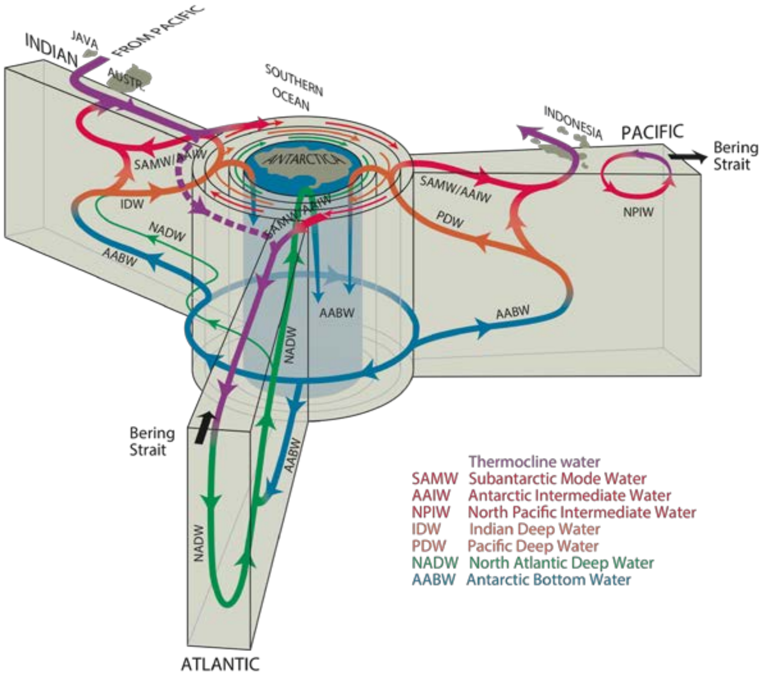
Three-Dimensional Pathways of the Northern Deep Waters to the Southern Ocean Surface

Lynne Talley
Scripps Institution of Oceanography
Workshop: Southern Ocean Dynamics and Biogeochemistry
Caltech Linde Center
5 February 2015



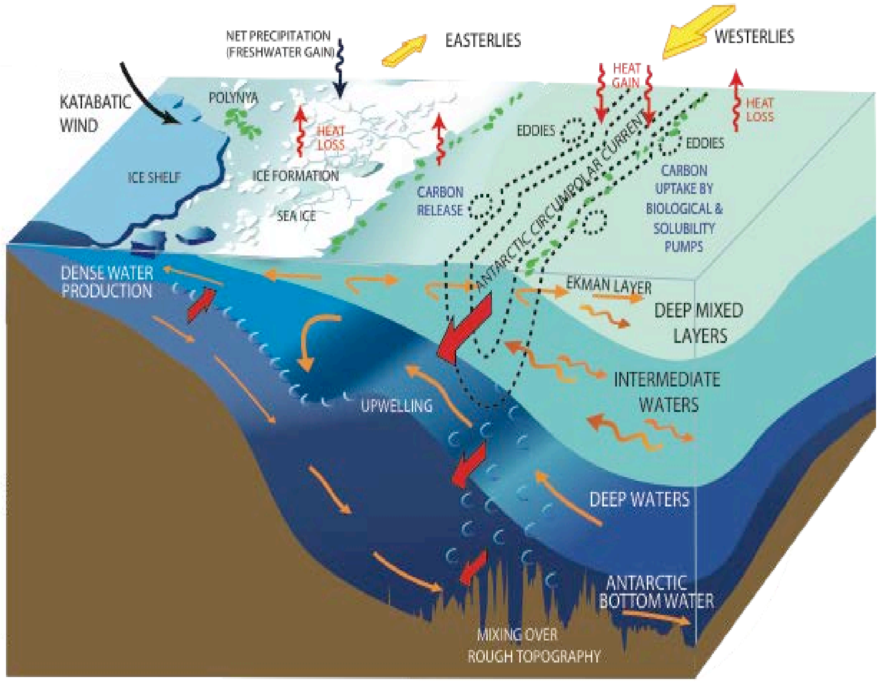
Thanks to: Joe Reid, Veronica Tamsitt, Ivana Cerovecki, Matt Mazloff (all SIO)

NSF OCE funding: collaborative research with Ryan Abernathey, Ivana Cerovecki on the upper limb of the S.O. overturning circulation

Thinking in progress: you can help

Yes, I'm using hydrographic observations

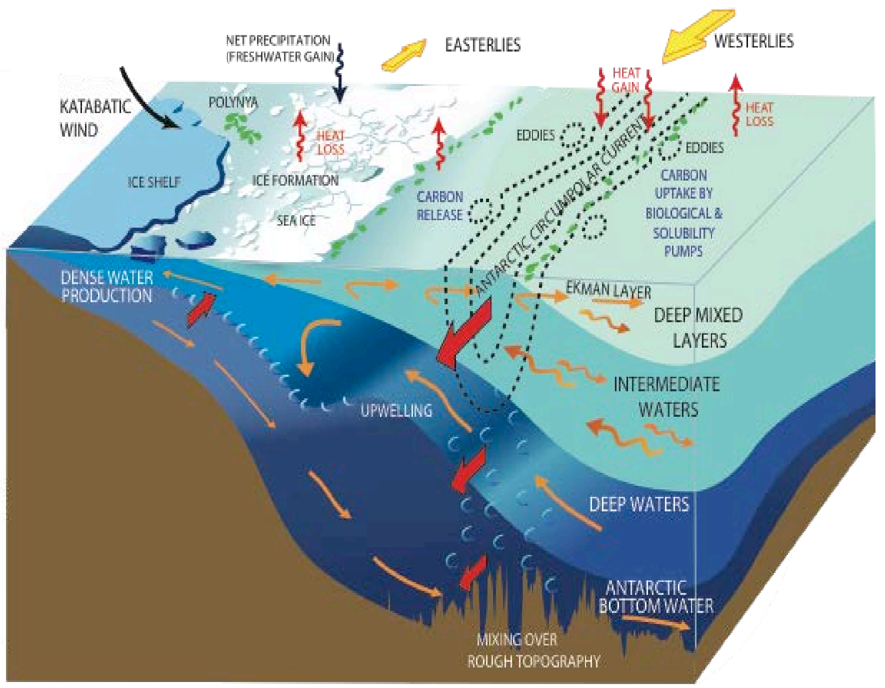
Southern Ocean zonally-averaged overturning schematic



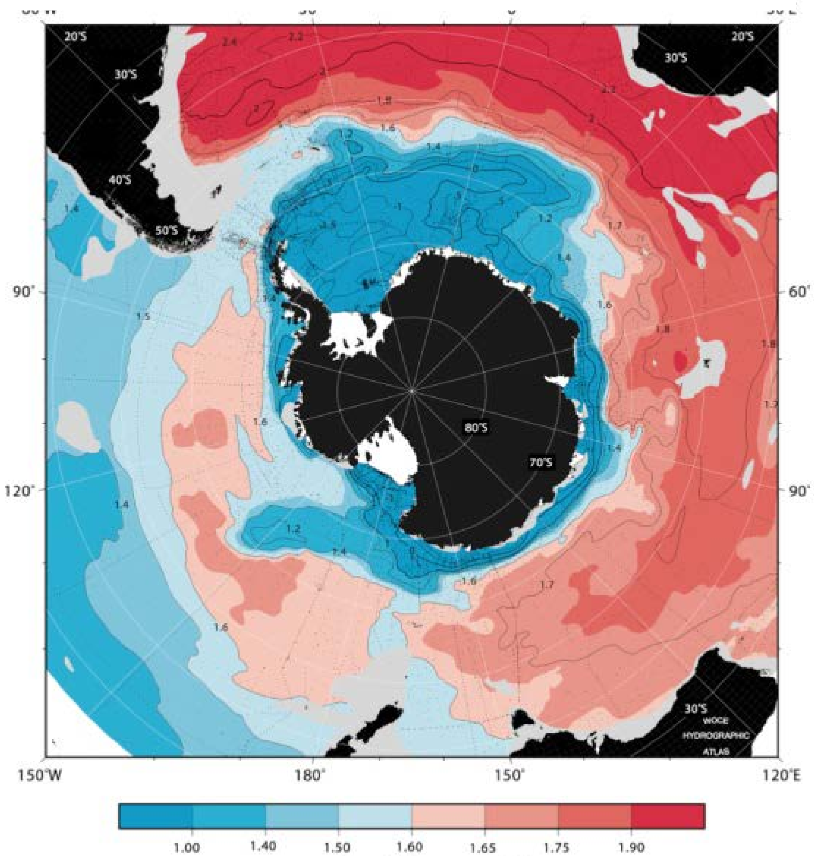
Adaptation of NRC (2011) figure
(most recent iteration Dec. 2014)

- Monolithic Deep Waters upwelling to near sea surface.
- Some of what we call Intermediate Water also transported southwards along with Deep Water (in fact net transport in the AAIW isopycnal layer is southwards, not northwards!)
- Monolithic Bottom Water moving out to the north.
- Heat gain and loss; carbon release and uptake - very rough relationship to ACC
- Winter ice edge extends much farther to north than depicted here (to ACC)

Zonal asymmetry in deep water entry



Potential temperature at $\gamma^N = 28.05$ (NADW isopycnal)

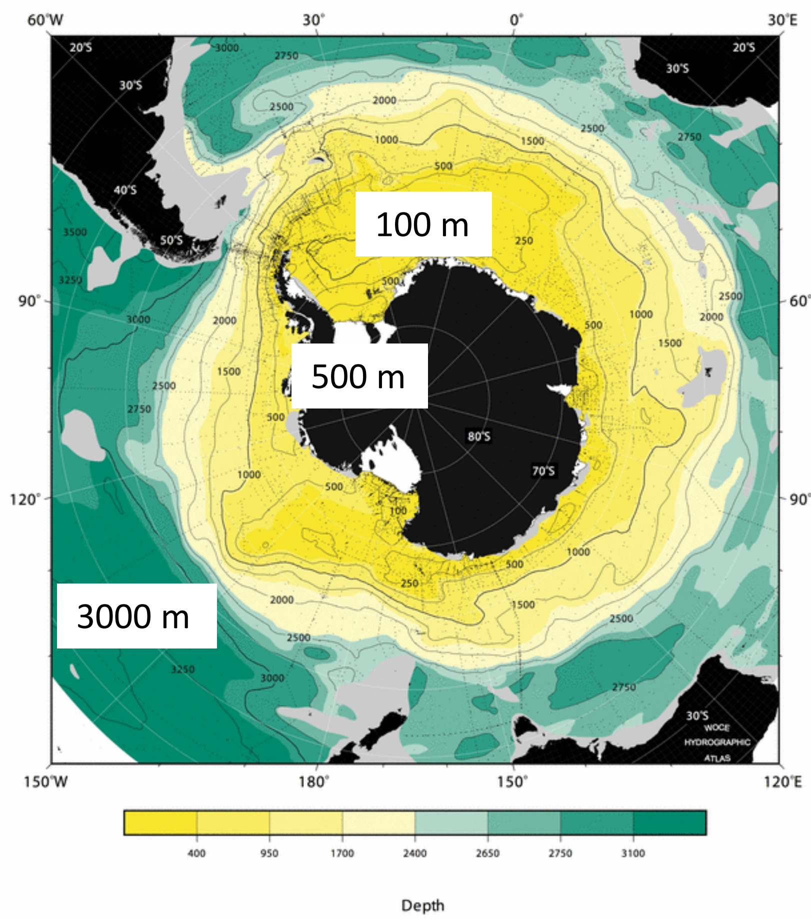


Orsi and Whitworth (2005)

Three-dimensional circulation: not just overturning, but significant horizontal structure, much of it under sea ice in winter

Zonal asymmetry in deep water entry

Depth of γ^N = 28.05 (NADW isopycnal)



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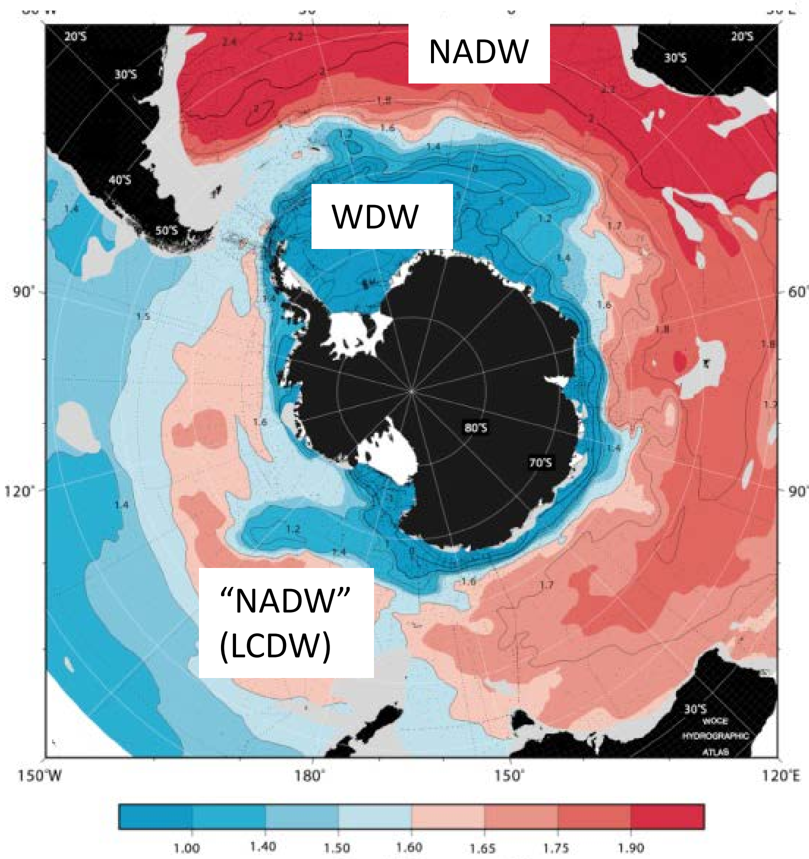
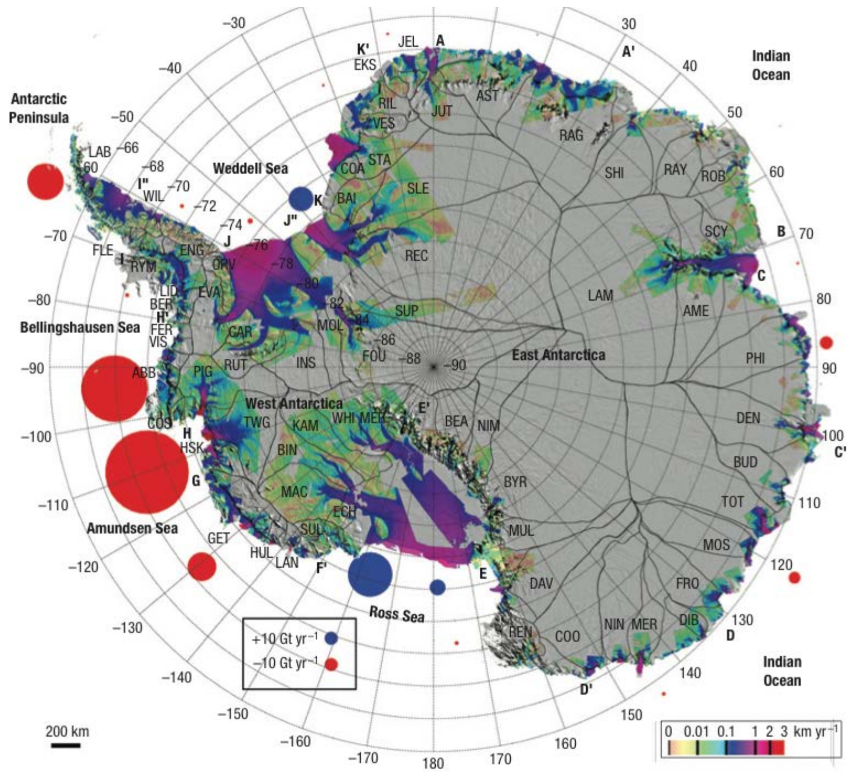


Orsi and Whitworth (2005)

Three-dimensional circulation: not just overturning, but significant horizontal structure, much of it under sea ice in winter

Zonal asymmetry in deep water entry

Glacial ice mass loss strongly associated with location of influx of warm water



Rignot et al. (2008)

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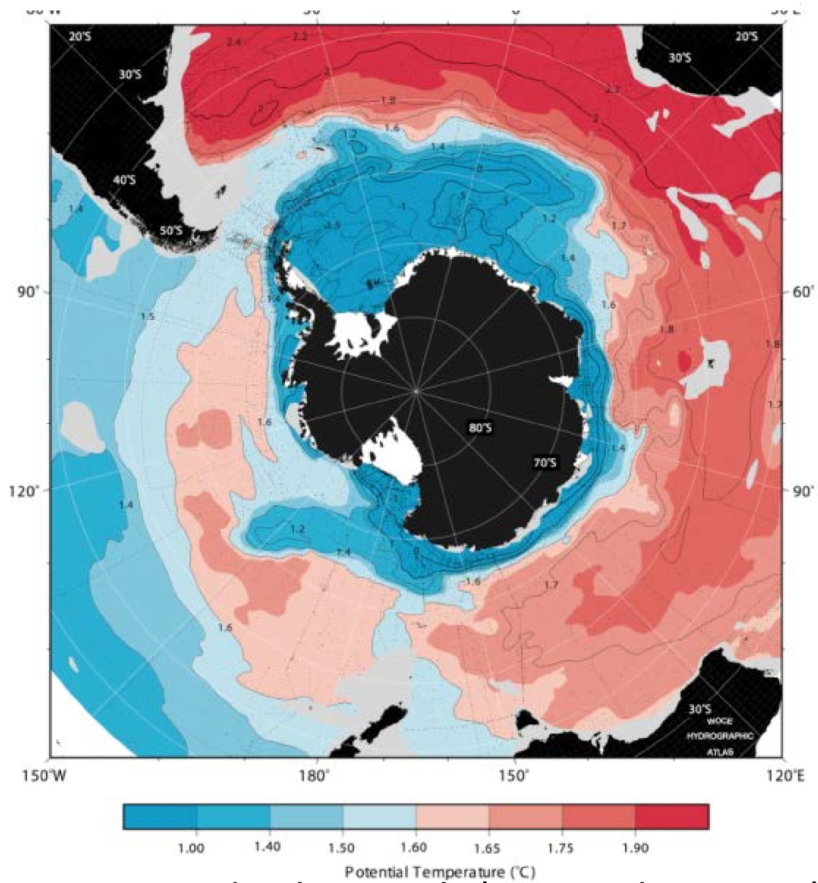


Orsi and Whitworth (WHP atlas, 2005)

Three-dimensional circulation: not just overturning, but significant horizontal structure, much of it under sea ice in winter

Global overturning circulation schematics

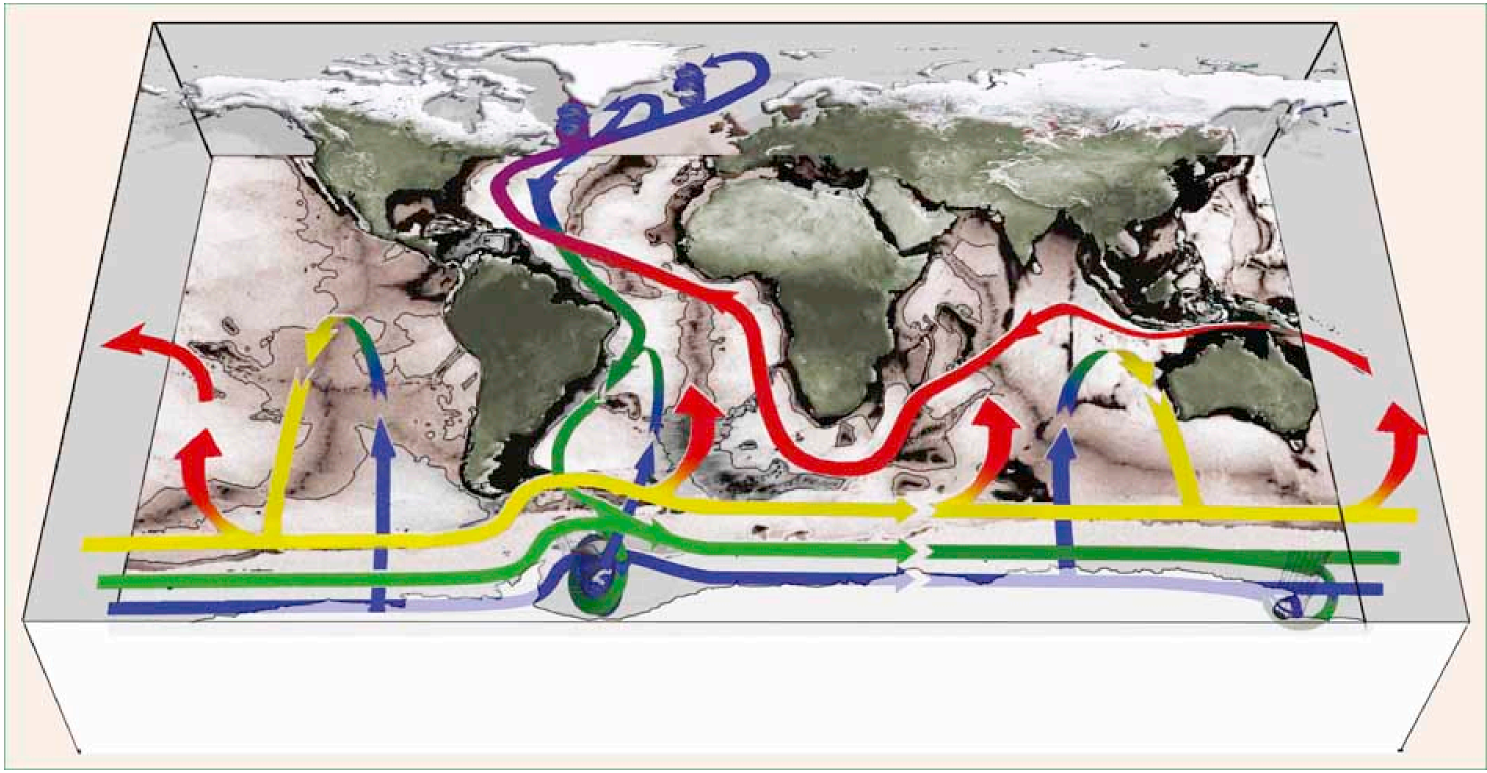
4 layer circulation

Dense water formation in Southern Ocean and northern North Atlantic

Deep water formation in Indian and Pacific through upwelling; return southwards to the Southern Ocean

Return to upper layer mainly through final step of upwelling in the Southern Ocean

Southern Ocean global overturning circulation is zonally asymmetric!
Zero order asymmetry: N. Atlantic has a northern deep water source, while Indian and Pacific make deep water only through low latitude upwelling



Marshall and Speer, 2012

Global overturning circulation schematics

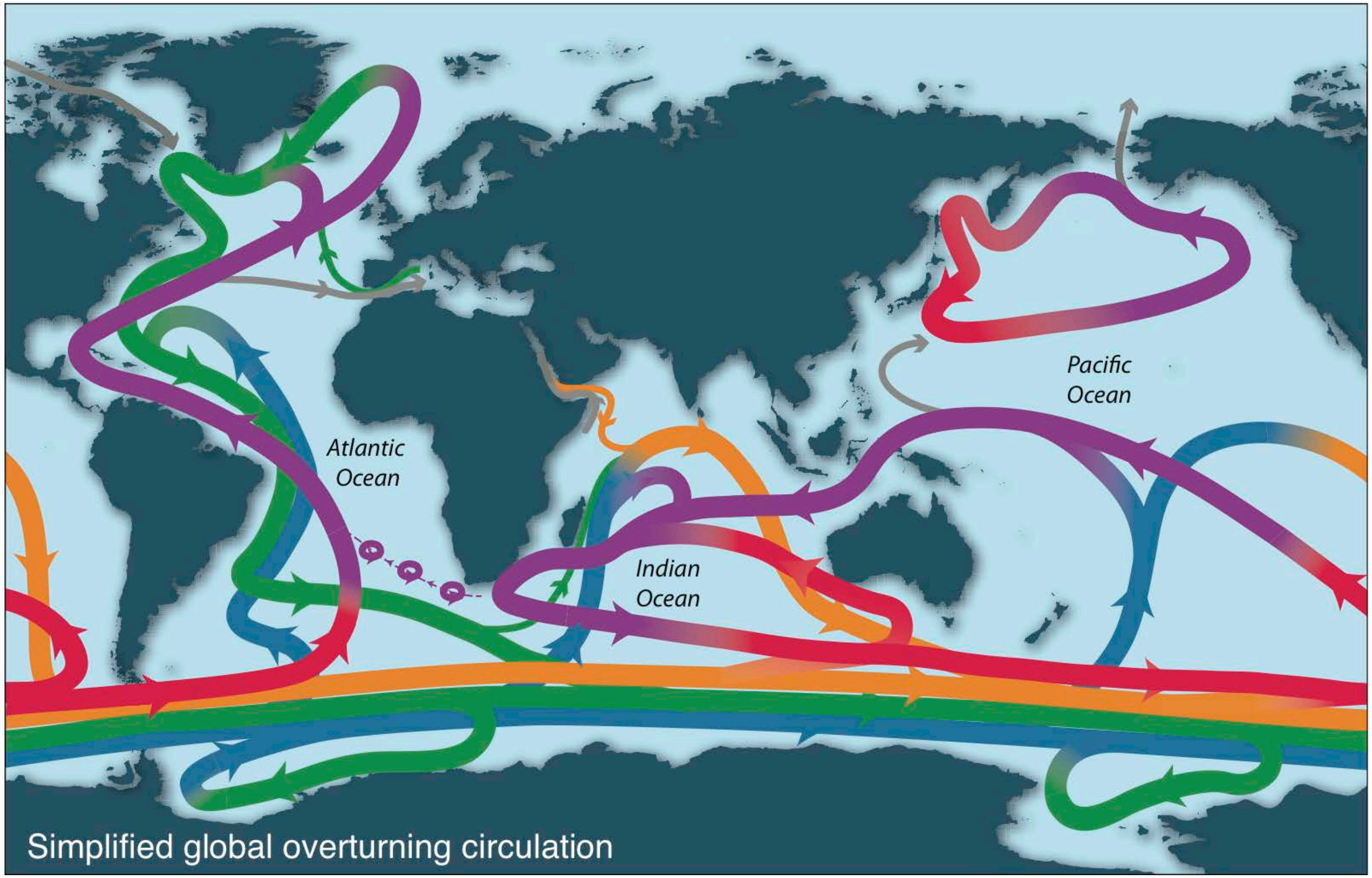
4 layer circulation

Same basics, but a little more complex

Additional features: some upwelling to thermocline in Indian and Pacific

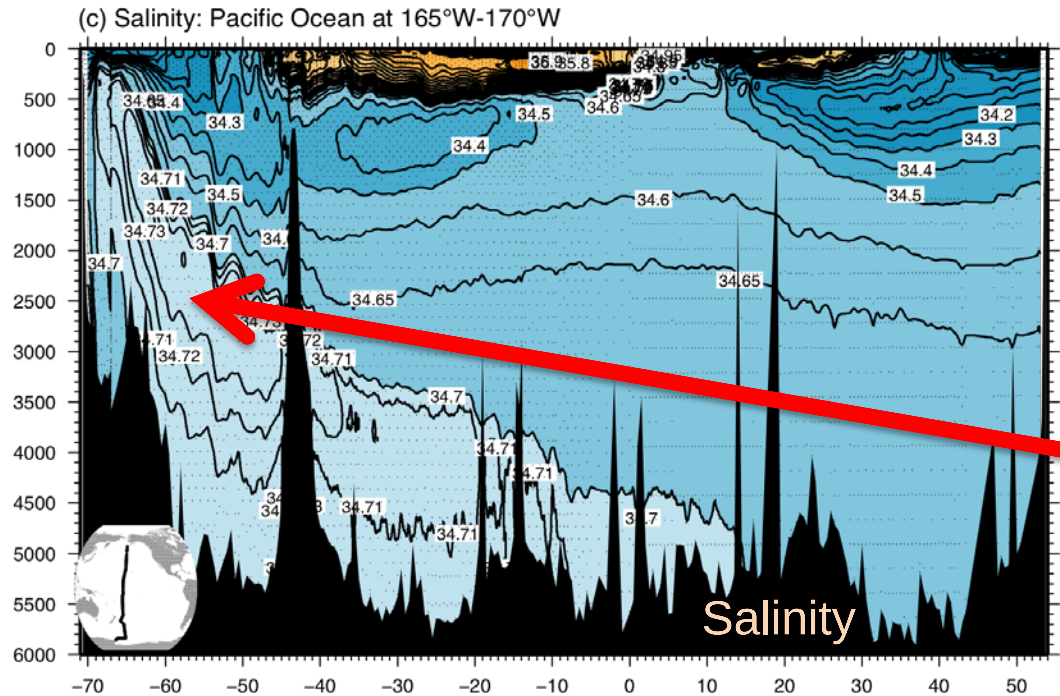
Agulhas retroflection

Other zonal asymmetries: Retroflection of much upper Indian Water into the Agulhas Return Current and then through the SAMW before returning to N. Atlantic



Talley (Oceanography, 2013), edited from Talley et al. 2011 (Descriptive Physical Oceanography, 6th ed.)

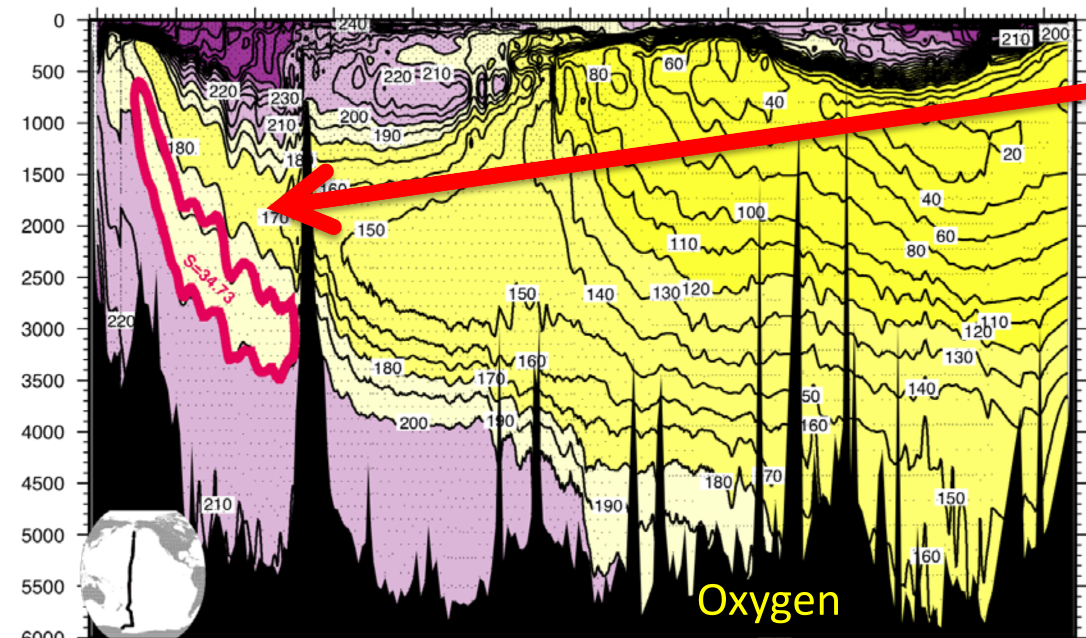
IDW/PDW and NADW layering in the Southern Ocean



Pacific Ocean section as example

Return path to feed NADW formation: upwelling in Southern Ocean – Pacific, Indian or North Atlantic Deep Water?

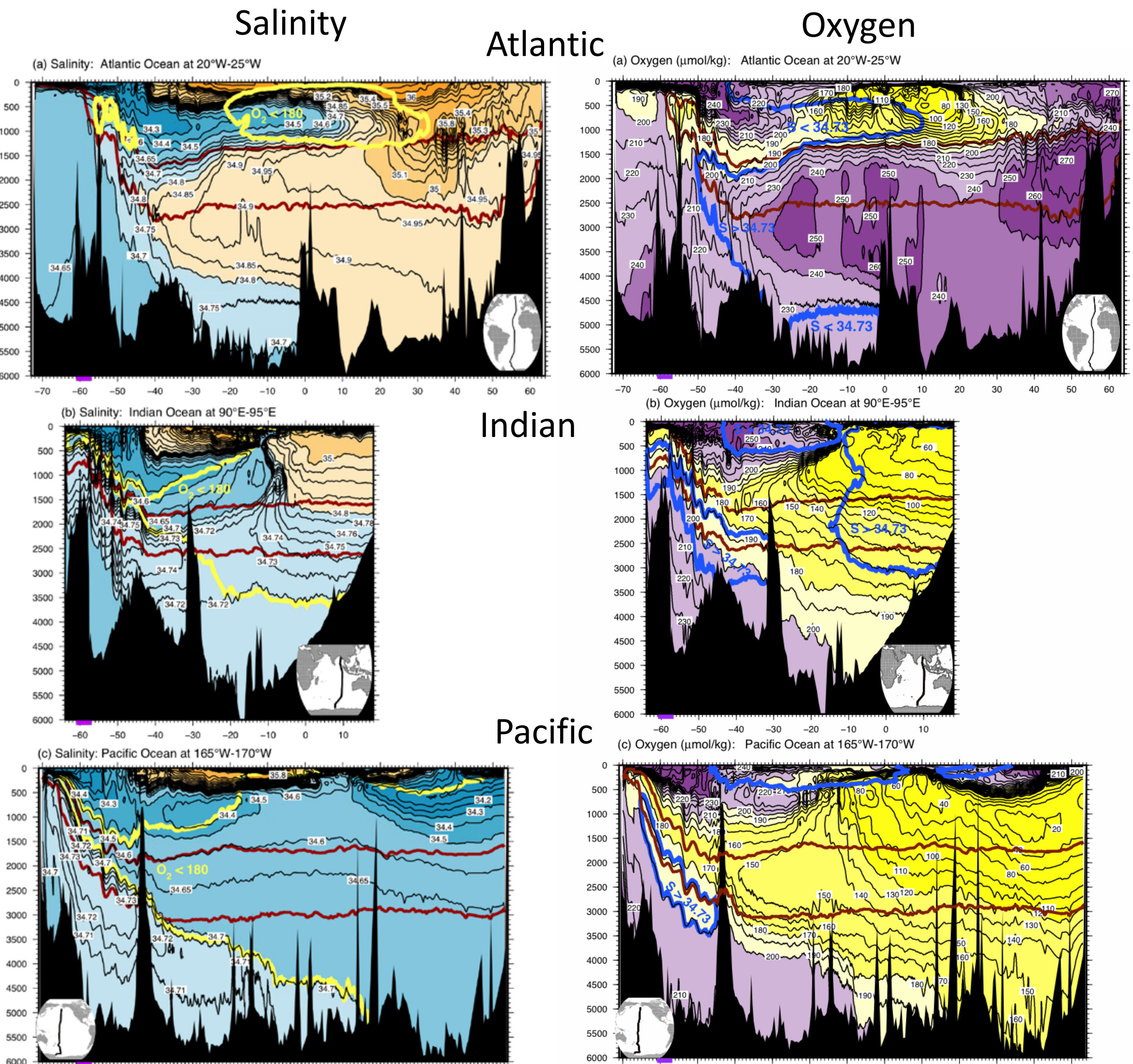
High salinity in ACC: North Atlantic Deep Water signal



Low oxygen in ACC: Pacific and Indian Deep Water signal

High salinity indicative of NADW rises up below and reaches sea surface south of the low oxygen IDW and PDW.

Which northern Deep Waters feed upper and lower S.O. cells?



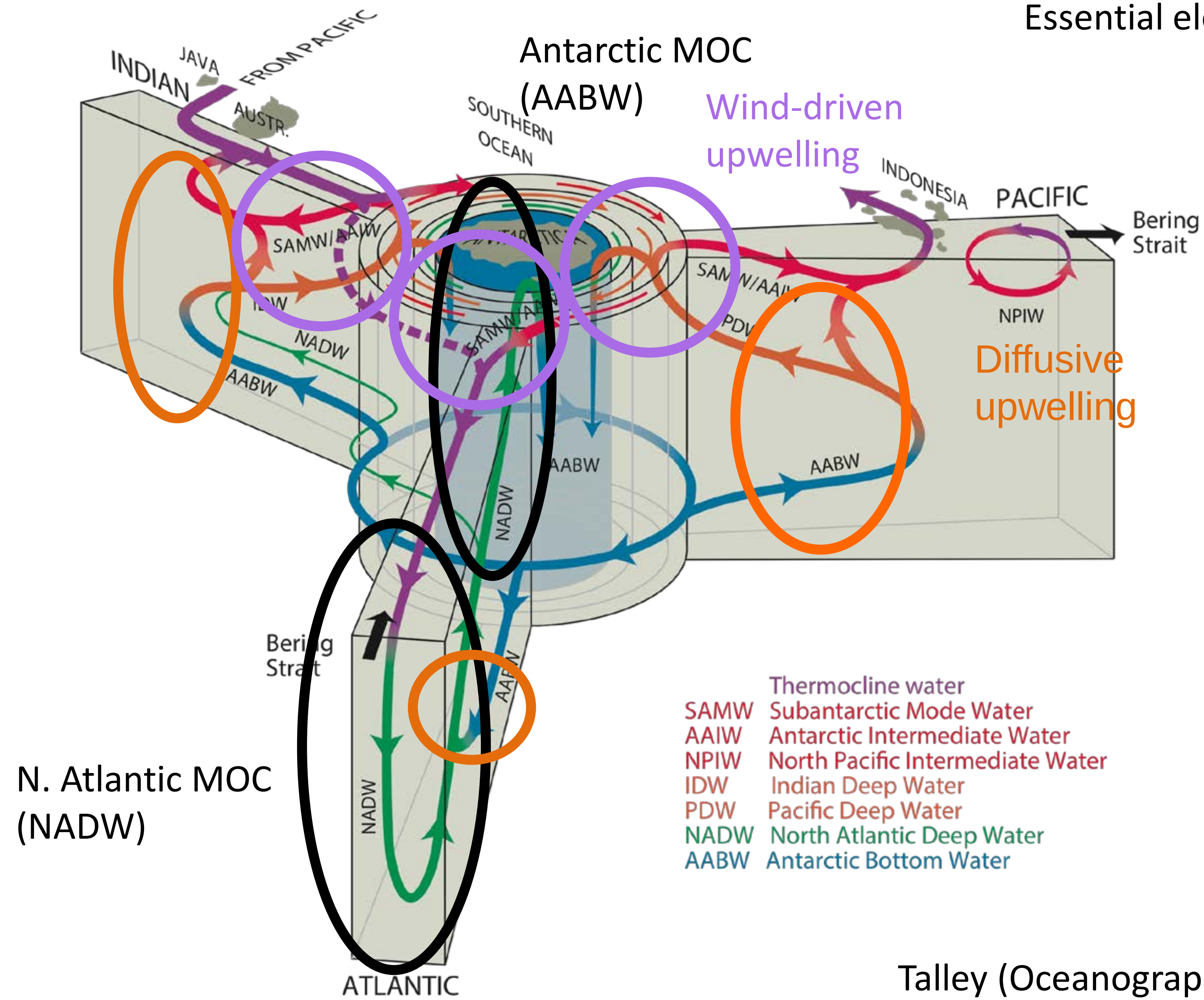
Low oxygen Indian and Pacific Deep Waters enter ACC and upwell at lower density than high salinity NADW.

Therefore we can argue that upwelled IDW/PDW feed upper cell (the northward surface Ekman transports and SAMW). IDW/PDW also join NADW to form AABW (although they do mix, so not so black&white)

Already pointed out in Speer et al. (2000) [Talley, 2013]

Processes for the Global Overturning Circulation

Essential elements of overturning circulation



Talley (Oceanography, 2013)

Movement of deep waters across D.P. latitudes and ACC

1. Where do the deep waters upwell to the surface? Where do they cross D.P. latitudes?
2. Which deep water is important for warming in Bellingshausen and Amundsen, west Antarctic Peninsula? (does that matter??)
3. Special upwelling sites along ridges?
4. Why the extruded thinnish layer of deep waters that cross and upwell at about 1000 m, compared with thick deep water layers north of about 45°S?

Answers to almost all: topography is the most important
Isopycnal mixing distribution

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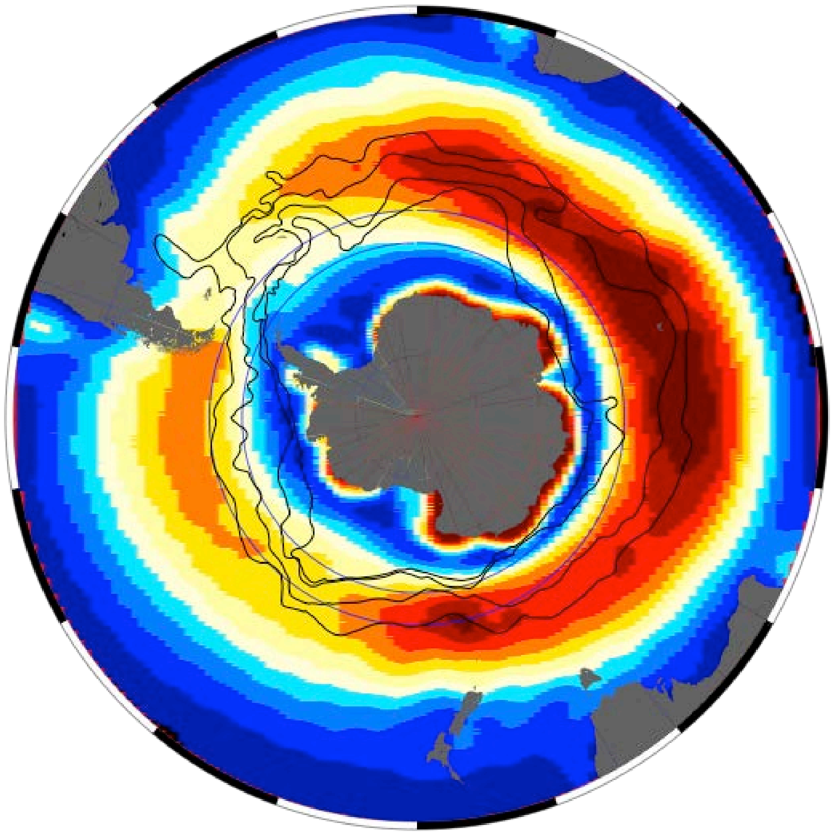
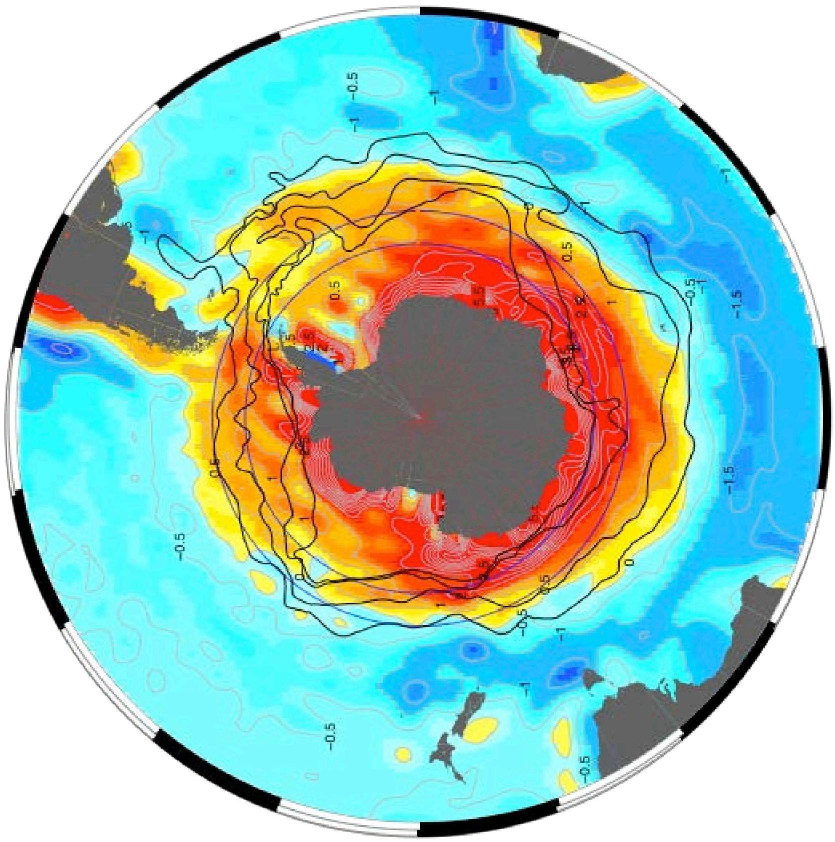
Wind stress (magnitude) and –curl





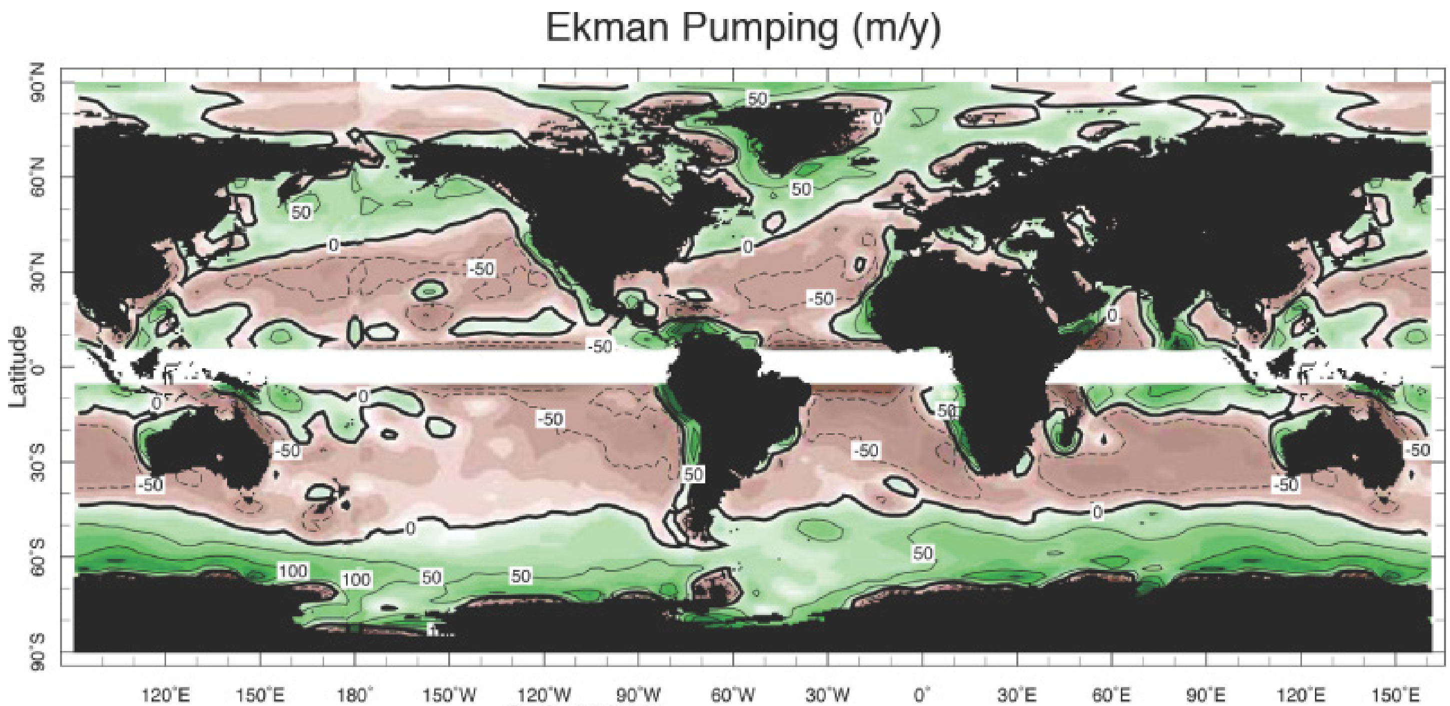
Wind stress magnitude

•Maximum westerlies mostly north of Drake Passage
•Easterlies at continent

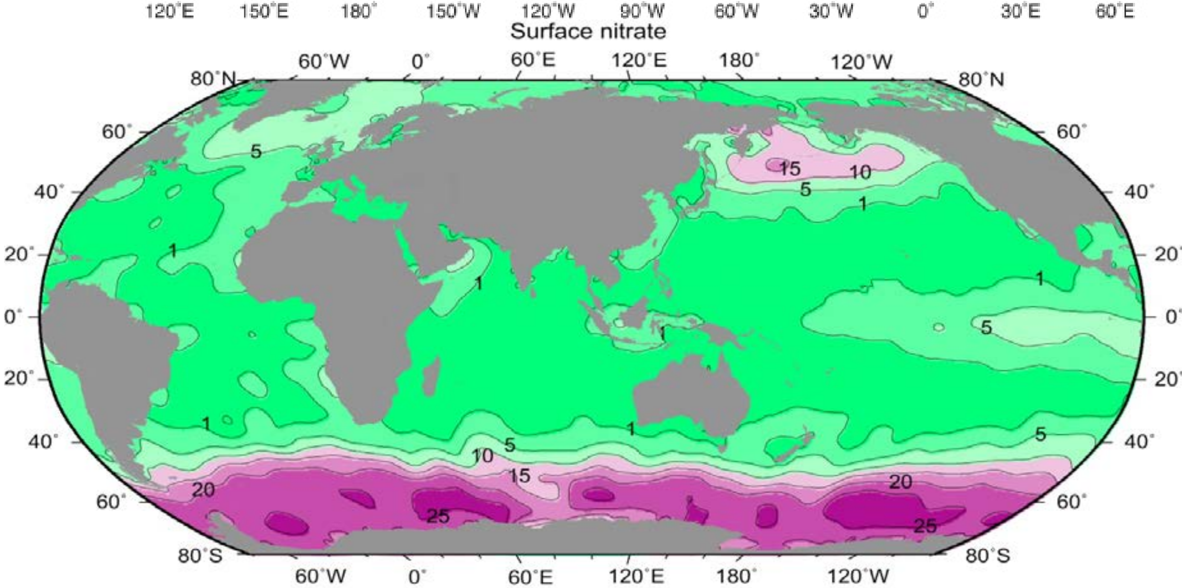
Wind stress curl
Red/yellow: Ekman upwelling
Blue: Ekman downwelling

Even the ACC Southern Boundary wanders north of D.P., following long ridges

Wind stress: upwelling and downwelling



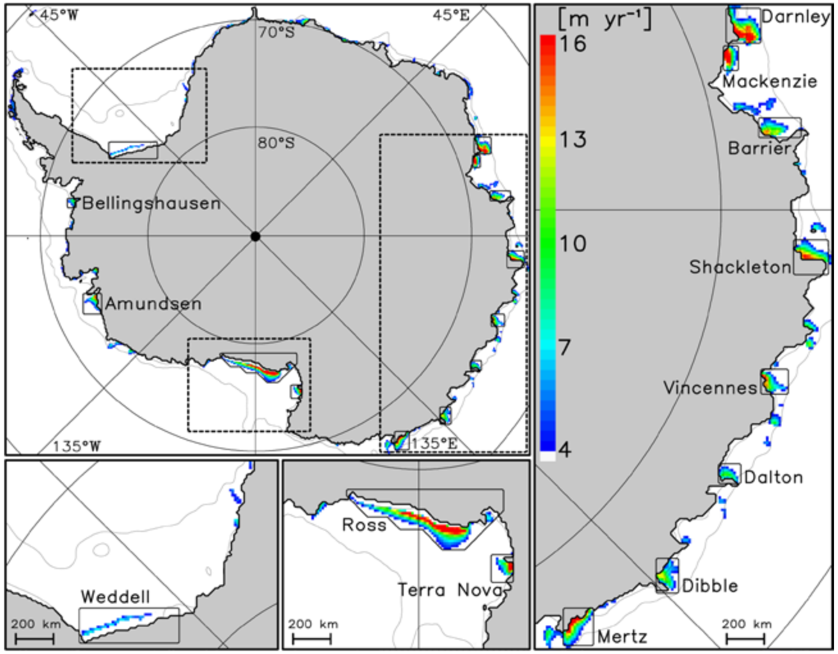
Marshall and Plumb (2007)



Nitrate (μmol/L) at the sea surface (climatology from Levitus et al. 1994)

High surface nutrients due to upwelling of deep water and incomplete usage

Aside: fate of upwelled water: lower cell



Lower cell

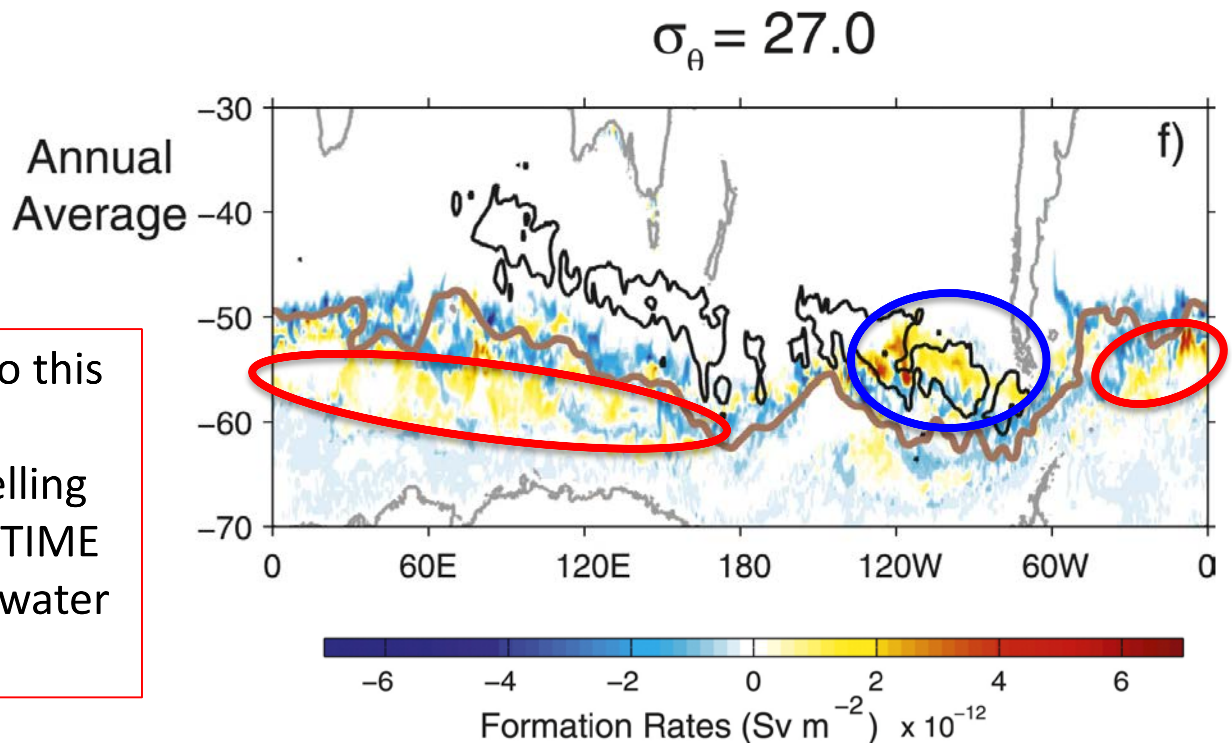
Cools to freezing

Brine rejection in coastal polynyas and subice cavities (not shown) creates dense shelf water.

Creates range of dense waters, denser of which flow northward back into ocean basins to north. → AABW

Aside: fate of upwelled water: upper cell

Formation into this density class through upwelling and SUMMERTIME heating/freshwater : obduction



SAMW – actual mode water formation (WINTERTIME heat loss) Convection and subduction

Example using Southern Ocean State Estimate (SOSE)

SE Pacific SAMW formation: Yellow-red is formation of new water. Blue is loss of water. (extension of Walin 1982 method, following Maze et al. 2009)

Black contour is the 300 m winter mixed layer depth.

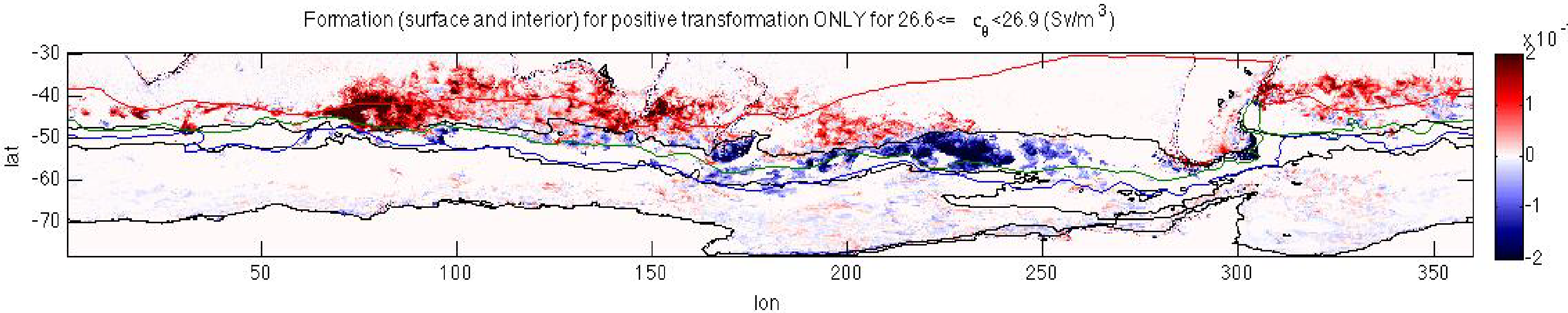
Cerovecki, Talley, Mazloff, Maze (JPO, 2013)

Water mass formation is due to both buoyancy gain and loss

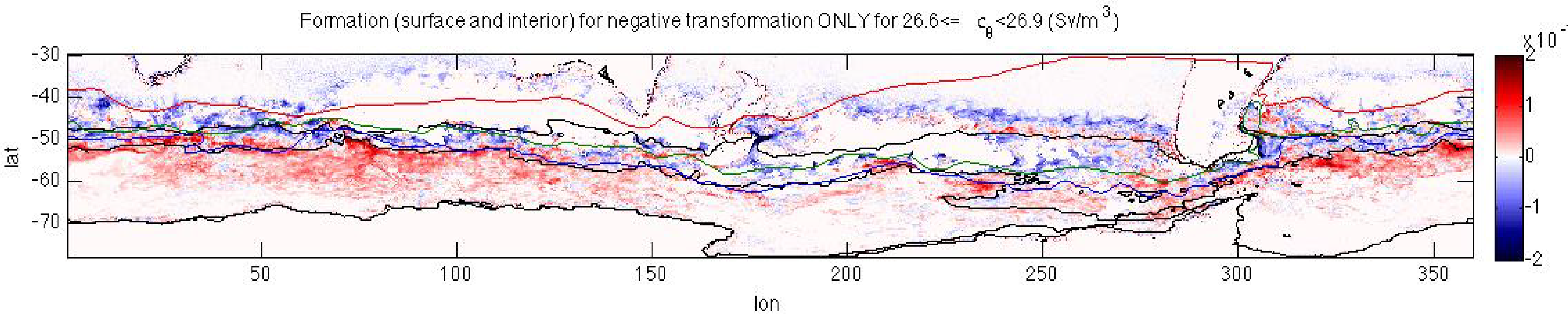
Example for SE Indian SAMW (largest of all SAMWs)

Formation (red) due to

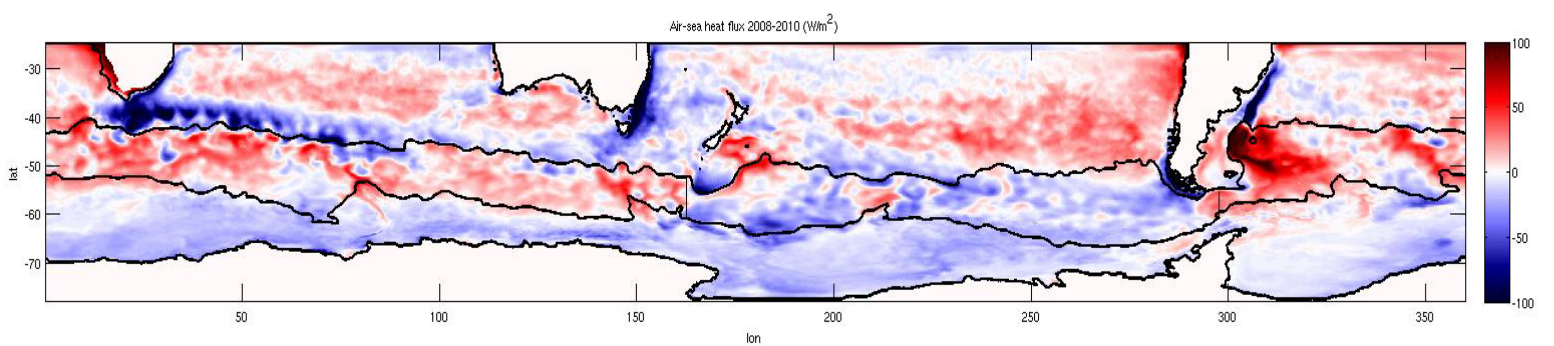
Buoyancy loss (cooling) SUBDUCTION



Buoyancy gain (heating, freshwater) OBDUCTION

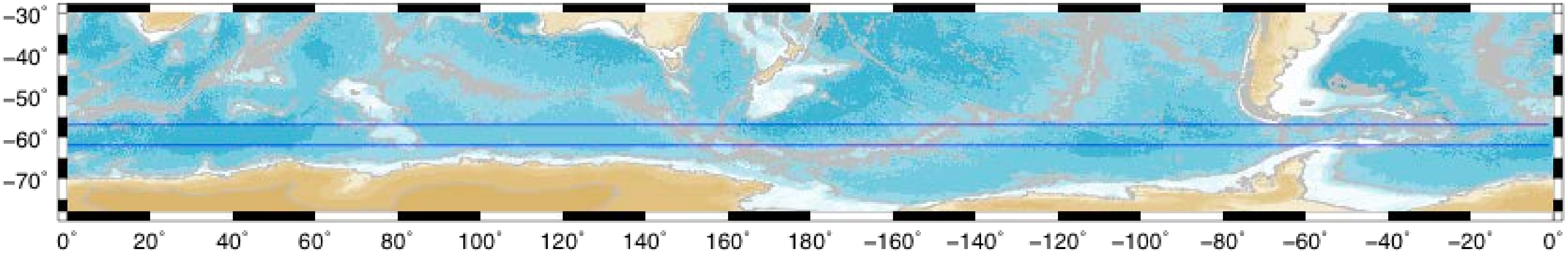


Air-sea heat flux (2008-2010)



SOSE output (Tamsitt, Mazloff, Cerovecki & Talley)

Return to deep waters: Where do deep waters enter the S.O. and upwell?



Why is the Southern Ocean dynamically special ?

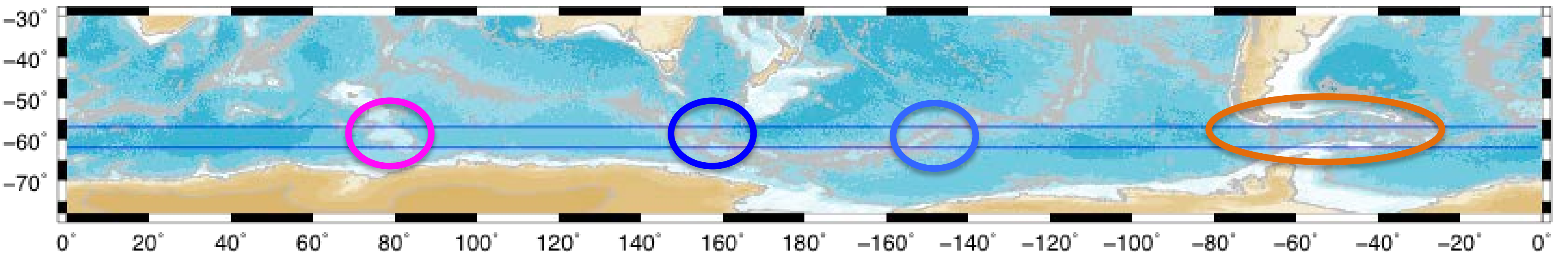
Drake Passage is open above "sill depth", so no zonal pressure gradient to support net southward upper ocean geostrophic transport across this latitude band (about 300 to 400 km wide 57°S to 60° or 61°S)

Water below "sill depth": easy net southwards and northwards transports.

Water above "sill depth": net meridional transport is ageostrophic. Ekman is principal mechanism (but balanced locally by baroclinic instability if it is crossing the ACC, so northward transport may be much lower than net Ekman transport) (residual mean discussion)

CDW can go north and NADW/IDW/PDW south to the extent that their transports balance, so properties (oxygen, salinity, etc) can be exchanged laterally along isopycnals

Where do deep waters enter the S.O. and upwell?



Minimum "DP" sill depth is not co-located with the minimum "strait" width.

Dynamical controls as in a strait where minimum lateral constriction does not coincide with minimum depth

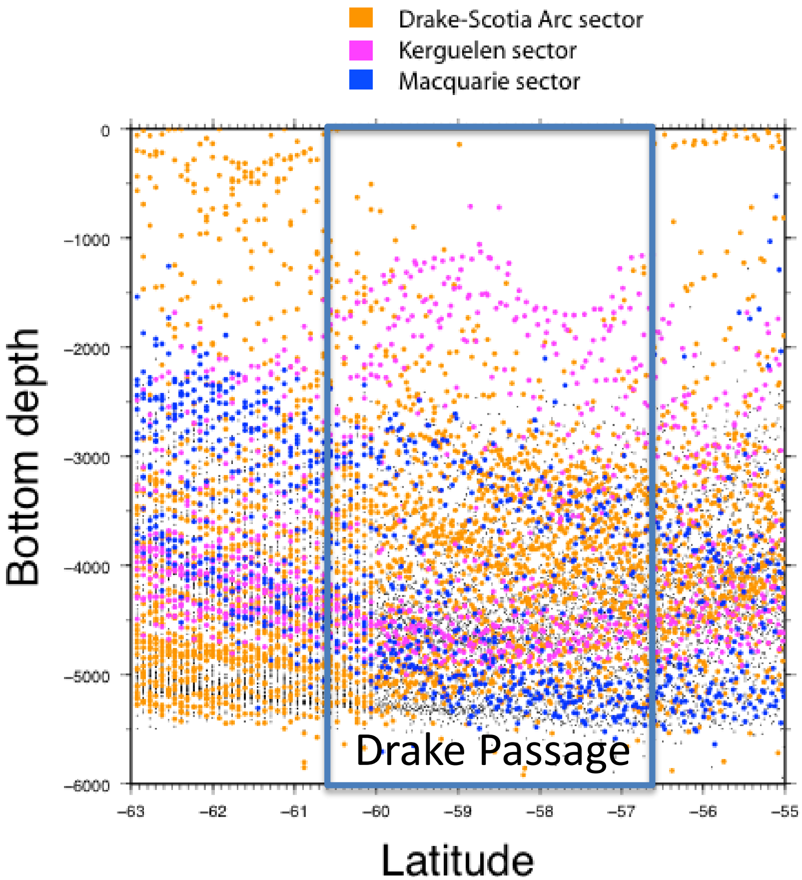
Most massive impediments are

Kerguelen Plateau (~1500 m)

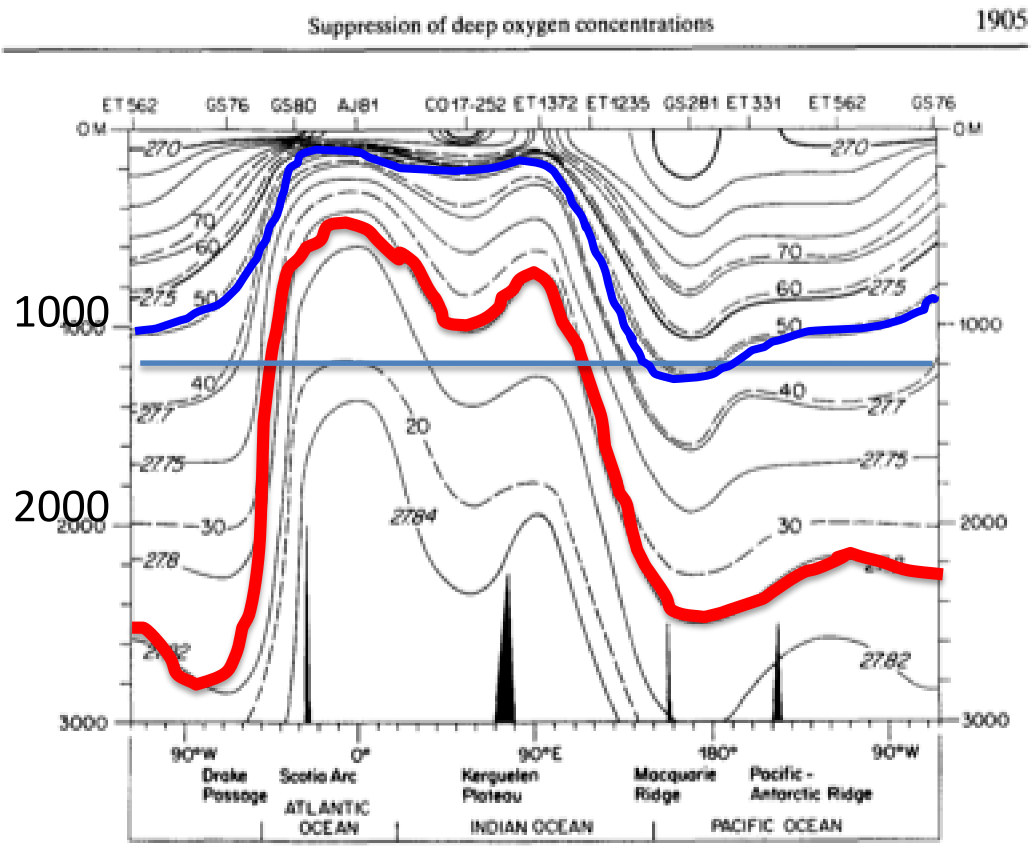
Scotia Arc and America-Antarctic Ridge (~2000 m)

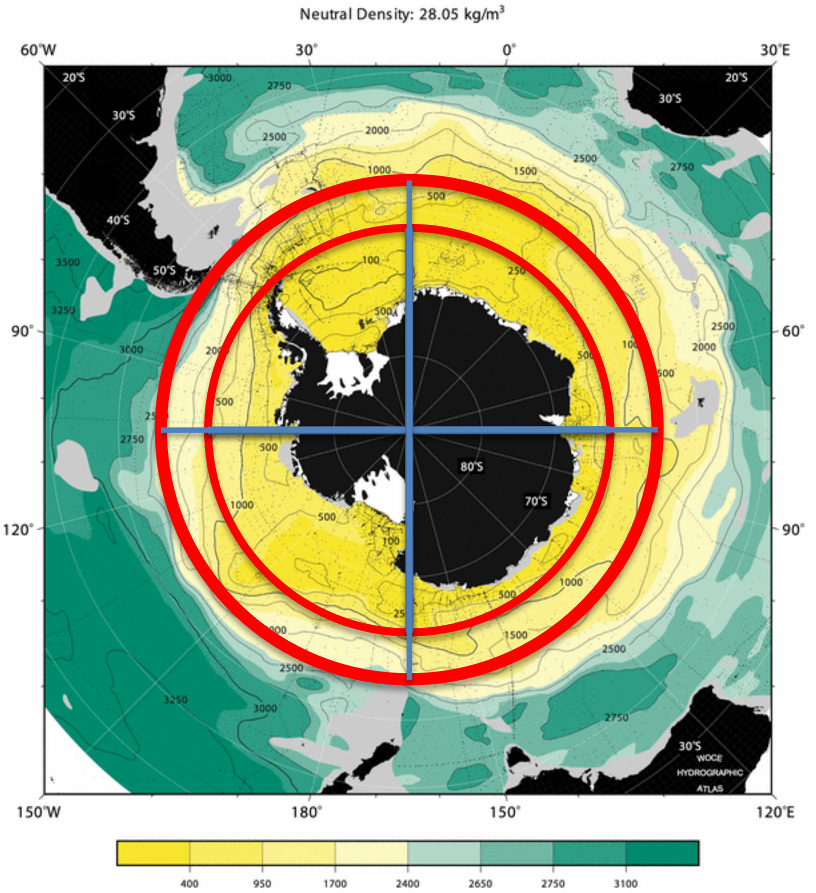
Macquarie Ridge and Southeast Indian Ridge (~2500 m)

Pacific-Antarctic Ridge (~2500 m)



Relation of NADW isopycnal to Drake Psg. Sill depth



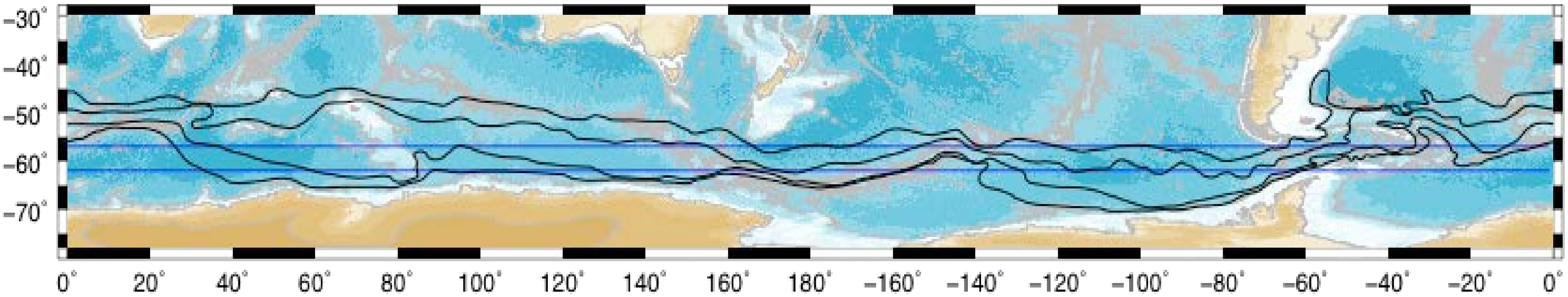


•The LCDW isopycnal 27.8 σ_θ (equivalent to γ^N = 28.04 used here – high salinity) is the lowest density at the sill depth in Drake Passage latitudes (Warren, DSR 1990)

•That means that NADW can cross southwards, but IDW/PDW have a much harder time

•This also means that Kerguelen is as important as Drake Psg. for controlling S.O. meridional and vertical transports (but those transports do not need to be localized at Kerguelen)

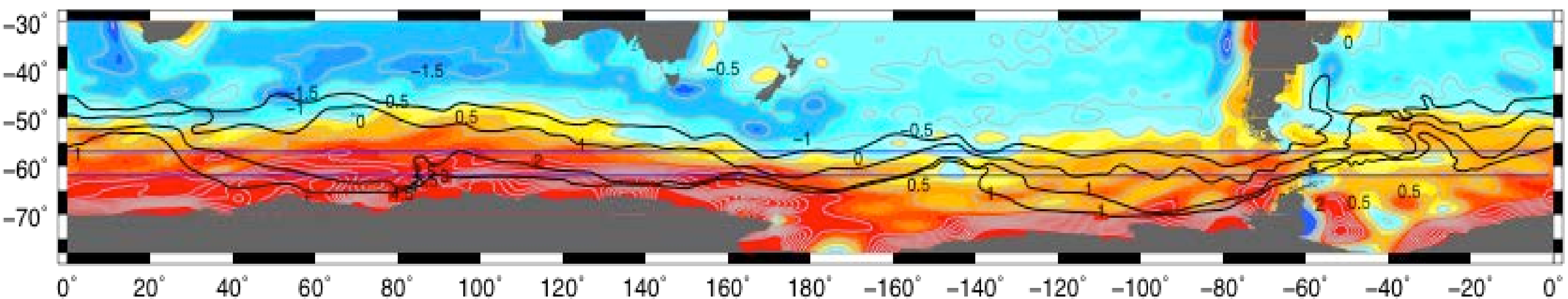
ACC fronts & Drake Passage, topography



ACC, represented by Orsi (1995) fronts, wanders around the Drake Passage latitudes.

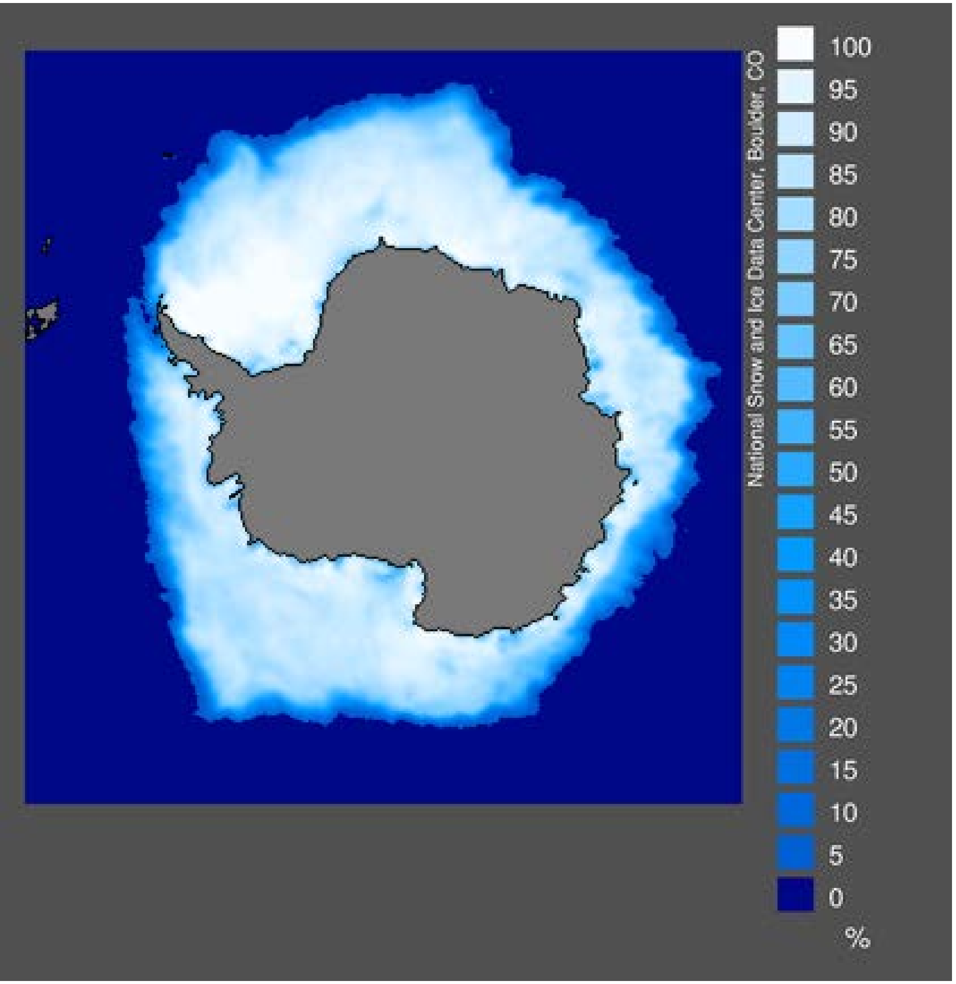
Subantarctic Front is almost entirely north of Drake Passage, and north of zero curl

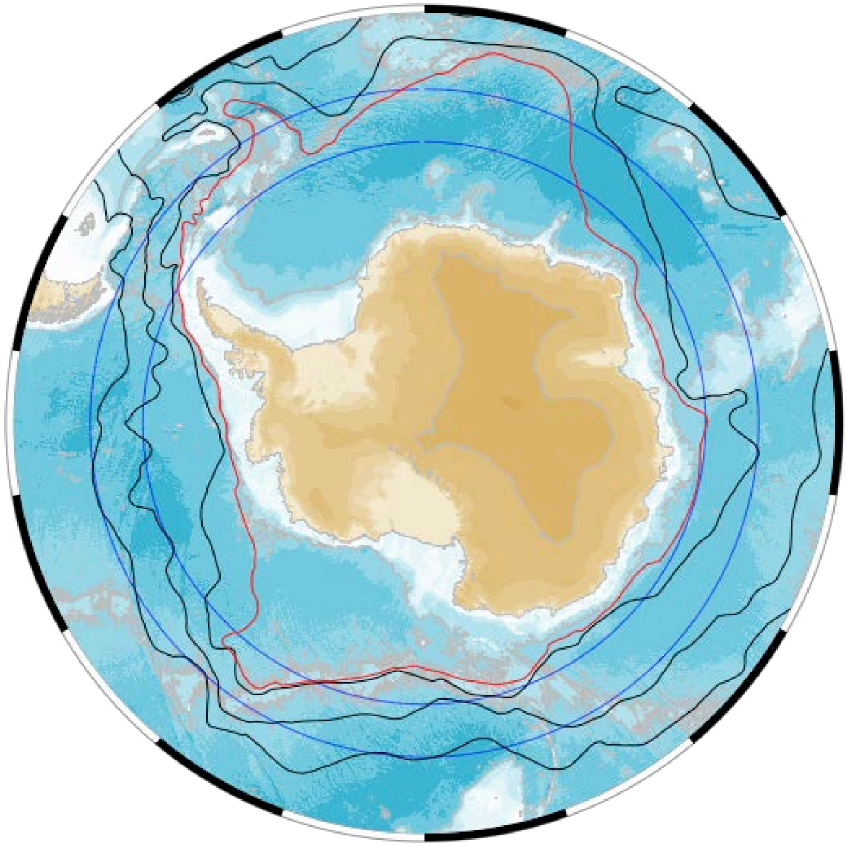
Southern Boundary (southern edge of UCDW oxygen minimum) mostly south of D.P. except where driven north along ridges in Pacific and Atlantic



Wind stress curl (yellow-red = upwelling)

Aside: Winter Antarctic sea ice





August, 2000

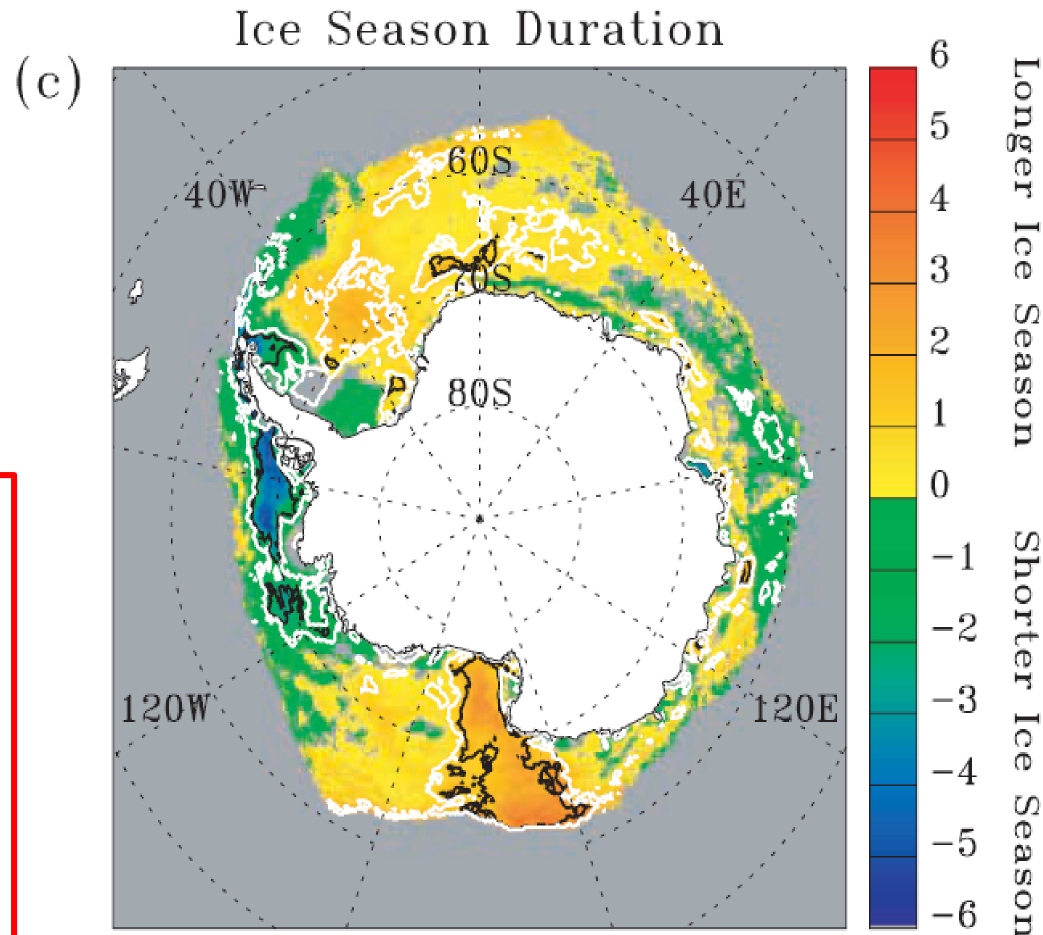
National Snow and Ice Data Center

- Winter ice guided by ACC
- Farthest northern excursions guided by ocean ridges
- ACC Southern Boundary in red (southernmost extent of UCDW oxygen minimum associated with ACC)

Aside: sea ice relationship to asymmetric circulation

Changes in sea ice duration: 1979 – 2006

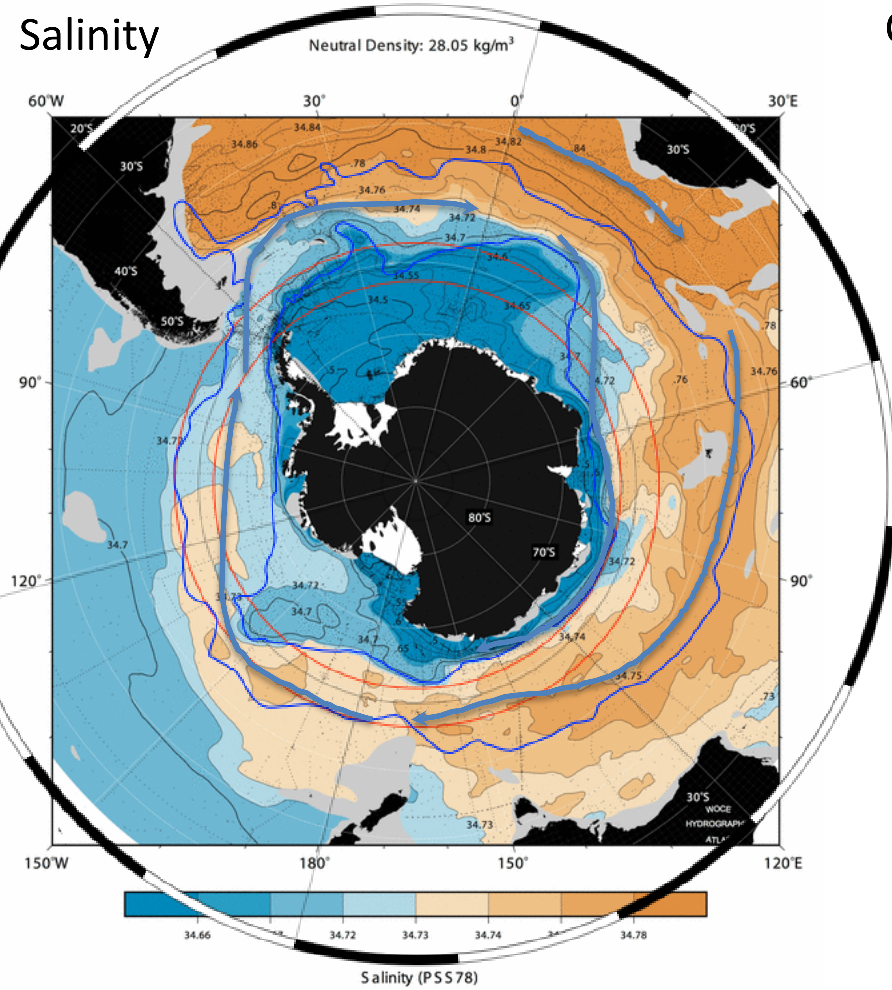
- Sea ice is expanding where the circulation is northward, largely topographically-trapped, advecting coldest waters.
- Sea ice decreasing where warmest waters encroach.
- Stronger circulation?? (See S4P, P16S results on poster on Tues. suggesting stronger ACC flow into Amundsen, Bellingshausen in recent years)



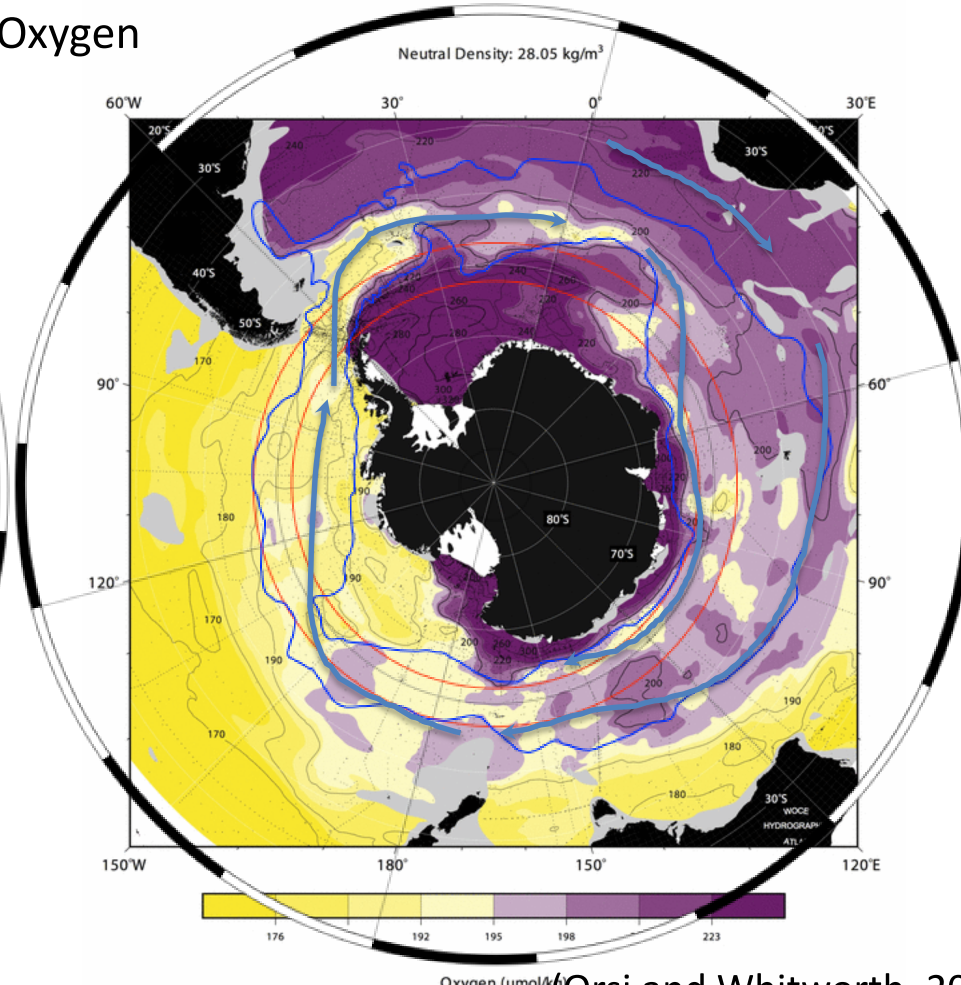
Stammerjohn et al. (2008)

NADW (LCDW) pathway (28.05 gamman)

Salinity



Oxygen



(Orsi and Whitworth, 2005 online WOCE Southern Ocean Atlas)

- Core of high salinity (also high oxygen):
- North of SAF to Kerguelen
- Along SAF east of Kerguelen to PAR/Eltanin FZ
- Cross DP latitudes at EFZ, into Amundsen
- Back north at Drake, southern side of ACC to Adelie Land

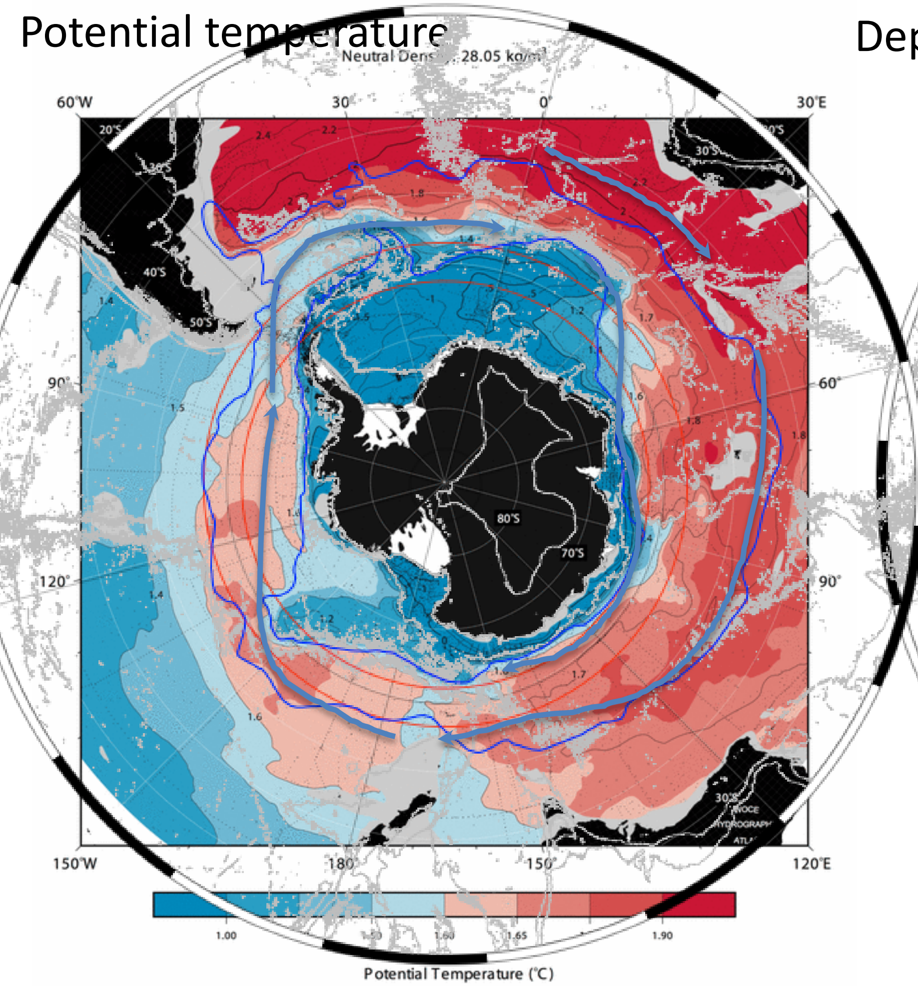
LCDW

North Atlantic Deep Water

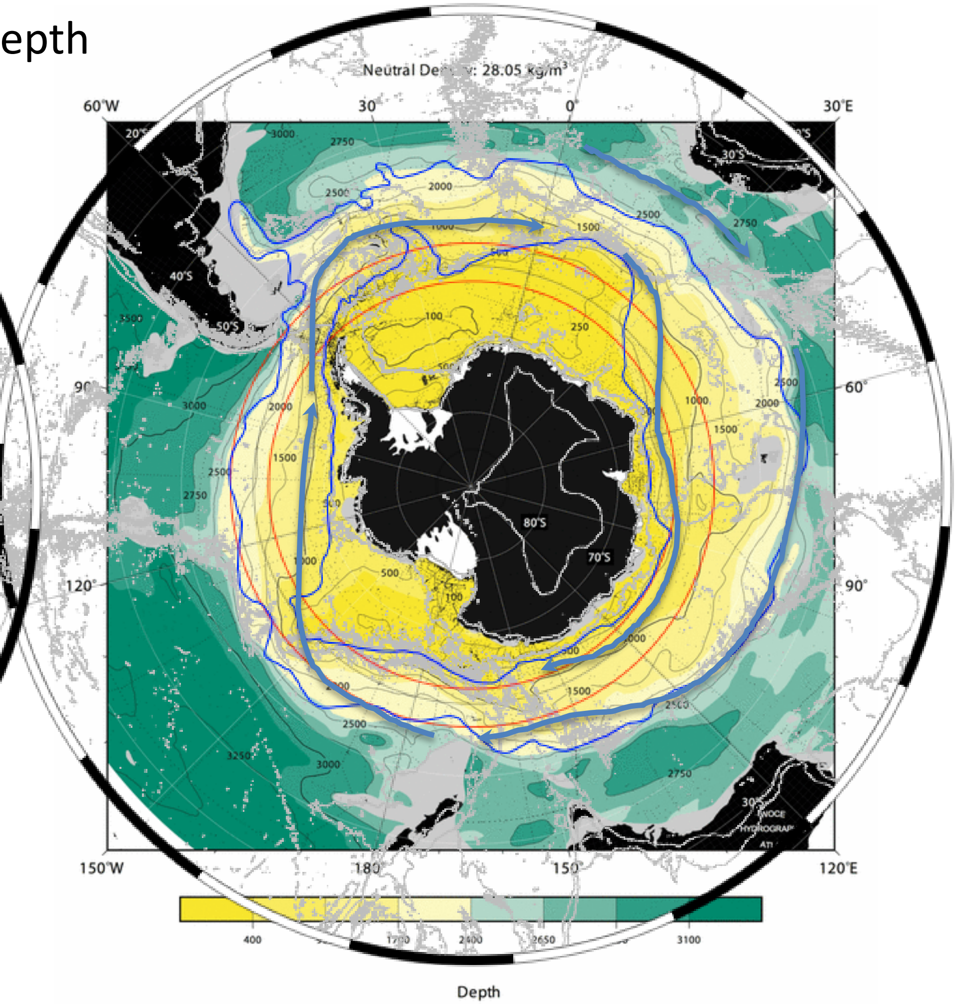
isopycnal $\gamma^N = 28.05$

NADW (LCDW) pathway (28.05 gamman)

Potential temperature



Depth

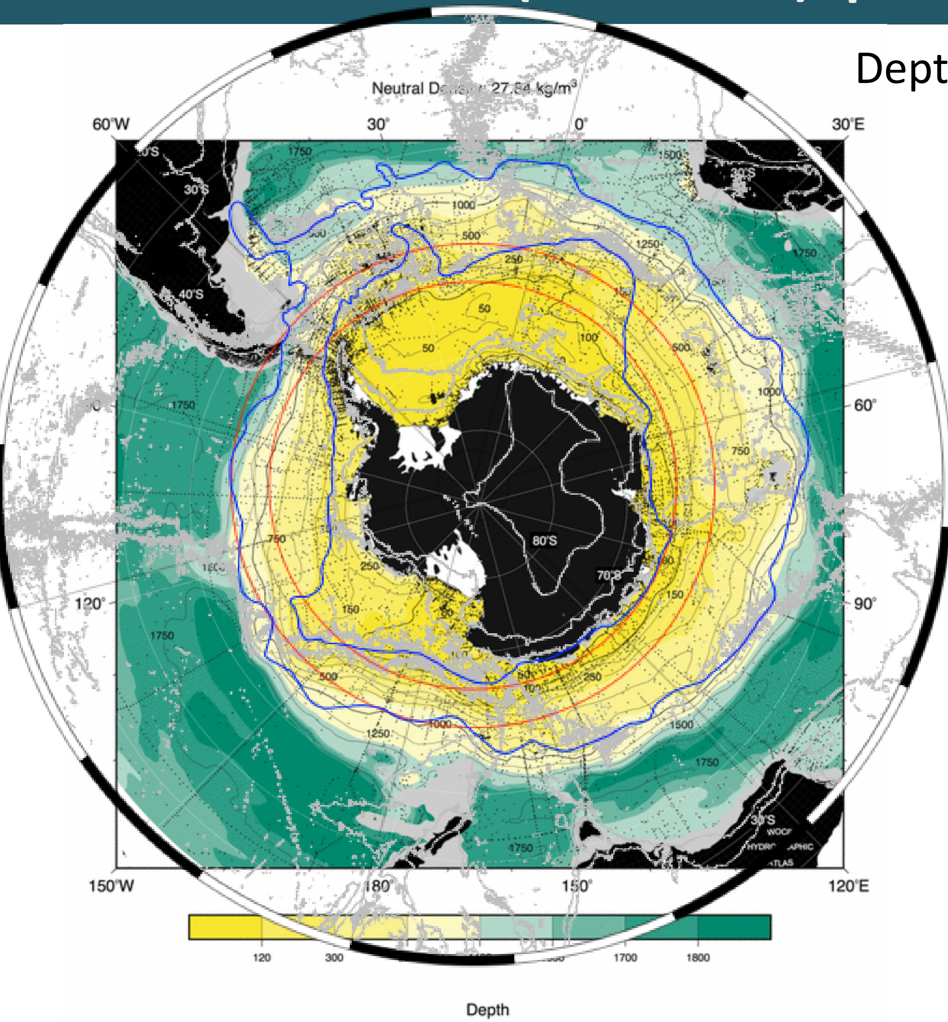


- Warm water to WAP but pretty deep there.
- -> Look to UCDW for heat on shelf at WAP

- Core at 2500-2700 m from Atlantic to Eltanin FZ
- Rises up to 1000 m in Am/Bell.
- Through Drake to SW Indian Ridge, up to 700 m there and to 500 m along Wilkes/Adelie Lnd

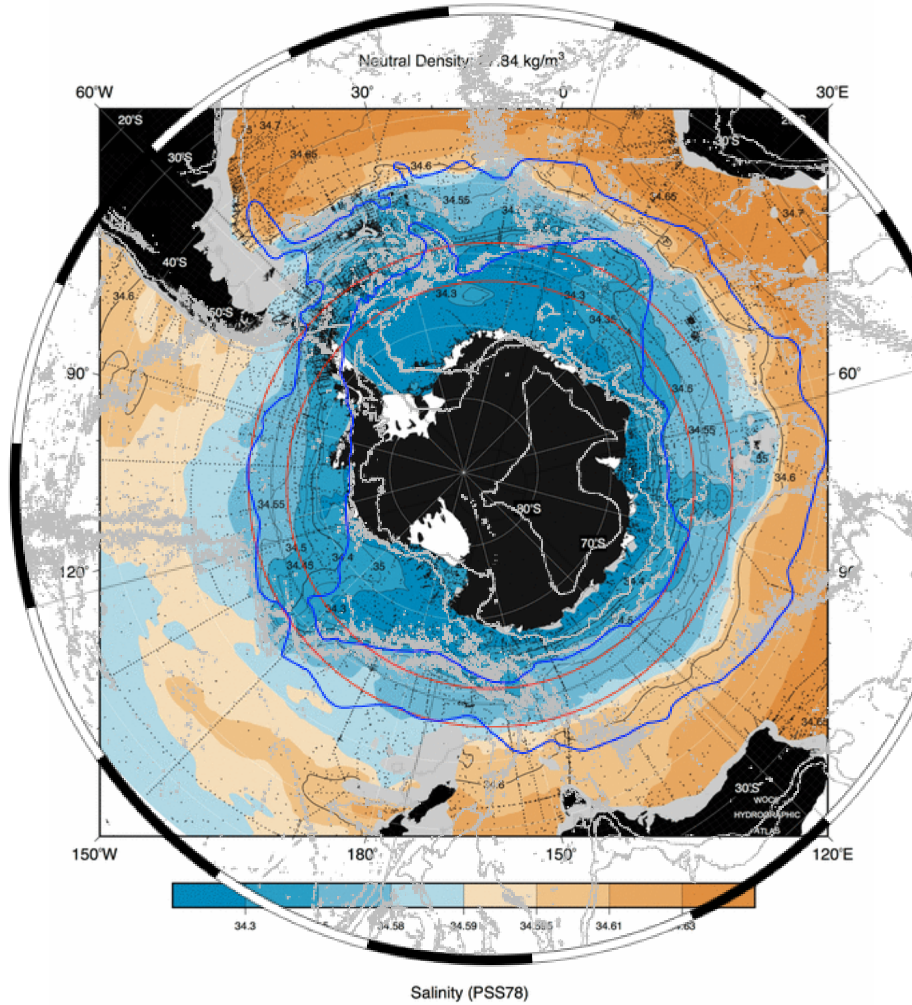
IDW/PDW (UCDW) pathway (27.84 gamman)

Depth



UCDW

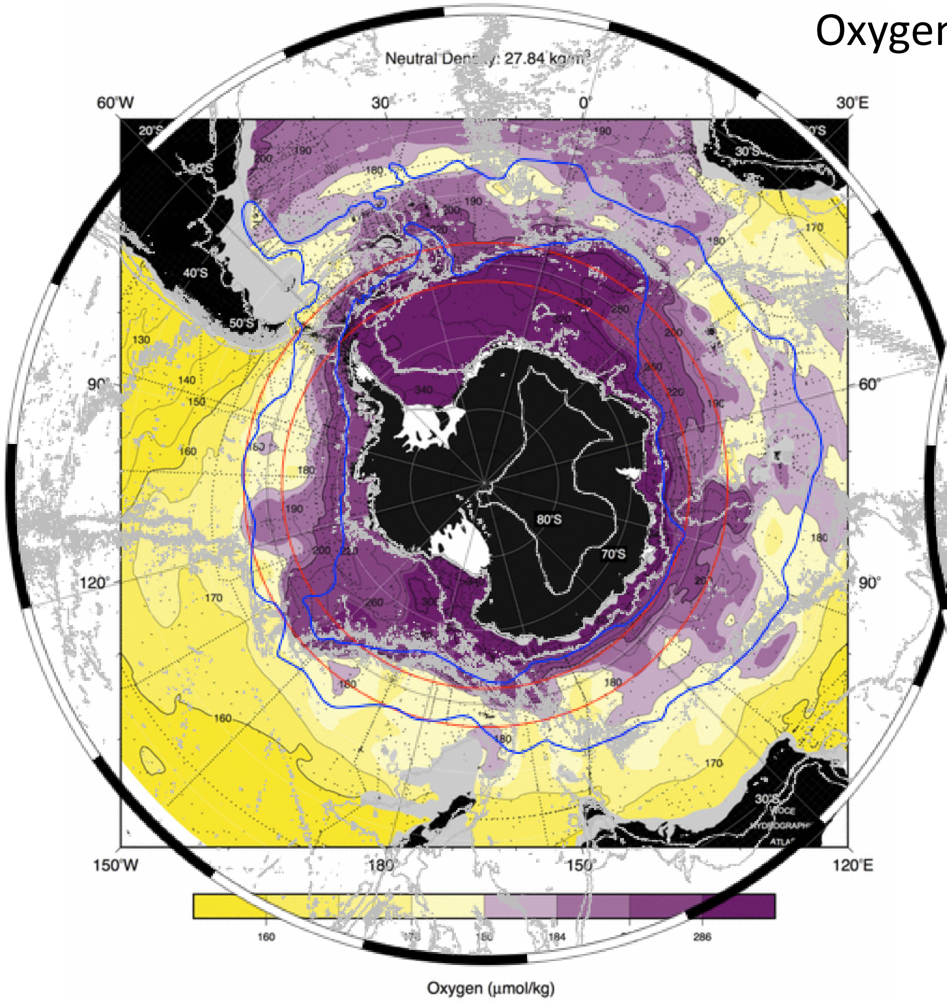
Indian Deep Water and Pacific Deep Water isopycnal γ^N = 27.84



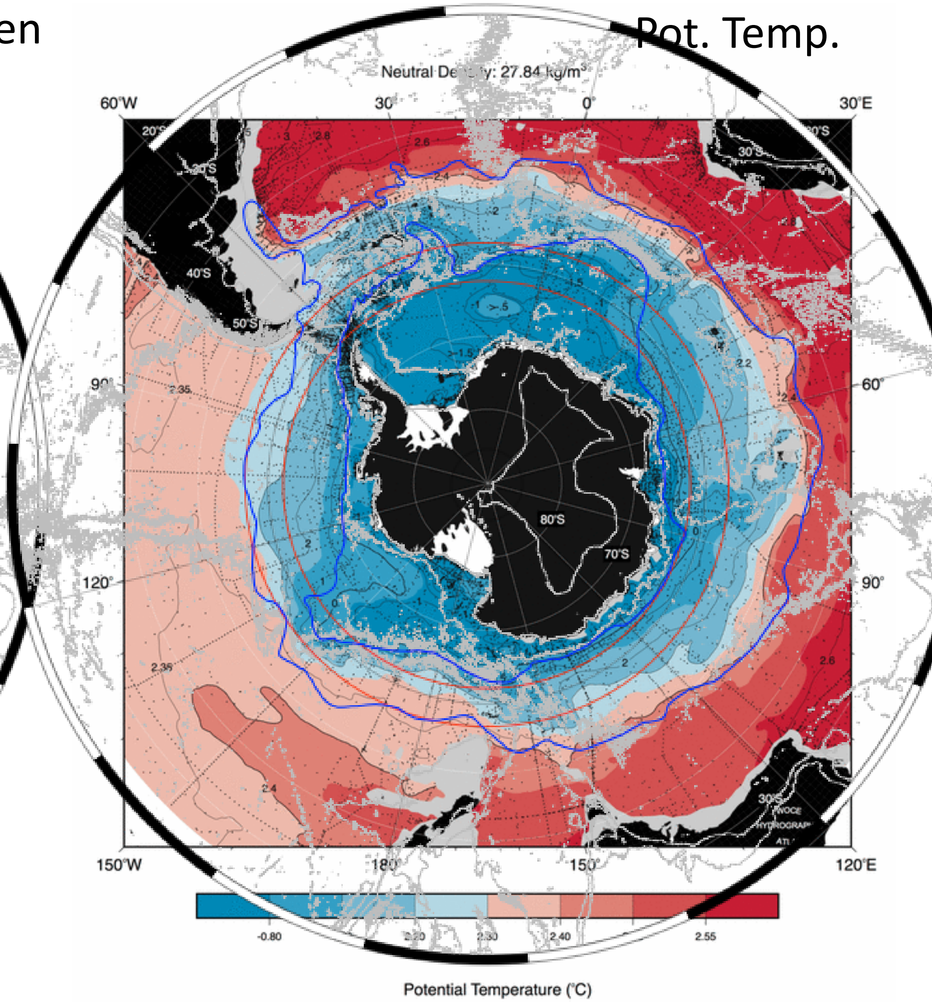
(Orsi and Whitworth, 2005
online WOCE Southern Ocean Atlas)

IDW/PDW (UCDW) pathway (27.84 gamman)

Oxygen



Pot. Temp.



- Low oxygen into DP lats south of Australia (east of Kerguelen)
- Crosses into Bellingshausen east of Eltanin FZ in Pacific.
- Warmest water close to continent (0°-2°C) due to the latter

(Orsi and Whitworth, 2005
online WOCE Southern Ocean Atlas)

Movement of deep waters across D.P. latitudes and ACC

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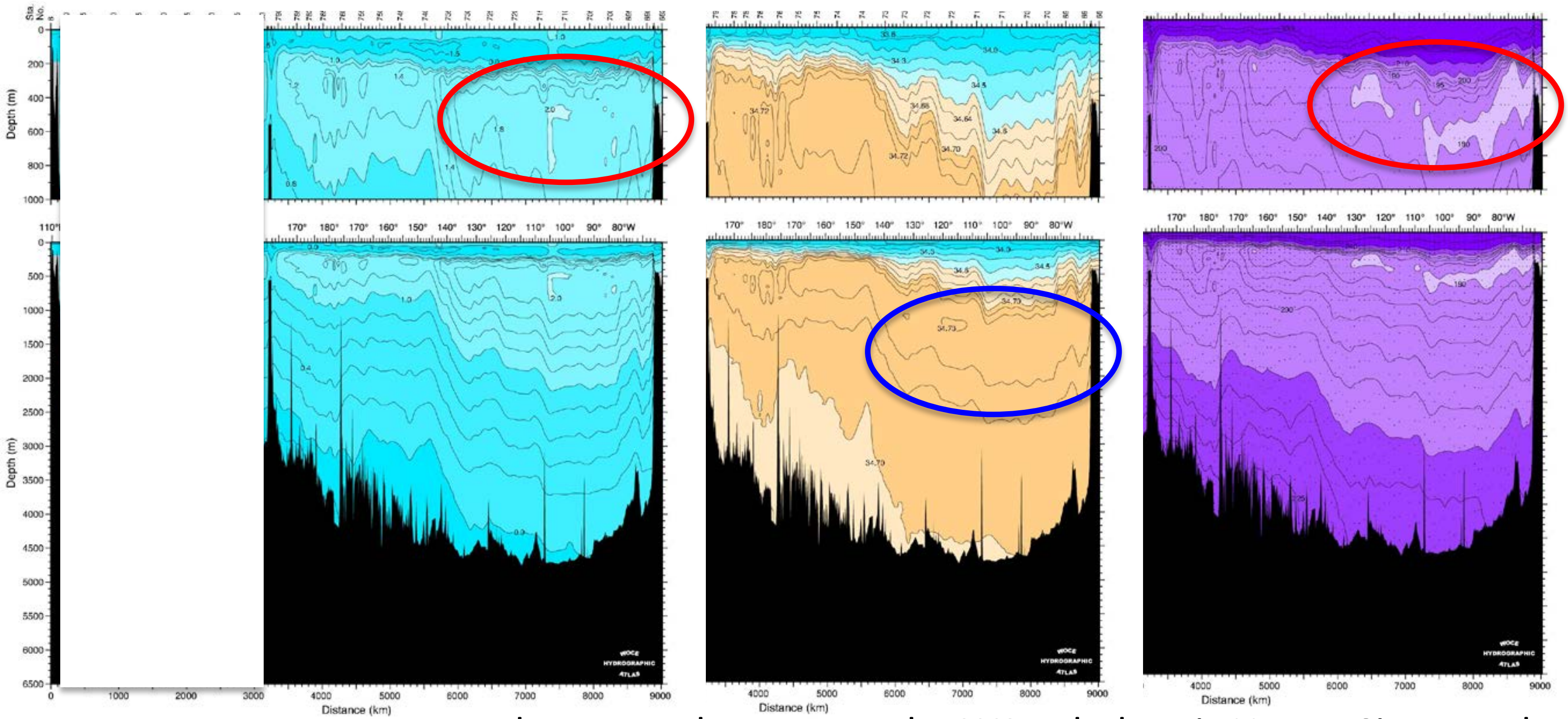
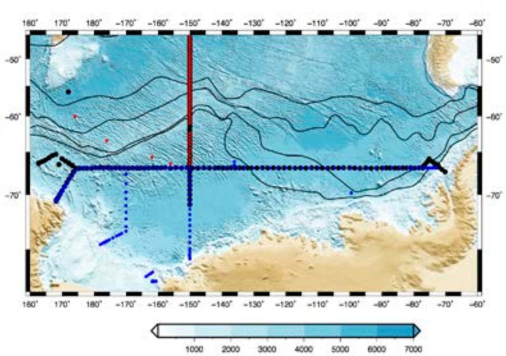
Answers to almost all: topography is the most important
Isopycnal mixing distribution

(3) Warm Deep Waters at WAP

GO-SHIP section P16S across Ross, Bellingshausen, Amundsen Seas



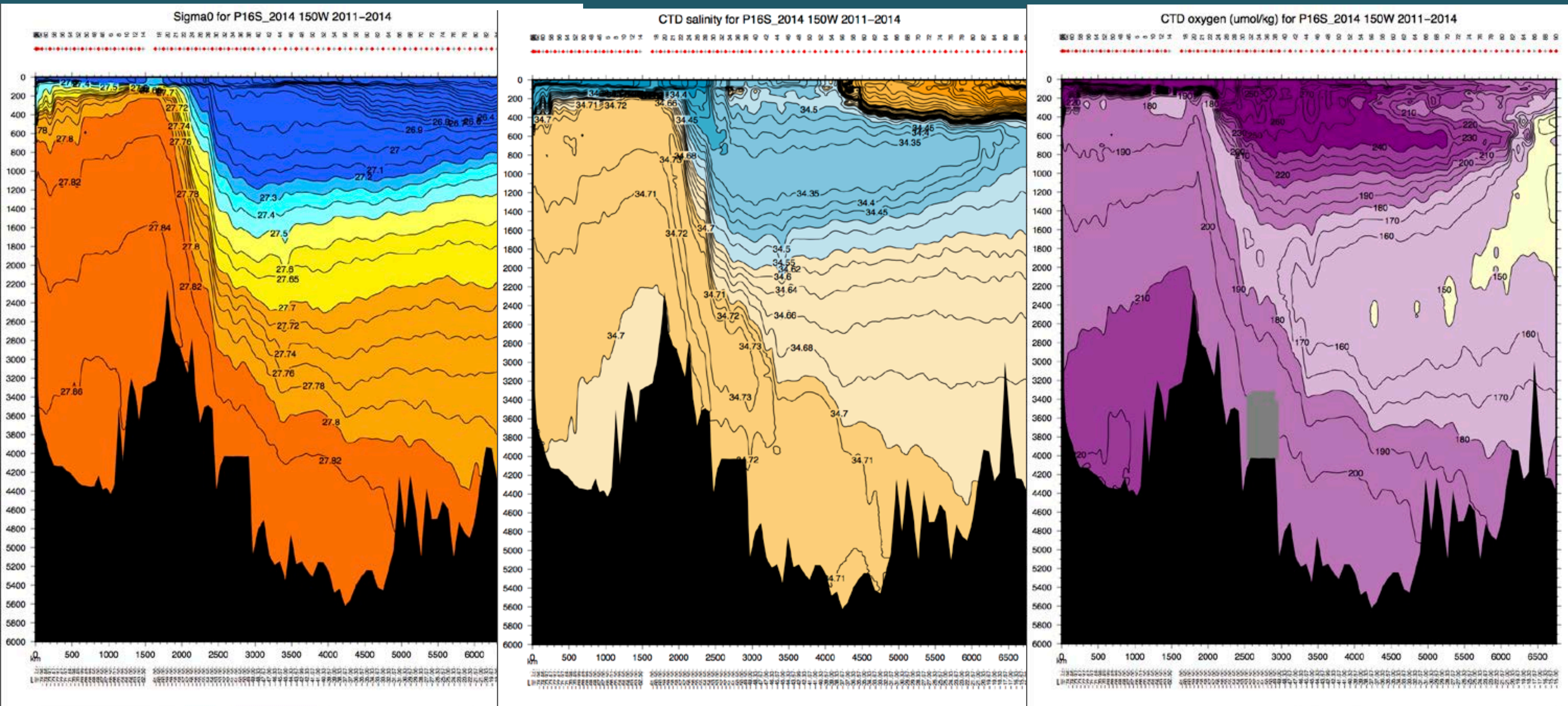


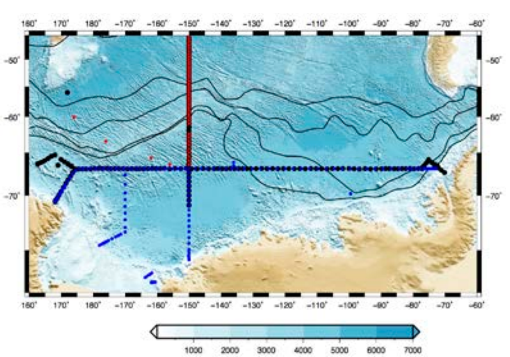
The water that warms the WAP shelves is Upper Circumpolar Deep Water, which comes from Indian/Pacific

Warm temperature maximum water is UCDW: low oxygen at 300-400 m

(LCDW or NADW is high salinity at 1000-1500 m)

(4) Ridge “chimneys” from the deep





Pacific-Antarctic Ridge strongly steers ACC. (Other region with similar steering is northern edge of Weddell Gyre, SW Indian Ridge)

Upwelling of IDW/PDW just north of upwelling of NADW to near surface.

Clear surface exchange downwards on the isopycnals.

Must have very large lateral component

Carbon air-sea exchange and ACC/topography

NATURE|Vol 463|7 January 2010 LETTERS

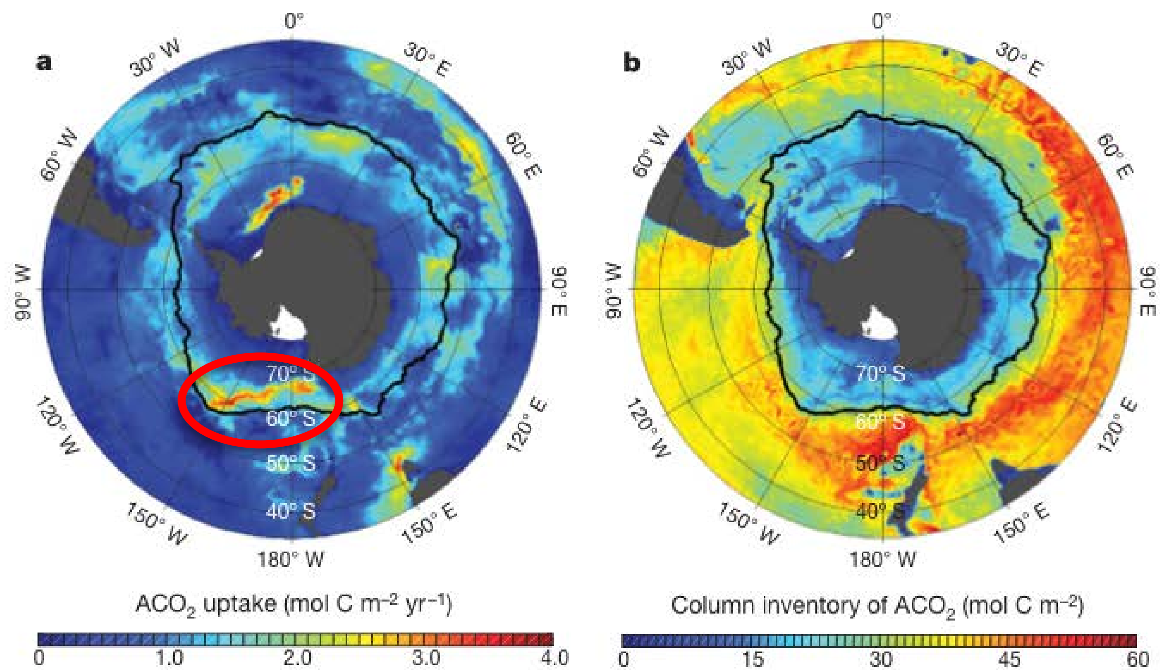
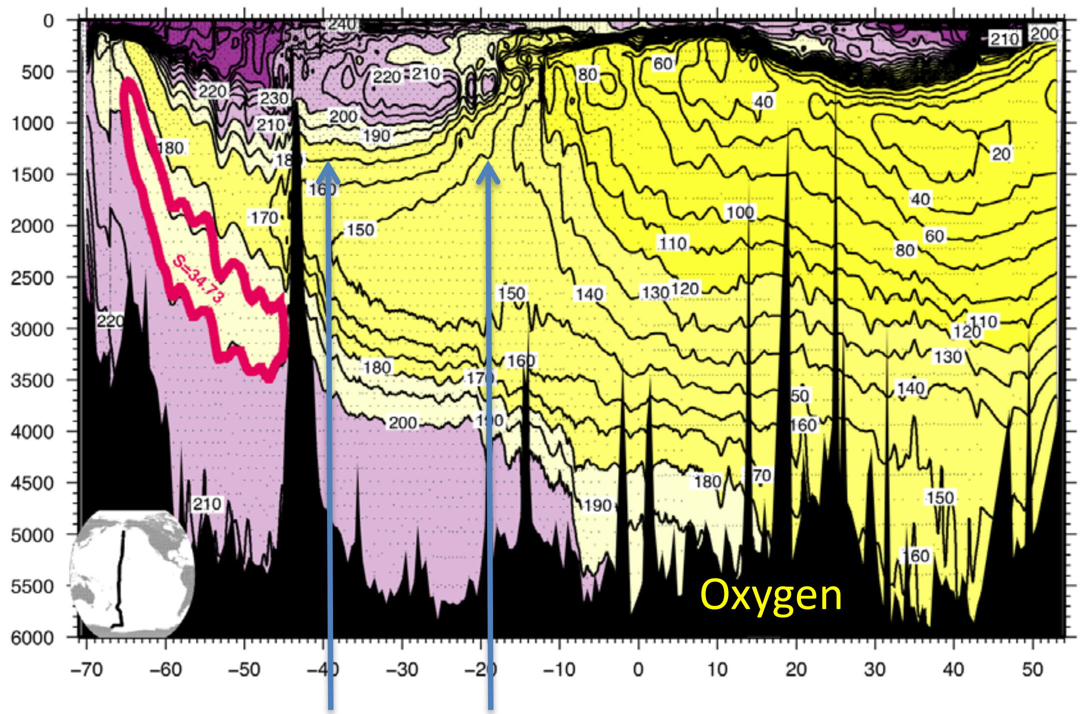


Figure 1 | Uptake and inventory of anthropogenic carbon. a, The 2-yr mean of ACO_2 uptake rates evaluated between January 2005 and December 2006; **b,** the column inventory of ACO_2 (storage) determined from a 5-d mean in December 2006. The black solid line represents the position of the APF calculated from satellite observations of sea surface temperature[29].

Ito, Woloszyn and Mazloff (Nature, 2010)

Diagnosed ACO2 uptake rates, using SOSE
Note very high rate over the Pacific-Antarctic Ridge: where P16S finds NADW/LCDW "chimney" to surface

(4) Thin deep layers in ACC



Pacific Deep Water example

Thickness of deep water layers changes at:

15-20°S (all three oceans): tropical-ST boundary, actively ventilated thermocline in subtropics

40-50°S (all three oceans): thinner at and south of the Subantarctic Front

Why???? (DIMES isopycnal mixing result – Ferrari/Nikurashin/Naveira Garabato – mixing enhanced beneath, not in, strongest velocity cores?) Implies isopycnal mixing is also important for moving IDW/PDW/NADW into ACC, but likely localized at topography (Naveira Garabato et al. 2011)

Movement of deep waters across D.P. latitudes and ACC

1. Where do the deep waters upwell to the surface? Where do they cross D.P. latitudes?
2. Which deep water is important for warming in Bellingshausen and Amundsen, west Antarctic Peninsula? (does that matter??)
3. Special upwelling sites along ridges?
4. Why the extruded thinnish layer of deep waters that cross and upwell at about 1000 m, compared with thick deep water layers north of about 45°S?

Answers to almost all: topography is the most important
Isopycnal mixing distribution

Summary 1

NADW moves southward into Antarctic at depths great enough to use topographic obstructions to cross Drake Passage. Geostrophic flow is possible.

NADW (LCDW) upwells to within 500 m of the surface only very close to Antarctica, mainly in Indian/Australian sector, involved in AABW formation on deep shelves

IDW/PDW (UCDW) upwells to sea surface farther north, within ACC. It is the densest upwelled deep water source for northward Ekman flux.
It also crosses into ACC and south of Drake Passage downstream of topographic obstructions, although it is shallower than NADW.
Geostrophic flow maybe difficult; isopycnal mixing processes?
The latter potentially setting thinness of the cross-ACC deep water extrusion?

The water that warms the WAP shelves is Upper Circumpolar Deep Water, which comes from Indian/Pacific Deep Waters, and is not derived from NADW (except for mixing)

Summary 2

Topography is critical for moving deep waters southward and upward into ACC, across Drake Passage latitudes.

- Kerguelen Plateau
- Pacific-Antarctic Ridge/East Pacific Rise
- Southwest Indian Ridge

Steering of ACC by Pacific-Antarctic and SW Indian Ridges allows sea ice edge to extend very far north; upwelled warmer water over these ridges marks boundary of winter ice

NADW/LCDW core pathway intersects these obstructions to cross Drake Psg. Lat

- spiral inwards, 2 loops around to reach coast at Adelie Land
- strong shift at Kerguelen – moves into ACC (SAF)
- strong shift at Eltanin FZ
  - moves across Drake Psg. Lat and strongly upward, far into ACC, into Amund/Bell.
- strong shift at Drake Passage – shift northward again, but stays within southern ACC
- spiral around one more time back through SW Indian Ridge to Adelie Land

IDW/PDW core pathway – above topography, includes vigorous exchange with sea surface south of ACC. Need much more involved tracking to figure out how it moves. (SOSE, Ryan Abernathey, etc)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