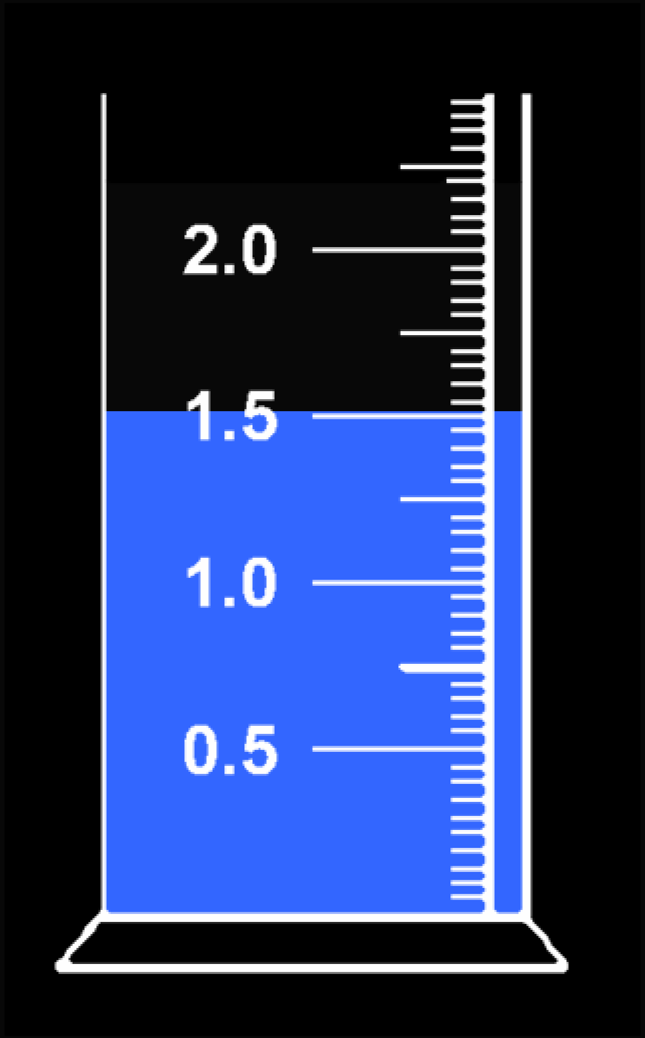
IPCC, 2001

- IPCC Assessment reports (1990, 1995, 2001)



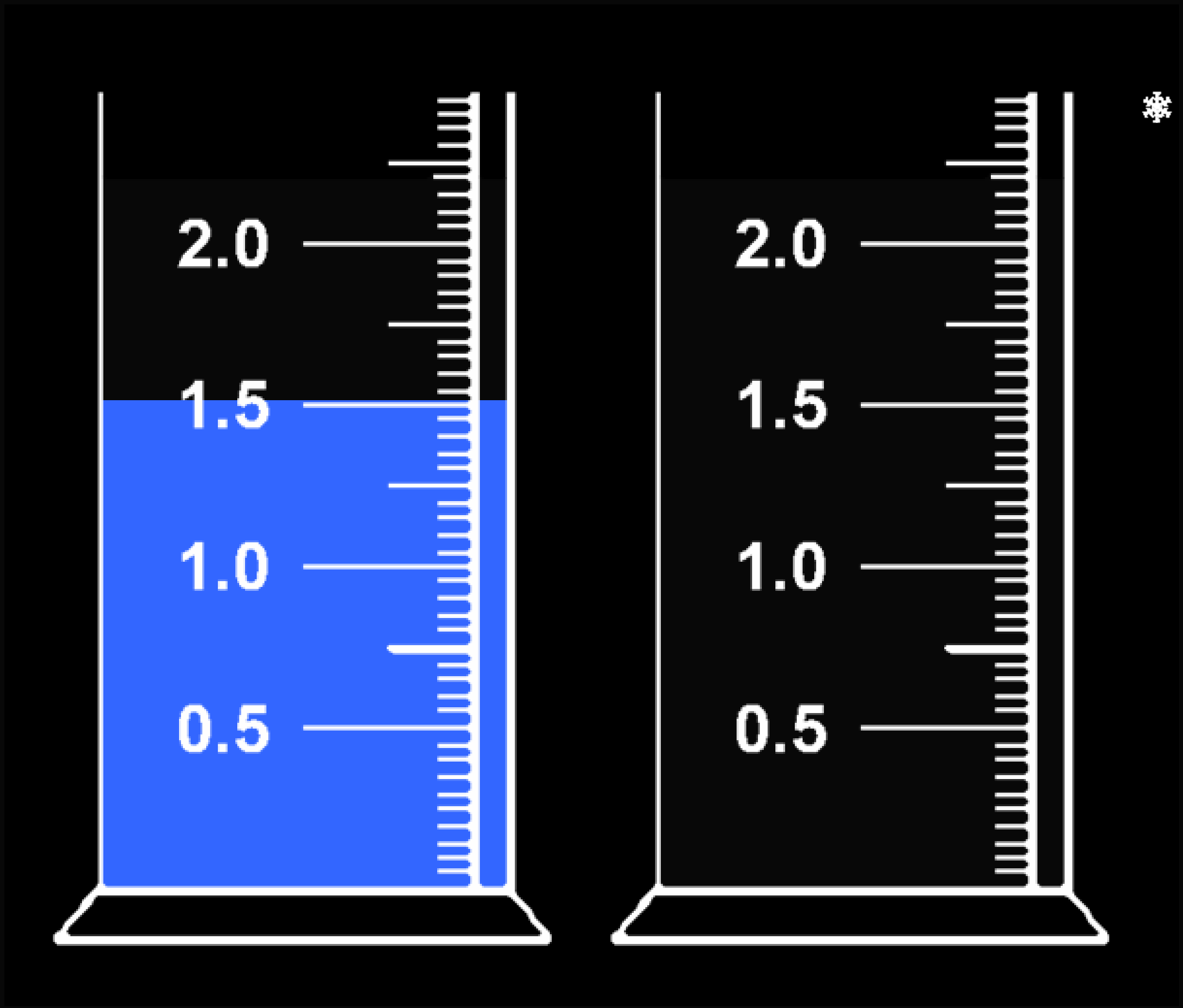
IPCC, 2001

- IPCC Assessment reports (1990, 1995, 2001)



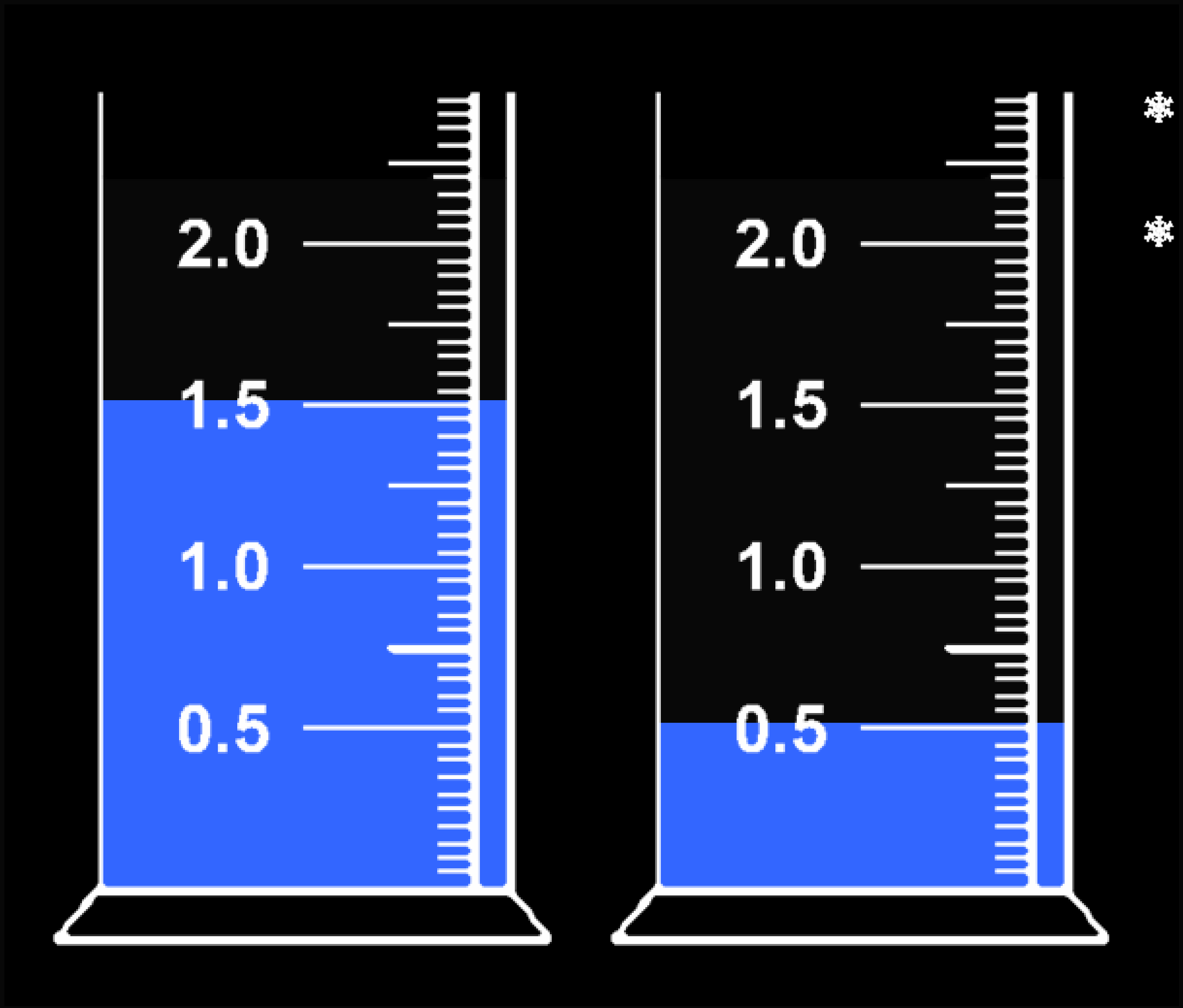
- According to tide gauges, global sea levels have risen by 1.5 mm per year during the 20th century
- This rise is ten times greater than at any other time during the past 3000 years

- IPCC Assessment reports (1990, 1995, 2001)



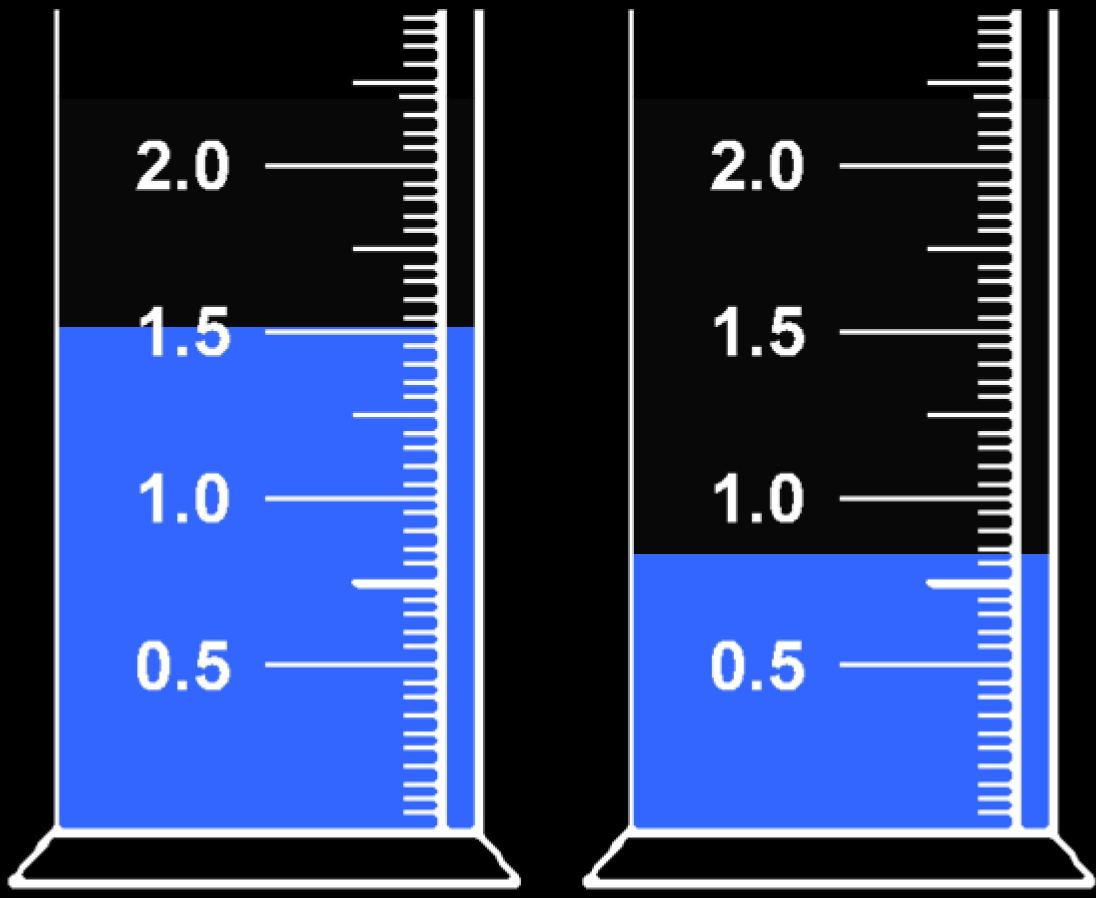
- Known sources include:

- IPCC Assessment reports (1990, 1995, 2001)



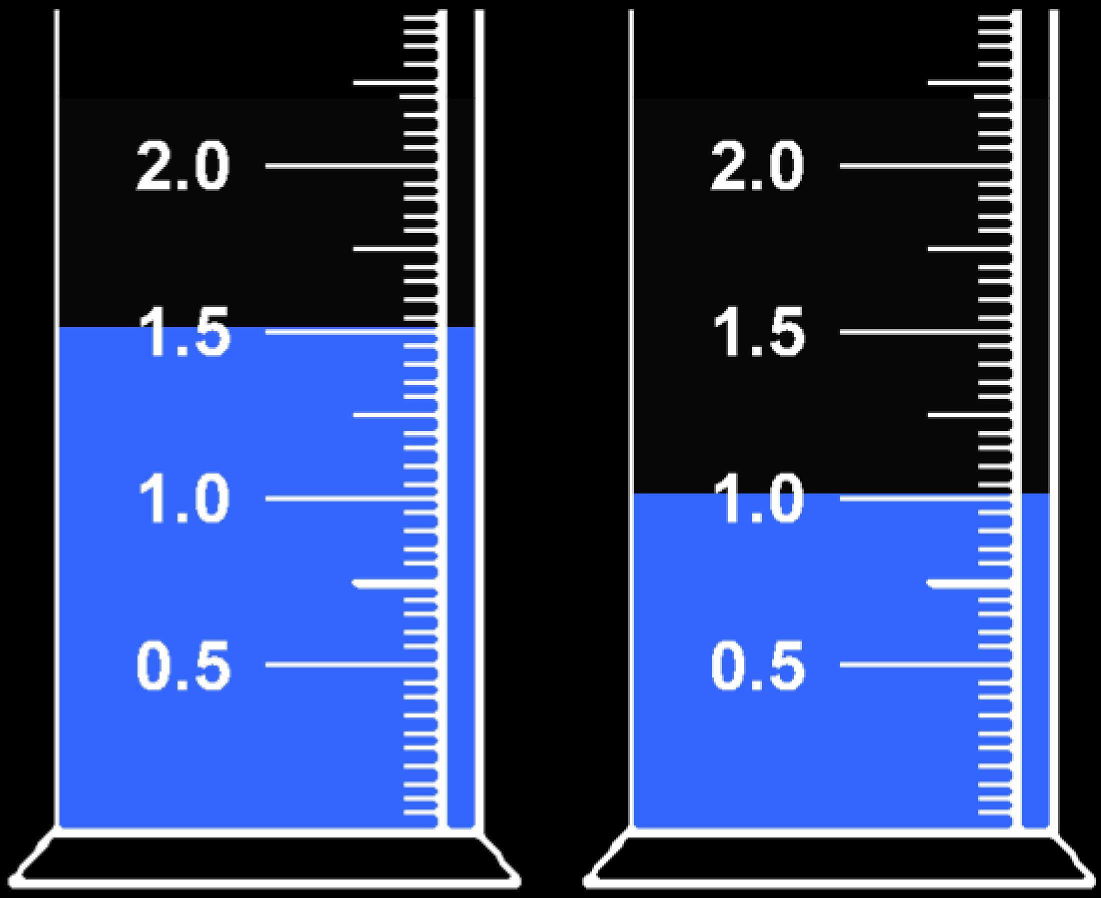
- Known sources include:
- Ocean expansion (0.5 mm)

- IPCC Assessment reports (1990, 1995, 2001)



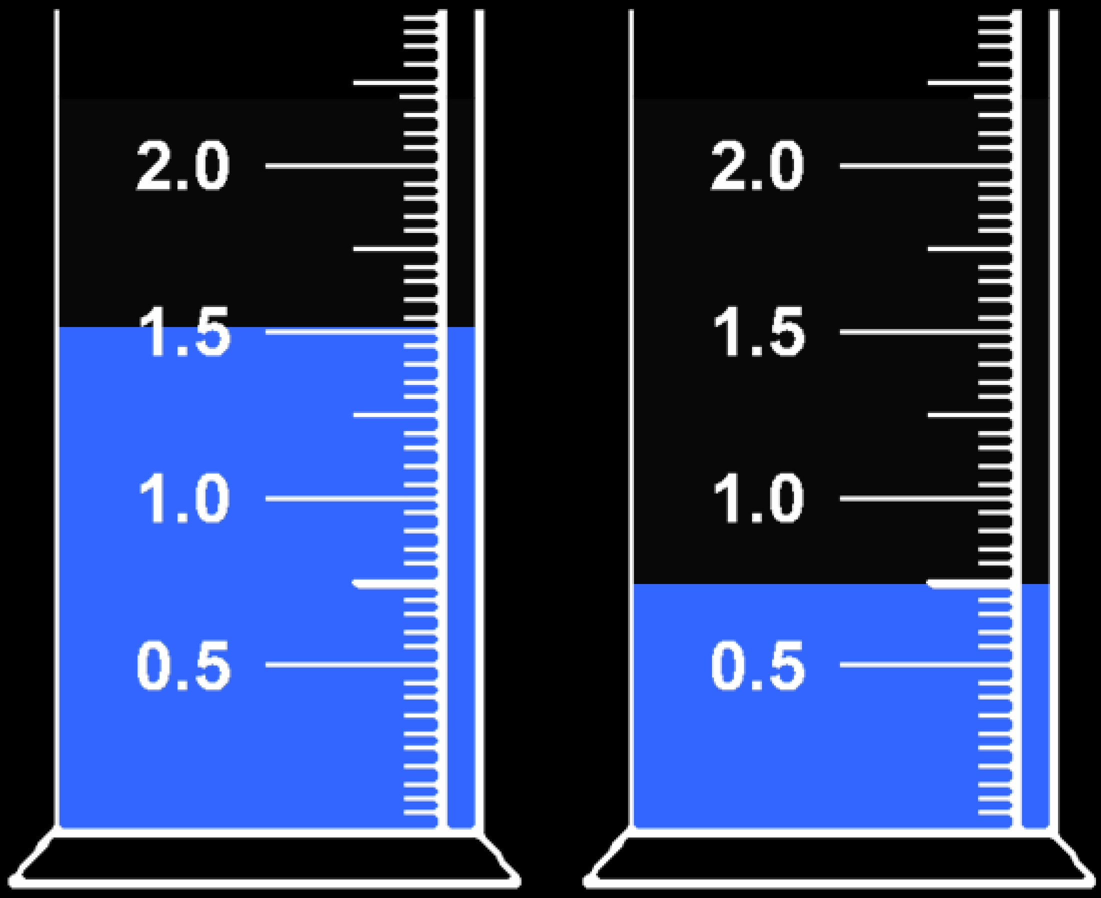
- Known sources include:
- Ocean expansion (0.5 mm)
- Glaciers (0.3 mm)

- IPCC Assessment reports (1990, 1995, 2001)



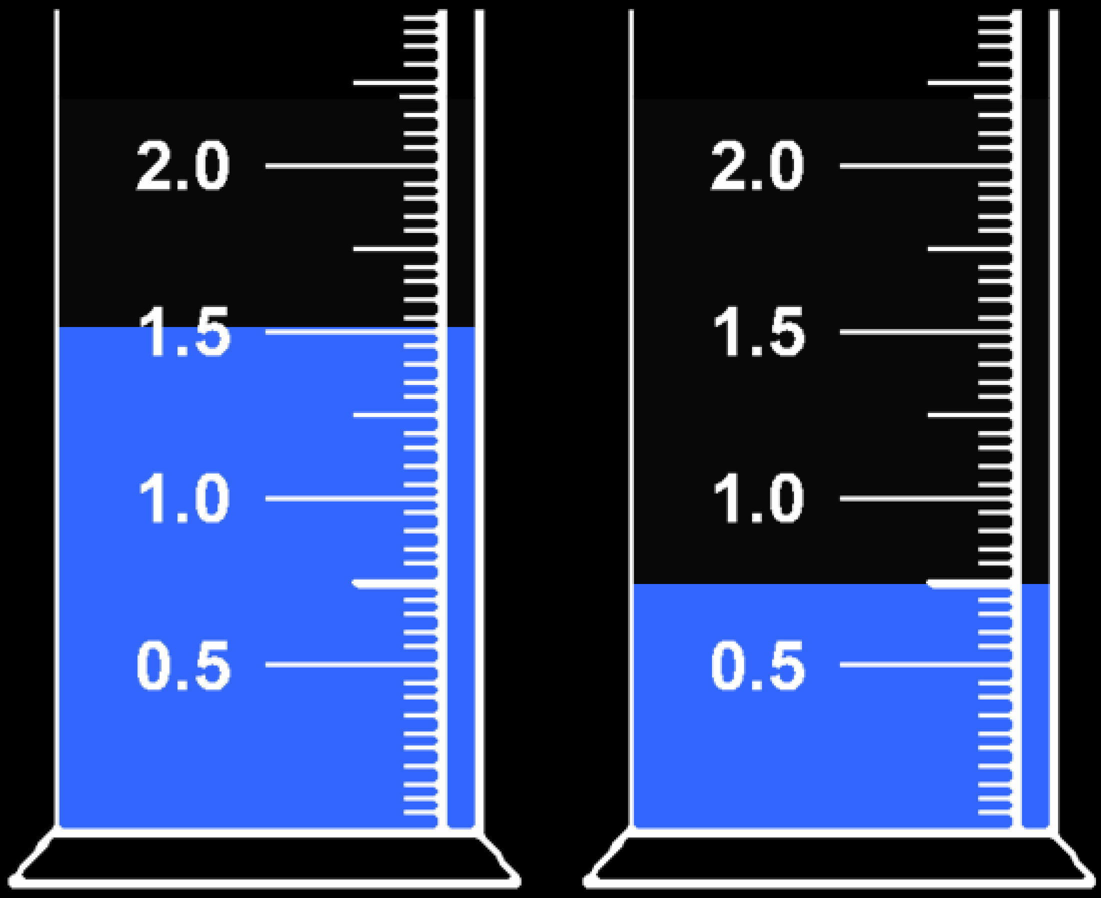
- Known sources include:
- Ocean expansion (0.5 mm)
- Glaciers (0.3 mm)
- Ice sheets (0.2 mm)

- IPCC Assessment reports (1990, 1995, 2001)



- Known sources include:
- Ocean expansion (0.5 mm)
- Glaciers (0.3 mm)
- Ice sheets (0.2 mm)
- Rivers (-0.3 mm)

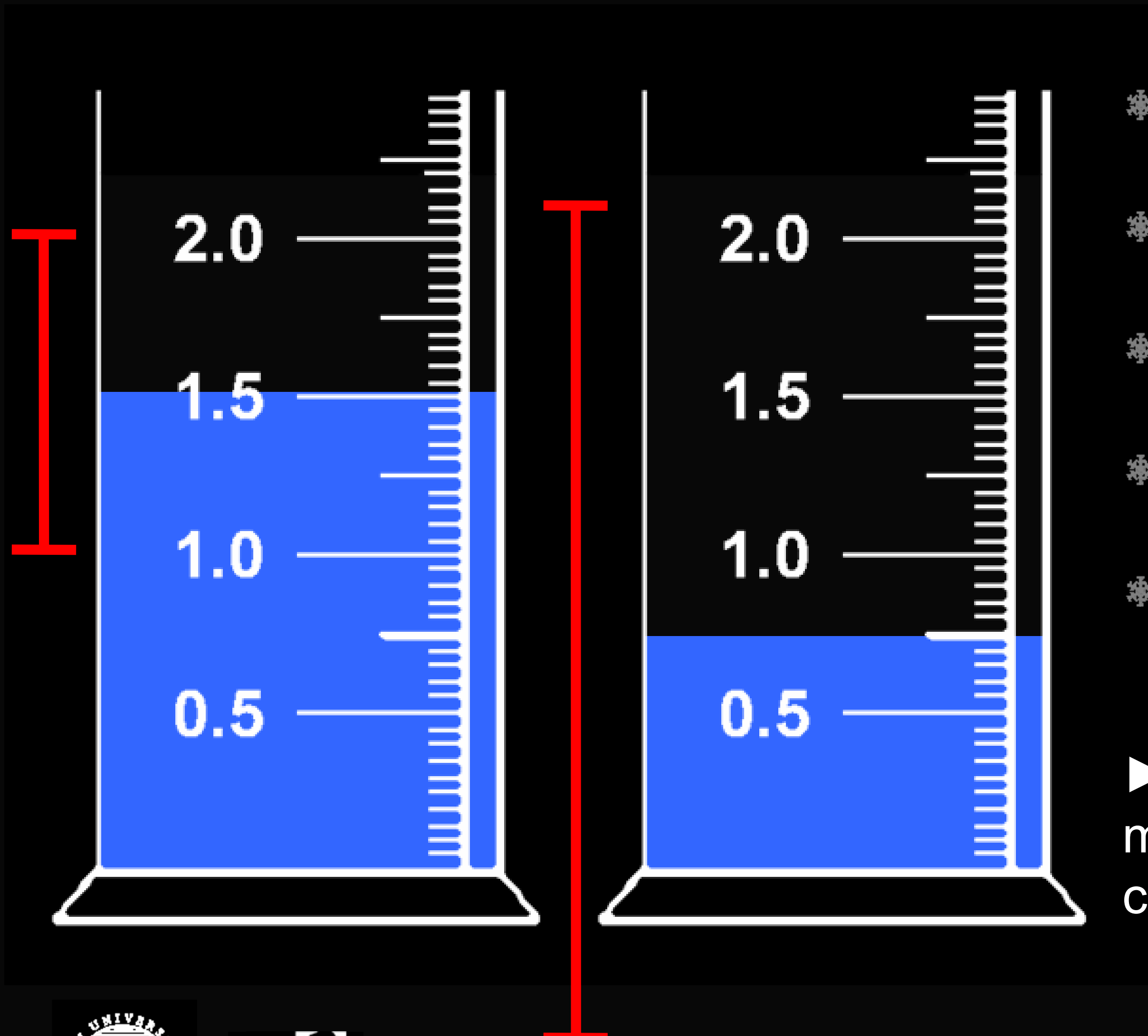
- IPCC Assessment reports (1990, 1995, 2001)



- Known sources include:
- Ocean expansion (0.5 mm)
- Glaciers (0.3 mm)
- Ice sheets (0.2 mm)
- Rivers (-0.3 mm)

► In 2001, only 50 % of measured rise explained by central estimates

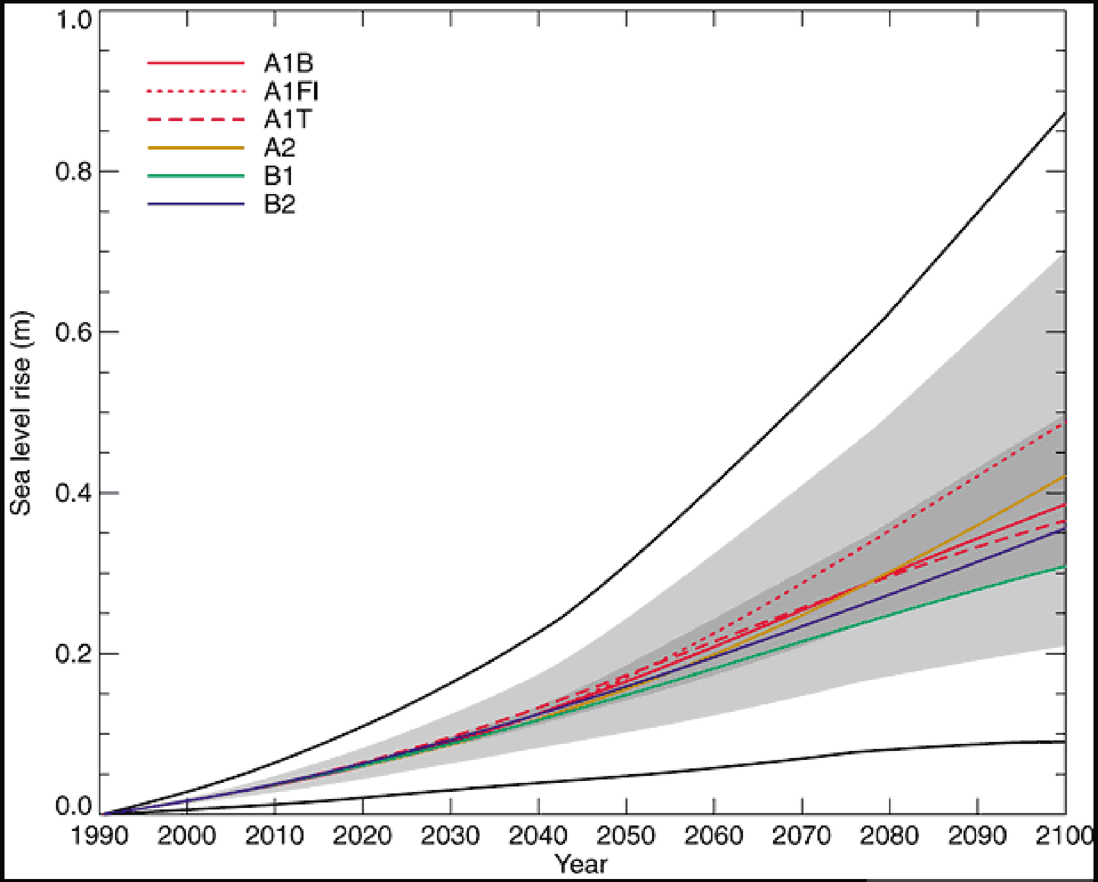
- IPCC Assessment reports (1990, 1995, 2001)



- Known sources include:
- Ocean expansion (0.5 mm)
- Glaciers (0.3 mm)
- Ice sheets (0.2 mm)
- Rivers (-0.3 mm)

► In 2001, only 50 % of measured rise explained by central estimates

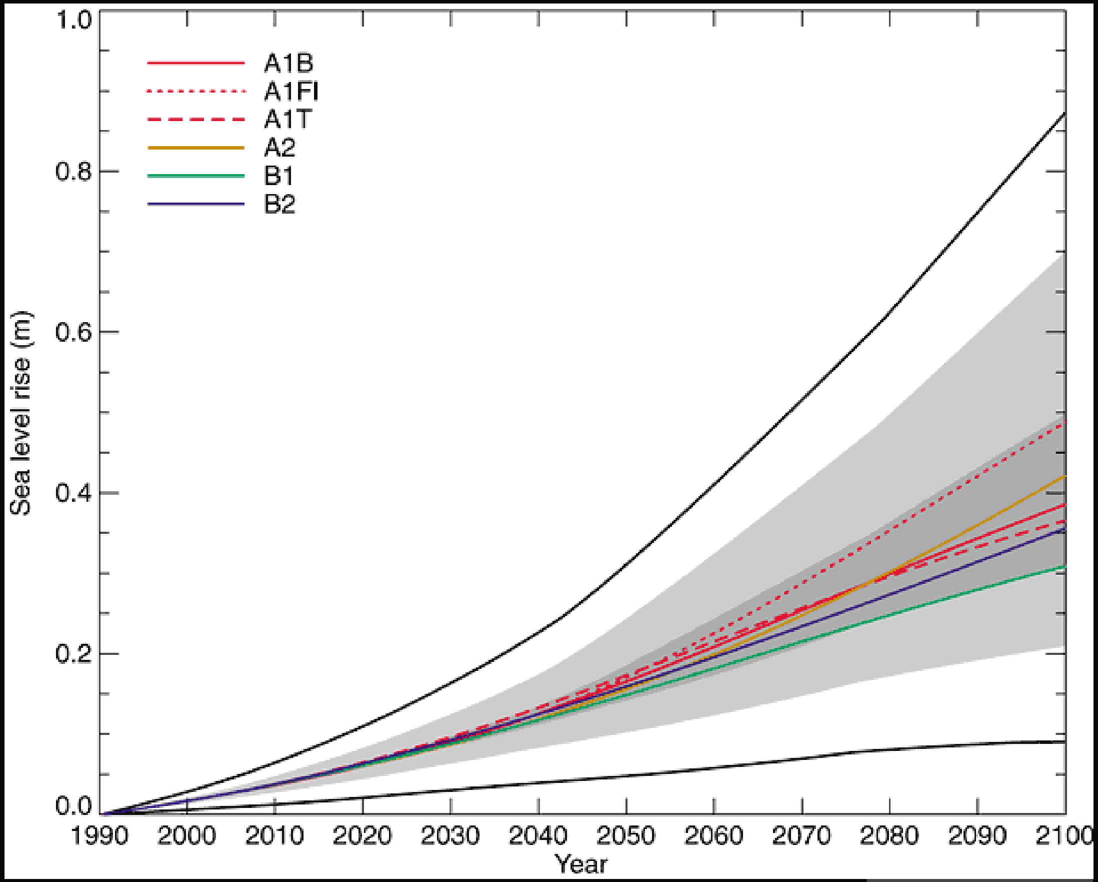
- IPCC Assessment reports (1990, 1995, 2001)



IPCC, 2001

- 21st C projection (2 x CO_2):
- Ocean expansion (× 3)
- Glaciers (× $^3/_4$)
- Ice sheets (× $^1/_2$)
- Rivers (**?**)

- IPCC Assessment reports (1990, 1995, 2001)

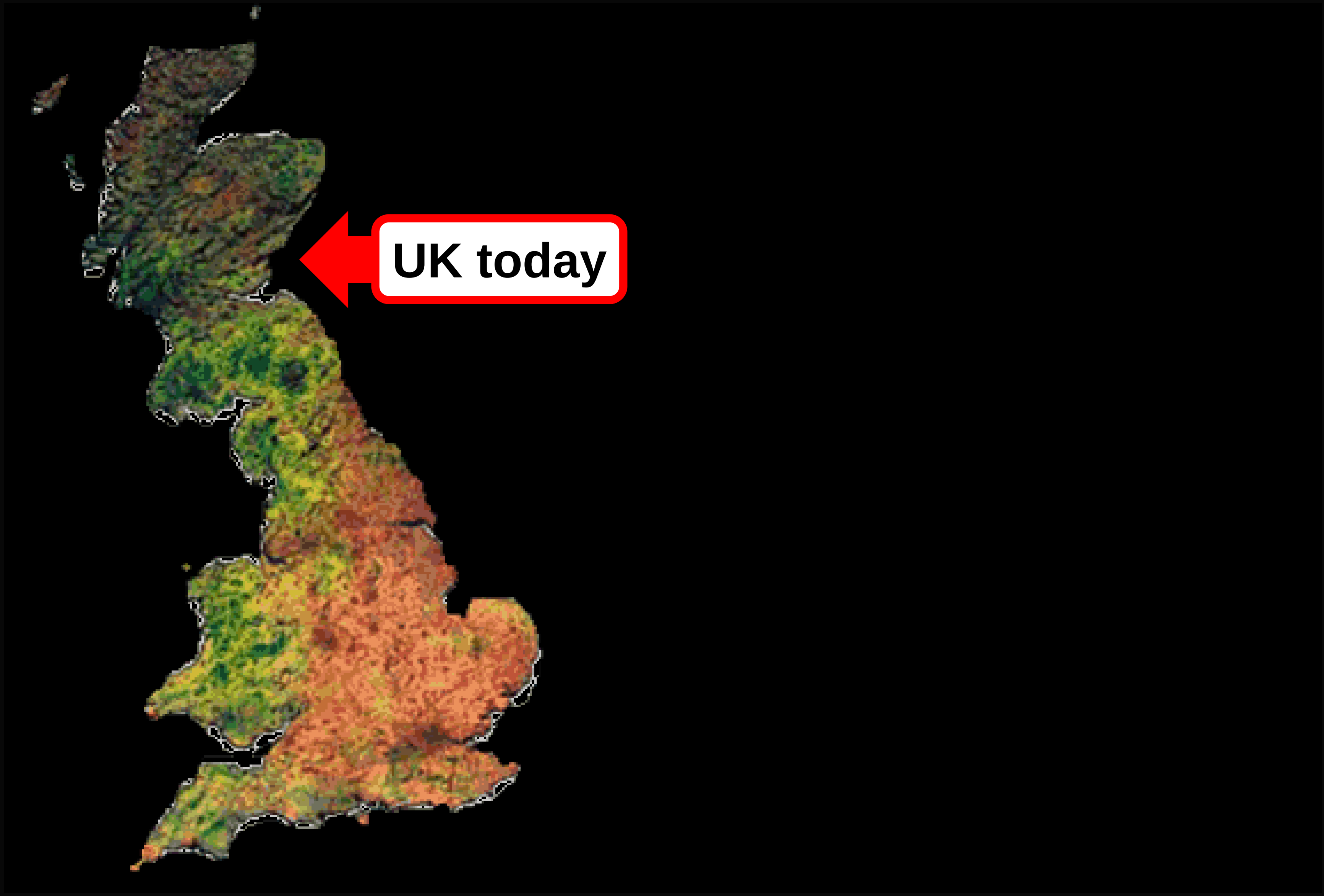


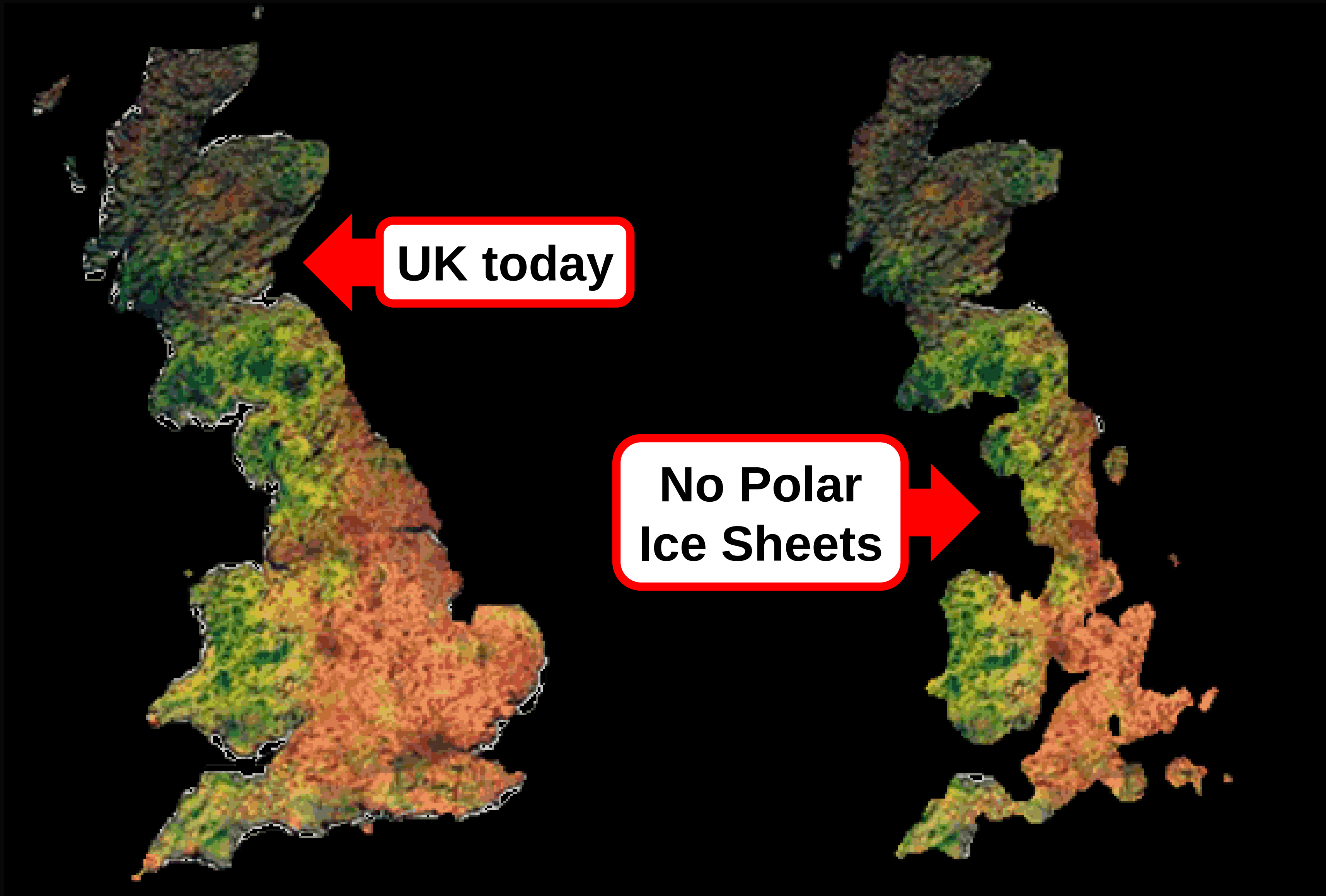
IPCC, 2001

- 21st C projection (2 x CO_2):
- Ocean expansion (× 3)
- Glaciers (× $^3/_4$)
- Ice sheets (× $^1/_2$)
- Rivers (**?**)

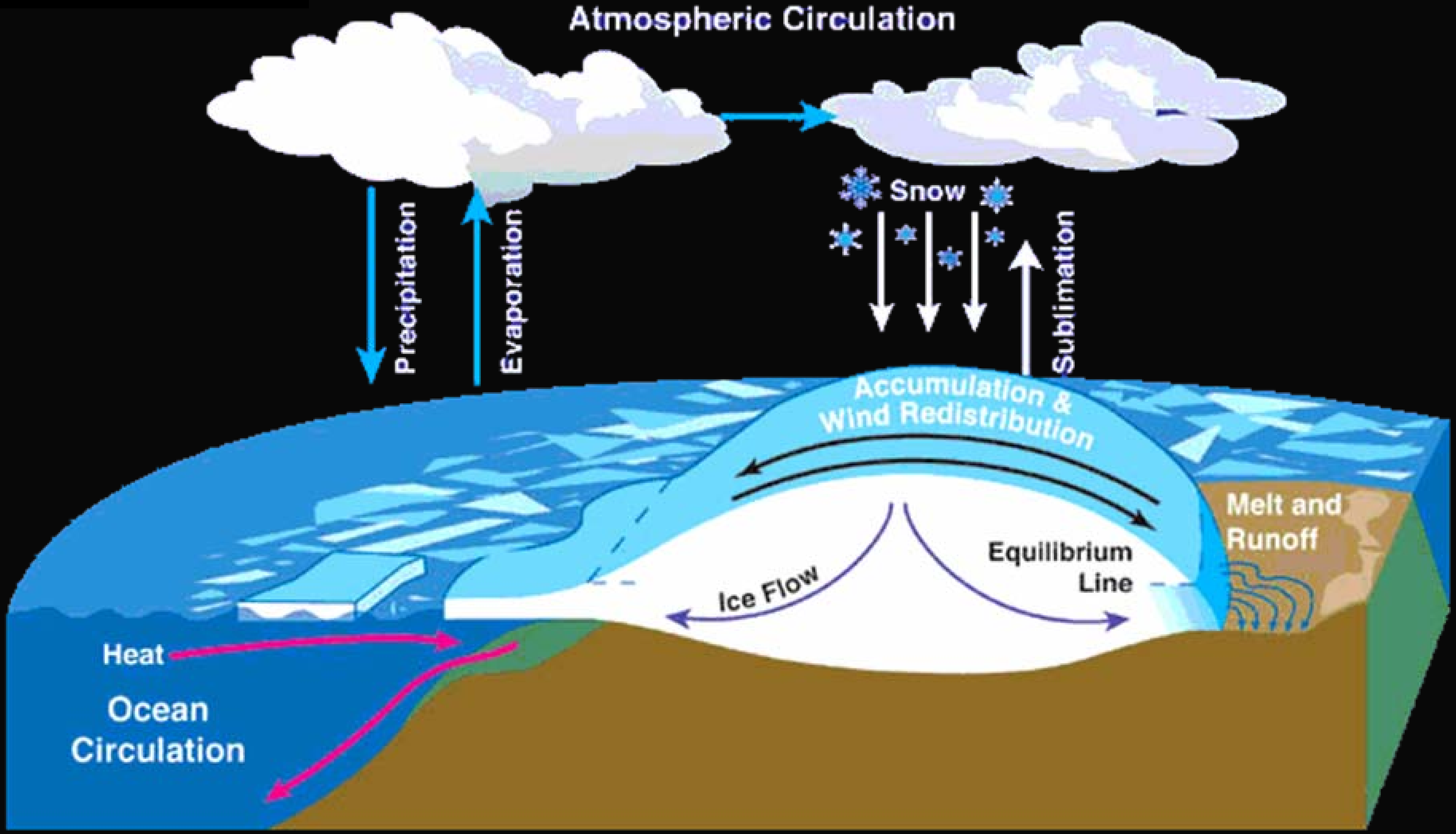
► ~ 0.5 m total sea level rise

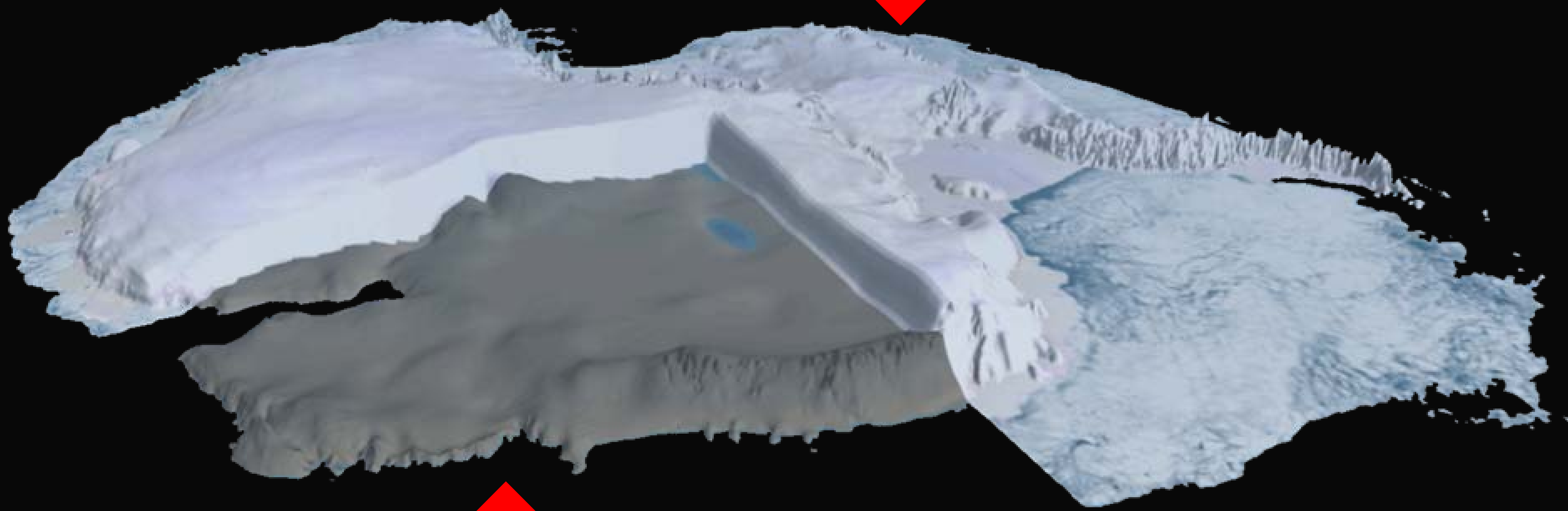
► Major contribution is ocean expansion

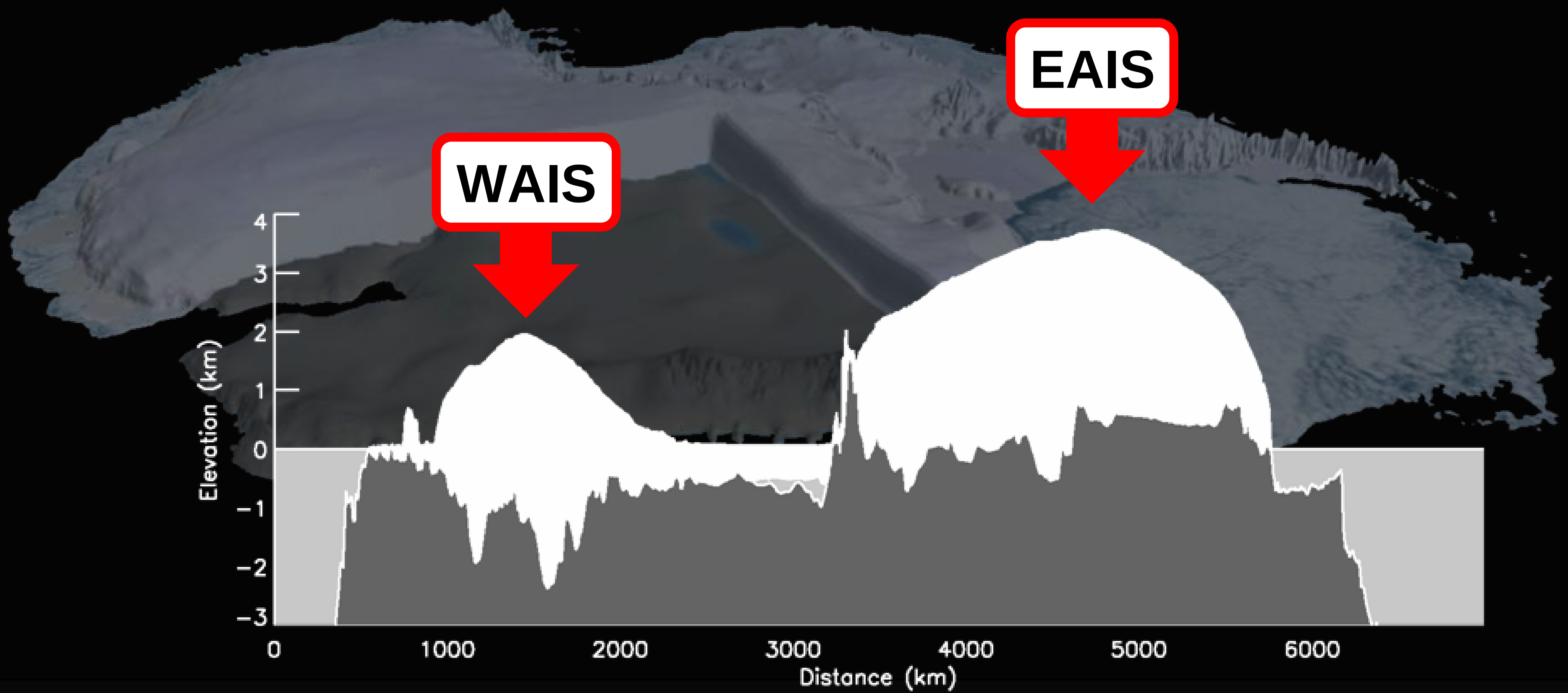

UK today

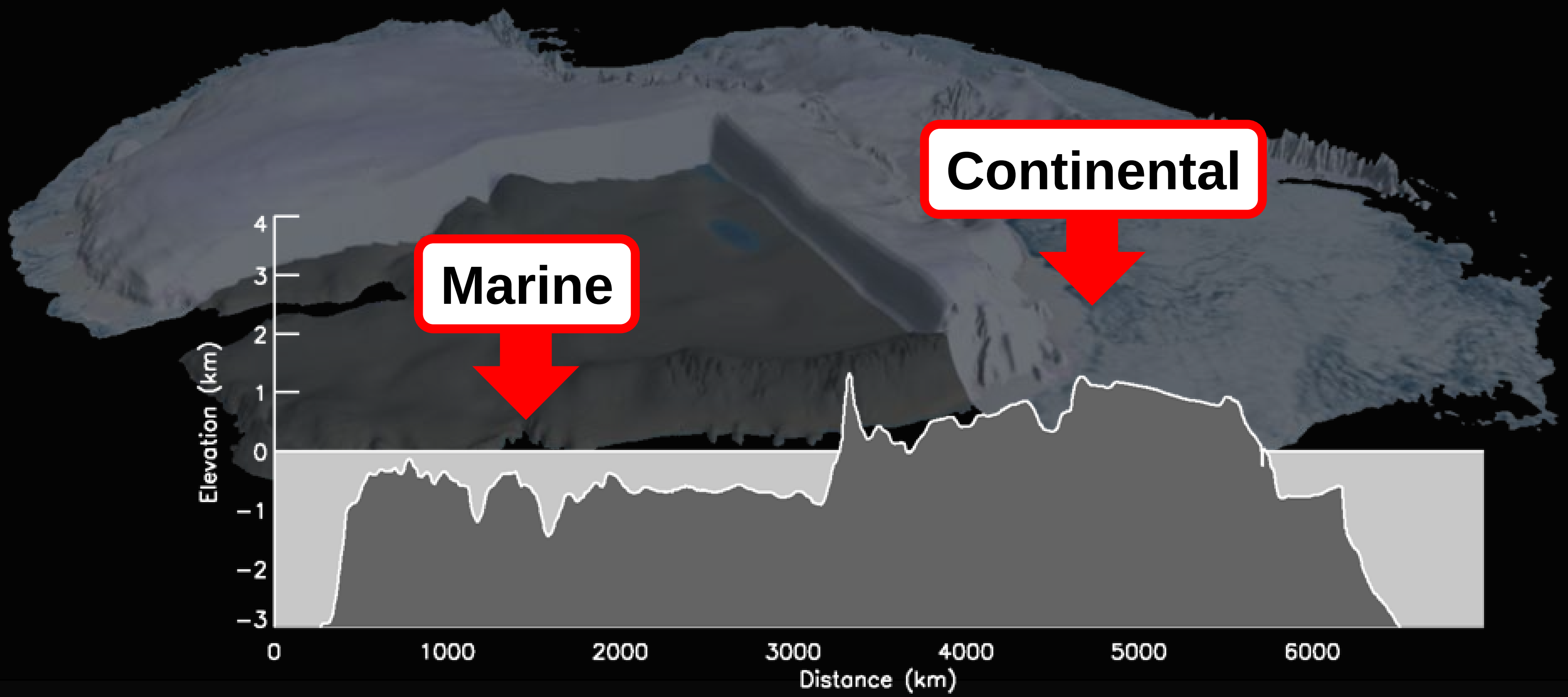

UK today
No Polar Ice Sheets

- Water cycle

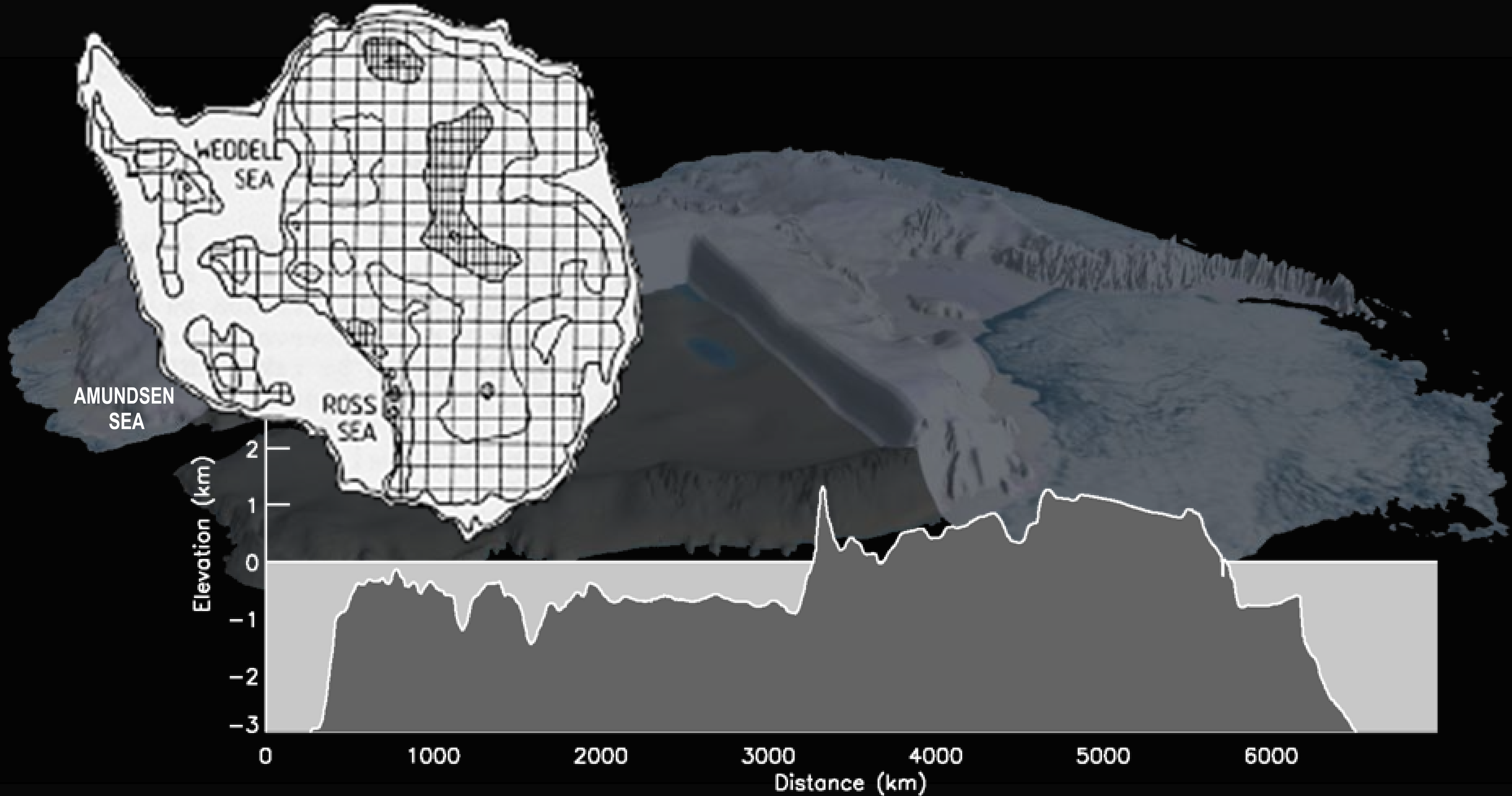

Atmospheric Circulation
Precipitation
Evaporation
Snow
Sublimation
Accumulation & Wind Redistribution
Melt and Runoff
Equilibrium Line
Ice Flow
Heat
Ocean Circulation

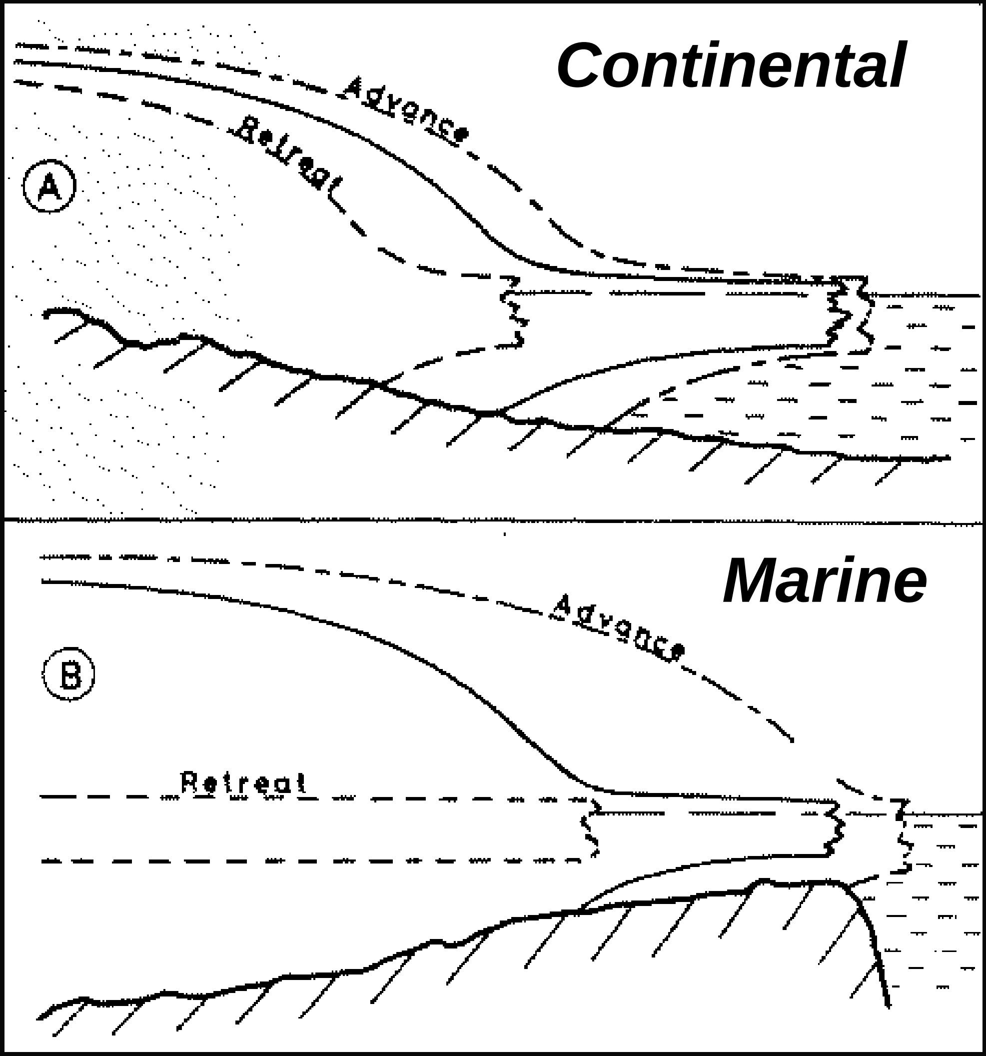

West Antarctic Ice Sheet
East Antarctic Ice Sheet


WAIS
EAIS
Elevation (km)
4
3
2
1
0
−1
−2
−3
0
1000
2000
3000
4000
5000
6000
Distance (km)

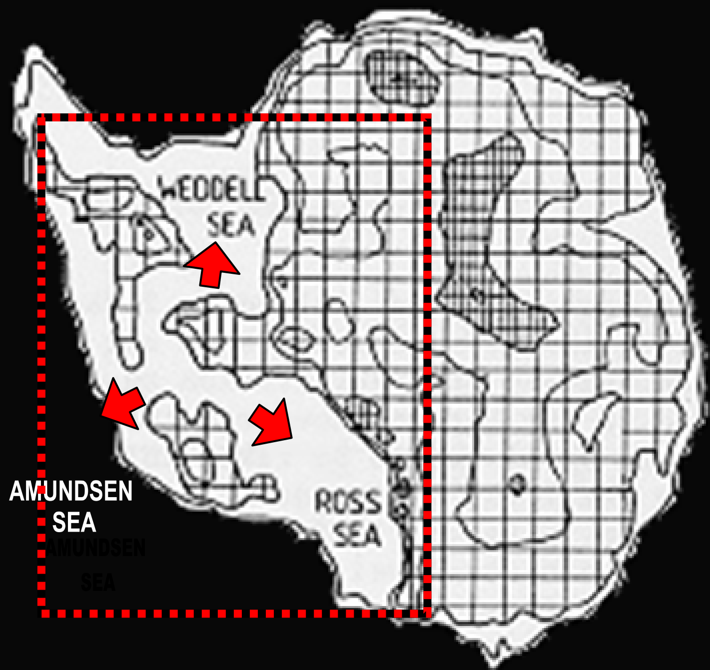

Continental
Marine
Elevation (km)
4
3
2
1
0
−1
−2
−3
0
1000
2000
3000
4000
5000
6000
Distance (km)

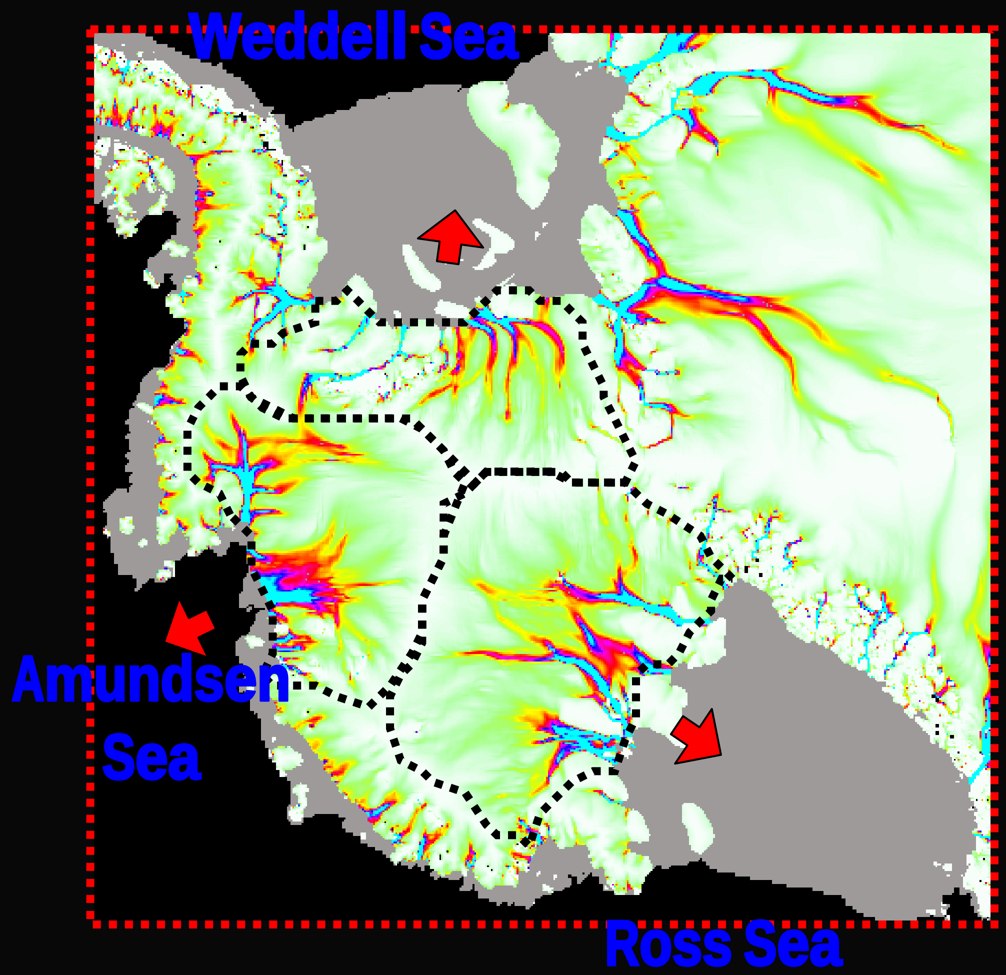
Antarctica & sea level



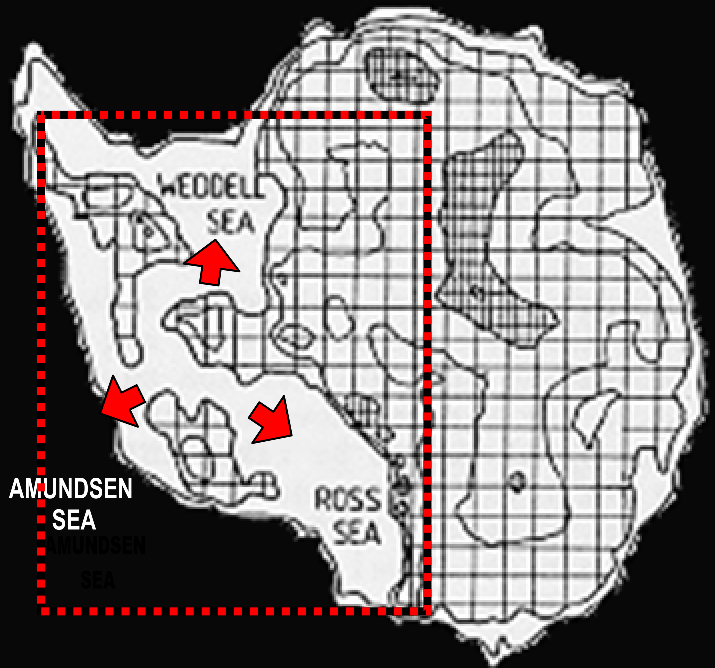


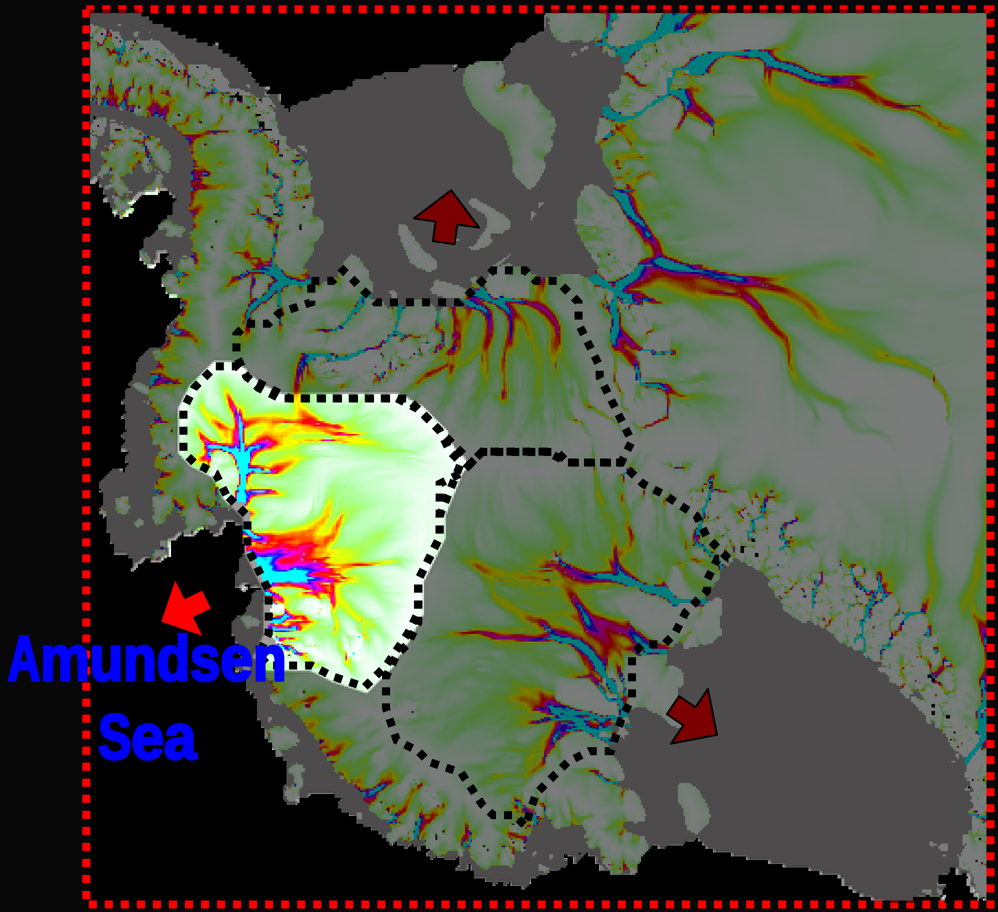
- Geometry of marine based ice sheets are unstable to advance or retreat – either event would be accelerating





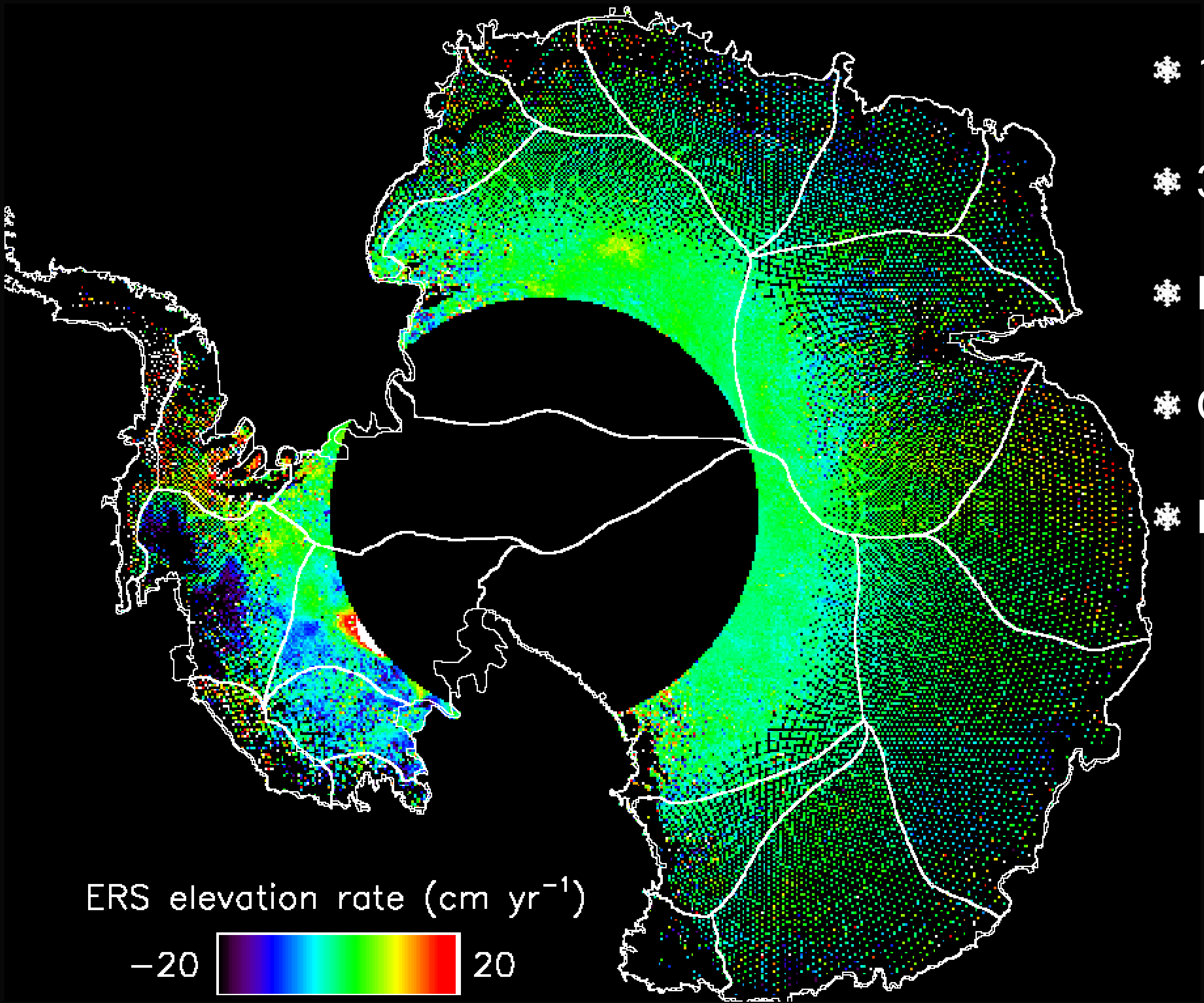
- West Antarctica is drained through three sectors





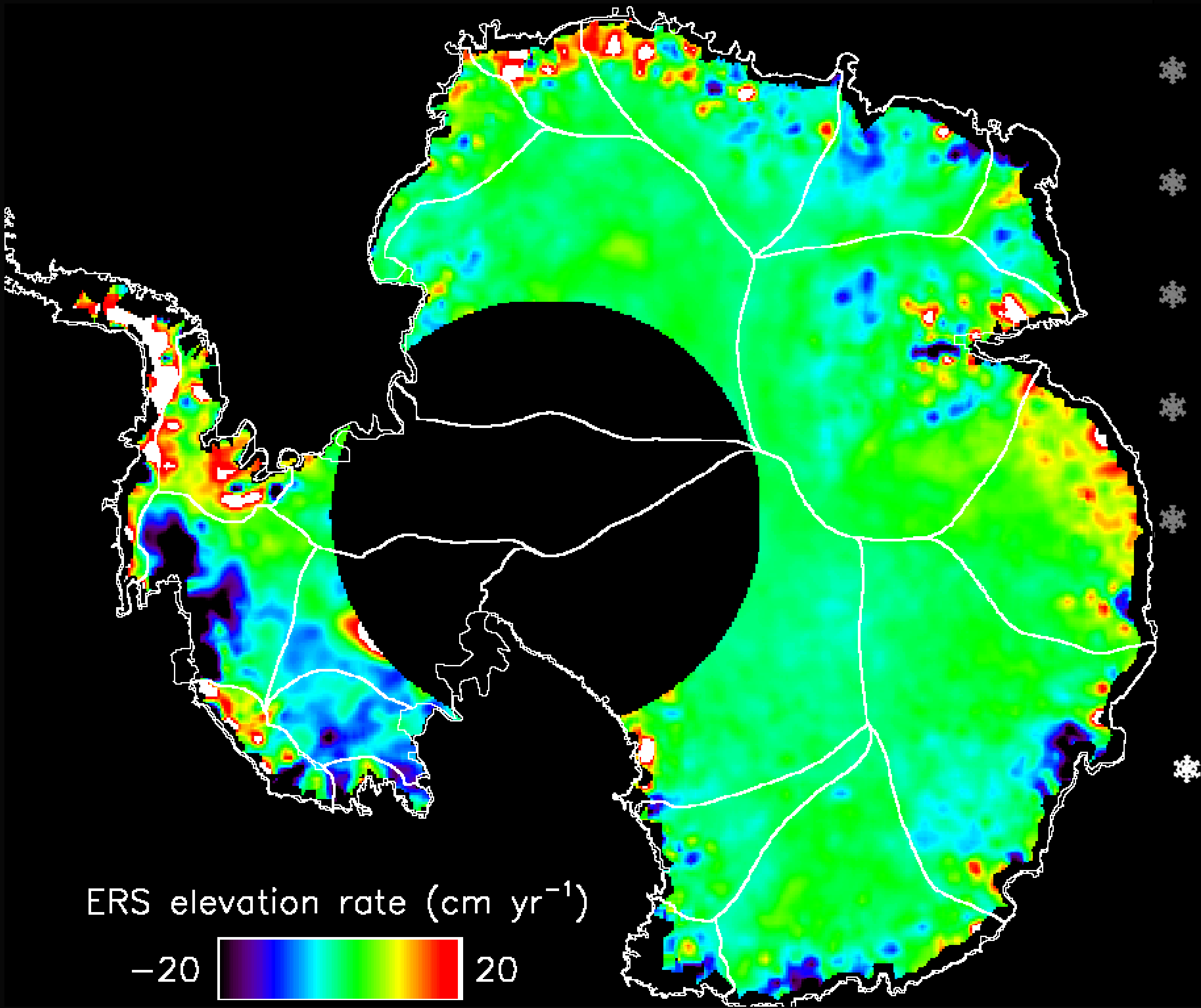
- Only Amundsen Sea sector has no ice shelf barrier and is grounded below sea level

Antarctic mass balance



- 1992-2004
- 35 day repeat
- ERS footprint ~ 10 km
- Orbit limit ~ 81.5°
- Density ∝ latitude

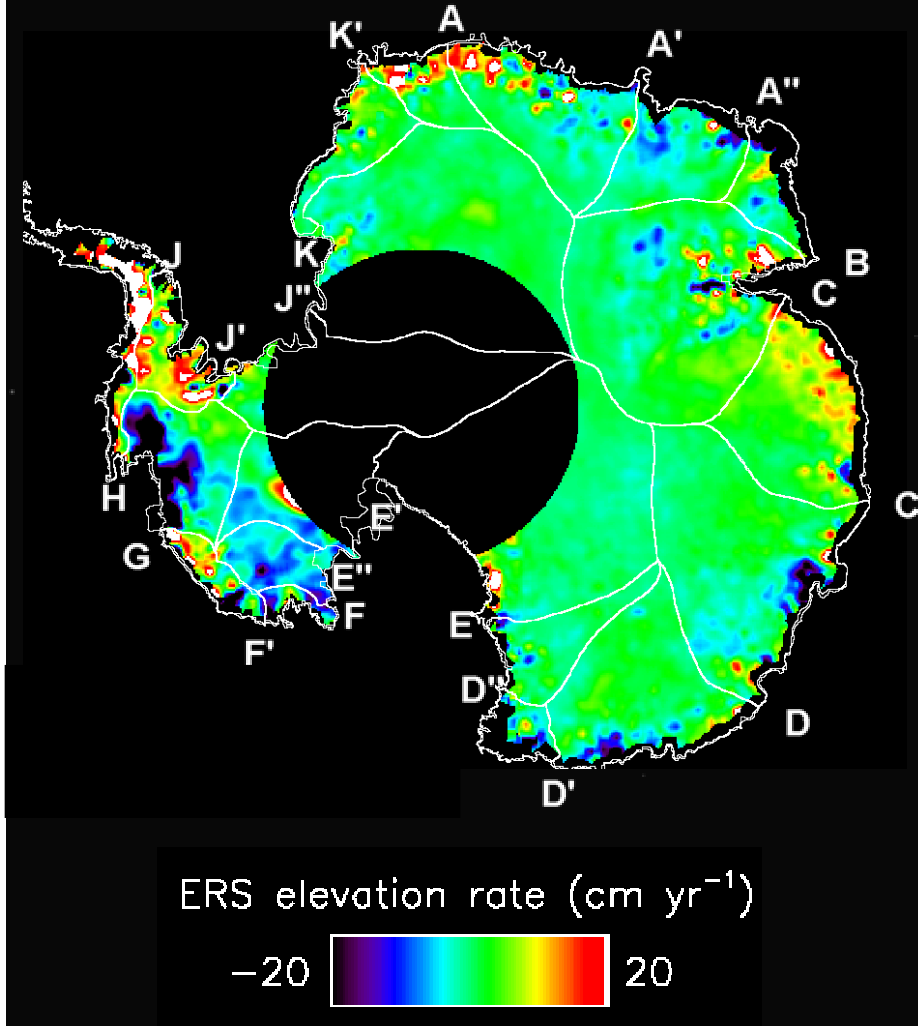
Antarctic mass balance



- 1992-2004
- 35 day repeat
- ERS footprint ~ 10 km
- Orbit limit ~ 81.5°
- Density ∝ latitude
- Trends ~ ±20 cm yr^{-1}

Basin	Area (10^6 km^2)	Observed Area (10^6 km^2)	Elevation rate (cm yr^{-1})
K-K'	0.24	0.22	2.4 ± 0.3
J''-K	1.59	0.97	0.7 ± 0.1
J'-J''	0.8	0.07	2.5 ± 0.4
J-J'	0.24	0.19	9.2 ± 0.4
H-J	0.28	0.12	16.6 ± 0.8
G-H	0.43	0.4	-6.6 ± 0.3
F'-G	0.13	0.11	4.1 ± 0.6
F-F'	0.06	0.04	-5.6 ± 0.7
E''-F	0.19	0.19	-5.0 ± 0.3
E'-E''	0.49	0.18	-0.9 ± 0.3
E-E'	1.55	0.8	0.1 ± 0.1
D''-E	0.28	0.26	0.1 ± 0.2
D'-D''	0.13	0.06	-0.1 ± 0.5
D-D'	0.74	0.67	0.7 ± 0.2
C'-D	1.15	1.08	0.1 ± 0.3
C-C'	0.7	0.63	4.9 ± 0.4
B-C	1.29	1.27	1.2 ± 0.1
A''-B	0.22	0.14	1.9 ± 0.4
A'-A''	0.42	0.37	-0.9 ± 0.2
A-A'	0.59	0.55	0.8 ± 0.1
K'-A	0.19	0.16	3.9 ± 0.3
WAIS	4.16	2.09	-0.5 ± 0.1
EAIS	7.54	6.4	1.1 ± 0.1
AIS	11.7	8.49	0.7 ± 0.1

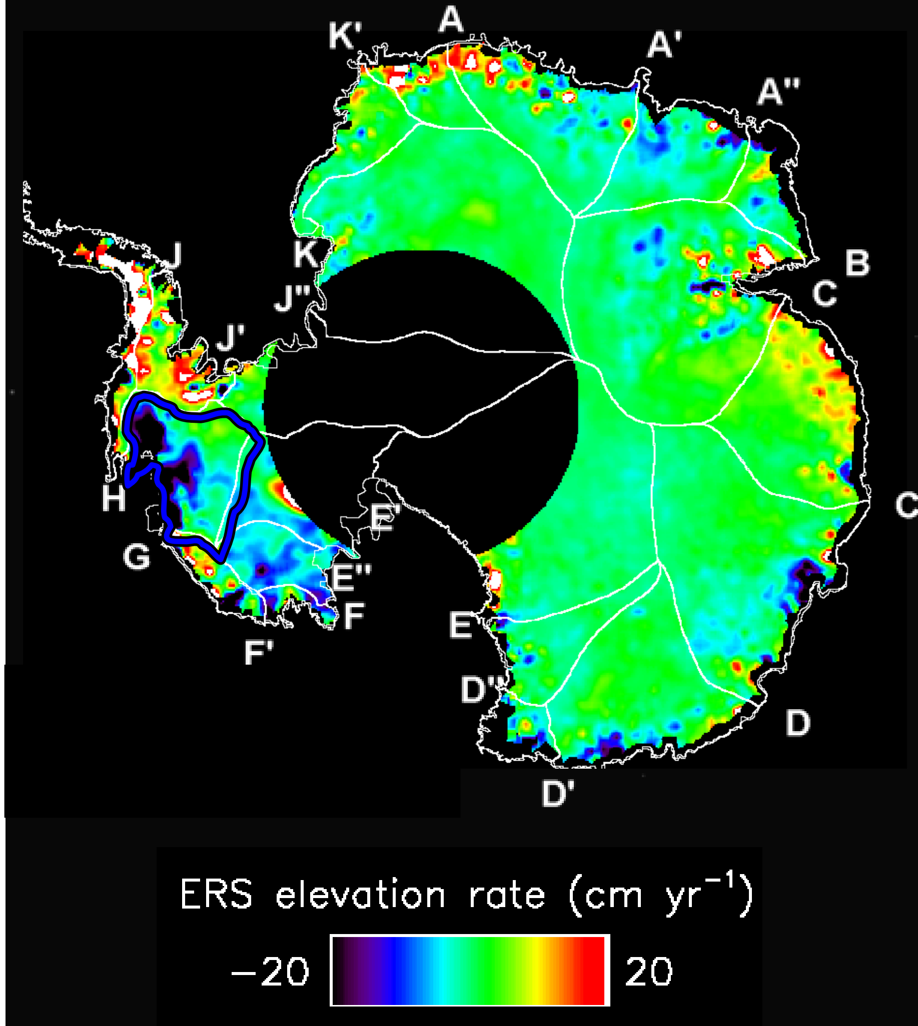
Table 1 Elevation change of the Antarctic ice sheet 1992 - 2004



Basin	Area (10^6 km^2)	Observed Area (10^6 km^2)	Elevation rate (cm yr^{-1})
K-K'	0.24	0.22	2.4 ± 0.3
J''-K	1.59	0.97	0.7 ± 0.1
J'-J''	0.8	0.07	2.5 ± 0.4
J-J'	0.24	0.19	9.2 ± 0.4
H-J	0.28	0.12	16.6 ± 0.8
G-H	0.43	0.4	-6.6 ± 0.3
F'-G	0.13	0.11	4.1 ± 0.6
F-F'	0.06	0.04	-5.6 ± 0.7
E''-F	0.19	0.19	-5.0 ± 0.3
E'-E''	0.49	0.18	-0.9 ± 0.3
E-E'	1.55	0.8	0.1 ± 0.1
D''-E	0.28	0.26	0.1 ± 0.2
D'-D''	0.13	0.06	-0.1 ± 0.5
D-D'	0.74	0.67	0.7 ± 0.2
C'-D	1.15	1.08	0.1 ± 0.3
C-C'	0.7	0.63	4.9 ± 0.4
B-C	1.29	1.27	1.2 ± 0.1
A''-B	0.22	0.14	1.9 ± 0.4
A'-A''	0.42	0.37	-0.9 ± 0.2
A-A'	0.59	0.55	0.8 ± 0.1
K'-A	0.19	0.16	3.9 ± 0.3
WAIS	4.16	2.09	-0.5 ± 0.1
EAIS	7.54	6.4	1.1 ± 0.1
AIS	11.7	8.49	0.7 ± 0.1

Table 1 Elevation change of the Antarctic ice sheet 1992 - 2004

Strong thinning



Isostatic uplift | **Surface accumulation** | **Ice divergence**

$$\frac{\partial h}{\partial t} = \frac{\partial \Delta_B}{\partial t} + \int_0^M dm \frac{\partial}{\partial t}\left(\frac{1}{\rho_f(m)}\right) + \left(\frac{1}{\rho_{ice}}\right)\left(\dot{M}_s + \dot{M}_b + \nabla.(Mv)\right)$$

Elevation change | **Firn densification** | **Basal accumulation**

Isostatic uplift

Surface accumulation

Ice divergence

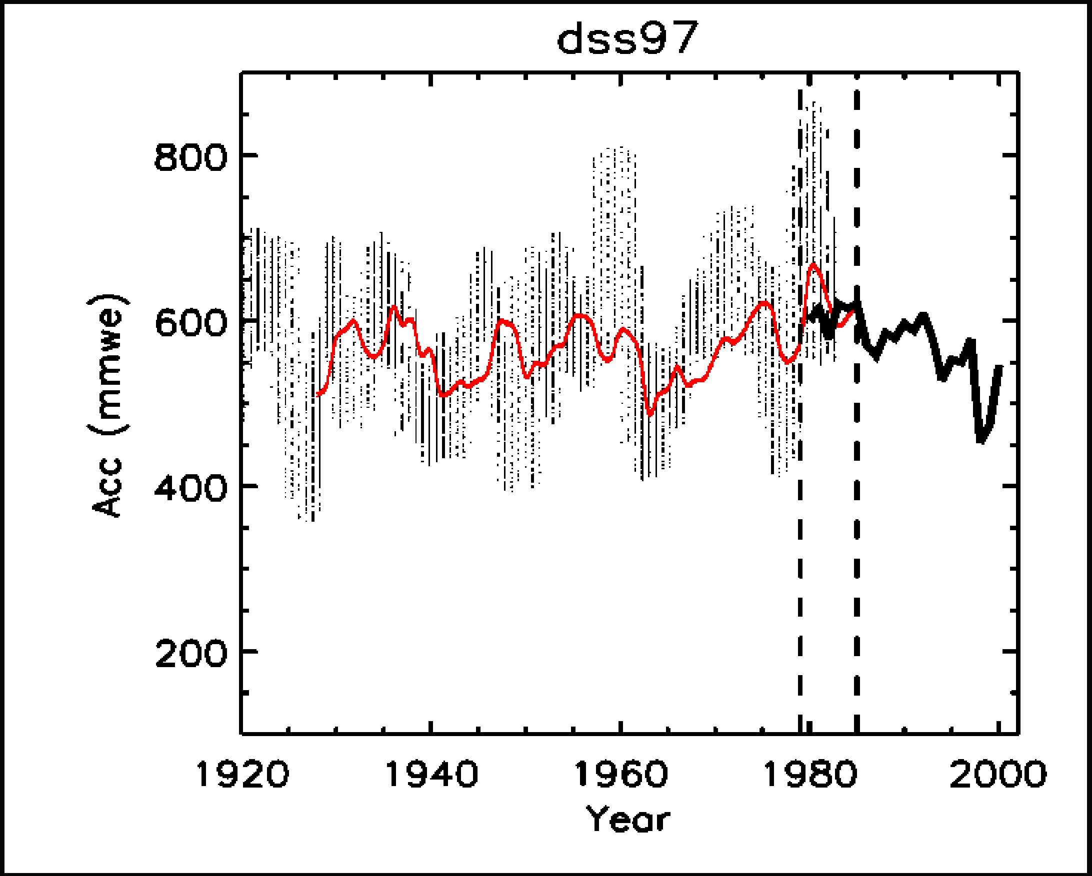
$$\frac{\partial h}{\partial t} = \frac{\partial \Delta_B}{\partial t} + \int_0^M dm \frac{\partial}{\partial t}\left(\frac{1}{\rho_f(m)}\right) + \left(\frac{1}{\rho_{ice}}\right)\left(\dot{M}_s + \dot{M}_b + \nabla.(Mv)\right)$$

Elevation change

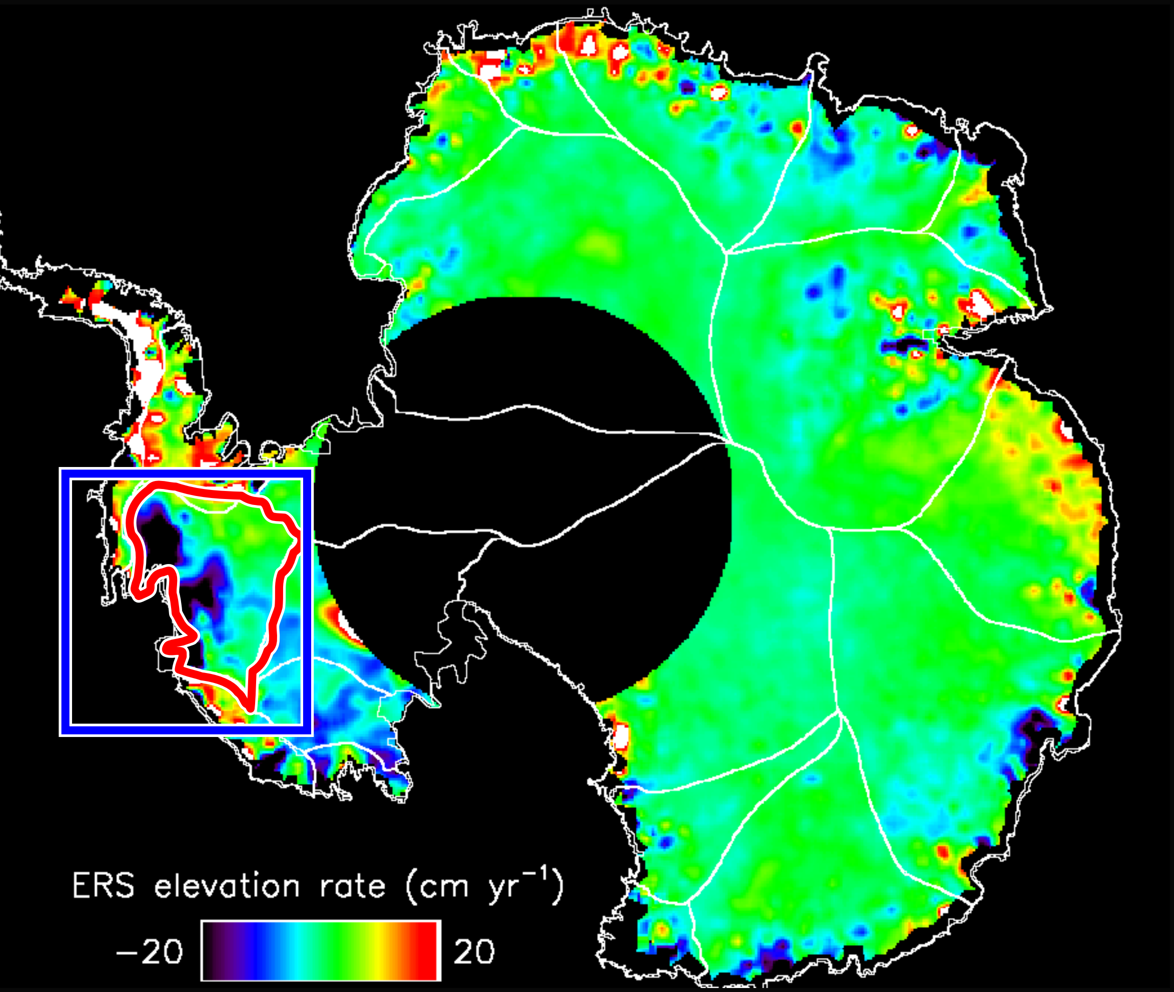
Firn densification

Basal accumulation

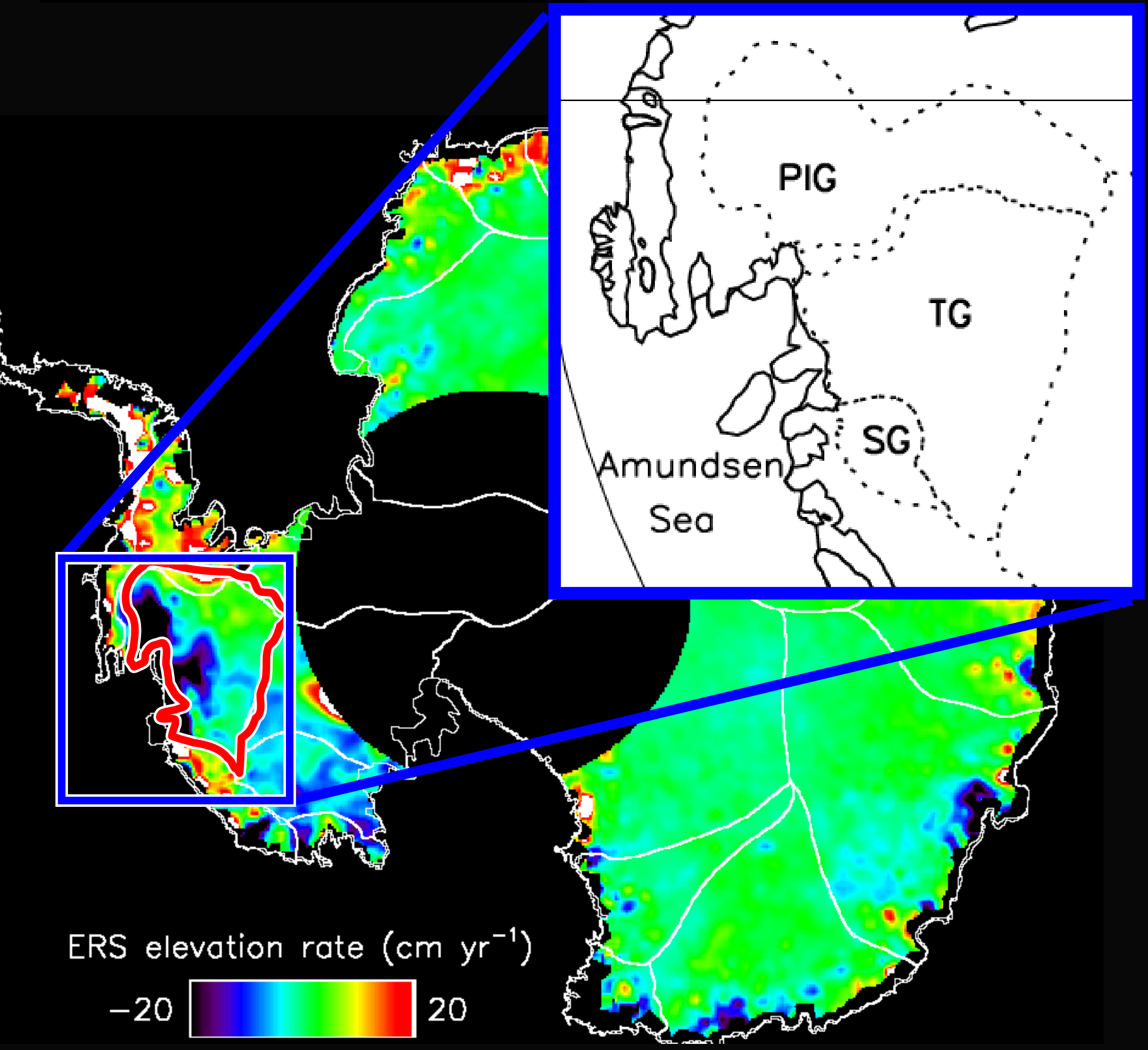
Elevation trends are due to either snowfall or ice flow



Snowfall typically fluctuates about a long term mean on decadal timescales by ~ 25 %

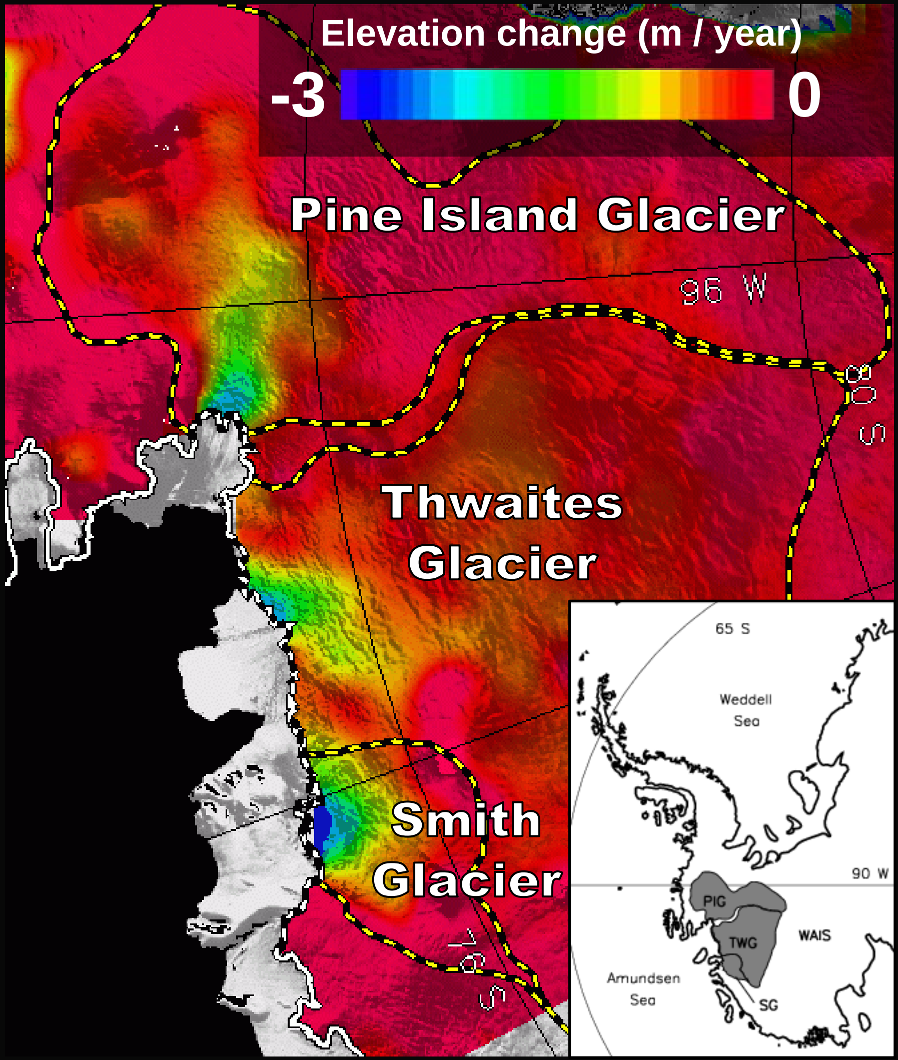


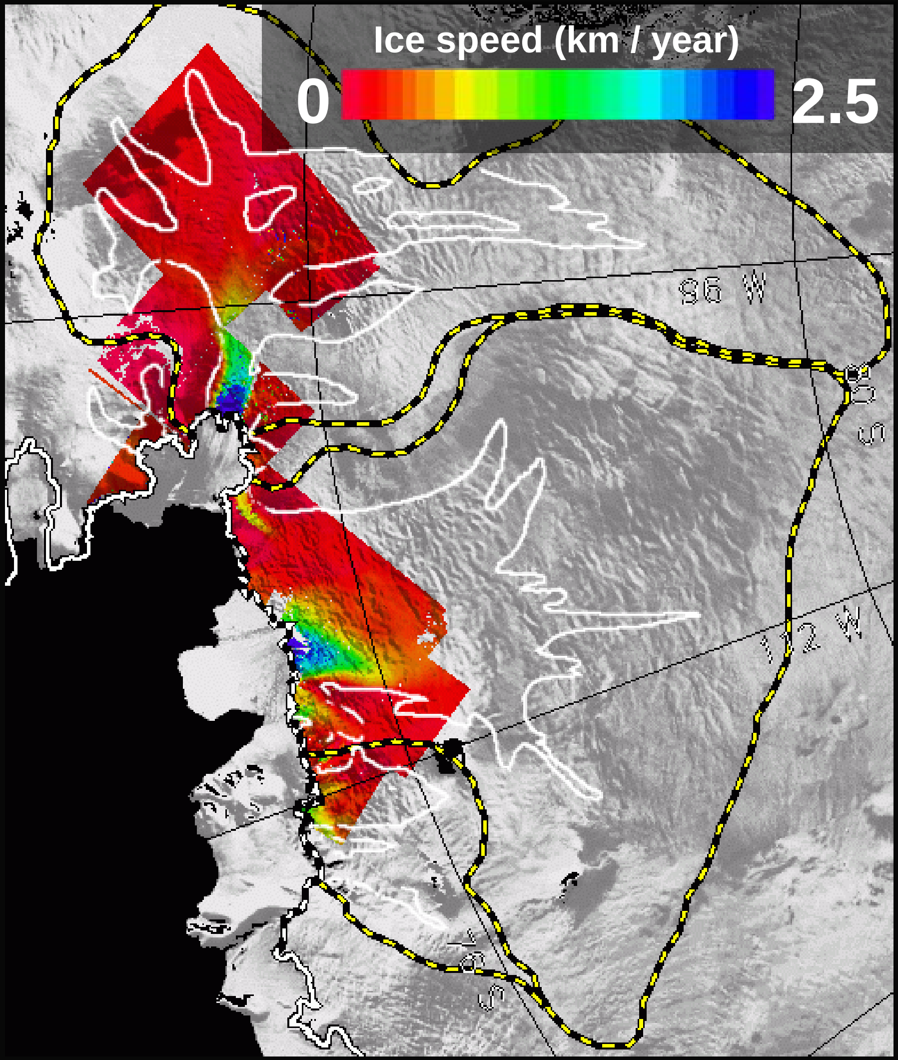
- On average, Amundsen Sea sector has deflated by 7 cm yr^{-1}
- Snowfall variability is 6 cm yr^{-1}
- Although mean deflation is comparable to snowfall variability, signal is highly coherent and peak rate is 50 times greater



- Amundsen Sea Sector is 40 % of WAIS
- Drained by the Pine Island, Thwaites, and Smith glaciers
- Ice volume sufficient to raise sea levels by 1.1 m

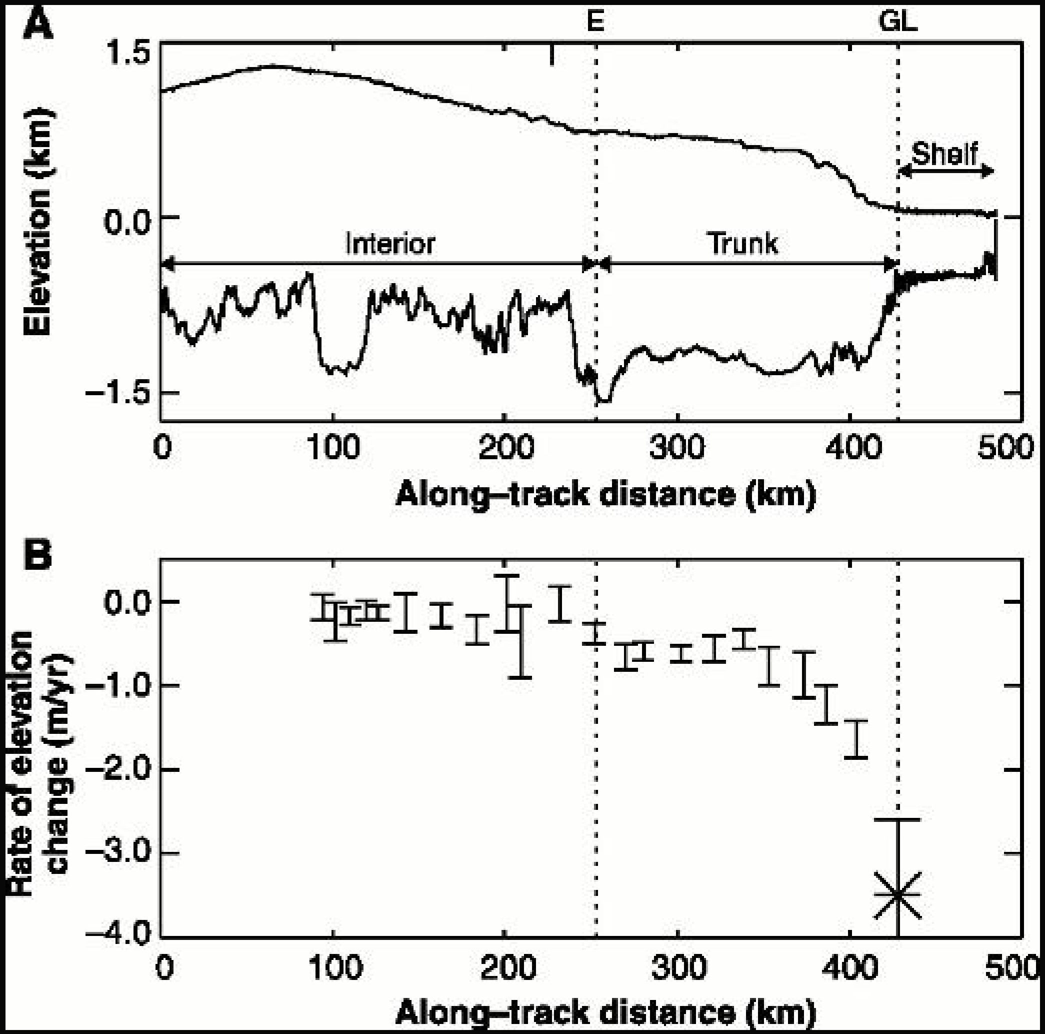
- Deflation is highly correlated with ice flow





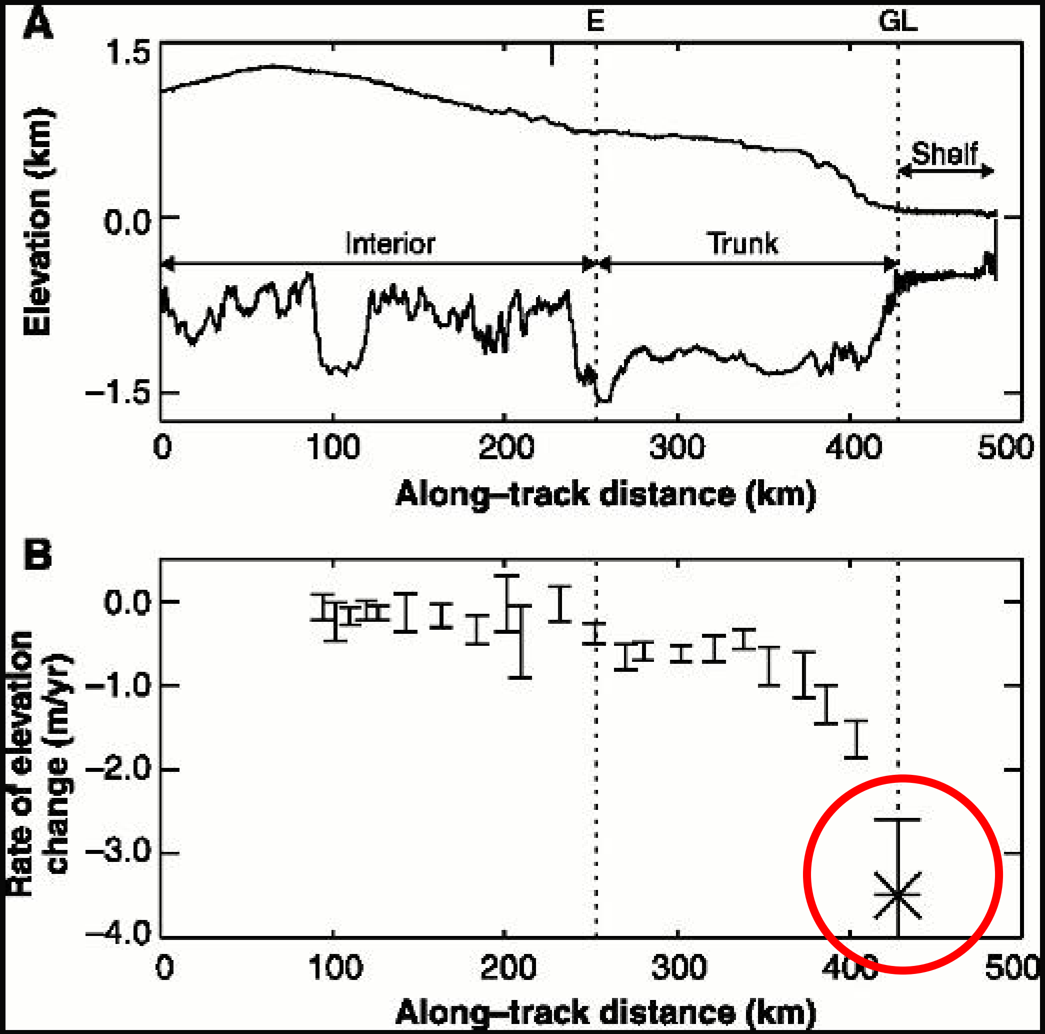
Pine Island Glacier

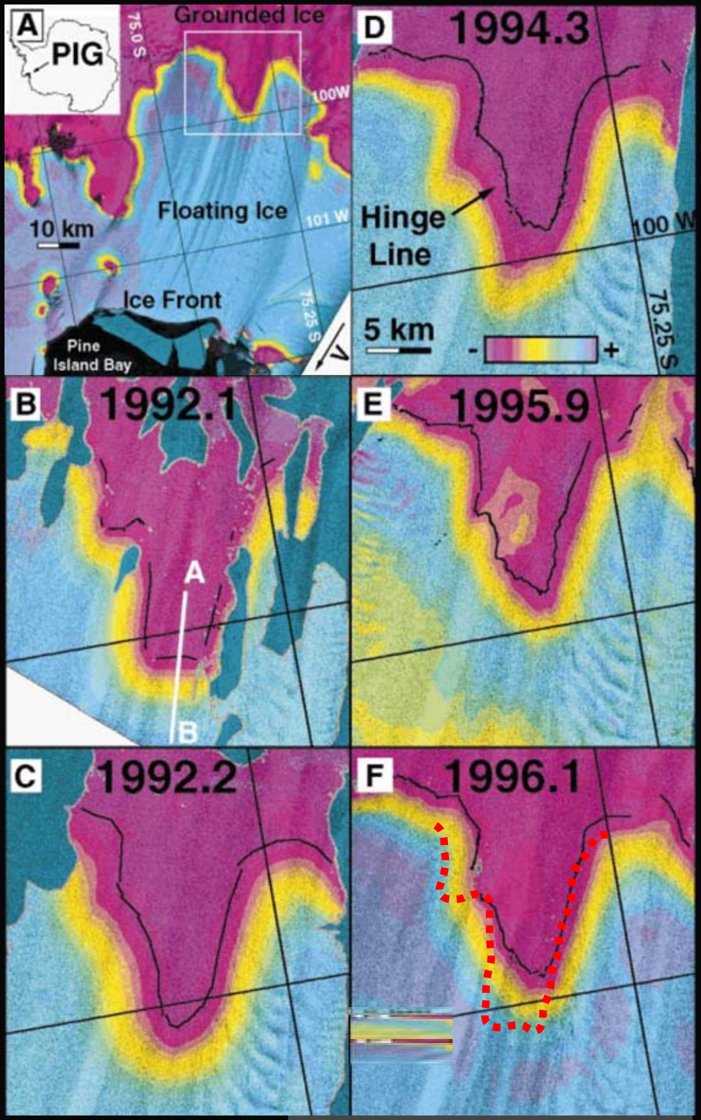
- Deflation peaks at 3 m yr^{-1} at grounding line, and extends 200 km inland



Pine Island Glacier

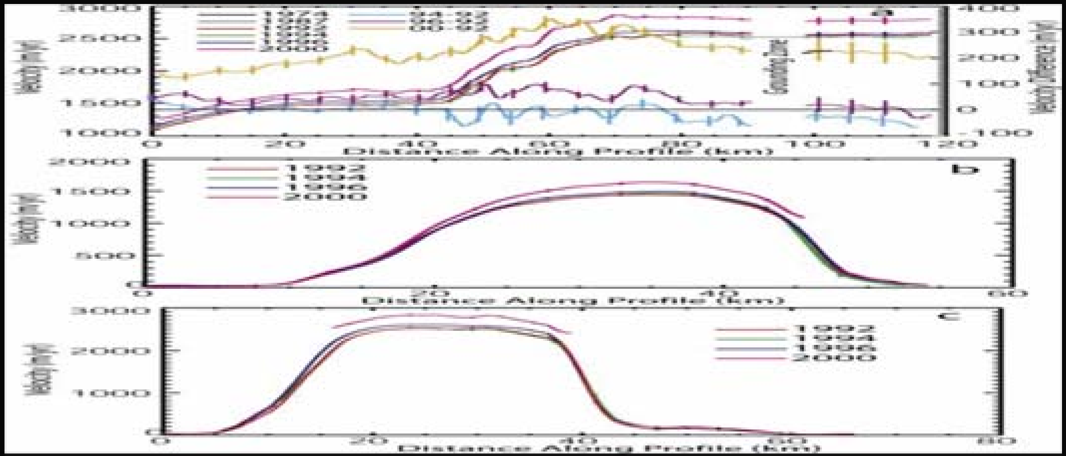
- Consistent with InSAR grounding line retreat

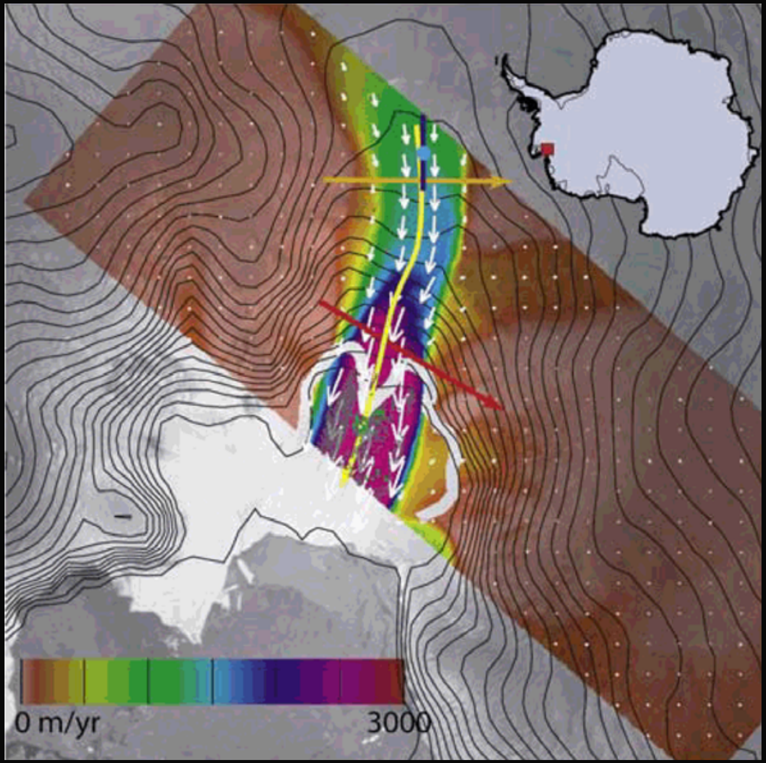




Rignot, *Science*, 1998

- Consistent with 20 % glacier acceleration

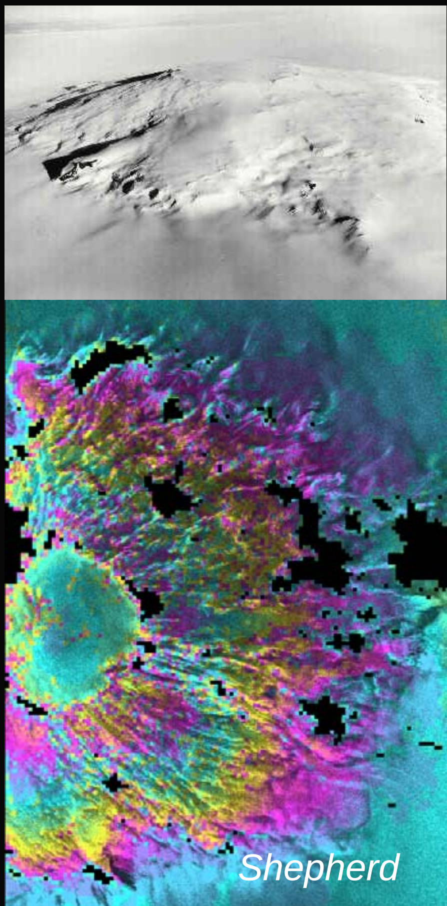


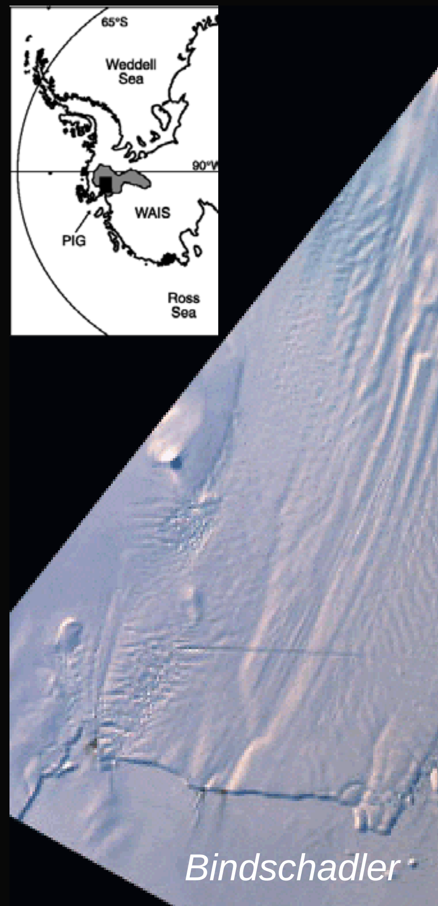


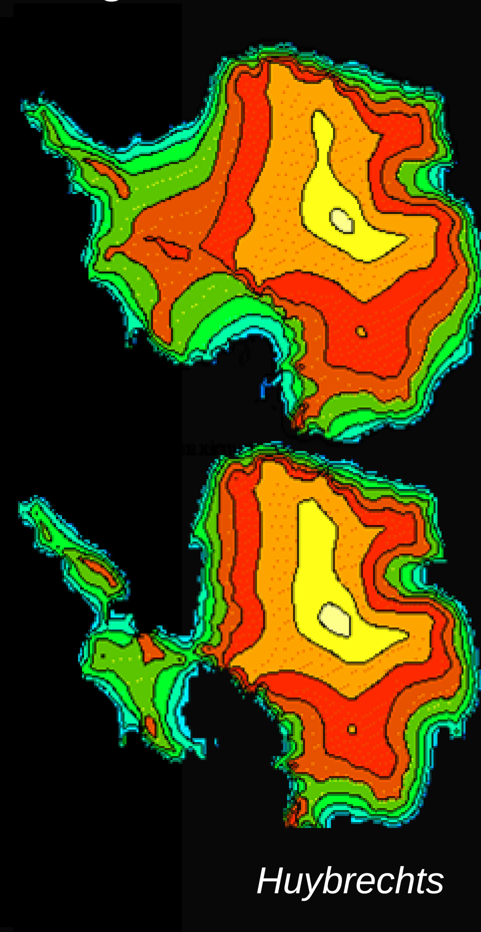
Joughin et al, *GRL*, 2003

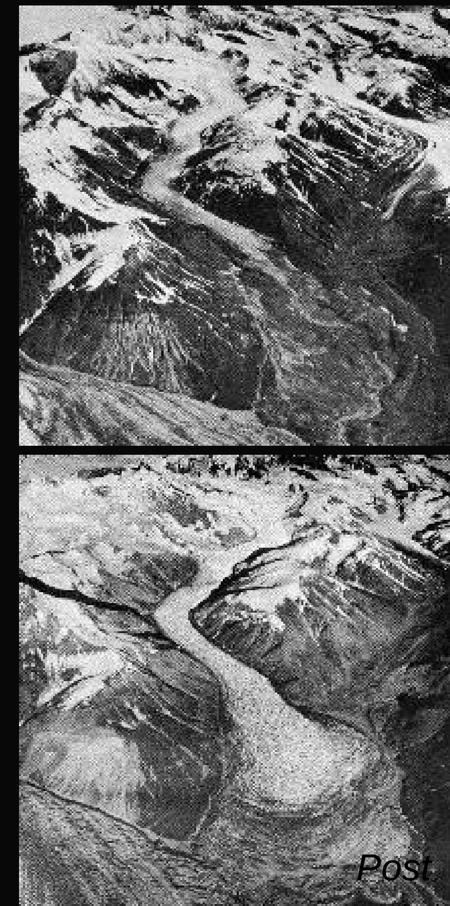
Origin of imbalance?

Geothermal	Ocean	Deglaciation	Surge







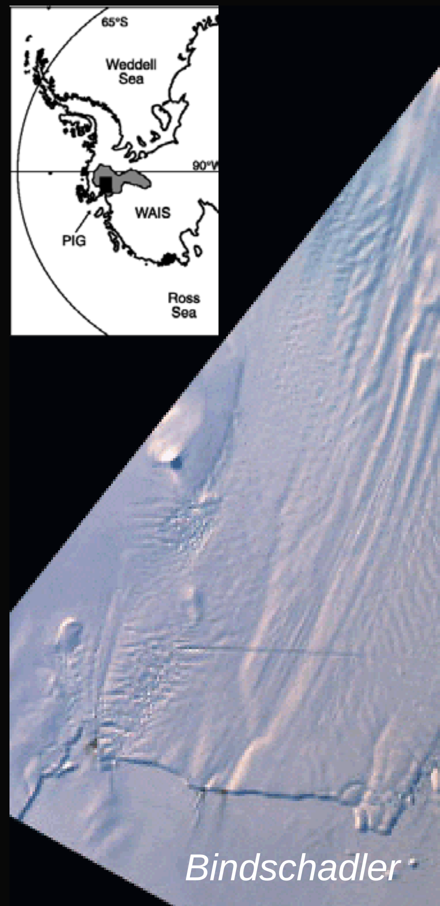


External → Internal

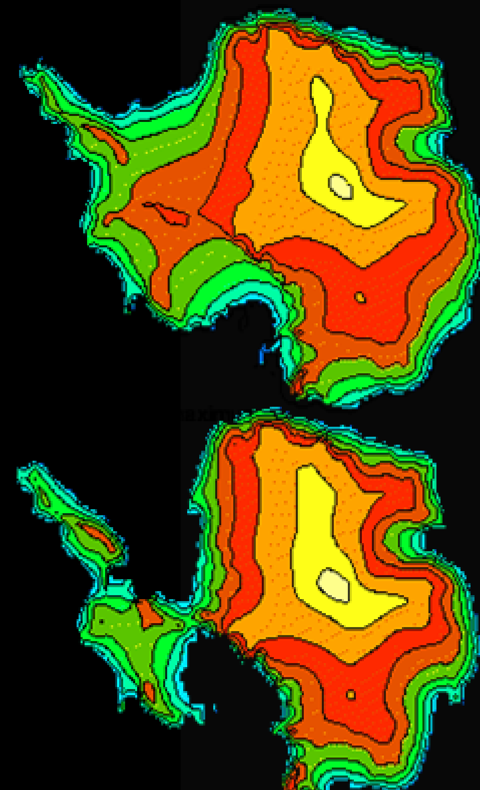
Origin of imbalance?

Geothermal

Ocean

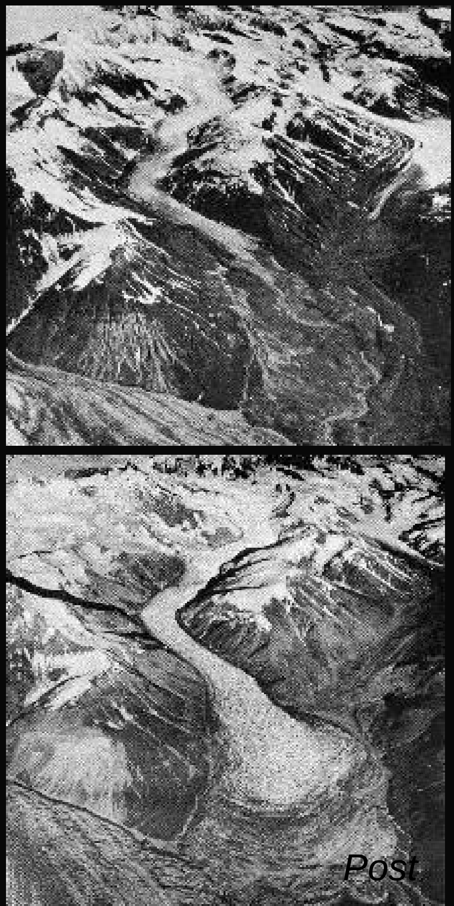


Deglaciation



Huybrechts

Surge

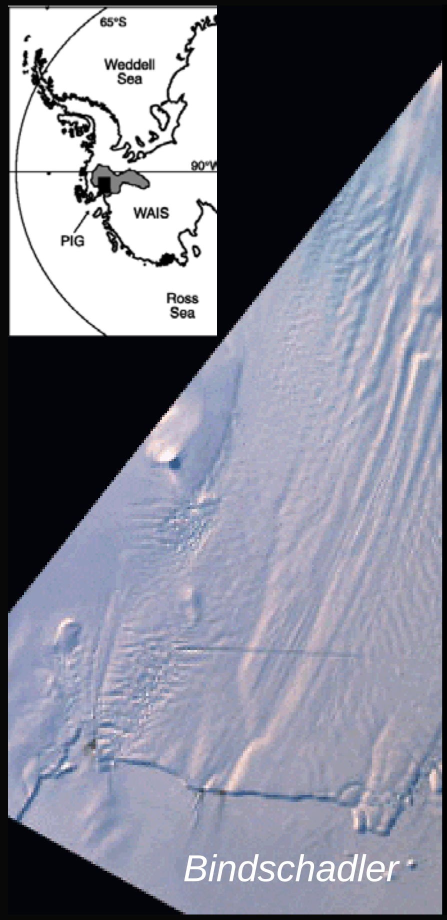


External → Internal

Origin of imbalance?

Geothermal

Ocean



Deglaciation

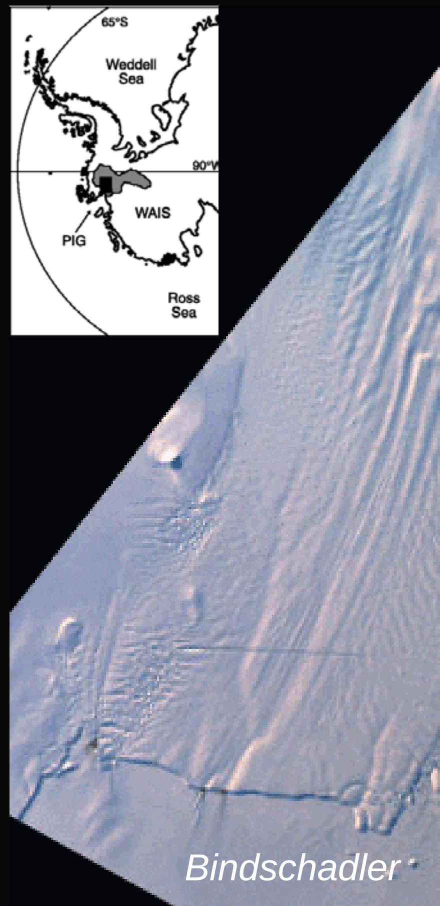
Surge

External → Internal

Origin of imbalance?

Geothermal

Ocean

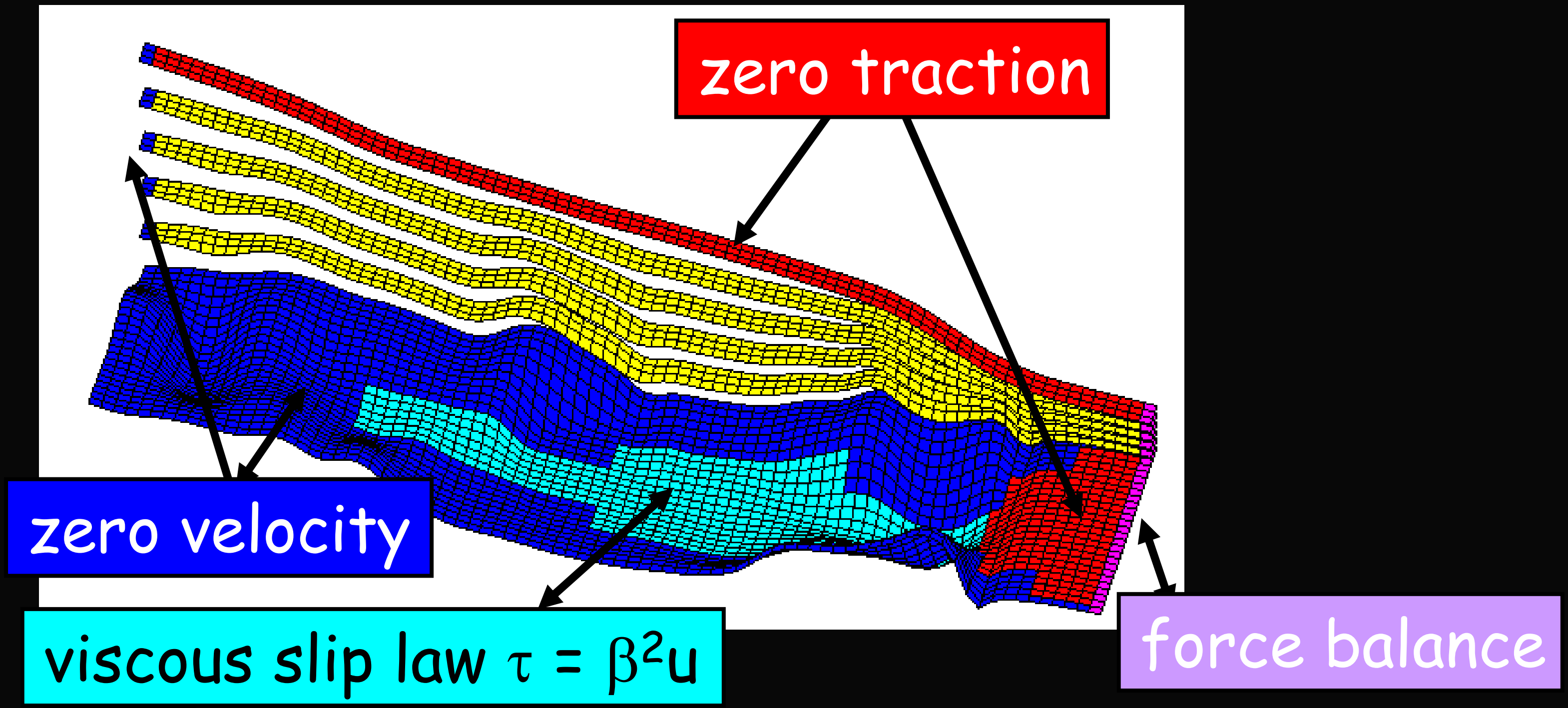


Deglaciation

Surge

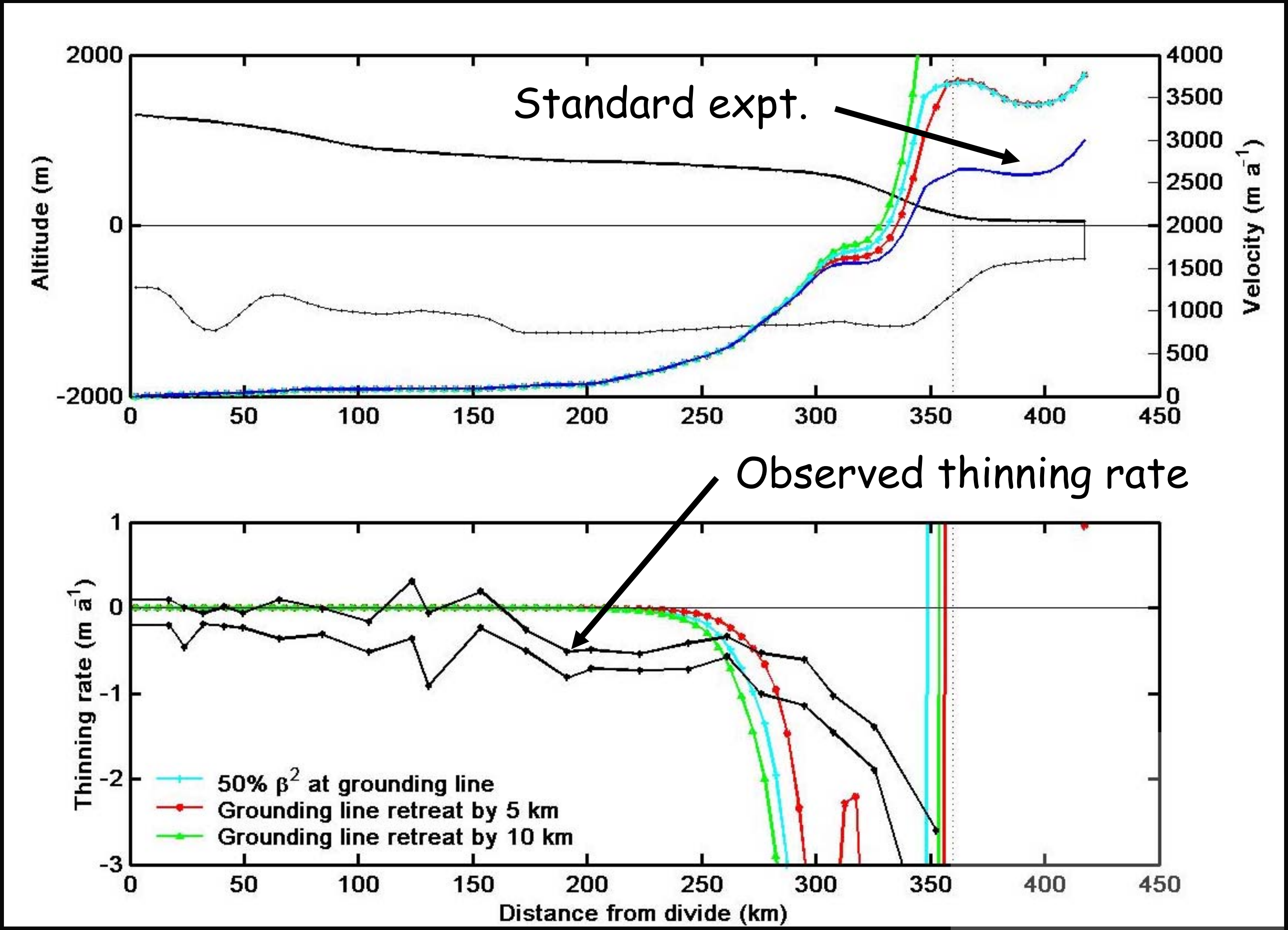
External → Internal

- ~ 3d model of PIG stress regime (longitudinal, lateral, vertical, gravitational)
- Glen's flow law
- Simplify by assuming down-stream component of velocity dominates
- Equations solved numerically by finite differences



Simulated perturbation of PIG

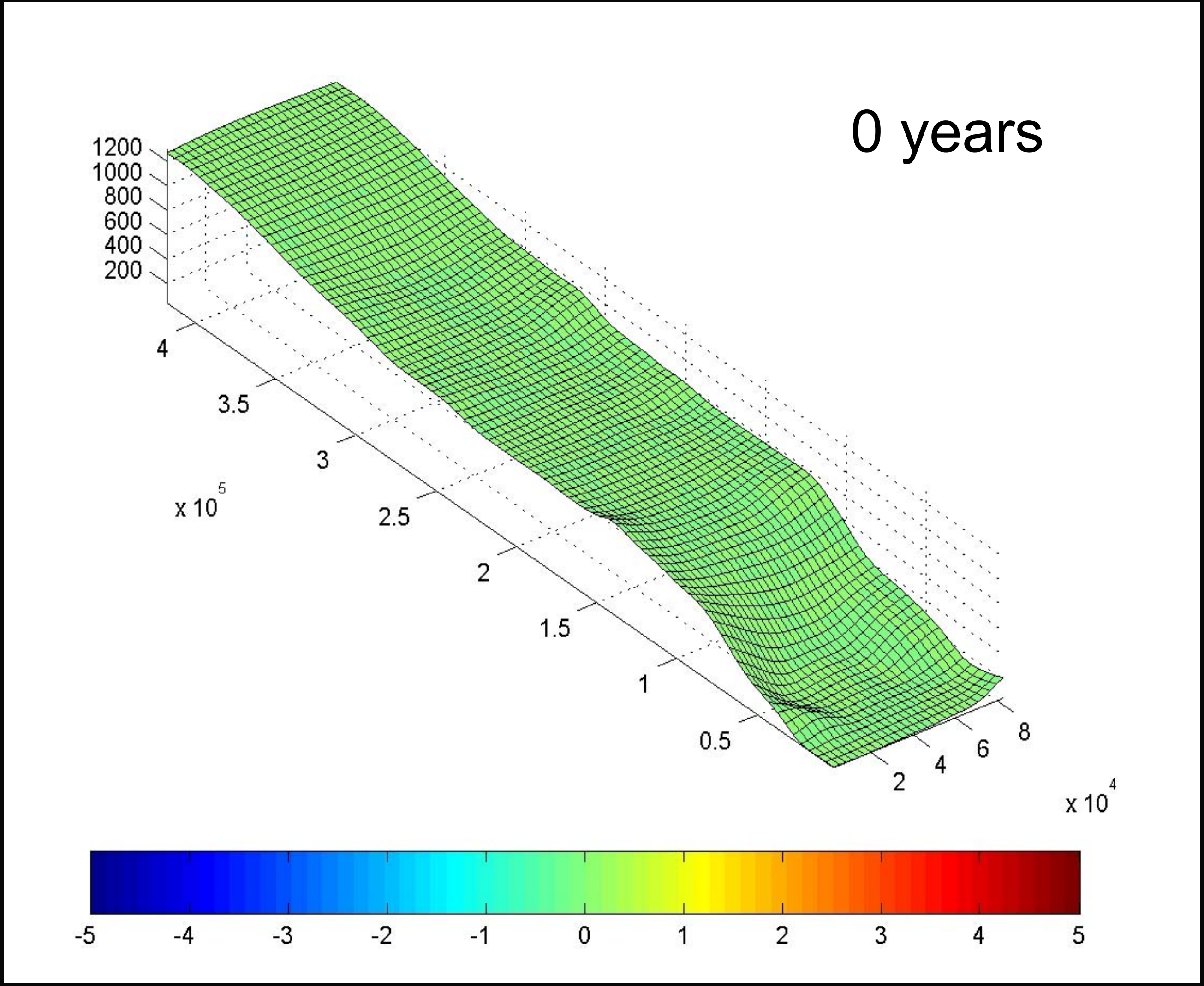
- Retreat of GL by 5 and 10 km, decrease ice plain traction by 50%
- Instant response is thinning up to 70 km from GL
- Insufficient to explain observed rates inland



Payne et al., 2004

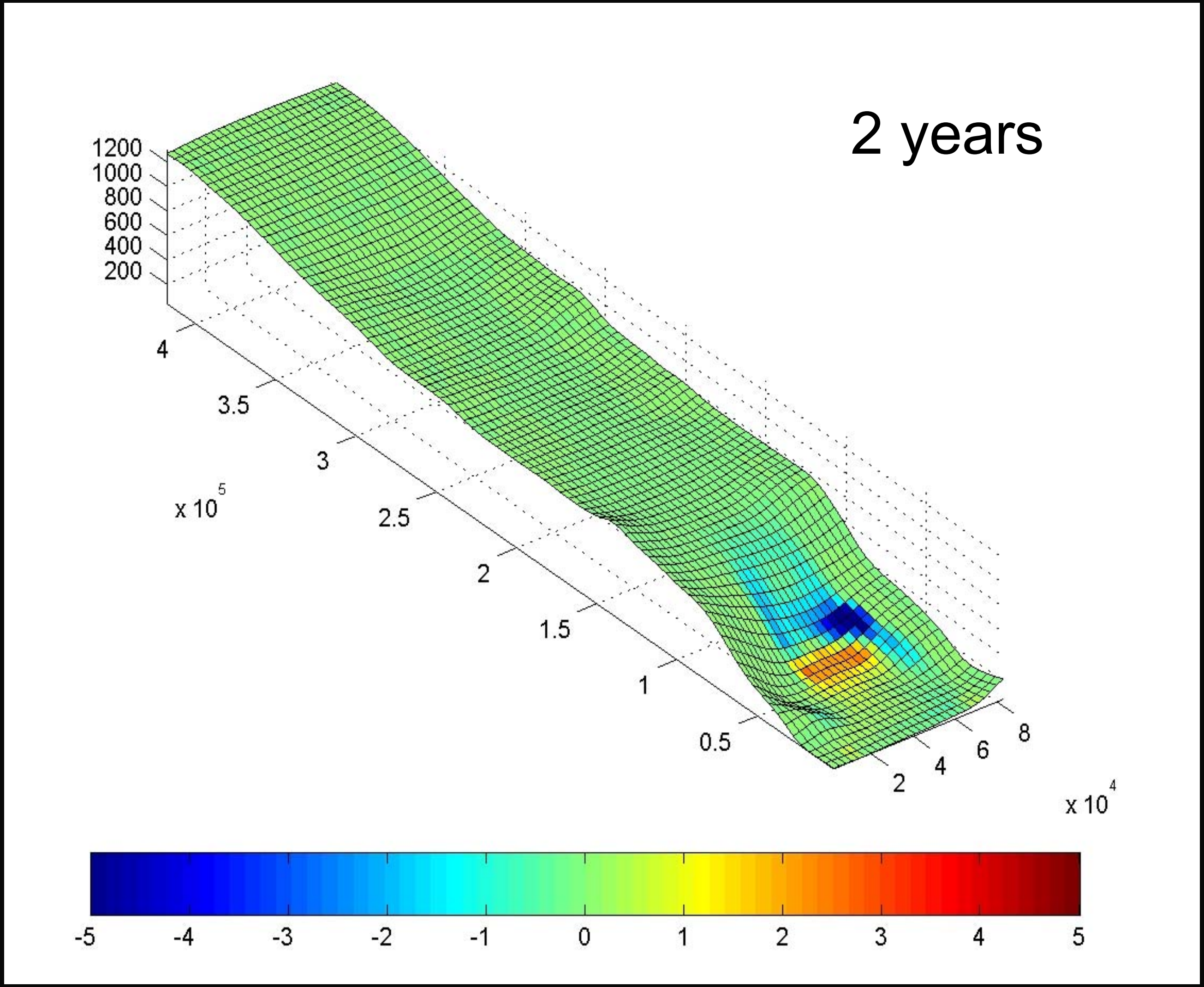
Simulated perturbation of PIG

- Introduce time-dependence
- 2d vertically-integrated model
- Assumes vertical shear minimal
- Dynamic boundary conditions at shelf front
- Glen's flow law
- Thickness evolution from ice flow perturbations



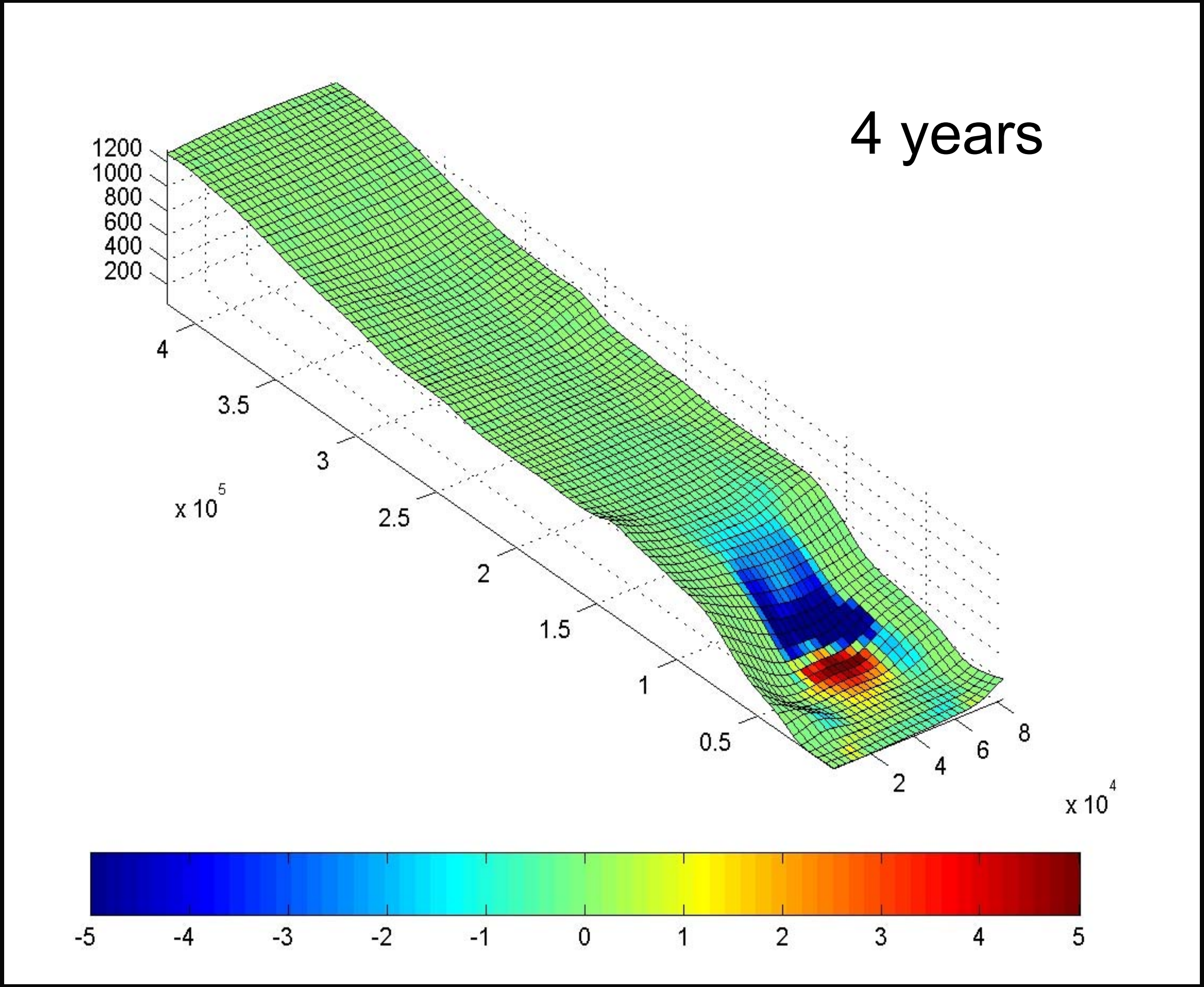
Simulated perturbation of PIG

- Introduce time-dependence
- 2d vertically-integrated model
- Assumes vertical shear minimal
- Dynamic boundary conditions at shelf front
- Glen’s flow law
- Thickness evolution from ice flow perturbations



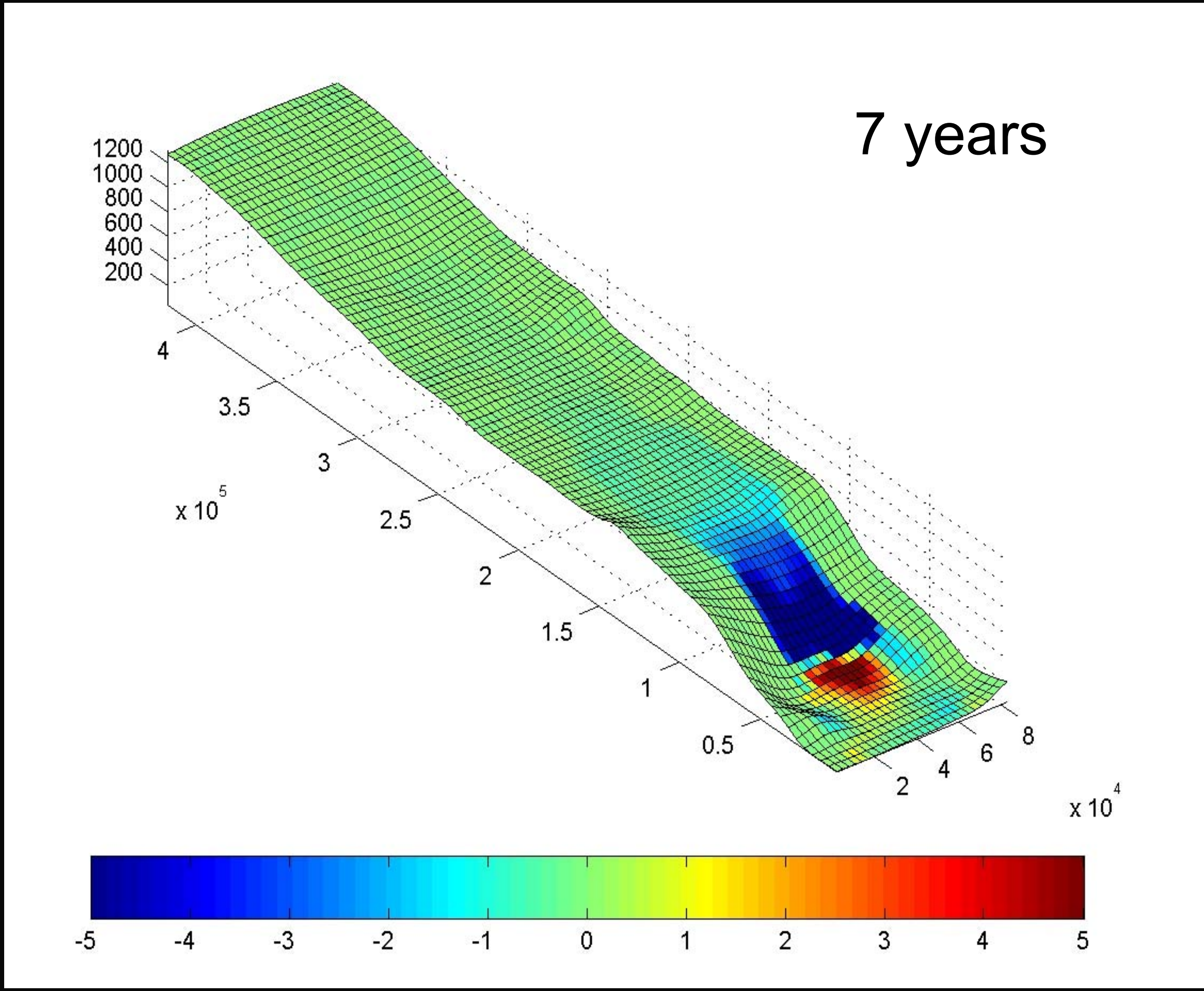
Simulated perturbation of PIG

- Introduce time-dependence
- 2d vertically-integrated model
- Assumes vertical shear minimal
- Dynamic boundary conditions at shelf front
- Glen's flow law
- Thickness evolution from ice flow perturbations



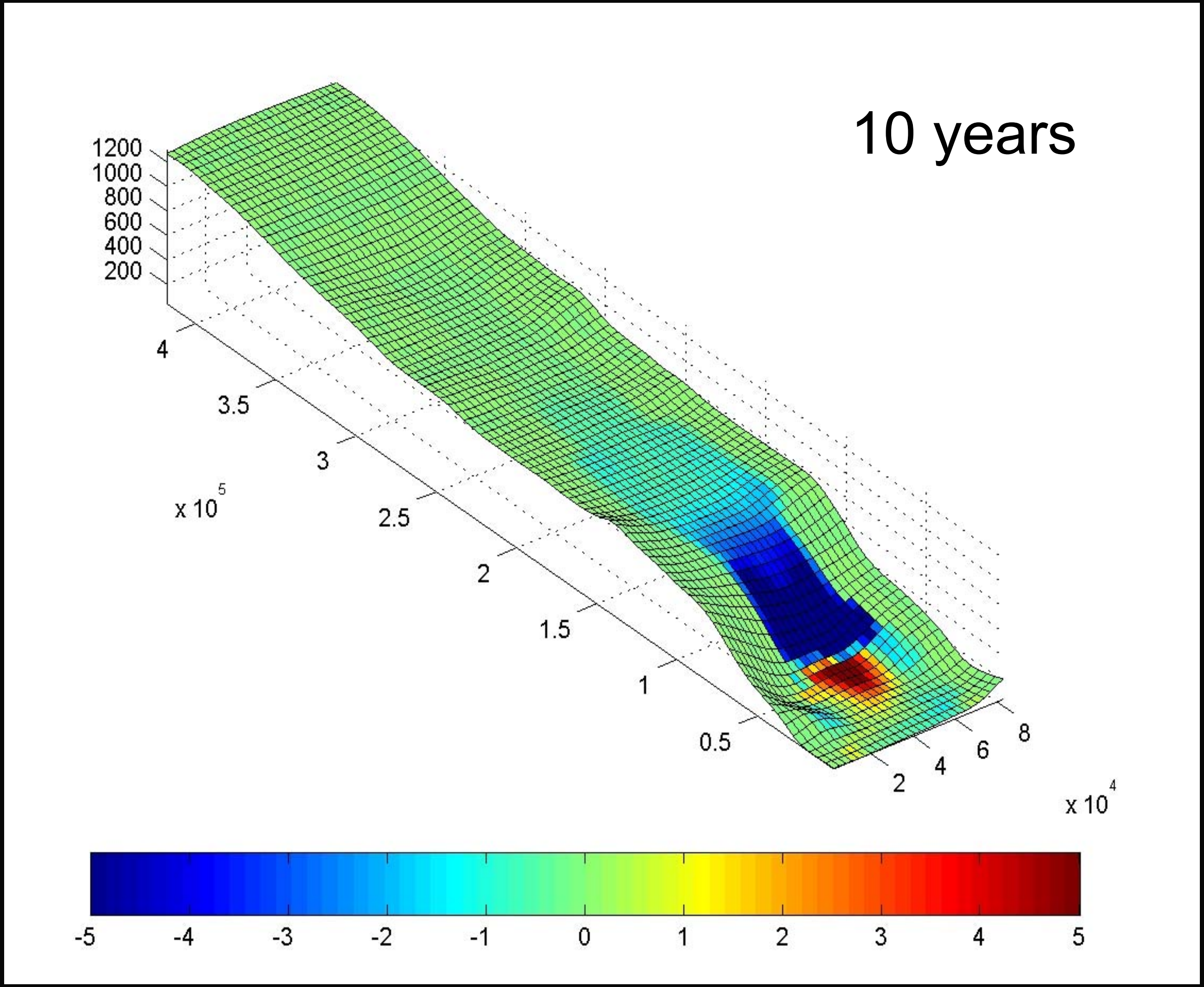
Simulated perturbation of PIG

- Introduce time-dependence
- 2d vertically-integrated model
- Assumes vertical shear minimal
- Dynamic boundary conditions at shelf front
- Glen's flow law
- Thickness evolution from ice flow perturbations



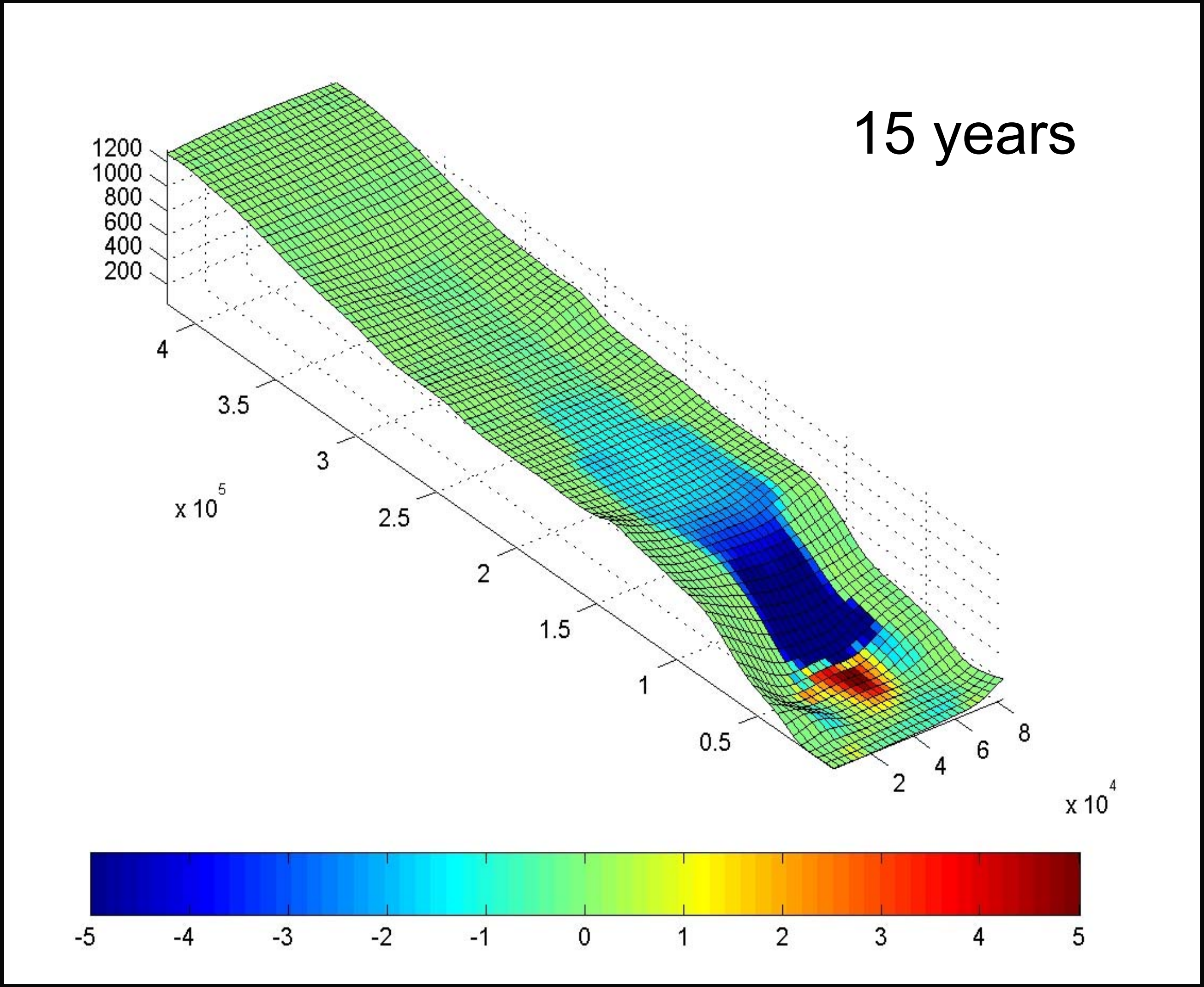
Simulated perturbation of PIG

- Introduce time-dependence
- 2d vertically-integrated model
- Assumes vertical shear minimal
- Dynamic boundary conditions at shelf front
- Glen's flow law
- Thickness evolution from ice flow perturbations



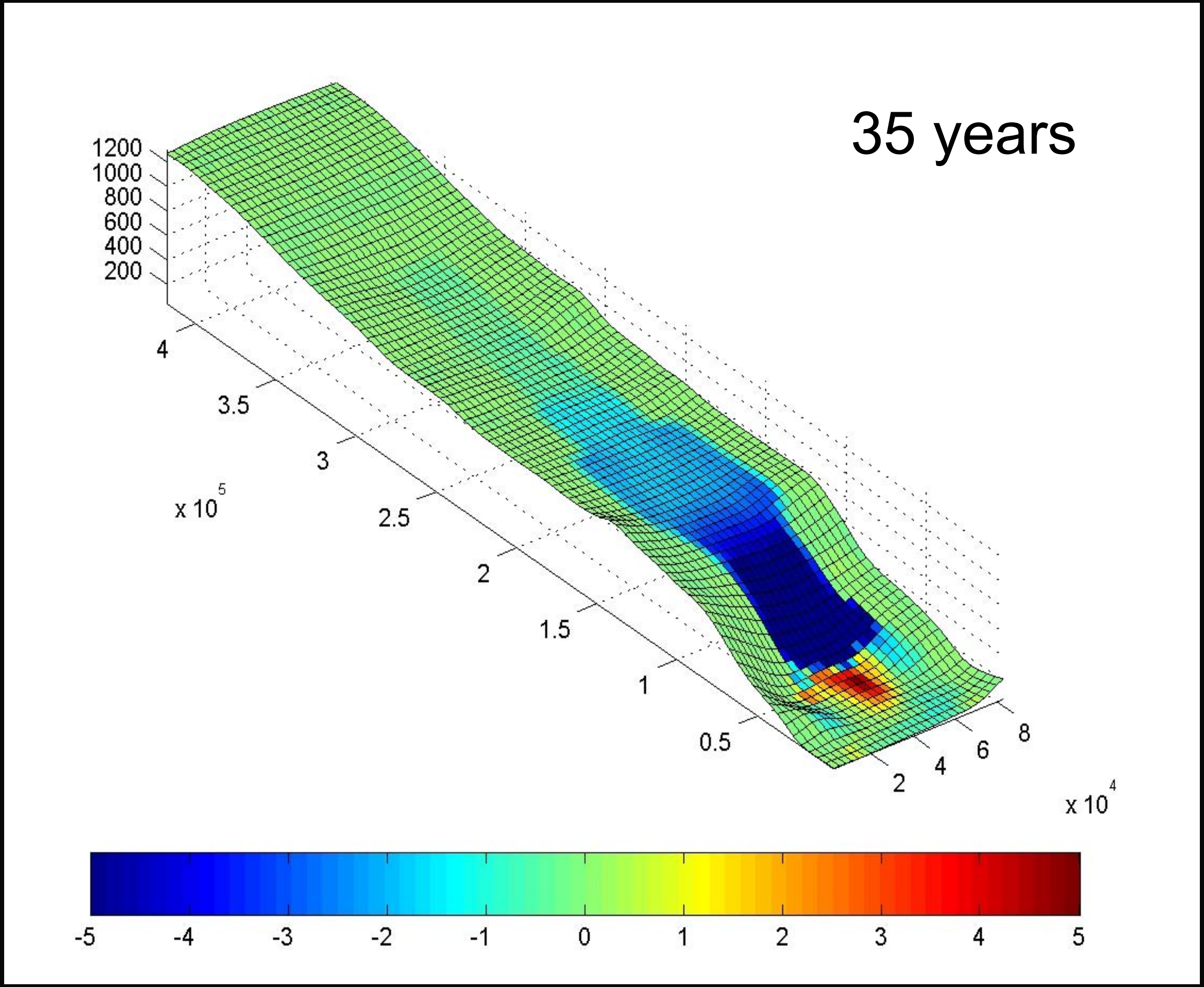
Simulated perturbation of PIG

- Introduce time-dependence
- 2d vertically-integrated model
- Assumes vertical shear minimal
- Dynamic boundary conditions at shelf front
- Glen's flow law
- Thickness evolution from ice flow perturbations



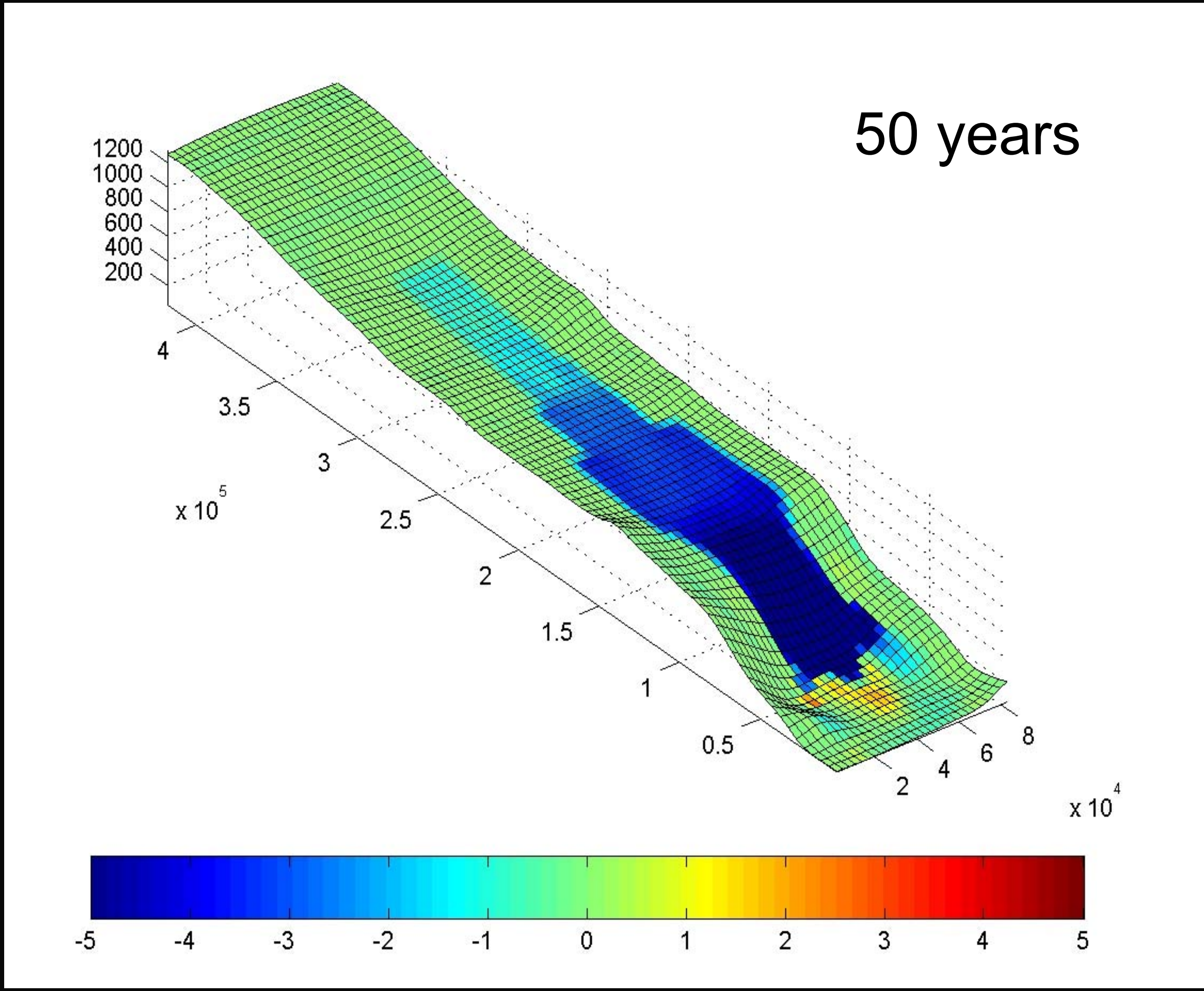
Simulated perturbation of PIG

- Introduce time-dependence
- 2d vertically-integrated model
- Assumes vertical shear minimal
- Dynamic boundary conditions at shelf front
- Glen's flow law
- Thickness evolution from ice flow perturbations



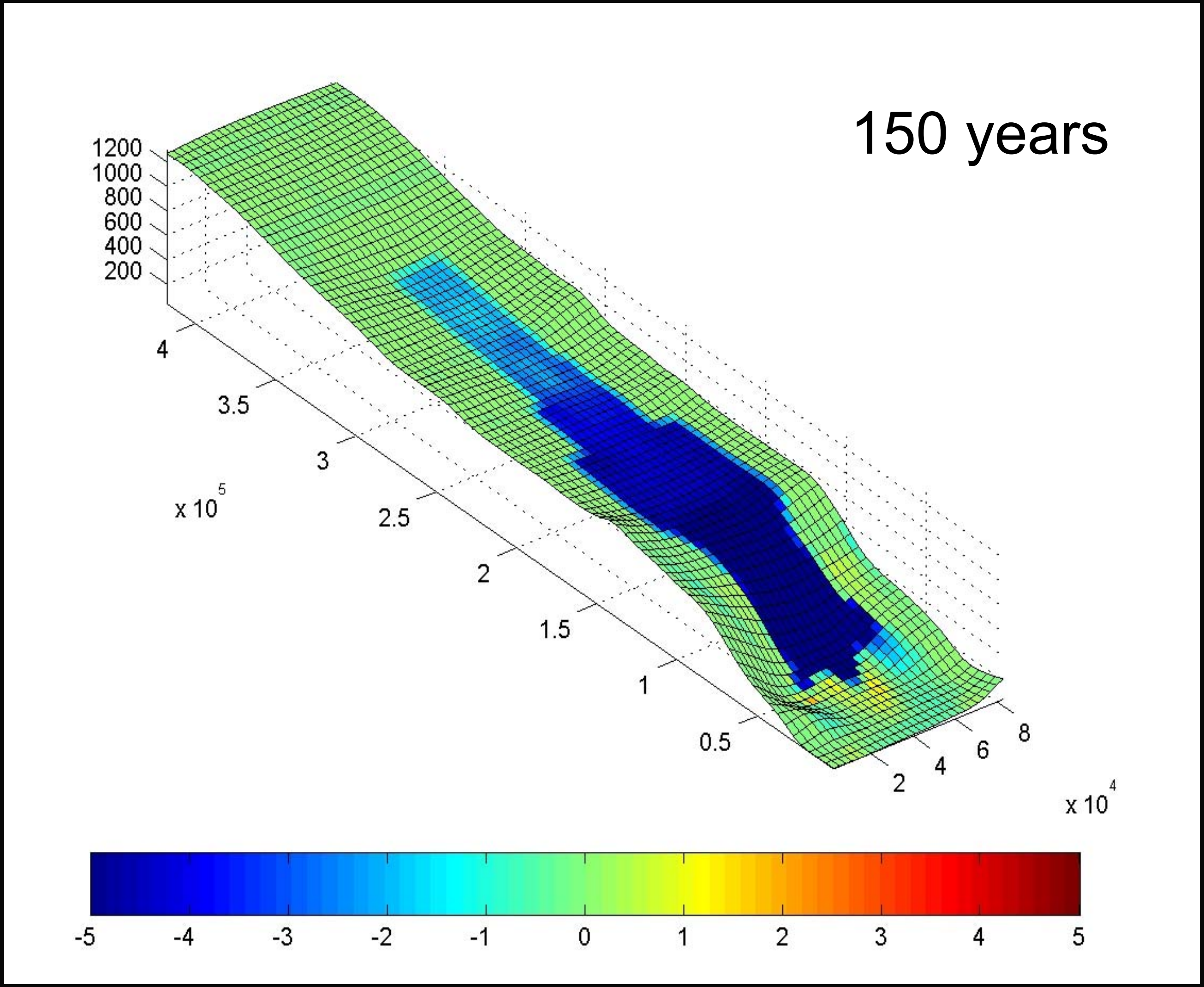
Simulated perturbation of PIG

- Introduce time-dependence
- 2d vertically-integrated model
- Assumes vertical shear minimal
- Dynamic boundary conditions at shelf front
- Glen's flow law
- Thickness evolution from ice flow perturbations



Simulated perturbation of PIG

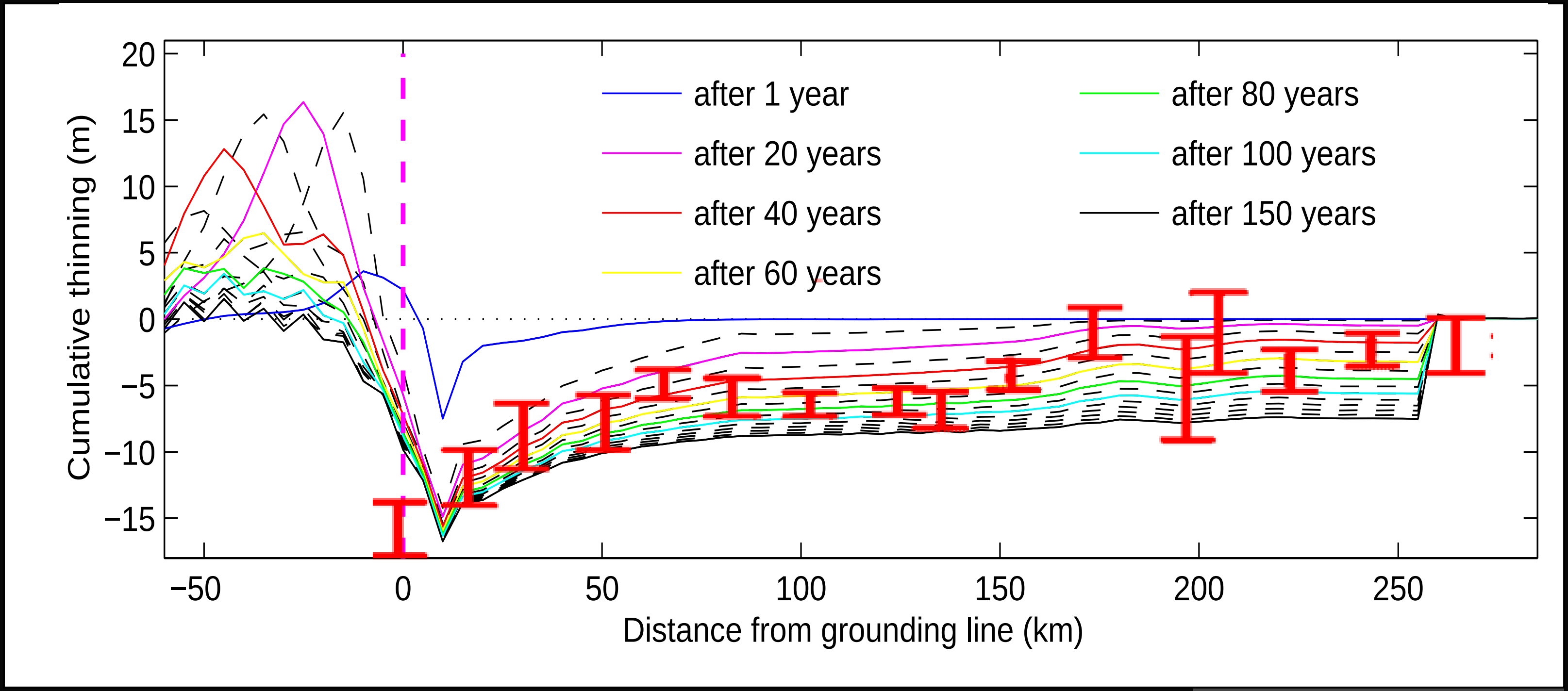
- Introduce time-dependence
- 2d vertically-integrated model
- Assumes vertical shear minimal
- Dynamic boundary conditions at shelf front
- Glen's flow law
- Thickness evolution from ice flow perturbations



Simulated perturbation of PIG

- Accumulated thinning matches observed changes inland

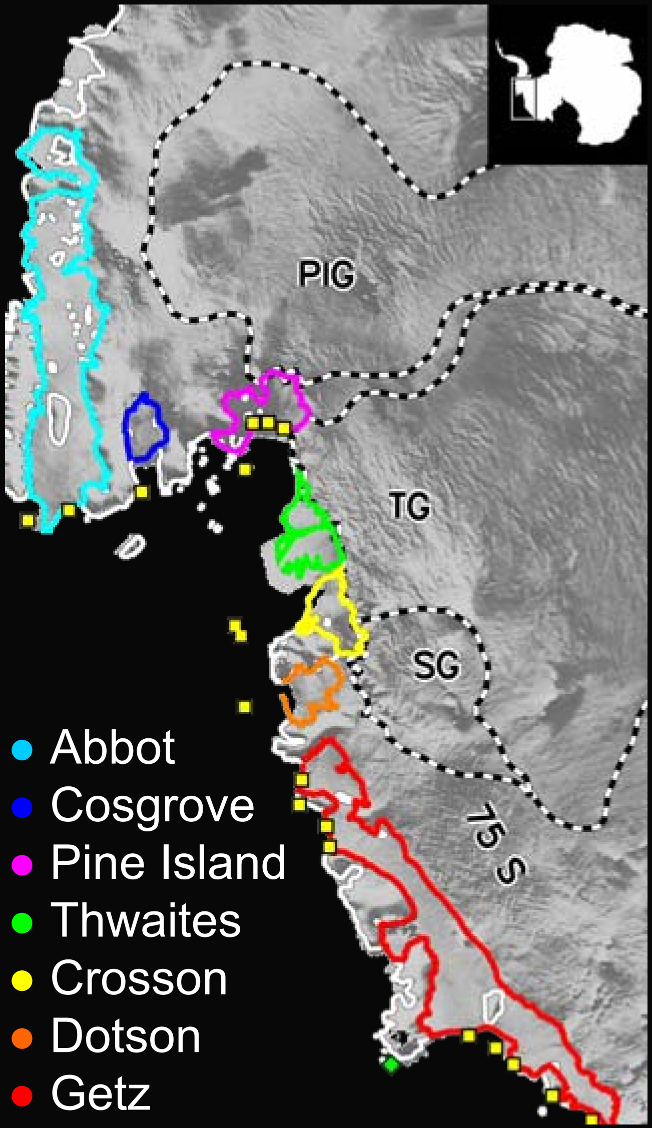
- Conclude that a reduction in ice thickness at the grounding line is sufficient to trigger inland thinning



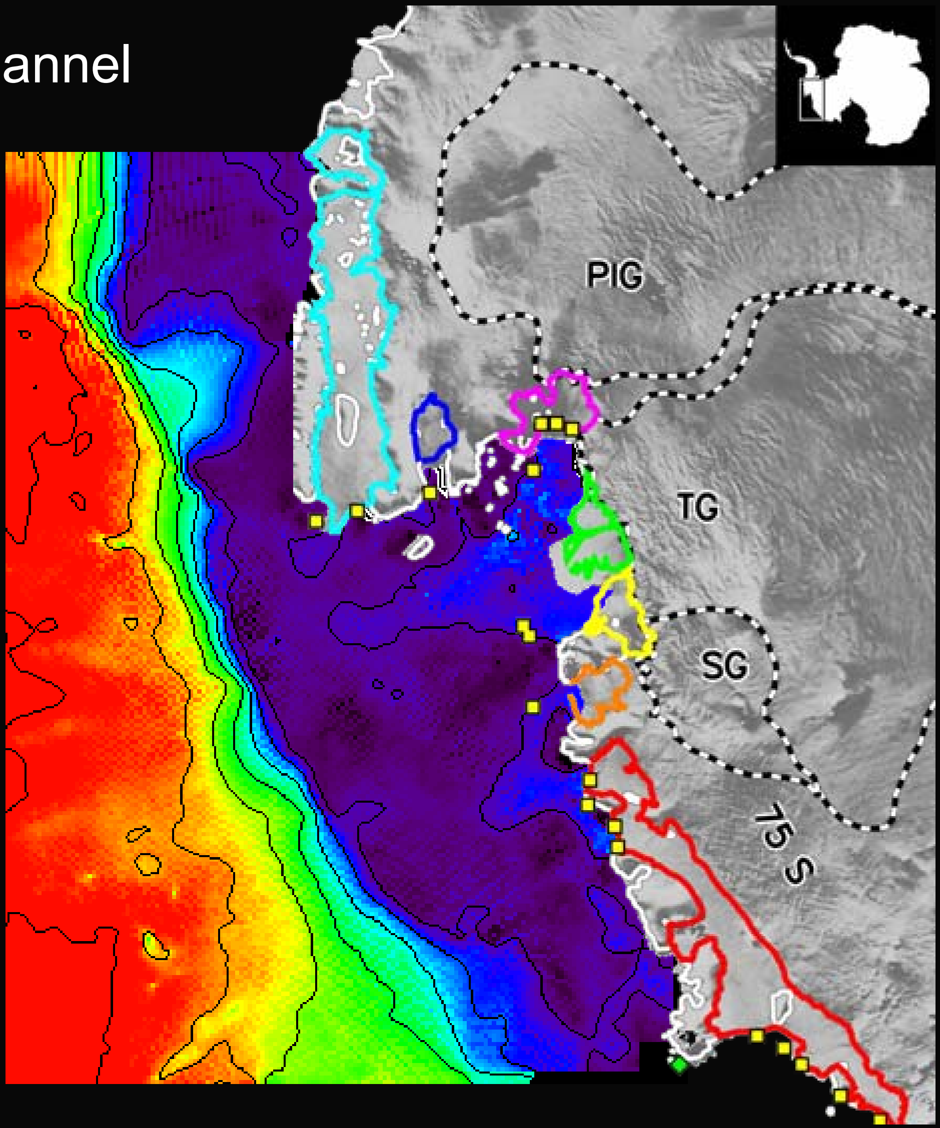
Payne et al., 2004

Origin of perturbation

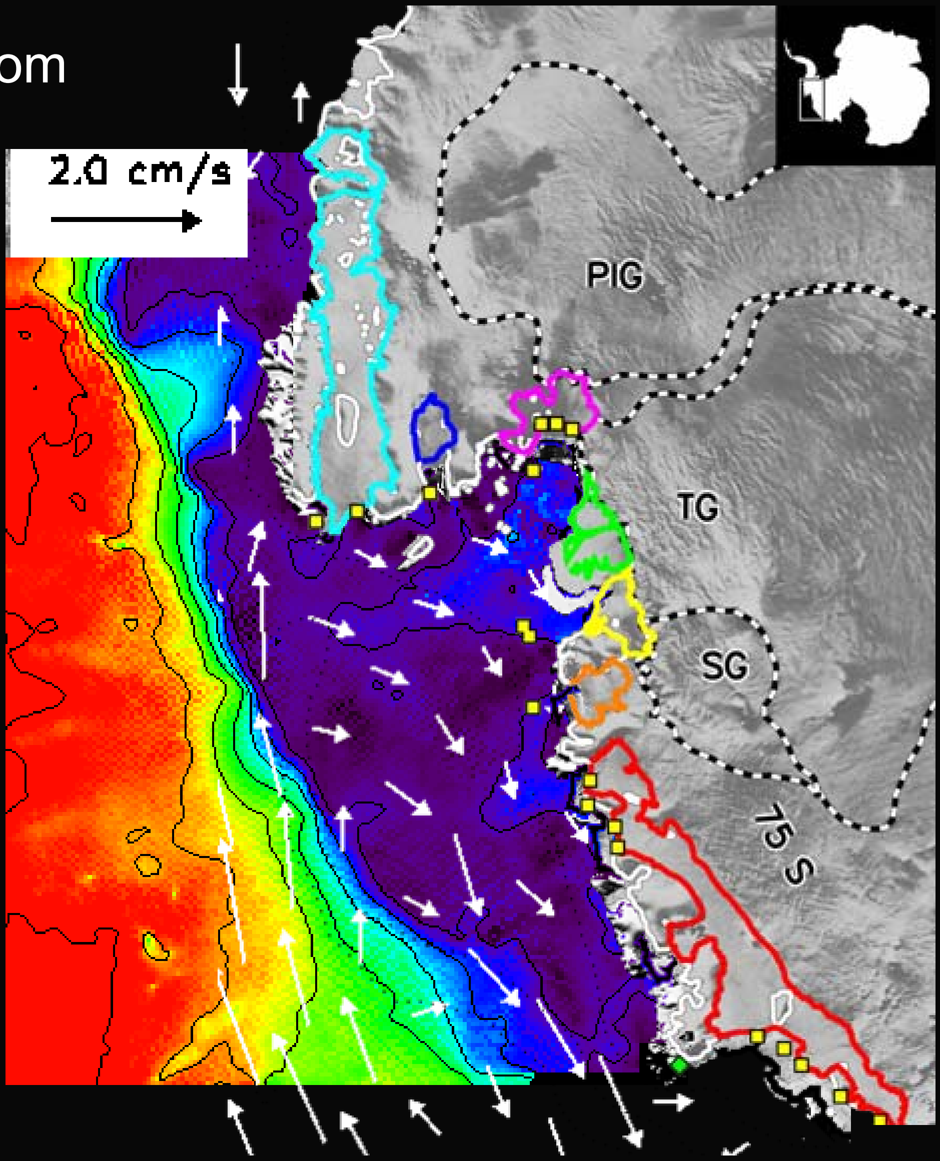
- Amundsen Sea glaciers terminate in short floating ice shelves



- Bathymetry shows deep troughs channel water to glacier grounding lines

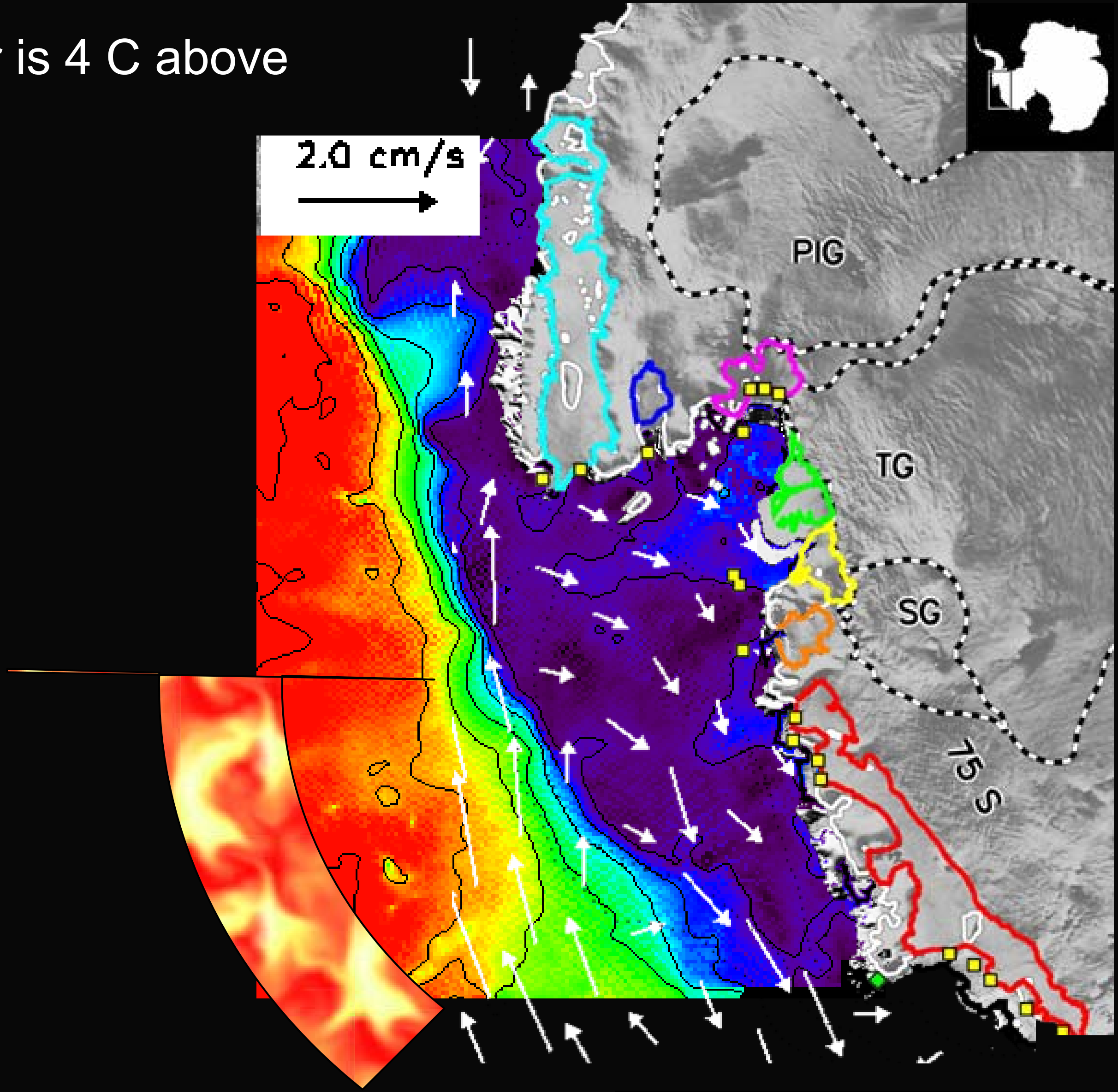


- Pine Island Bay gyre draws water from continental shelf

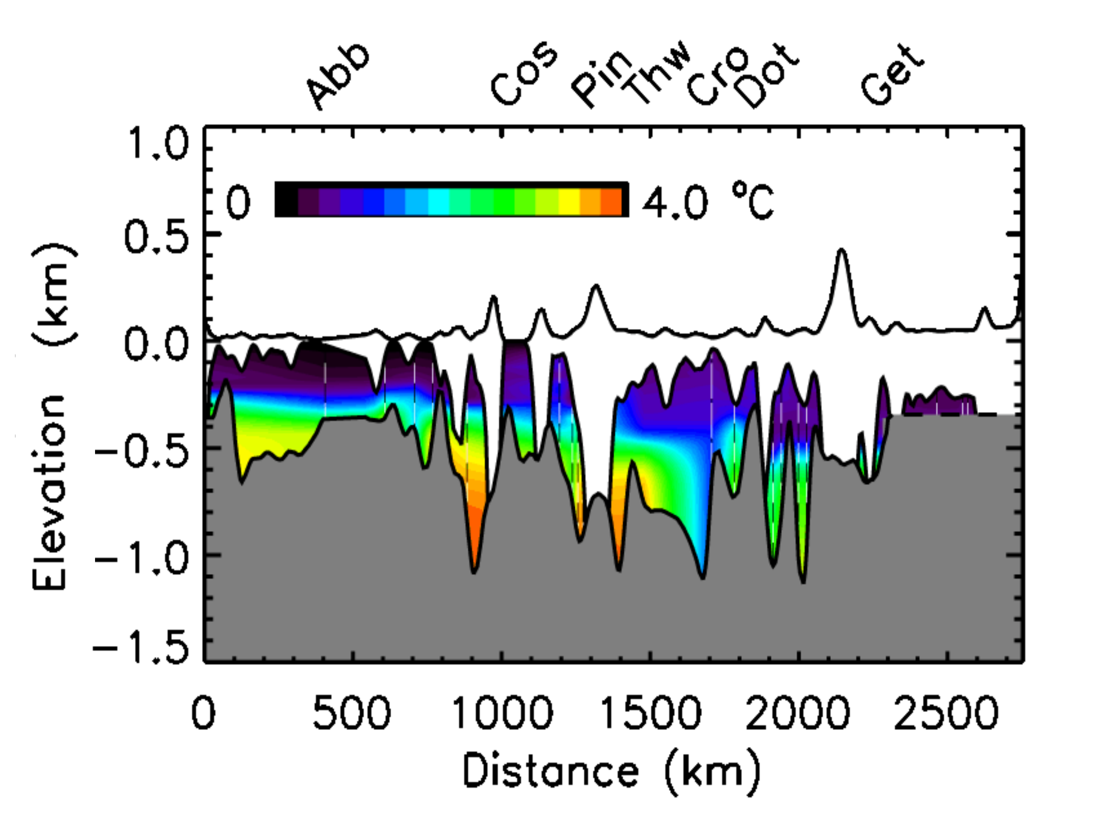


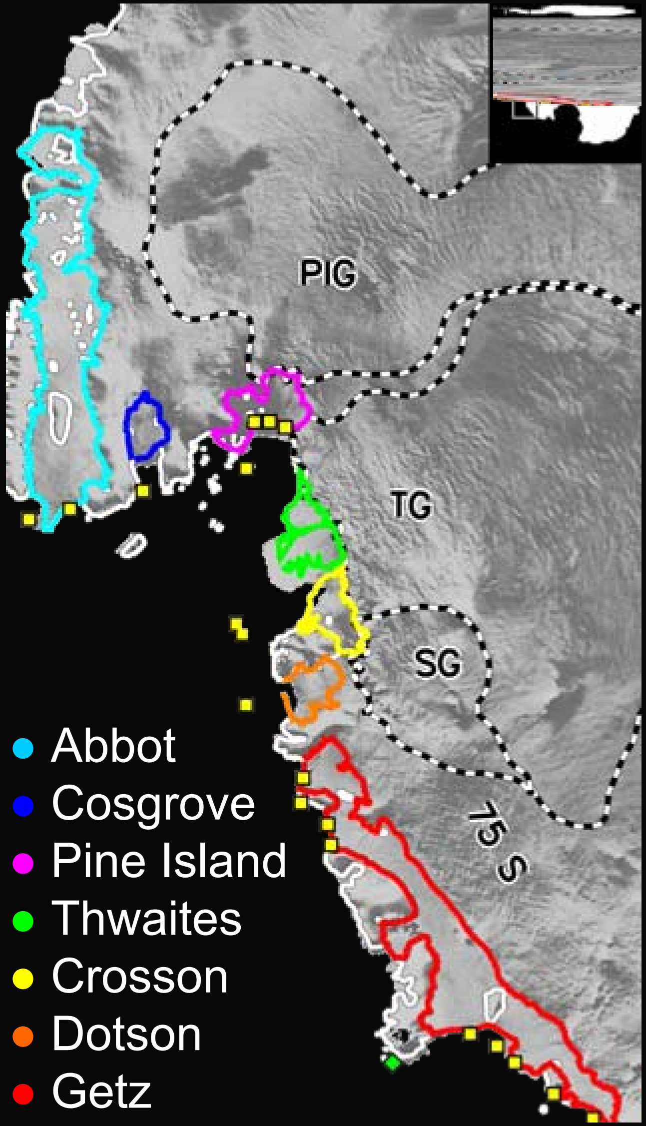
Origin of perturbation

- Circumpolar Deep water is 4 C above freezing point

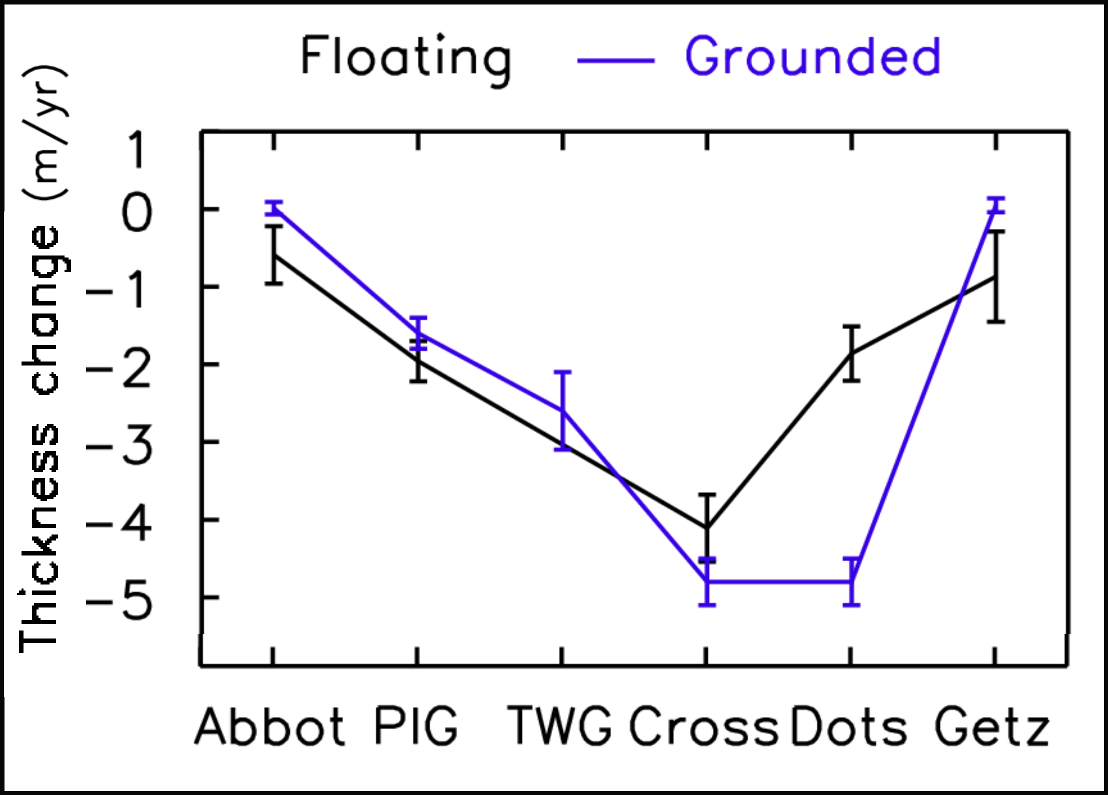


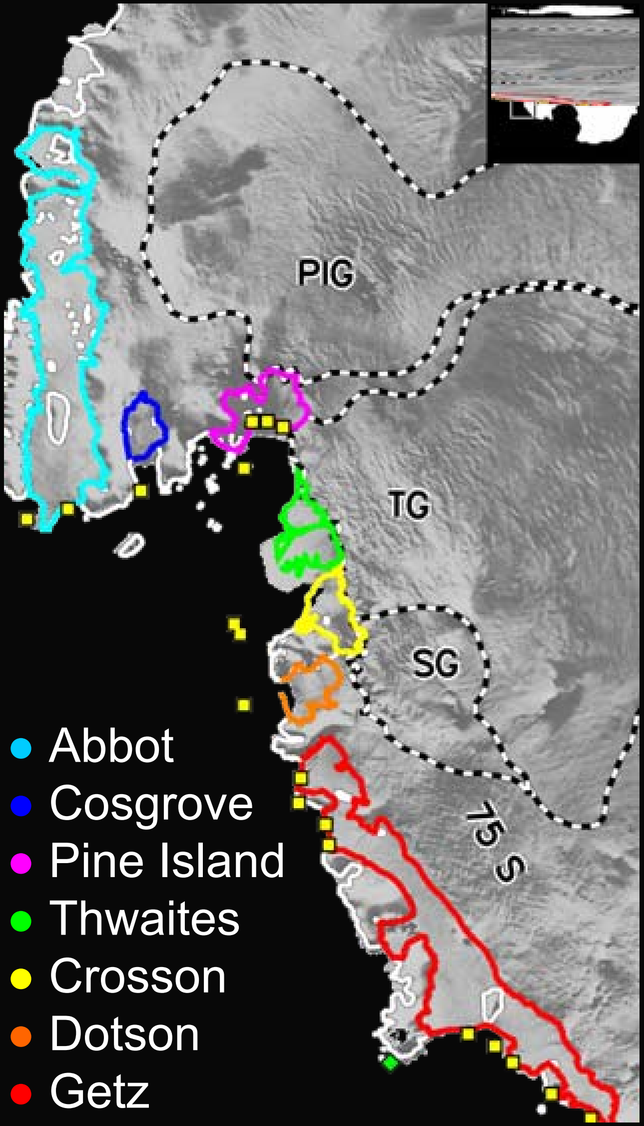
- Warm CDW infiltrates Pine Island Bay and reaches glacier grounding lines





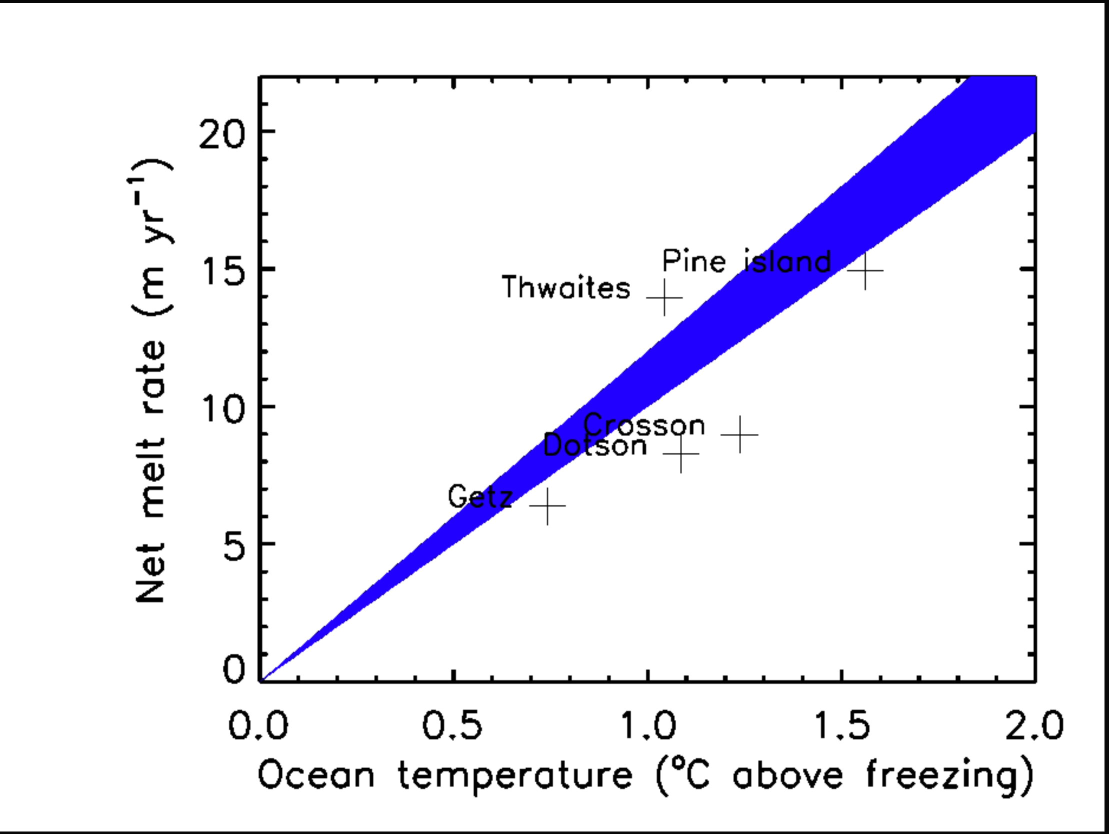
- Ice shelf thinning mirrors that of tributary glaciers

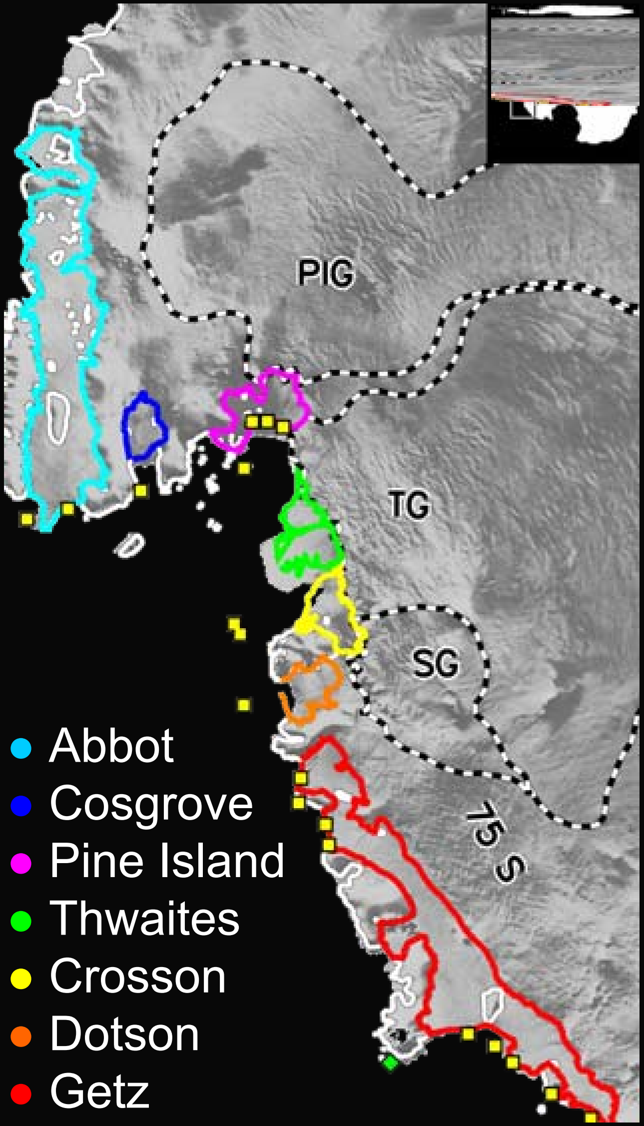




Origin of perturbation

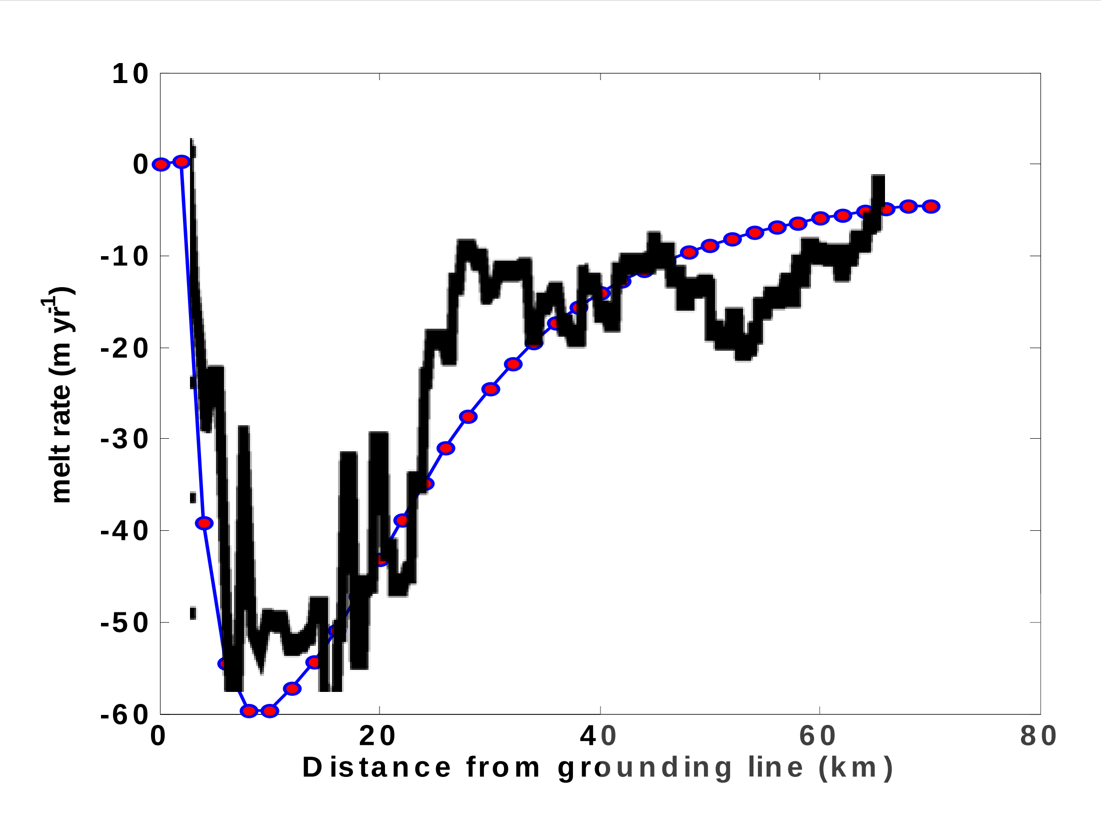
- Thinning is correlated with melt potential of ocean current (10 m yr^{-1} C^{-1})



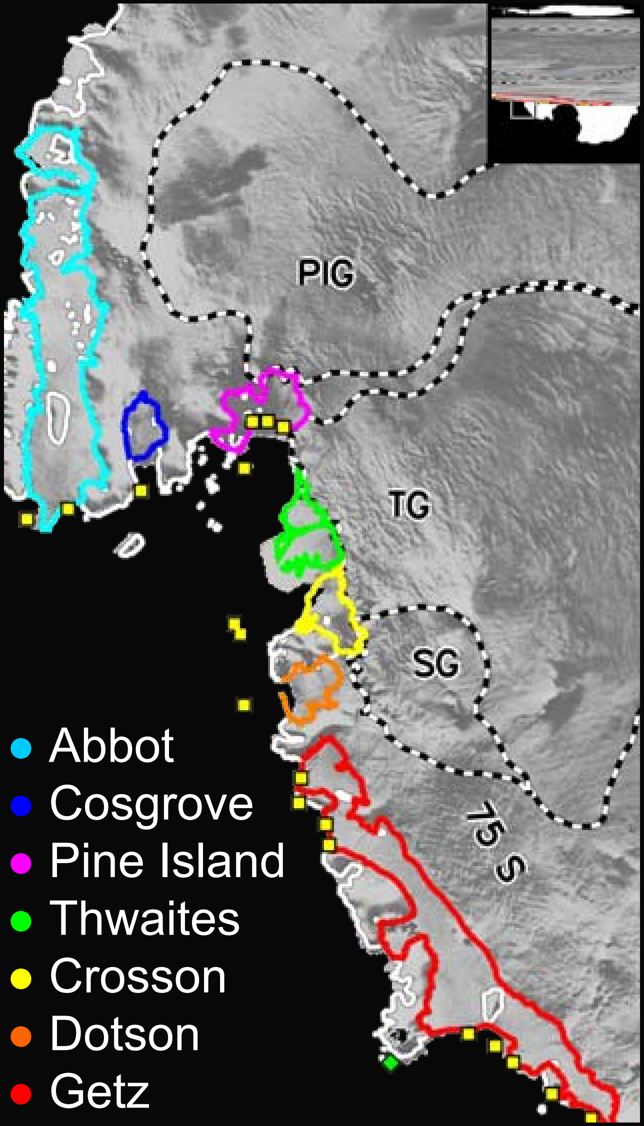


Origin of perturbation

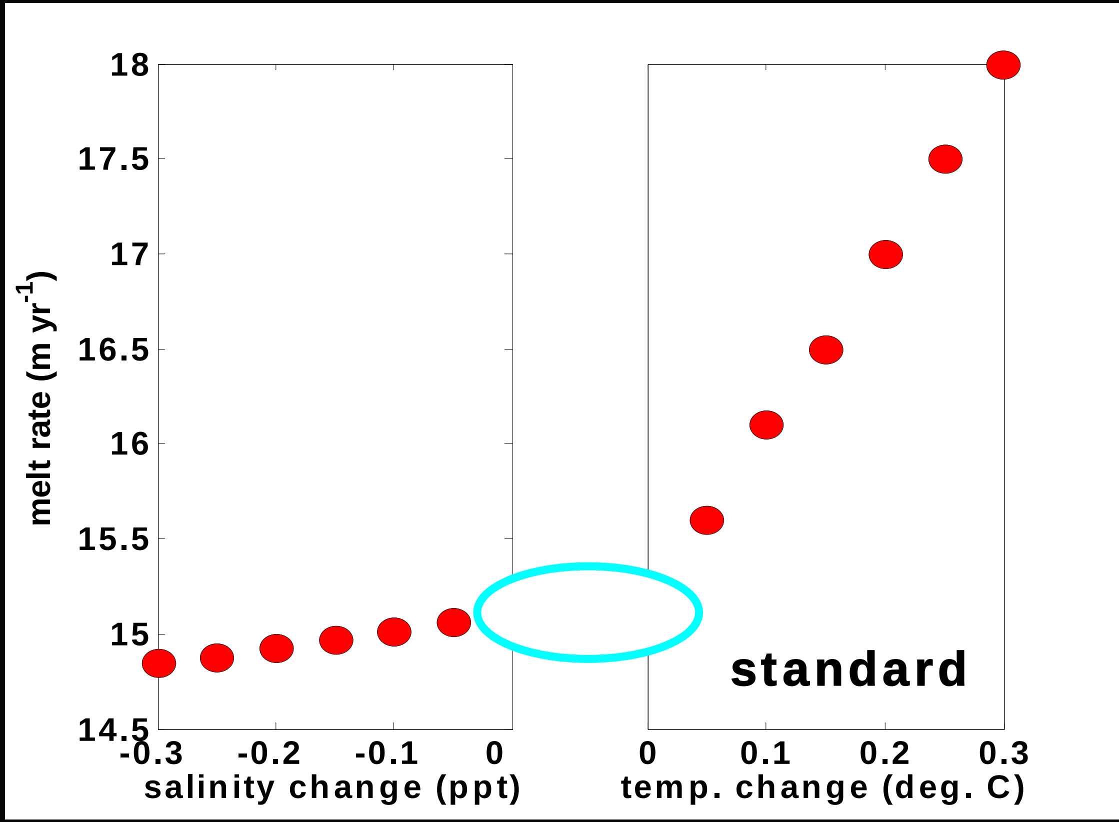
- 2d plume model of ice-ocean interaction beneath PIG reproduces observed pattern of steady-state ice melting

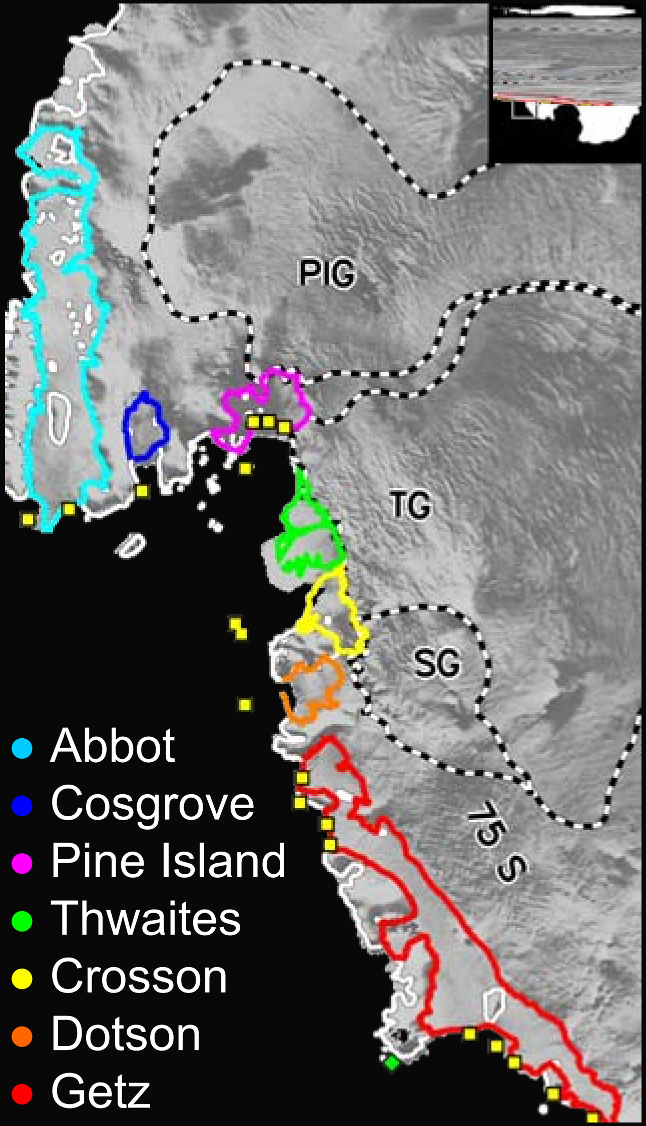


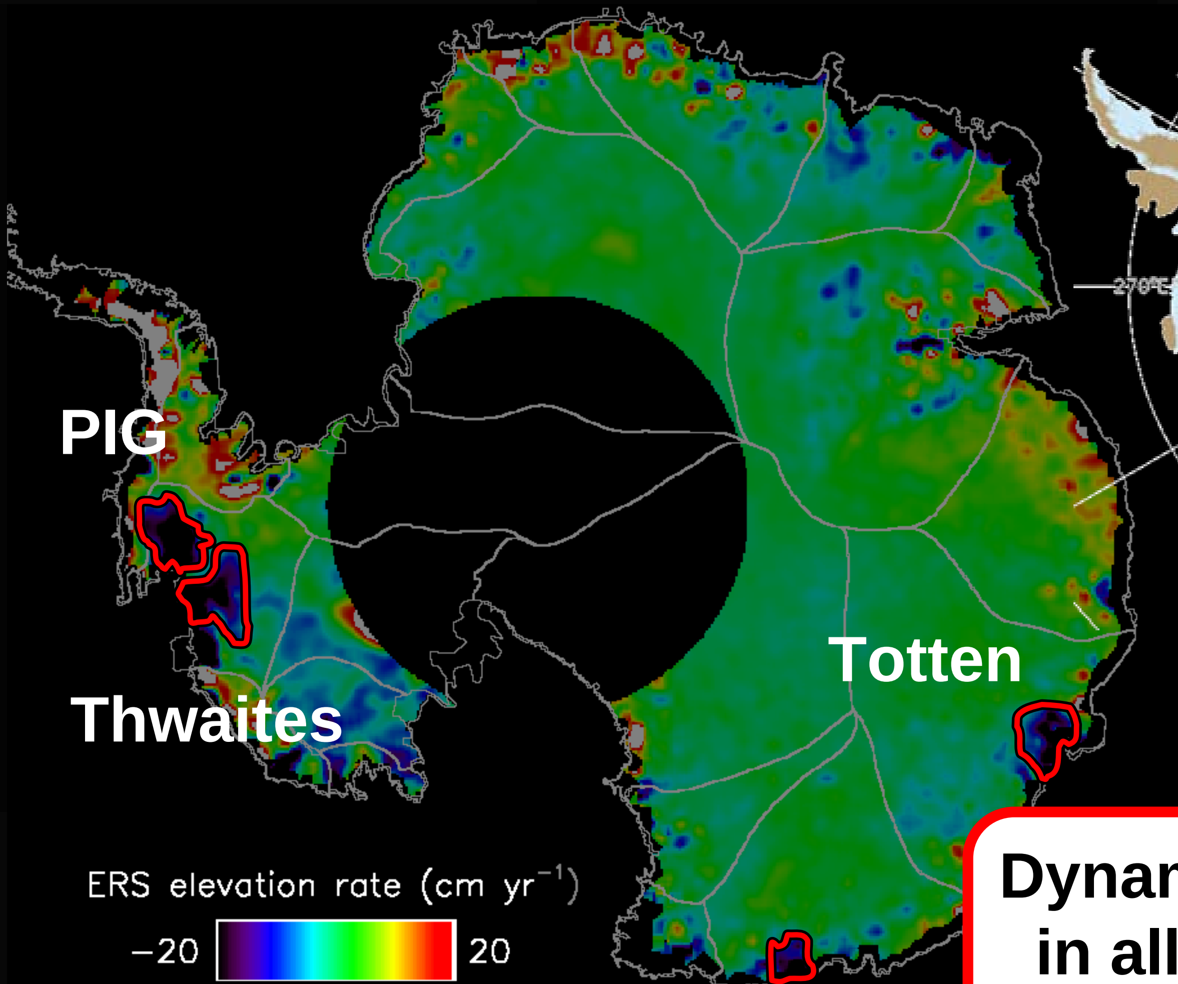
Payne et al, *JGR* (2006)



- Perturbation experiment shows a 0.5 °C warming of ocean temperature is sufficient to cause observed ice shelf thinning

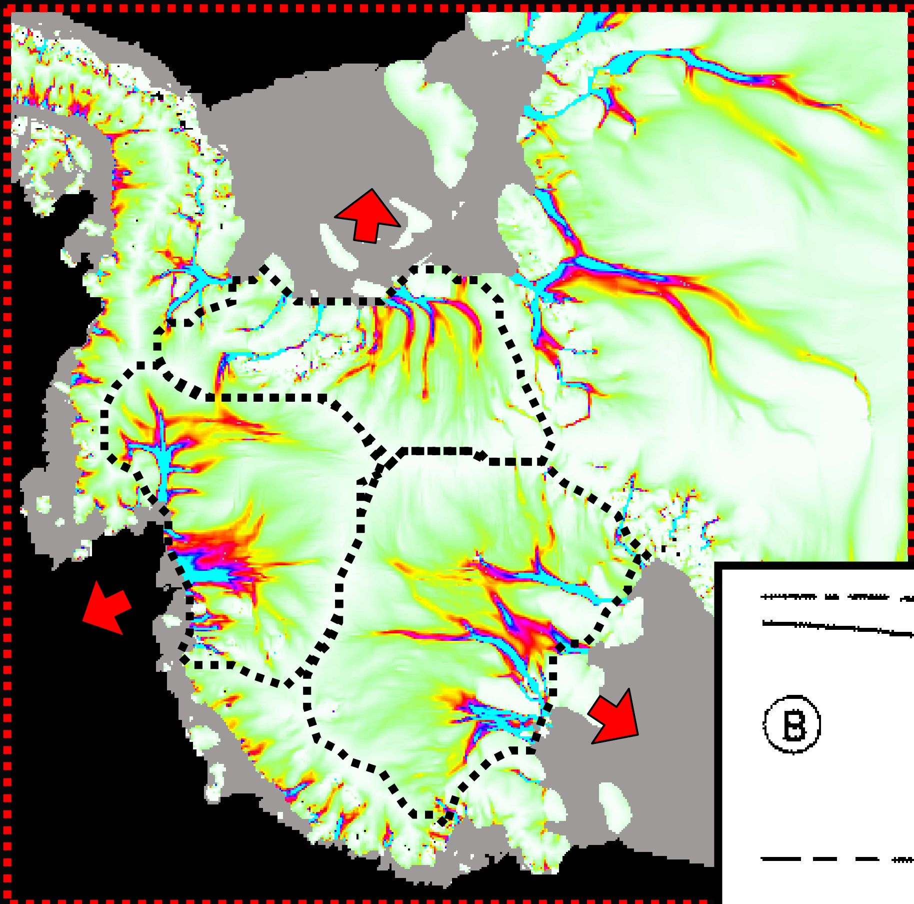




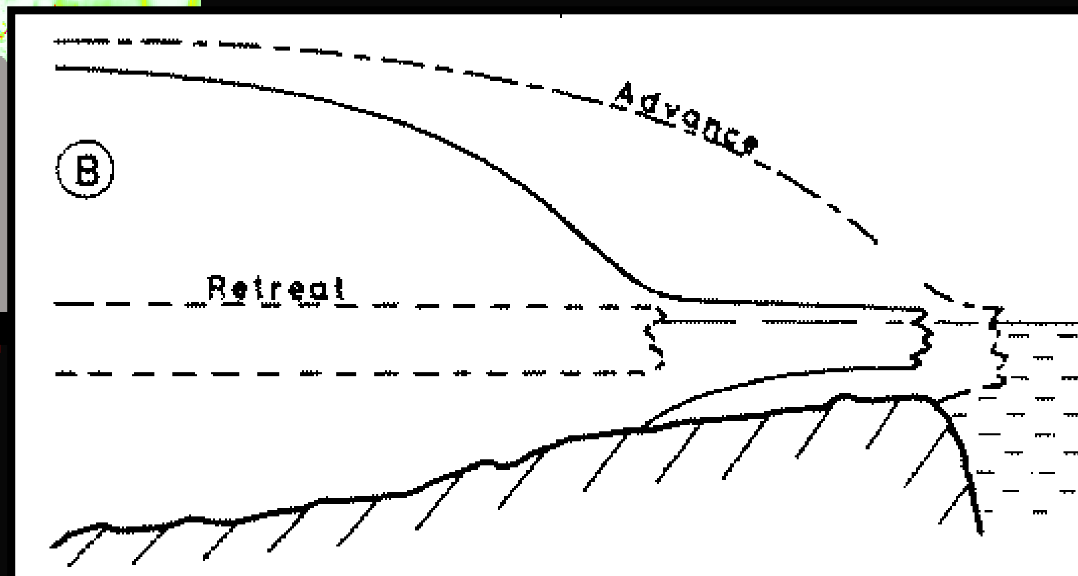


Cook

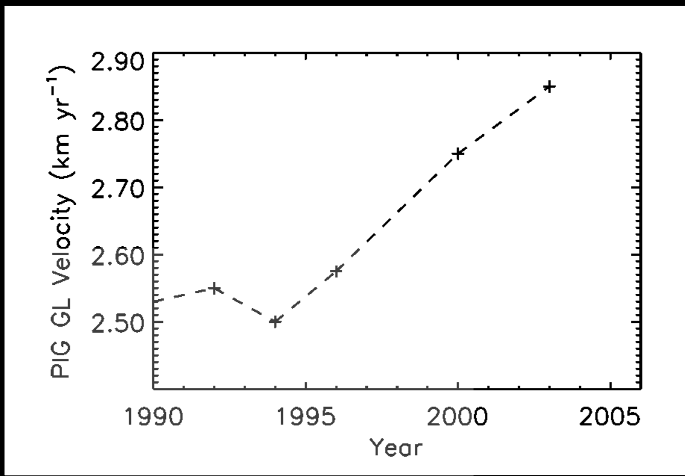
Dynamic thinning ongoing in all submarine sectors of Antarctica



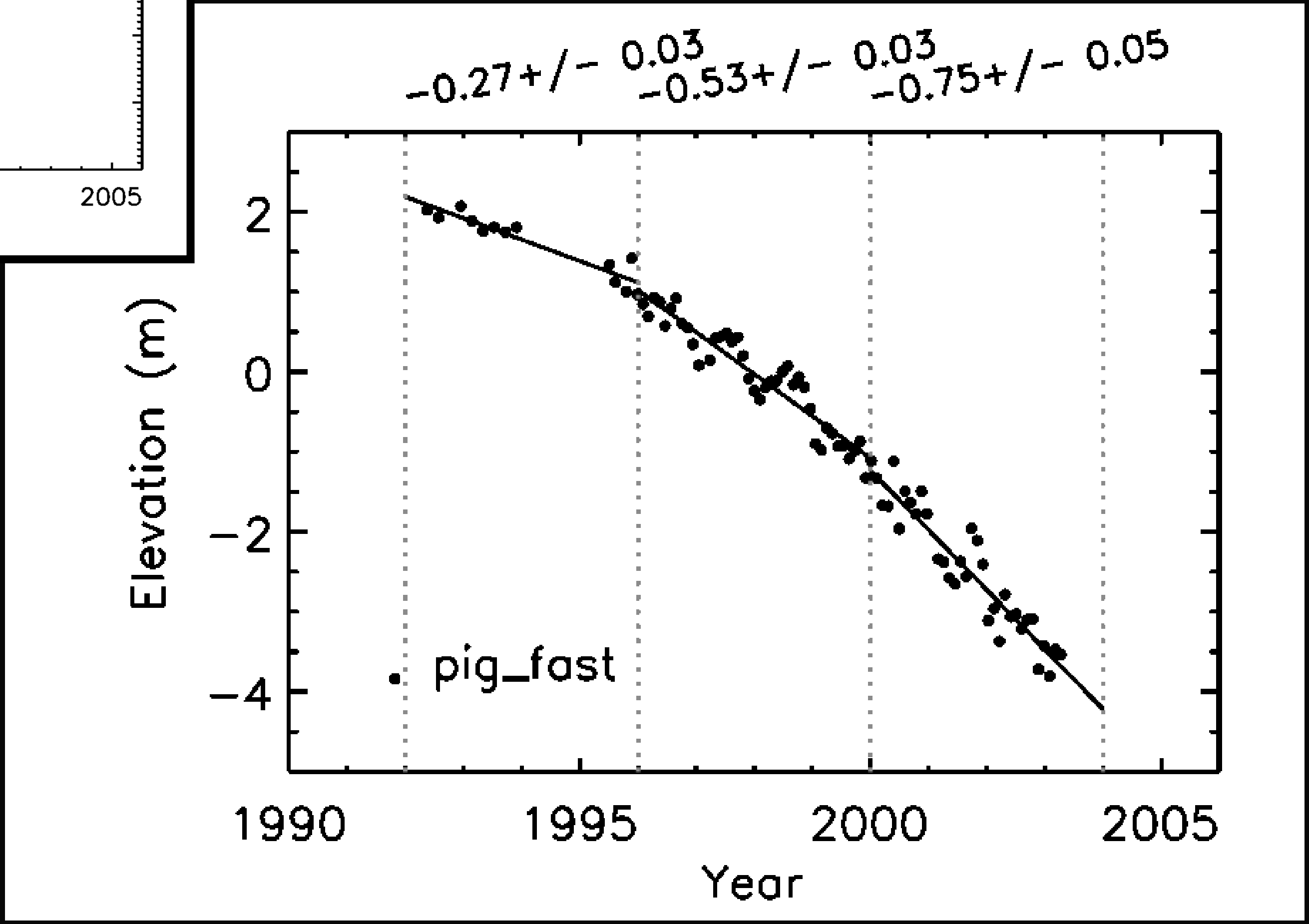
Retreat of submarine glaciers is supposed to be an accelerating process

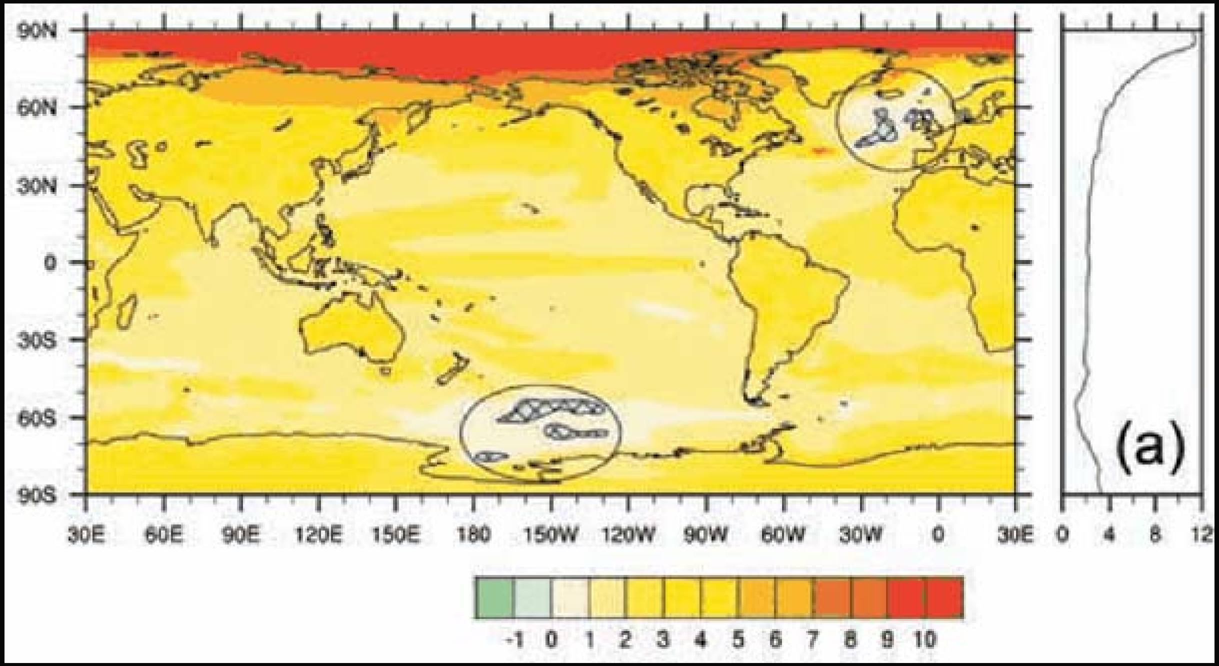


PIG deflation *is* accelerating



Joughin et al., *GRL*, 2003





Ocean temperatures are set to rise by 1.0 C around Antarctica

- Amundsen Sea glaciers are losing 30 Gt of ice each year
- Equivalent to a sea level contribution of 0.1 mm yr^{-1}
- Triggered by ocean currents 0.5°C above freezing
- Consistent with rate of global warming during 20^{th} century
- All coastal, submarine glaciers in Antarctica are in retreat
- PIG retreat has accelerated over last decade
- Global oceans set to warm 1°C next century
- 21^{st} century response not in current sea level projections

- Amundsen Sea glaciers are losing 30 Gt of ice each year
- Equivalent to a sea level contribution of 0.1 mm yr^{-1}
- Triggered by ocean currents 0.5°C above freezing
- Consistent with rate of global warming during 20th century
- All coastal, submarine glaciers in Antarctica are in retreat
- PIG retreat has accelerated over last decade
- Global oceans set to warm 1°C next century
- 21st century response not in current sea level projections

Summary

- Amundsen Sea glaciers are losing 30 Gt of ice each year
- Equivalent to a sea level contribution of 0.1 mm yr^{-1}
- Triggered by ocean currents 0.5°C above freezing
- Consistent with rate of global warming during 20^{th} century
- All coastal, submarine glaciers in Antarctica are in retreat
- PIG retreat has accelerated over last decade
- Global oceans set to warm 1°C next century
- 21^{st} century response not in current sea level projections

- Amundsen Sea glaciers are losing 30 Gt of ice each year
- Equivalent to a sea level contribution of 0.1 mm yr^{-1}
- Triggered by ocean currents 0.5°C above freezing
- Consistent with rate of global warming during 20^{th} century
- All coastal, submarine glaciers in Antarctica are in retreat
- PIG retreat has accelerated over last decade
- Global oceans set to warm 1°C next century
- 21^{st} century response not in current sea level projections

Summary

- Amundsen Sea glaciers are losing 30 Gt of ice each year
- Equivalent to a sea level contribution of 0.1 mm yr^{-1}
- Triggered by ocean currents 0.5°C above freezing
- Consistent with rate of global warming during 20^{th} century
- All coastal, submarine glaciers in Antarctica are in retreat
- PIG retreat has accelerated over last decade
- Global oceans set to warm 1°C next century
- 21^{st} century response not in current sea level projections

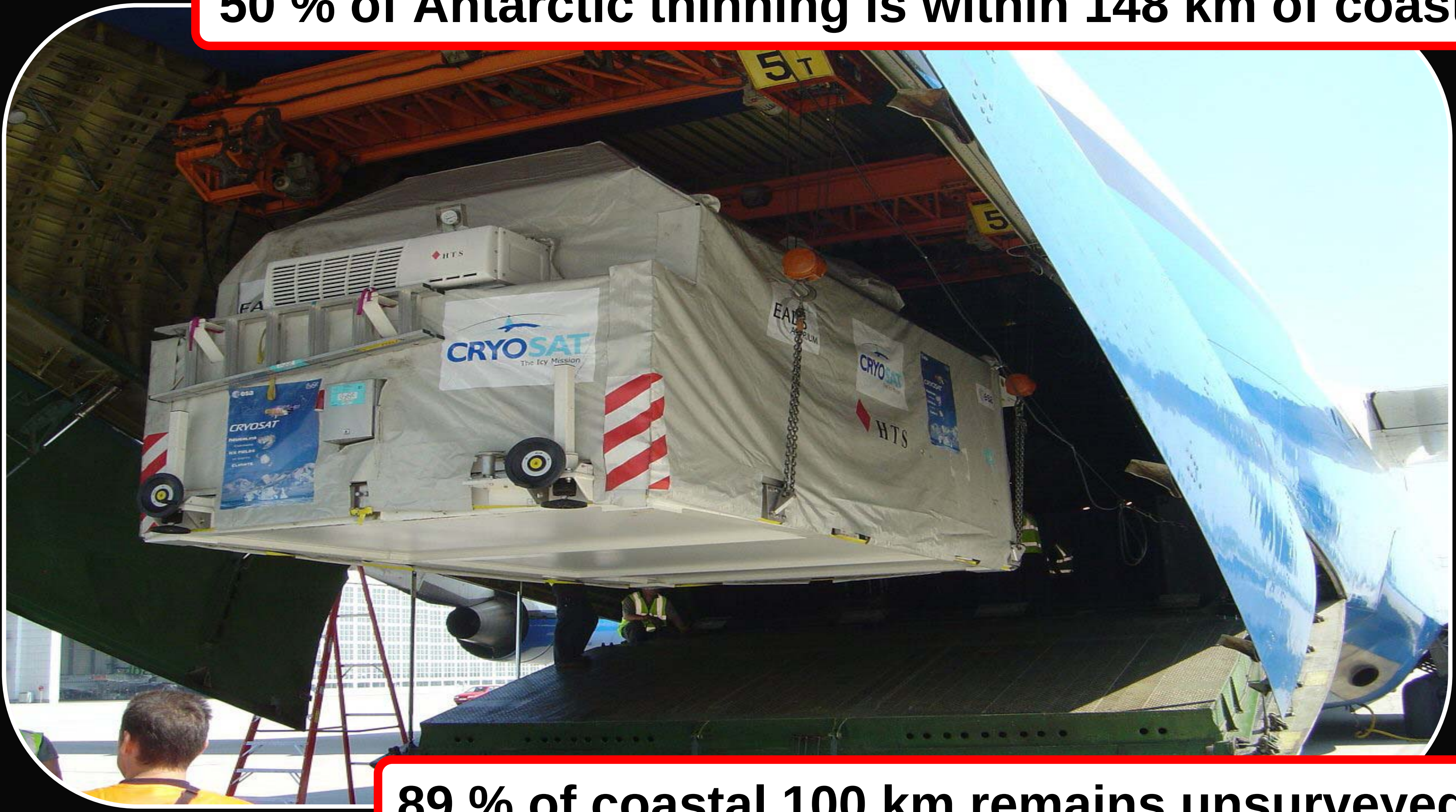
- Amundsen Sea glaciers are losing 30 Gt of ice each year
- Equivalent to a sea level contribution of 0.1 mm yr^{-1}
- Triggered by ocean currents 0.5°C above freezing
- Consistent with rate of global warming during 20th century
- All coastal, submarine glaciers in Antarctica are in retreat
- PIG retreat has accelerated over last decade
- Global oceans set to warm 1°C next century
- 21st century response not in current sea level projections

- Amundsen Sea glaciers are losing 30 Gt of ice each year
- Equivalent to a sea level contribution of 0.1 mm yr^{-1}
- Triggered by ocean currents 0.5°C above freezing
- Consistent with rate of global warming during 20^{th} century
- All coastal, submarine glaciers in Antarctica are in retreat
- PIG retreat has accelerated over last decade
- Global oceans set to warm 1°C next century
- 21^{st} century response not in current sea level projections

Summary

- Amundsen Sea glaciers are losing 30 Gt of ice each year
- Equivalent to a sea level contribution of 0.1 mm yr^{-1}
- Triggered by ocean currents 0.5°C above freezing
- Consistent with rate of global warming during 20th century
- All coastal, submarine glaciers in Antarctica are in retreat
- PIG retreat has accelerated over last decade
- Global oceans set to warm 1°C next century
- 21st century response not in current sea level projections

50 % of Antarctic thinning is within 148 km of coast



89 % of coastal 100 km remains unsurveyed