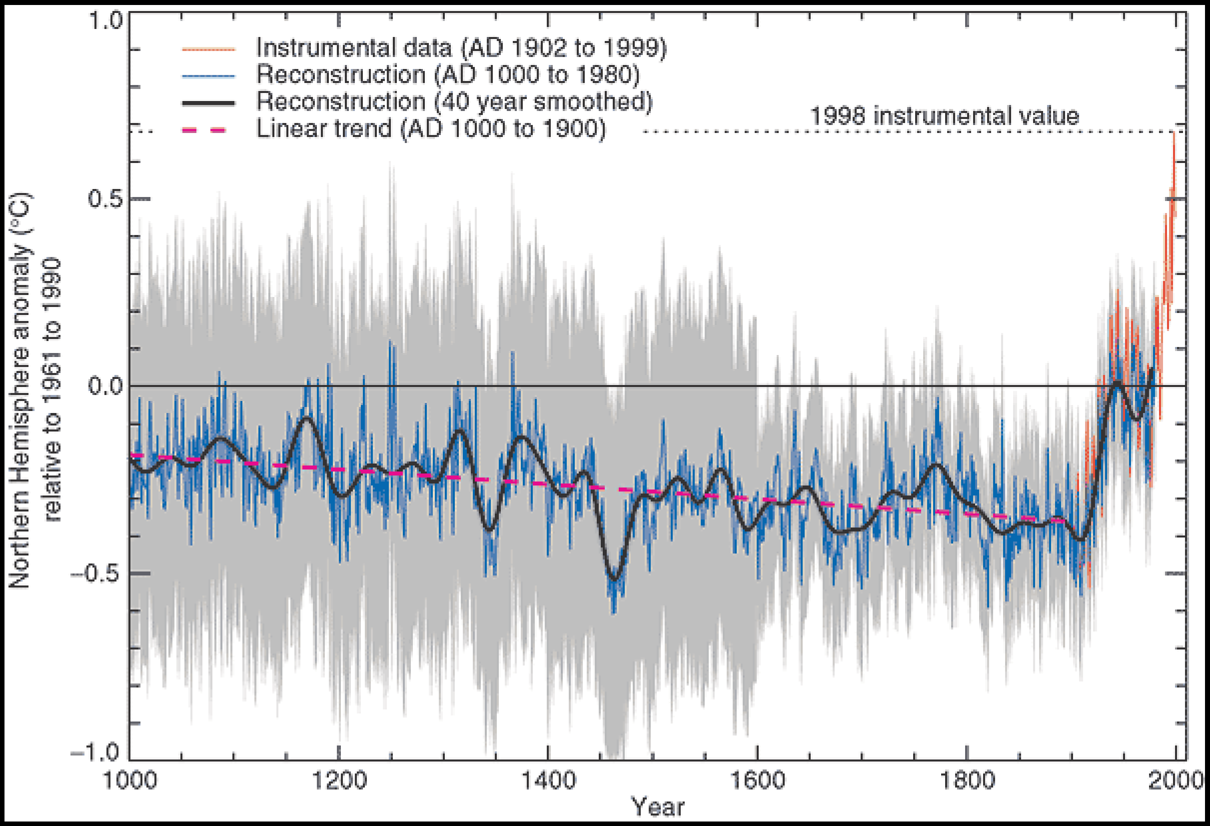
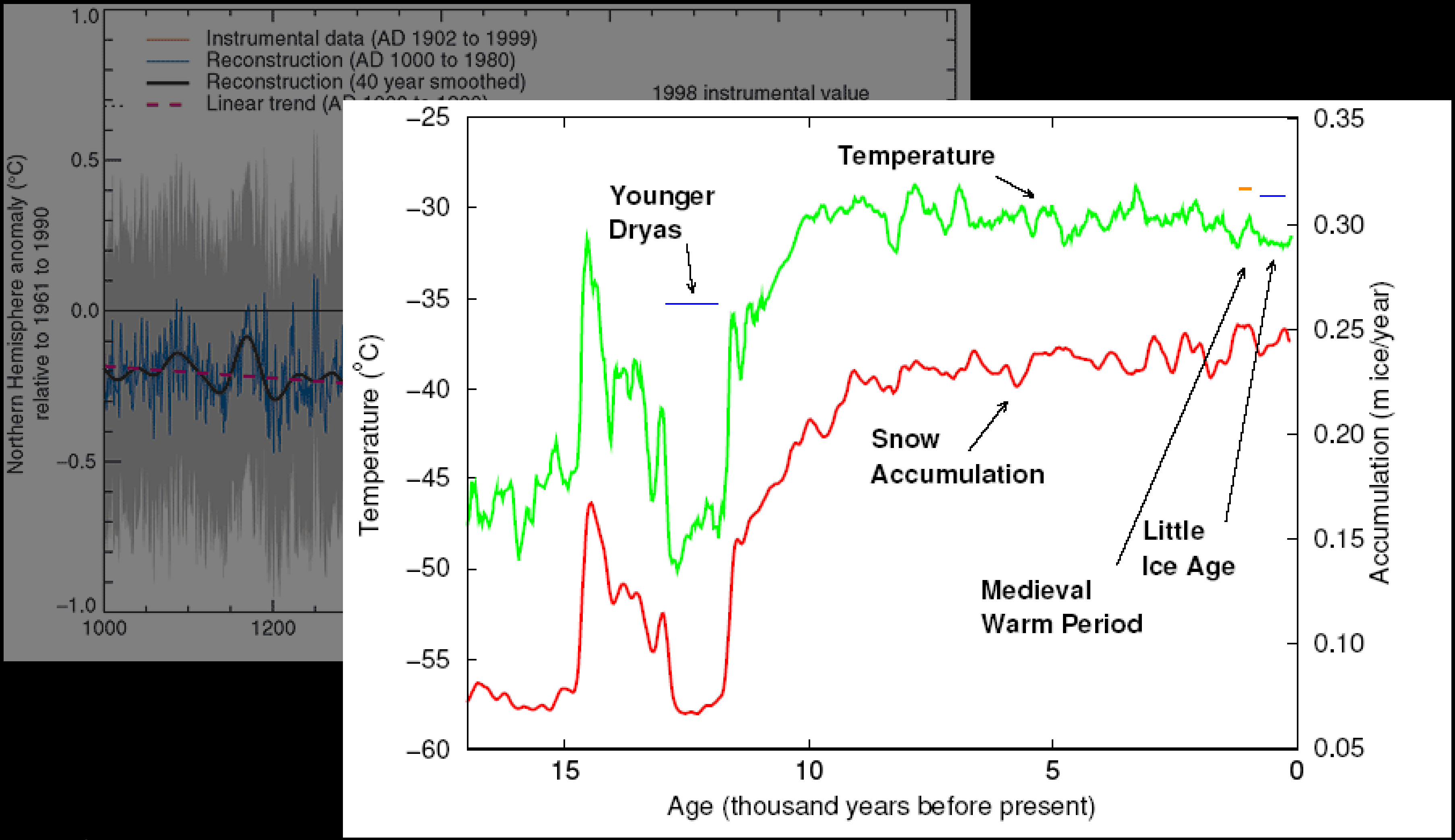
Abrupt Climate Change: Why did Larsen Ice Shelf collapse?

Andrew Shepherd
University of Edinburgh

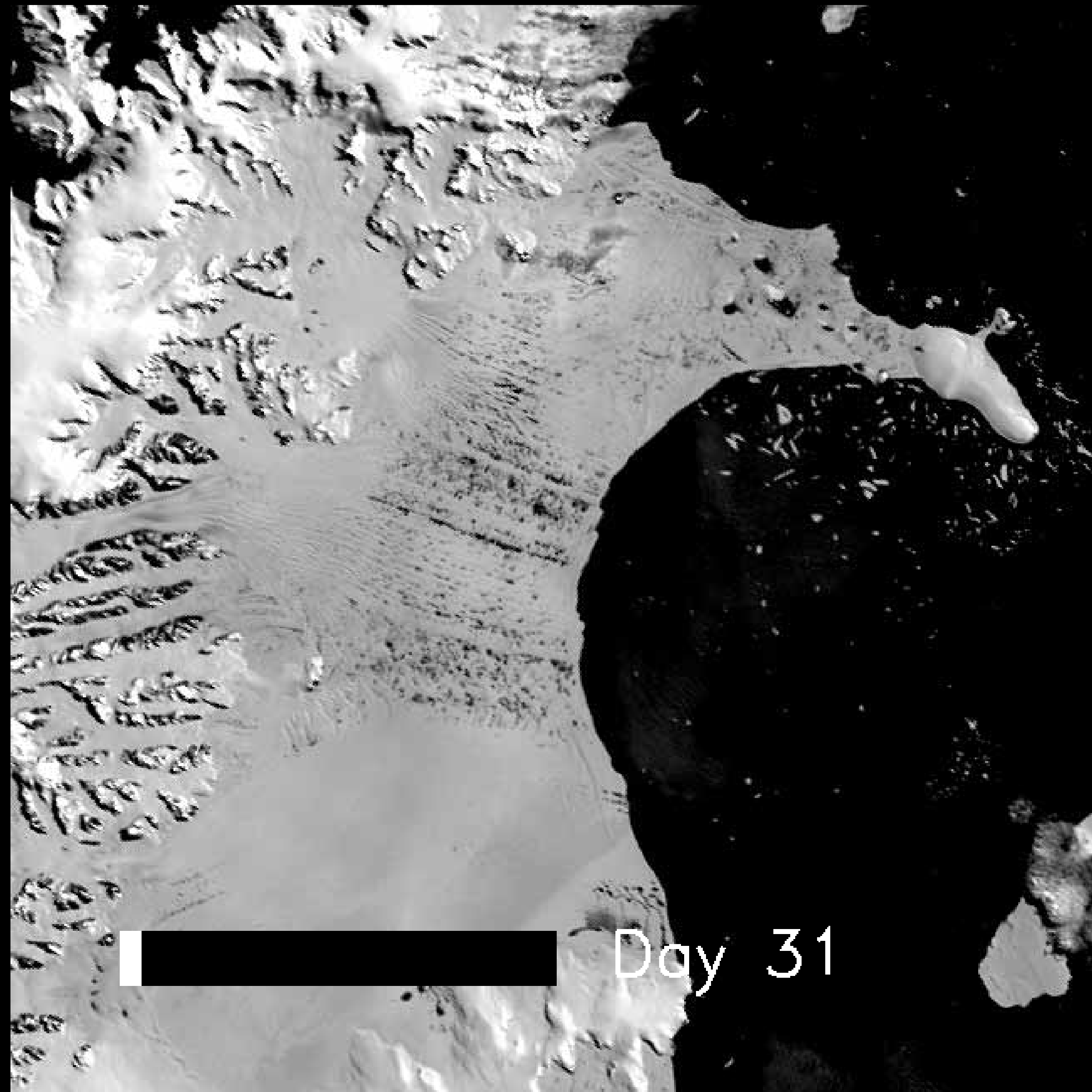


- 1° C per century

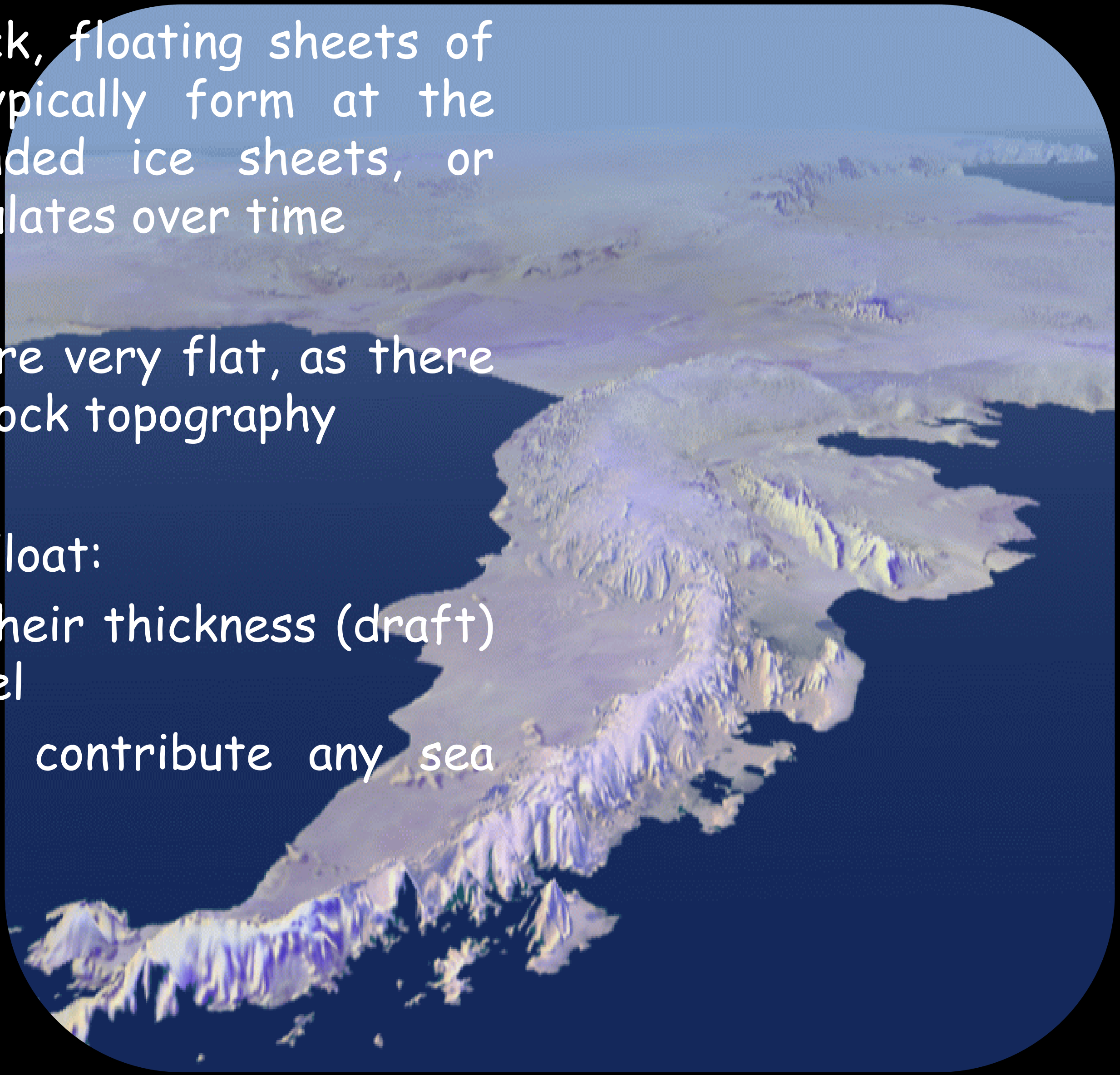


- 10° C per century

L2 – Larsen ice shelf

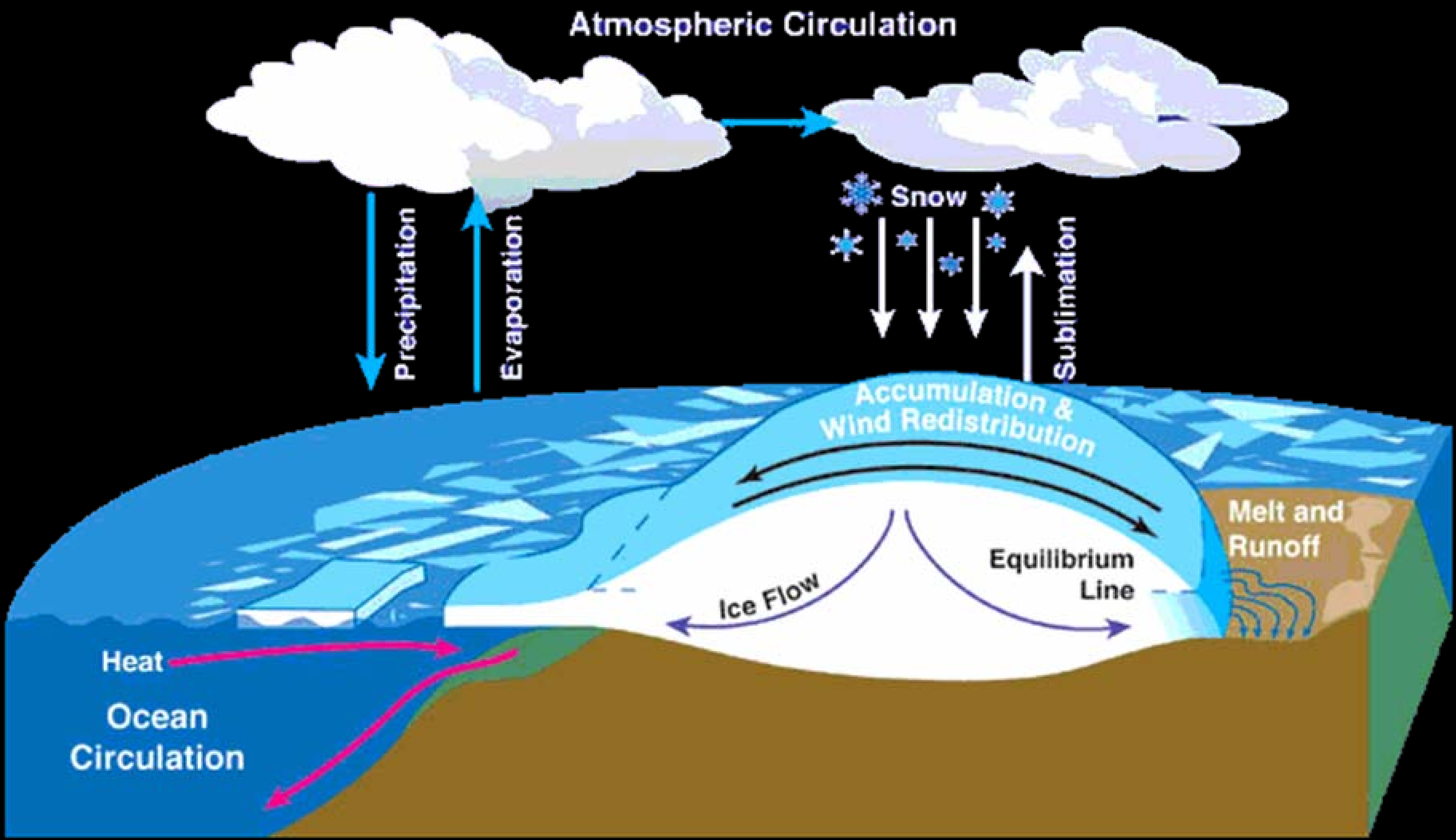

Day 31

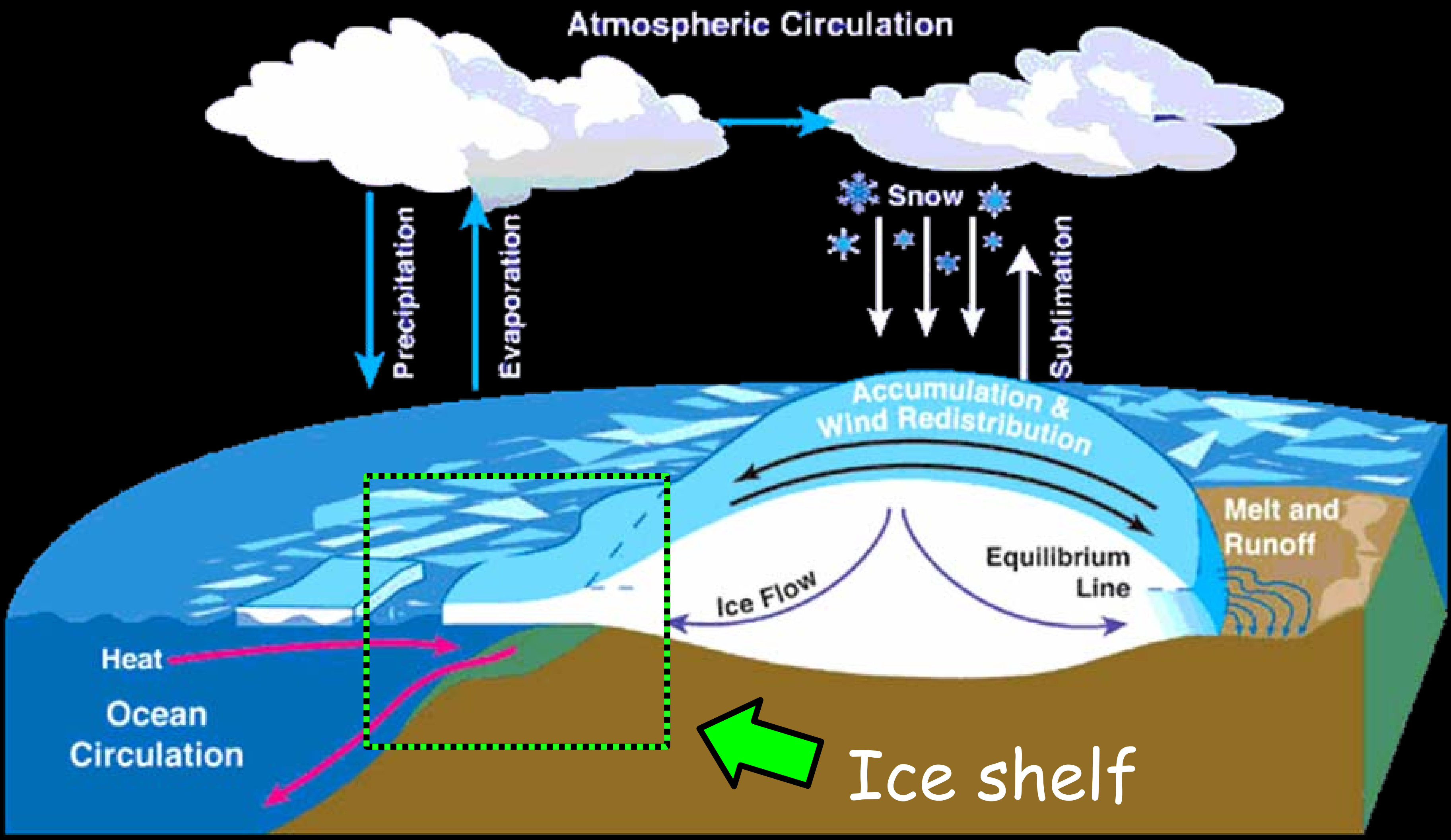
What is an ice shelf?



- Ice shelves are thick, floating sheets of flowing ice that typically form at the periphery of grounded ice sheets, or where sea ice accumulates over time
- Ice shelf surfaces are very flat, as there is no underlying bedrock topography
- Because ice shelves float:
  - around 90 % of their thickness (draft) lies below sea level
  - their ice cannot contribute any sea level change

What is an ice shelf?




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

Sea-ice develops into fast ice

Marine terminating glaciers form floating tongues

Snowfall leads to thickening

Bas

Icebergs calving

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Marine terminating glaciers form floating tongues

ed

Icebergs calving

Basal melting

Surface runoff

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Icebergs calving

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Marine terminating glaciers form floating tongues

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Basal freezing leads to thickening

Icebergs calving

What is an ice shelf?

Marine terminating glaciers form floating tongues

ng leads
ening

Ice shelves formed

Icebergs calving

Basal melting

Surface runoff

Sea-ice de... into fas...

Snowfall leads to thickening

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into fas

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ned

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Surface runoff

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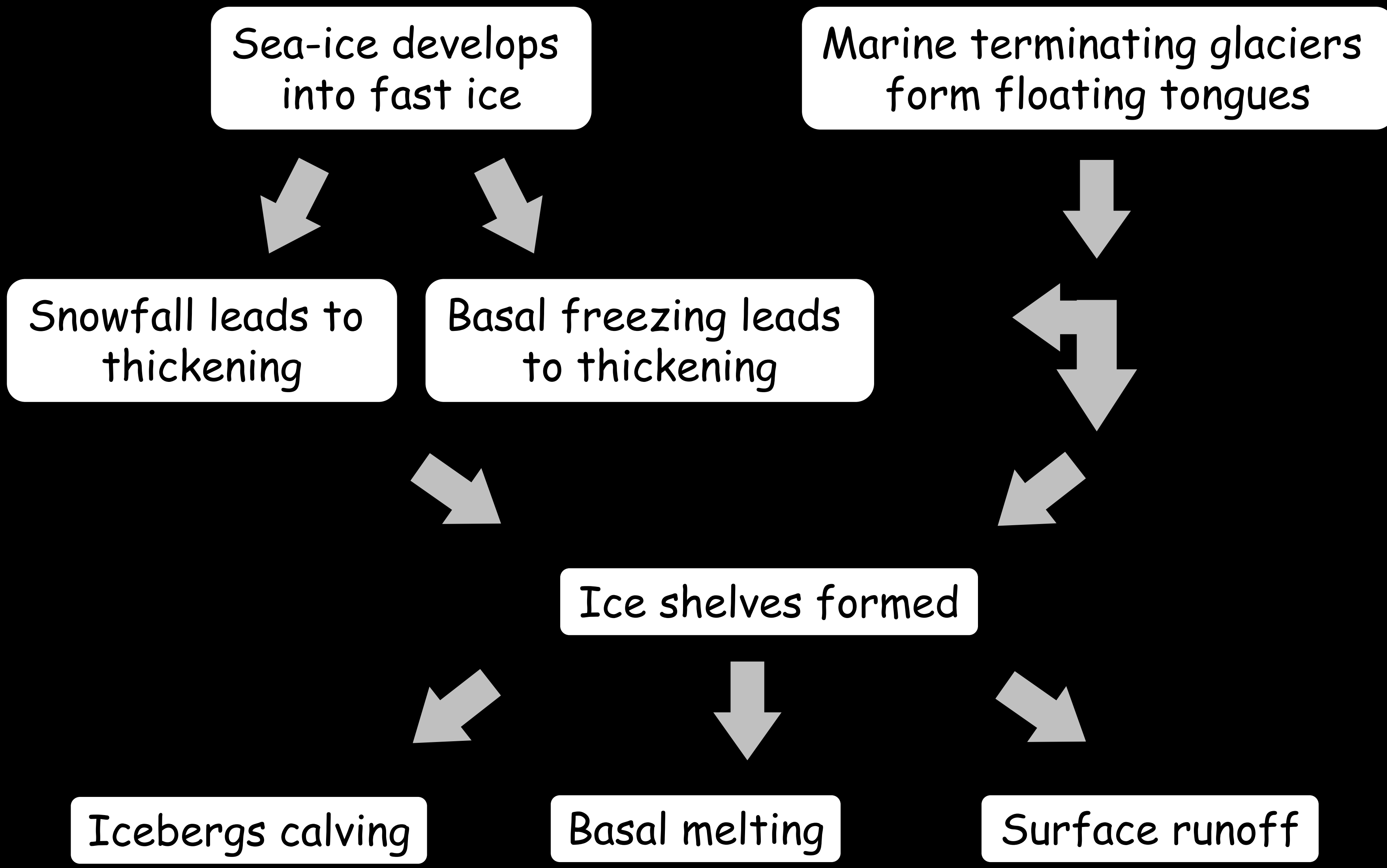
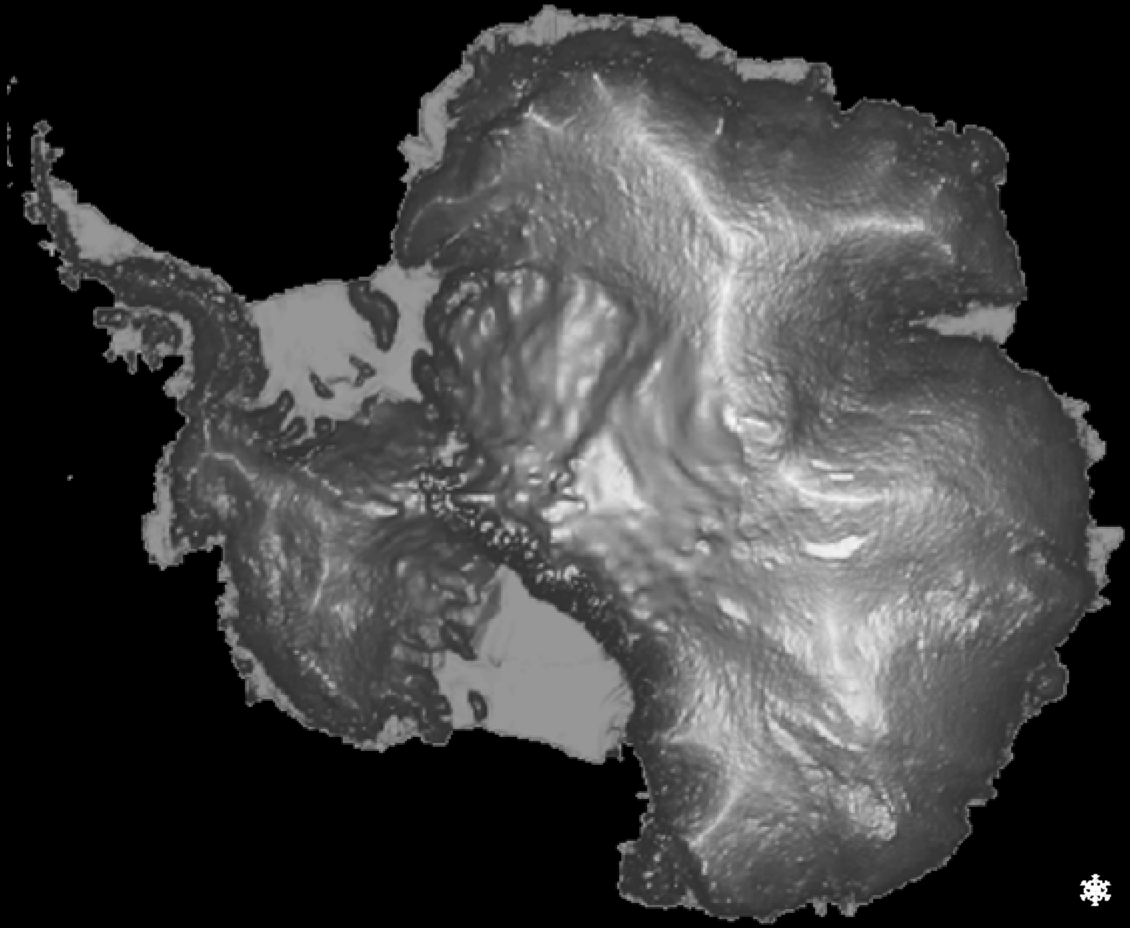
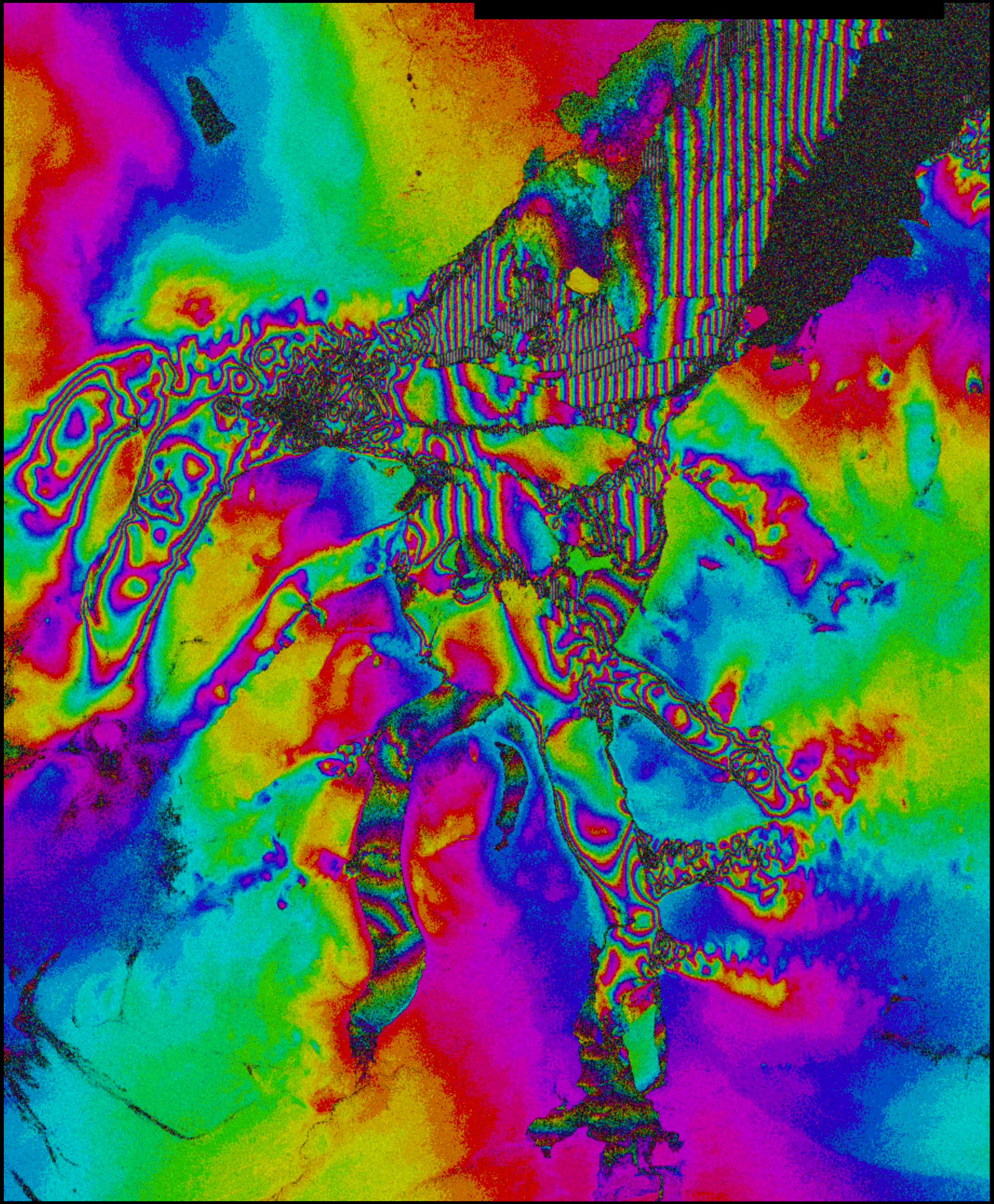


- Ice shelves are primarily an Antarctic phenomenon, because virtually all of its land area is covered by the ice sheet.

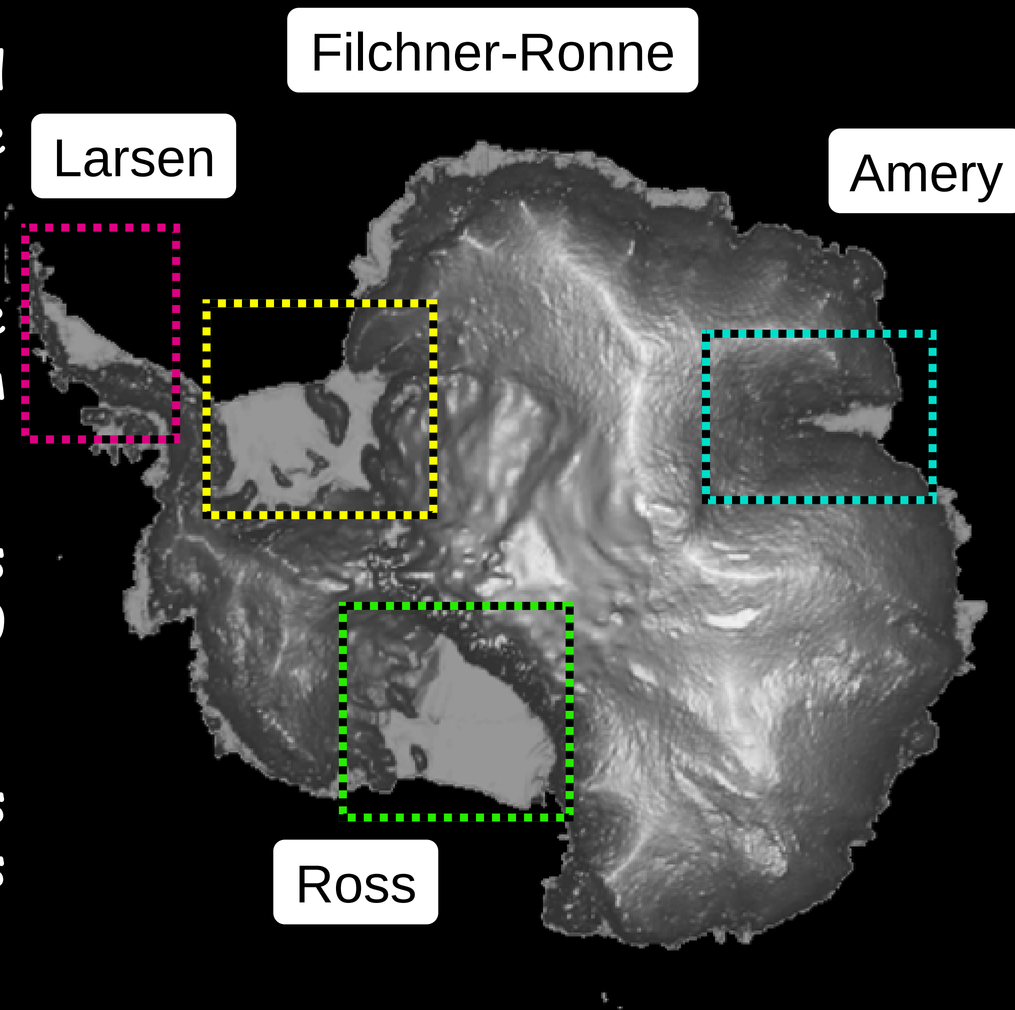


- In contrast, most of the Greenland coastline is land.

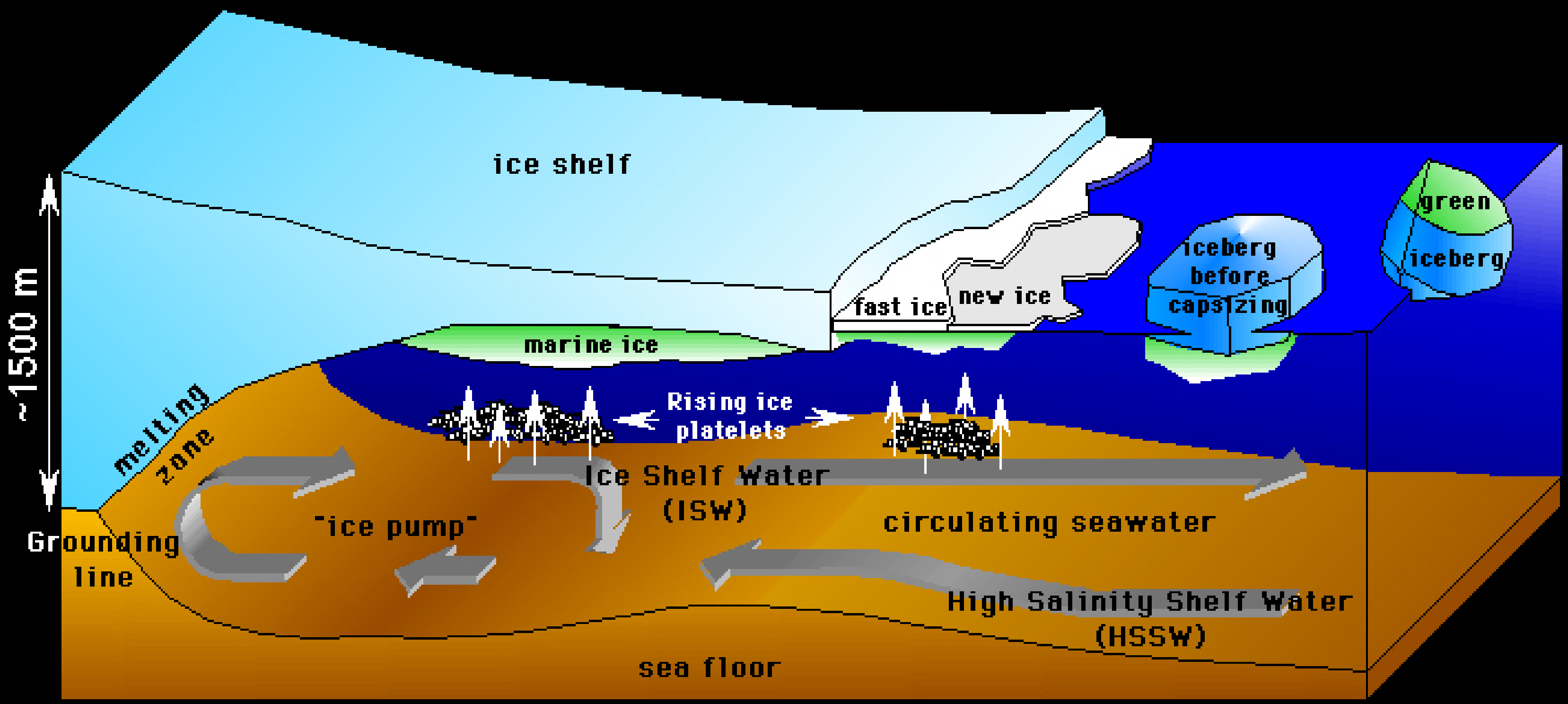
- … although there are a few Arctic ice shelves, but these are very small in comparison



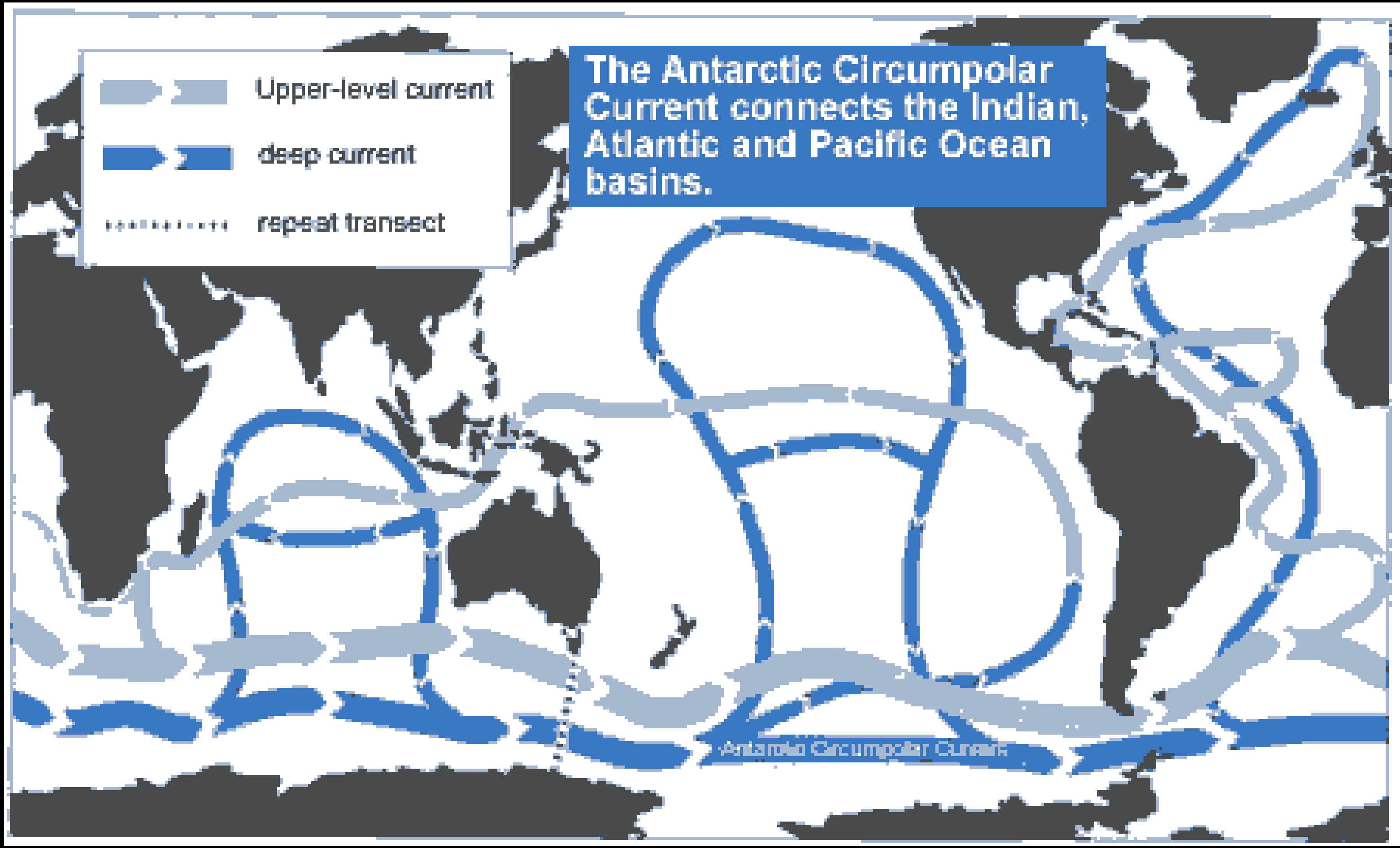
- About 50% of the Antarctic coastline has ice shelves
- About 11% of the area and 2.5% of the volume of the Antarctic ice mass is floating
- Ross & Ronne ice shelves are the largest, up to 1000 m thick and the area of France
- Climate at Larsen Ice Shelf is very different as it is 1000 km farther north
- In summer, melting is is widespread, and mass loss occurs through runoff



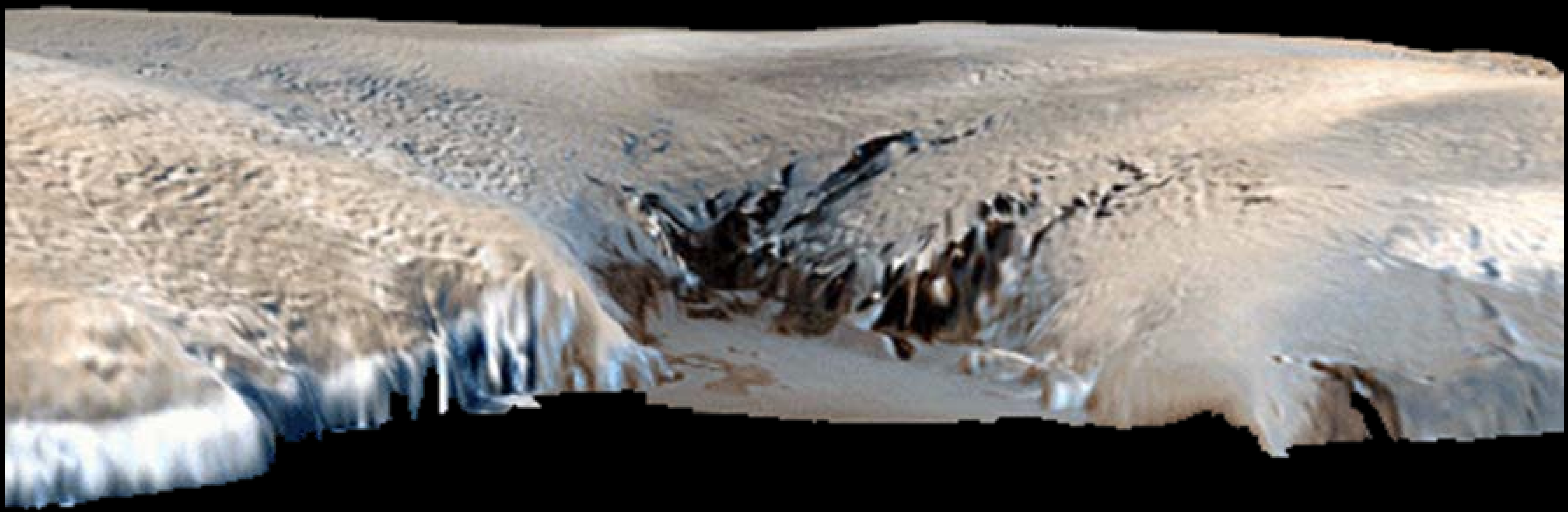
- Ice shelves are sensitive indicators of changes in climate because they are exposed to both the oceans and atmosphere…

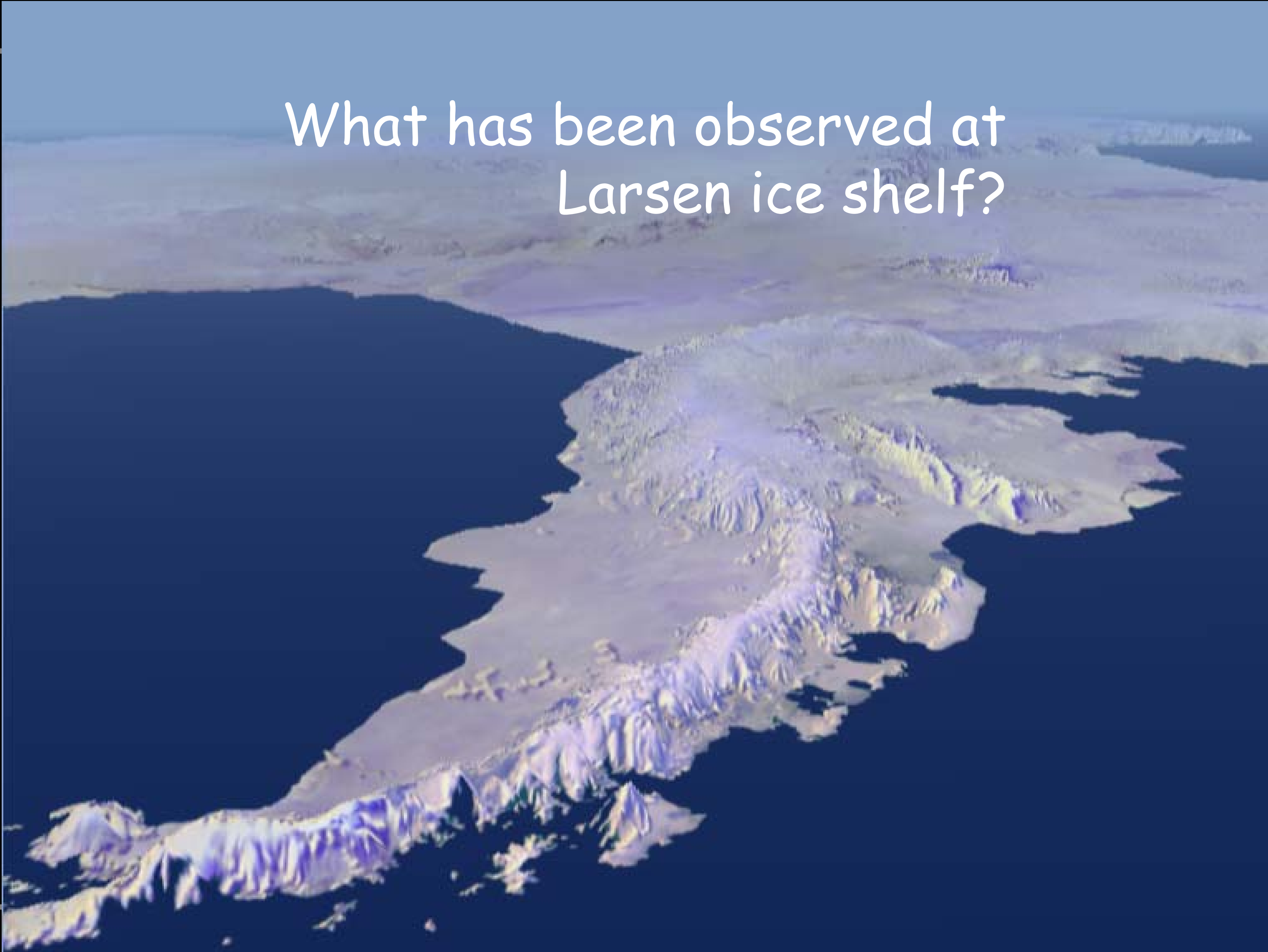


- Although ice shelves can't contribute to sea level, since they are already afloat, release of their ice affects patterns of ocean circulation



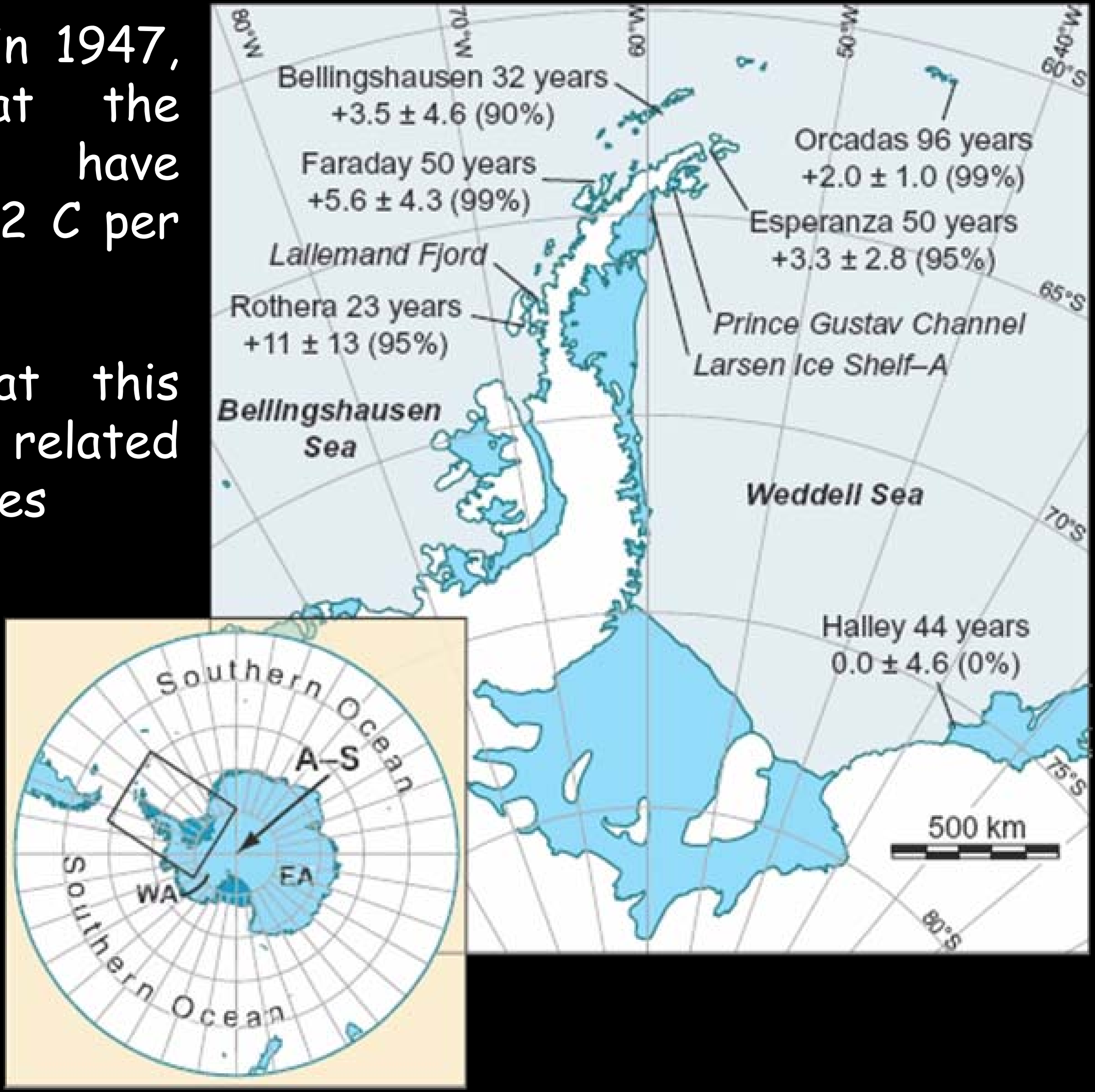
- Also, because ice shelves form between ice sheets and the ocean, their removal could affect the flow of glaciers grounded upstream.



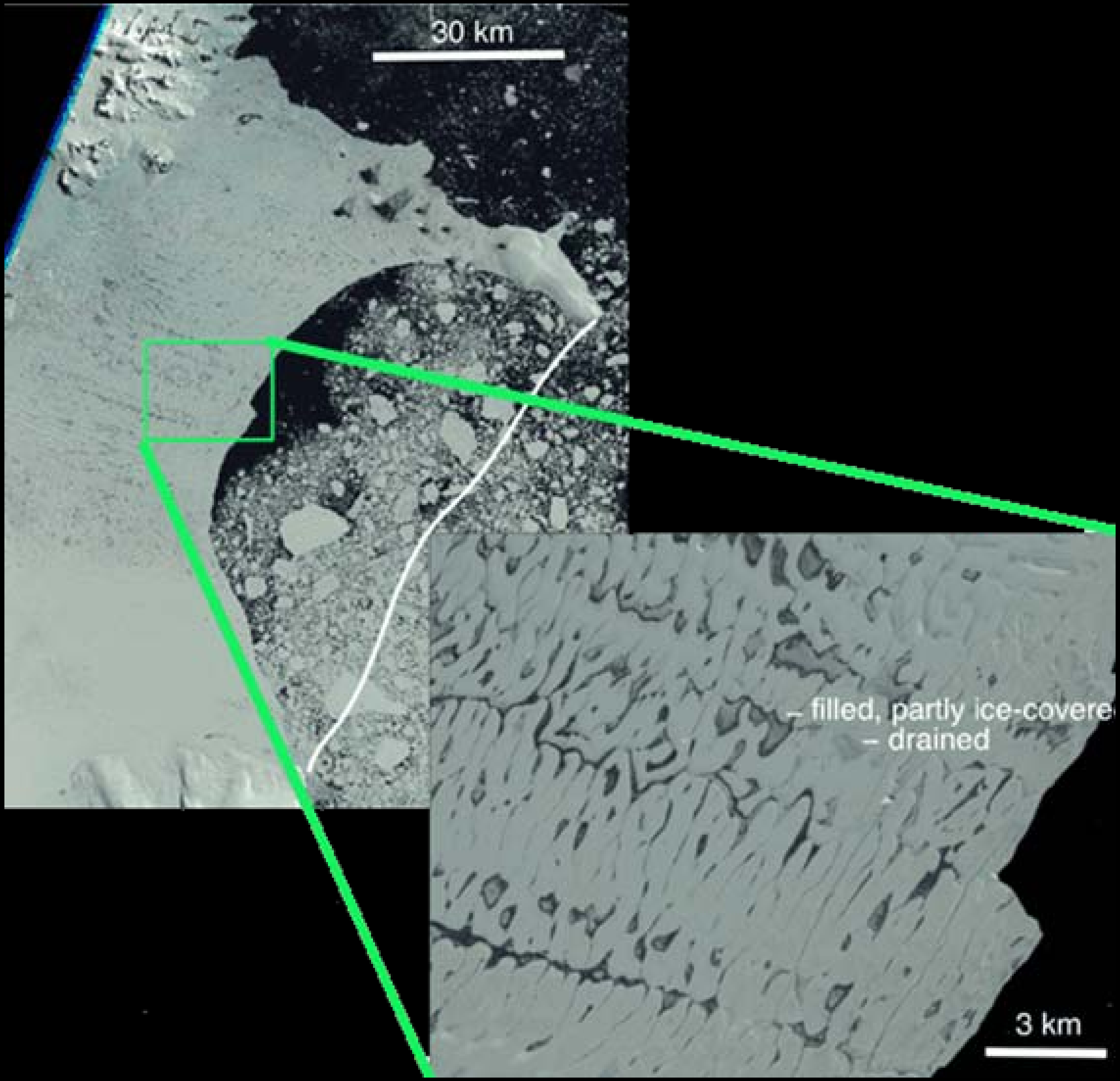

What has been observed at
Larsen ice shelf?

What has been observed at Larsen?

- Since records began in 1947, air temperatures at the Antarctic Peninsula have steadily increased by 2 C per century
- It's likely that that this warming is in some way related to the ice shelf collapses

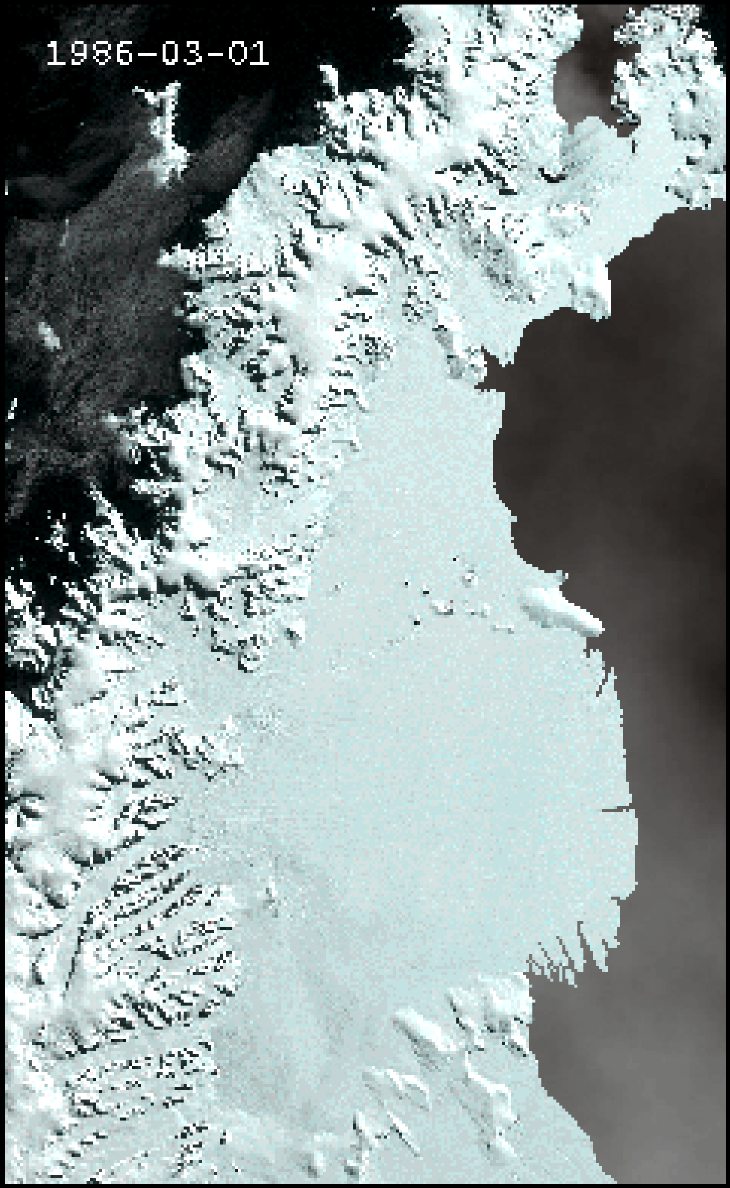


- As temperatures have risen, more melt-water has been produced.



What has been observed at Larsen?

- Antarctic Peninsula ice shelves have retreated by 300 km^2 each year since 1980.
- The gradual retreat has been punctuated by two catastrophic collapses, in 1995 and 2002, when ~ 3000 km^2 sections of the Larsen Ice Shelf fragmented into millions of icebergs.



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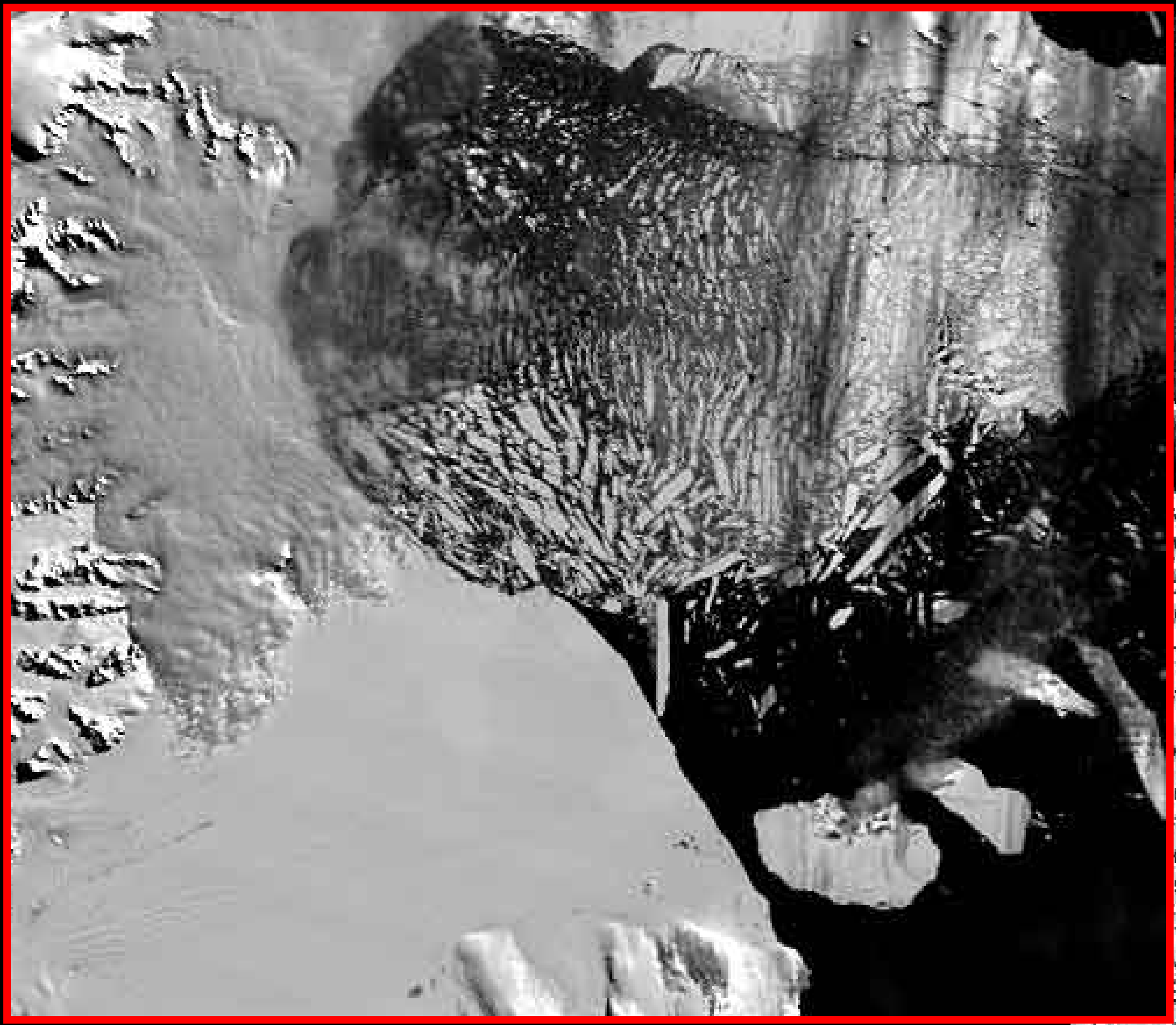
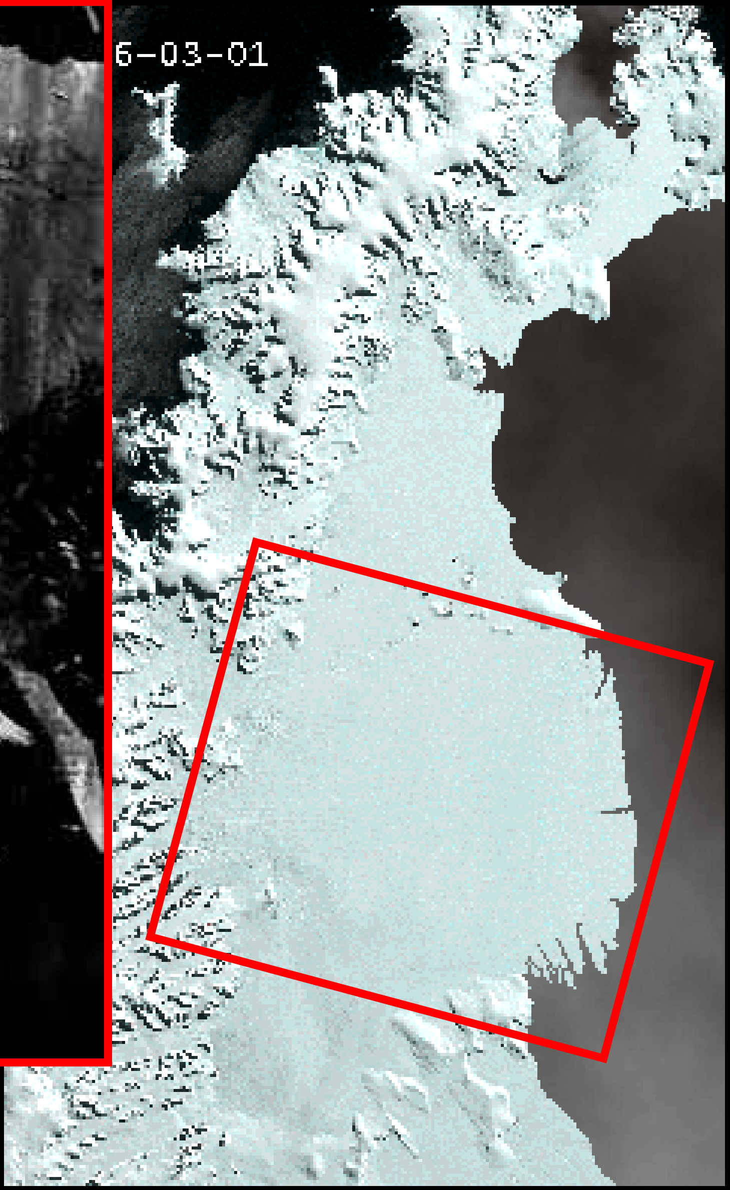
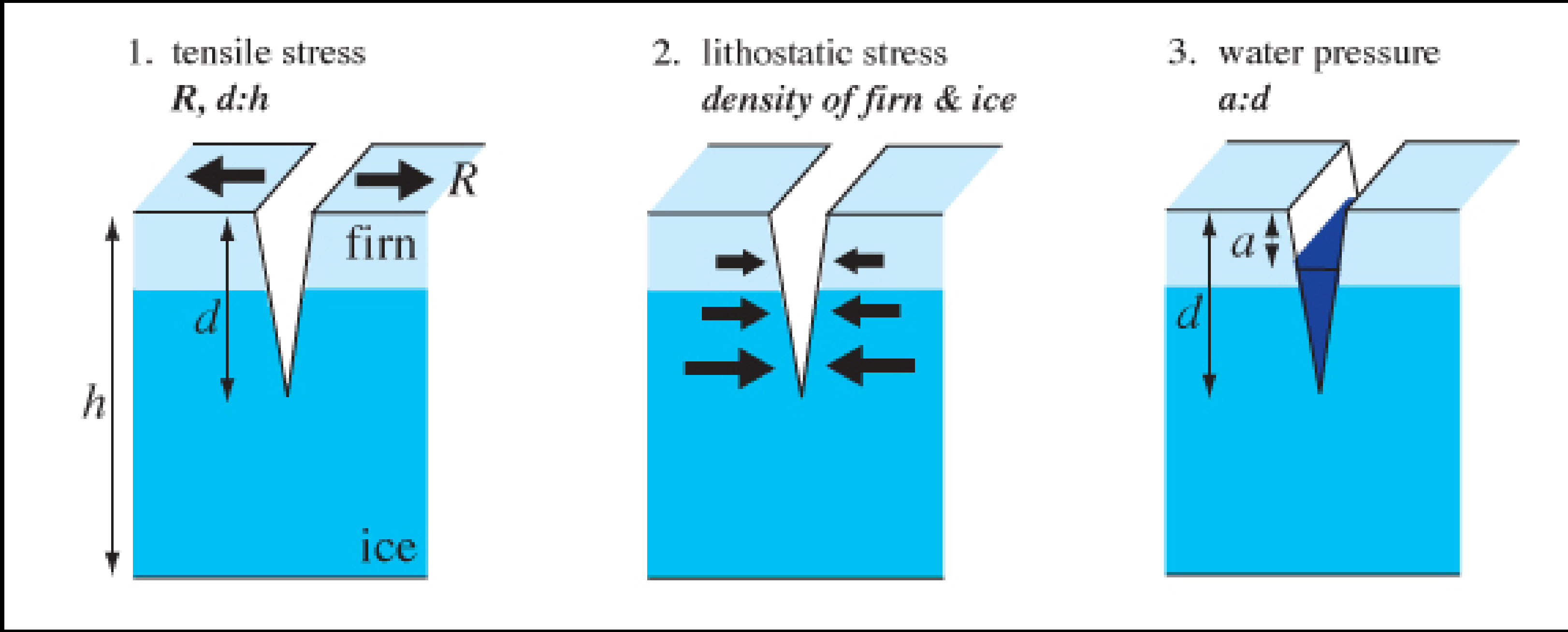


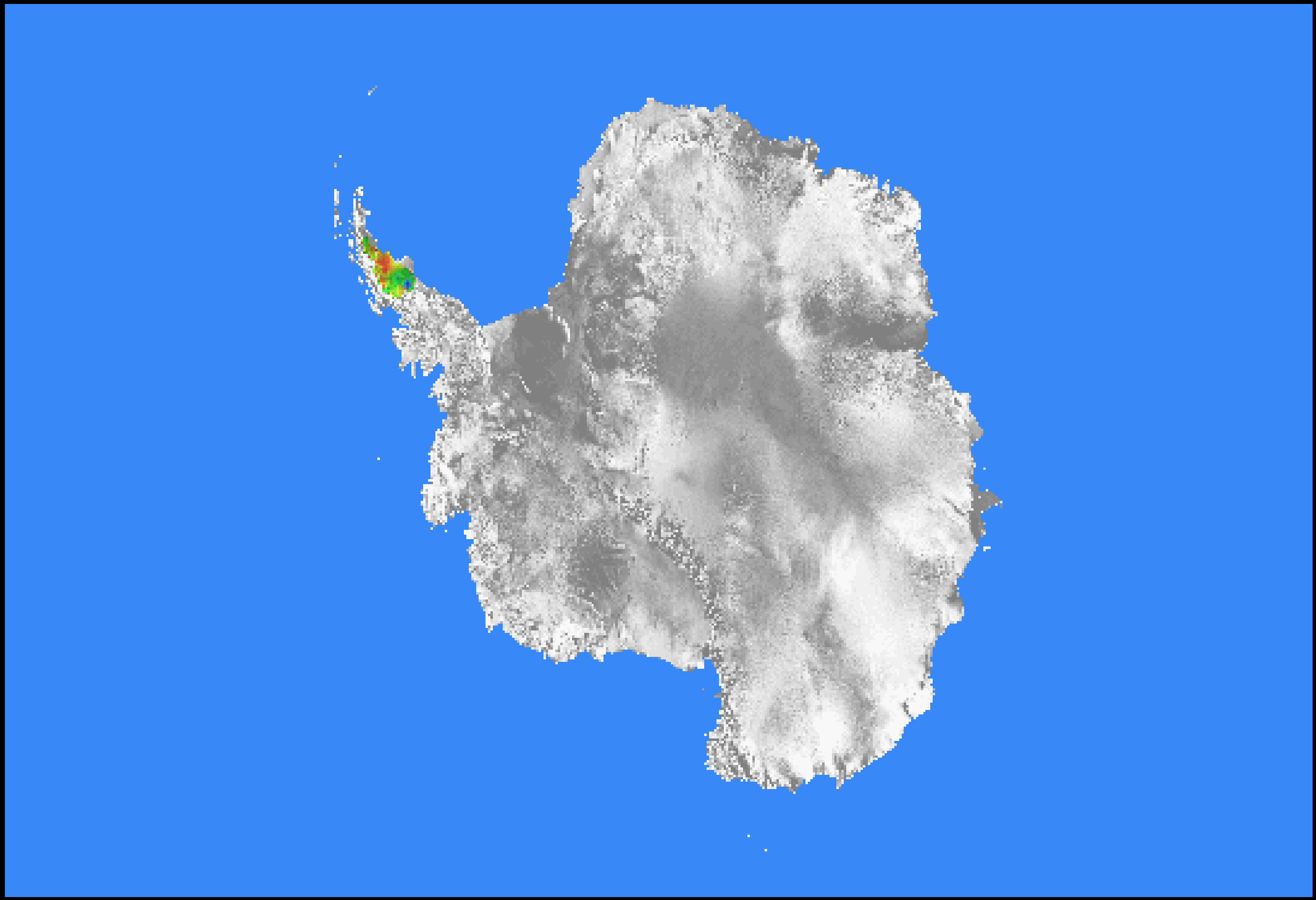


- One theory is that melt-water fills open crevasses to their brims, allowing crevasses to crack through to the base of the ice shelf and causing fragmentation.

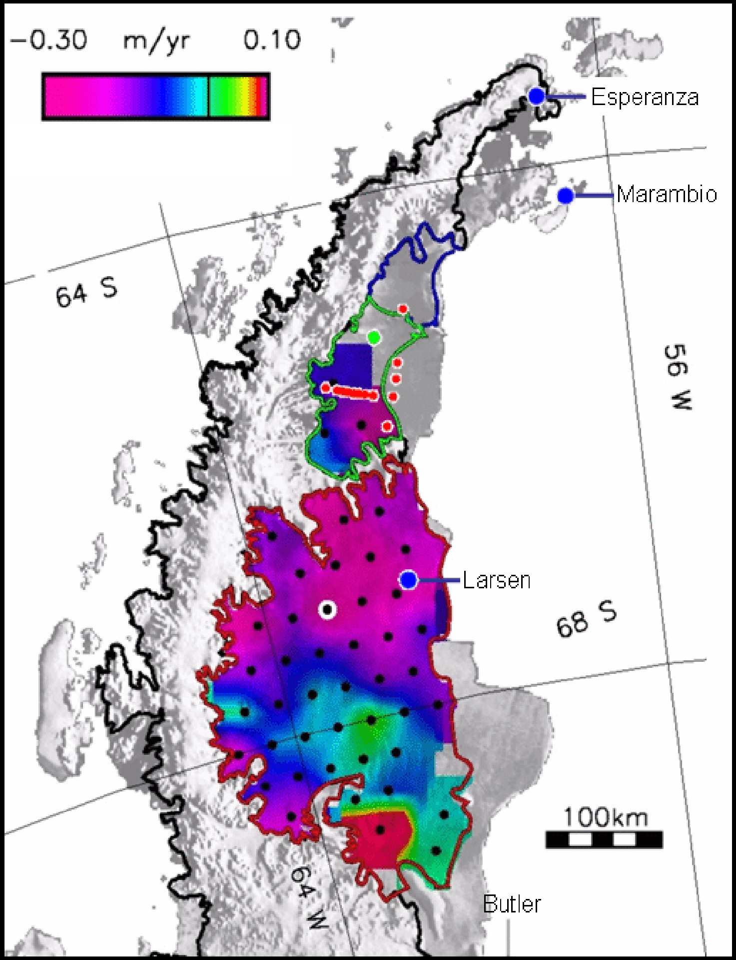
- … but, there are no observations to support this theory



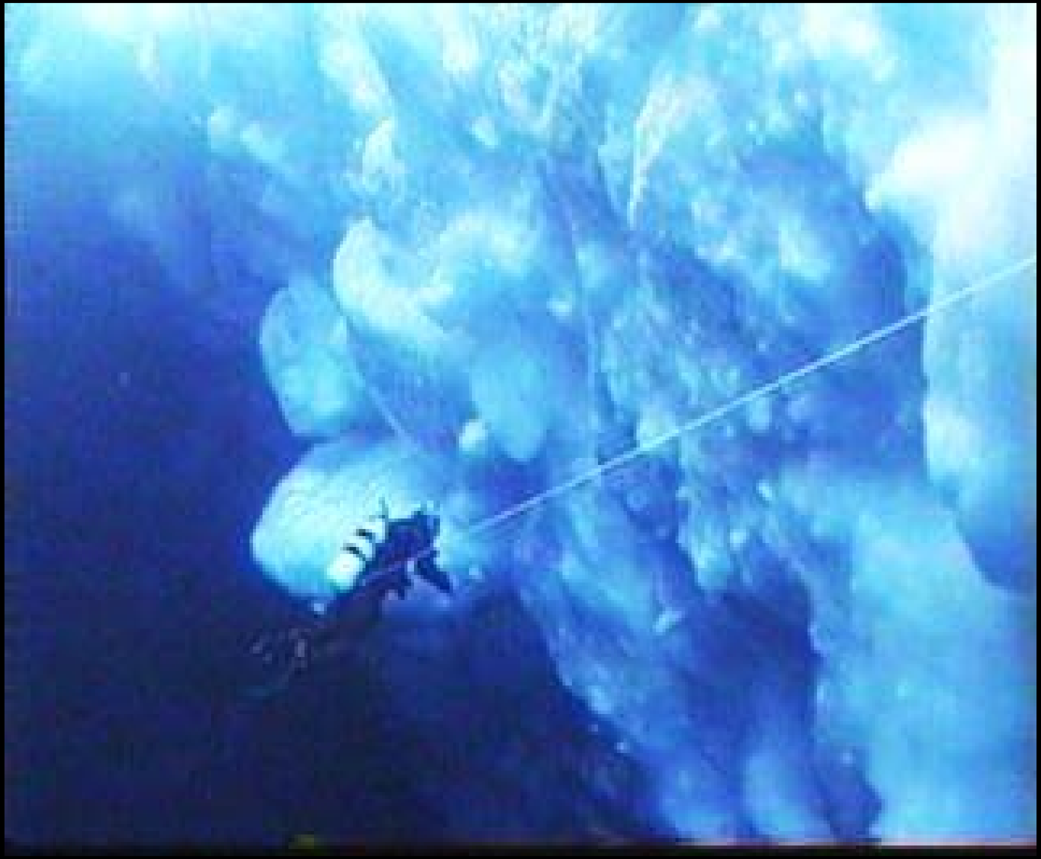
- At the same time, satellite radar altimeter data show that since 1992 the Larsen Ice Shelf has lowered by around 30 cm per year.



What has been observed at Larsen?



- Because the ice shelf is buoyant, the lowering could arise from a number of alternative changes



Sea level change

Sea density change

Surface accumulation

Ice flow

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

Elevation change

Firn densification

Basal melting

What has been observed at Larsen?

Sea level change <10%

Sea density change <5%

Surface accumulation <10%

Ice flow

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

Elevation change

Firn densification <20%

Basal melting

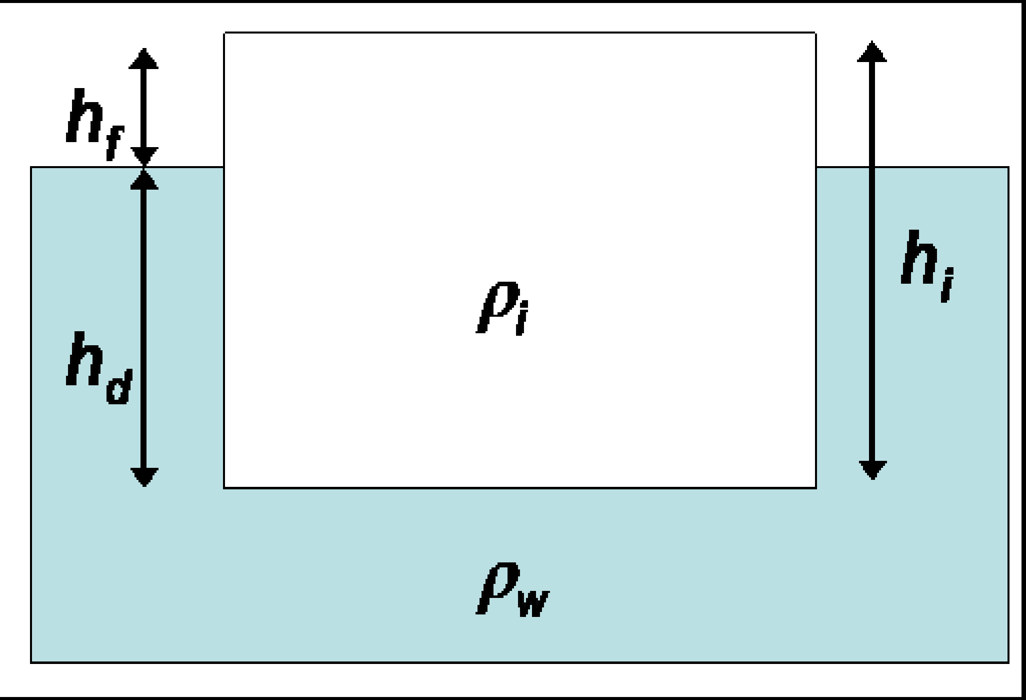
- Archimedes Principal states that a body suspended in a fluid is buoyed according to balanced forces. For an ice shelf of unit cross section area, the weight of ice is balanced by that of the displaced water (hydrostatic equilibrium):

$$\rho_w g h_d = \rho_i g h_i$$

$$\rho_w g \left(h_i - h_f\right) = \rho_i g h_i$$

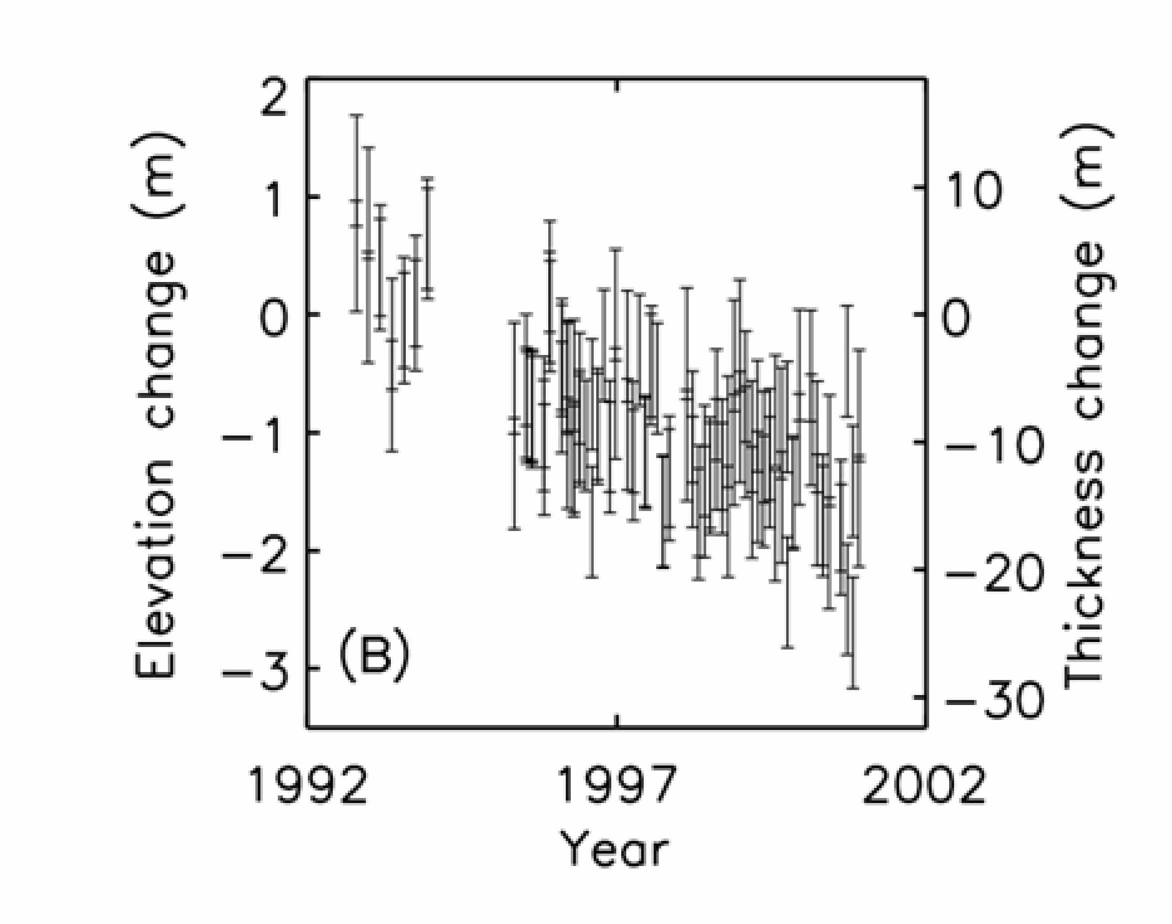
$$h_f = h_i \left(1 - \frac{\rho_i}{\rho_w}\right)$$

$$h_f \approx \frac{1}{9} h_i$$



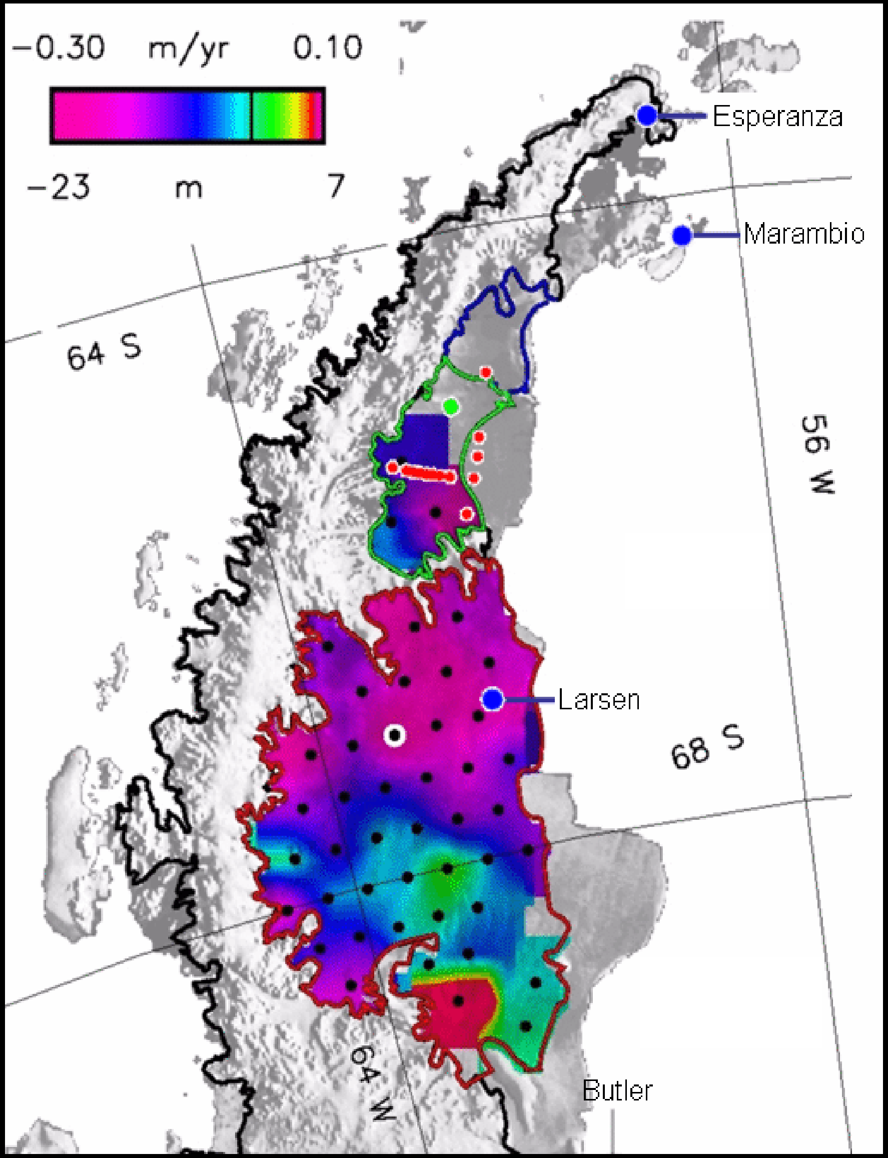
- For ice mass loss (e.g. at the base), the surface lowering is $^1/_9$ of the thinning.

- Conclusion: the lowering reflects a tenfold greater unbalanced basal ice melting of 23 m in total - up to 7 % of the ice shelf thickness in the past decade.



What is origin of ice thinning?

Origin of thinning?

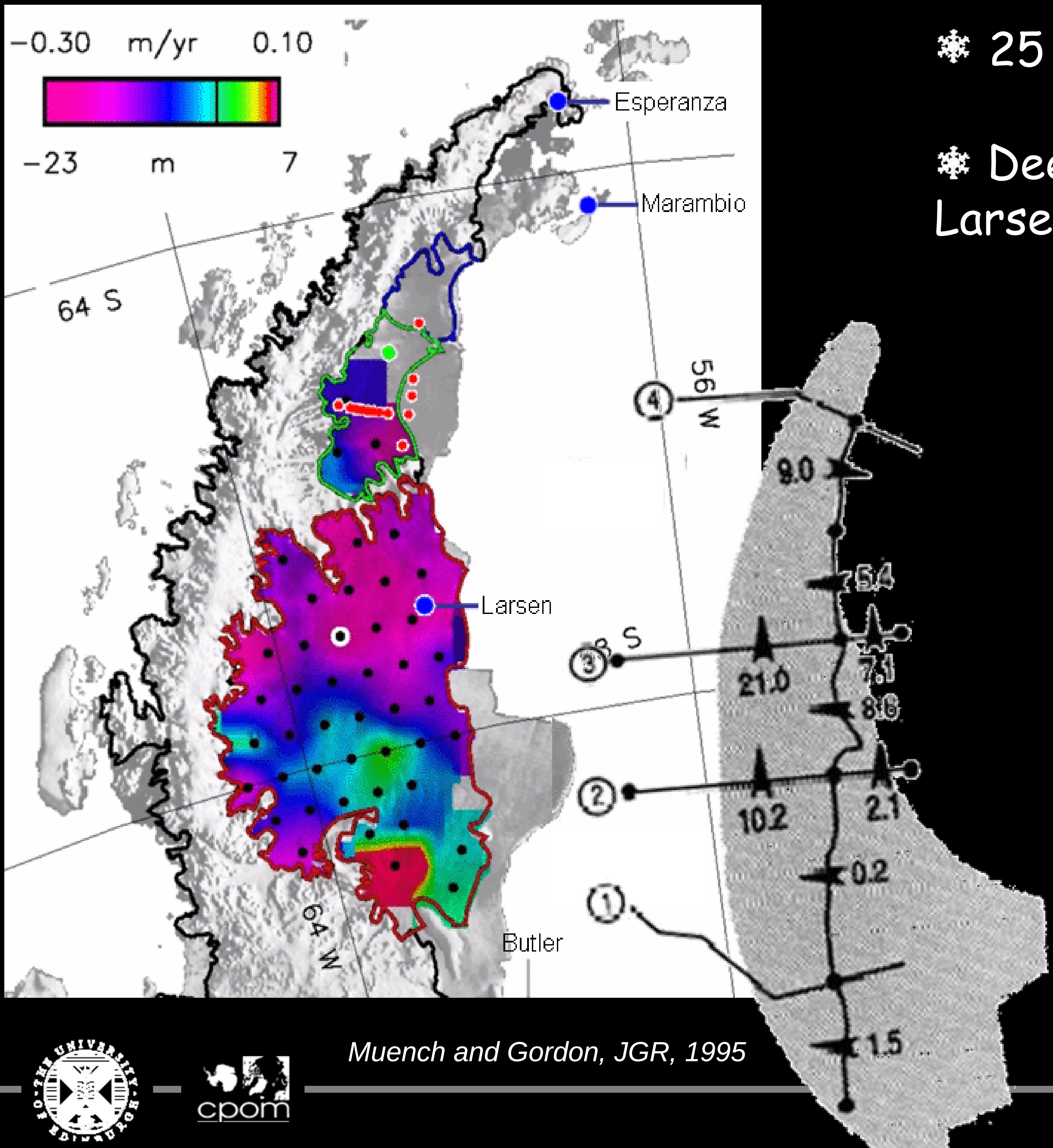


Muench and Gordon, JGR, 1995

- 25 m thinning per decade

Origin of thinning?

- 25 m thinning per decade
- Deep ocean transport toward Larsen



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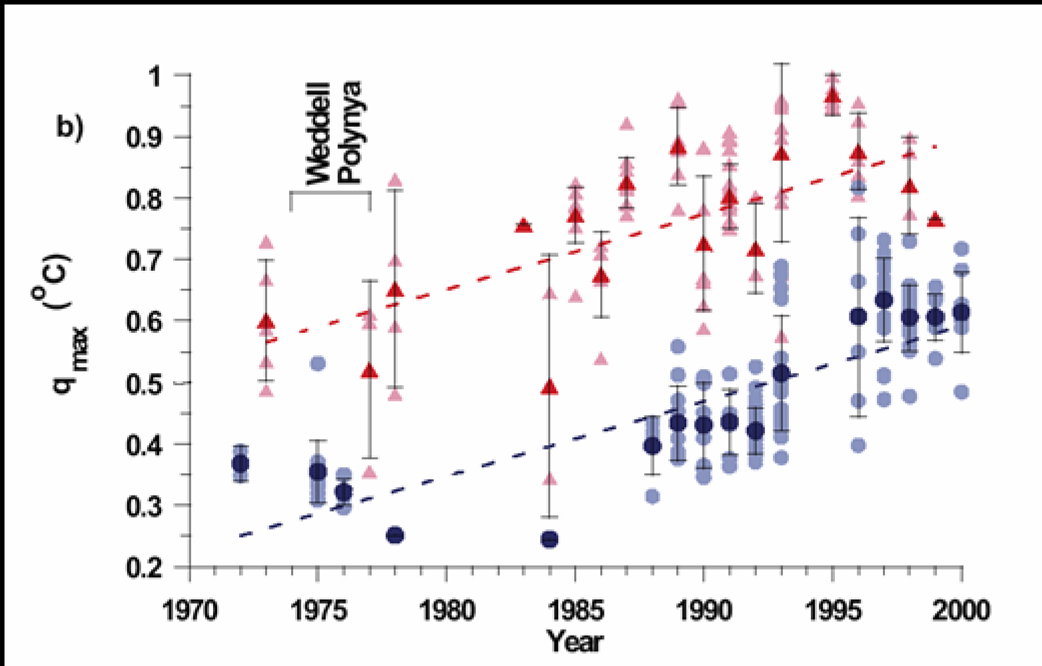
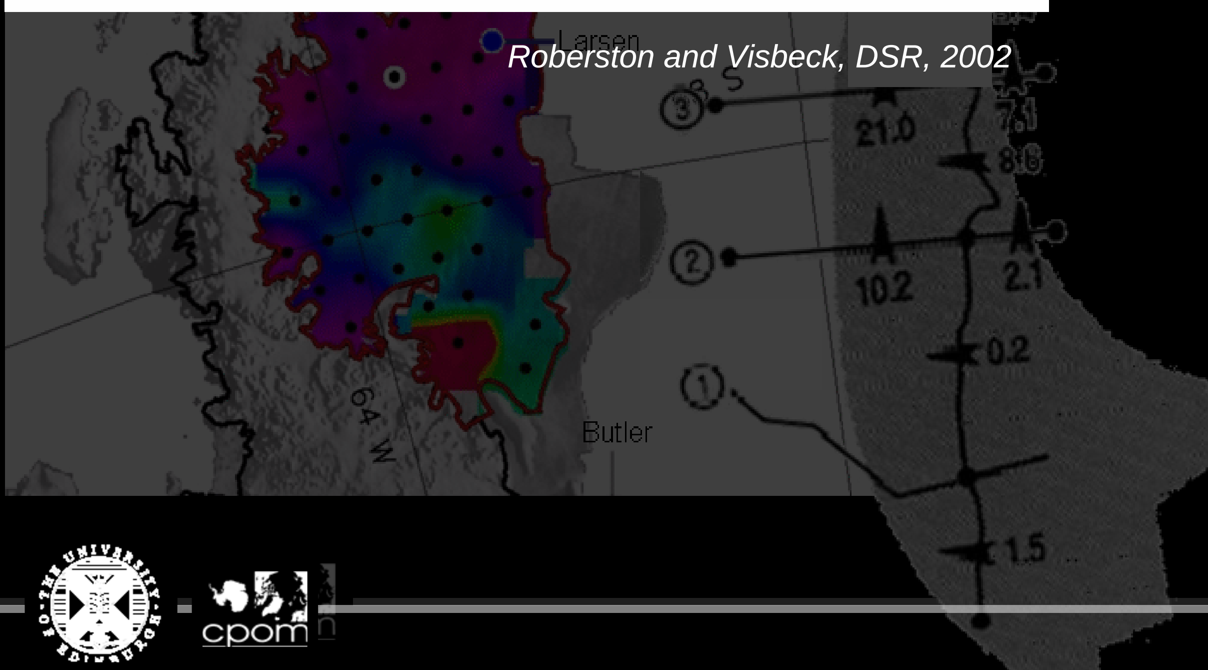
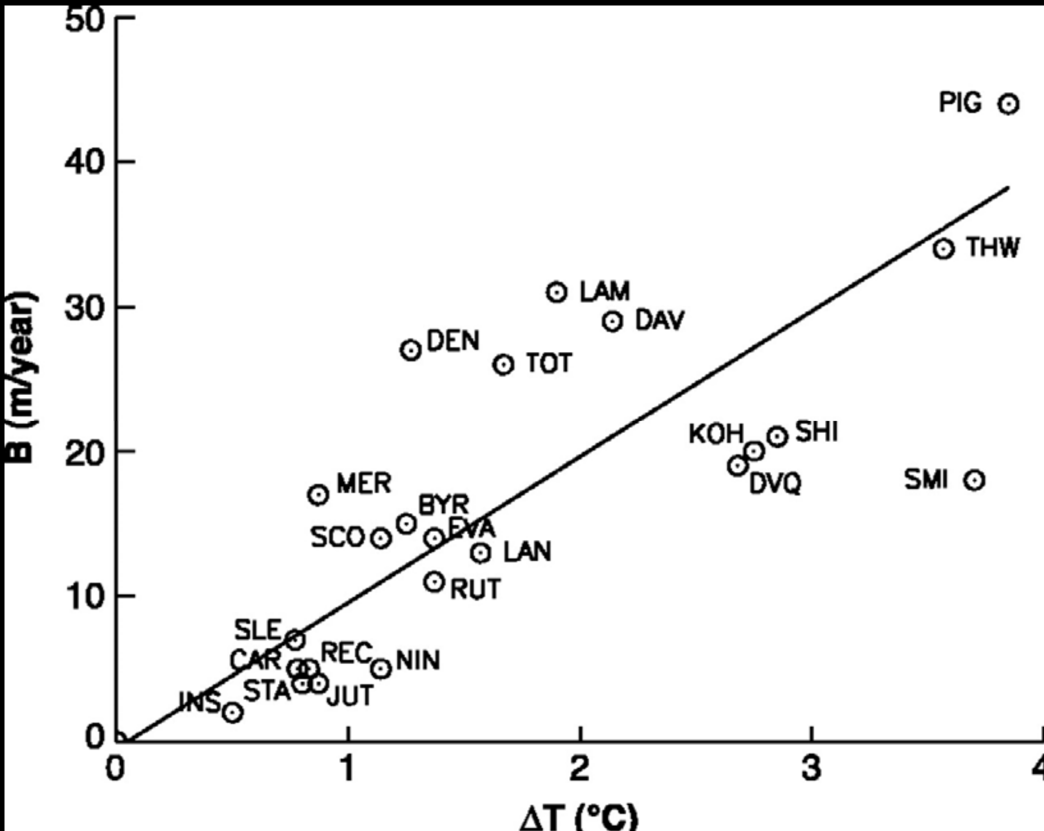




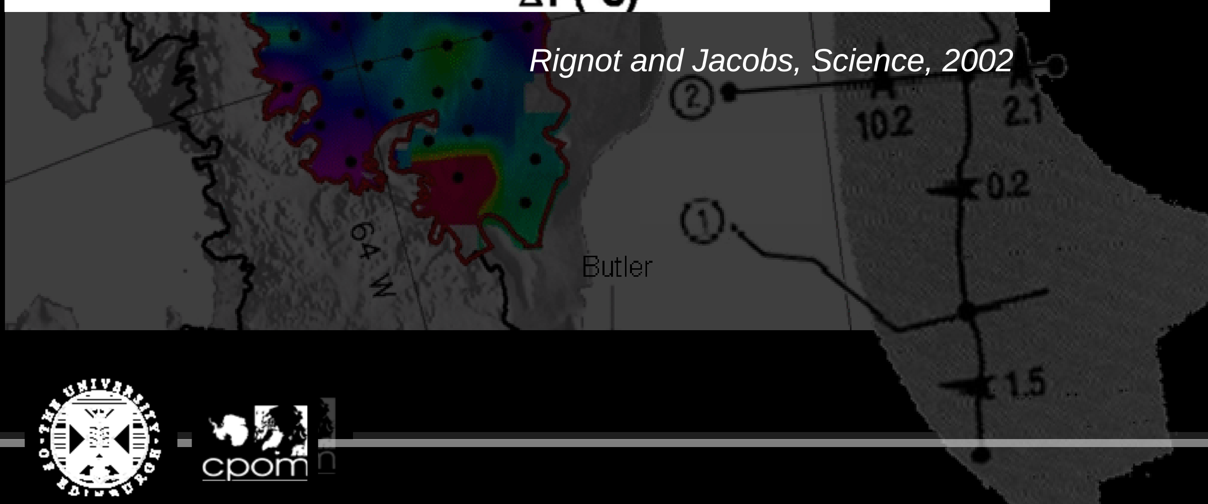
Roberston and Visbeck, DSR, 2002

- 25 m thinning per decade
- Deep ocean transport toward Larsen
- Weddell deep water has warmed 0.4 C since 1970

Origin of thinning?



Rignot and Jacobs, Science, 2002



- 25 m thinning per decade
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- 1 C warming melts 10 m ice

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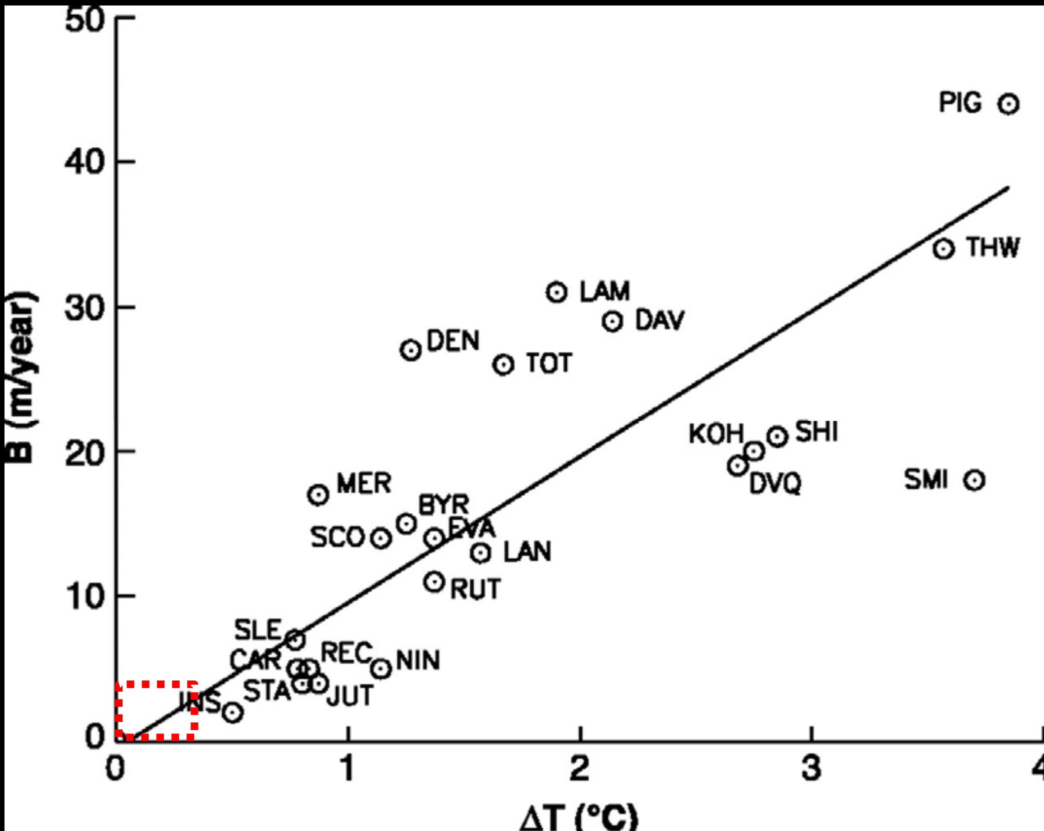

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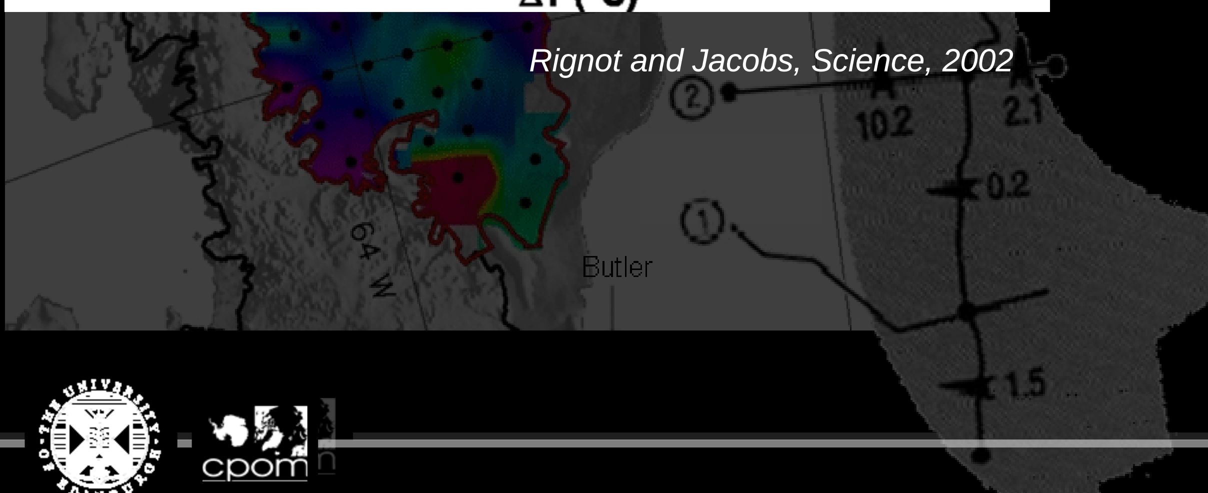

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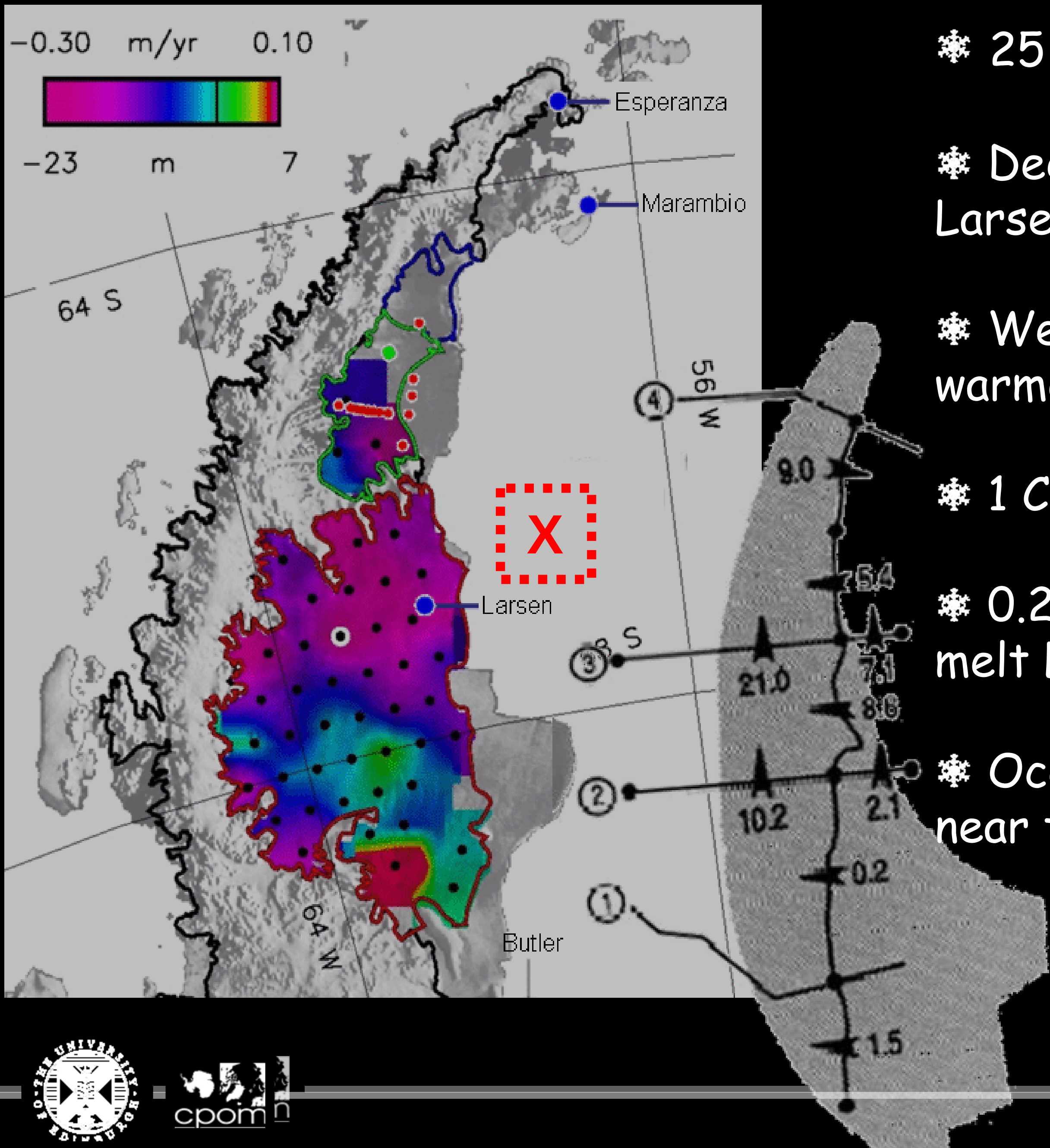
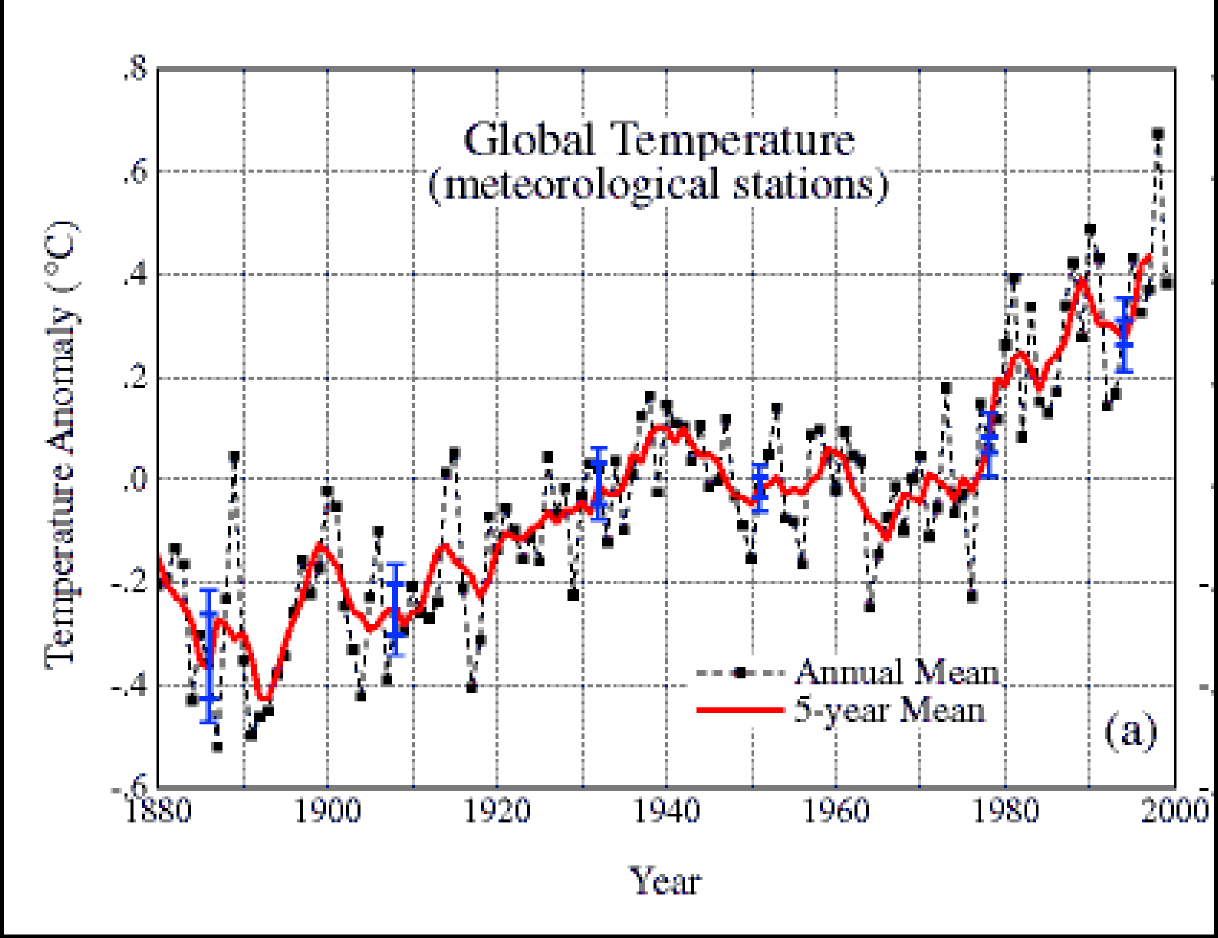


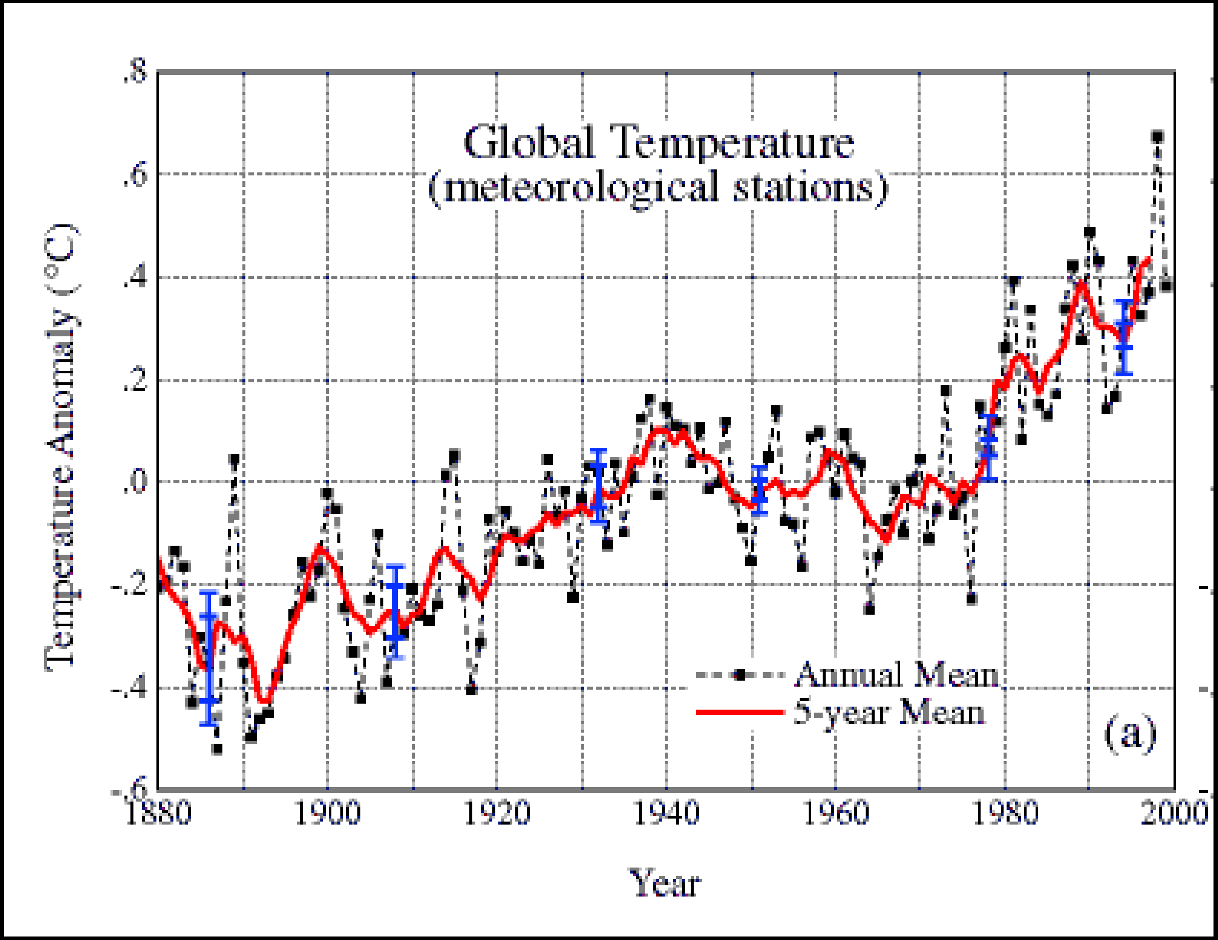
- 25 m thinning per decade
- Deep ocean transport toward Larsen
- Weddell deep water has warmed 0.4 C since 1970
- 1 C warming melts 10 m ice
- 0.25 C warming sufficient to melt Larsen
- Ocean is 0.3 C above freezing near to shelf front

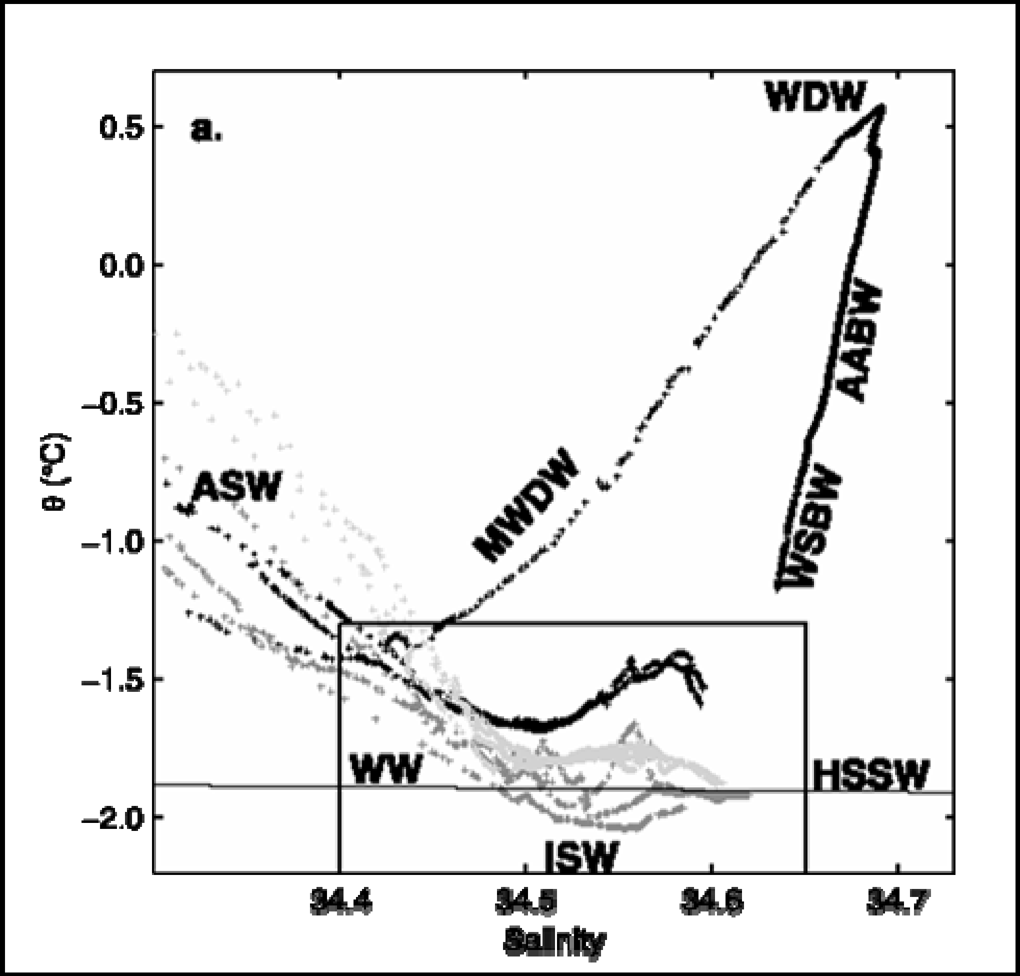
- Such a temperature change is more in line with the 2 C global climate warming over the past century, rather than the 10 C air temperature anomaly.



- Such a temperature change is more in line with the 2 C global climate warming over the past century, rather than the 10 C air temperature anomaly.

- If this is the case, then the ice shelf disintegration and regional climate warming may both be related to fluctuations in the global oceans, and not a local anomaly as was previously thought.

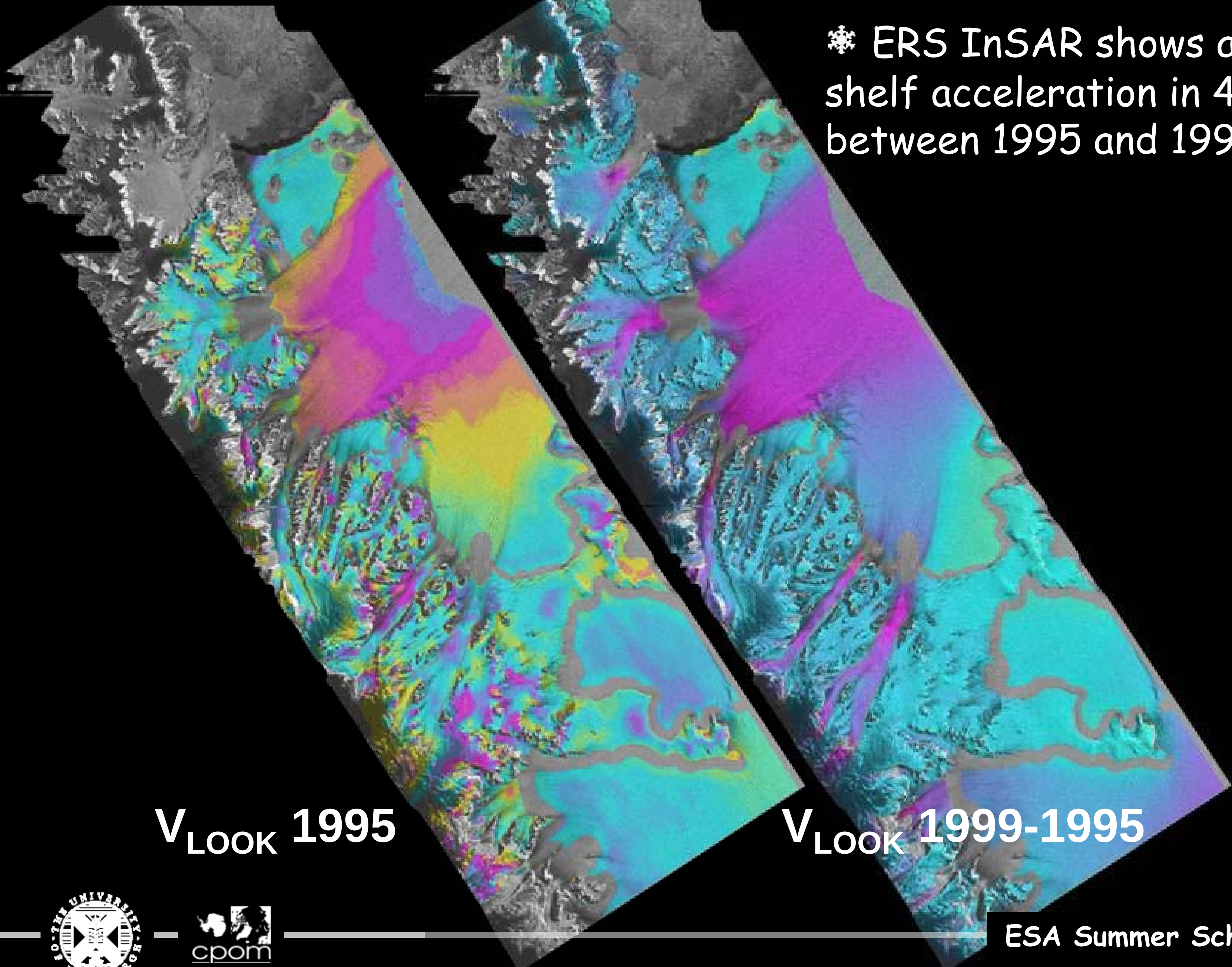




❄ but.... ocean chemistry shows no evidence that warm water infiltrates the submarine cavity beneath Larsen ice shelf

Origin of thinning?

- ERS InSAR shows a 20 % ice shelf acceleration in 4 years between 1995 and 1999

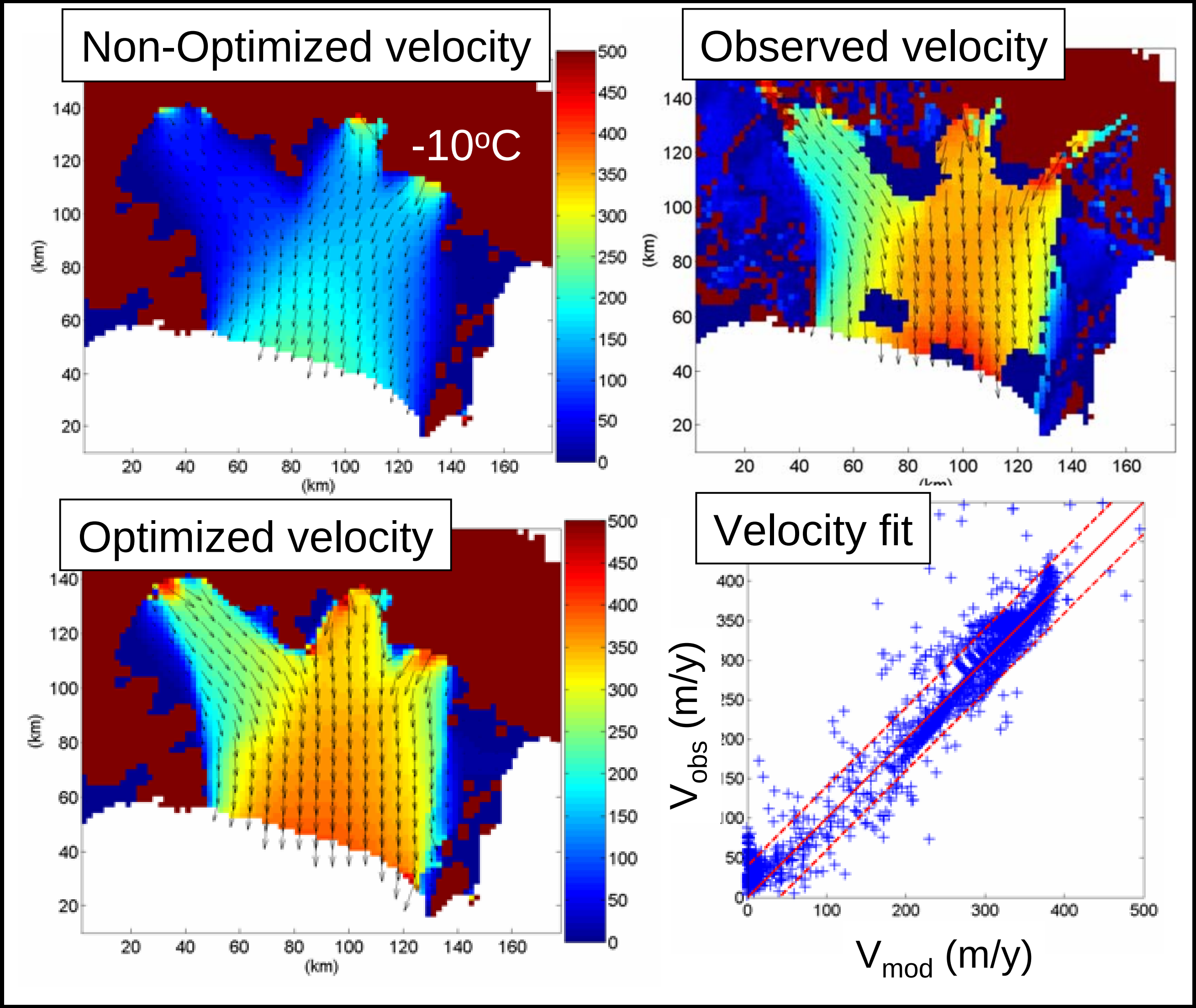


- Assimilate data into a 2D ice flow model to test hypotheses

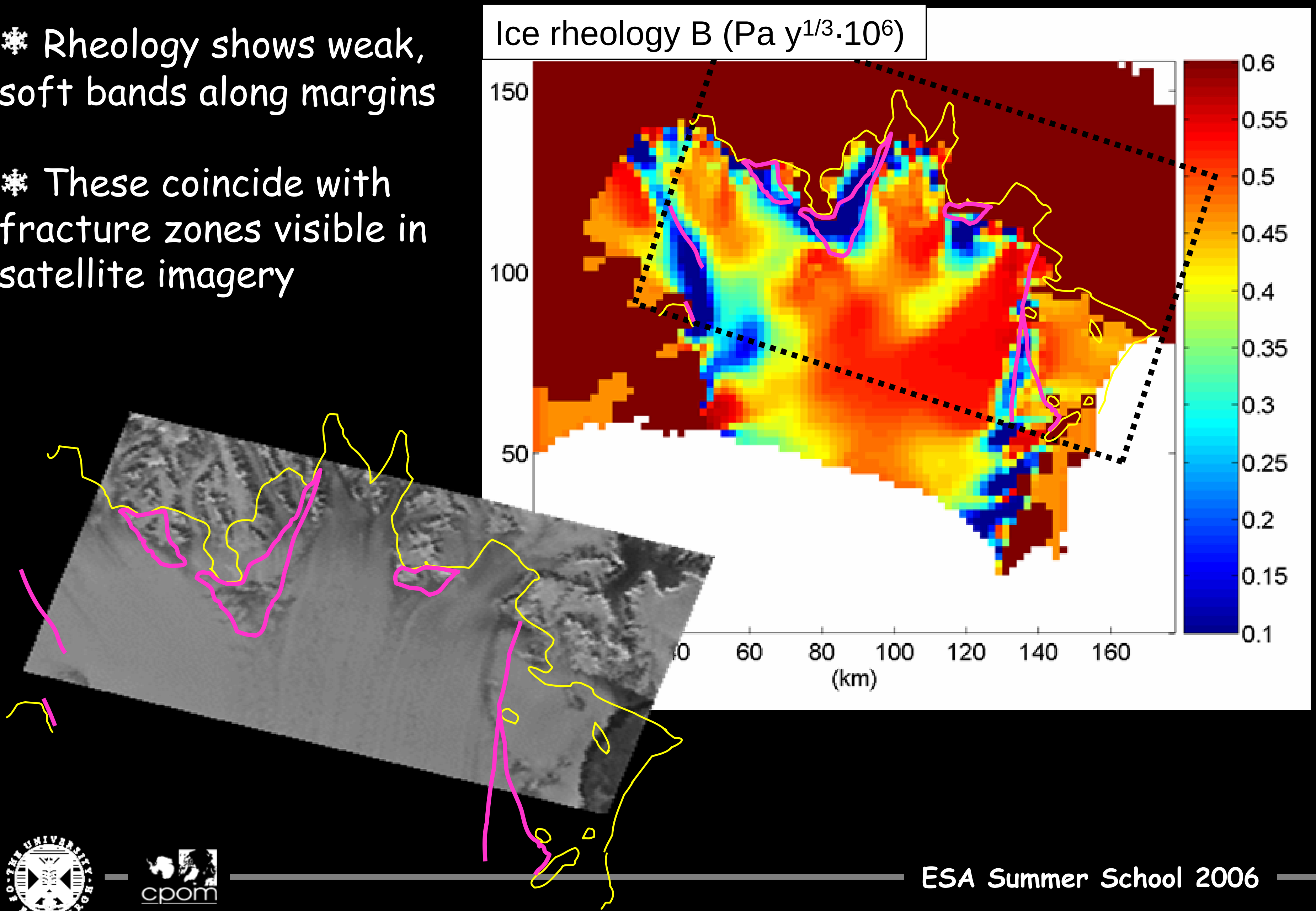
- Simultaneous optimization for rheology & boundary velocity

- Non-optimised flow too slow, with no shear margins

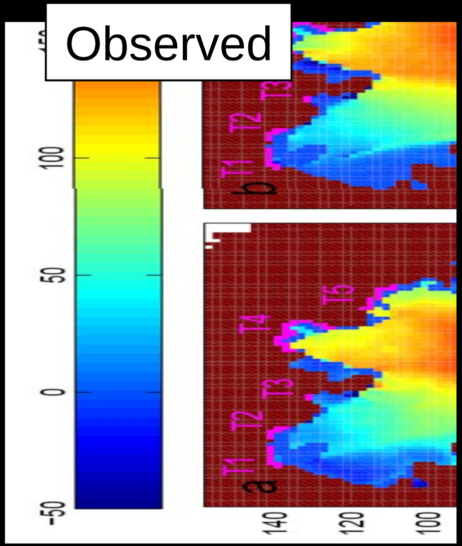
- Optimised flow agrees with spatial pattern & magnitude



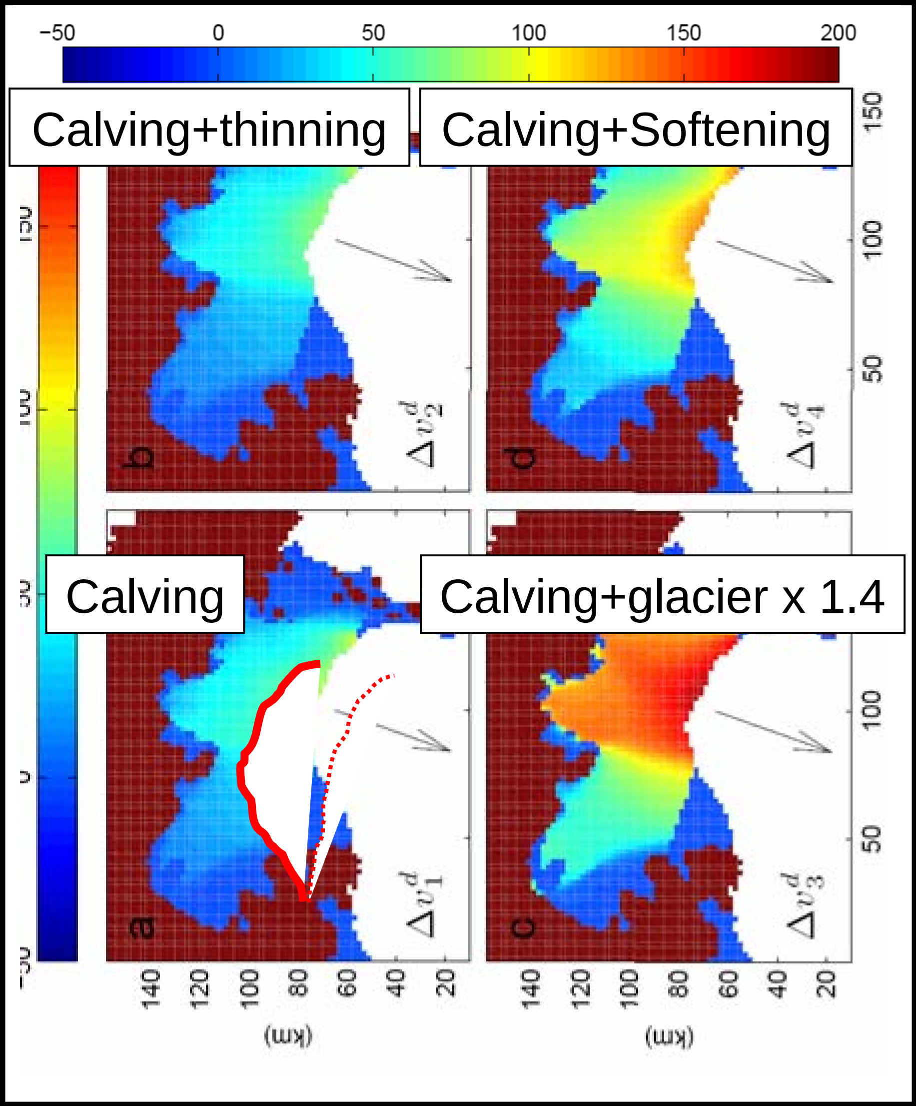
- Rheology shows weak, soft bands along margins
- These coincide with fracture zones visible in satellite imagery



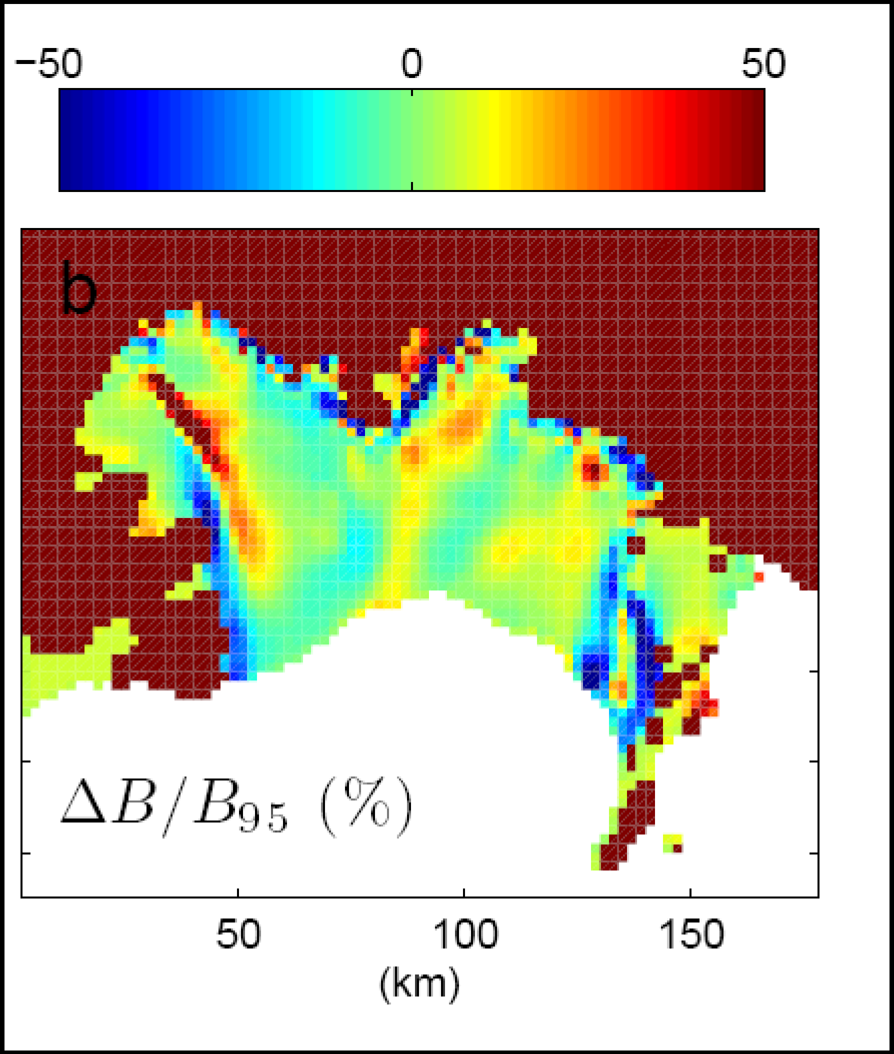
- Potential causes of acceleration



- Calving + softening of shear margins most plausible explanation



- ~ 50 % increase in softening at shear margins yields closest fit to observed acceleration
- Only 20 % of observed thinning is explained by acceleration
- Implies that softening has resulted from a combination of surface and basal melting



- Ice shelf thinning before, during, after collapse
- Uniform, high basal melting unlikely
- Ice shelf accelerated by 20% prior to collapse
- Thinning at odds with acceleration
- Frontal retreat + margin softening explains acceleration
- Flow & collapse mainly controlled by weak zones
- Surface & basal melting weaken margins
- Stability of other ice shelves remains uncertain

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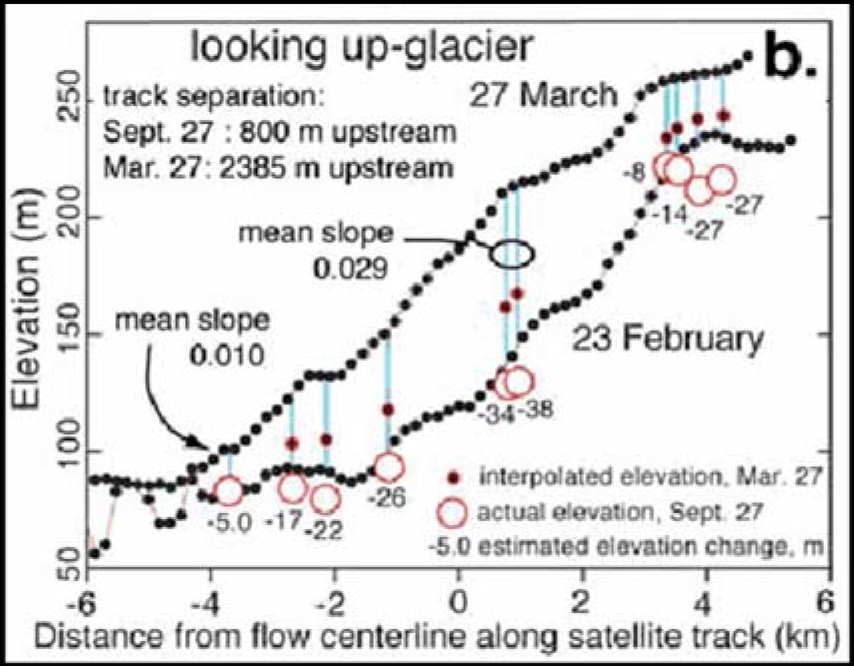
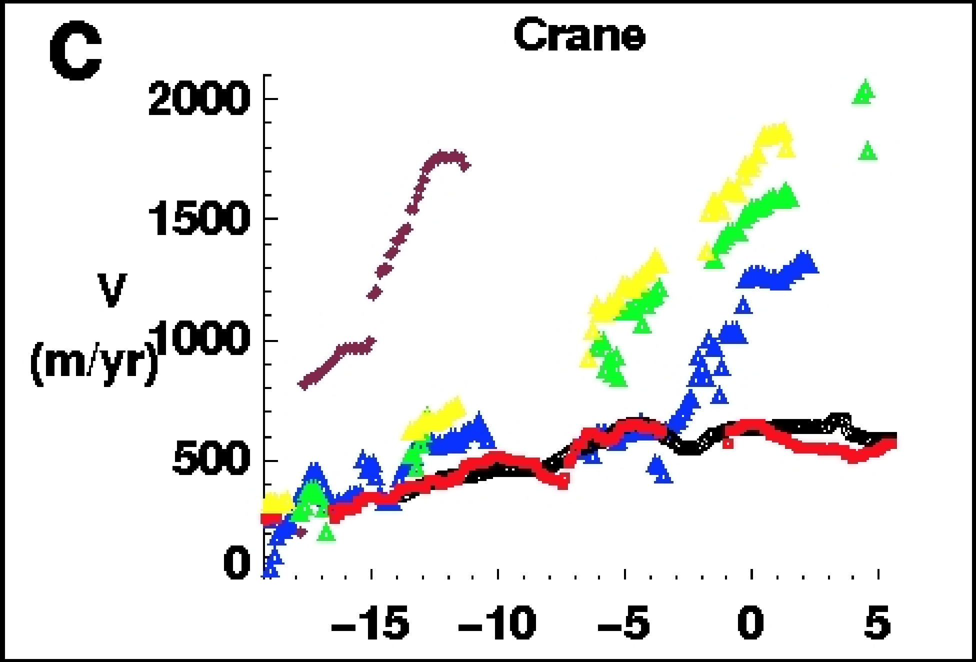


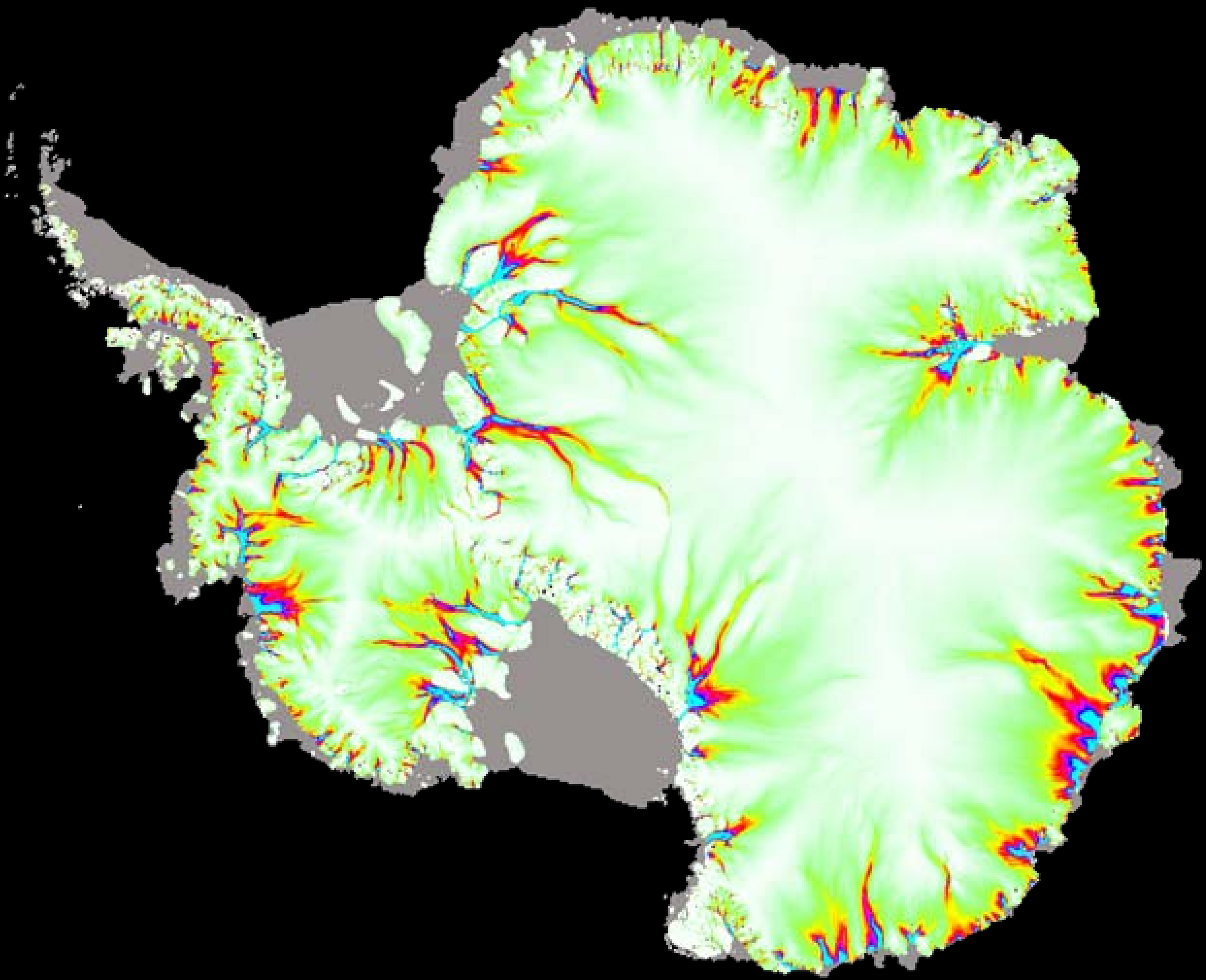
Scambos et al., *GRL*, 2004

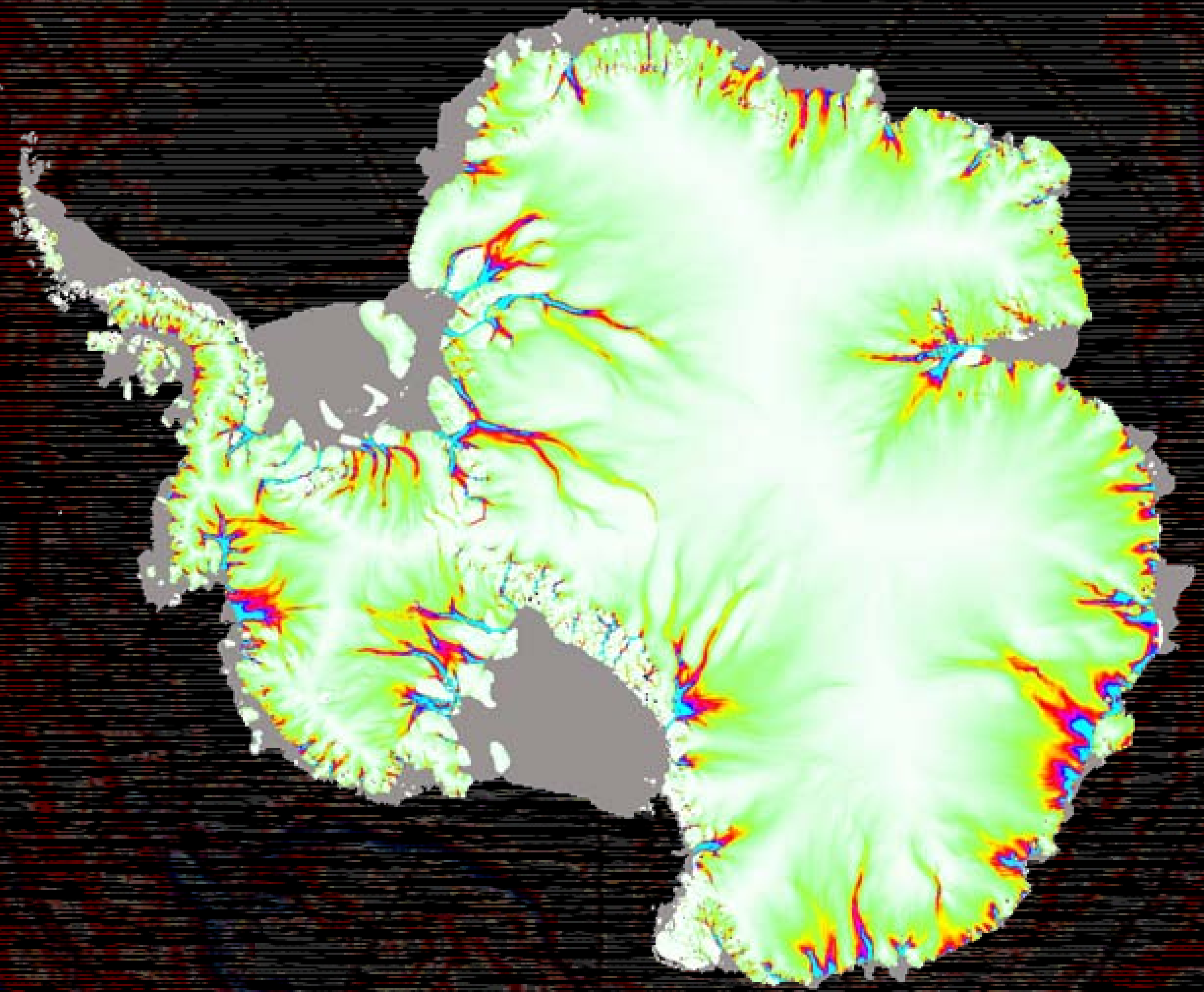


Rignot et al., *GRL*, 2004

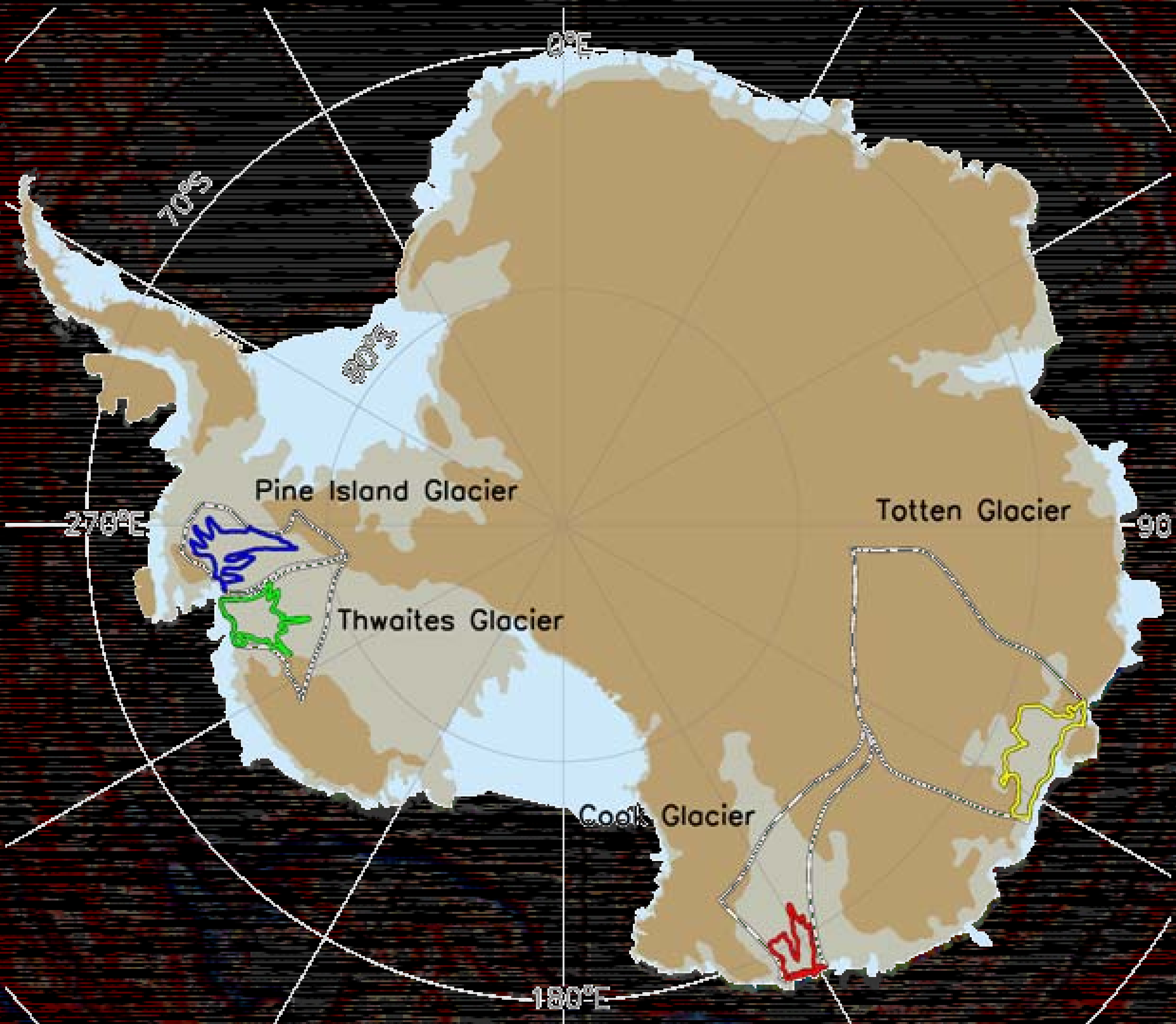
Glacier drawdown after collapse

- Ice shelves fringe Antarctica

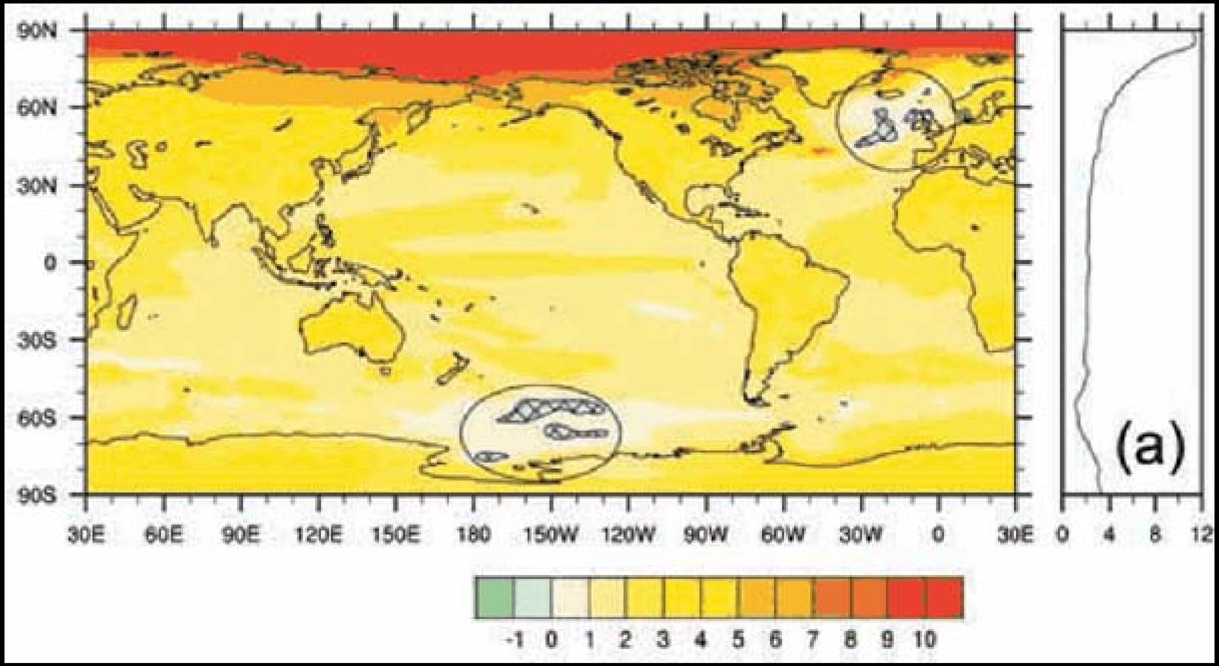




- Ice shelves fringe Antarctica
- CDW nearby several



- Ice shelves fringe Antarctica
- CDW nearby several
- Submarine sectors are all in retreat



Kim et al., *GRL*, 2005

- Ice shelves fringe Antarctica
- CDW nearby several
- Submarine sectors are all in retreat
- Ocean temperatures set to rise
- > 10 m esl exposed