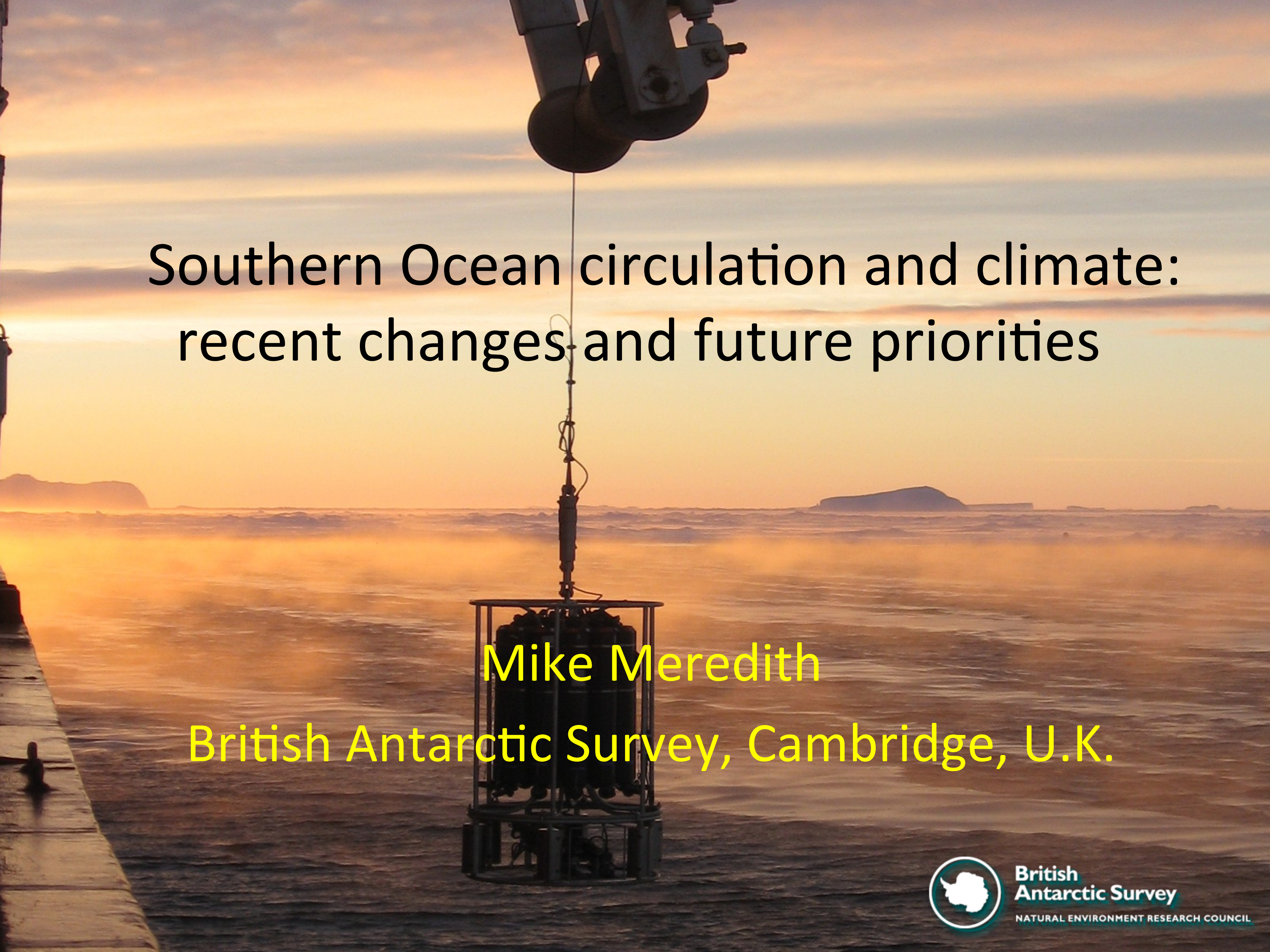

Southern Ocean circulation and climate: recent changes and future priorities

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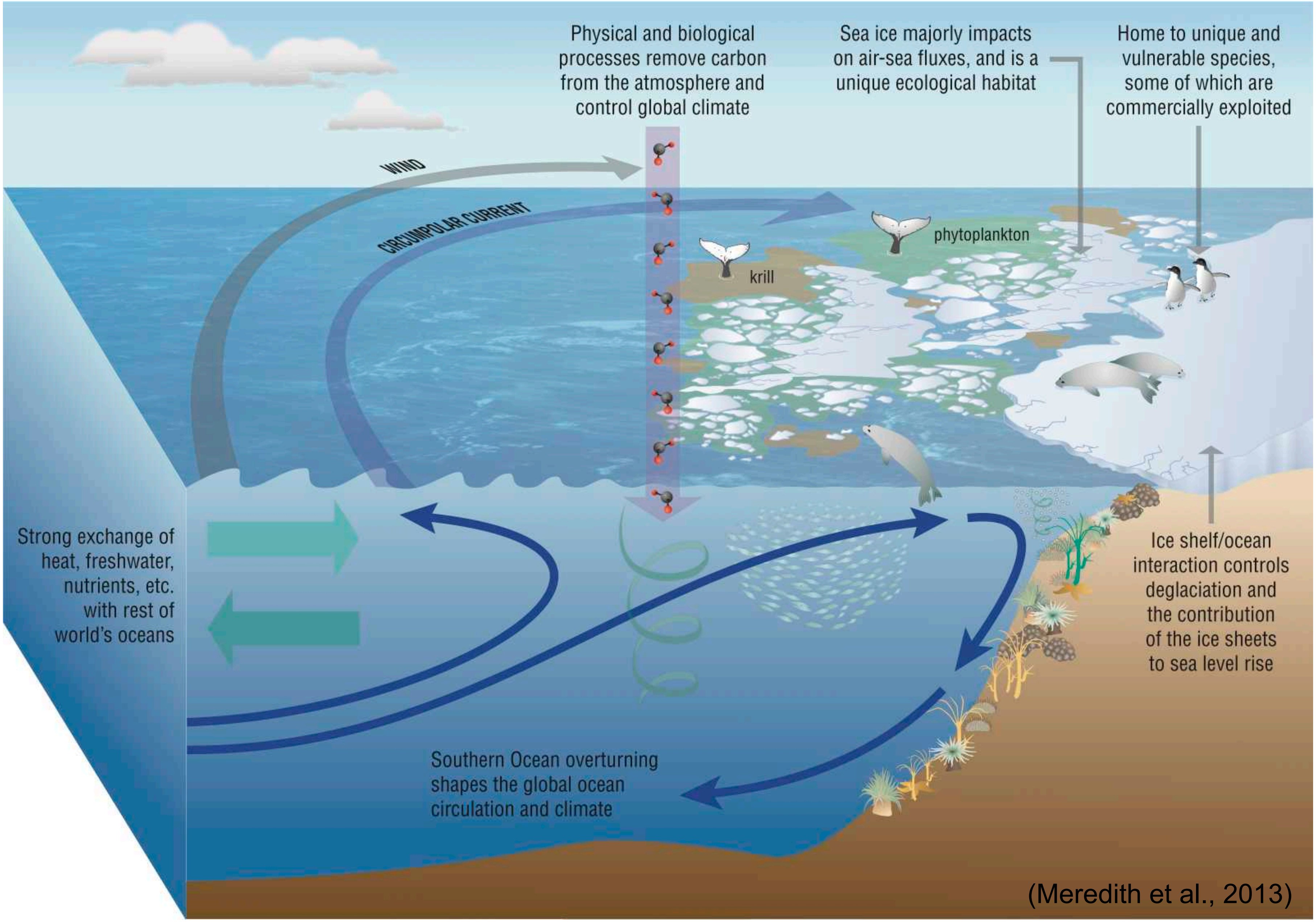
Aim of talk

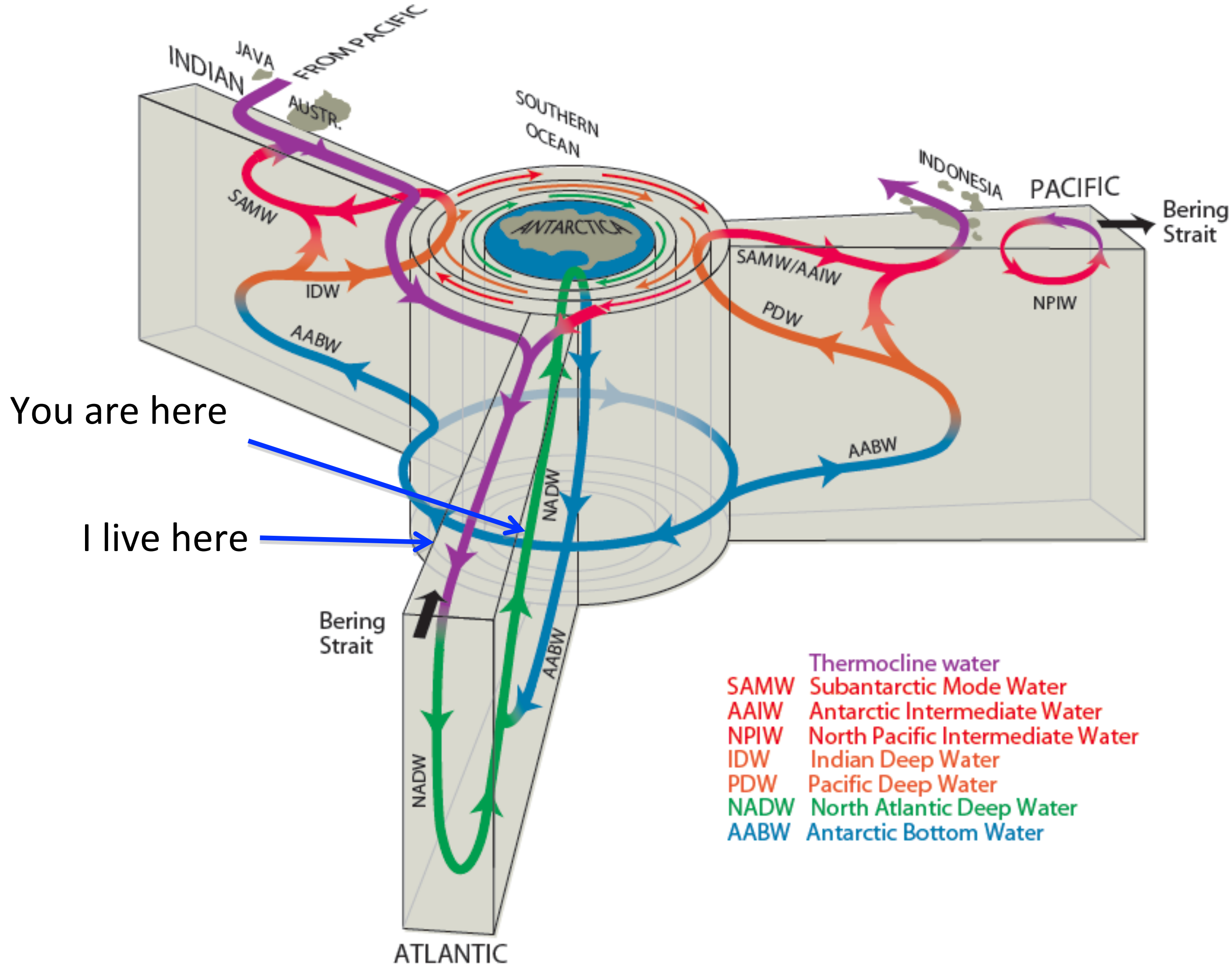
To give an overview of:-

– What do we know about how the Southern Ocean is changing, and why?
– How do these things matter?
– What are the gaps?
– What are the priorities for action?



An overview of scientific and societal drivers…

Schematic of the global ocean overturning circulation.



The whole climate system would look different if the Southern Ocean were different. Worth understanding it.

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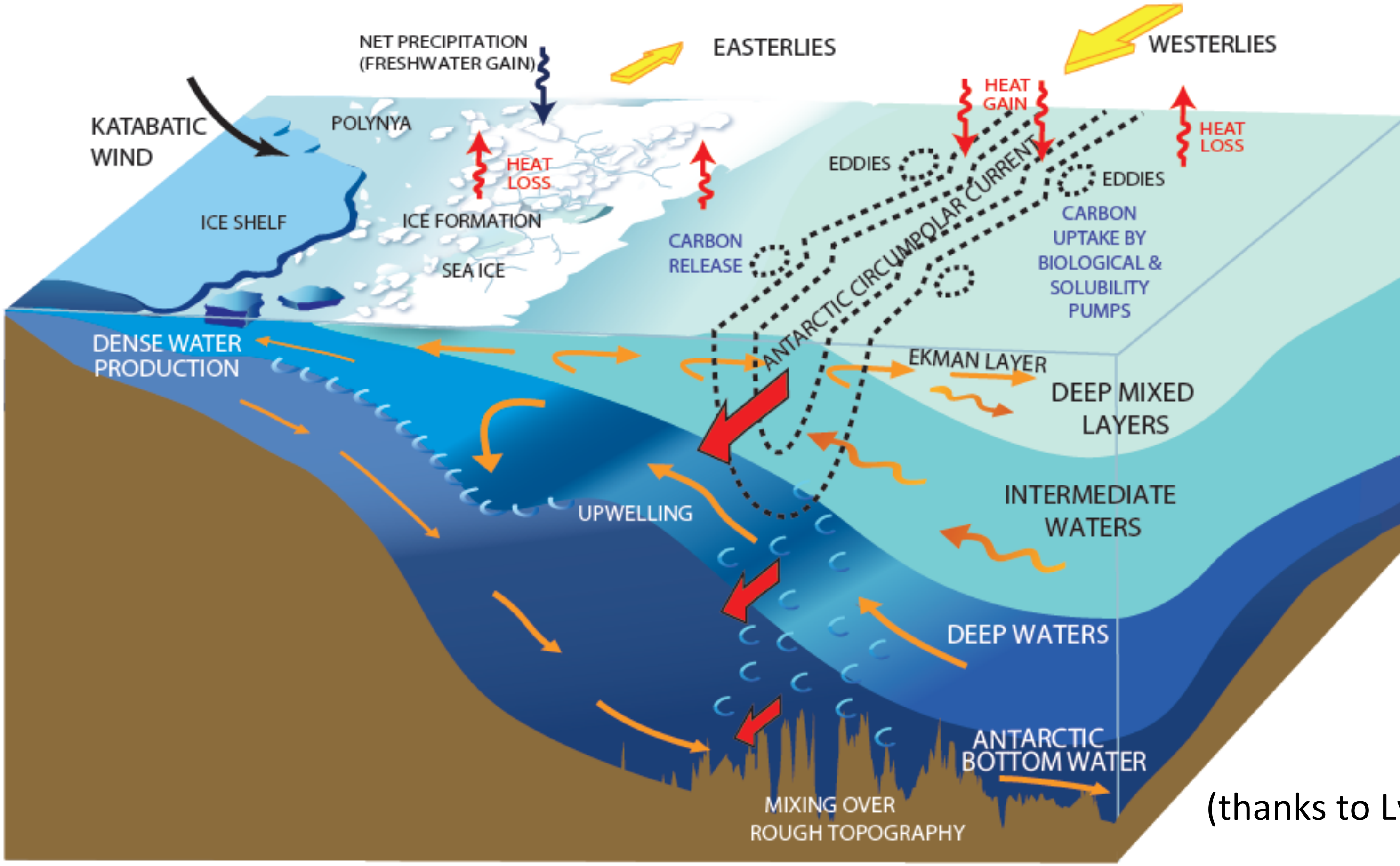
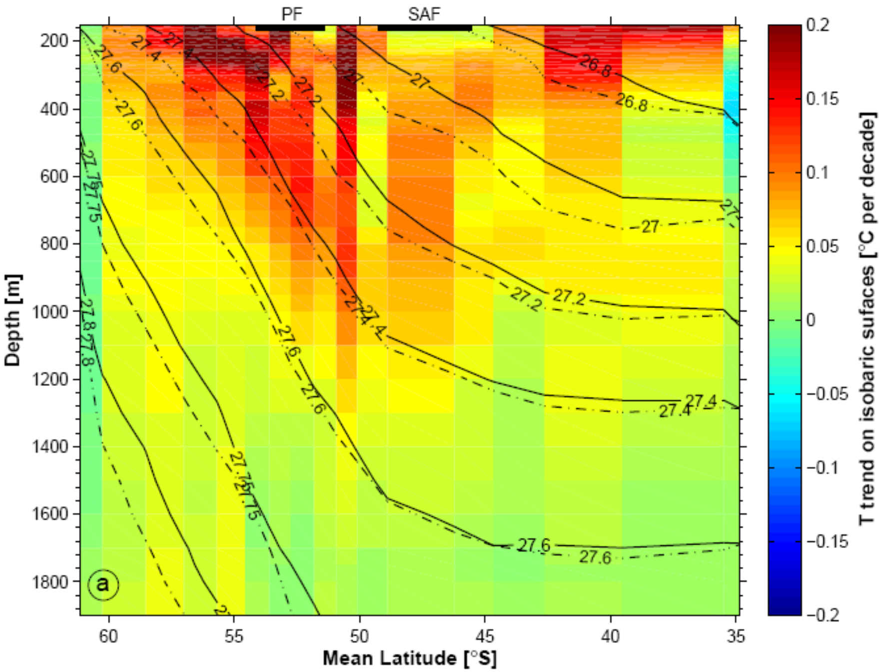


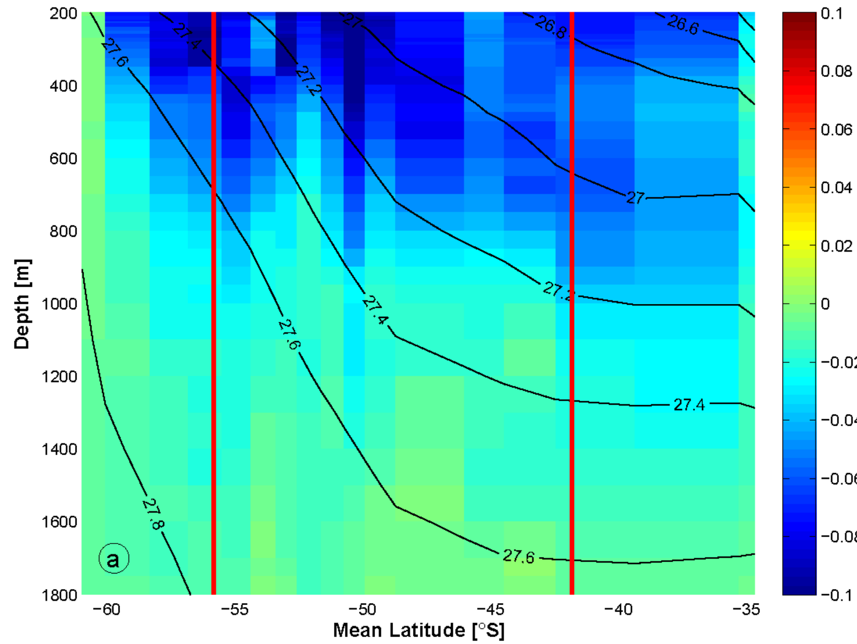
(thanks to Lynne Talley)

- Southern Ocean circulation is four-dimensional
- It is the main place in the world where deep waters upwell to the surface, and is thus a key part of the global carbon cycle
- The forcings are changing, perhaps most notably the strengthening winds

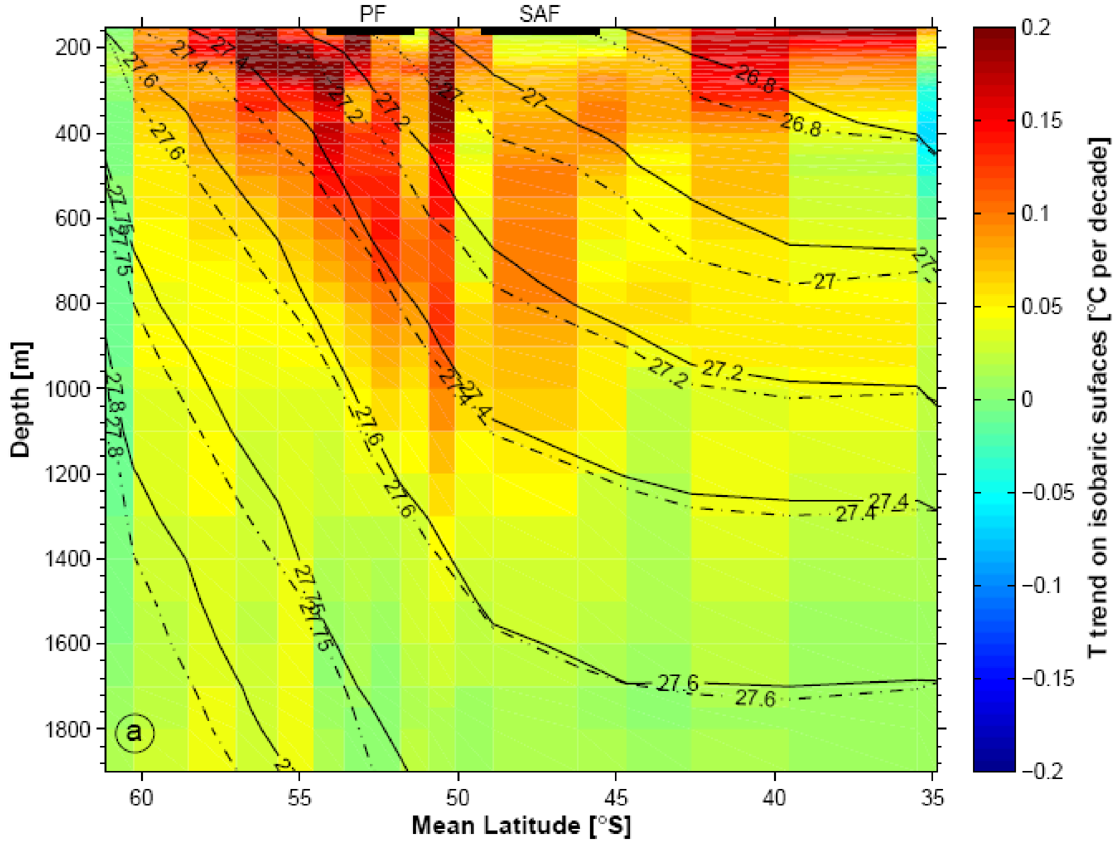
Most conspicuous changes: upper water column in ACC is warming and freshening…



(Böning et al., *Nature Geoscience*, 2008)



- Freshening seems consistent (to first order) with an accelerating hydrological cycle (e.g. Helm et al. 2010).
- Rate of warming exceeds that of the global ocean as a whole. Why?

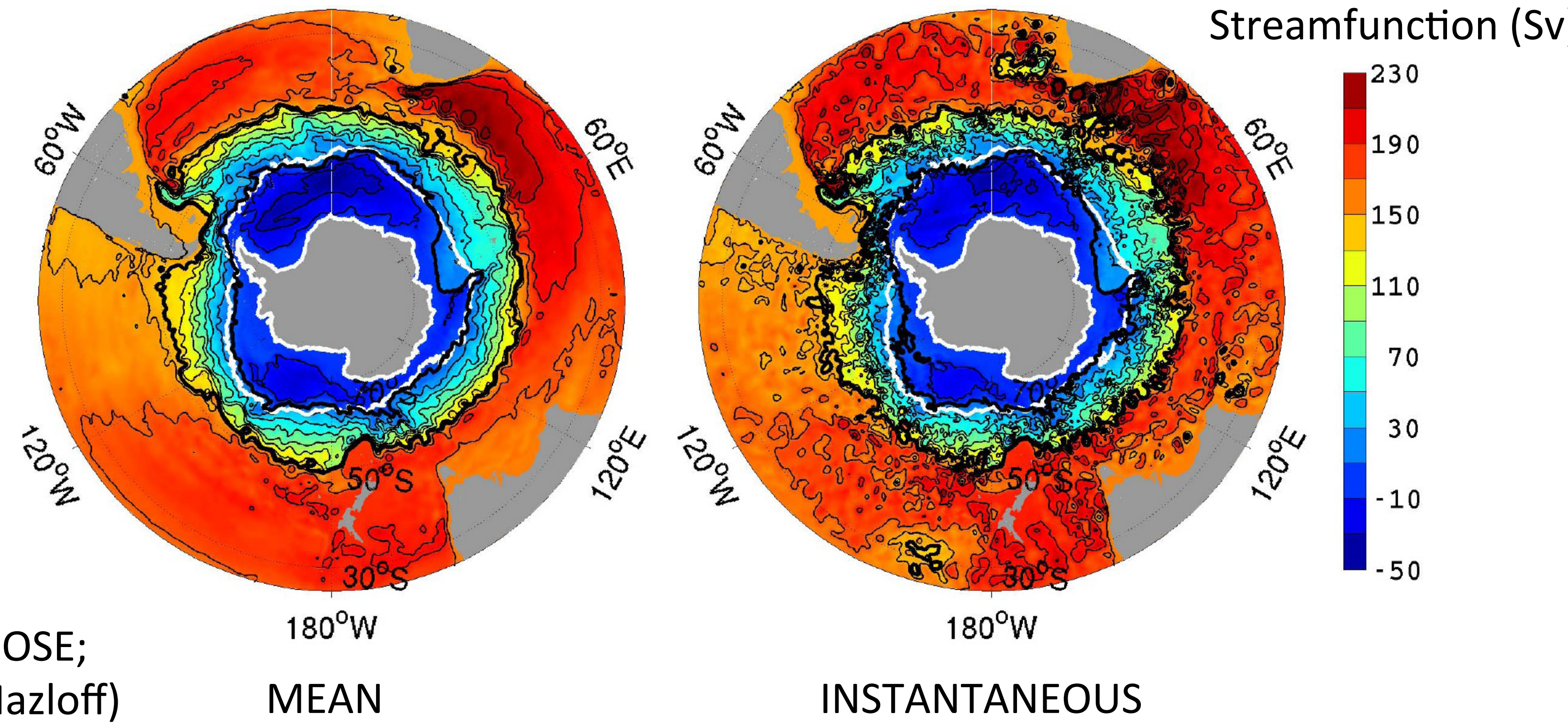


(Böning et al.,

Nature Geoscience, 2008)

- One putative explanation is that ACC has moved south, thus causing apparent warming (offset partially by water mass cooling; Meijers et al., 2011).
- Was also argued that ACC transport had stayed ~constant, because isopycnal slopes had not changed….
- Was also argued that overturning had stayed ~constant (and hence carbon sink had not changed) because isopycnal slopes had not changed… but…
- Need to understand how ACC actually works to assess which of this is likely/possible/unlikely…!

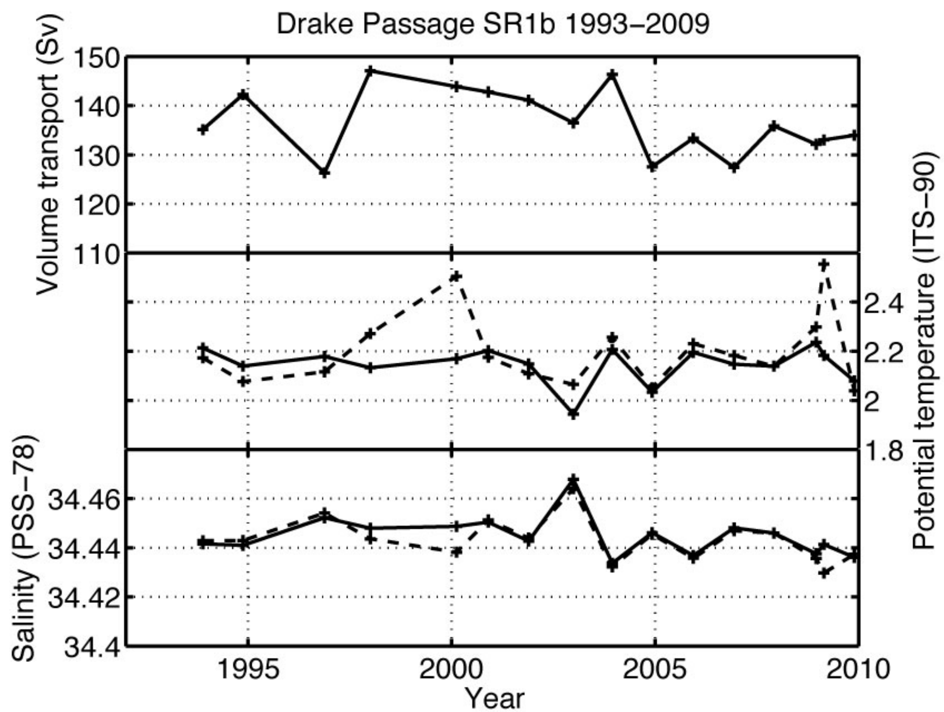
ACC is often conceived as featuring 3 or 4 discrete current cores …



(from SOSE;
Matt Mazloff)

- Reality is that even in the mean flow, the streamlines merge and diverge
- Instantaneous flows are even more complex.

Some coarse resolution models suggest that ACC could intensify in response to strengthening winds ...



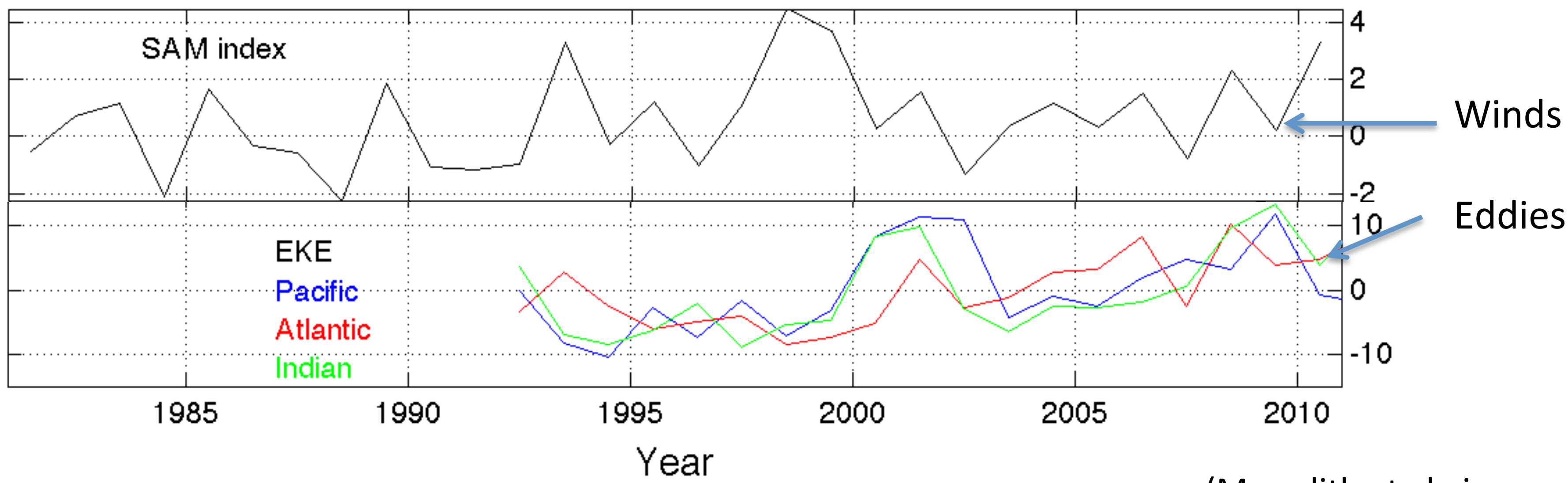
(Meredith et al., 2010;
King and Jullion, submitted)

Average of Drake Passage (1993-present) transports is 136 ± 7 Sv …
Same as pre-1990 mean, within errors. Why?

Difficult to interpret as a time series because of the aliassing issue. But a large (= double-digit) increase seems unfeasible…

One idea for small variance is that the ACC horizontal flow is "eddy saturated"….

So if the ACC transport hasn't changed (much) on decadal timescales, has the eddy field?



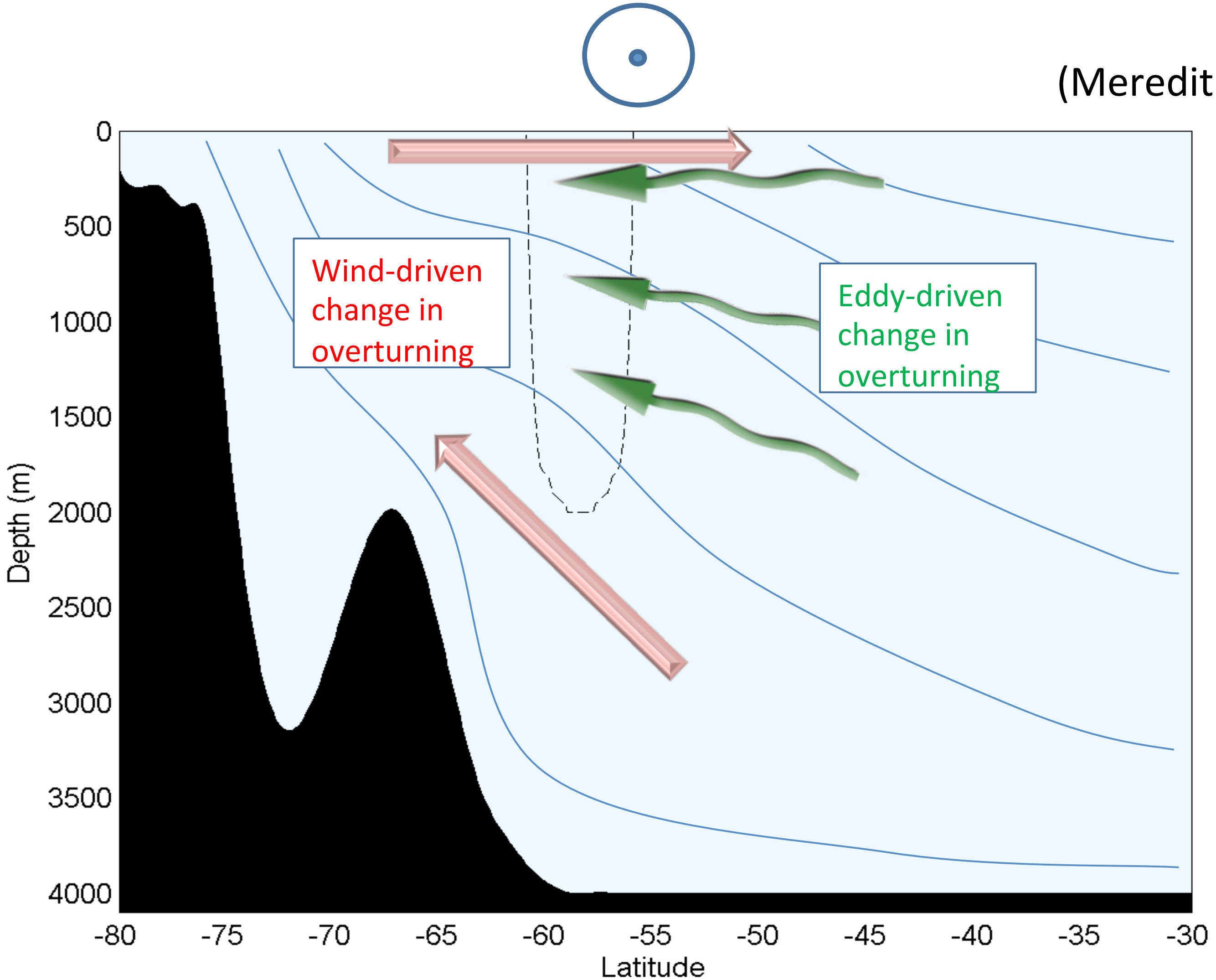
(Meredith et al., in prep)

Rather interestingly, yes…

Decadal trend in EKE, with values in 2008-09 as high as in 2002.

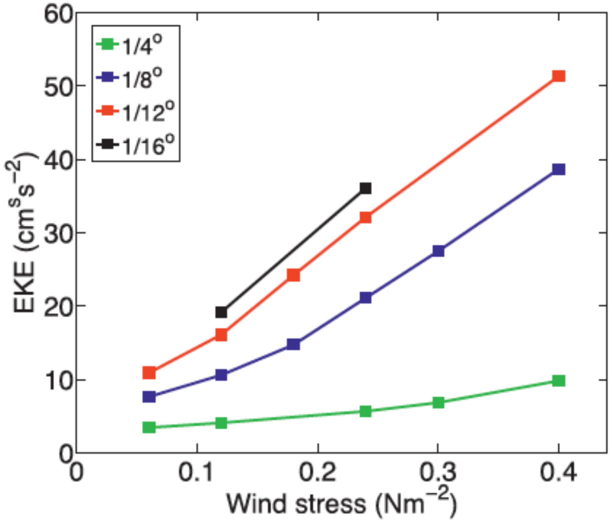
What are implications of this for overturning circulation?

(Meredith et al. 2013)



Strengthening winds gives acceleration of Ekman-driven overturning, but this is compensated to some degree by a response of the eddy-driven overturning: "eddy compensation".

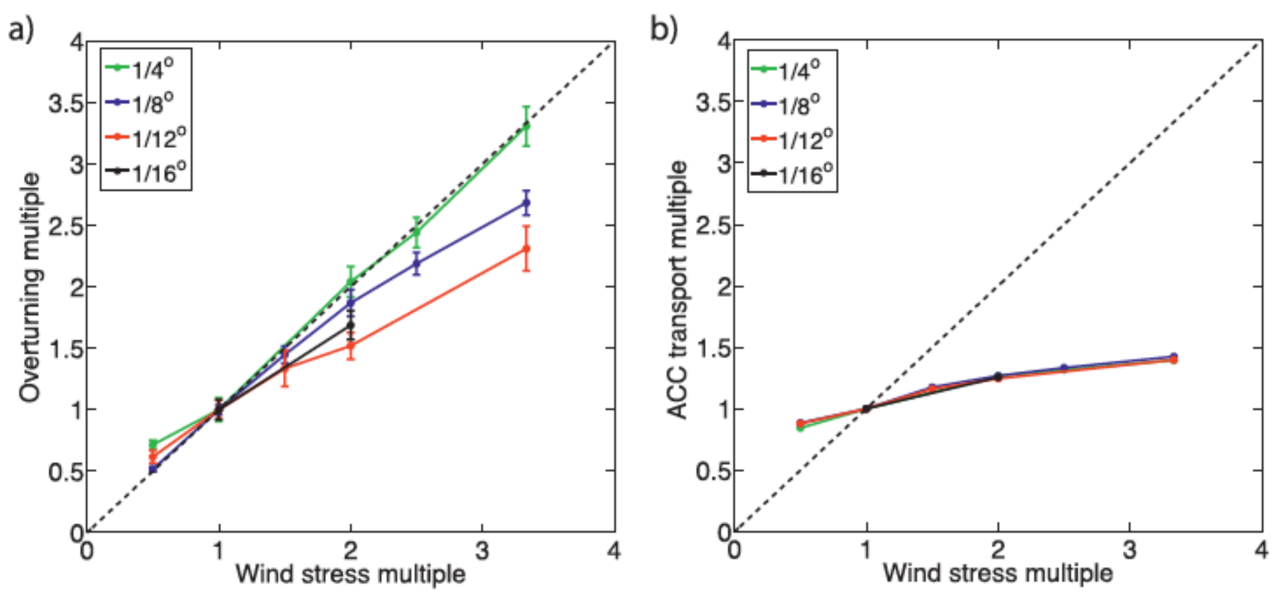
These have different spatial patterns, which is important for e.g. upwelling of carbon.



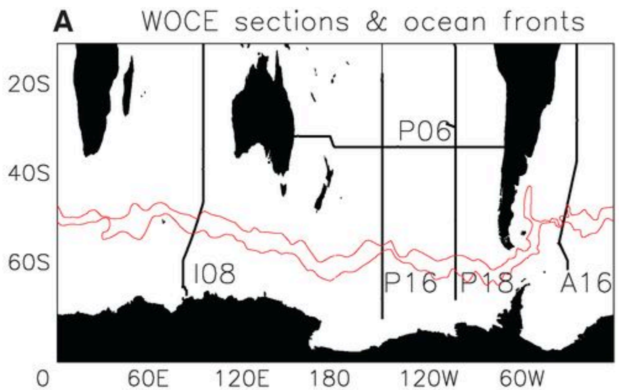
Theory and eddy-permitting/eddy-resolving models indicate that eddy saturation (of the ACC flow) of a given level does not imply eddy compensation (of the overturning circulation) of the same level.

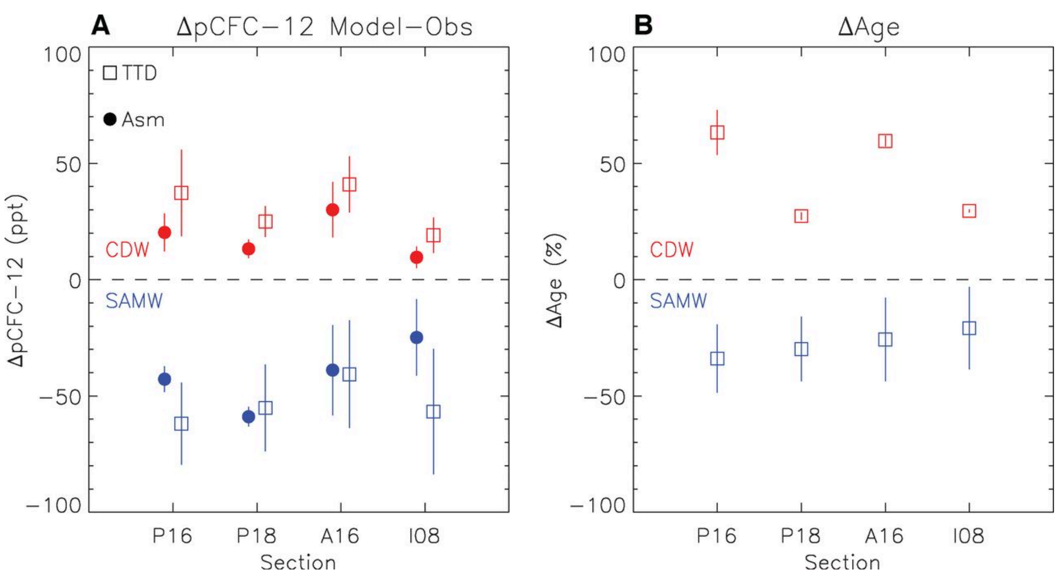
Near-complete ACC eddy saturation does NOT imply that overturning is invariant with respect to wind forcing.

Strong relevance to postulated saturation of Southern Ocean carbon sink (e.g. le Quere et al., 2007).



(Morrison and Hogg, 2013)



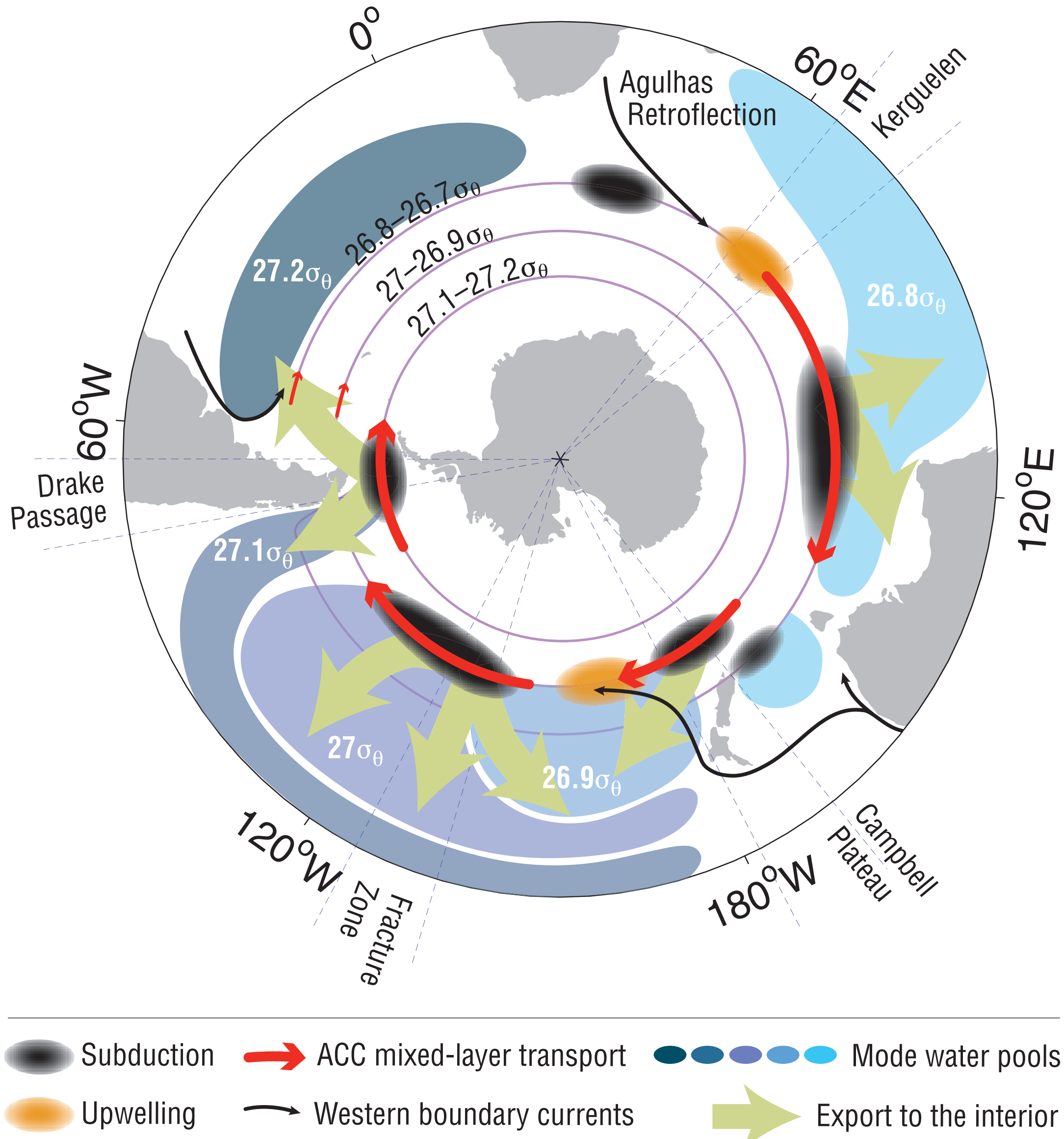


From observations, there are indications that the overturning has indeed strengthened.

Analysis of transient tracer data indicates mode waters are getting younger, and Circumpolar Deep Water is getting older…

Use of dissolved gas tracers means that results translate well to carbon upwelling/ drawdown.

(Waugh et al. 2013)



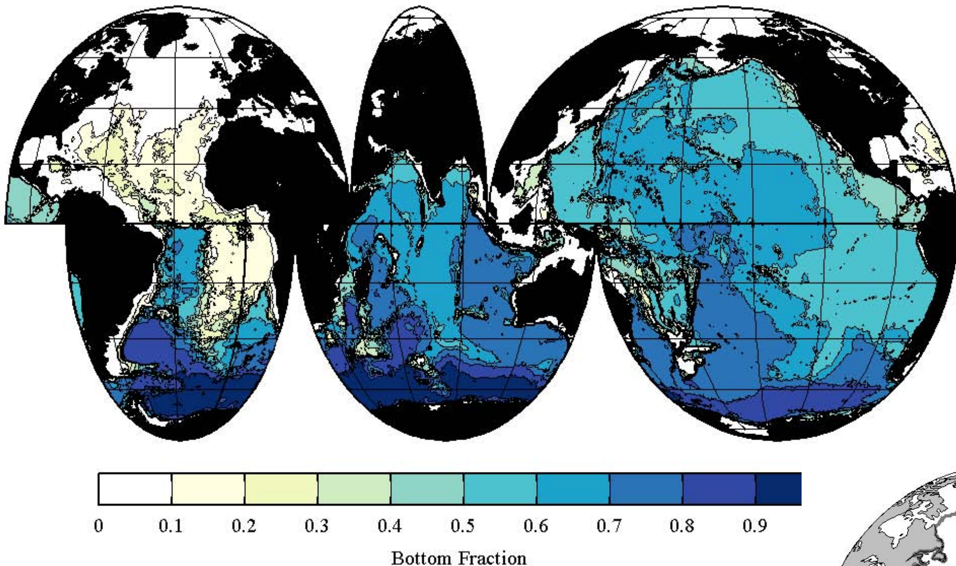
(Sallee et al., 2012)

All very enlightening, but important to note that whilst much progress has been made using theories of zonally-averaged flows, or flows along streamlines, it is increasingly being observed that the real ocean is more complex than this…

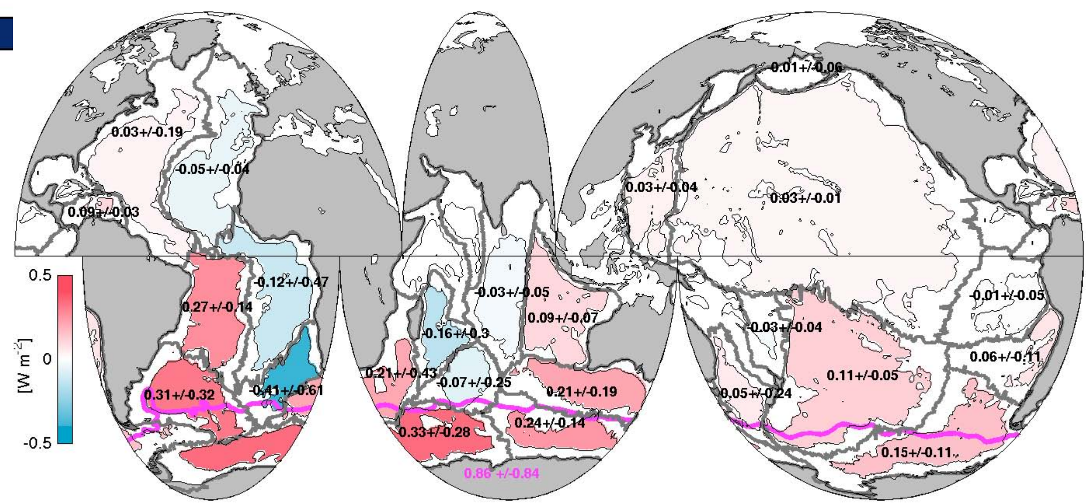
Regional and local processes can dominate some of the key changes. These include the spatial variability in where waters upwell and subduct, and where carbon enters the interior.

How will this (already complex) pattern change as circulation, stratification and mixing all change in the future?

Not just the upper waters of the ACC that are warming…



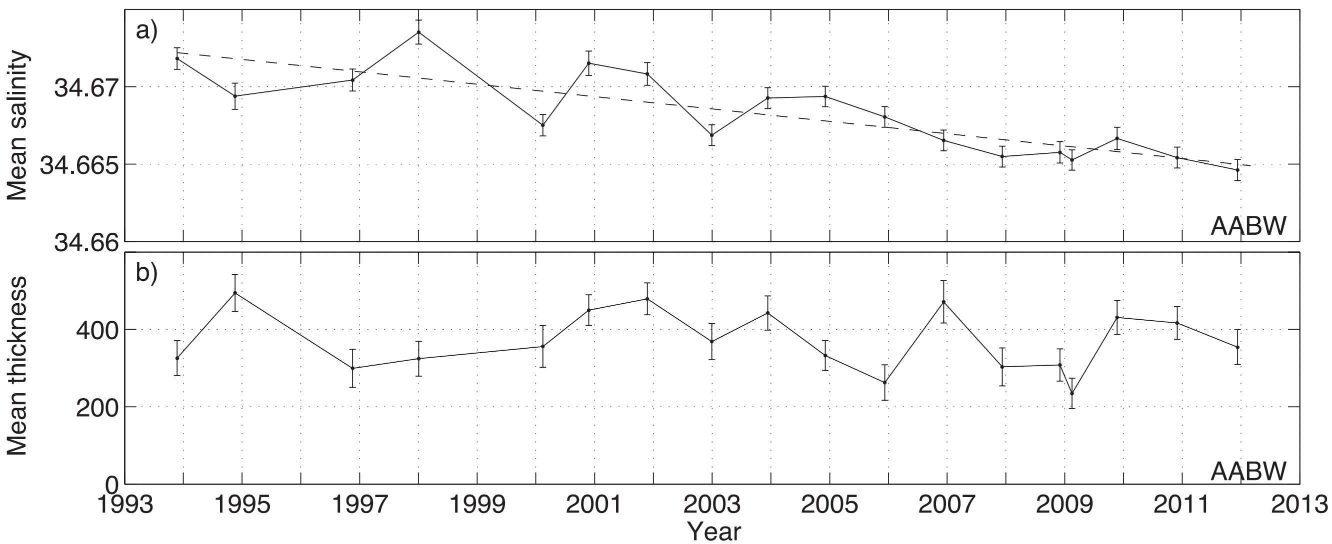
(Purkey and Johnson, 2010)



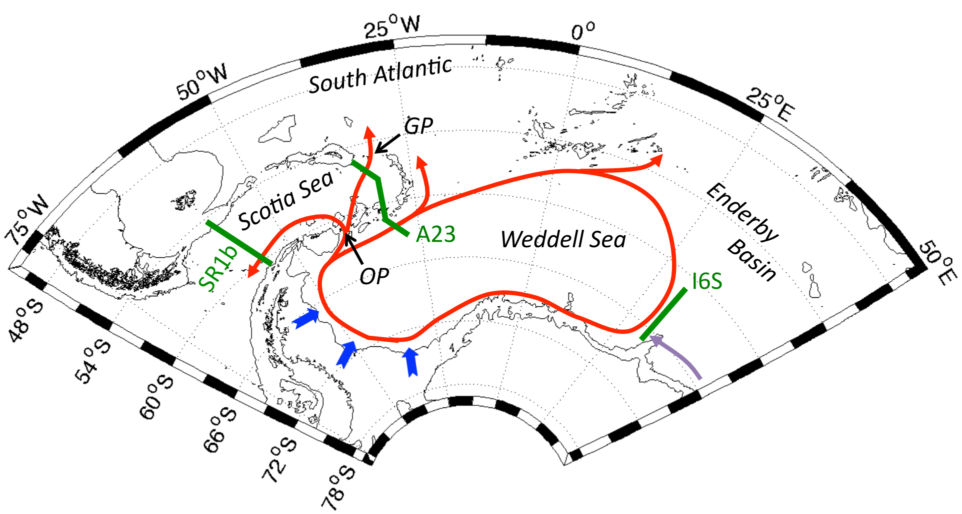
Dense waters of Antarctic origin are warming also, with implications for sea level rise, the global heat budget, and benthic biodiversity.

Proposed causes include changes in rate of formation and export, and/or changes in the properties of the waters as they are formed.

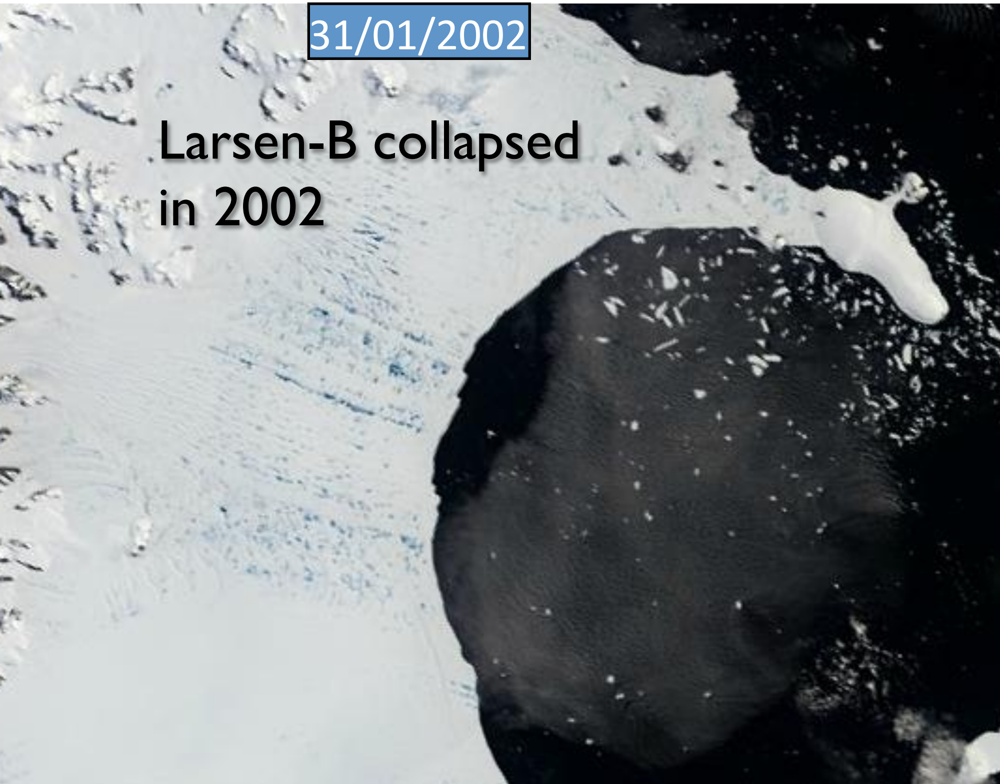
Large freshening signals in e.g. Ross Sea (Jacobs et al., 2002, etc) known about for some time. Freshening of AABW that escapes Weddell Sea now detected also…

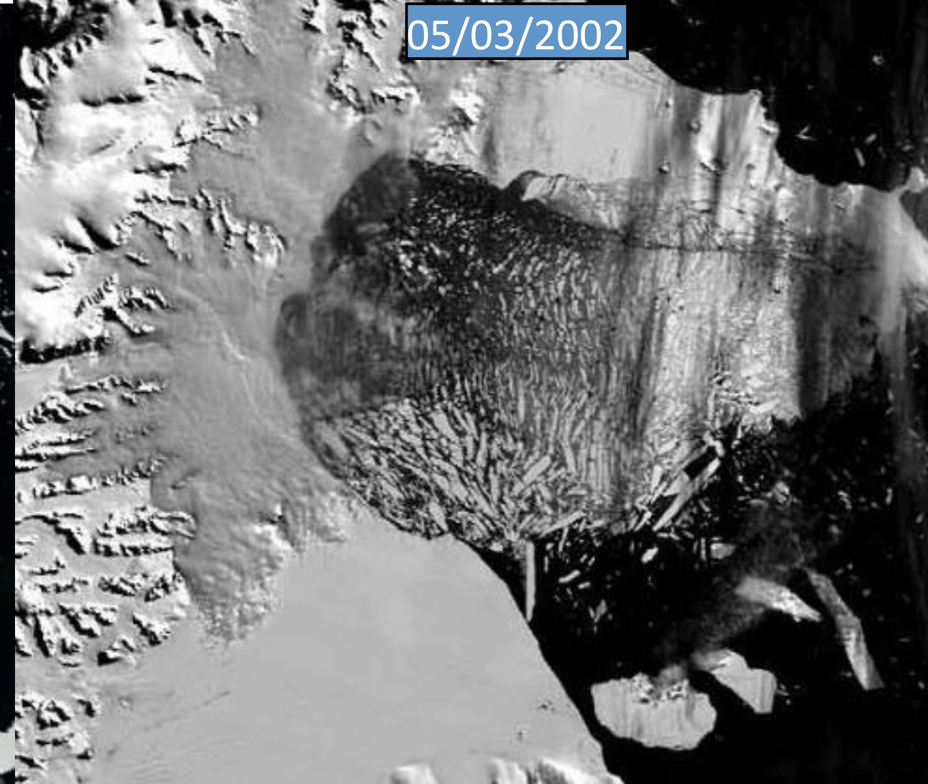


(Jullion et al. 2013)



A freshening trend is clear, believed due to greater input of glacially-derived waters primarily…


31/01/2002
Larsen-B collapsed
in 2002

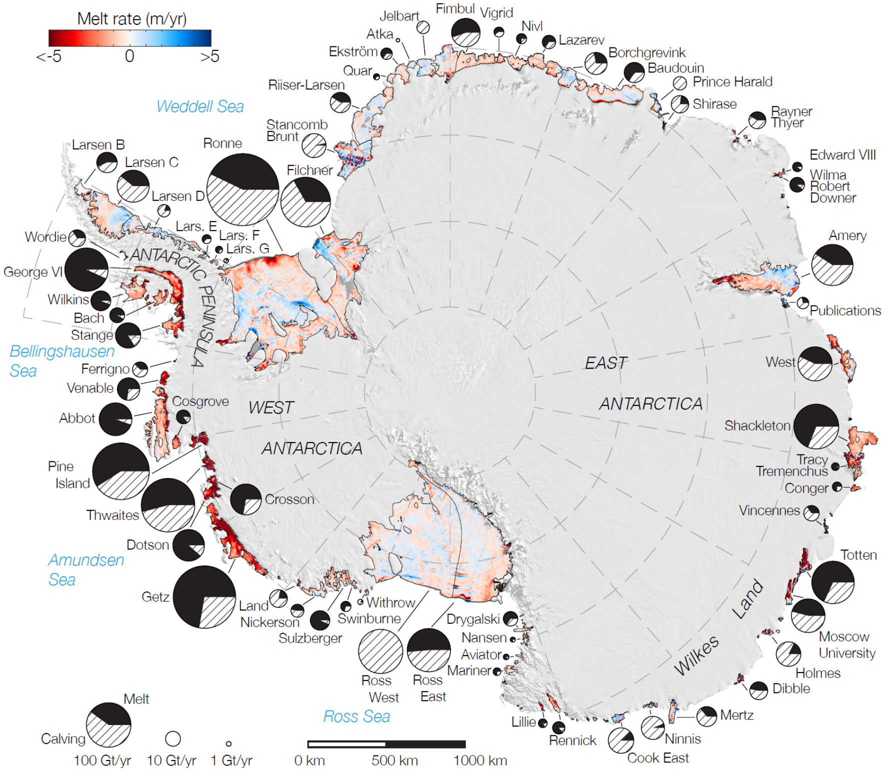

05/03/2002


April 2002
melange
Glaciers surged following
removal of buttressing
Crane Glacier

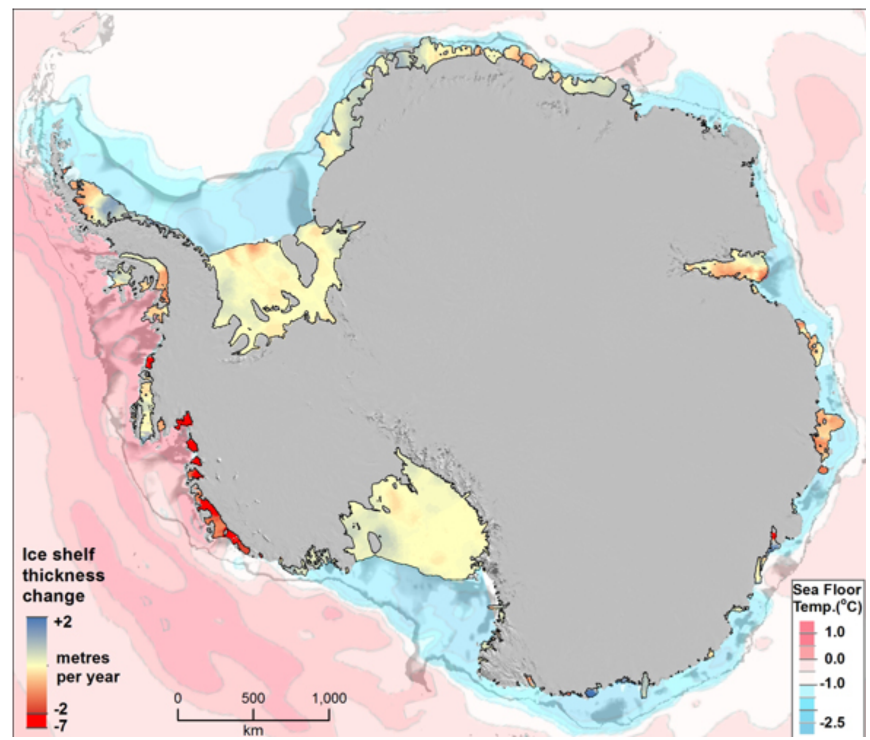

February 2003

Different modes of freshwater discharge in different sectors (warm vs. cold) – role of ocean particularly apparent in many parts of West Antarctica, but atmospheric processes believed to be more important in e.g. Larsen region.

Anthropogenic influence suspected in both cases…



(Rignot et al., 2013)



(Pritchard et al. 2012)

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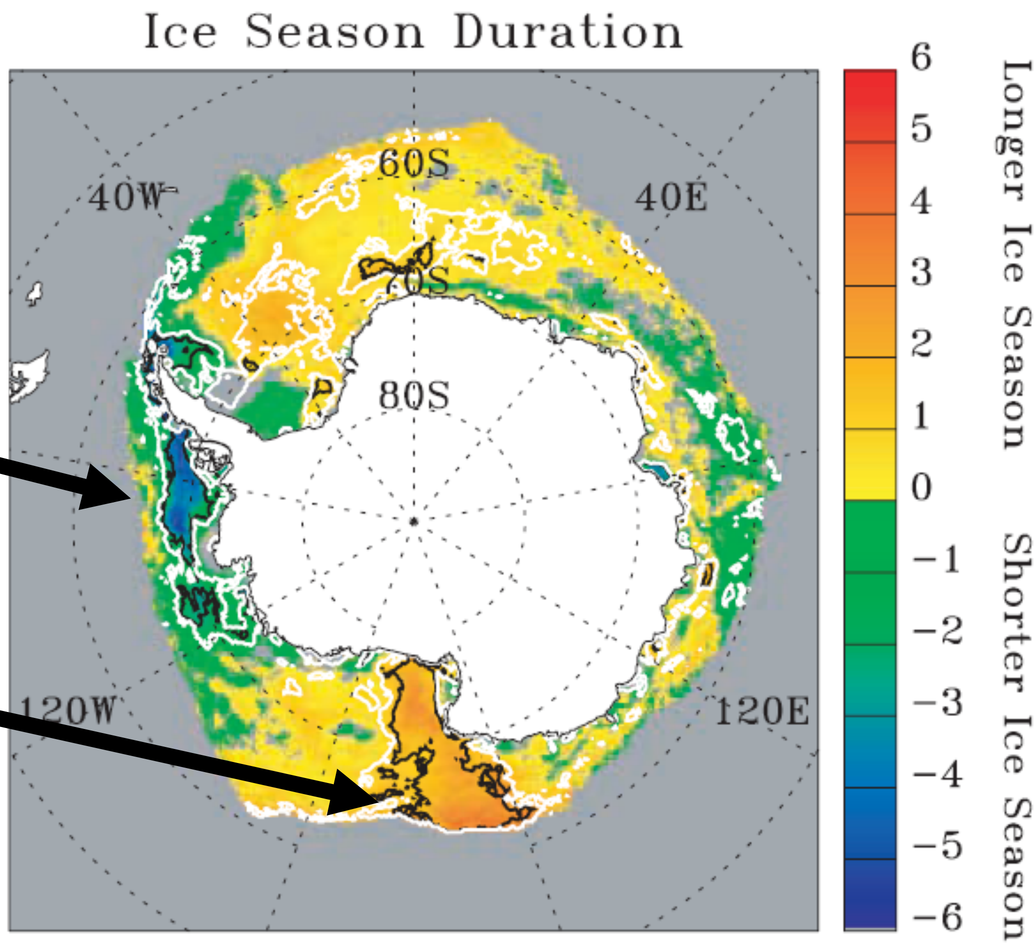
Complexity in Antarctic sea ice also: slight increase (c.f. Arctic) Cause is under debate, but is it even the right question?

Changes in sea ice duration: 1979 – 2006

-83 ± 23 days

57 ± 13 days



(Stammerjohn et al., 2008)

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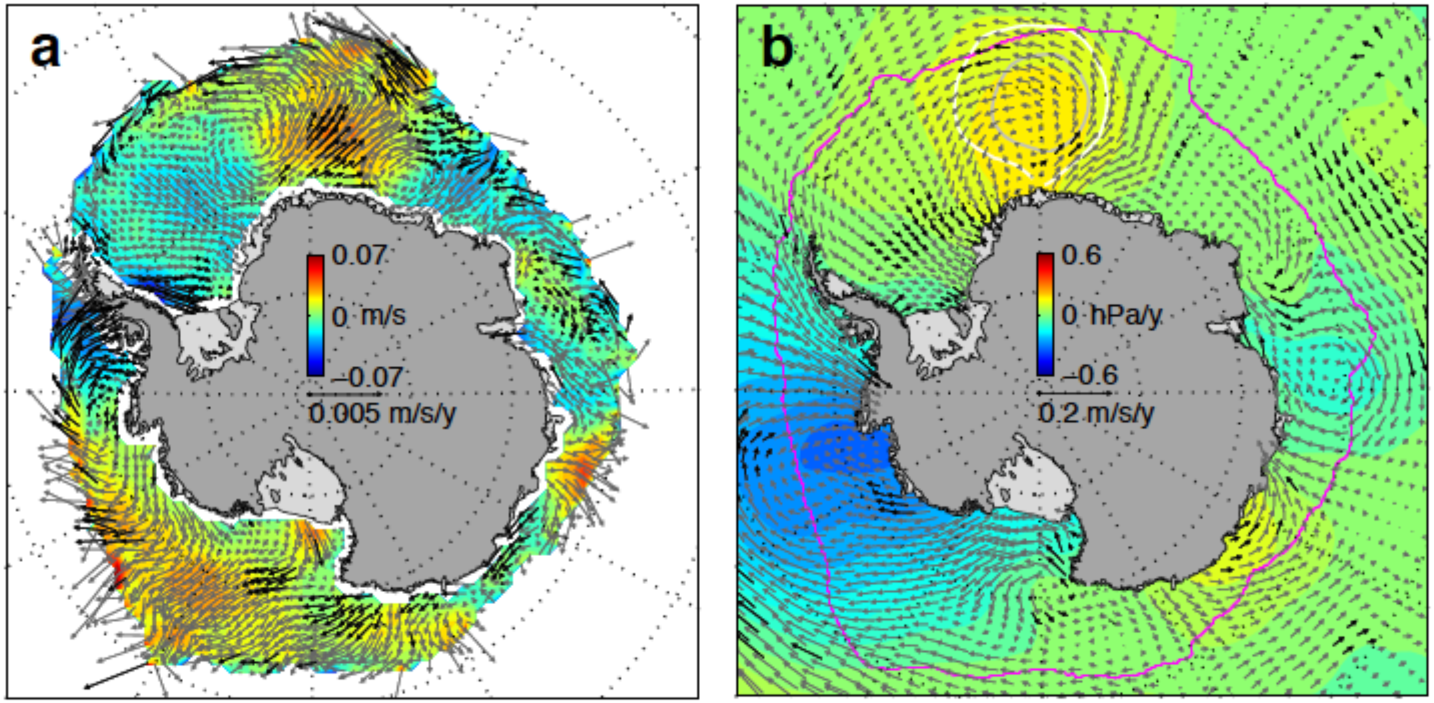
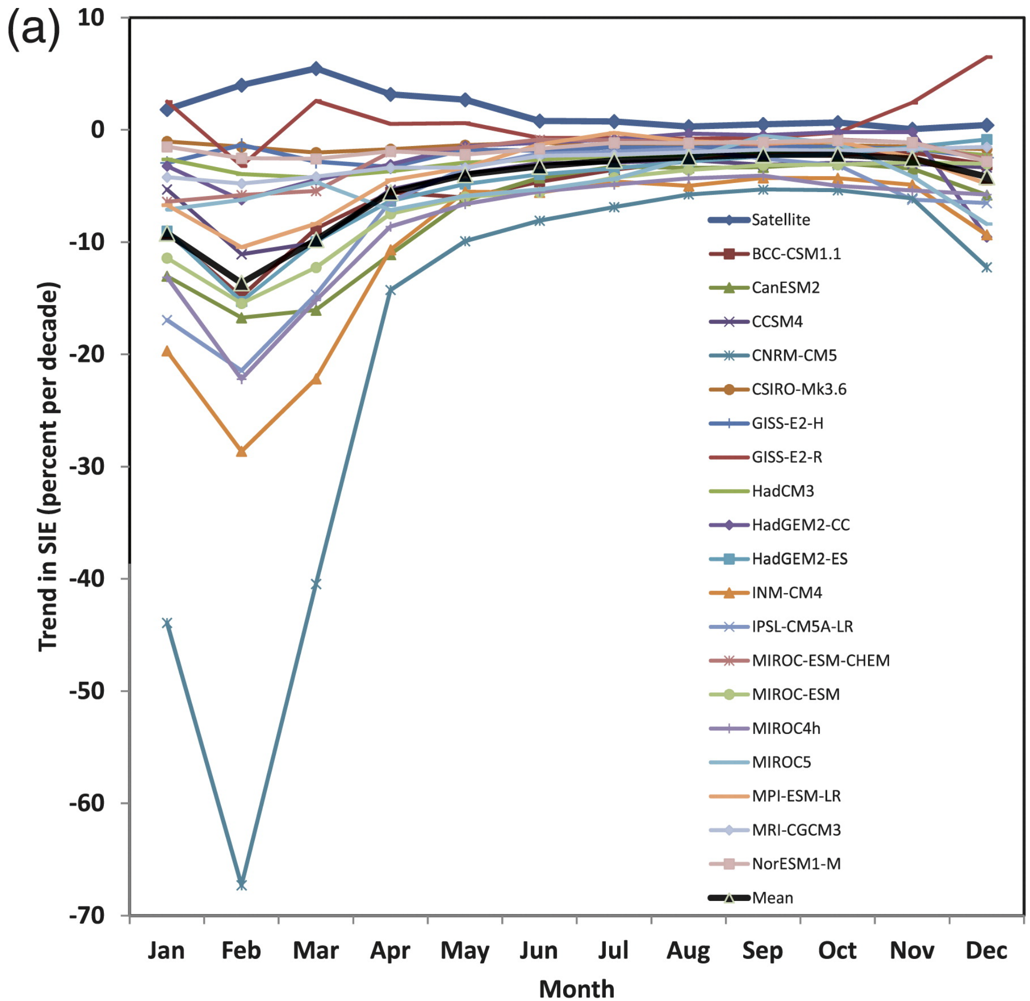
Was recently argued that changes in wind-forcing (potentially including some anthropogenic influences) was the main cause of the changes, with both dynamic (advection) and thermodynamic (melting/freezing) processes being altered.



(Holland and Kwok, 2012)

Even more recently, increasing glacial discharge from Antarctica was invoked, with stabilisation of the water column and suppression of vertical heat flux being key (Bintanja et al., 2013). Might work in a circumpolar sense, but unless it can explain the dipole….



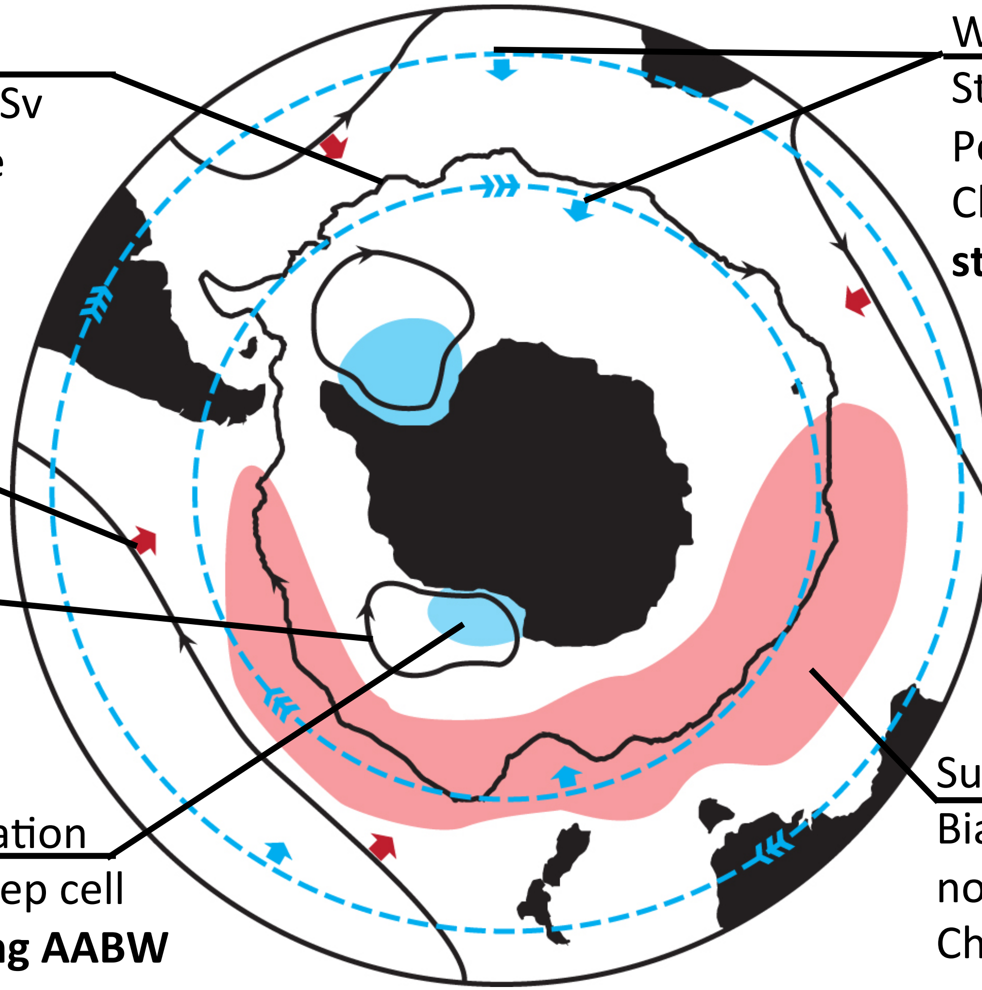
To what extent can we look to latest IPCC class models to inform us on the causes of the trends?

(Turner et al., 2013)

Summary: The Southern Ocean in CMIP5 climate models

ACC
Strength: 155±51 Sv
Position: Accurate
Change: **Variable**

Winds
Strength: Weaker
Position: Biased north
Change: **Shift south and strengthen**



Gyres
Subtropical:
Shift south
Subpolar:
variable

Water masses
Biased warm
Change: **Warm and freshen**

Overturning circulation
Strength: Weak deep cell
Change: **Weakening AABW formation**

Surface mixed layer
Biased shallow and northwards
Change: **Shallows**

(courtesy Andrew Meijers)

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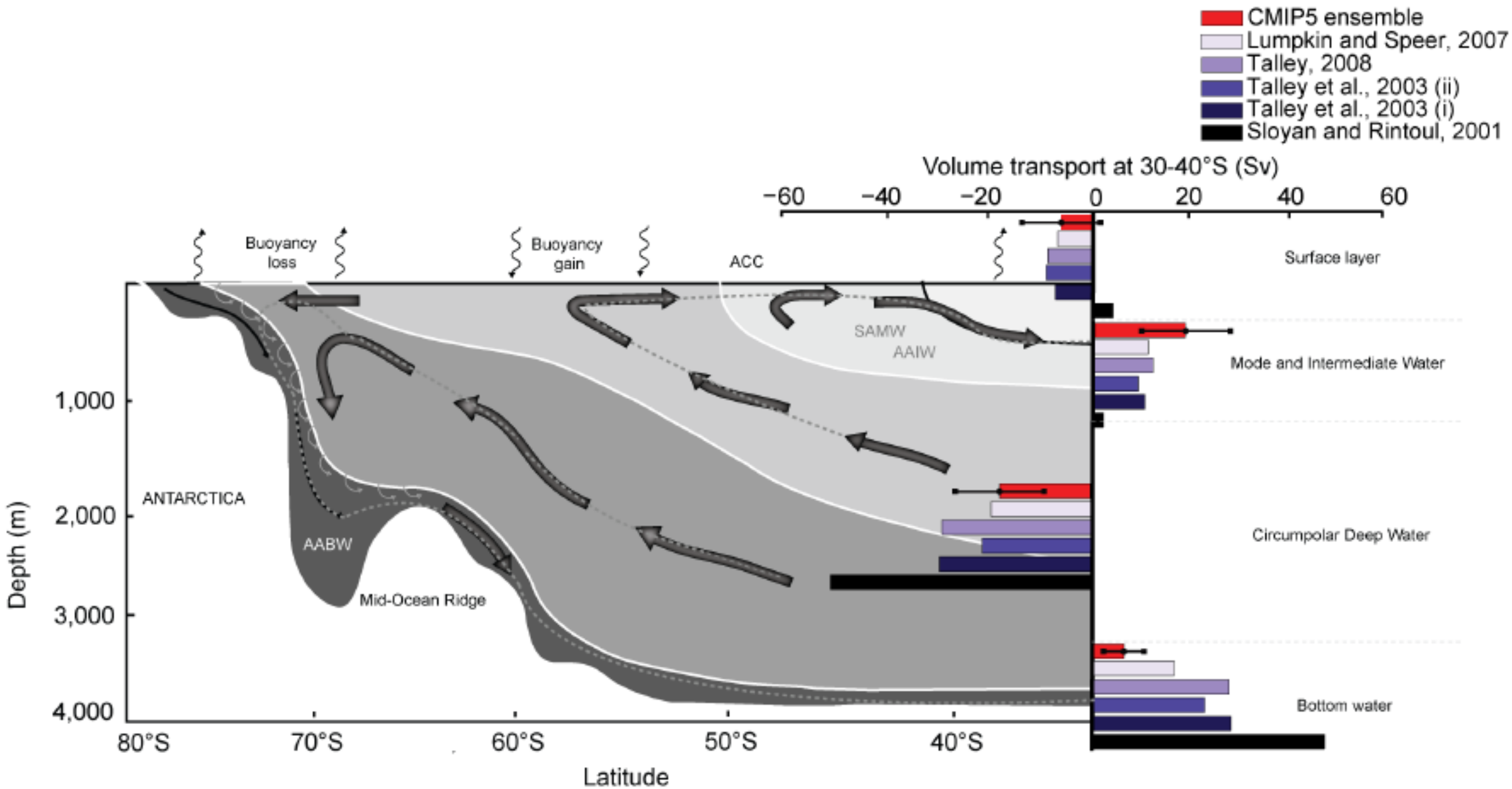
Overturning circulation: Weak lower cell and AABW formation



(Sallee et al., 2013)

Summary of postulated changes, and current views (mine, mostly)

- Upper Southern Ocean has got warmer – yes, multiple causes?
- Upper Southern Ocean has got fresher – yes, accelerating hydrological cycle?
- Deep water exported from Southern Ocean has got warmer – yes, causes still being worked on
- Deep Southern Ocean has got fresher – yes, probably due to glacial melt input
- Winds have caused ACC to accelerate – possibly a very little, but certainly not much
- Winds have caused eddy field to intensify – yes
- Winds have caused ACC to move south – possibly, but data not really good enough
- Winds have caused overturning to accelerate – probably
- Sea ice extent has increased – yes, a little; cause(s) under debate
- Glacial ice discharge has increased – yes, around western Antarctica at least

What are the priorities, and how do we make progress?

Need continuous monitoring of overturning, as well as horizontal flow. How do we do this in a sustained way?

Need to understand whether almost-eddy-saturated state will persist (hysteresis?), and whether level of eddy compensation of overturning is time variable.

Understanding of likelihood of catastrophic change (e.g. Larsen C, FRIS?) – limited predictive skill at present, but implications could be significant.

At same time as improving models' predictive skill, need better sustained systematic observations of the forcings (heat fluxes, freshwater fluxes, wind stress) and transfers (CO_2 fluxes etc) including in (partially) ice-covered oceans.

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What are the priorities, and how do we make progress?

Need a focus on interactions between the changing overturning circulation and the mixed layer – where and how do the major subductions, upwellings, entrainments happen, how do they vary, what sets the values of physical and biogeochemical tracers that enter the oceanic mid-depths, how will these change etc?

Increasingly seeing how non-zonal the Southern Ocean changes are, and the key processes. Need to develop theory beyond zonal-average concepts (or along-streamline averages) to incorporate the effects of regionally-varying (and sometimes very localised) processes.

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