CSIRO

# Seeing below the ice: what progress has been made since 2012?

Steve Rintoul
Antarctic Climate and Ecosystems Cooperative Research Centre
Centre for Southern Hemisphere Oceans Research
CSIRO Oceans & Atmosphere
Hobart, Tasmania , Australia
steve.rintoul@csiro.au

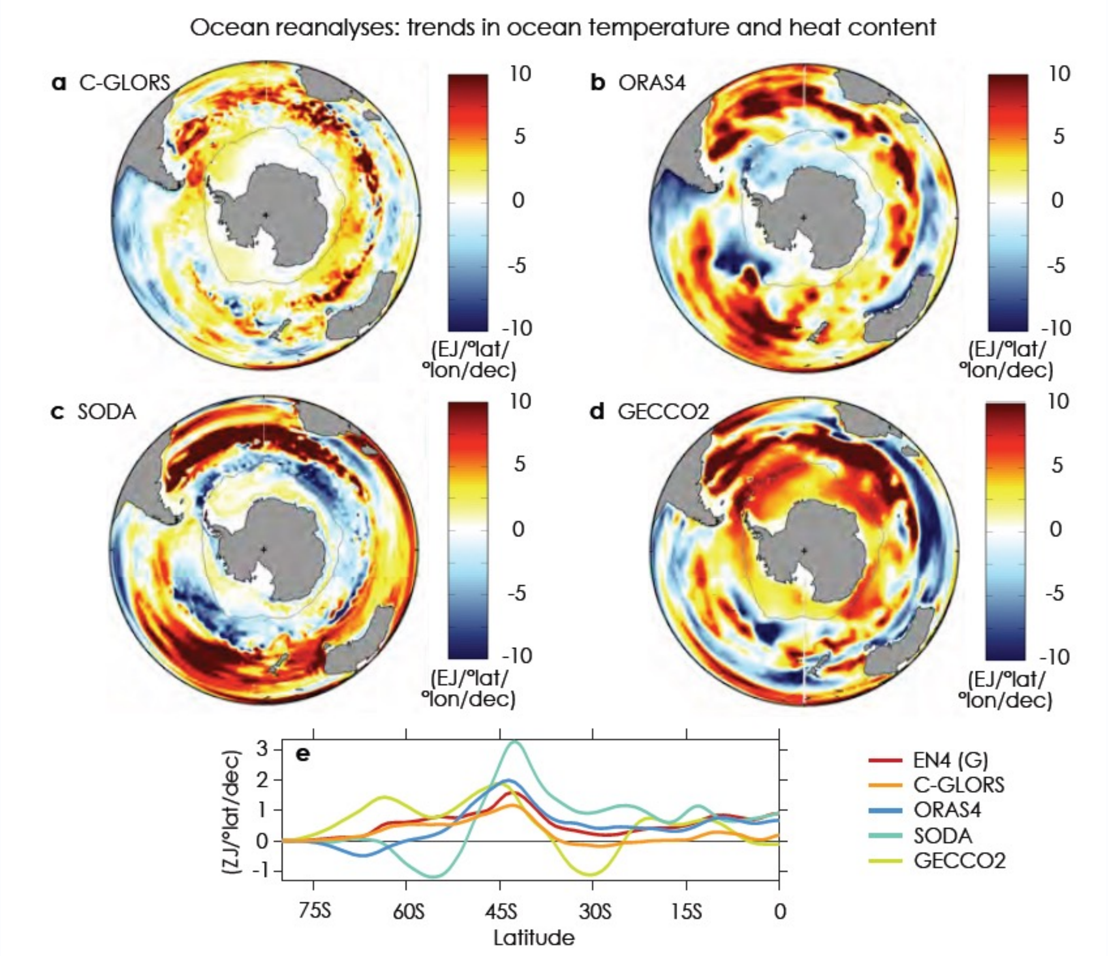
ANTARCTIC GATEWAY PARTNERSHIP
A Special Research Initiative of the Australian Research Council

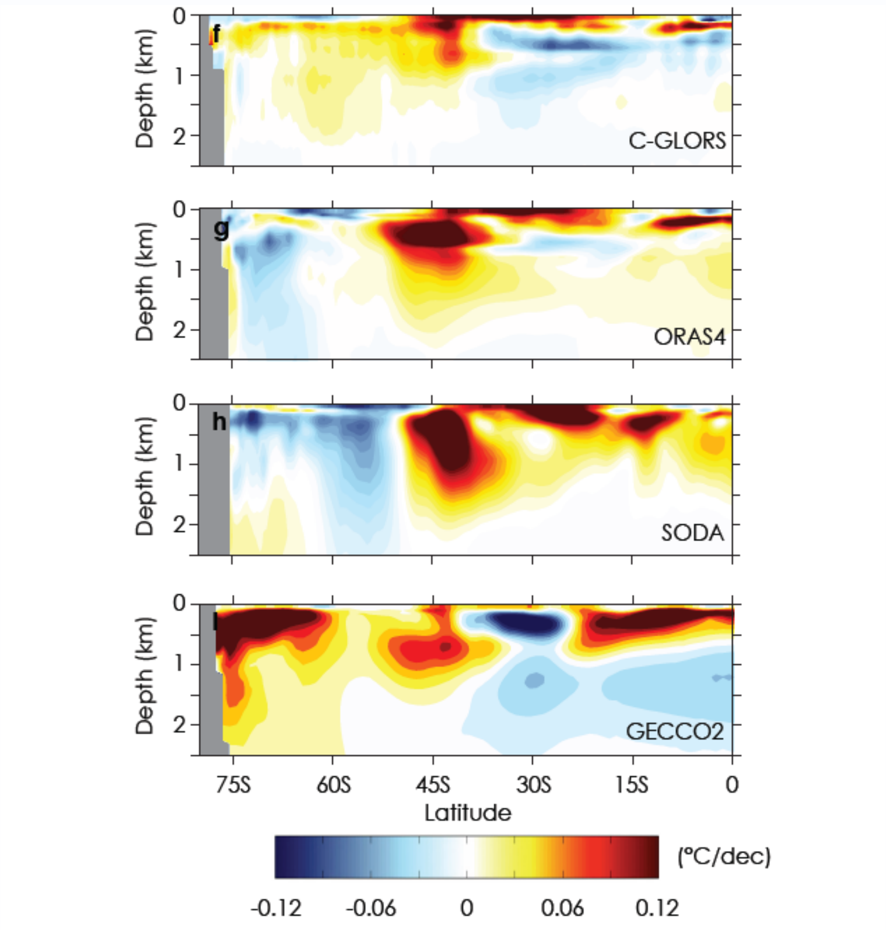
ACE CRC
ANTARCTIC CLIMATE & ECOSYSTEMS COOPERATIVE RESEARCH CENTRE

www.csiro.au

# Theme 1: Circulation and heat/freshwater/carbon inventory

# Southern Ocean heat content & temperature trends



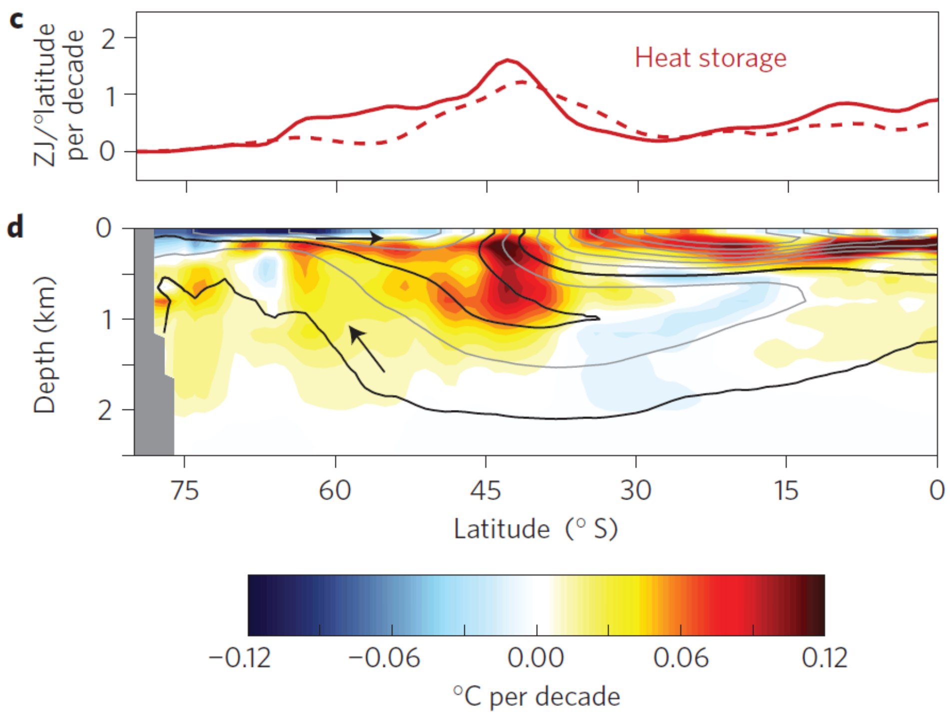





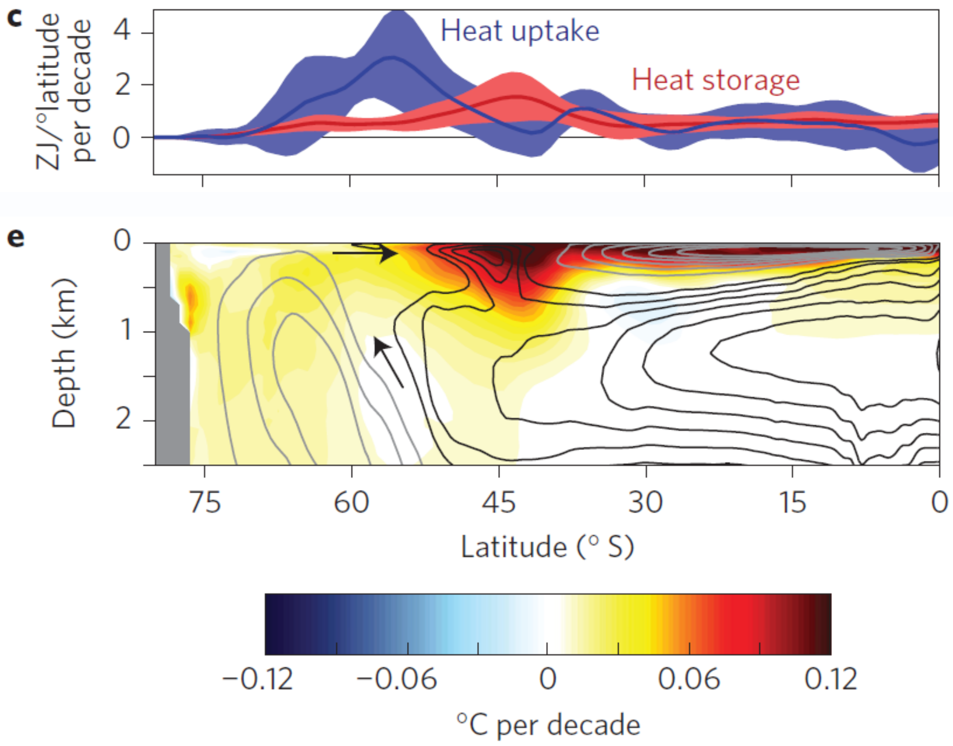

Armour et al., Nature Geoscience, 2016 (Suppl. Mat.)

# Heat uptake south of ACC, heat storage north of ACC

Observations



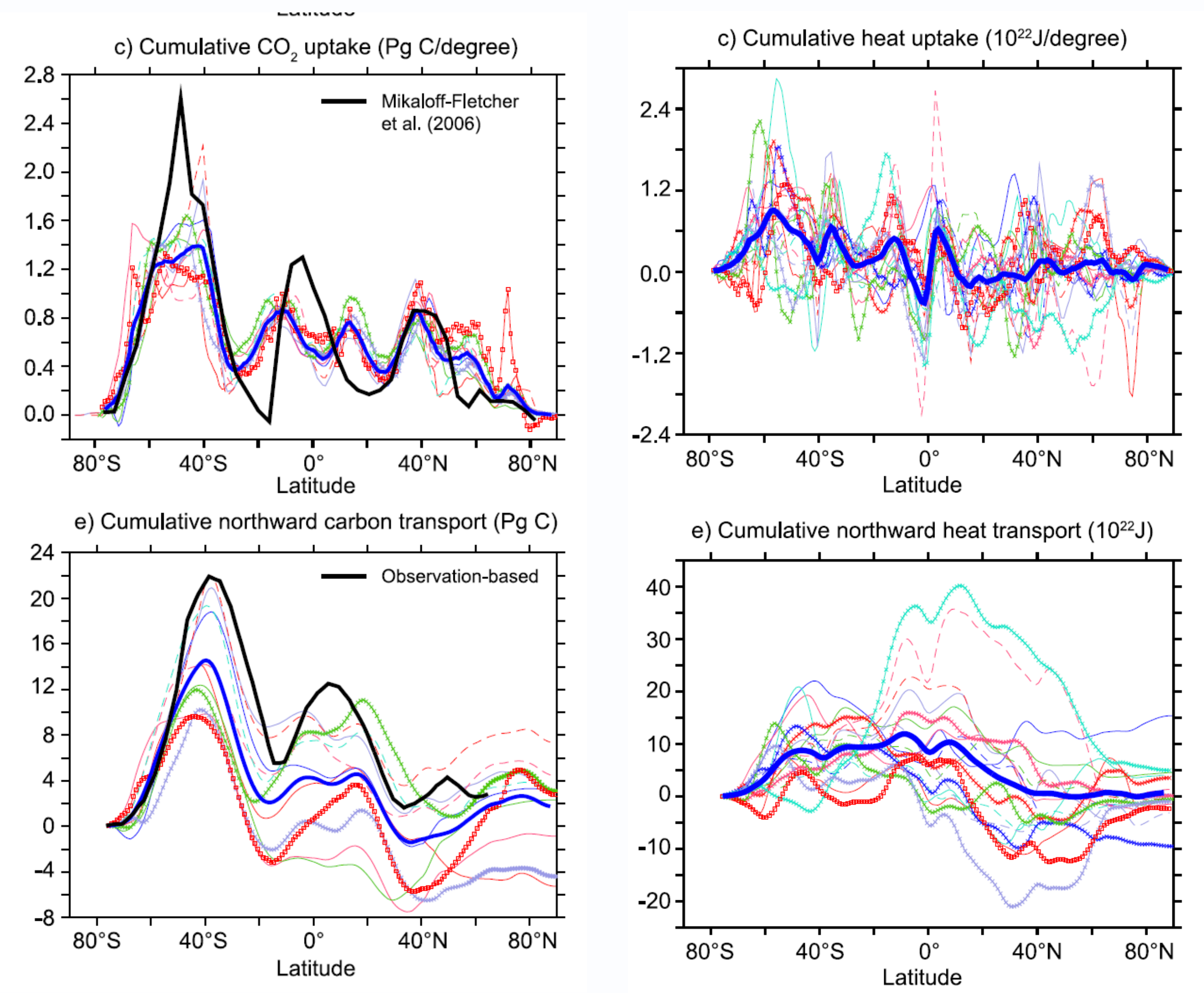

Models




Armour et al., Nature Geoscience, 2016

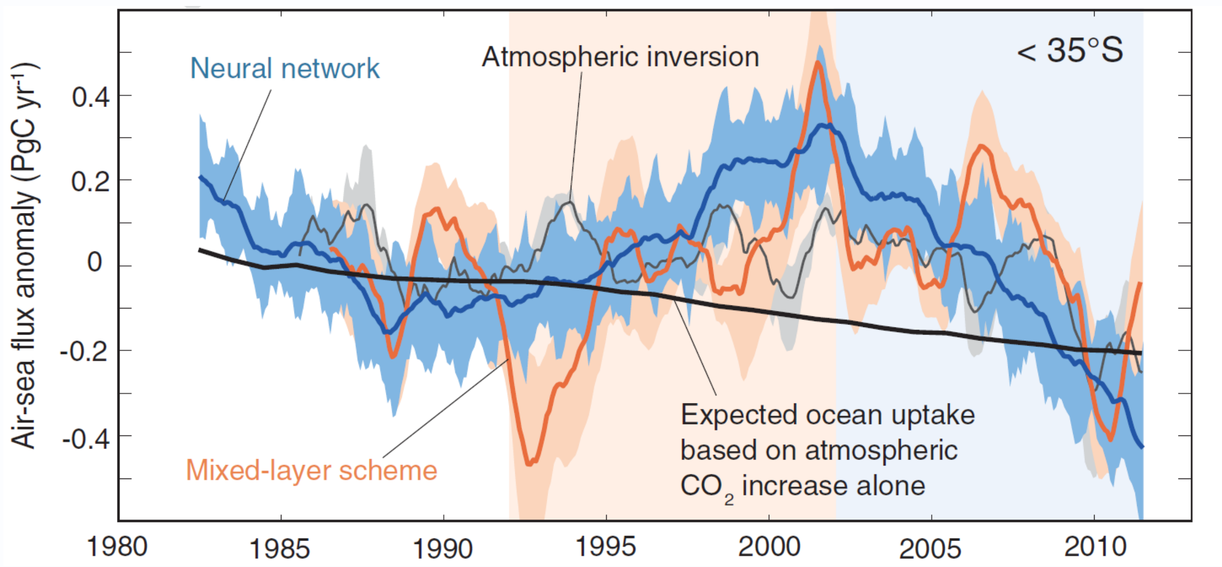
# Southern Ocean dominance in ocean heat and carbon uptake

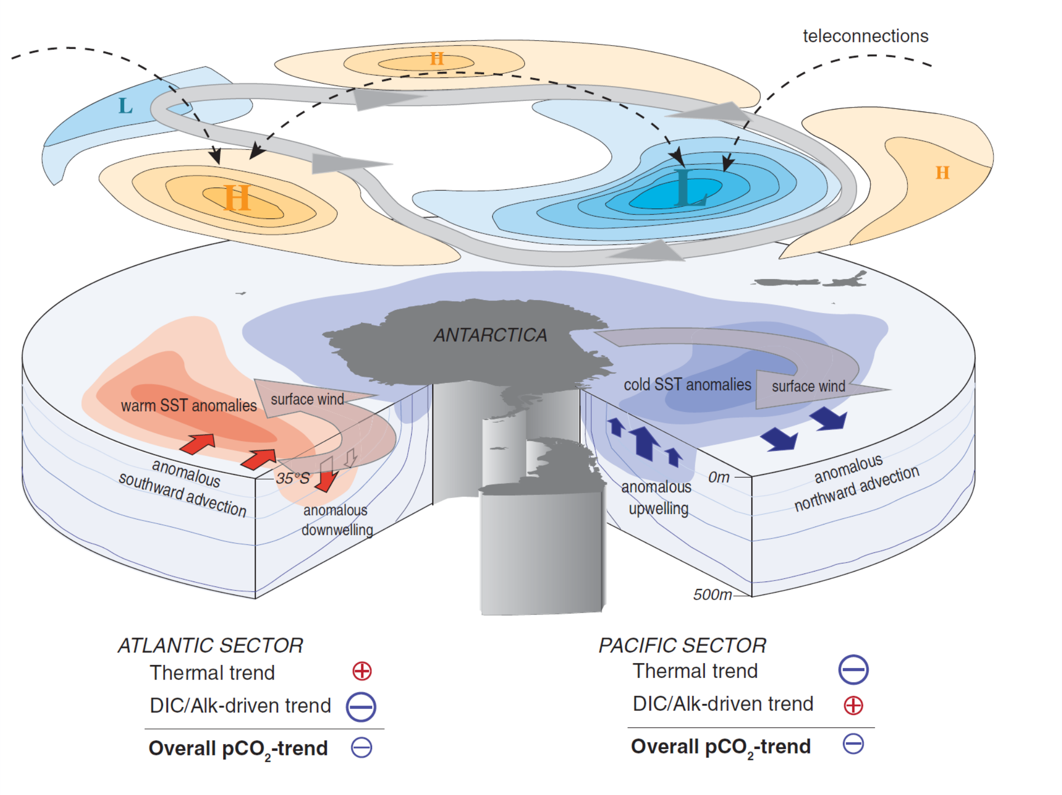
Southern Ocean accounts for 42% of anthropogenic carbon uptake, and 75% of anthropogenic heat uptake.




Frölicher et al., JCLIM, 2015

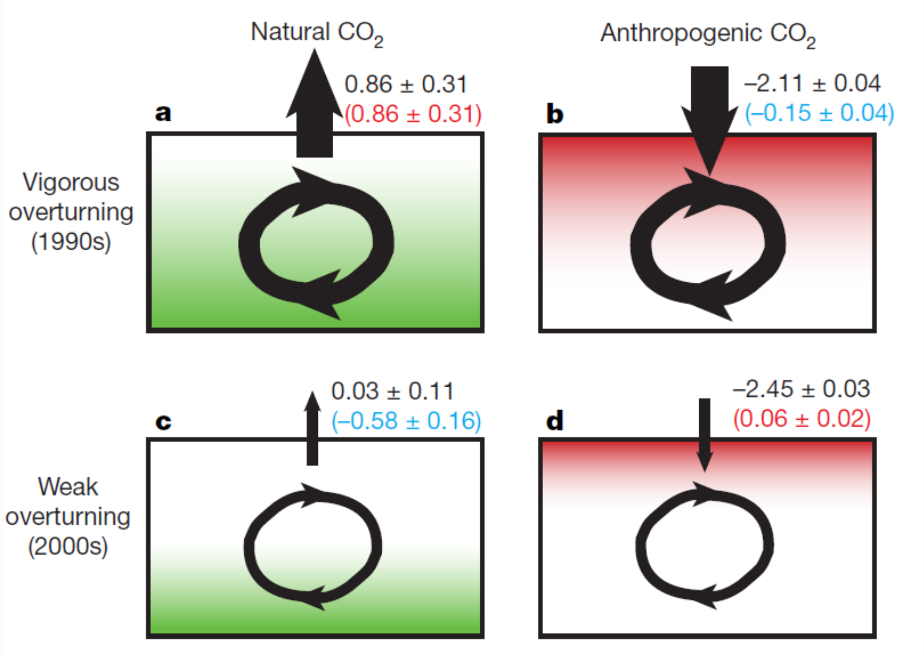
# “Reinvigoration” of Southern Ocean carbon sink



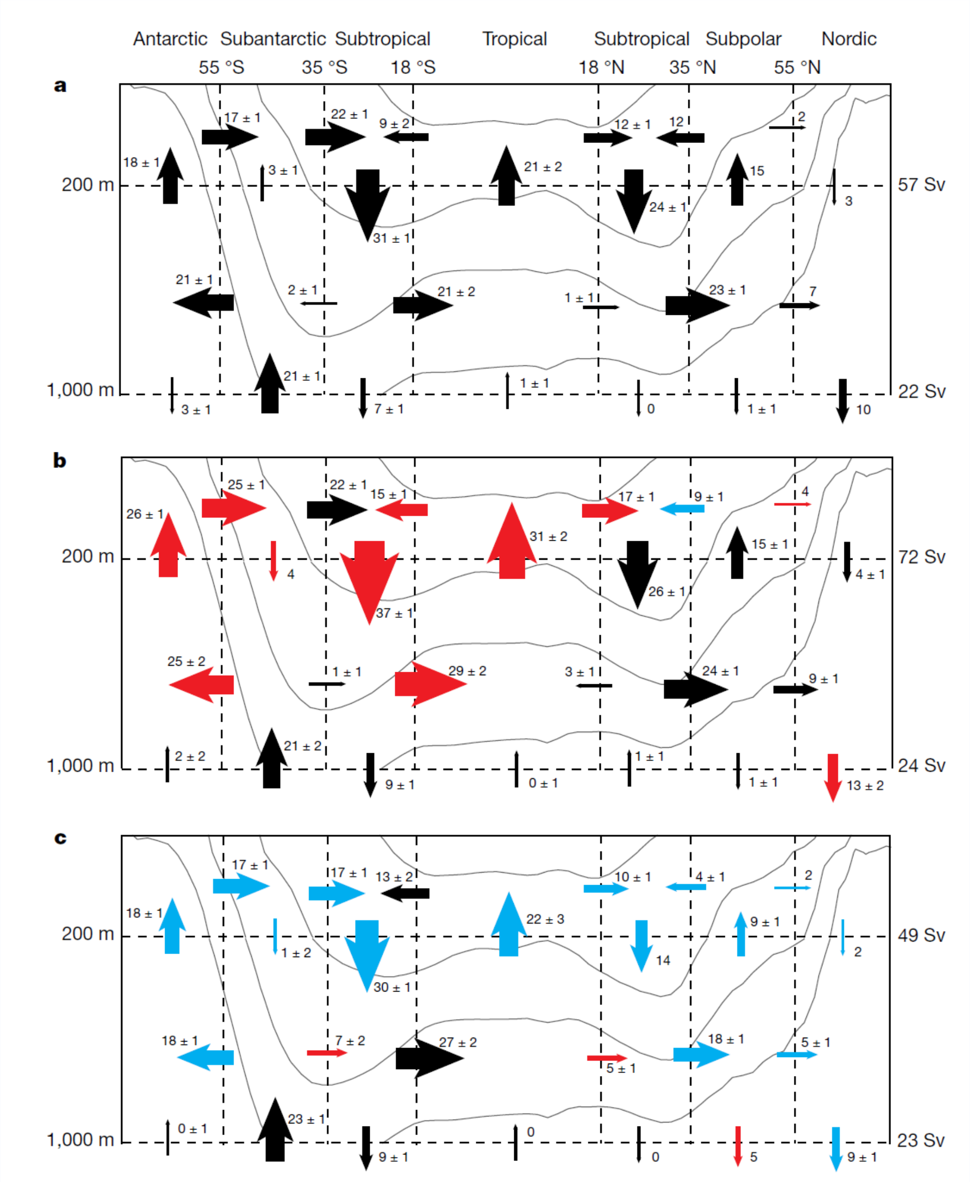




Landschutzer et al., 2016

# Weaker upper cell drives increase in ocean carbon storage in 2000s

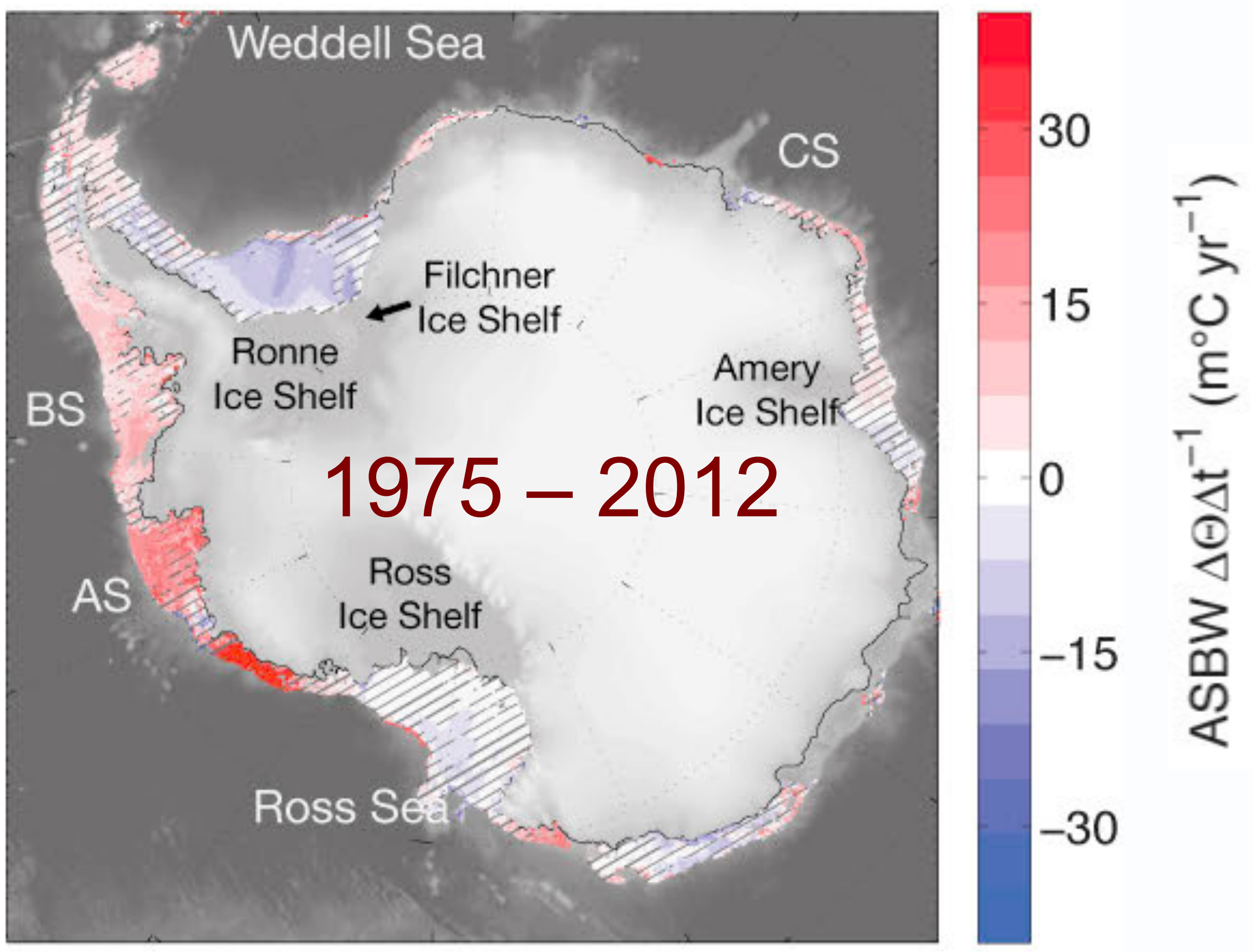



*"To track the timing and magnitude of these effects, the variability of the ocean circulation and CO2 uptake must be monitored carefully over time."*




DeVries et al., Nature, 2017

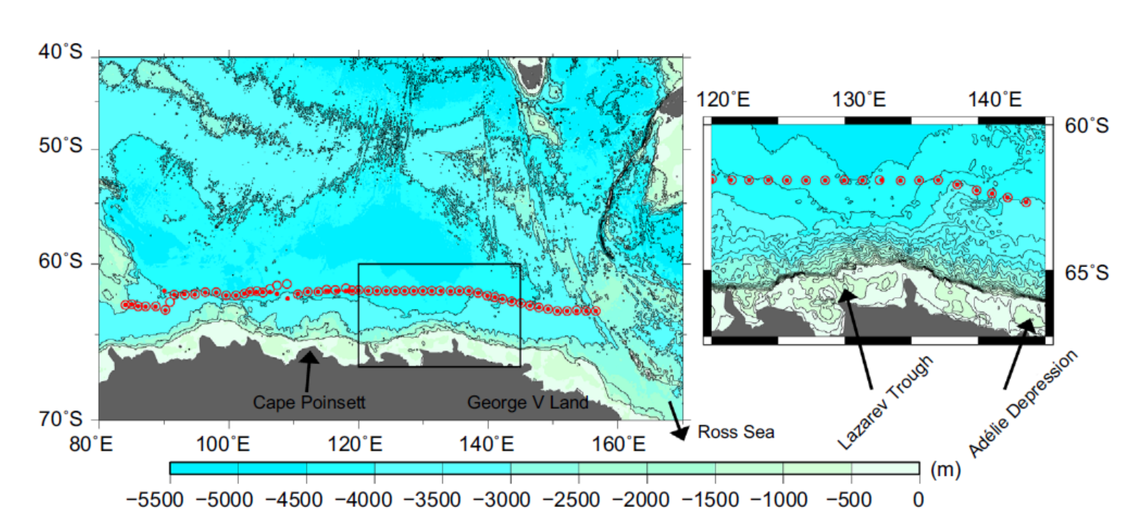
# Trend in Antarctic continental shelf bottom water

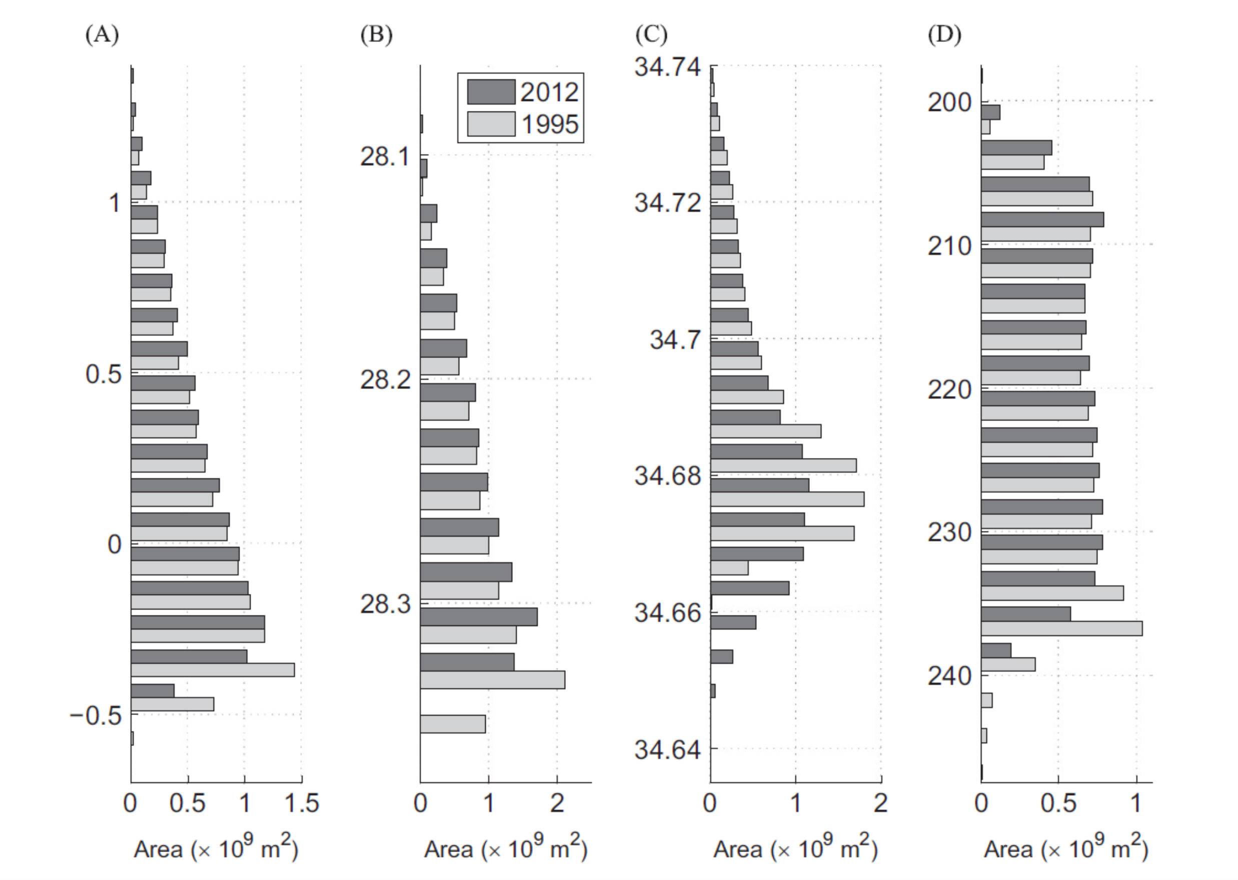





Schmidtko et al. 2014

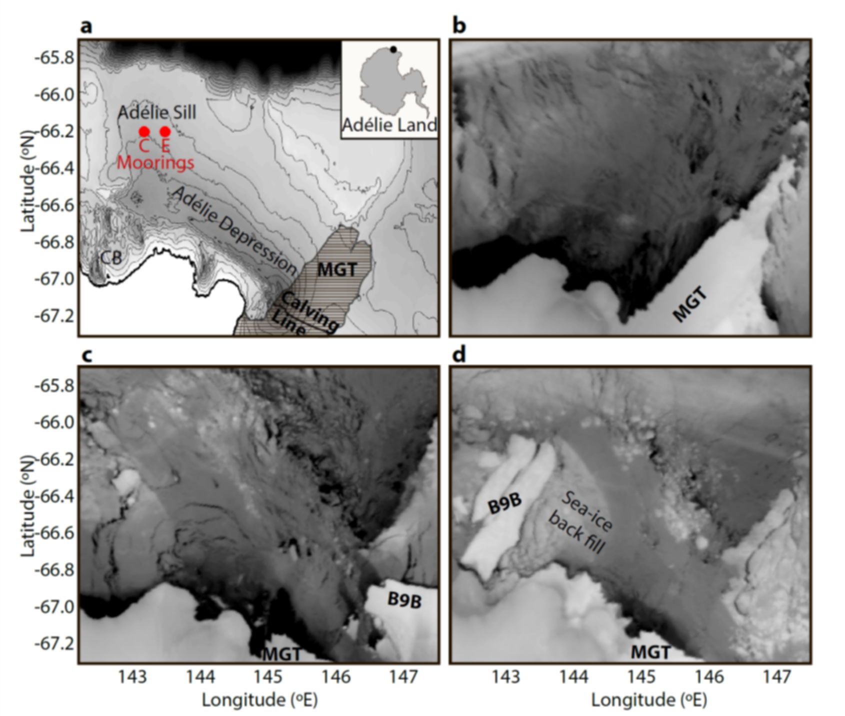
# Warming, freshening and contraction of AABW

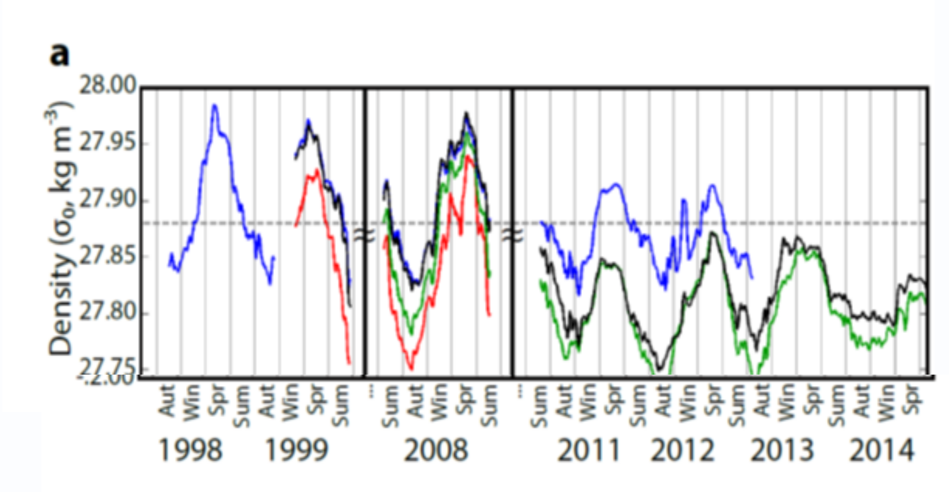


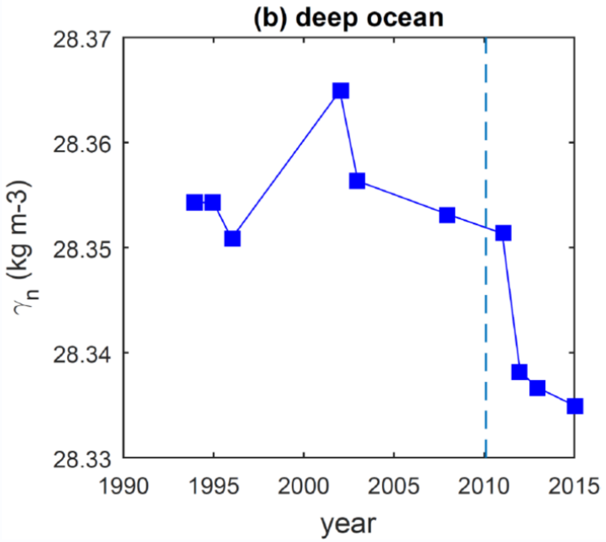



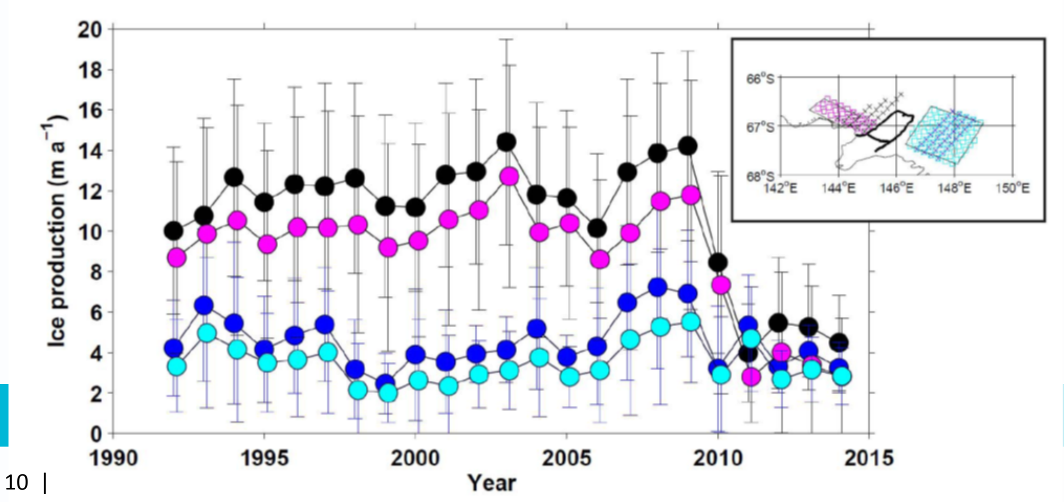

Katsumata et al., DSR-II, 2015

# Sensitivity of bottom water formation to forcing



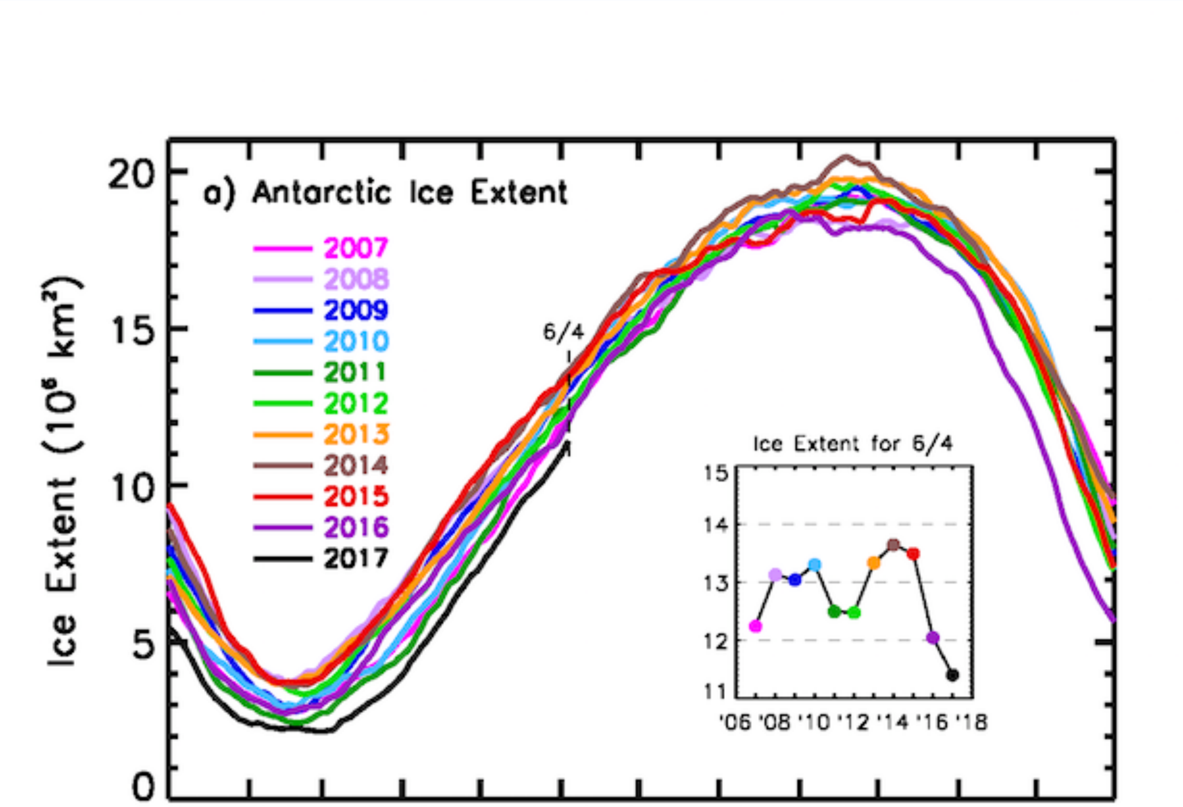






Snow et al., submitted

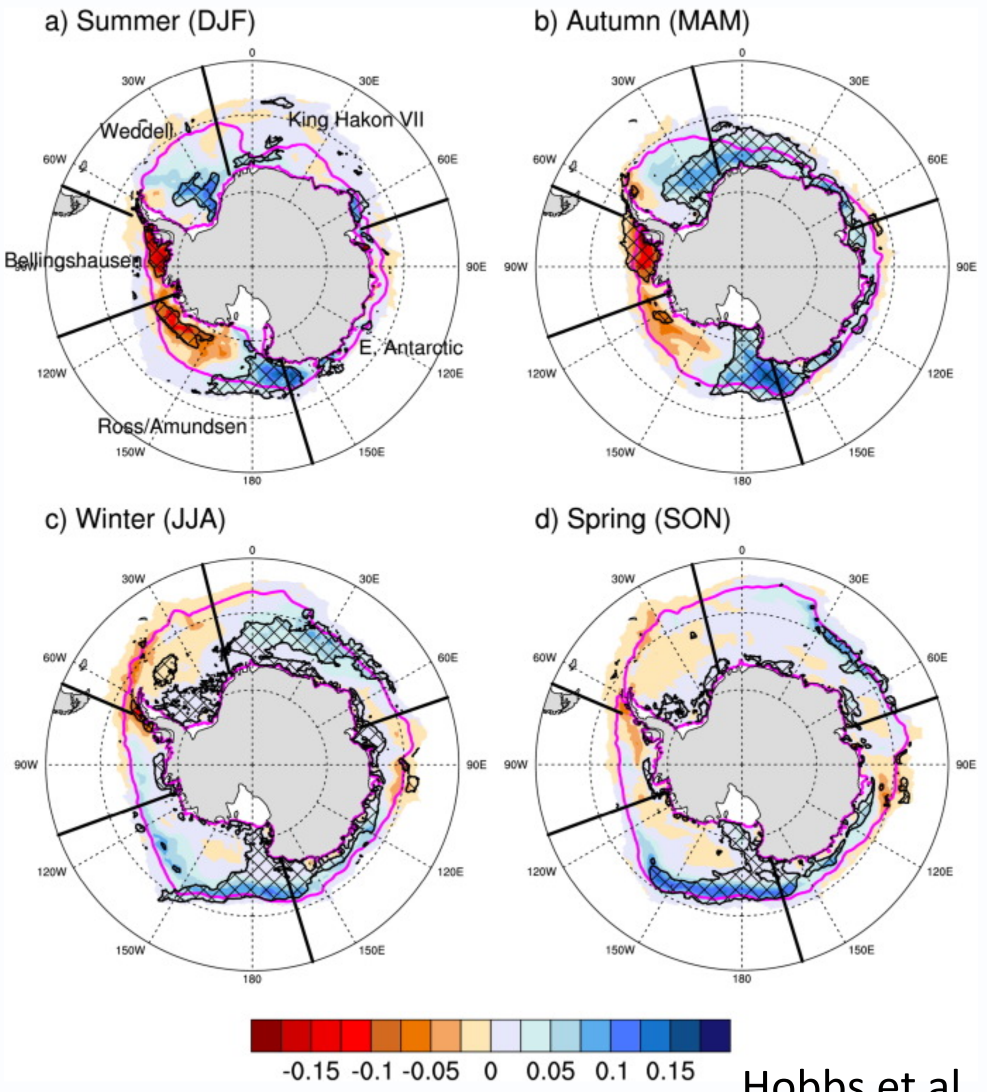
# Theme 2: ocean – sea ice interaction

# Antarctic sea ice




https://neptune.gsfc.nasa.gov/csb/index.php?section=234

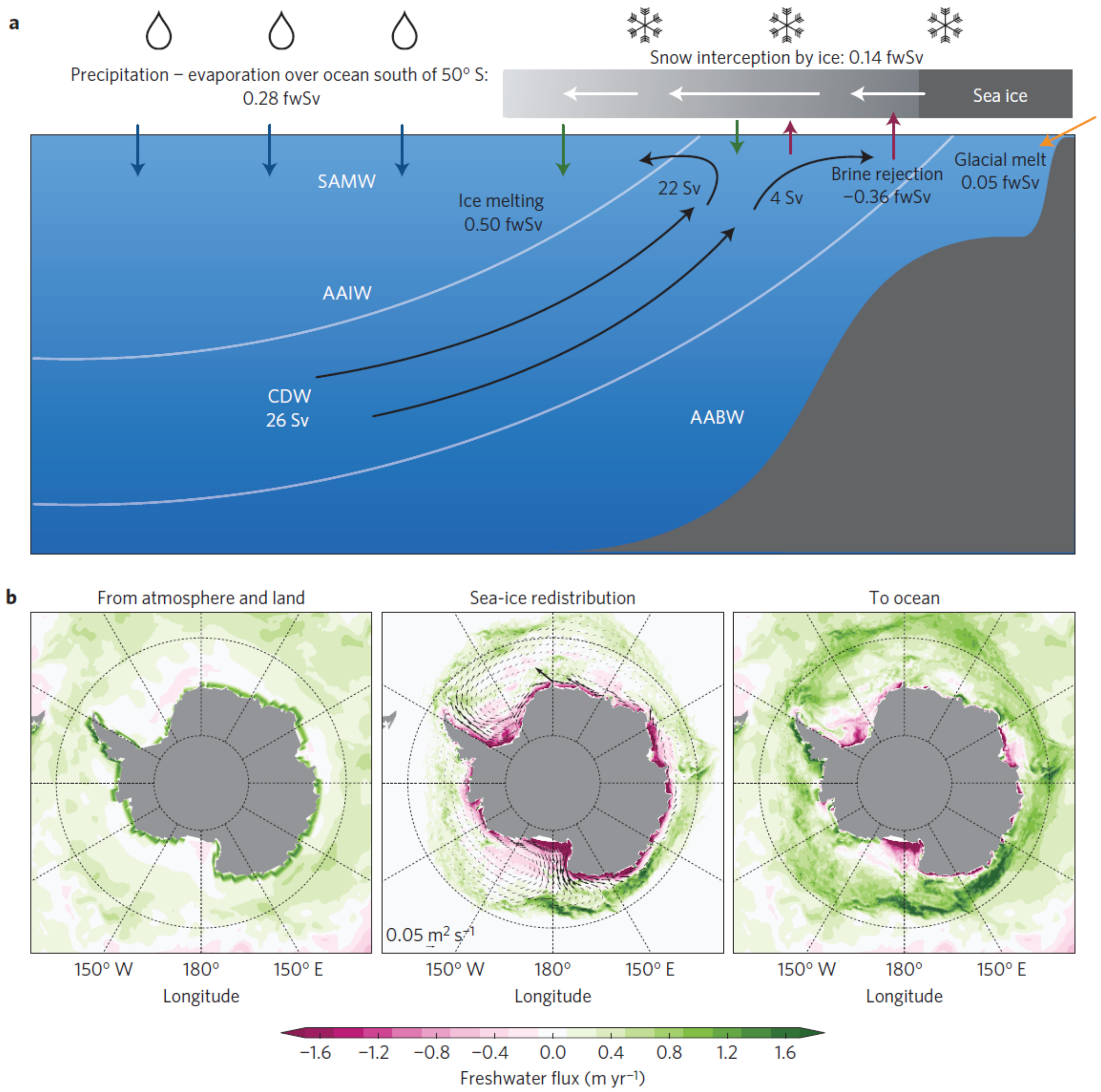
Sea ice concentration trends (fraction/decade)




Hobbs et al., 2016

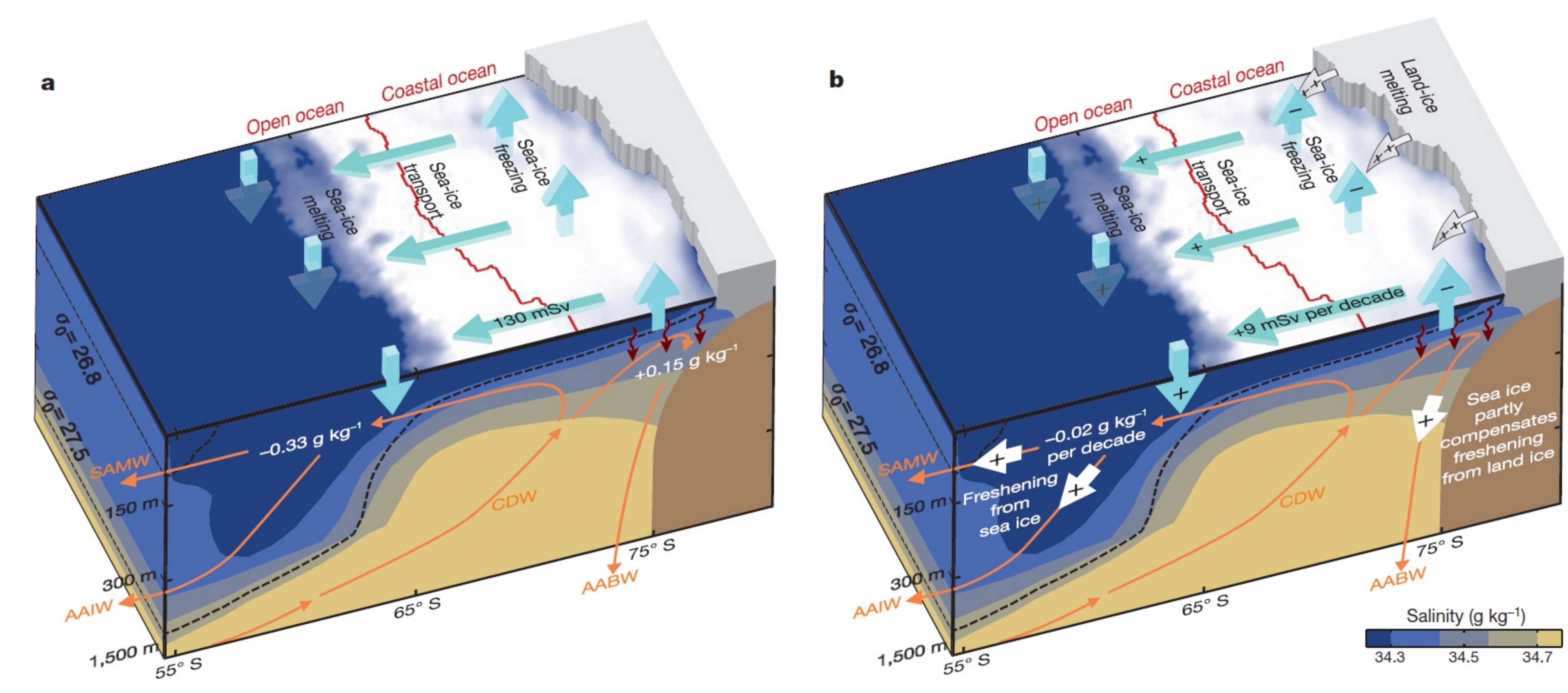
# Water mass transformation by the sea ice freshwater conveyor belt

*"The intricate, temporally variable relationship between ice formation, freshwater fluxes, and mixing highlights the need for year-round observations to accurately quantify the net water-mass transformation driven by sea-ice processes."*



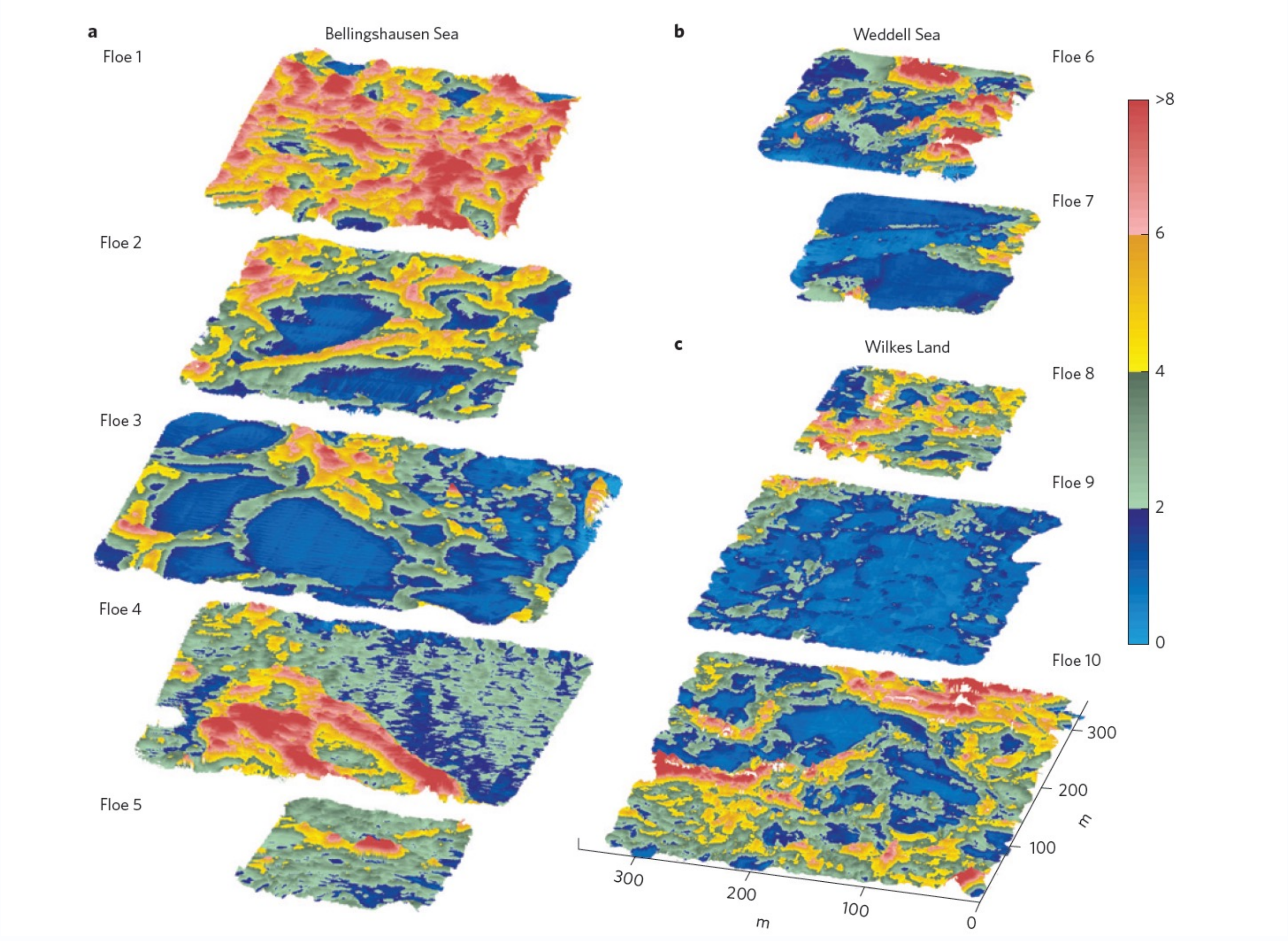

Abernathey et al., Nature Geoscience, 2016

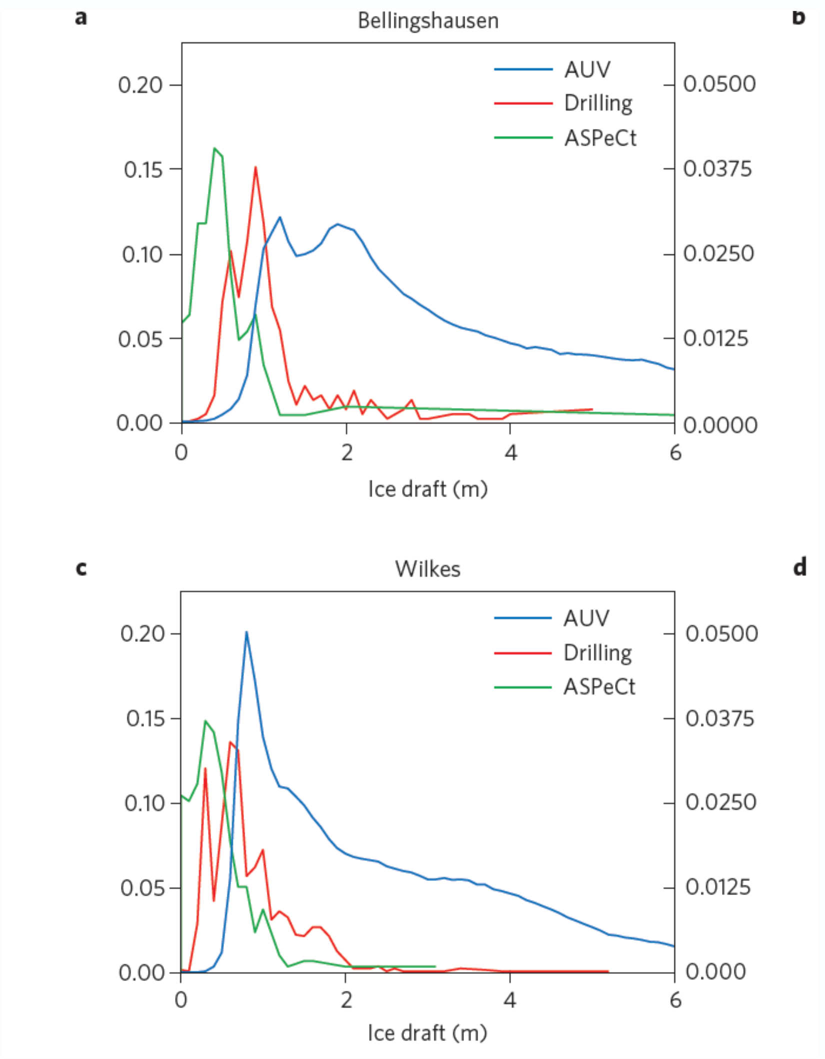
# Increased sea ice transport explains freshening trends




Haumann et al., Nature, 2016

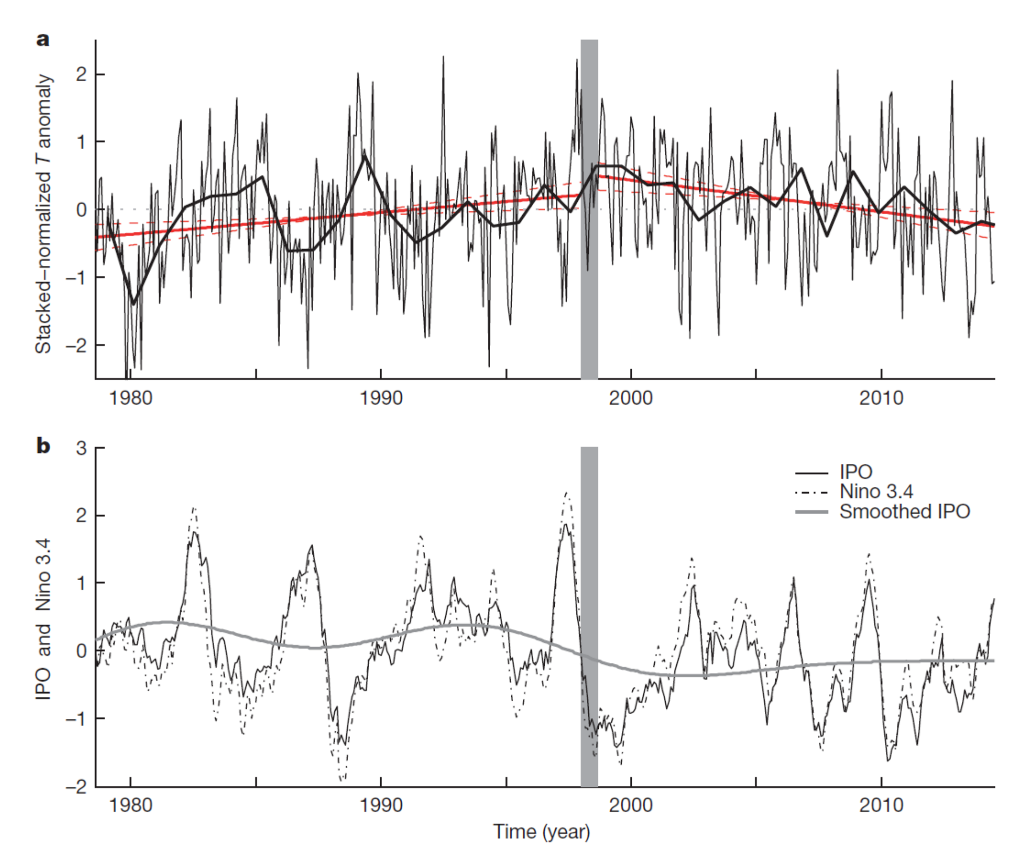
# How thick is Antarctic sea ice?

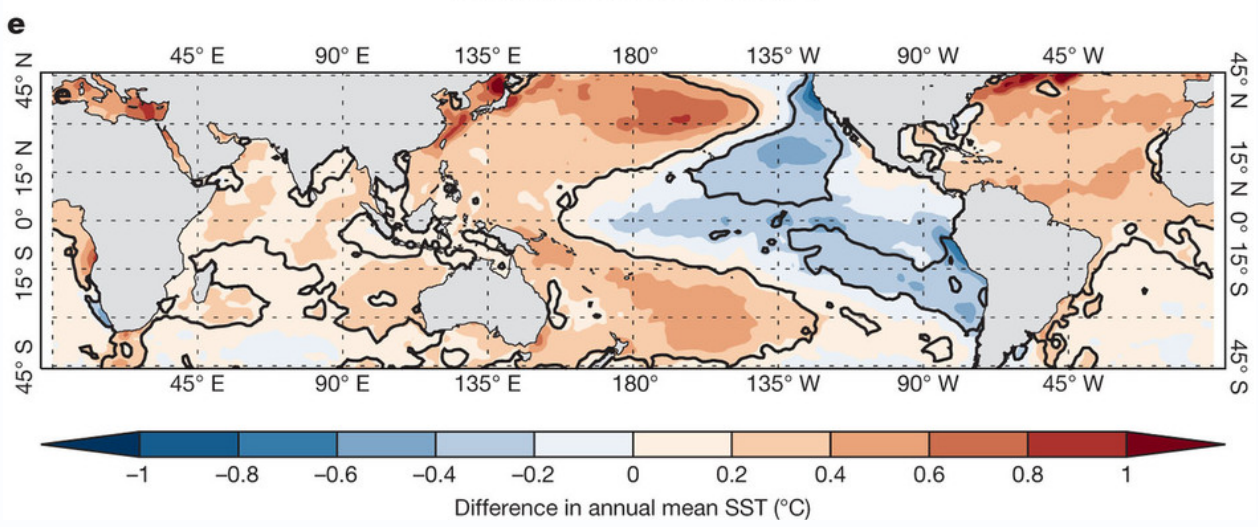



Williams et al., Nature Geoscience, 2015

# Natural variability and teleconnections






Turner et al., Nature, 2016

# Theme 3: Ocean – ice shelf interaction

# Marine Ice Sheet Instability underway in West Antarctica?

**Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011**

E. Rignot[1,2], J. Mouginot[1], M. Morlighem[1], H. Seroussi[2], and B. Scheuchl[1]

GRL, 2014

**Marine Ice Sheet Collapse Potentially Underway for the Thwaites Glacier Basin, West Antarctica**

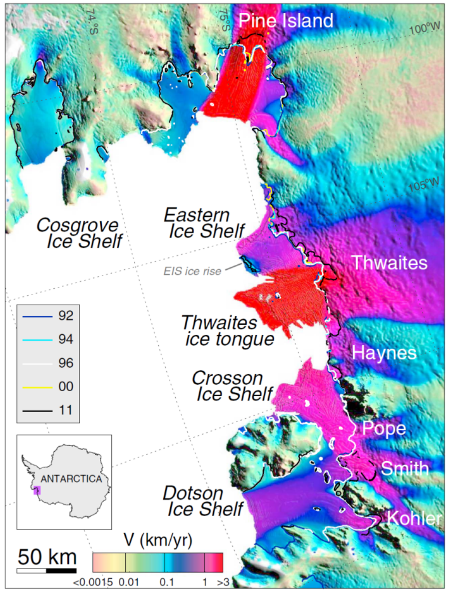
Ian Joughin,* Benjamin E. Smith, Brooke Medley

Science, 2014

**Retreat of Pine Island Glacier controlled by marine ice-sheet instability**

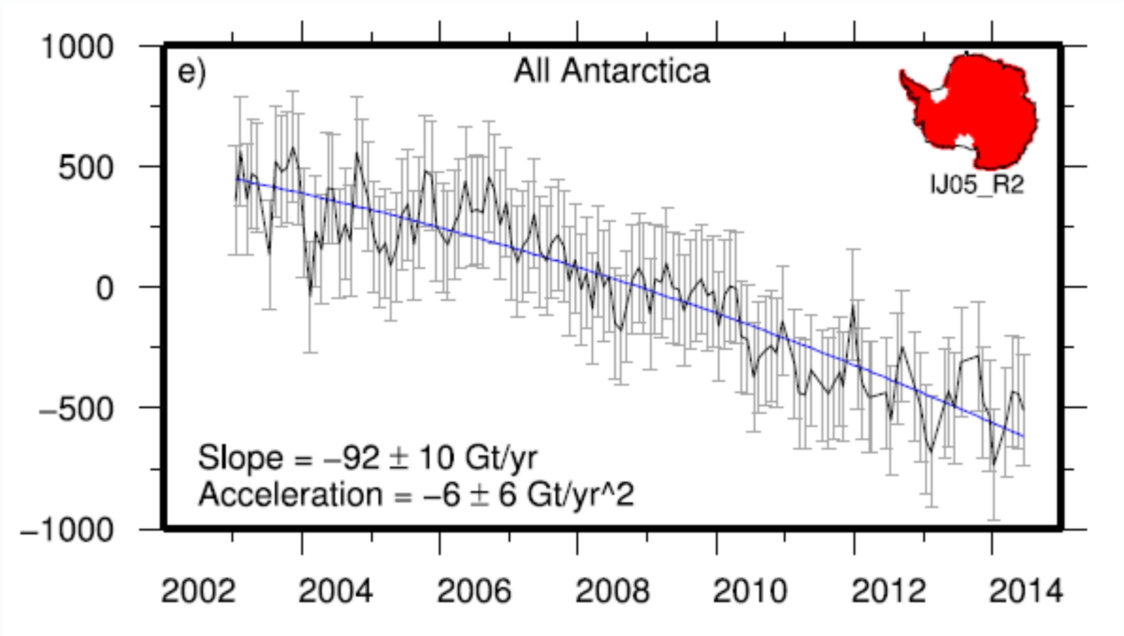
L. Favier[1,2], G. Durand[1,2]*, S. L. Cornford[3], G. H. Gudmundsson[4,5], O. Gagliardini[1,2,6], F. Gillet-Chaulet[1,2], T. Zwinger[7], A. J. Payne[3] and A. M. Le Brocq[8]

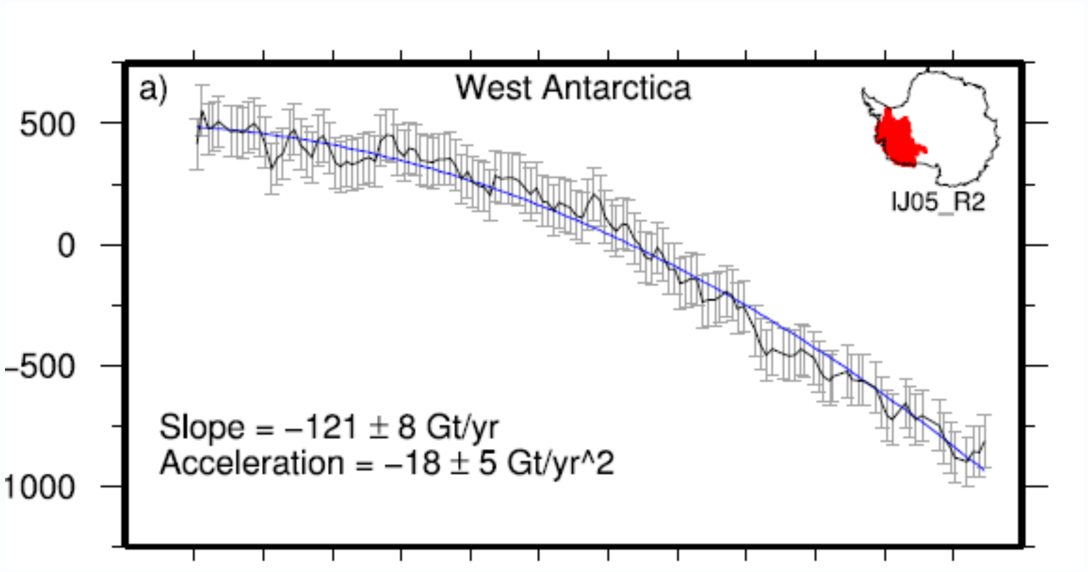
Nature Climate Change, 2014




Rignot et al 2014

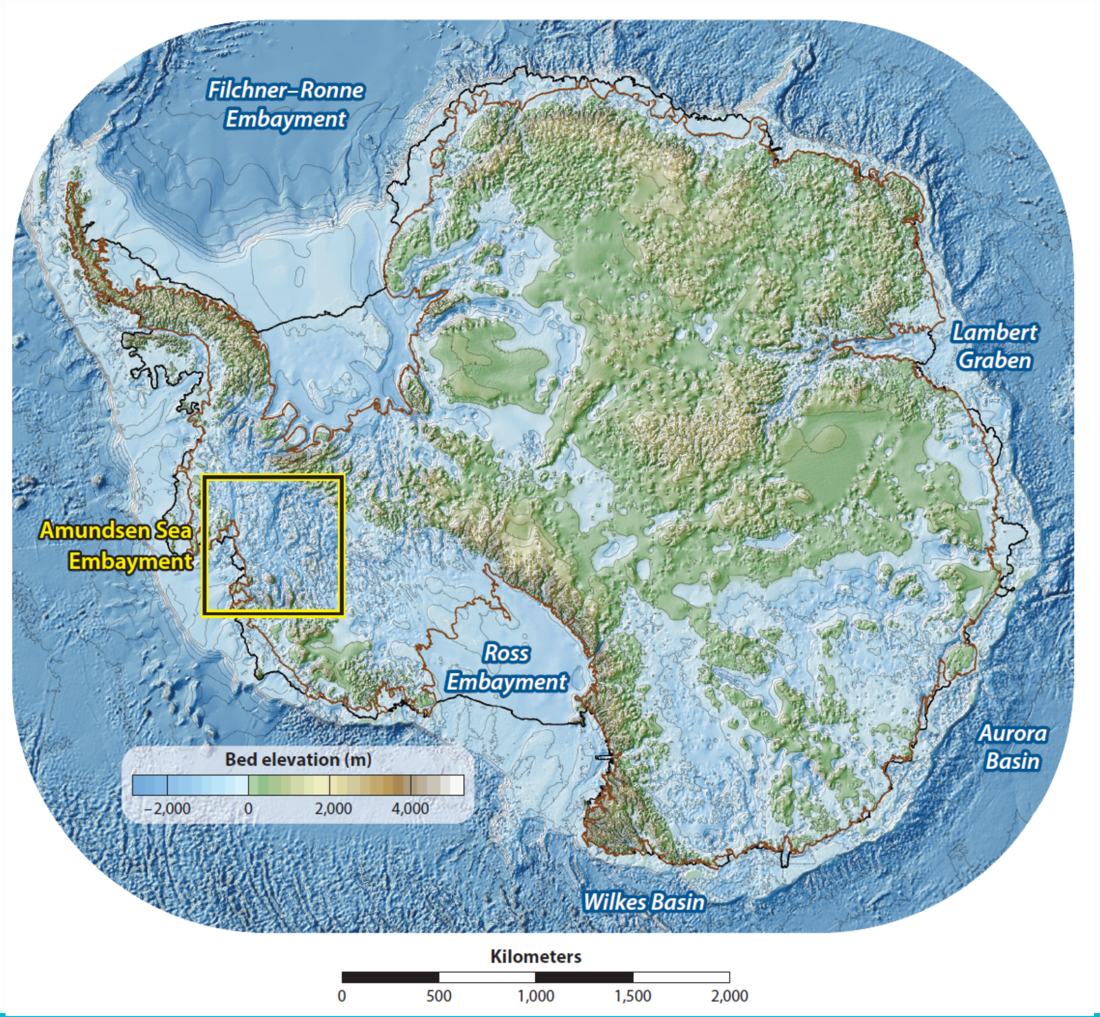
# Acceleration of mass loss from ice shelves



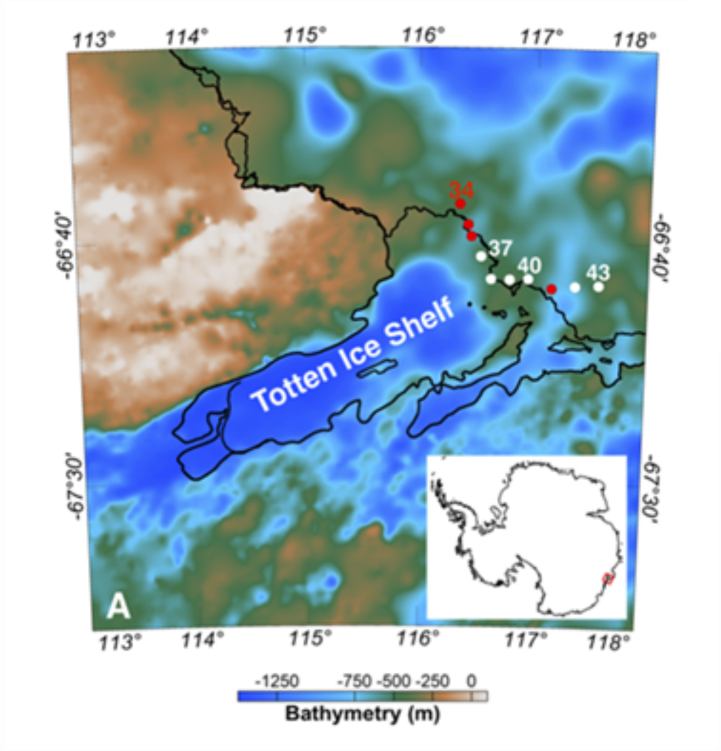

Paolo et al, Science, 2015

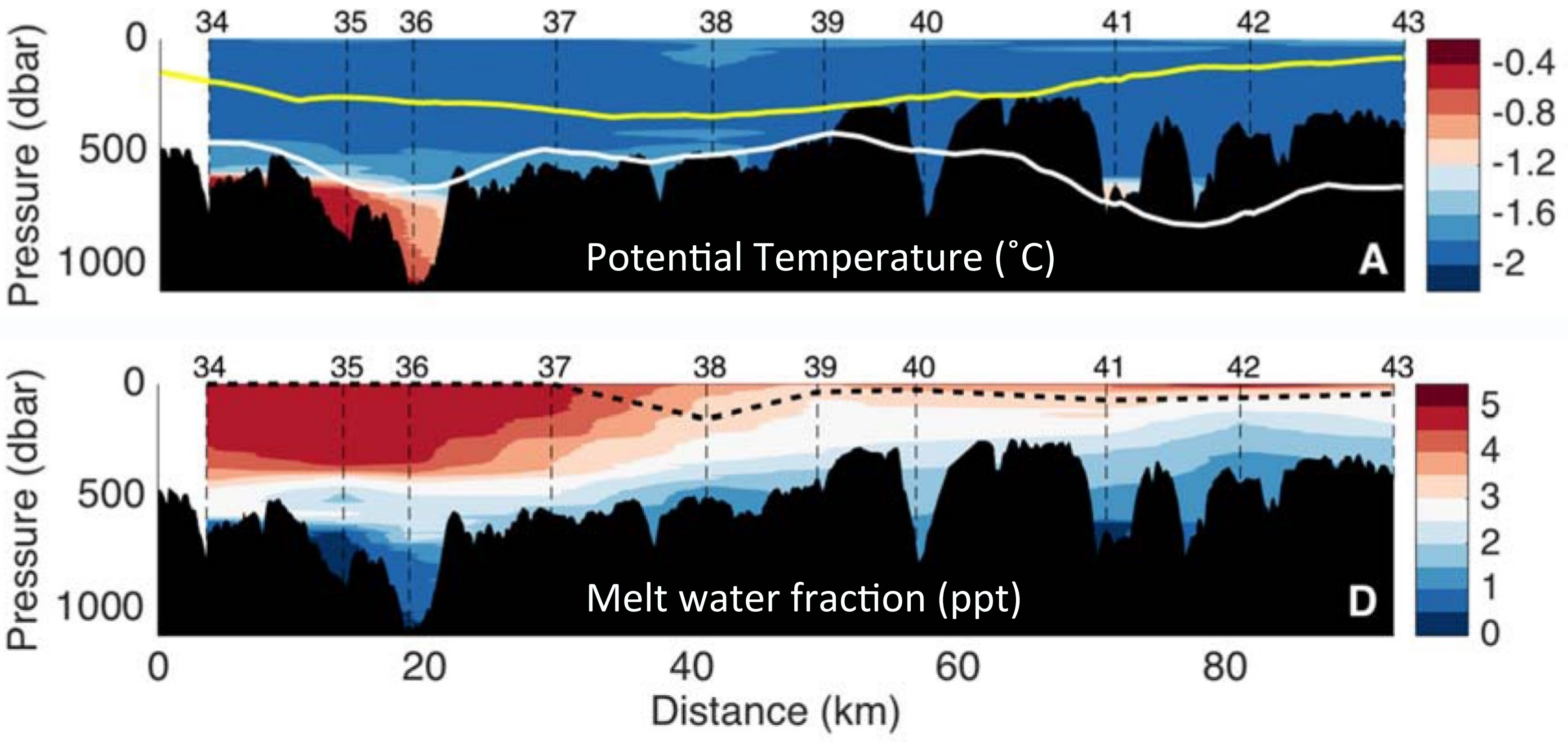
# Much of the Antarctic Ice Sheet is grounded below sea level




Bedmap2 data (Fretwell et al 2013); from Alley et al. (2015)

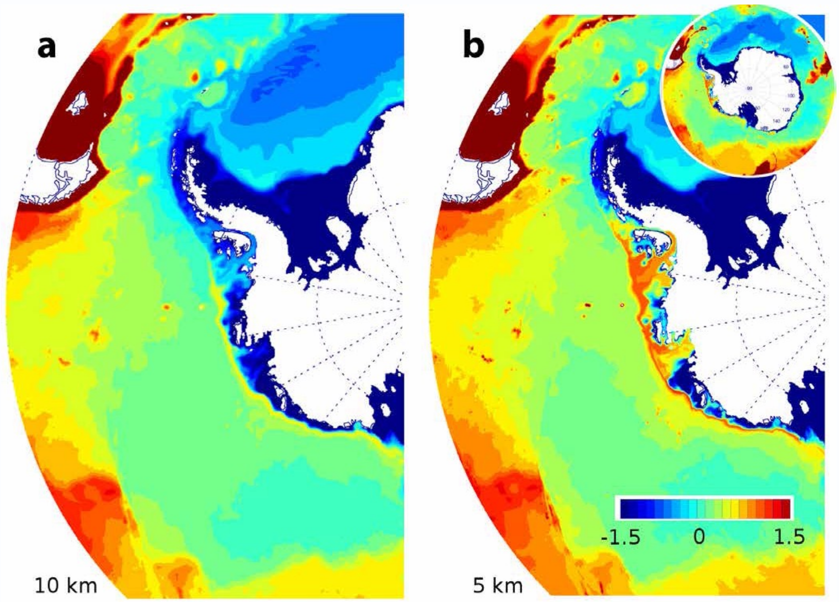
# Warm water inflow, melt water outflow from ice shelf cavity



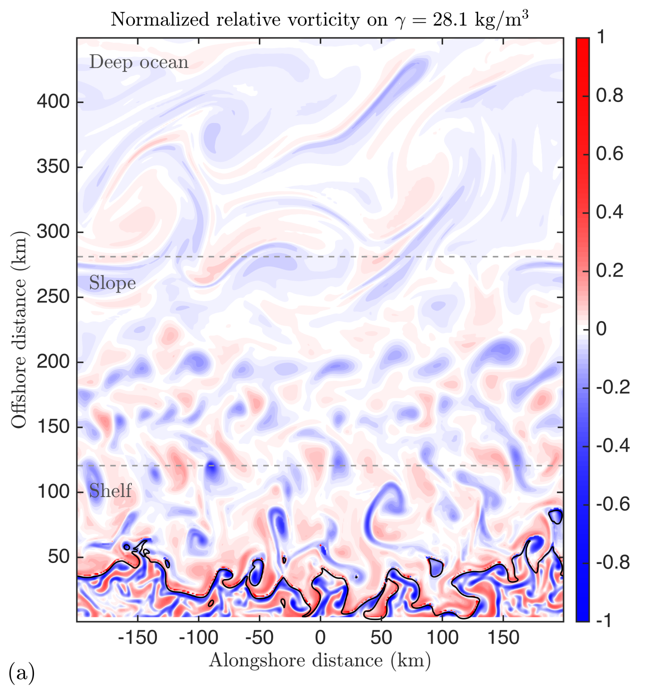




Rintoul et al., Science Advances 2016; Silvano et al., Oceanography, 2016; Silvano et al., JGR-Oceans, 2017

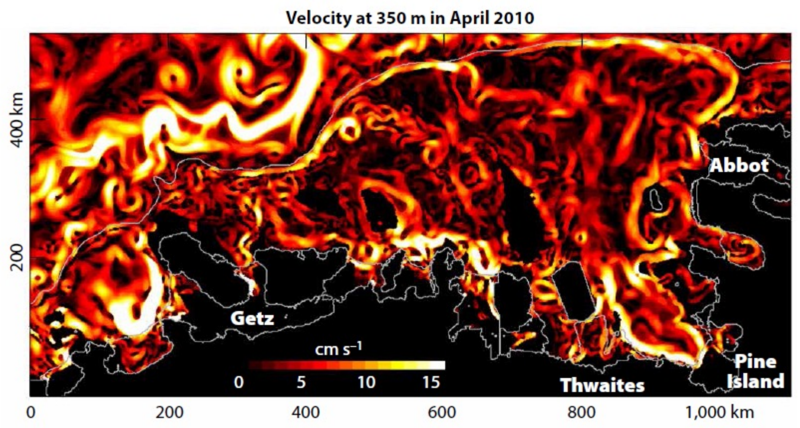
# How does warm water reach ice-shelf cavities?




Dinniman et al., 2015; Nakayama et al., 2014



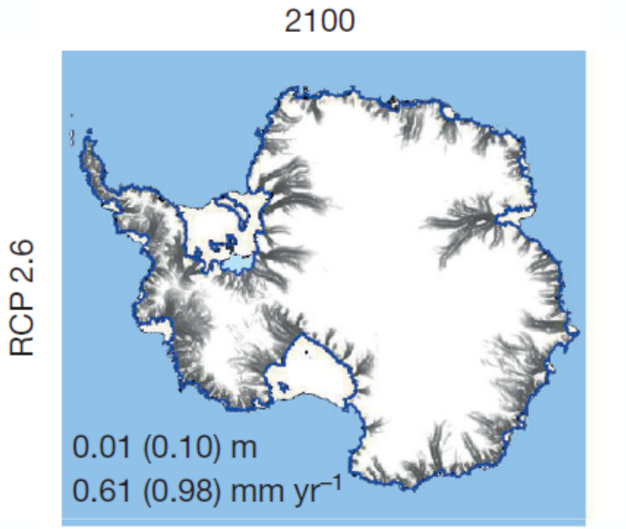

Stewart and Thompson, 2016




St Laurent et al., 2015

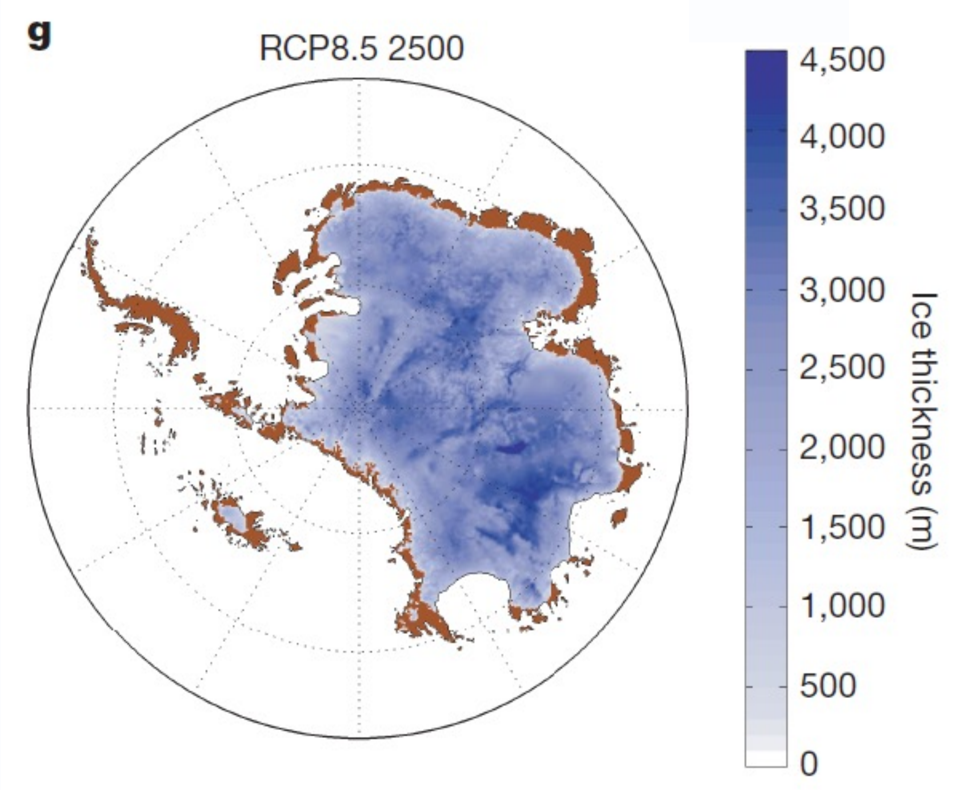
Many factors influence heat transport to ice shelf cavities: eddies, tides, wind, Antarctic Slope Front, topographic interactions, polynya dynamics, …. and often act on small spatial scales.

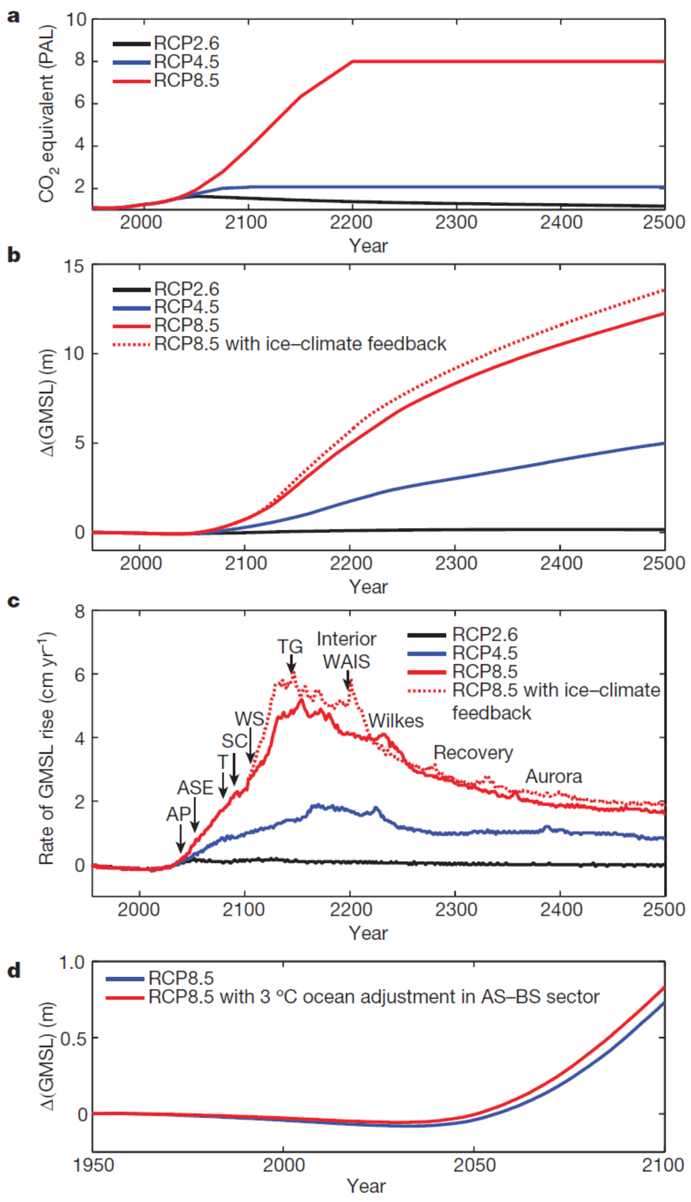
# Antarctic commitment to future sea level rise




Golledge et al., Nature, 2015

# Hydrofracturing and ice cliff failure result in large and rapid contribution to sea level rise






DeConto & Pollard, Nature, 2016

# Summary

- The report from the 2012 workshop provides a strong foundation for a new strategy for under – ice observations.
- Recent advances provide even stronger motivation for under – ice observations.
- Substantial progress has been made in the past 5 years.
- Our job is to build on the previous report to articulate a compelling vision for under – ice observations in Antarctica and to provide a roadmap for practical implementation of an integrated, circumpolar effort to fill this blind spot in the global ocean observing system.

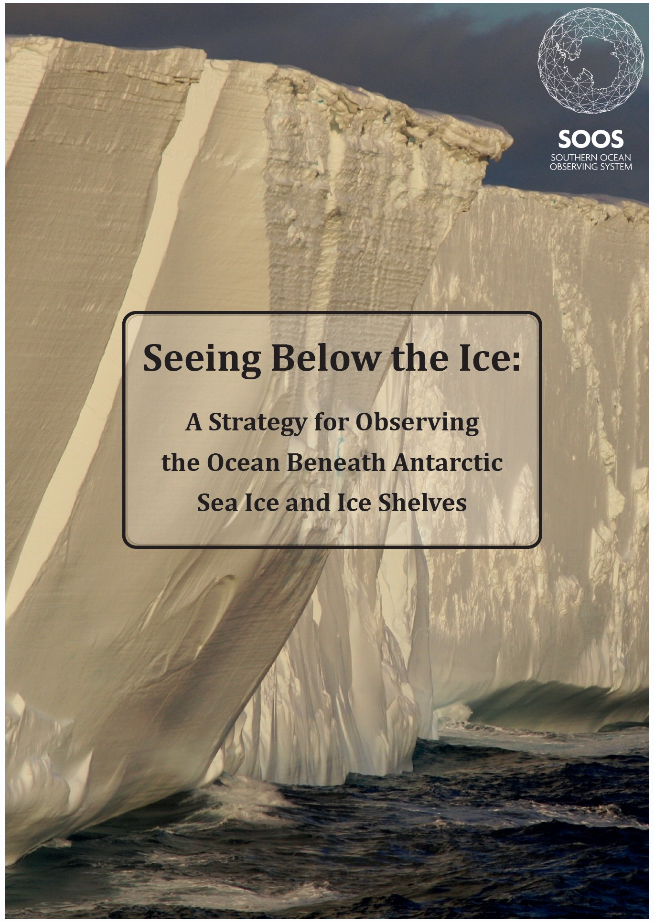
# Outline

- Seeing below the ice (2012): themes & objectives
- A brief and eclectic review of new discoveries motivating under – ice observations

E. van Wijk

# Seeing below the ice v1.0

- Result of a workshop held in Hobart in 2012
- Articulated a community view of the motivation for under-ice observations
- Identified scientific objectives and key questions in 3 themes:
  - Circulation and inventories of heat, freshwater and carbon in the sea ice zone
  - Ocean – sea ice interaction
  - Ocean – ice shelf interaction
- Outlined an integrated under – ice observing strategy and path to implementation




*A partial success: raised the profile of under – ice observations, but did not fully succeed in motivating scientists and funding agencies to implement a comprehensive observing system.*

# Themes and Objectives

Circulation and inventories of heat, freshwater and carbon in the sea ice zone

- To quantify how much heat, freshwater and carbon are stored by the ocean between the winter sea ice edge and the Antarctic continent.
- To understand the processes responsible for ocean storage of heat, freshwater and carbon and their sensitivity to changes in forcing

Ocean – sea ice interaction:

- To determine the processes controlling the circumpolar and regional distribution of sea ice concentration and thickness.
- To determine how and why the concentration/thickness of sea ice varies over time-scales from days to millennia.
- To understand and quantify coupled interactions between Antarctic sea ice, the ocean, the atmosphere and ice shelves.

Ocean – ice shelf interaction:

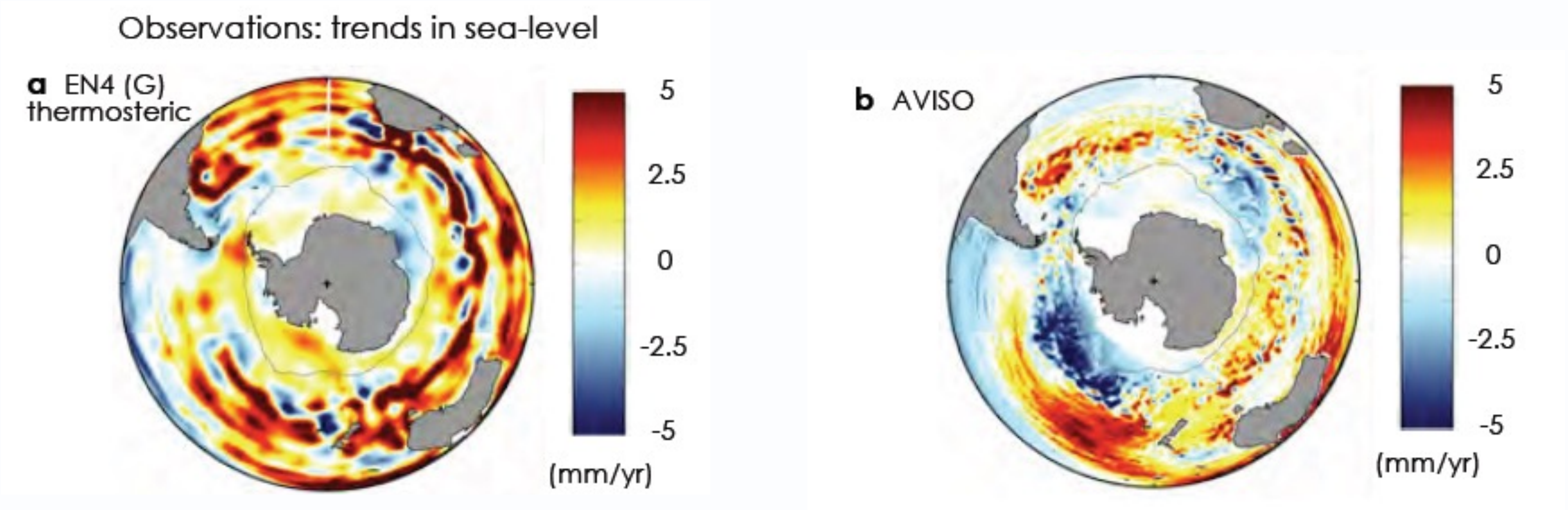
- To determine the sensitivity of Antarctic ice shelves to changes in ocean circulation & temperature.
- To assess the effect of basal melt of floating ice shelves on the mass balance of the Antarctic Ice Sheet and its contribution to sea level rise.
- To determine the response of the ocean to changes in freshwater flux input from Antarctica.

# Rye et al

# Bea current meter study (i.e. circulation in sea ice zone)

# Something from Naveira – Garabato paper?

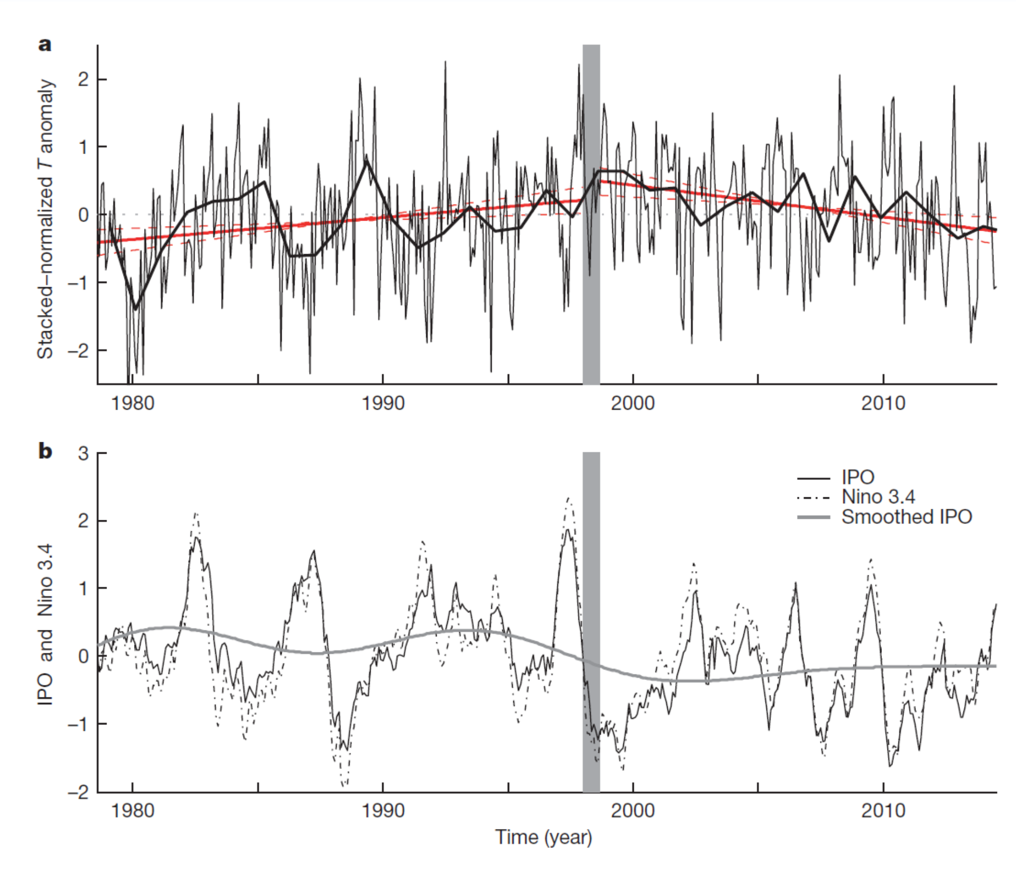
# Sea-level trends

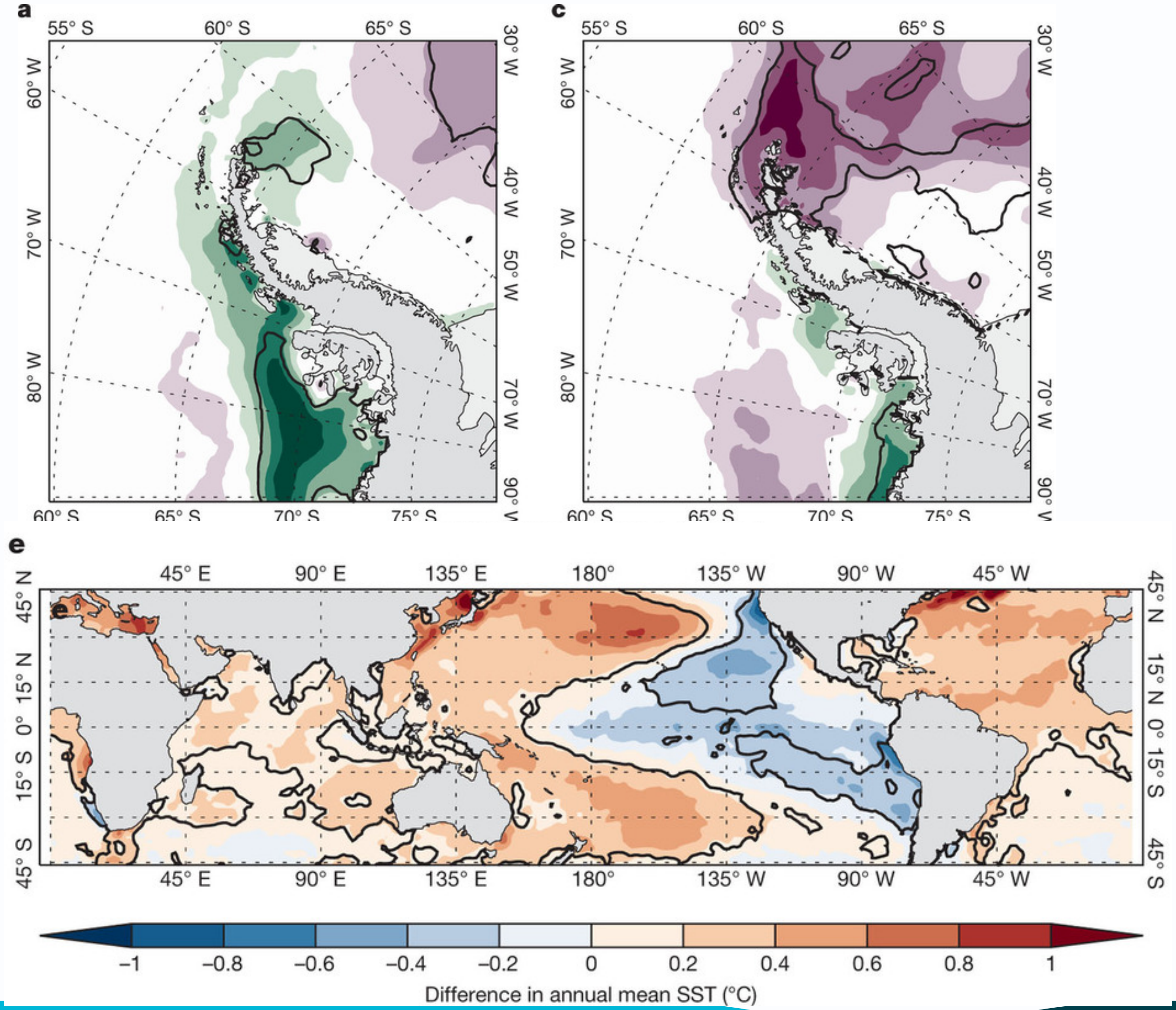





Armour et al., 2016

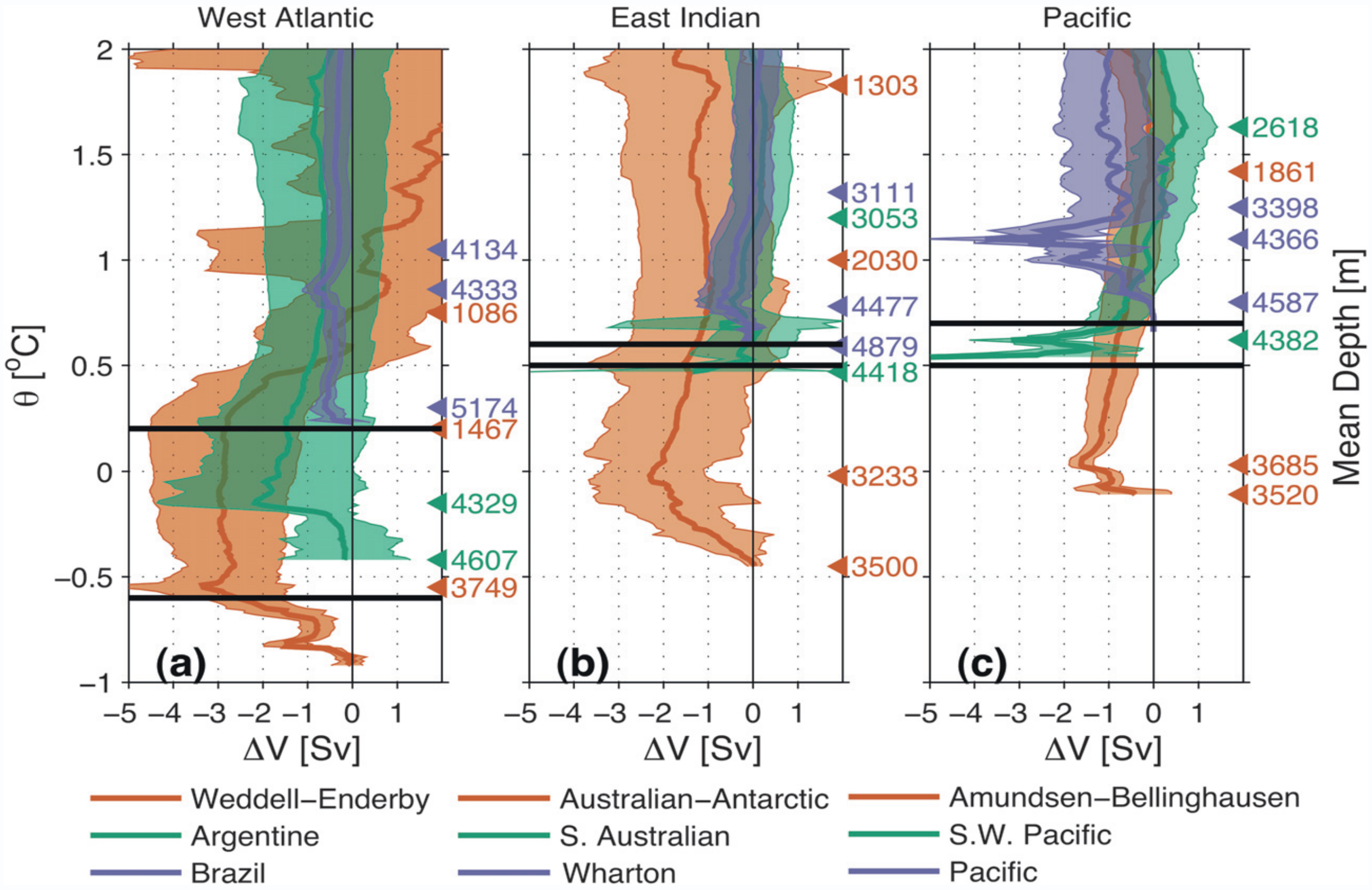
# Natural variability and teleconnections explain trends on AP



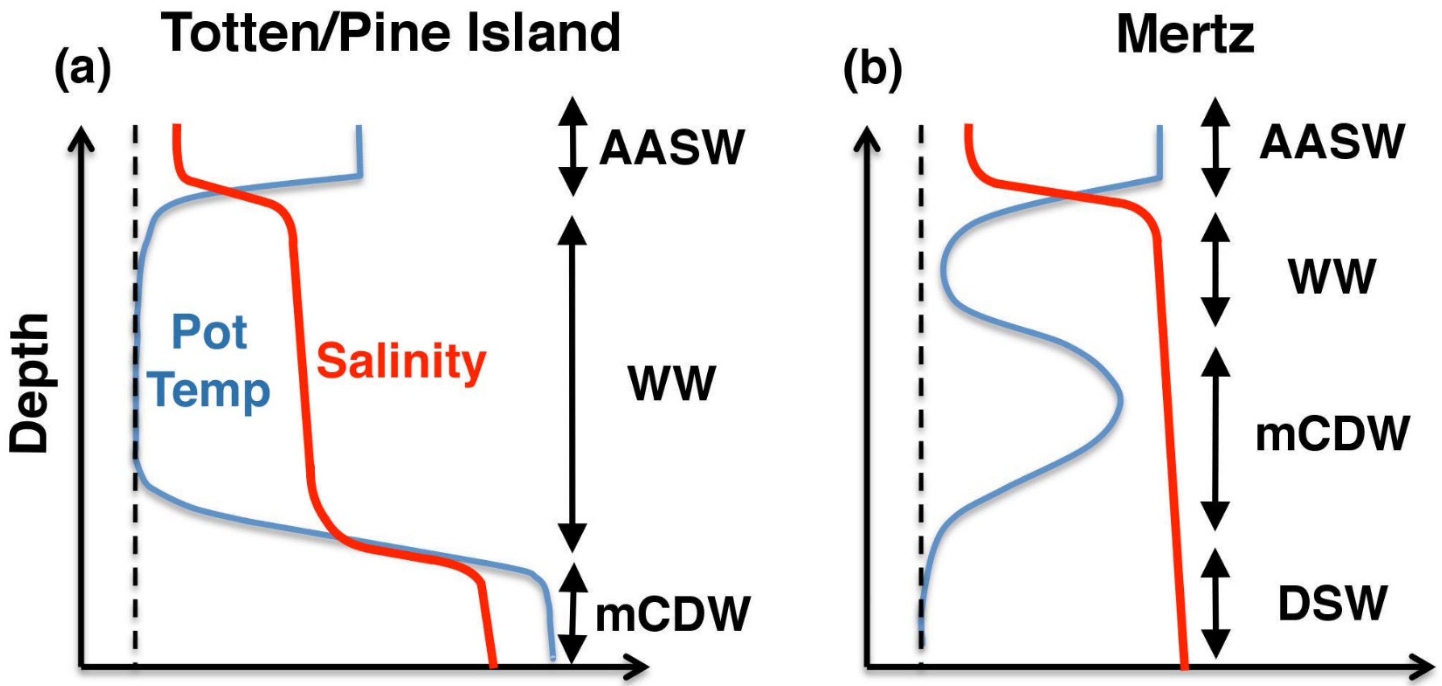

Turner et al., Nature, 2016

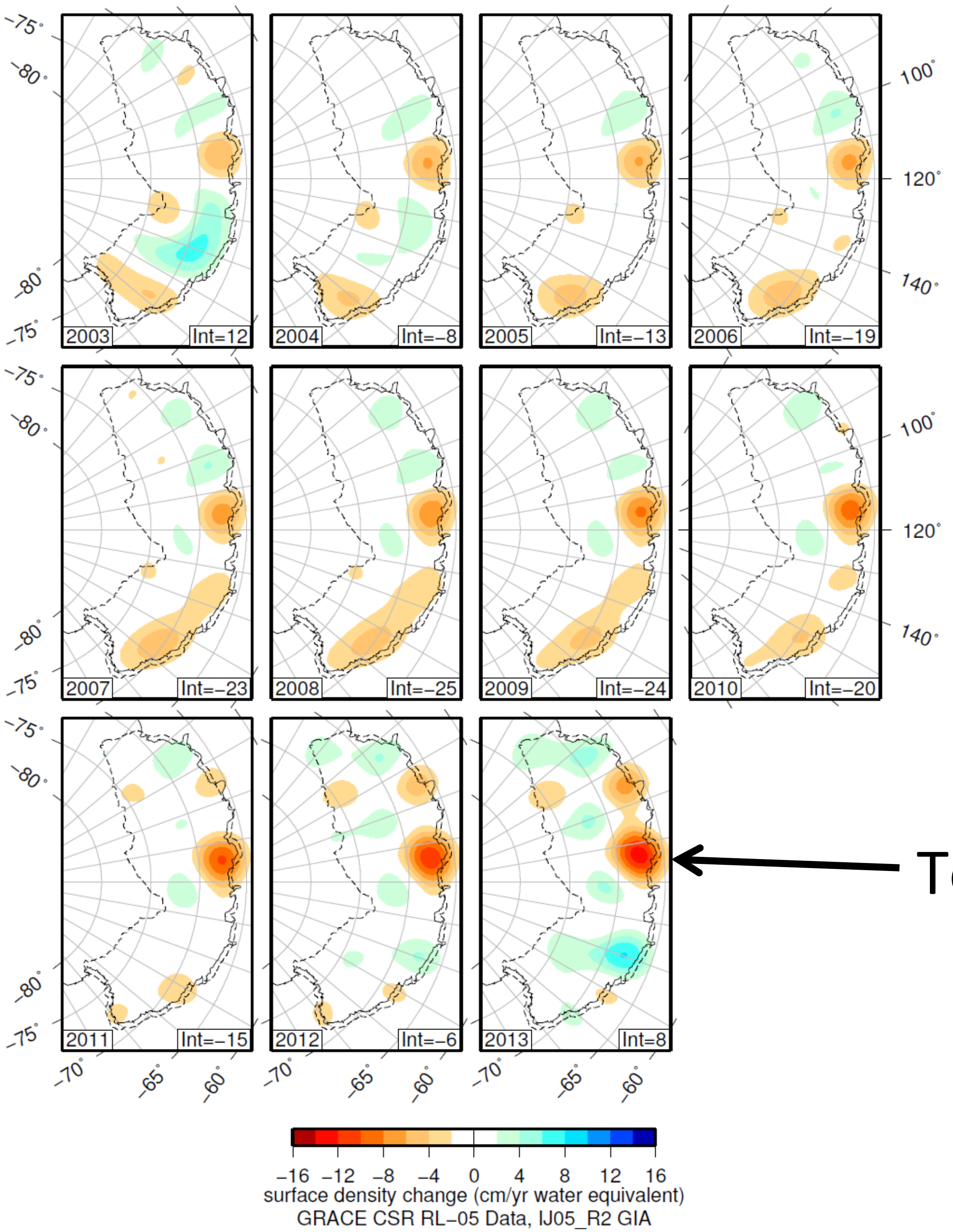
# Warming, freshening and contraction of Antarctic Bottom Water




Purkey & Johnson, 2013

# Ocean stratification at Totten similar to West Antarctica



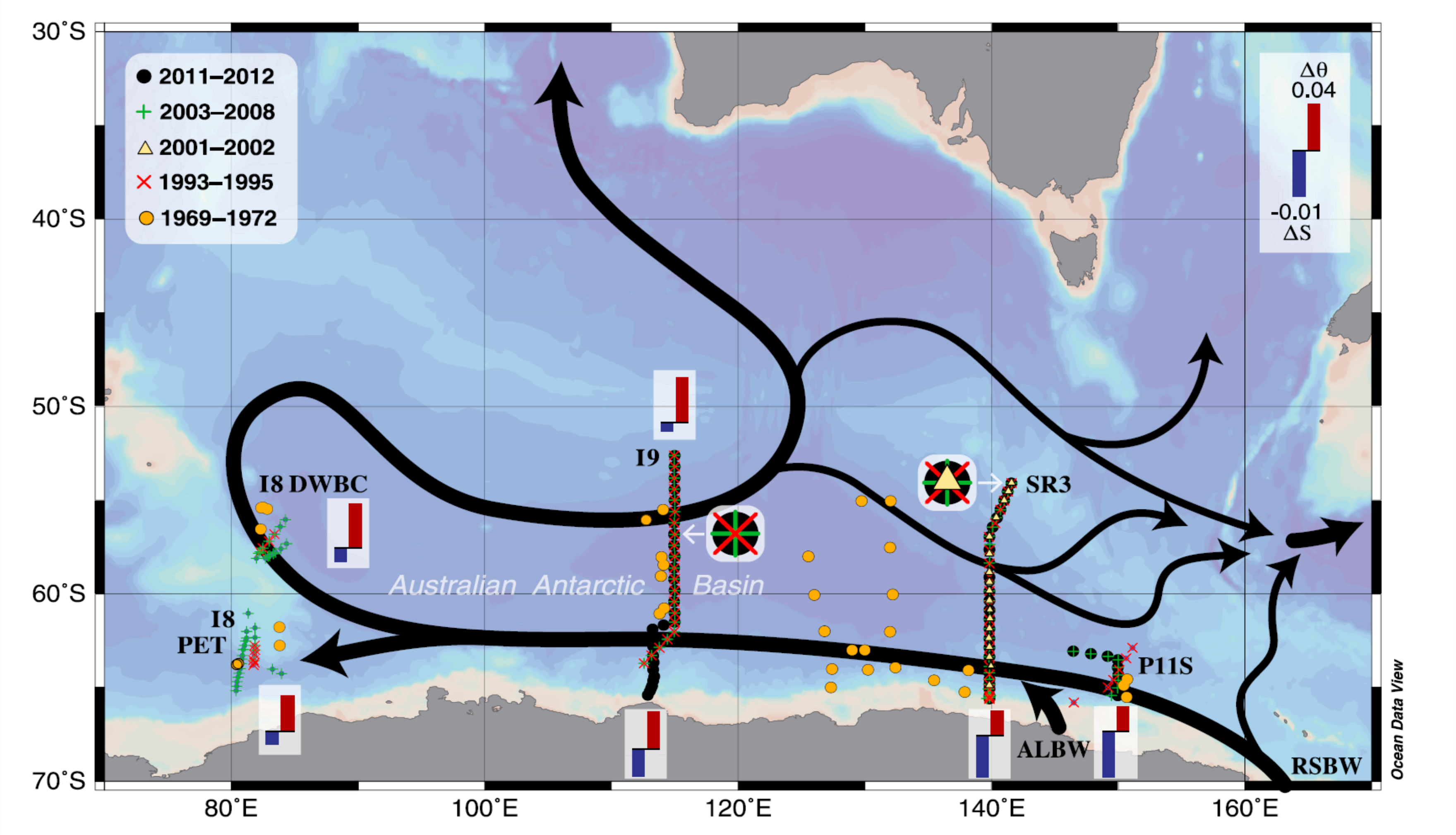



Loss of mass from East Antarctica (cm/yr) between 2003 to 2013 from satellite gravity measurements.

Totten Glacier

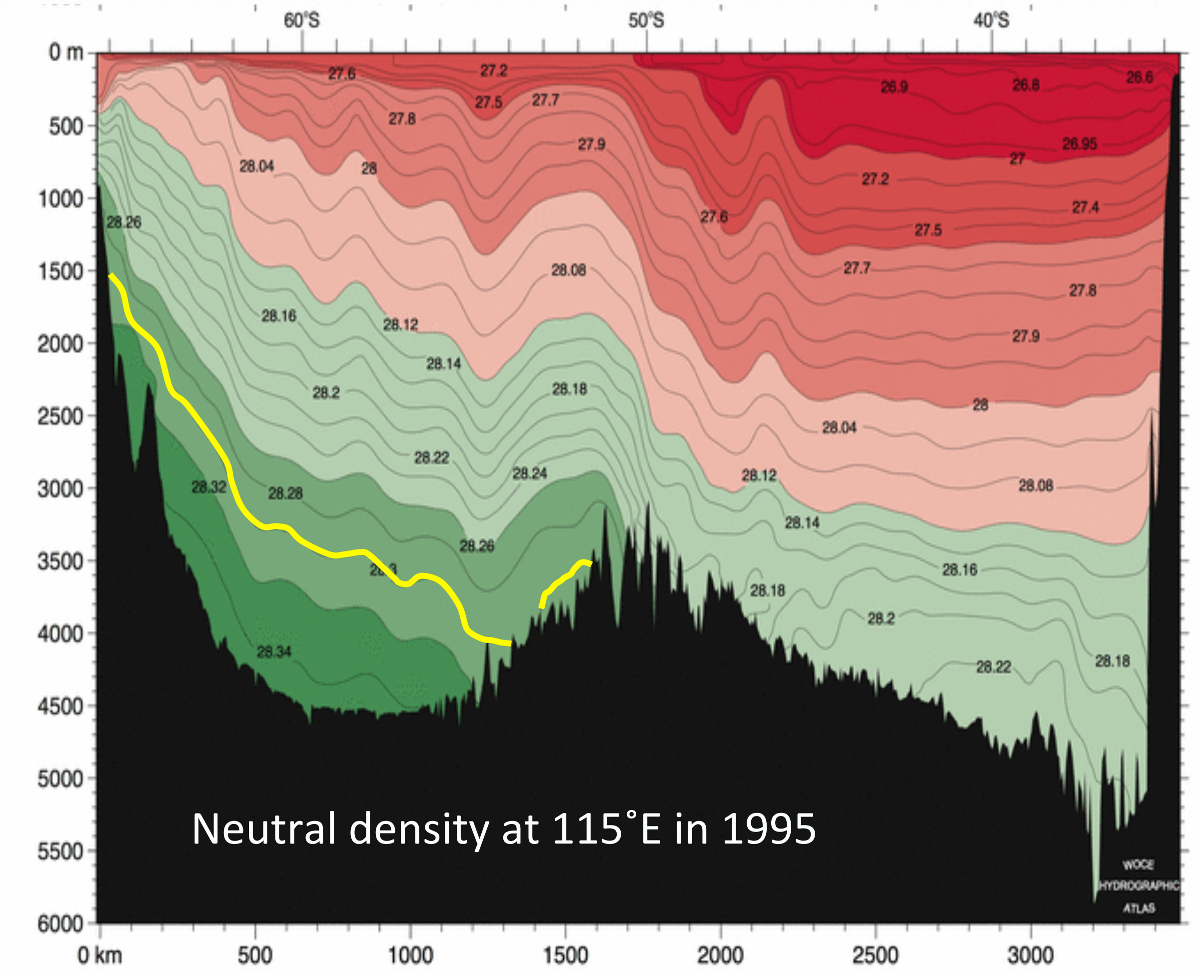
Harig & Simons 2015 (supp mat.)

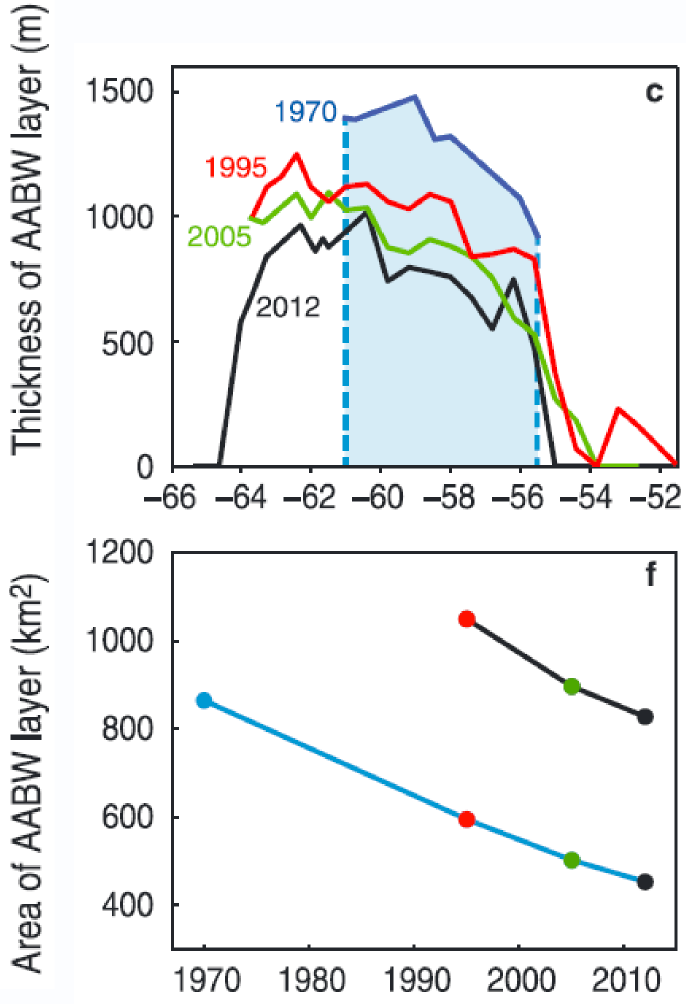
# Antarctic Bottom Water in the Australian – Antarctic Basin




van Wijk and Rintoul, GRL, 2014

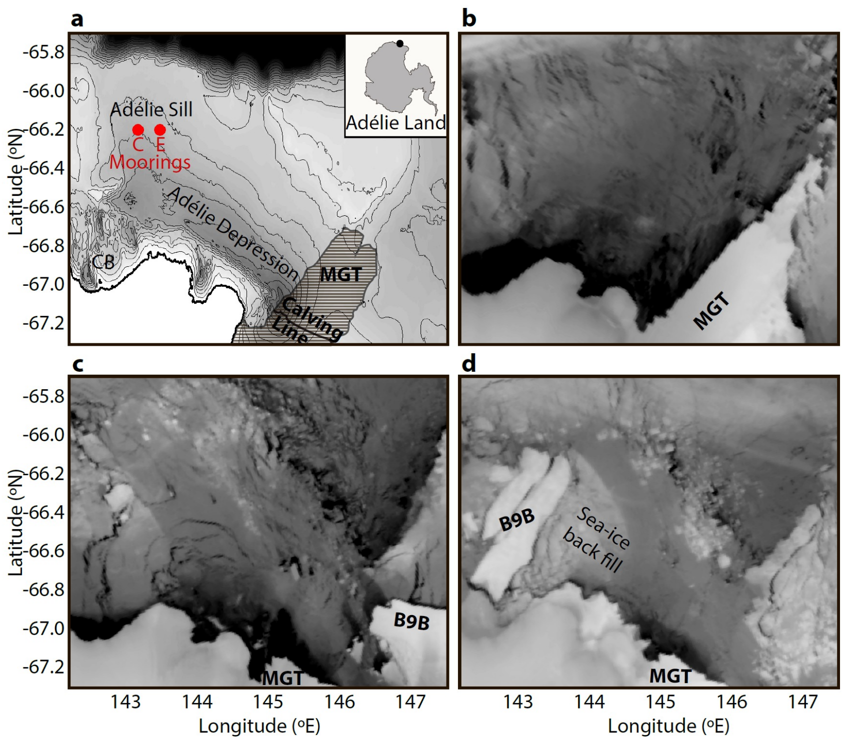
# Antarctic Bottom Water layer contracted by ~50% between 1970 and 2012



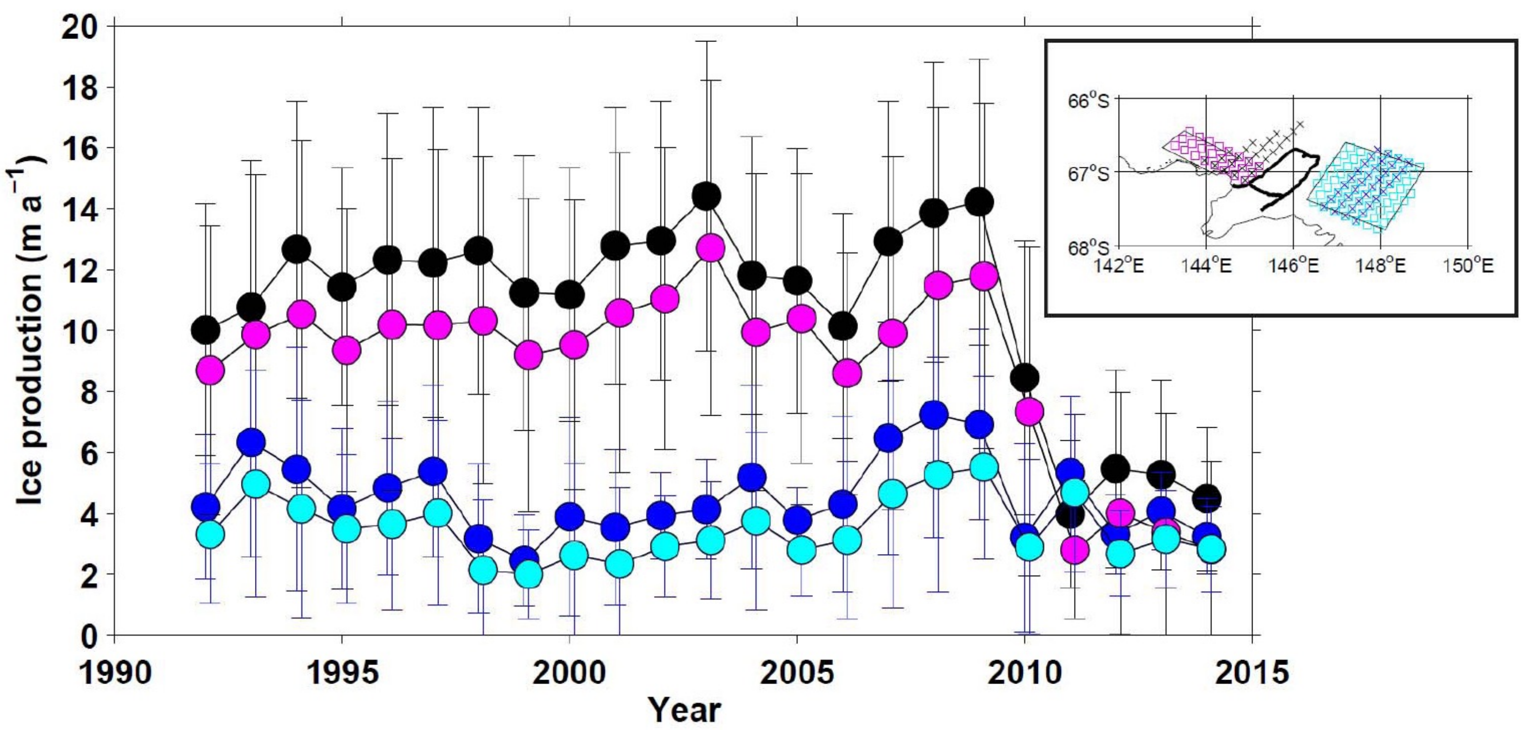




Van Wijk & Rintoul, Geophysical Research Letters, 2014

# A natural experiment:  calving of the Mertz Glacier Tongue

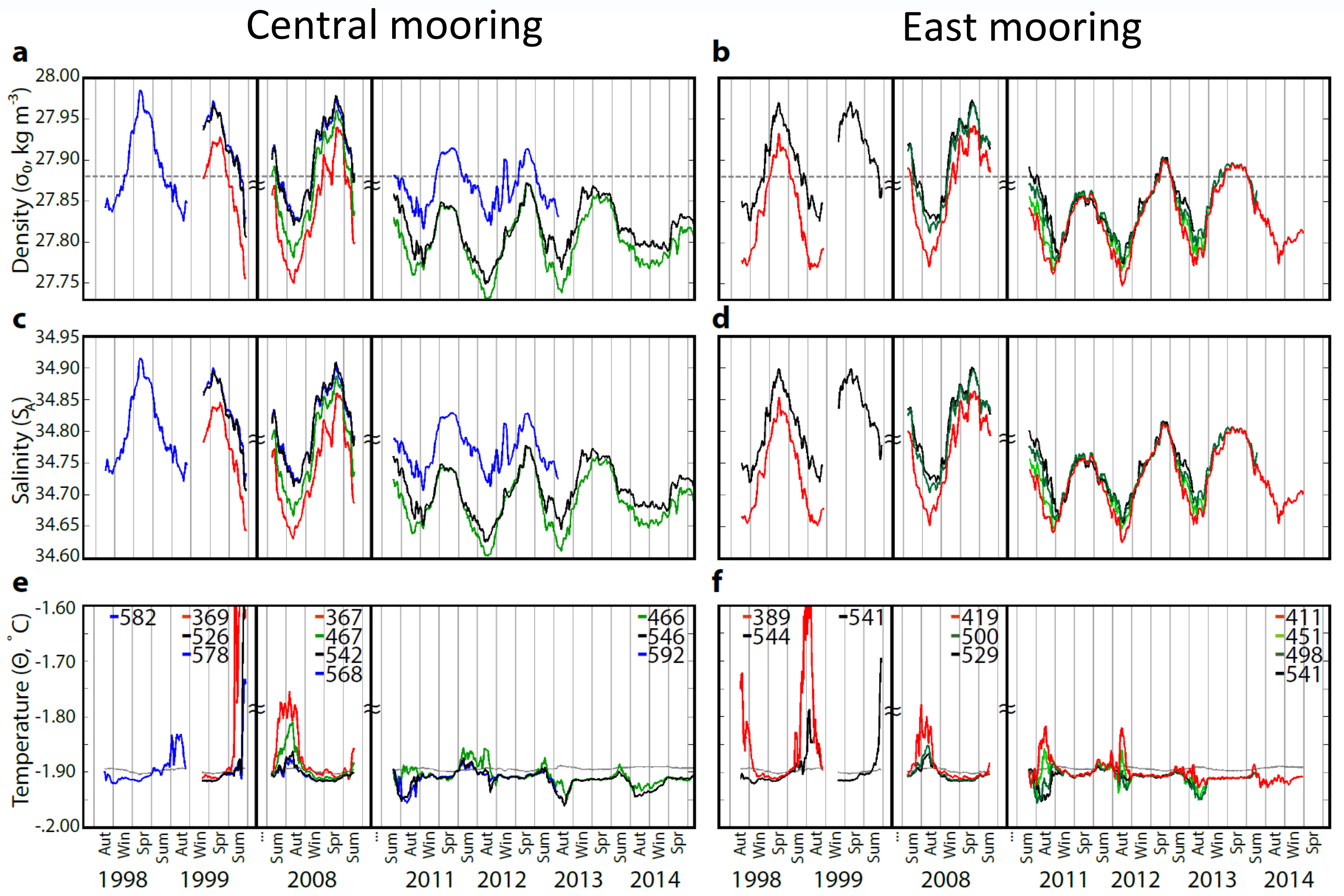



Snow et al., in prep



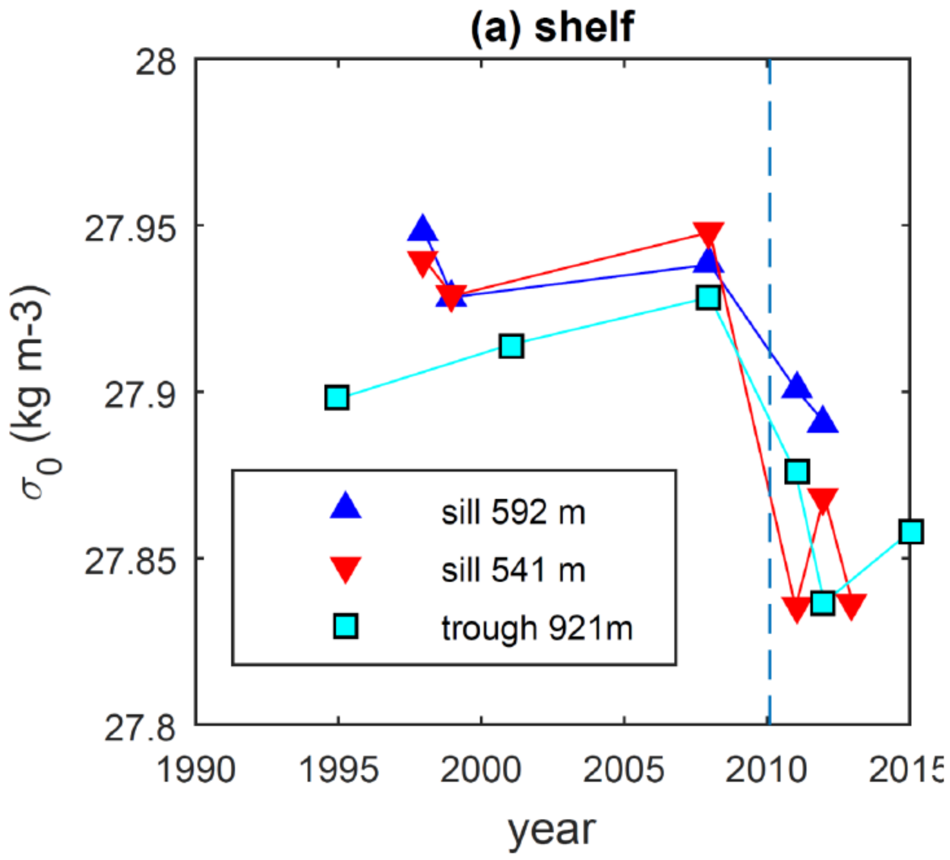

Aoki et al., in prep

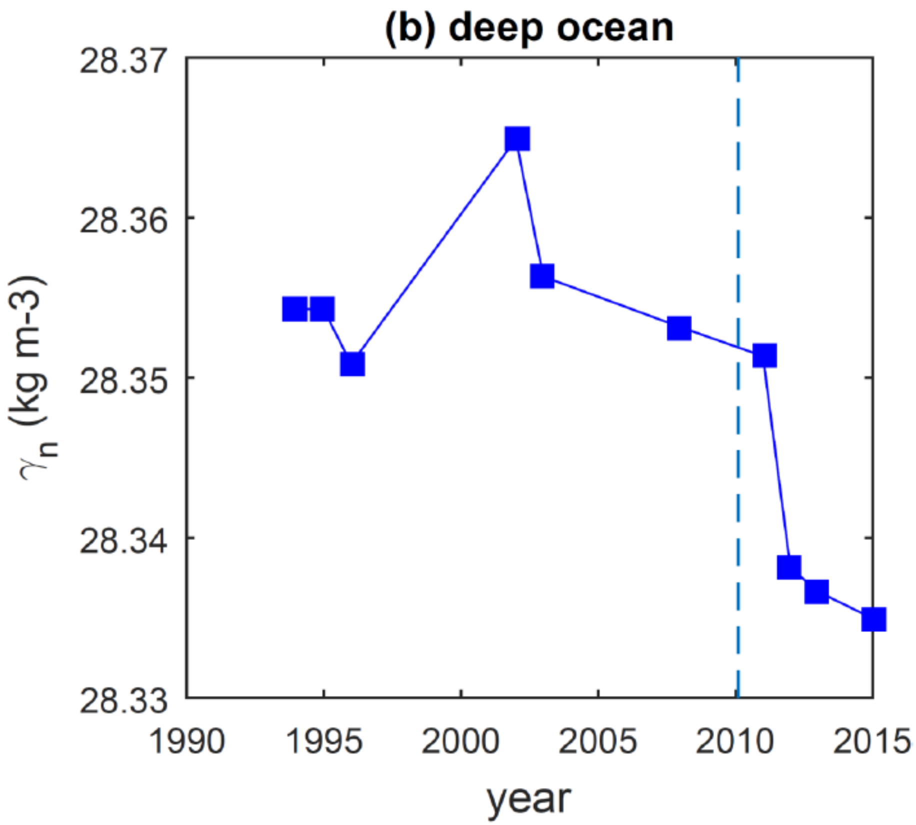
# Sharp reduction in density of dense shelf water export



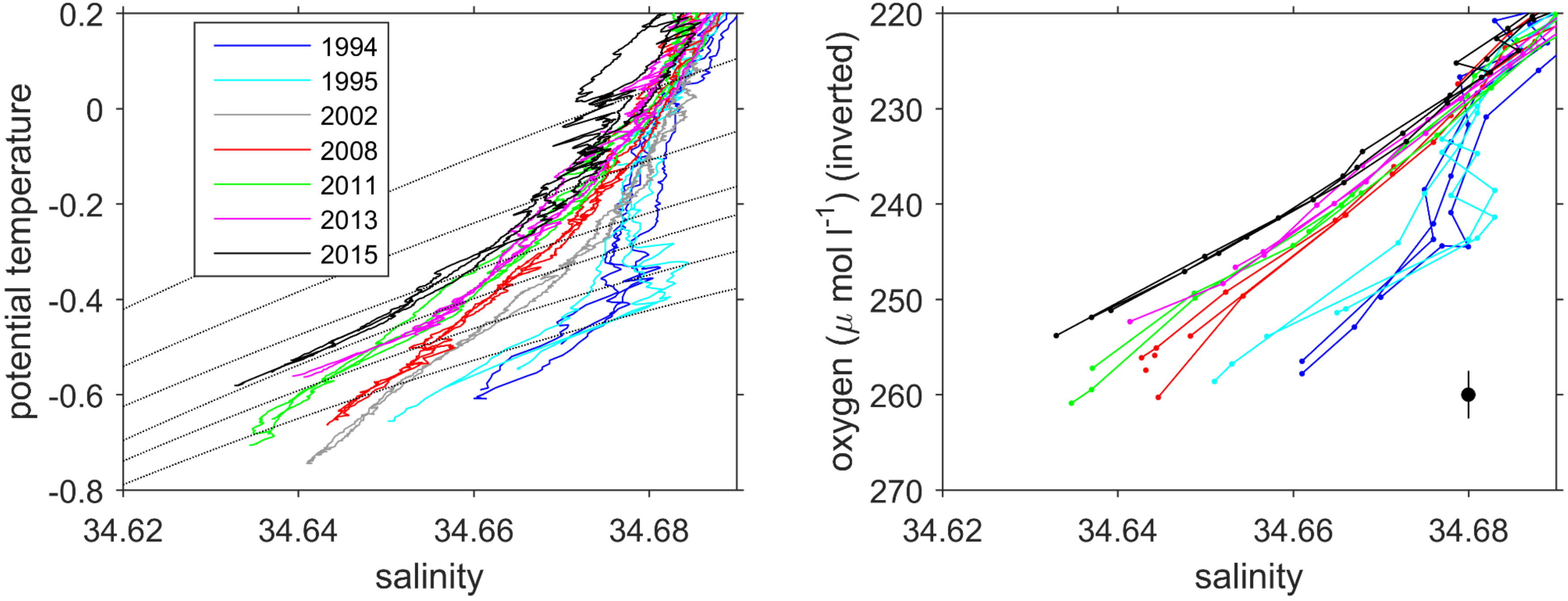

Snow et al., in prep

# Sharp drop in density of bottom water after calving

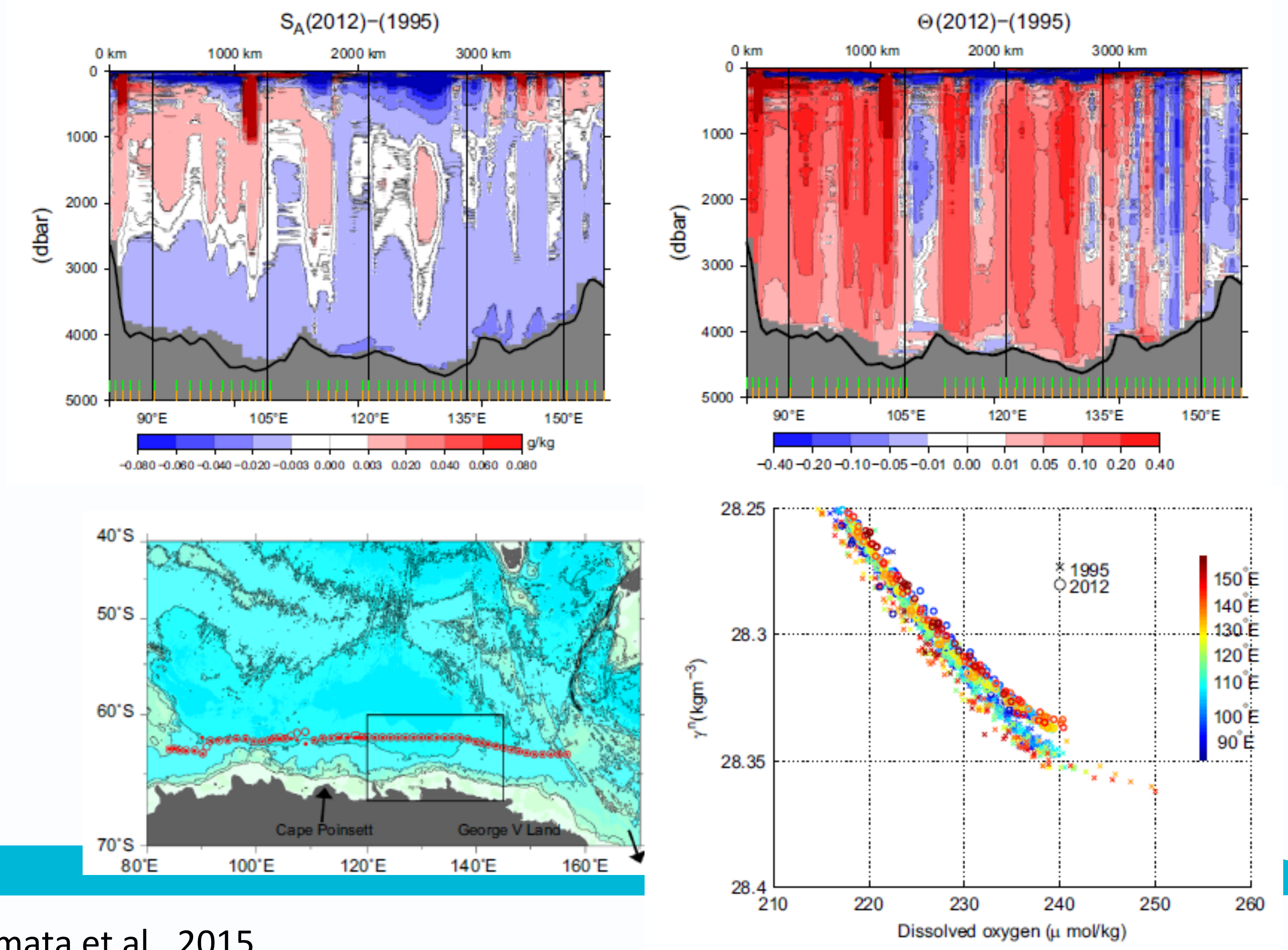


# Warmer, lighter AABW after calving, small decrease in oxygen



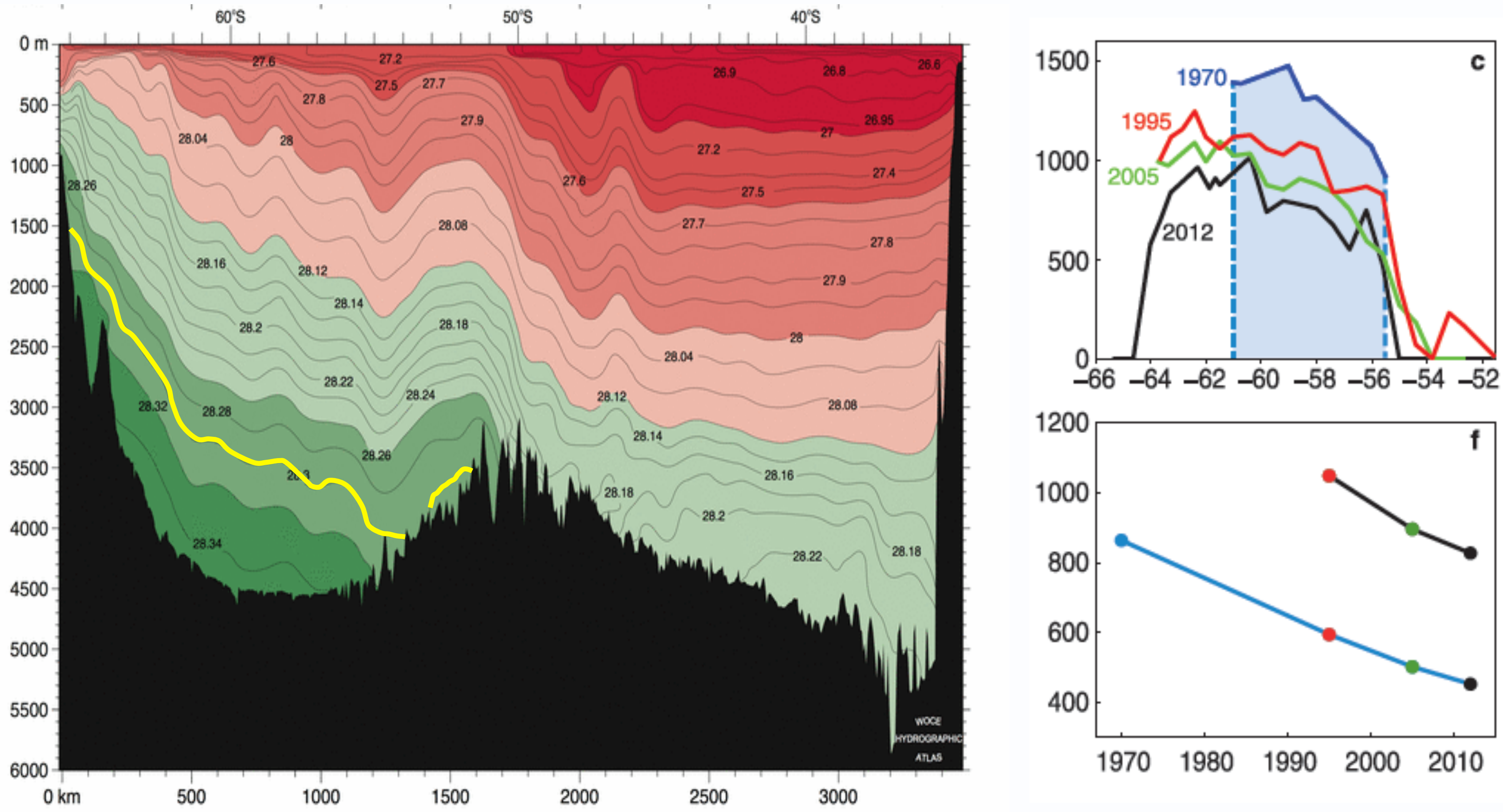
# Change on S4 (~63S), 1995 to 2012



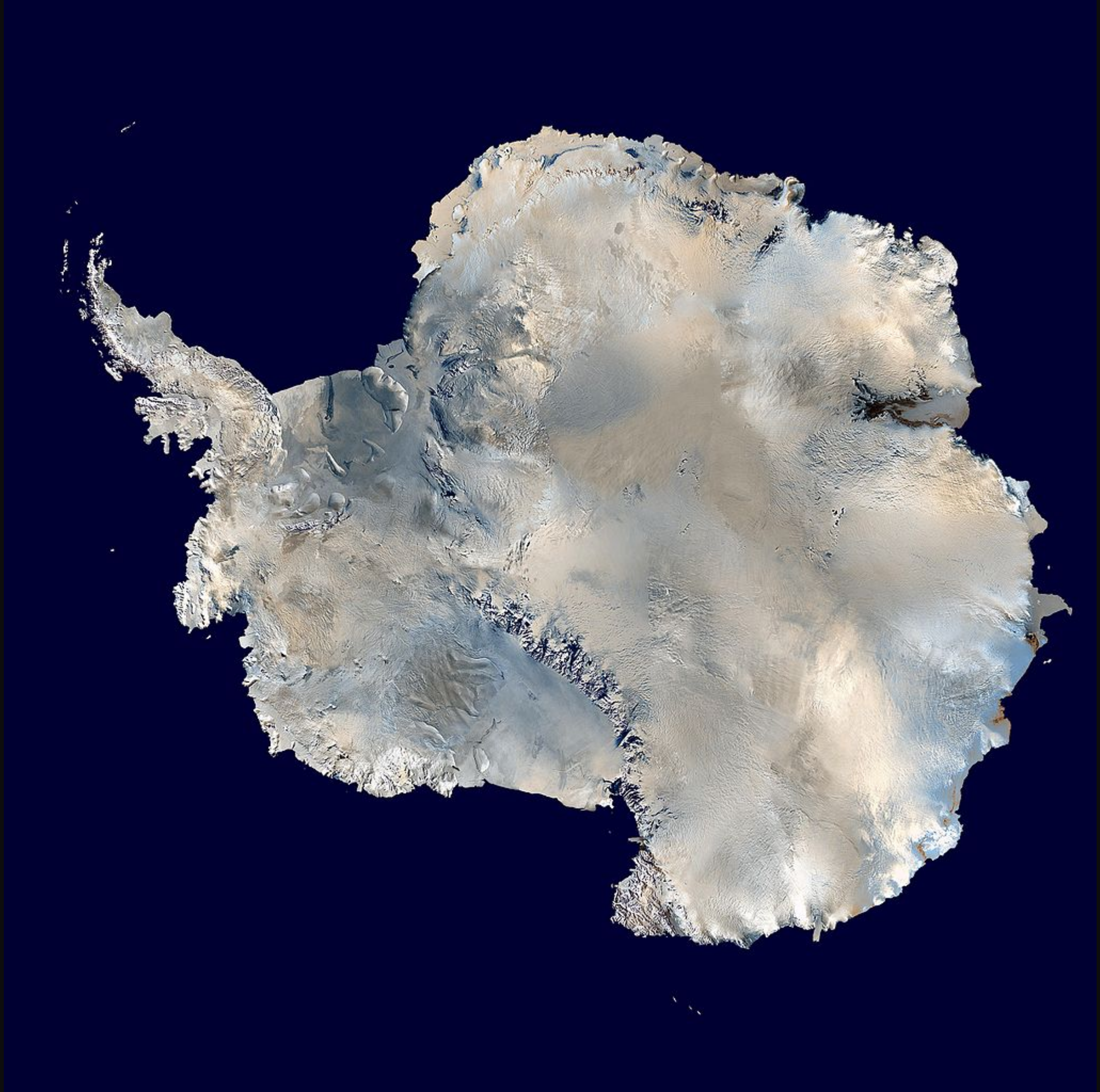

Katsumata et al., 2015

# A revolution in ocean observing

# Antarctic Bottom Water layer contracted by 50% between 1970 and 2012




Van Wijk & Rintoul, Geophysical Research Letters, 2014



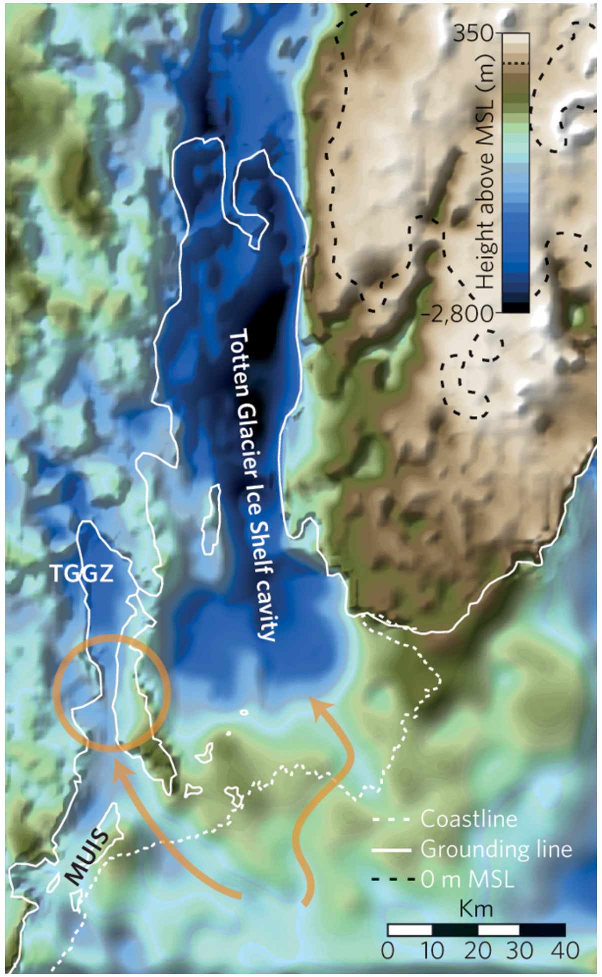
# Much of the Antarctic Ice Sheet sits on bedrock far below sea level

BEDMAP-2

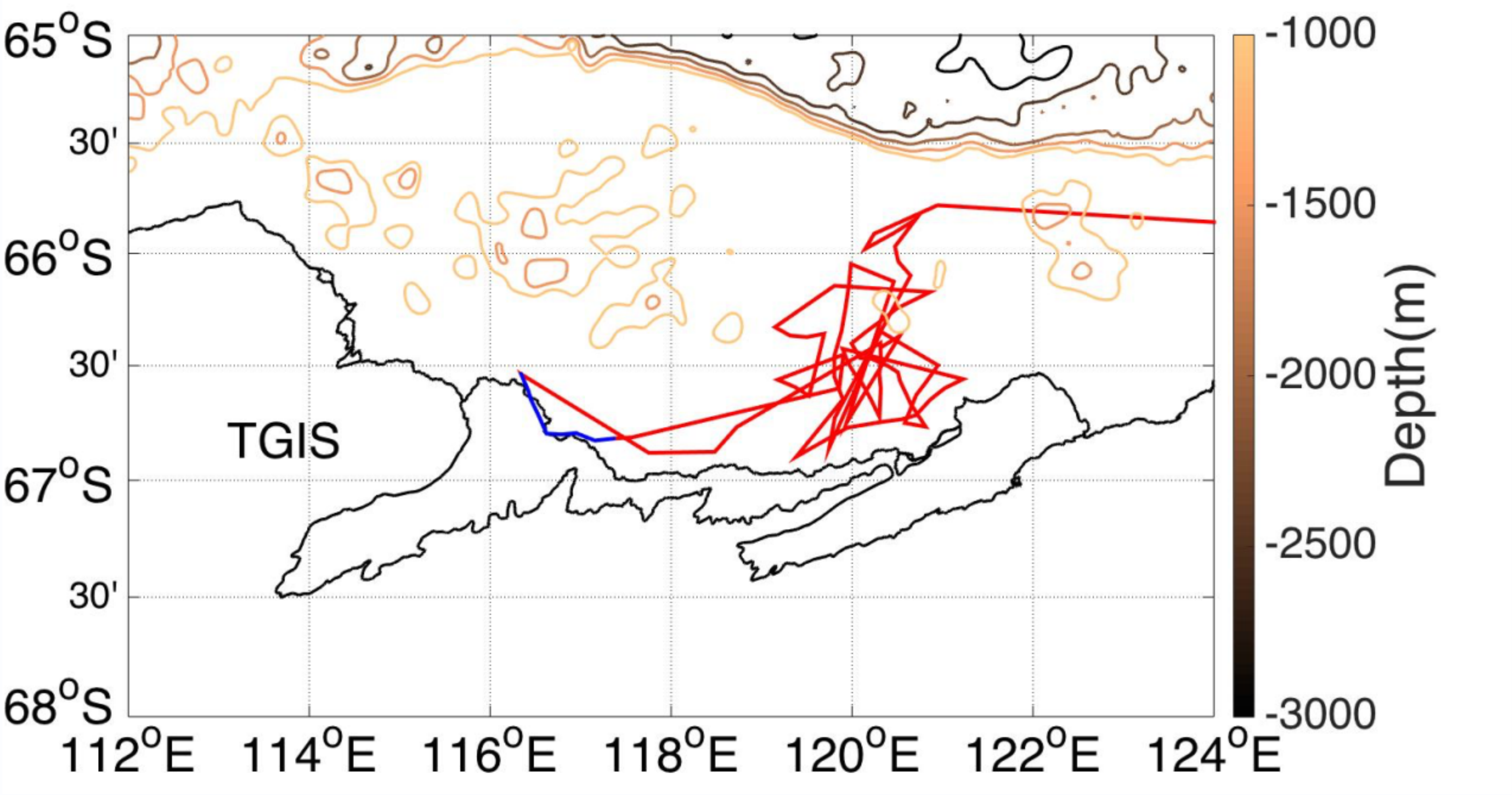

An expedition to the Totten Glacier
AURORA AUSTRALIS

# Why focus on the Totten Glacier?

- Ice volume equivalent to 3.9 m of global sea level rise
- Marine ice sheet - potentially unstable
- Likely contributed to past sea level rise
- Thinning rapidly, but we don't know why
- No oceanographic data near the glacier



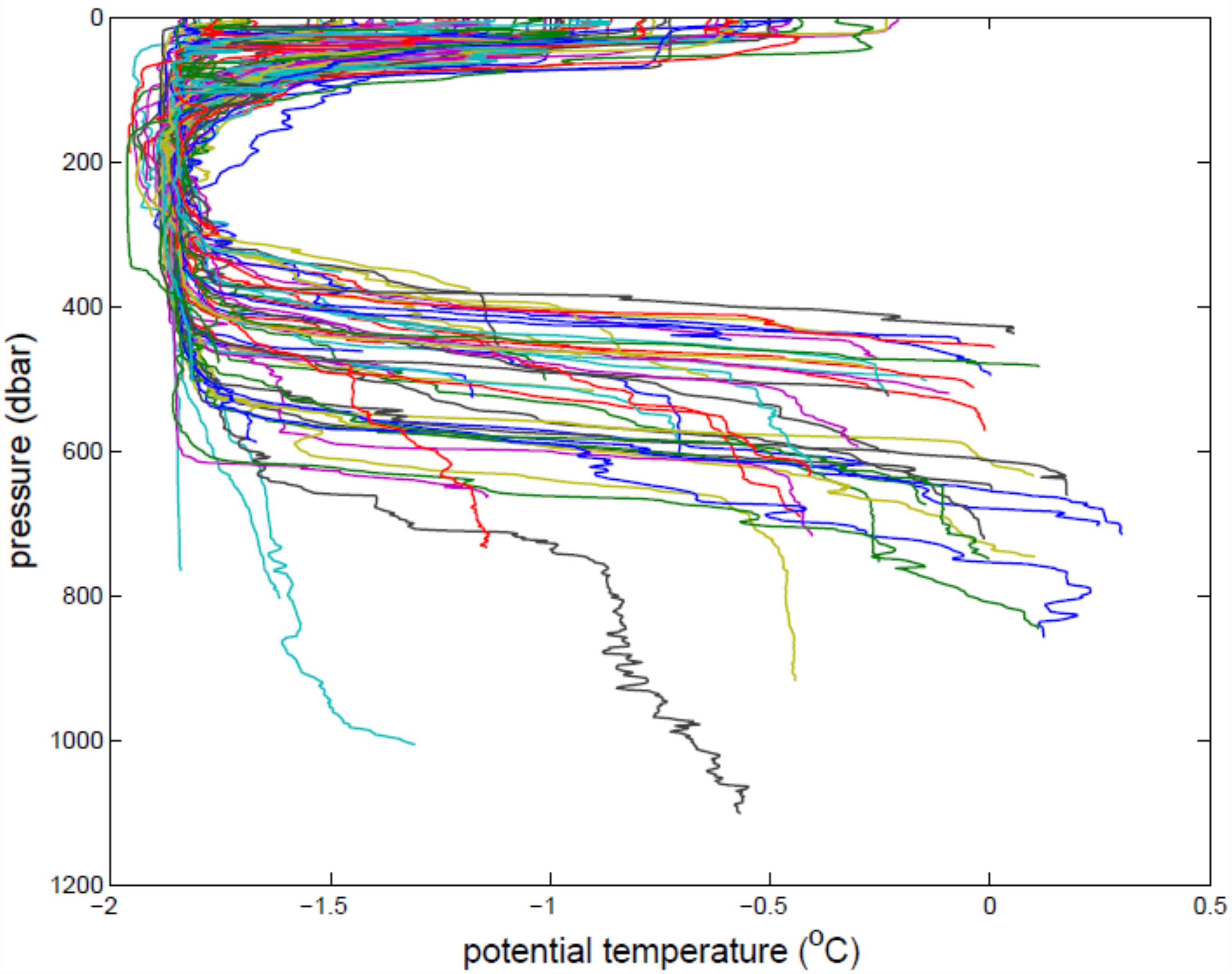

Fretwell et al 2015


65°S
30'
66°S
30'
67°S
30'
68°S
112°E
114°E
116°E
118°E
120°E
122°E
124°E
TGIS
-1000
-1500
-2000
-2500
-3000
Depth(m)

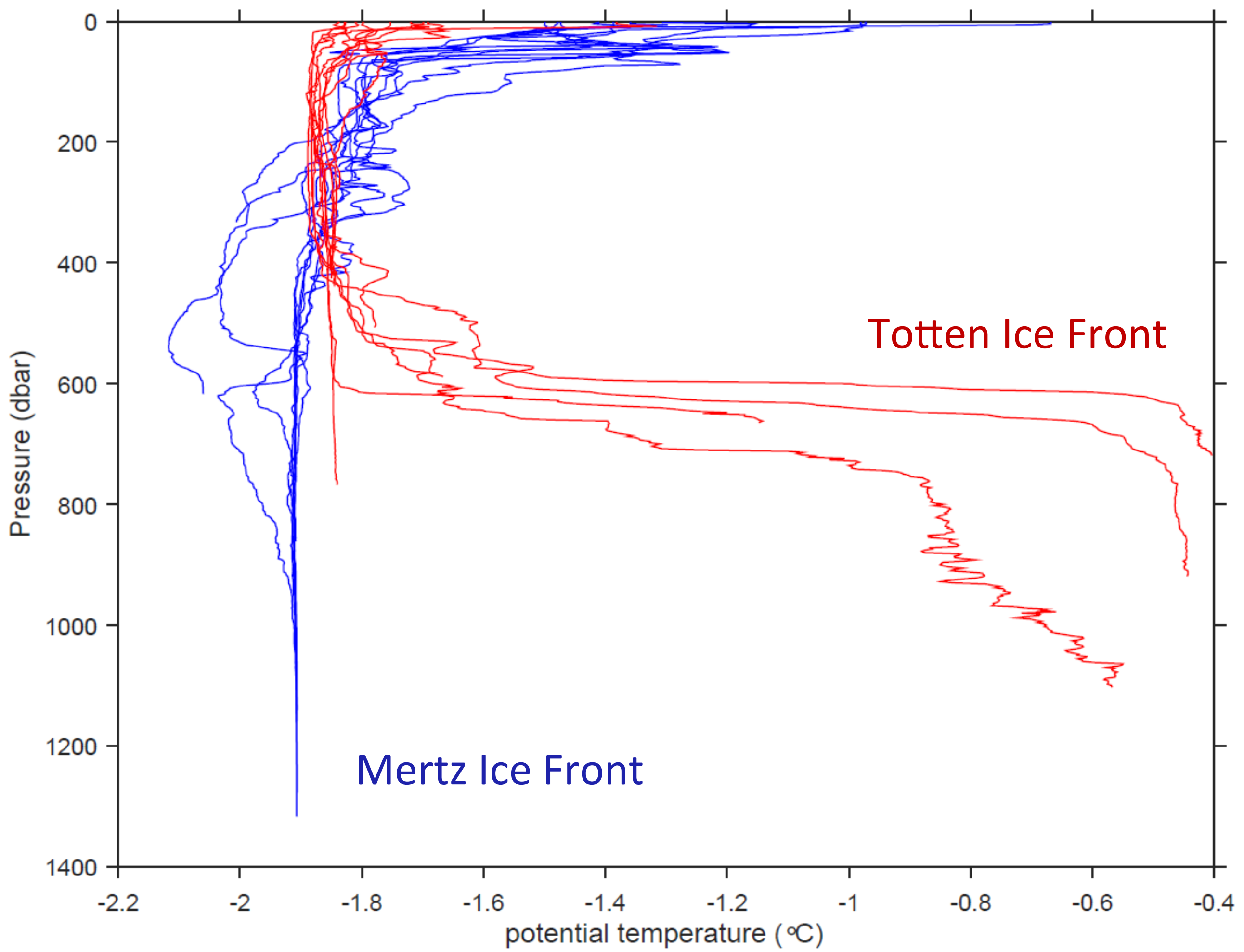


A. Silvano

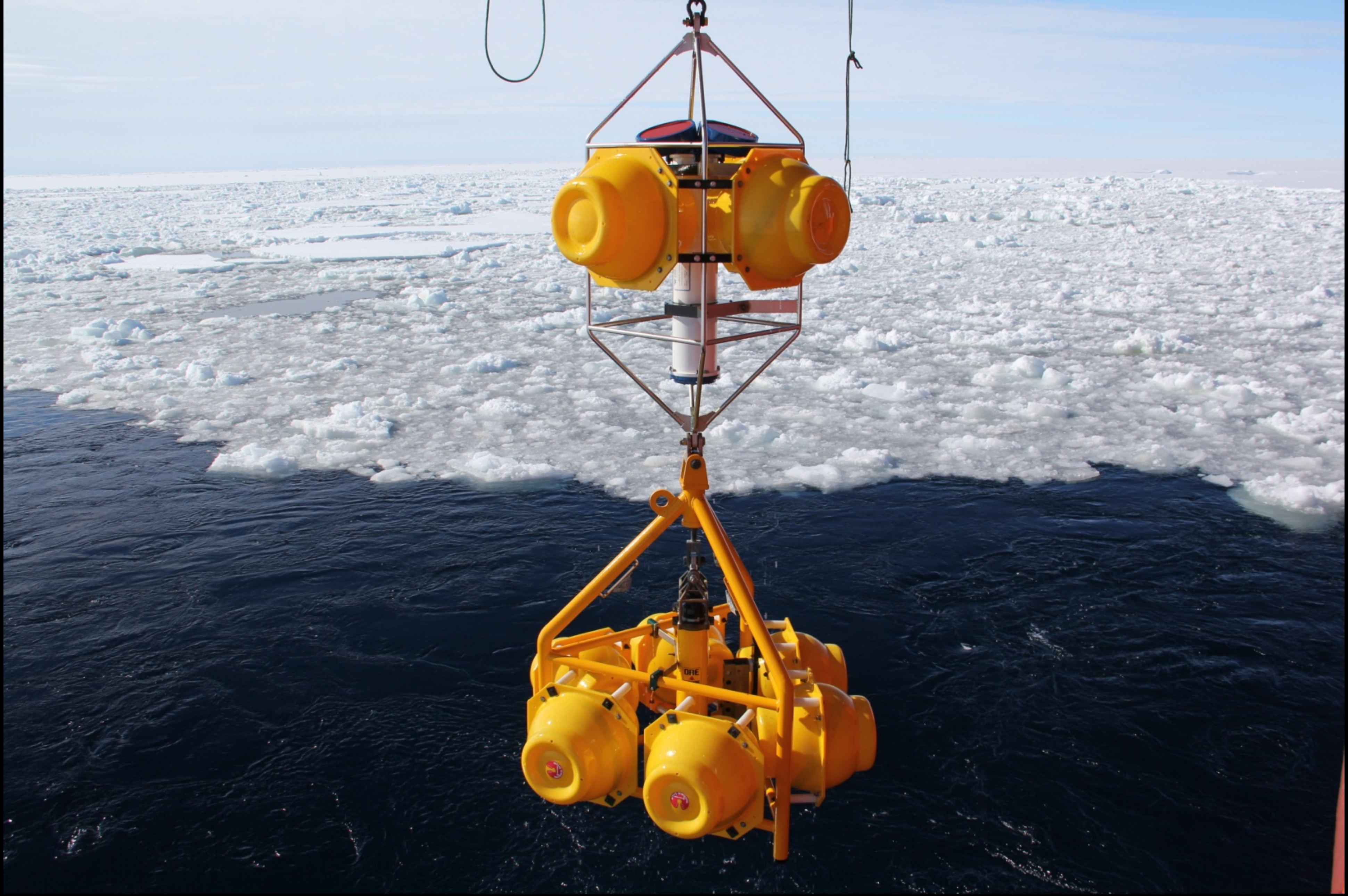
# Lots of warm water on the Totten shelf



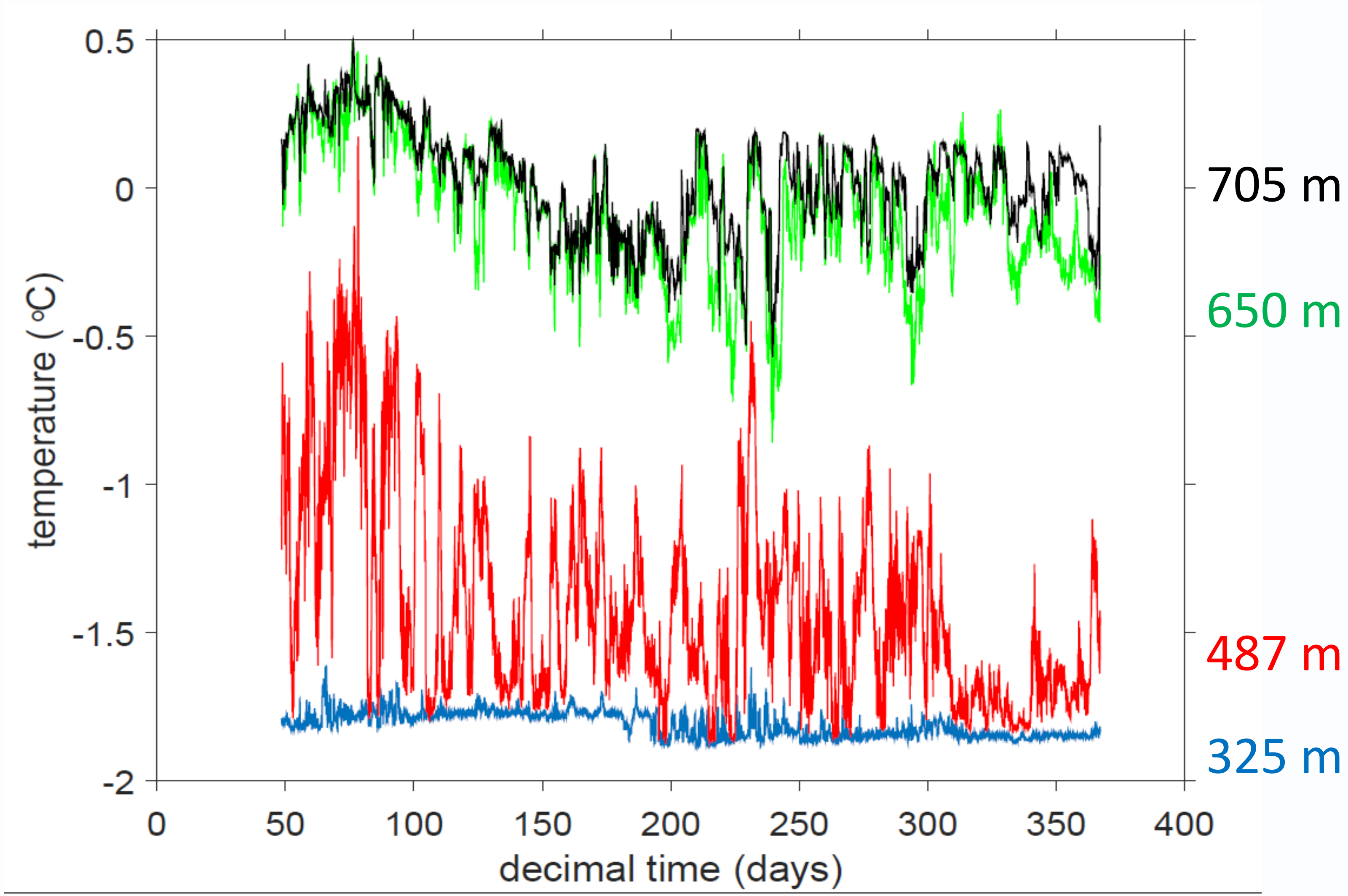
# Not all East Antarctic glaciers are alike




mooring



# Warm water present at depth year-round




Esmee van Wijk

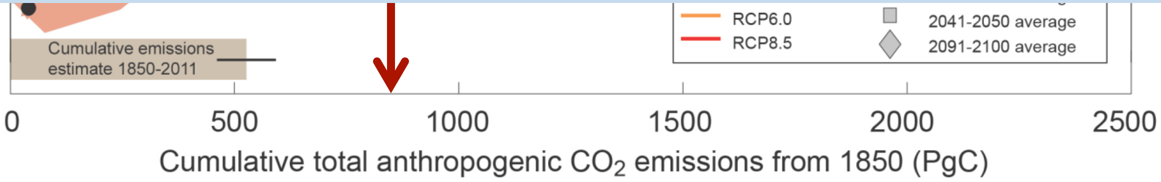
# Time is running out to hit the 2°C target

We have a total of 800 billion tonnes of carbon to spend, if we want a 66% chance of keeping warming < 2°C.

We have already used 550 billion tonnes.

We emit about 10 billion tonnes each year.

We run out of “safe” emissions in 25 years if we keep emitting carbon at the present rate.



# Summary

The oceans have a profound influence on climate.

The Southern Ocean is particularly important – and is changing.

The fate of the Antarctic Ice Sheet lies in the ocean.

The East Antarctic Ice Sheet is likely more vulnerable to ocean change than we thought.

Therefore sea level will likely rise more than we expected.

Continued high emissions commit us to future change that we cannot reverse.

# Thanks to:

Captain & crew of Aurora Australis
Students and colleagues
Antarctic Climate and Ecosystems Cooperative Research Centre
ARC Special Research Initiative for the Antarctic Gateway Partnership
Integrated Marine Observing System
Australian Antarctic Division
CSIRO

# What if we don't hit the 2°C target?

Larger and more rapid change

Increased likelihood of crossing "tipping points"

For sea level, warming greater than 2°C results in an irreversible commitment to >10m of sea level rise

How long it takes to realise this commitment depends on how warm it gets (ie how much carbon we emit)

# Thanks to:

- Captain + crew of Aurora Australis
- Students and colleagues
- Antarctic Climate and Ecosystems CRC
- Australian Research Council Special Research Initiative for the Antarctic Gateway Partnership
- Integrated Marine Observing System
- Australian Antarctic Division
- CSIRO


Peter Schuller

# Open questions:

Has ocean heat flux to the Totten Glacier changed and caused thinning observed by satellite?

Why does so much warm water reach the Totten?

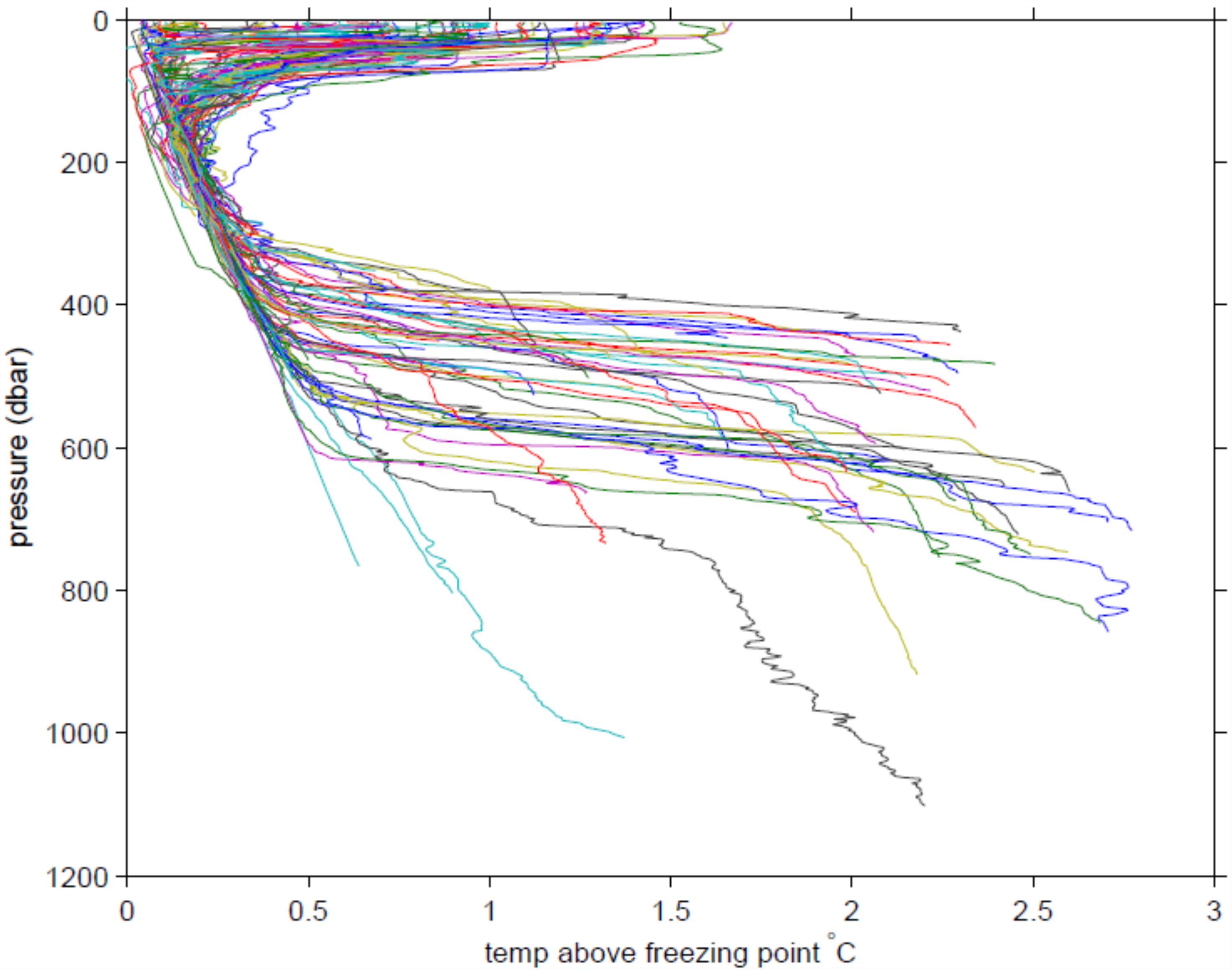
What controls the delivery of ocean heat to the ice shelf?

Does the deep trough observed at the ice front extend to the grounding line?

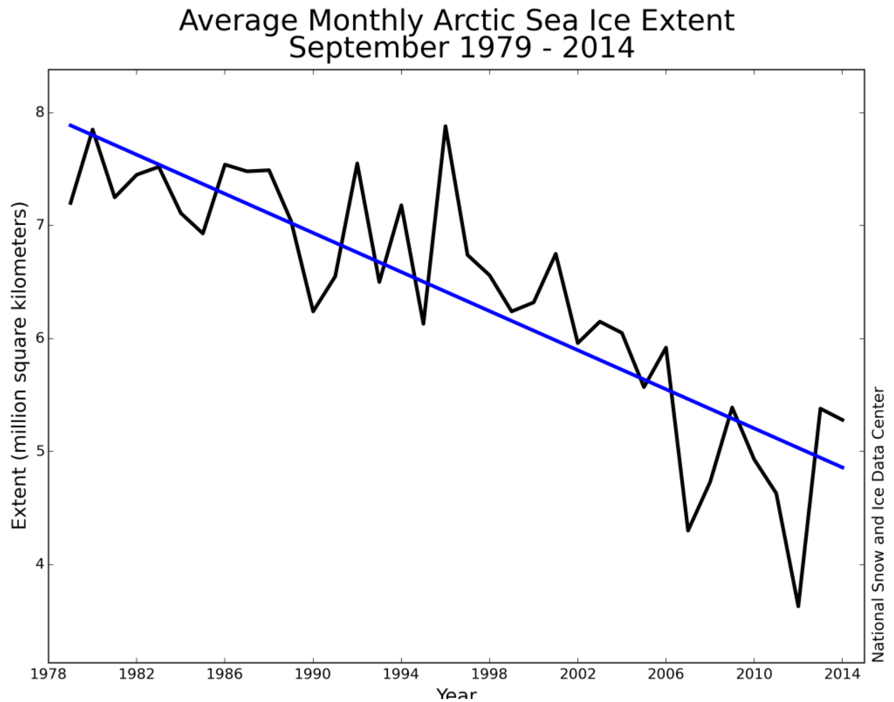
How stable is the Totten Glacier?

How much, and how fast, will the Totten Glacier contribute to global sea level rise?

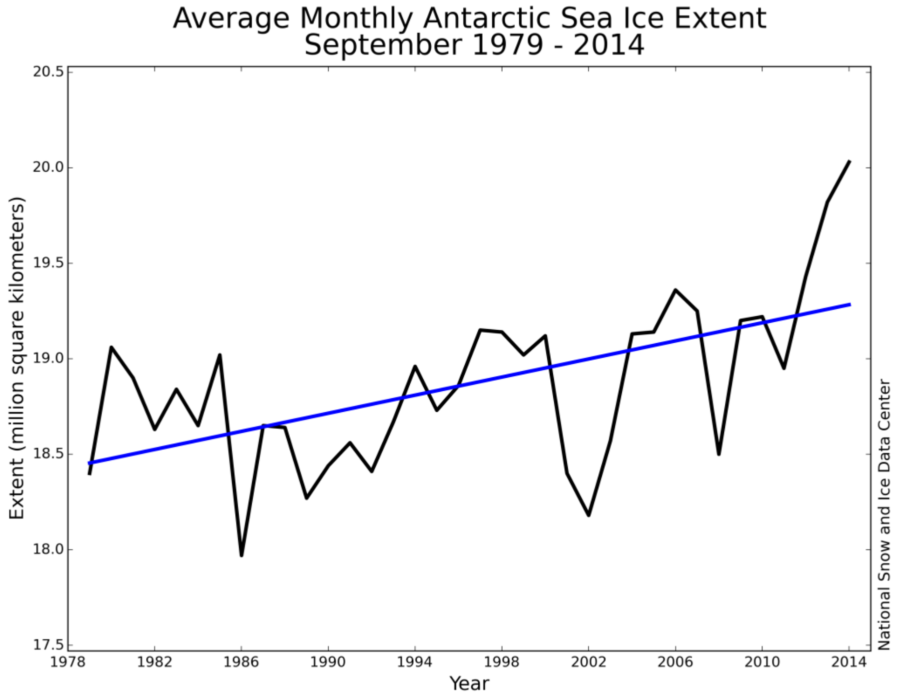
# Temperature above local pressure freezing point



Doug Thost




**Arctic:** summer minimum sea ice extent is decreasing by 10% per decade



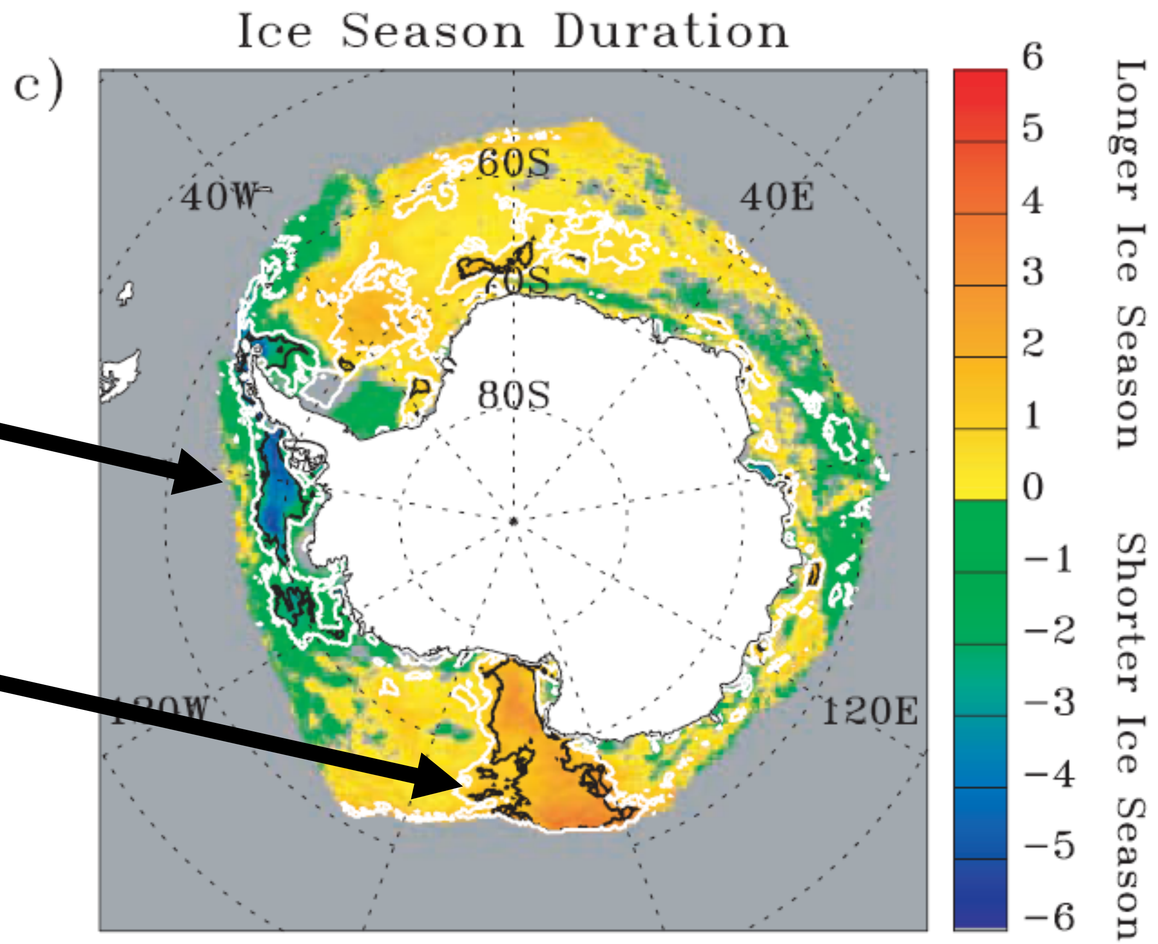

**Antarctic:** winter maximum sea ice extent is increasing by 1.3% per decade

# Large regional changes in Antarctic sea ice

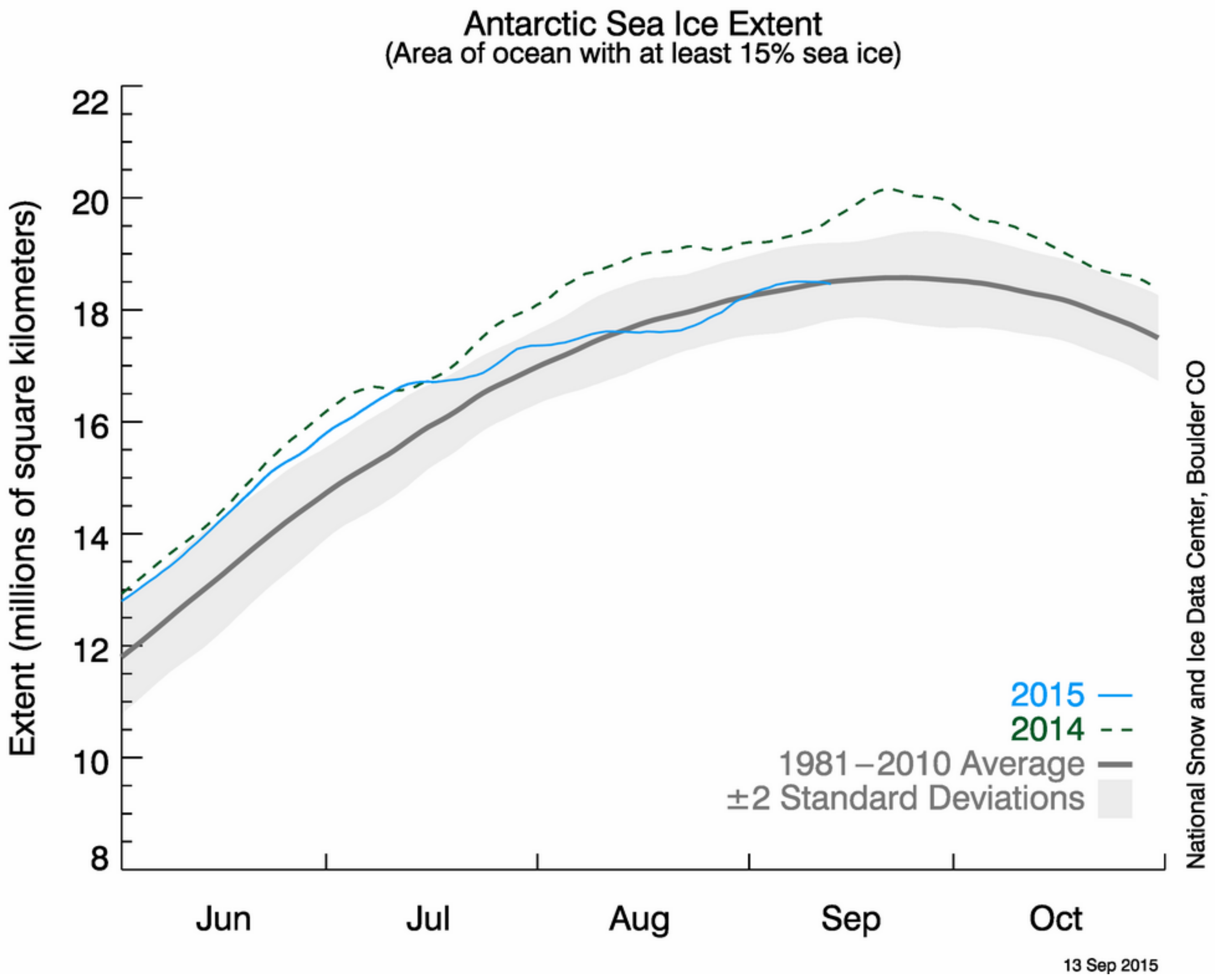
Changes in sea ice duration: 1979 – 2006

-83 ± 23 days

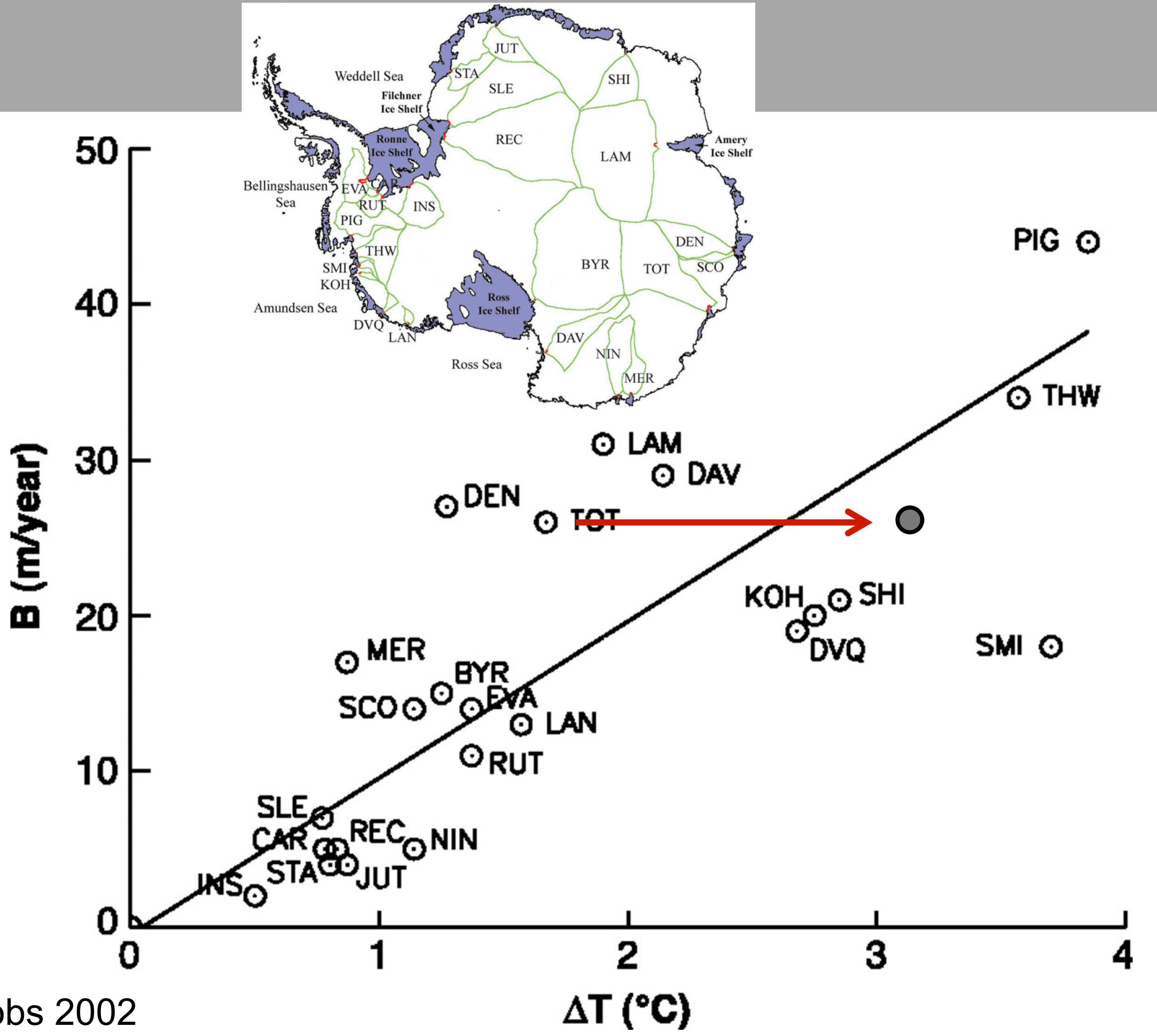
57 ± 13 days



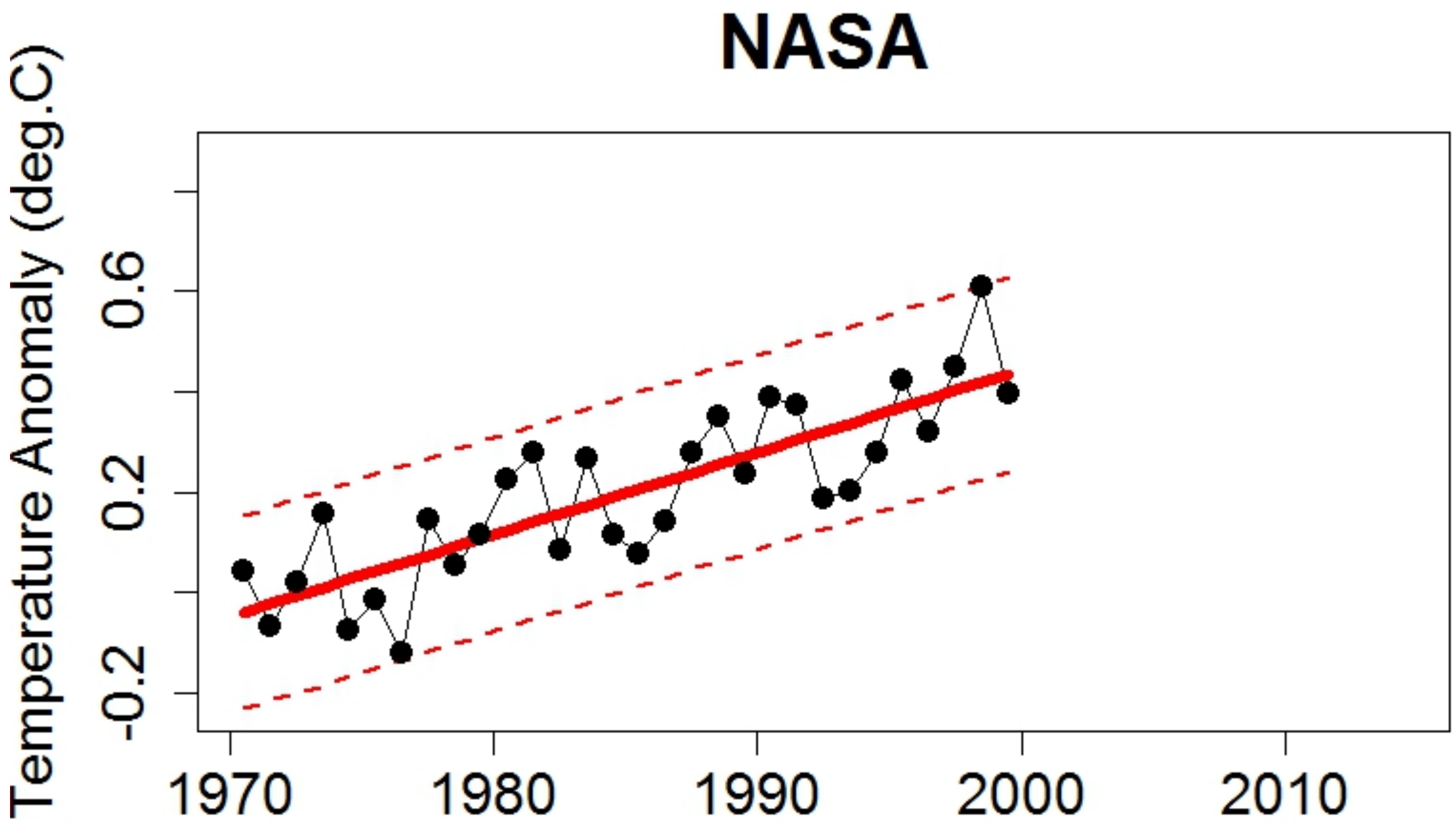

Stammerjohn et al. (2008)



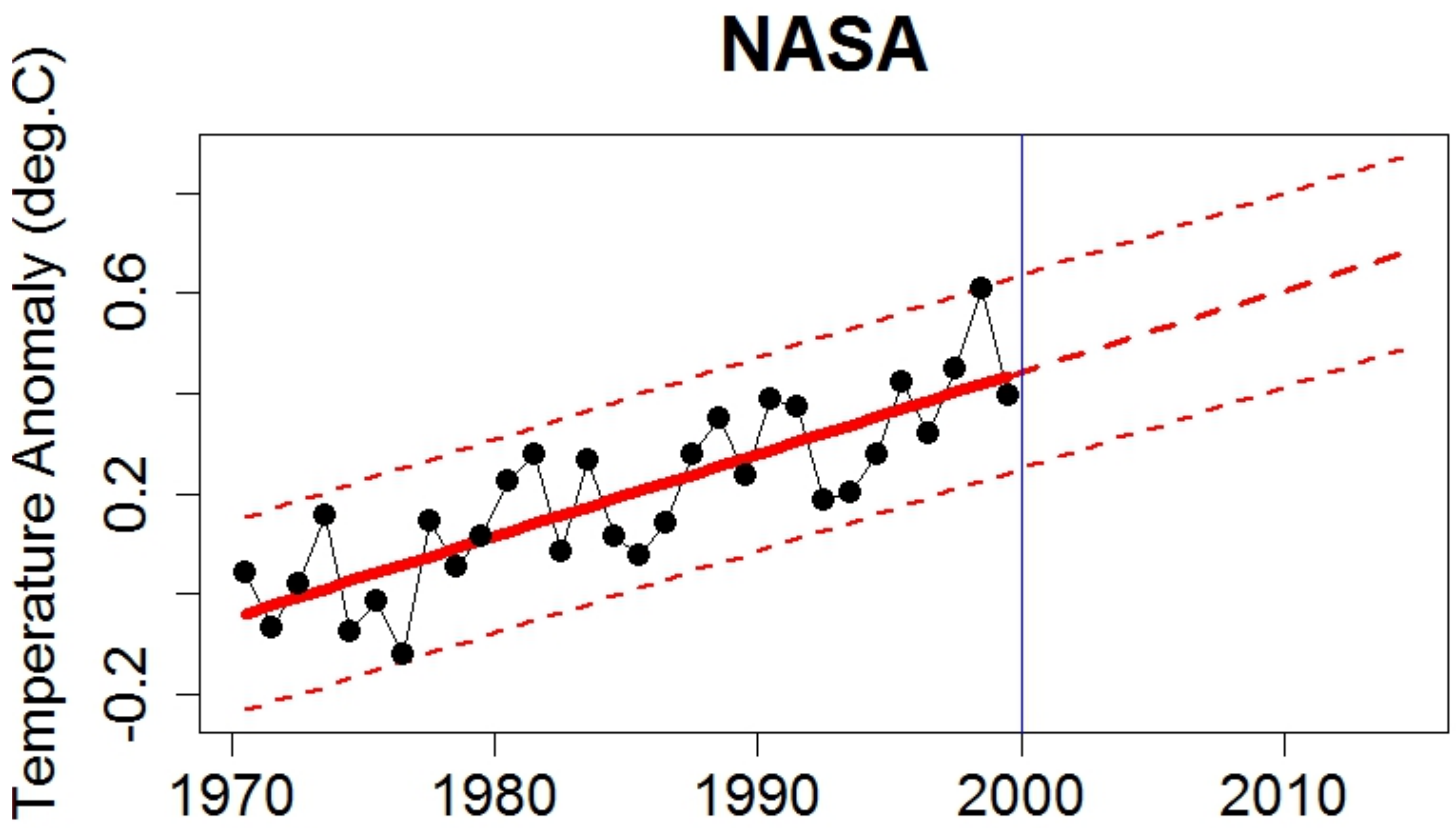
Antarctic Sea Ice Extent
(Area of ocean with at least 15% sea ice)
Extent (millions of square kilometers)
22
20
18
16
14
12
10
8
Jun
Jul
Aug
Sep
Oct
2015
2014
1981–2010 Average
±2 Standard Deviations
National Snow and Ice Data Center, Boulder CO
13 Sep 2015

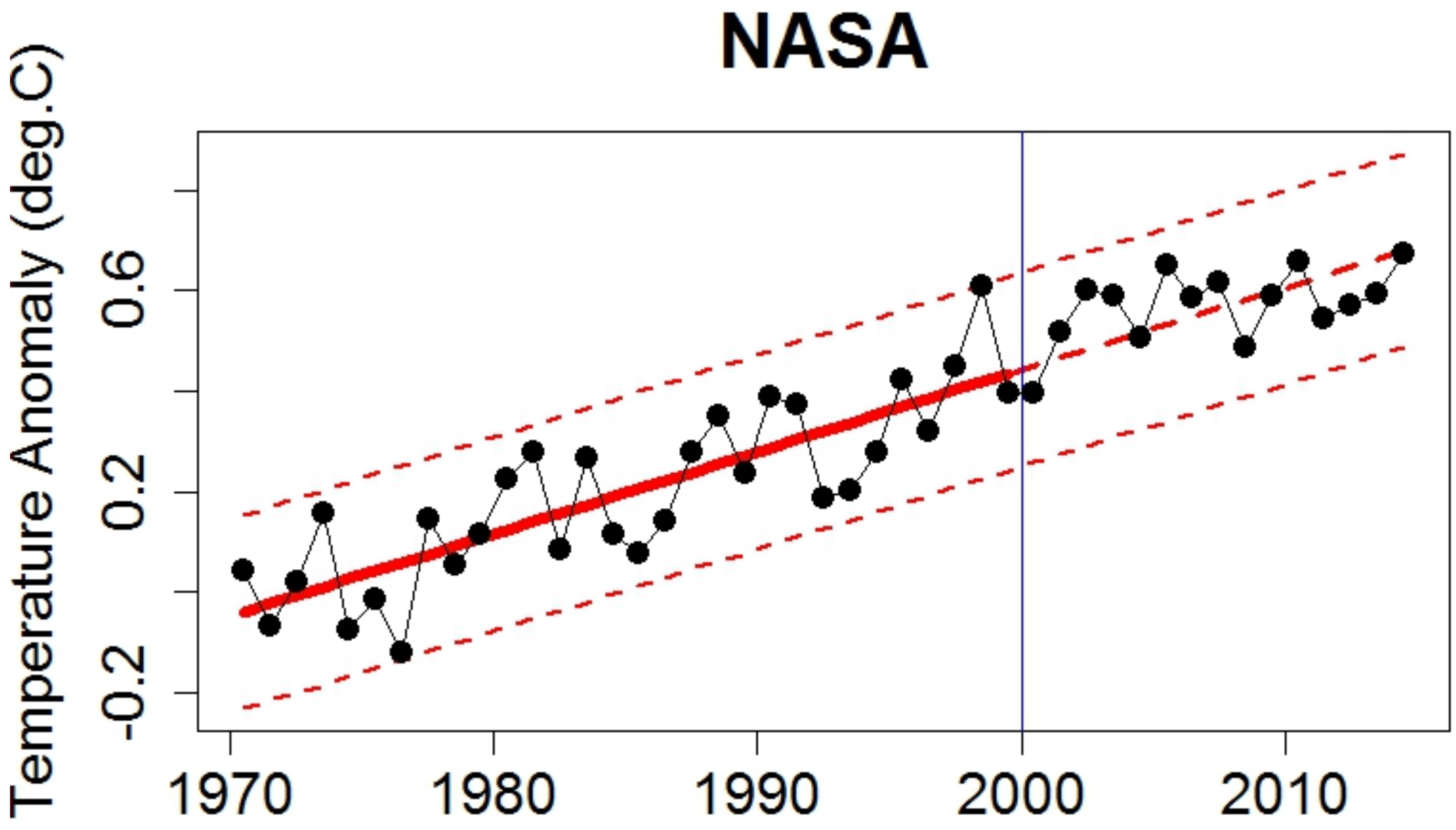



Rignot & Jacobs 2002

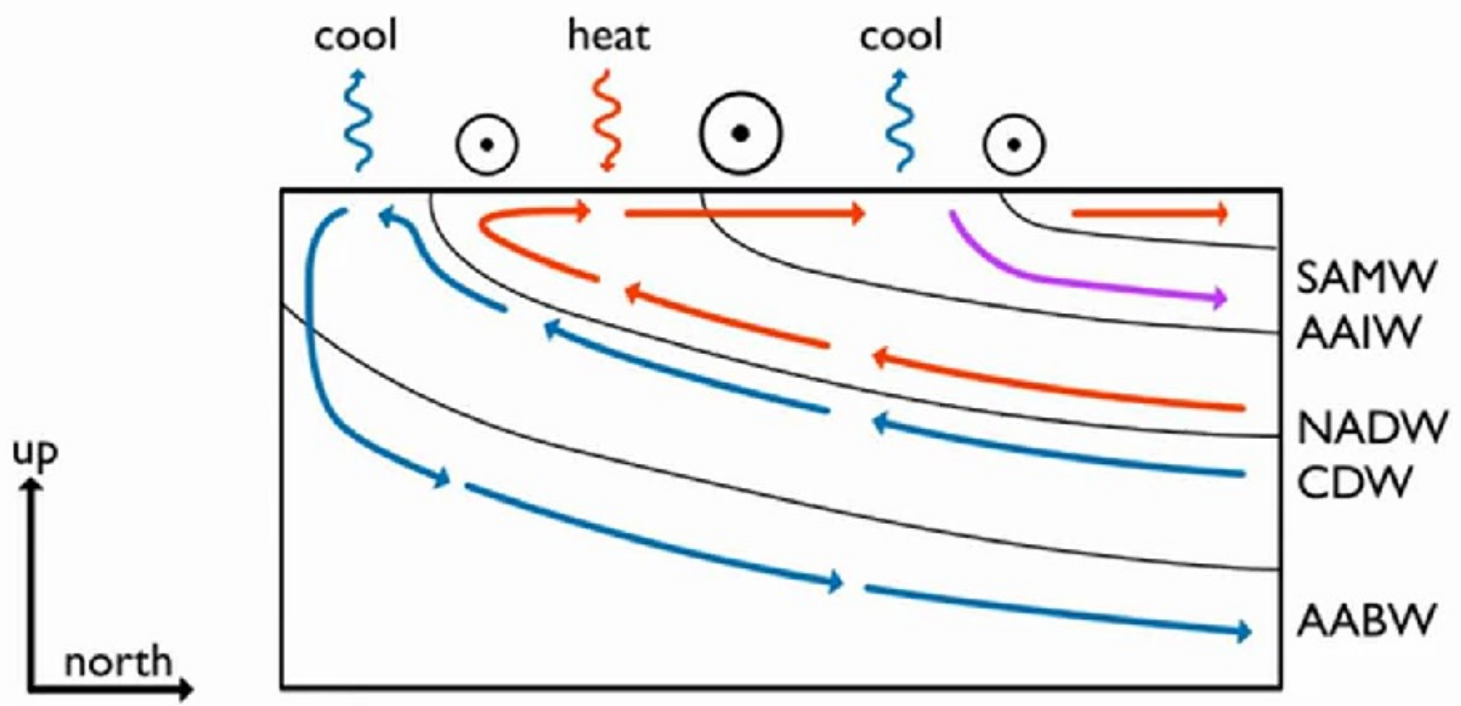



https://tamino.wordpress.com/2015/01/20/its-the-trend-stupid-3/


NASA
Temperature Anomaly (deg.C)
-0.2
0.2
0.6
1970
1980
1990
2000
2010


NASA
Temperature Anomaly (deg.C)
-0.2
0.2
0.6
1970
1980
1990
2000
2010

# The overturning circulation and the Antarctic Circumpolar Current are linked




Abernathey et al., 2011; https://vimeo.com/17822148

# Headlines of IPCC 5th Assessment Report

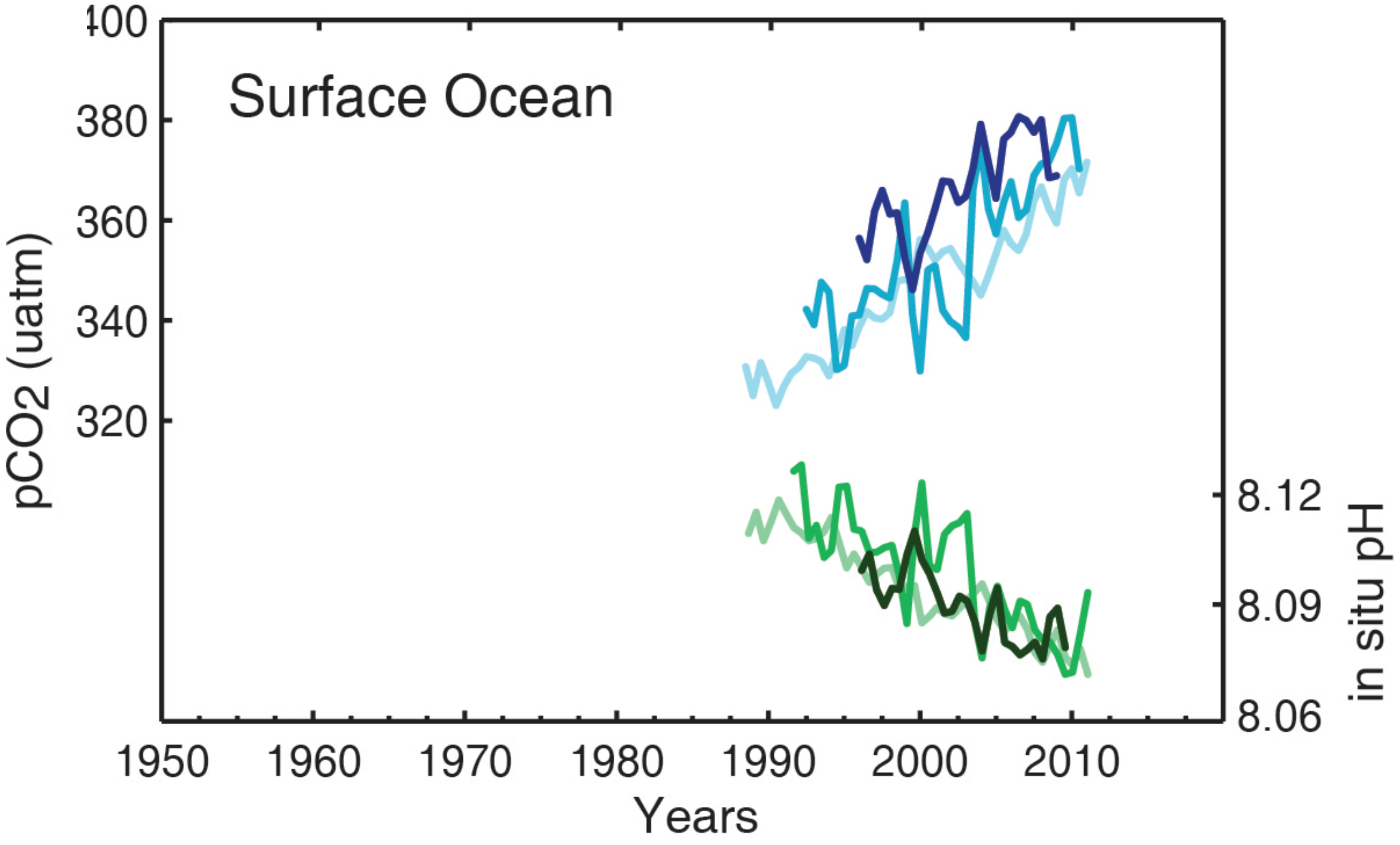
• Warming is unequivocal. Many observed changes are unprecedented on timescales of decades or millenia.

• Human influence on climate is clear.

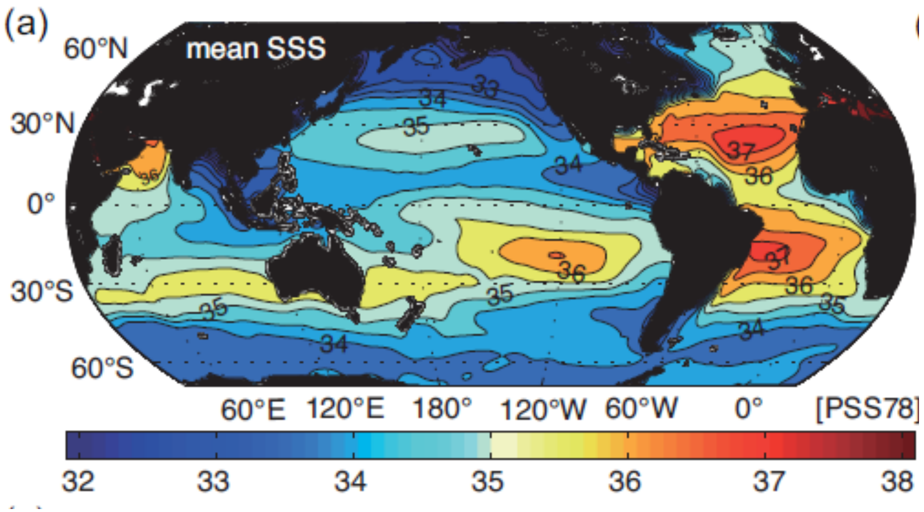
• Climate will continue to change in future.

• Limiting climate change will require substantial and sustained reductions in emissions.

# Ocean uptake of carbon dioxide is acidifying the ocean



# Changes in ocean salinity:  the ocean "rain gauge"




1 Circumpolar Current =

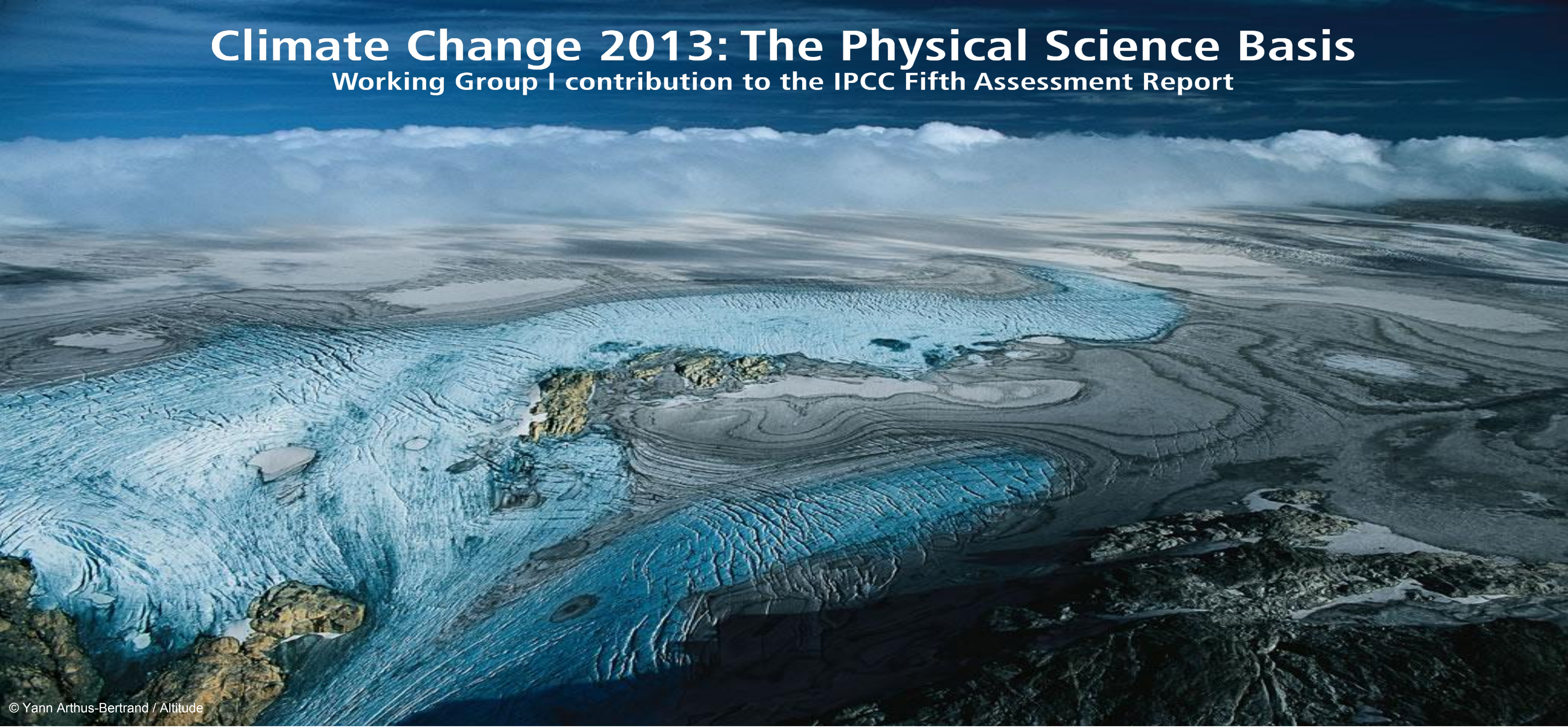
454 billion stubbies/second

# West Antarctic Ice Sheet

- Contains ice volume equivalent to 5 m of global sea level rise (3.3 m in marine-based ice sheet)
- Marine ice sheet – potentially unstable
- Has collapsed and re-formed many times in the past
- Thinning rapidly, at accelerating rate – marine ice sheet instability already underway? (Joughin et al., 2014; Rignot et al., 2014; Favier et al., 2014)
- Thinning result of basal melt of the floating ice shelves
- West Antarctica believed to be more vulnerable to basal melt because it is closer to warm waters of the ACC – the "soft underbelly of the Antarctic Ice Sheet" (Hughes, 1980)

# Climate Change 2013: The Physical Science Basis

## Working Group I contribution to the IPCC Fifth Assessment Report

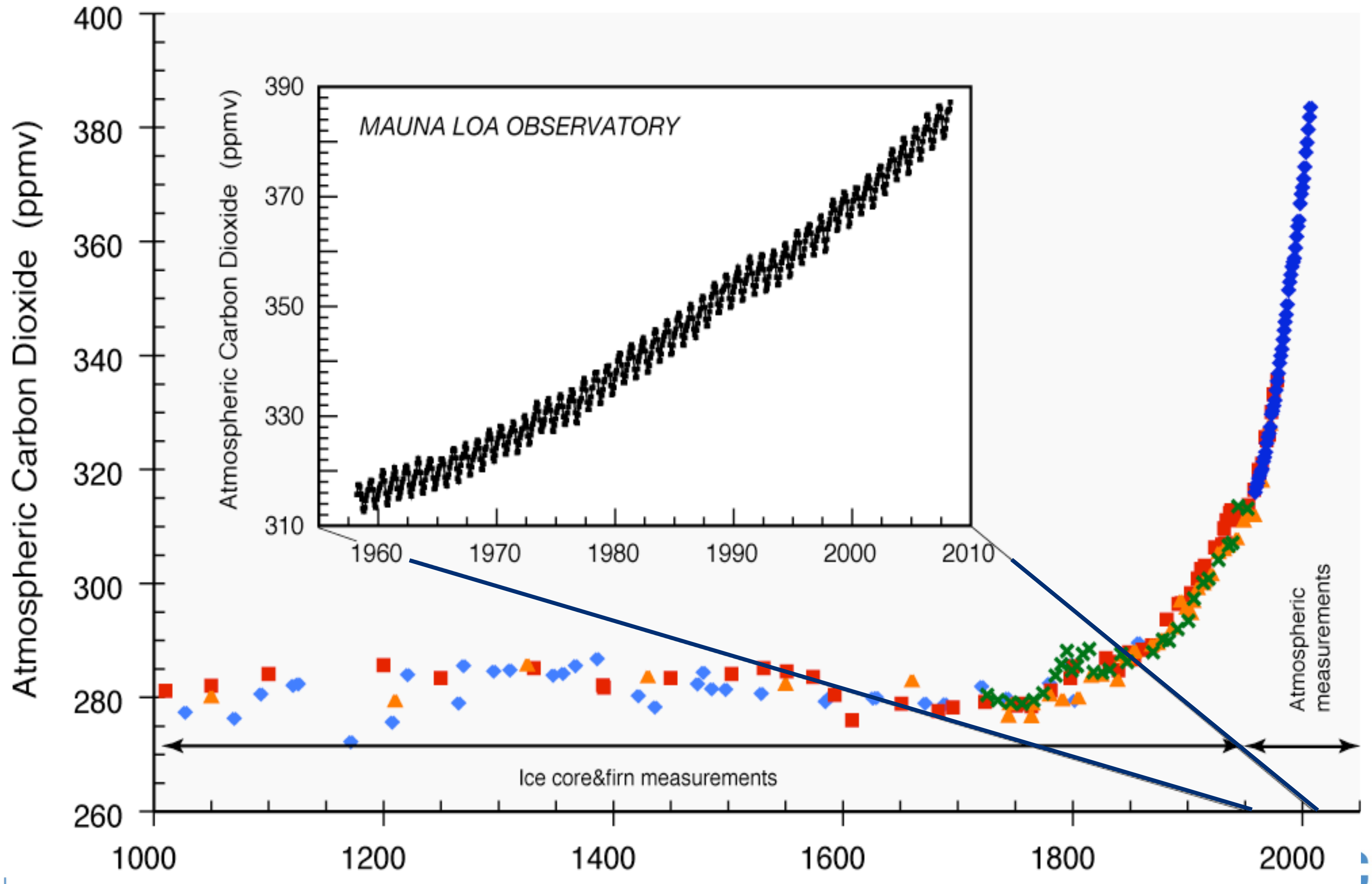




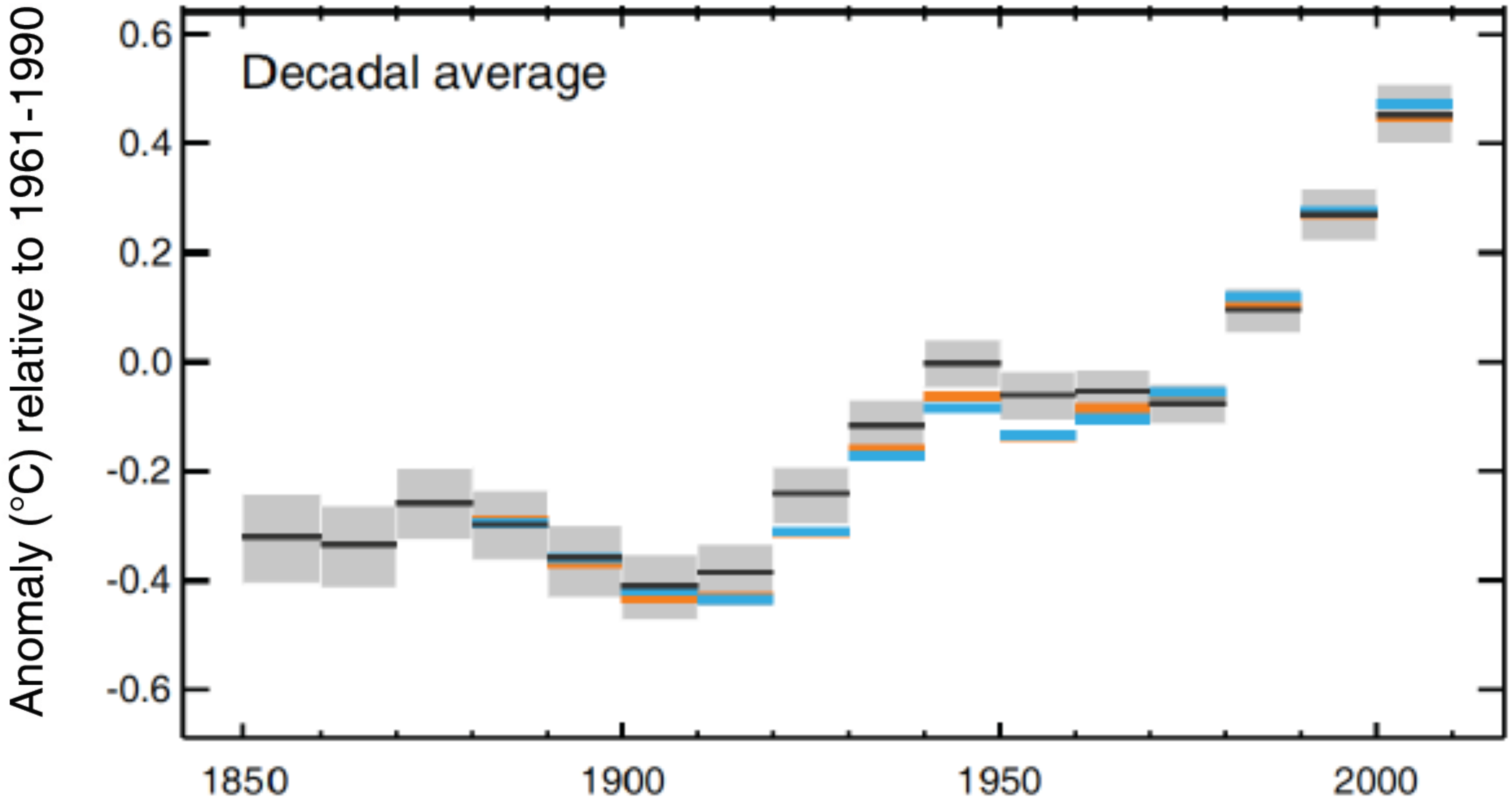

ipcc
INTERGOVERNMENTAL PANEL ON climate change

WMO UNEP

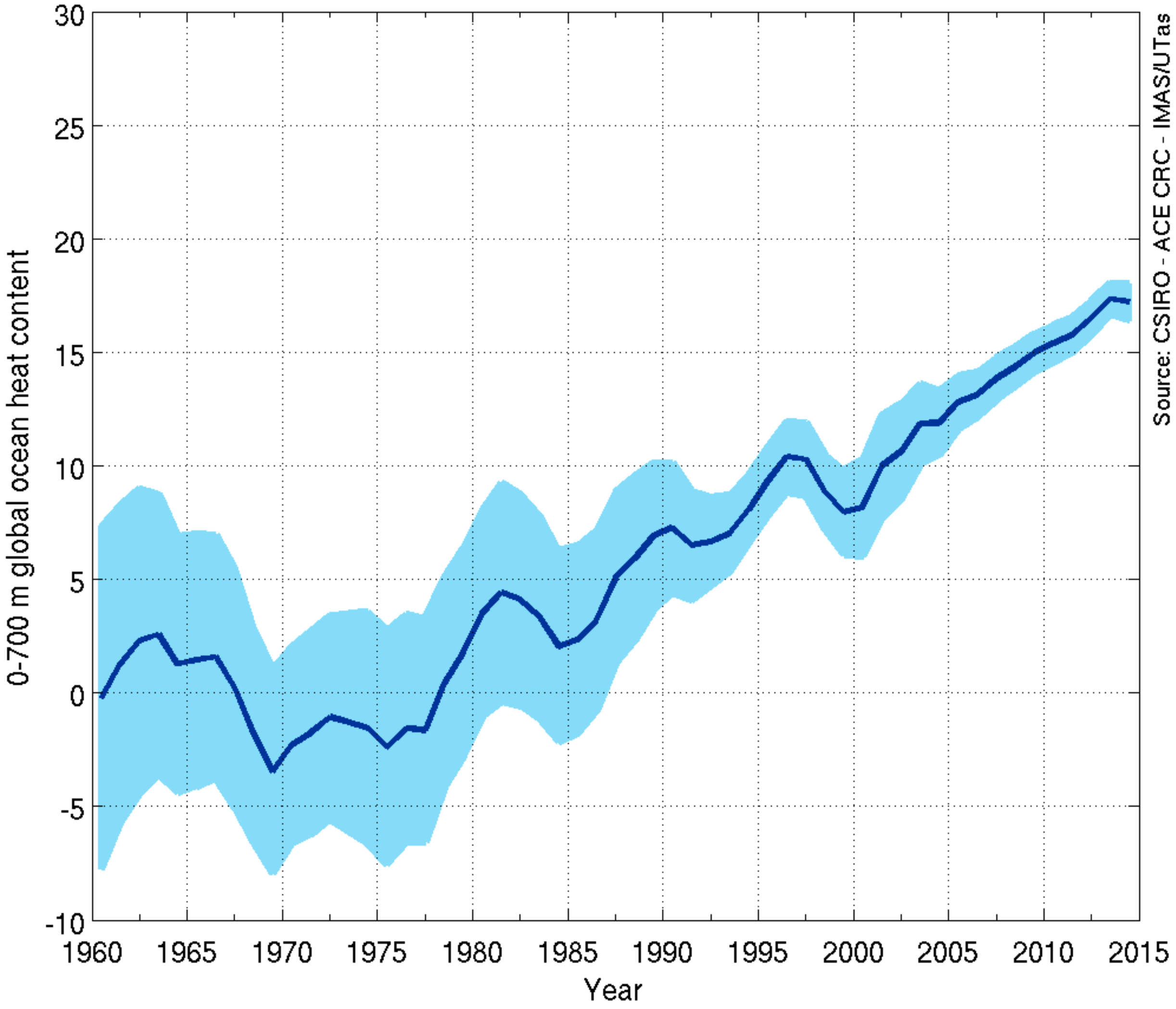
# Atmospheric carbon dioxide has increased by 40%



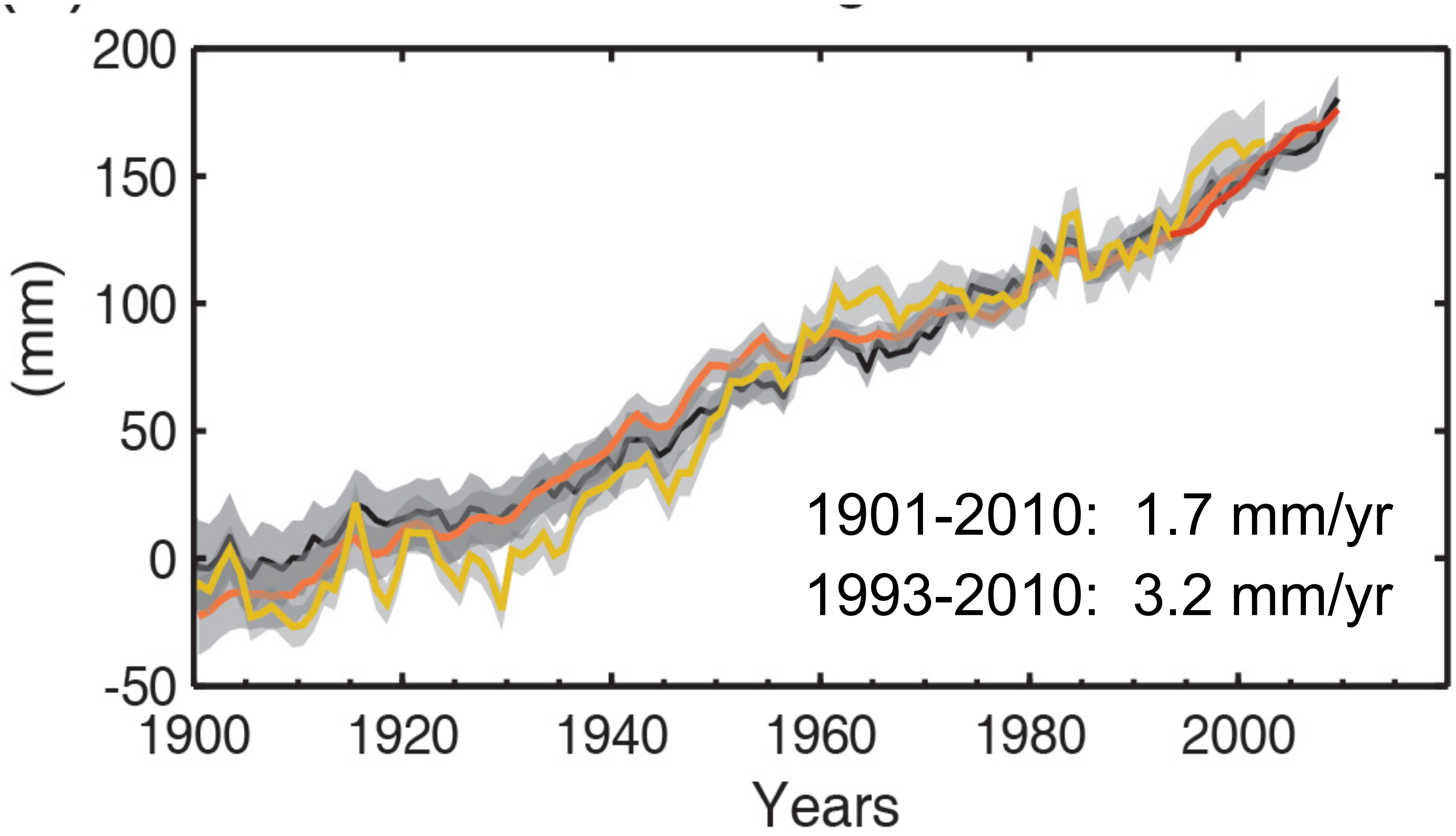
# Each of the last three decades has been warmer than any previous decade since 1850.



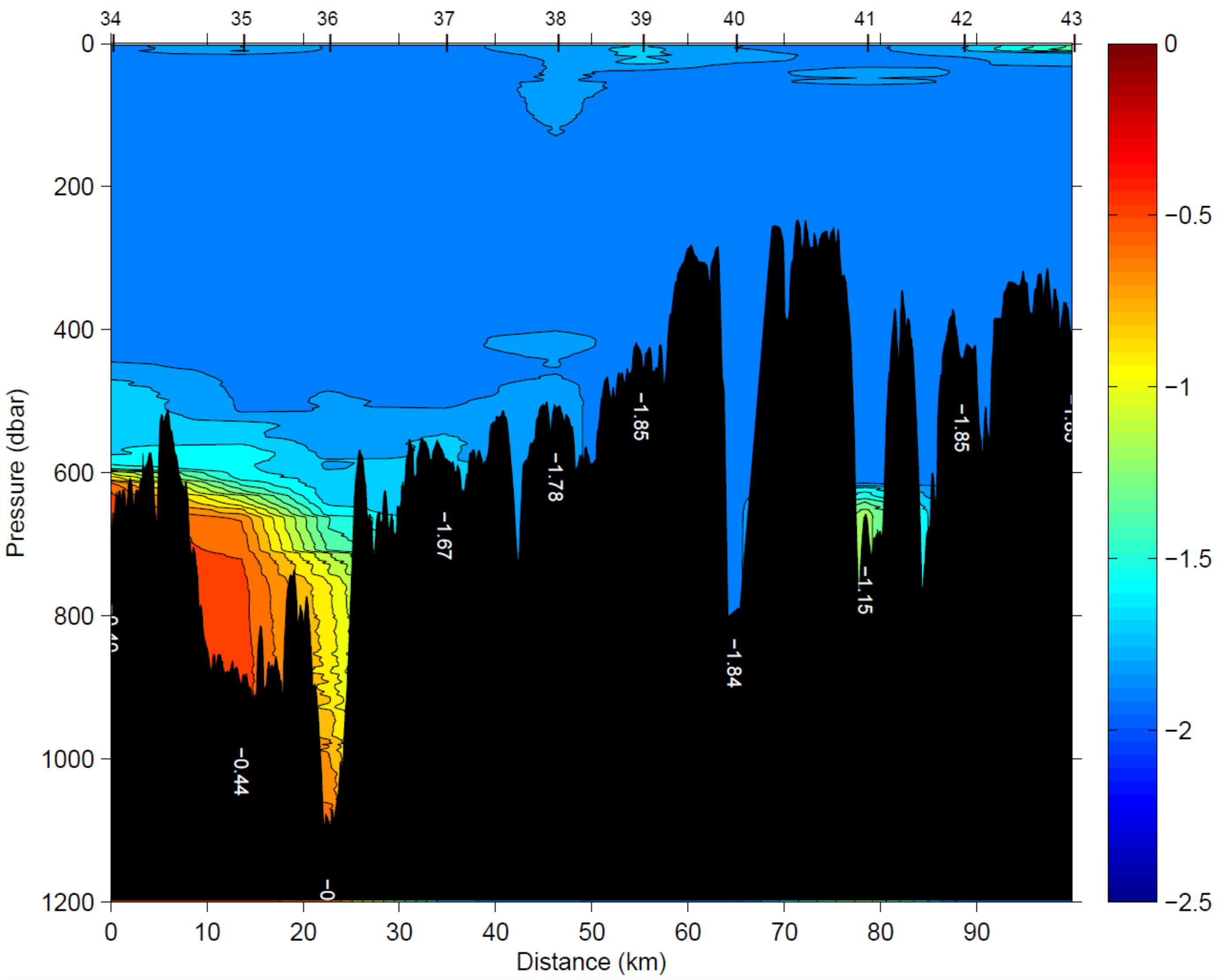
# The ocean has warmed since 1970



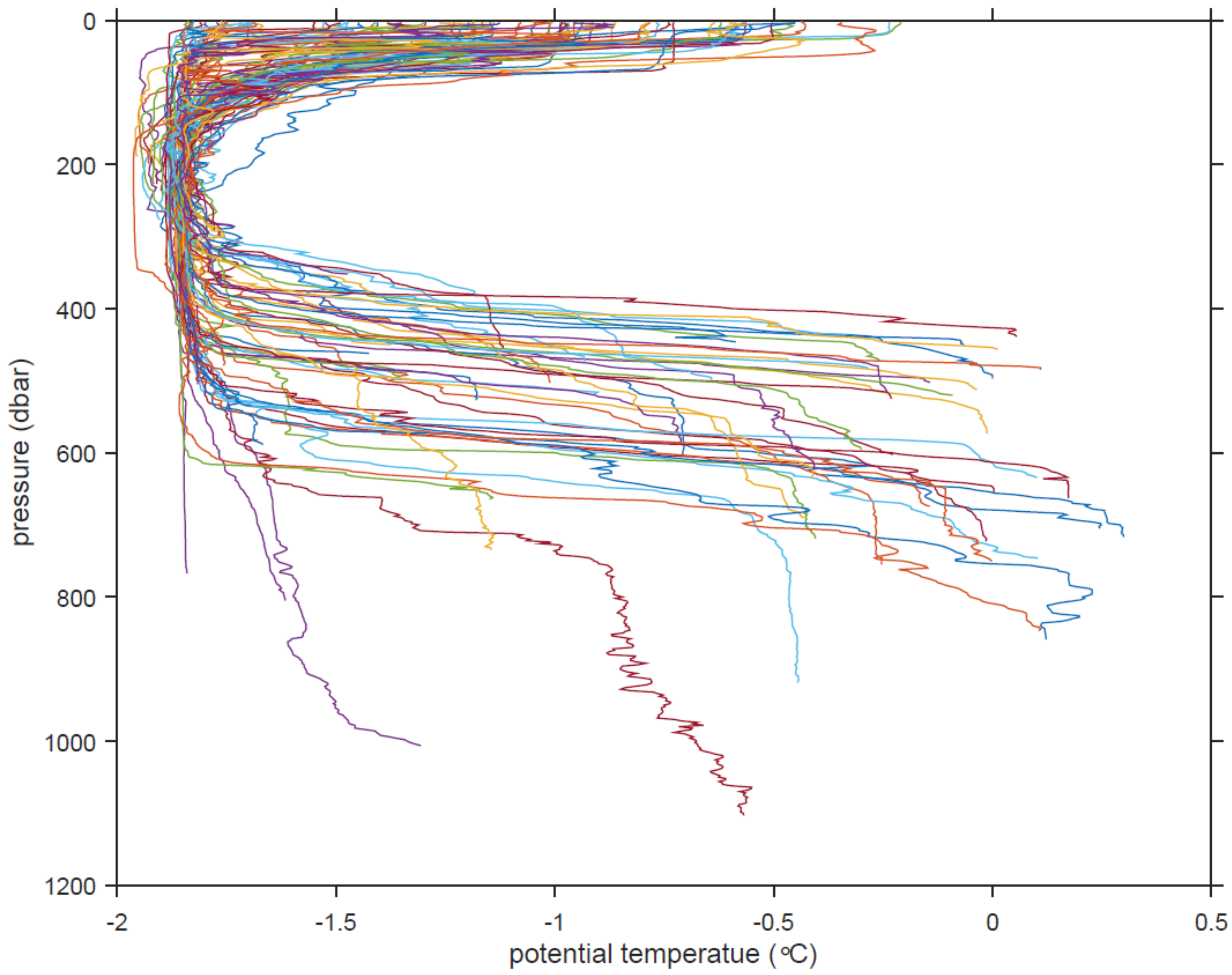
# Global mean sea level increased by 0.19 m between 1901 and 2010



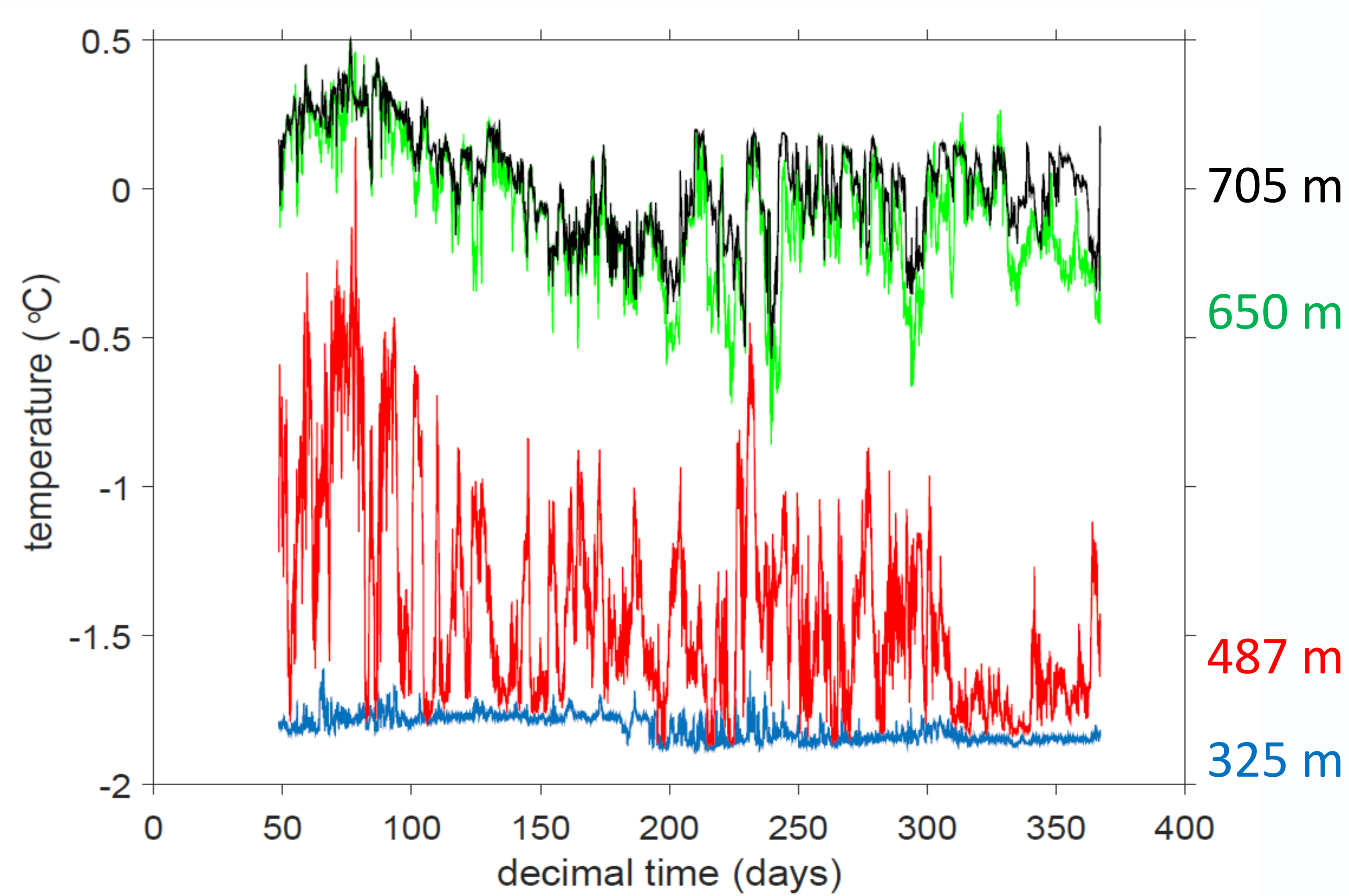
# A deep channel at the Totten ice front allows warm water to enter ice-shelf cavity



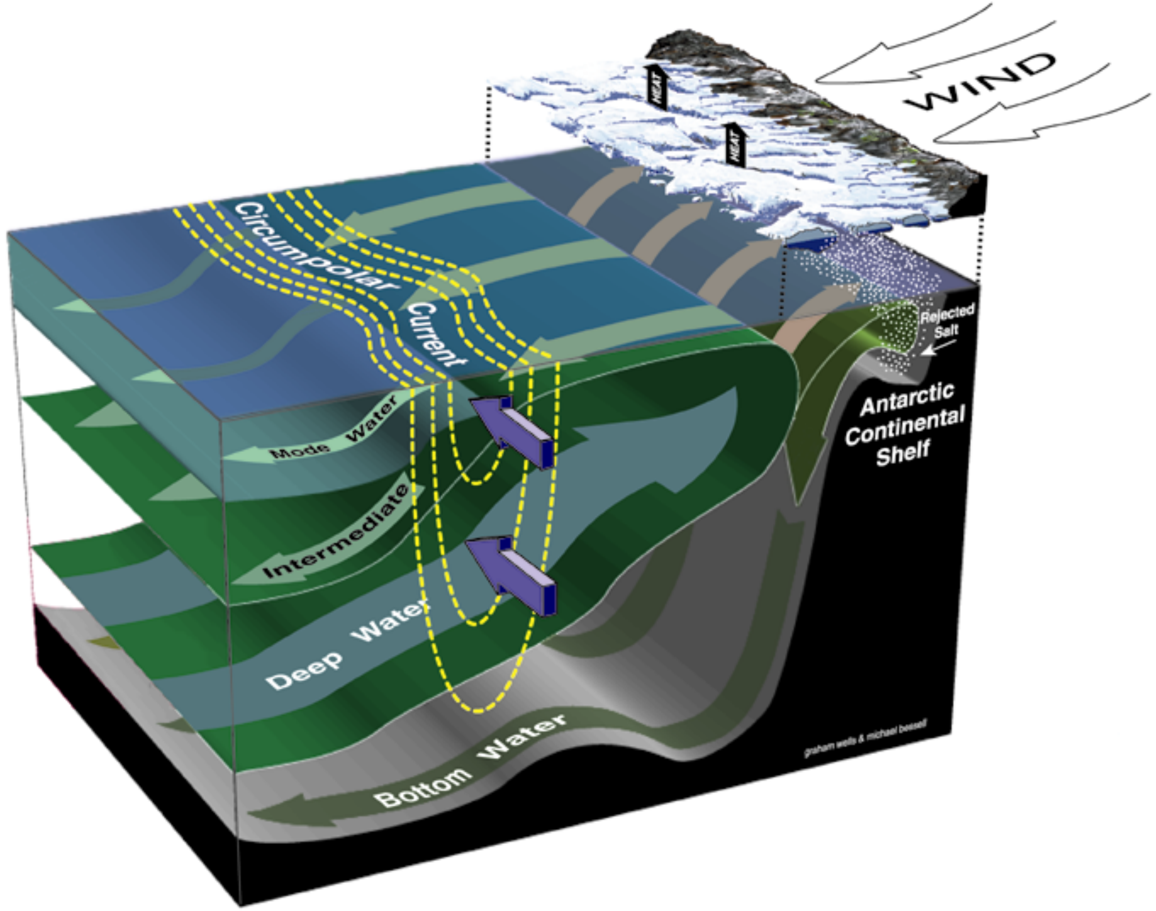
# Lots of warm water on the Totten shelf



# Warm water present at depth year-round



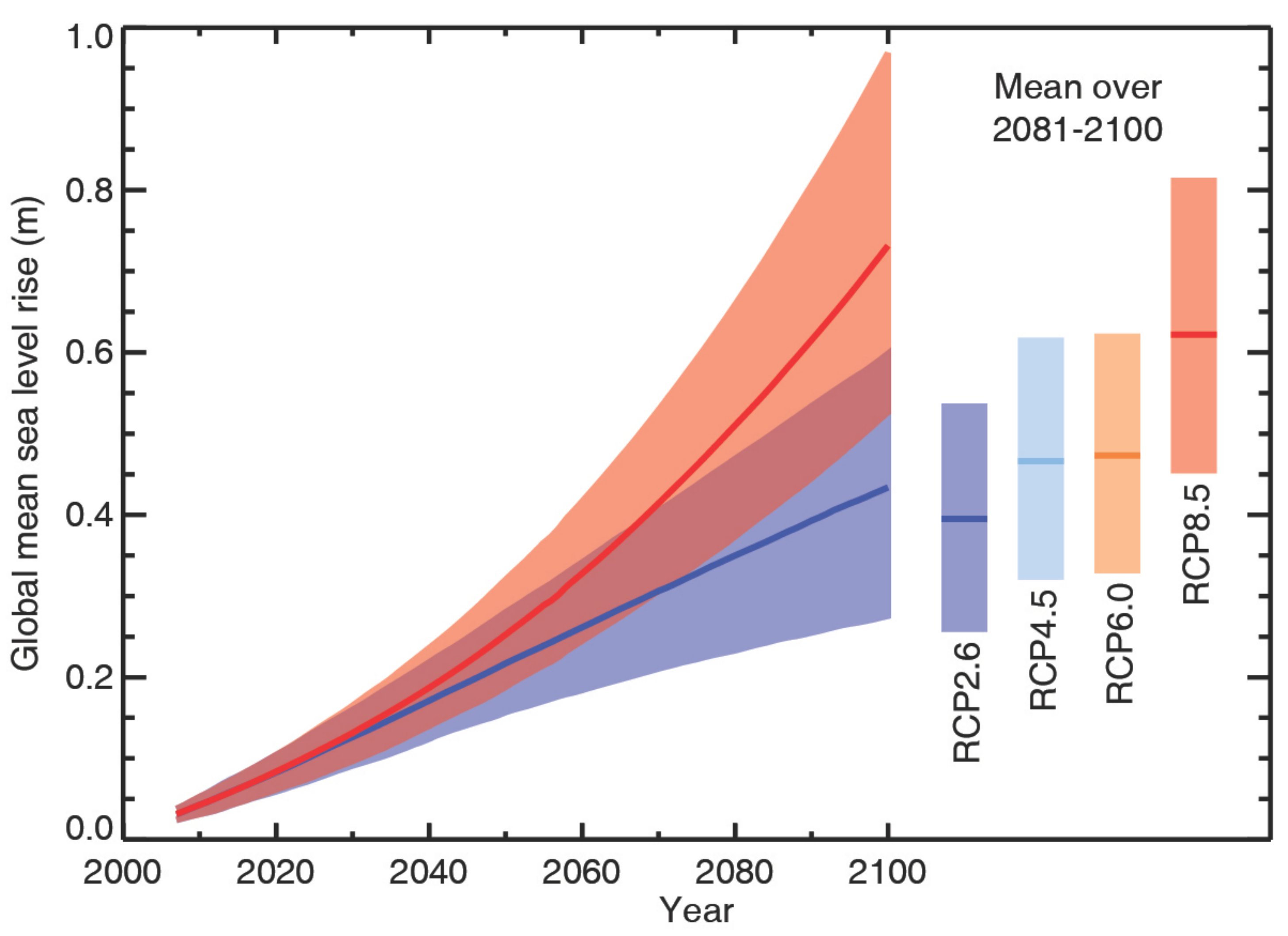
# How will warming, freshening and changes in winds influence the overturning circulation?



# How will ocean acidification (and other stressors) affect marine ecosystems?


# How will warming and changes in circulation affect ice shelves and sea level rise?

# Future sea level rise



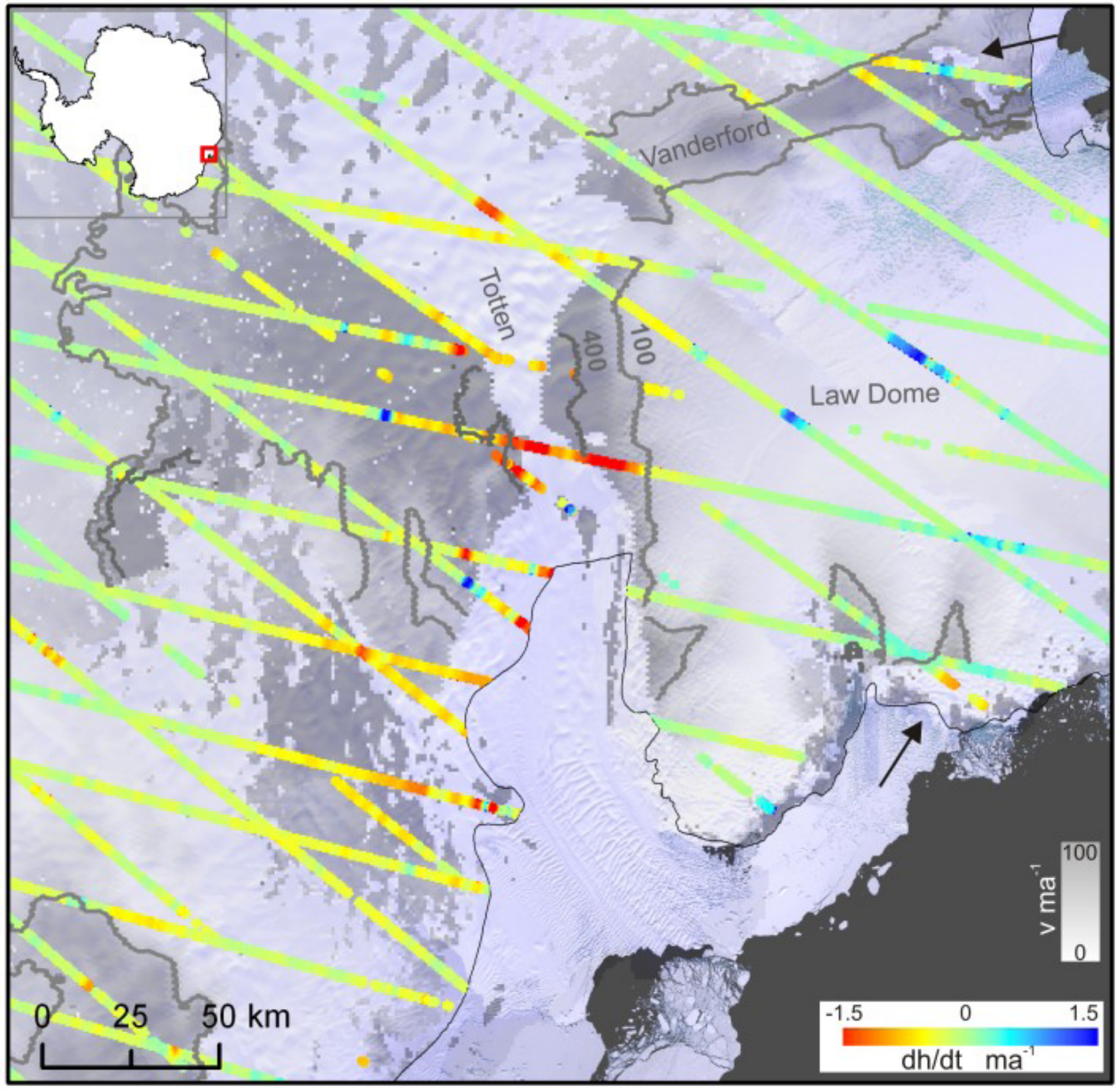
# Sea level rise beyond 2100: IPCC

It is *virtually certain* that global mean sea level rise will continue for many centuries beyond 2100.

By 2300, there is *medium confidence* that GMSL rise will be less than 1 m if $CO_2$ concentrations stay below 500 ppm, but 1 to more than 3 m for 700–1500 ppm.

Larger sea level rise could result from sustained mass loss by ice sheets, and some part of the mass loss might be irreversible.

# What does the future hold?






Pritchard et al 2009 Nature (Supp Info)

# Potential temperature at Mertz Glacier