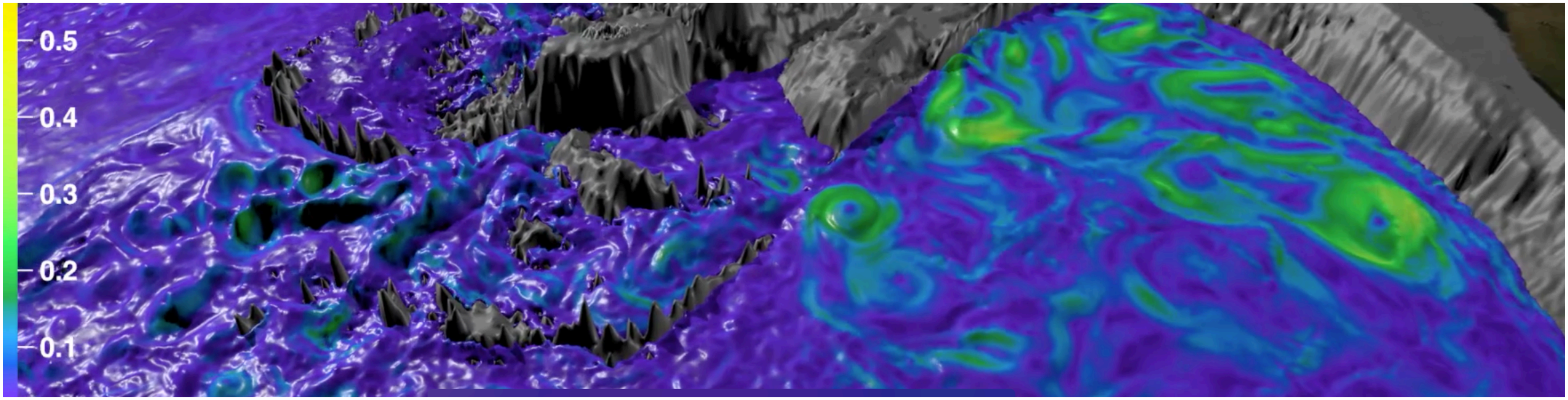
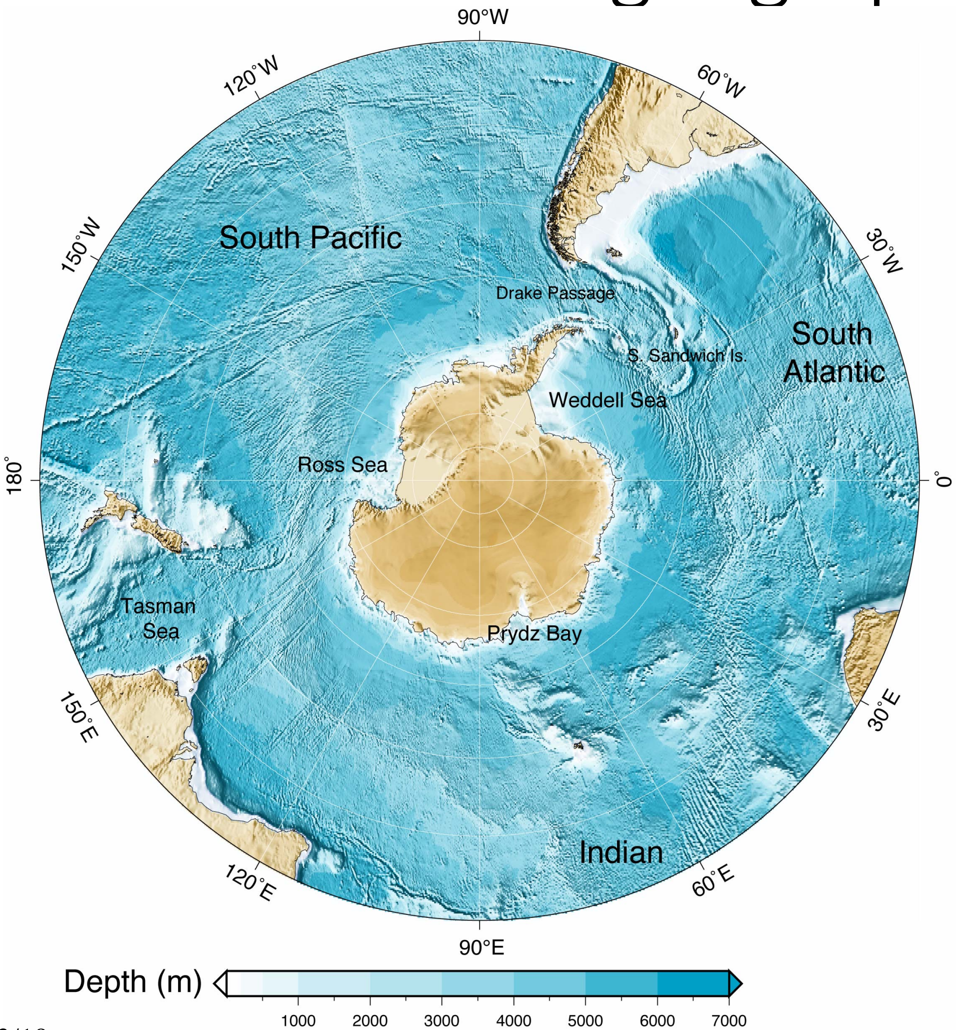


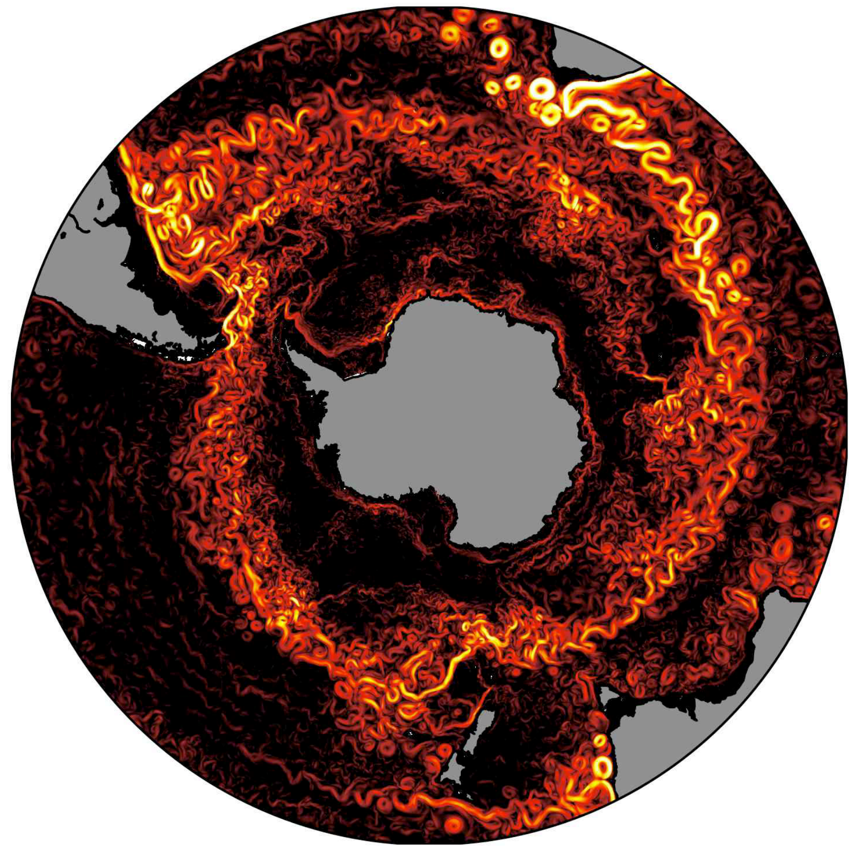
SIO 210: Southern Ocean circulation

- Geography: open at Drake Passage
- Circulation: atmosphere-like (no boundaries)
  - Creates mix of Sverdrup and non-Sverdrup balance general circulation
  - Antarctic Circumpolar Current
  - Antarctic subpolar gyres (Weddell and Ross Seas)
- Water mass modification and formation:
  - Impacts of the ACC, sea ice (brine rejection) and widespread Ekman upwelling
  - Connections (inflow and outflow) with Atlantic, Pacific, Indian

- READING:
  - DPO Chapter 13 (Southern Ocean) – selected parts

Southern Ocean geography and surface currents

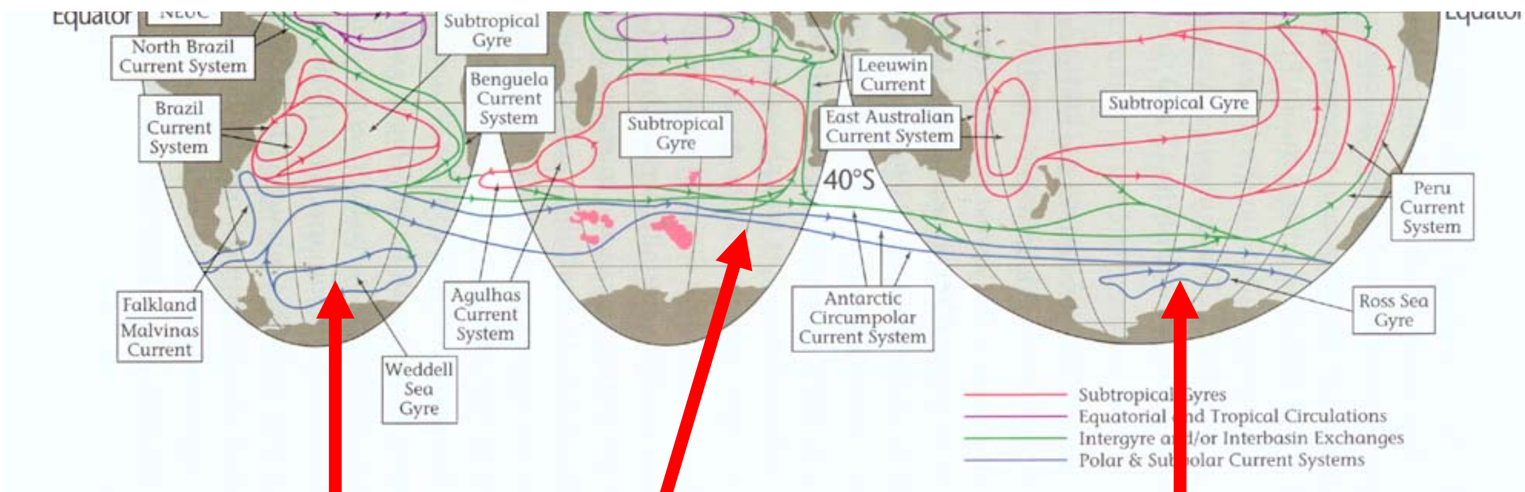




Talley SIO210 (2019)

DPO Fig. 2.12

Schematic of surface circulation (Schmitz, 1995)



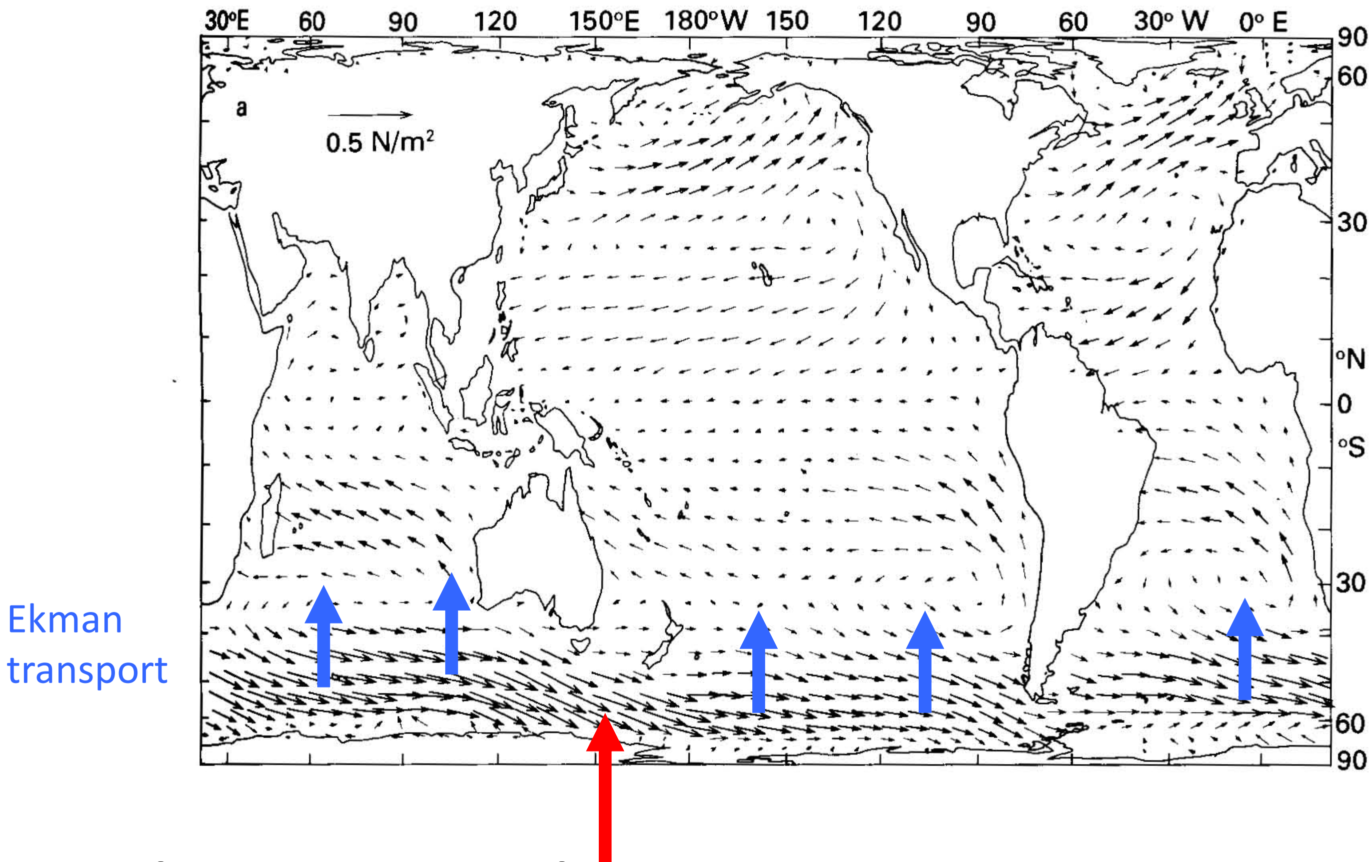
Weddell Sea gyre
(cyclonic)

Ross Sea gyre
(cyclonic)

Antarctic Circumpolar Current encircling Antarctica, starting farthest north off S. America as the Malvinas/Falkland Current, shifting southward as it moves eastward until it flows through Drake Passage

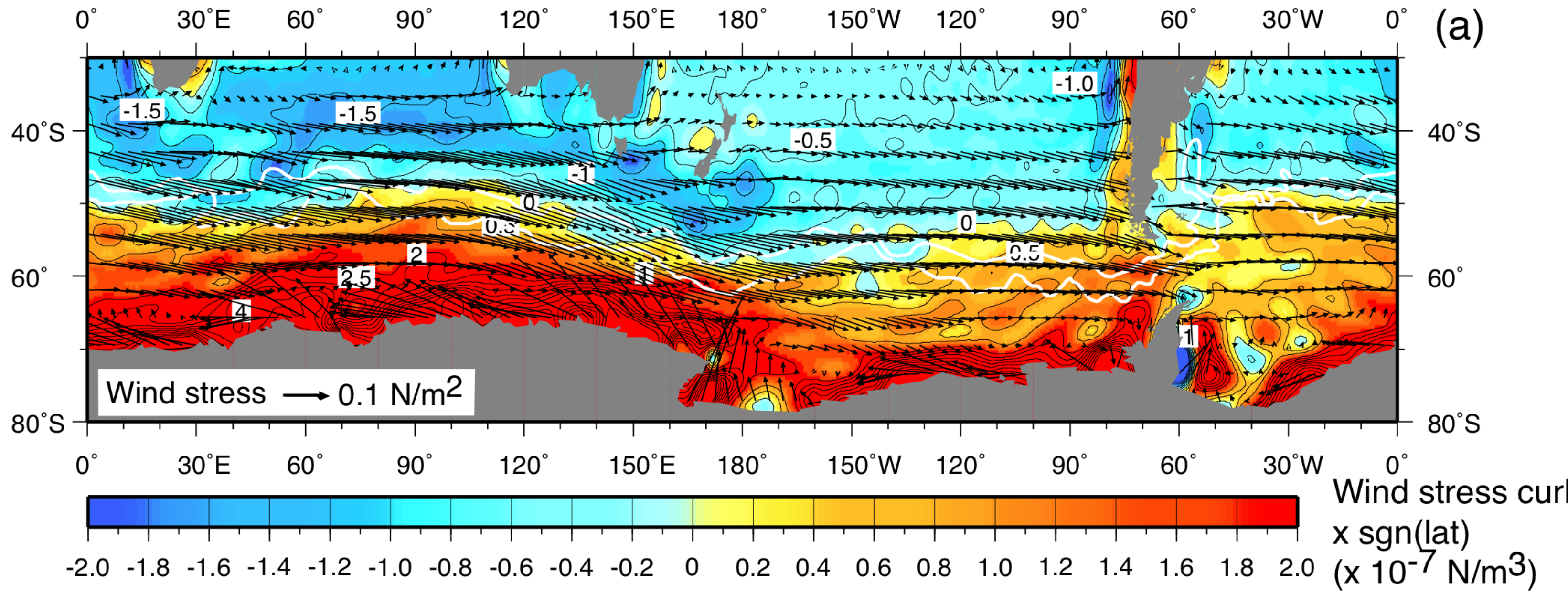
DPO Fig. 14.1

Dynamics: (1) Annual mean wind stress, Ekman stress



Southern Ocean westerlies are strong. (Fig. from Tomczak and Godfrey)

Dynamics: (2) Wind stress curl and Ekman pumping



Westerly winds decrease in strength towards Antarctica

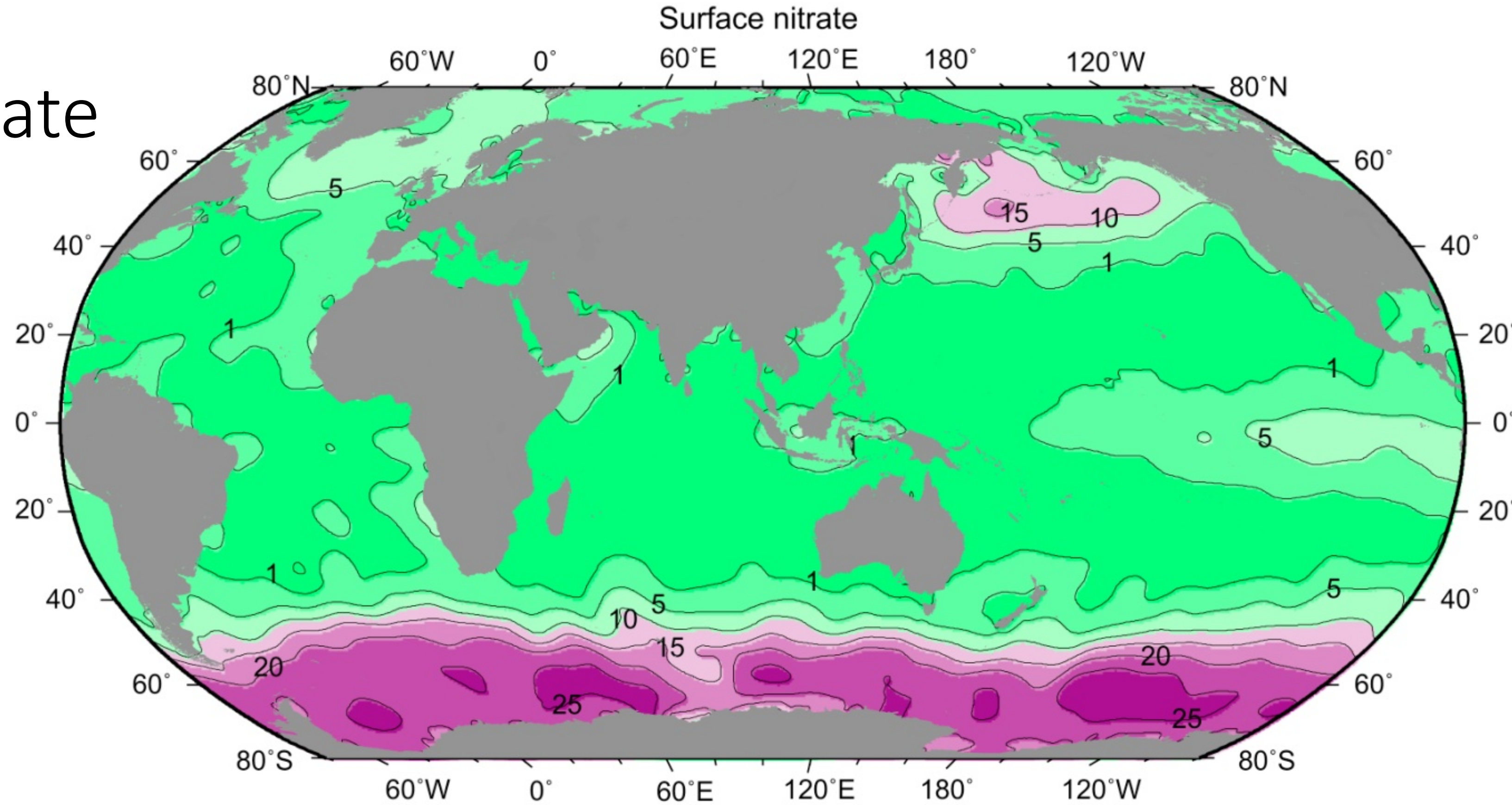
Easterlies along Antarctic coast, including "katabatic" winds (very cold, continental winds)

→equatorward Ekman transport, Ekman downwelling north of ACC

→AND Ekman upwelling south of the maximum westerly winds

DPO Fig. 13.2

Evidence of upwelling: Surface nitrate



High surface values reflect upwelling.

Driven by Ekman suction.

DPO Fig. 4.23

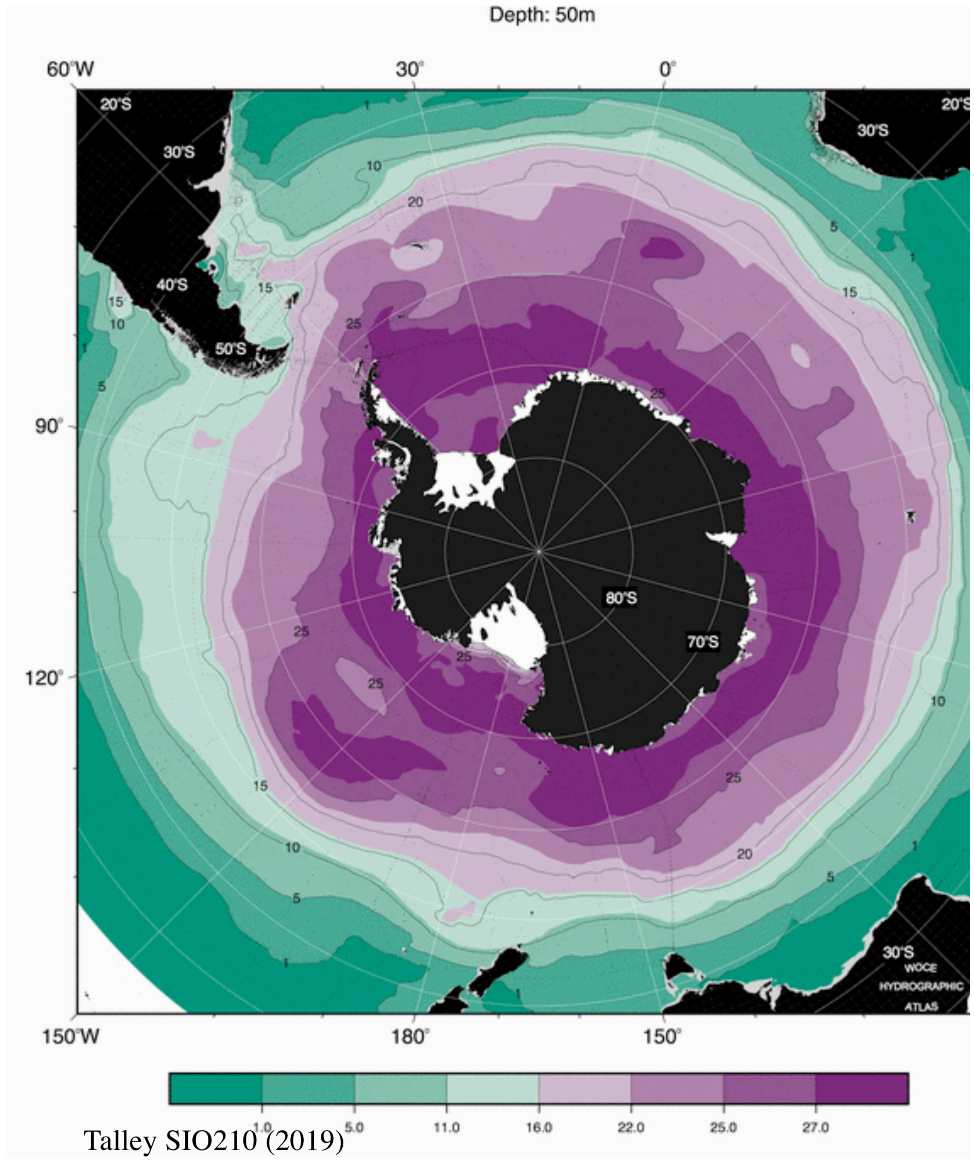
Evidence of upwelling: Near-surface nitrate

High surface values reflect upwelling.

Driven by Ekman suction.

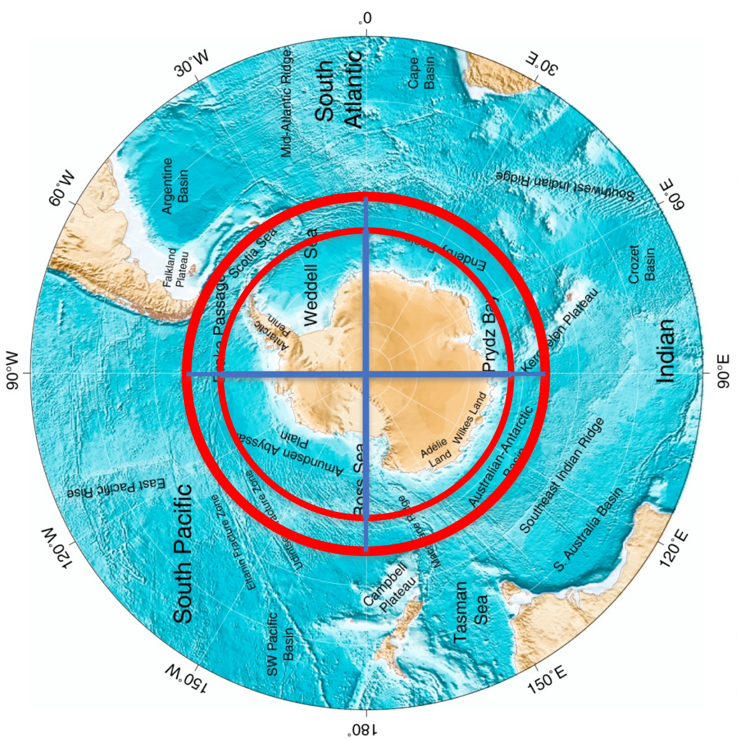
http://woceatlas.tamu.edu

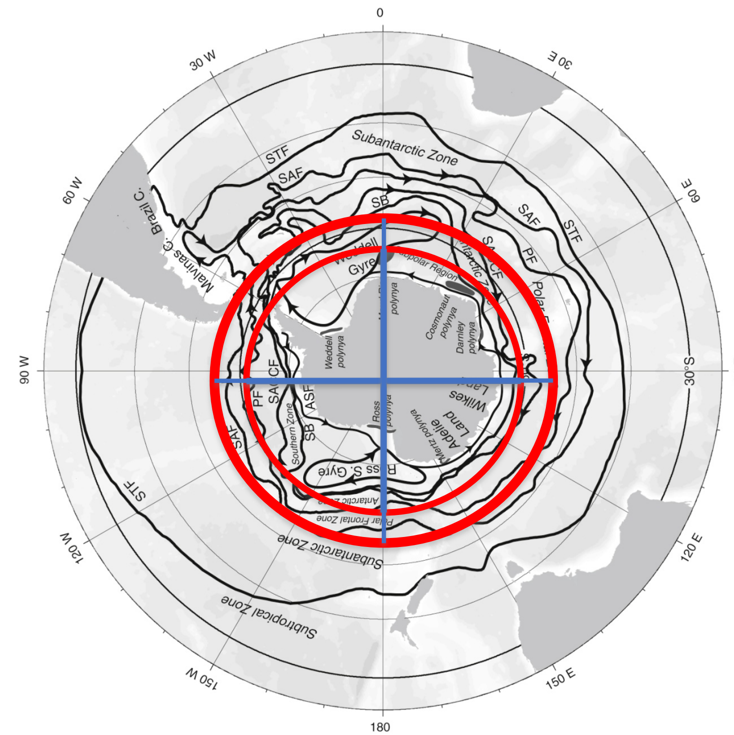
(Orsi and Whitworth, 2005)



Talley SIO210 (2019)

Dynamics: (3) Open channel at Drake Passage latitude





Drake Passage is open down to about 2000 m depth.
Therefore, no western boundary from surface to 2000 m.

(Deeper than 2000 m, there are numerous boundaries due to topography.)

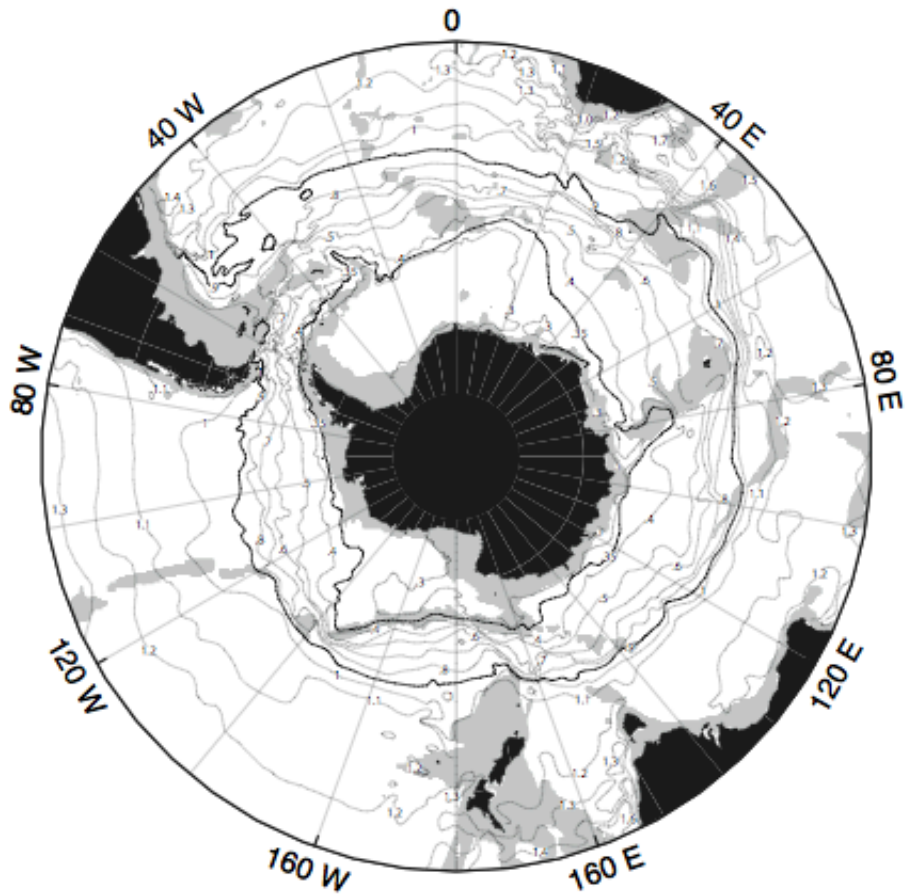
Antarctic Circumpolar Current

No meridional boundary at Drake Passage latitudes

Different dynamics from normal gyres (which have western and eastern boundaries)

Westerly wind stress causes current that extends to bottom, flows eastward

Shear from 50 cm/sec at surface to about 5-10 cm/sec at bottom



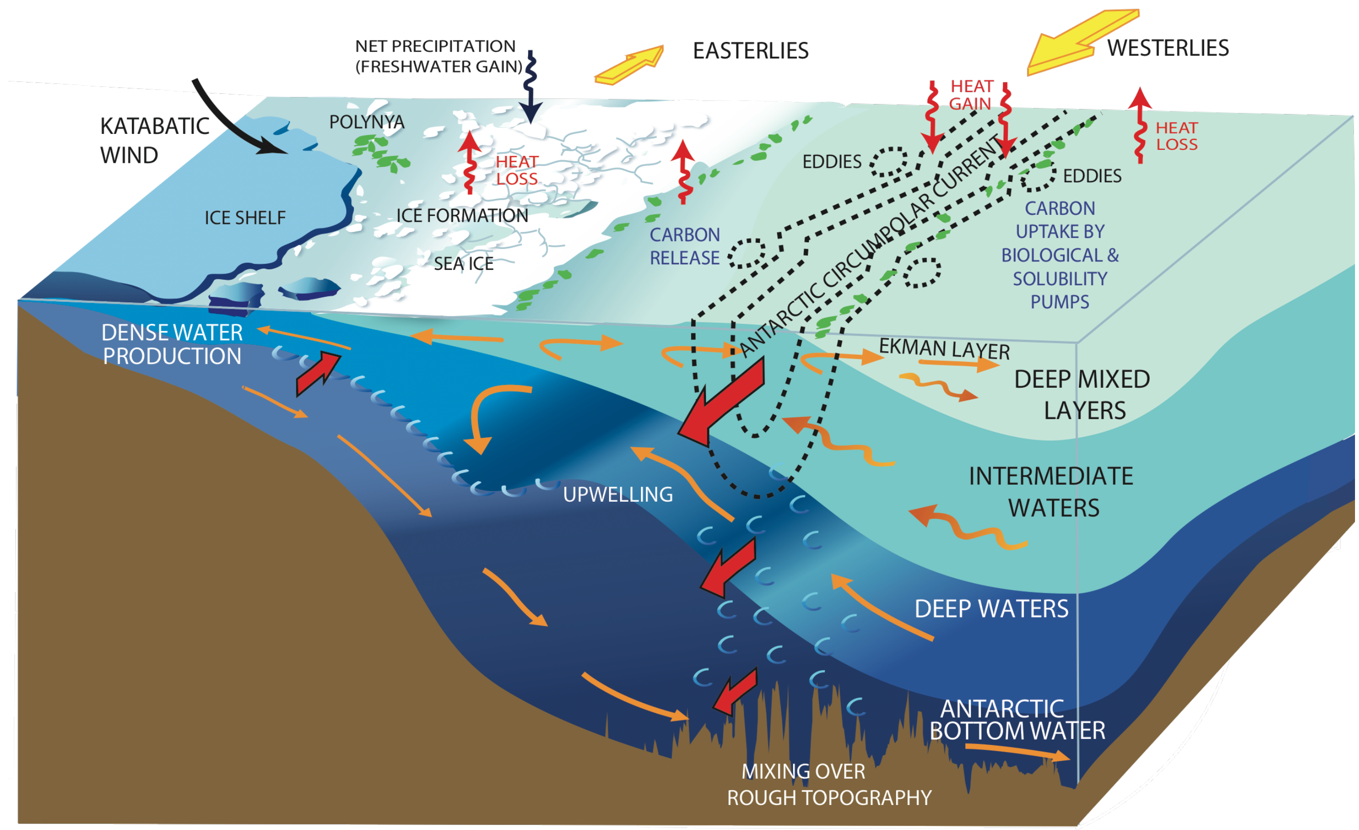
Geopotential ht. anomaly 50/1000dbar

(Orsi et al., 1995) DPO Fig. 13.8

Dynamics: (4) Deep to surface upwelling

Because of the open Drake Passage latitude band:

Southern Ocean is the only place where there is direct upwelling from deep waters to the sea surface over a very large region.

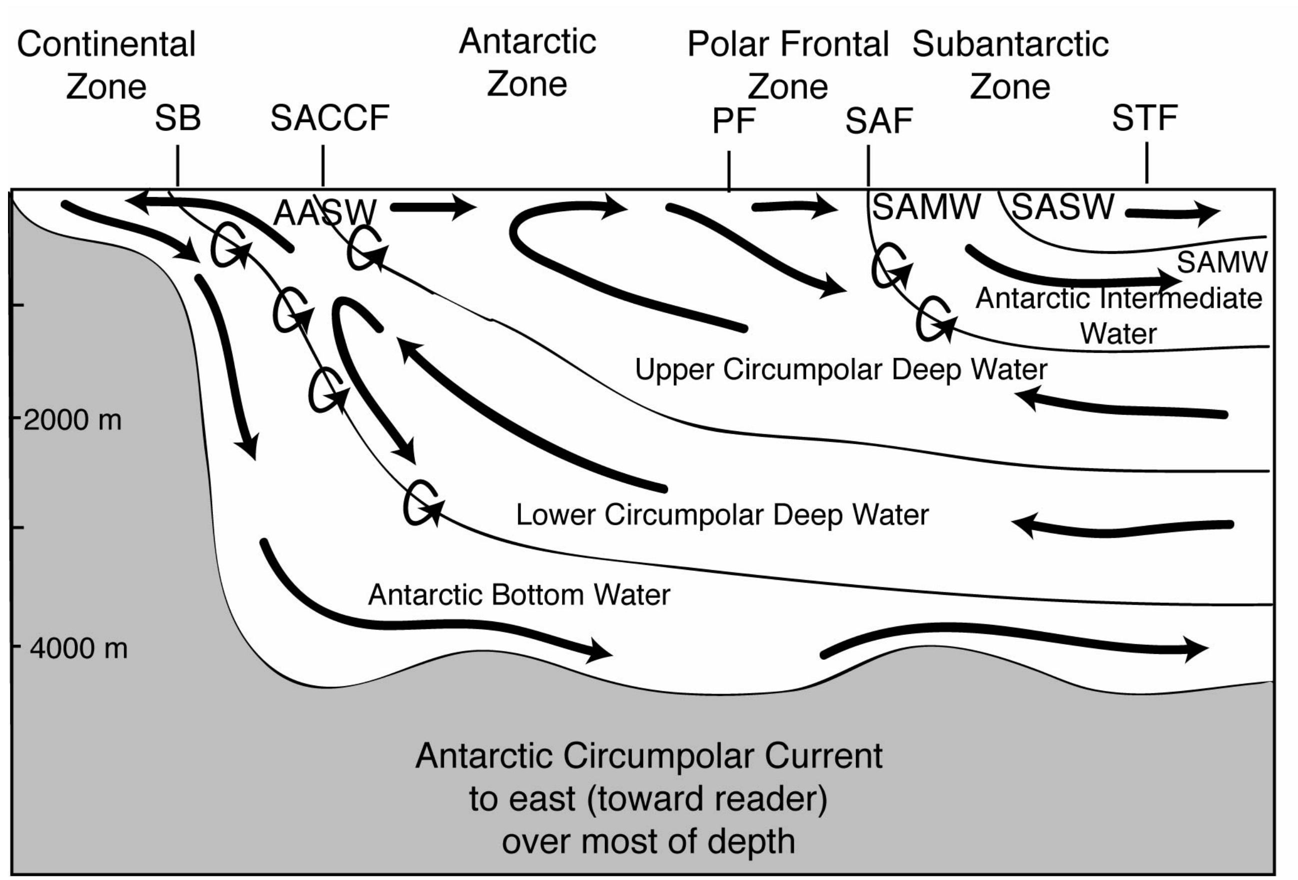


After NRC (2011)

Dynamics: (4) Deep to surface upwelling

Because of the open Drake Passage latitude band:

Southern Ocean is the only place where there is direct upwelling from deep waters to the sea surface over a very large region.

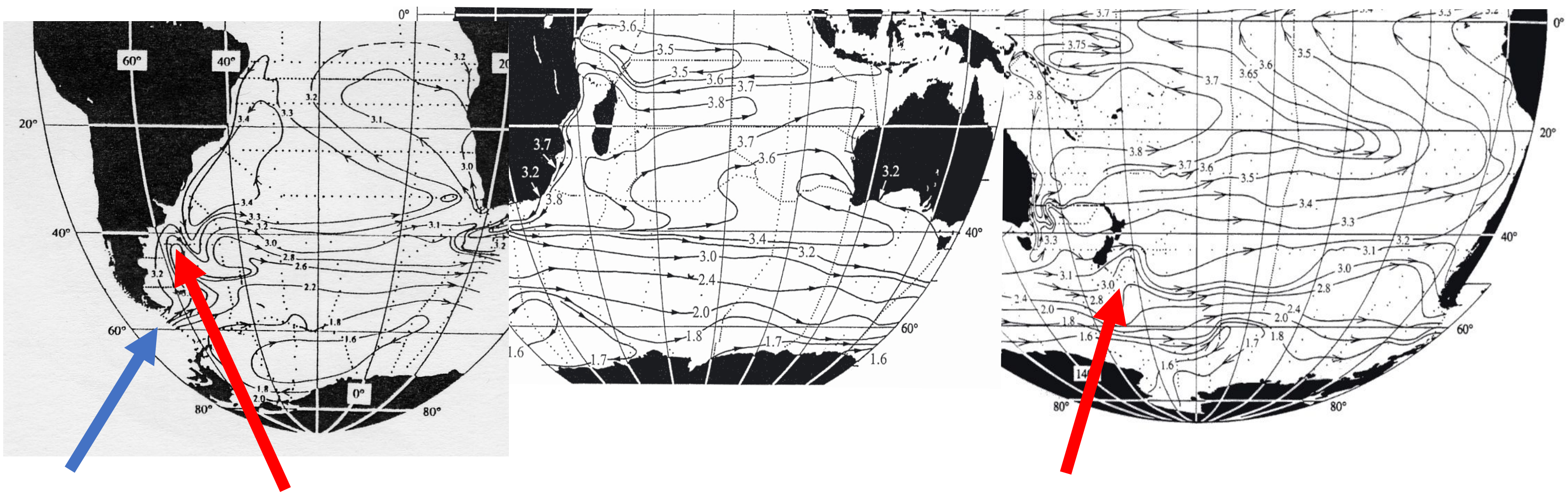


DPO Fig. 13.4 (after Speer et al. 2000)

Dynamics: (5) ‘Zonal asymmetry’ of the ACC

Asymmetry (dependence on longitude)
Northern side of the ACC is:

- farthest north at Argentina in the Malvinas Current
- farthest south entering Drake Psg from Pacific



Malvinas (Falkland Current): semi-western boundary current at S. America

(Similar effect of Campbell Plateau on ACC)

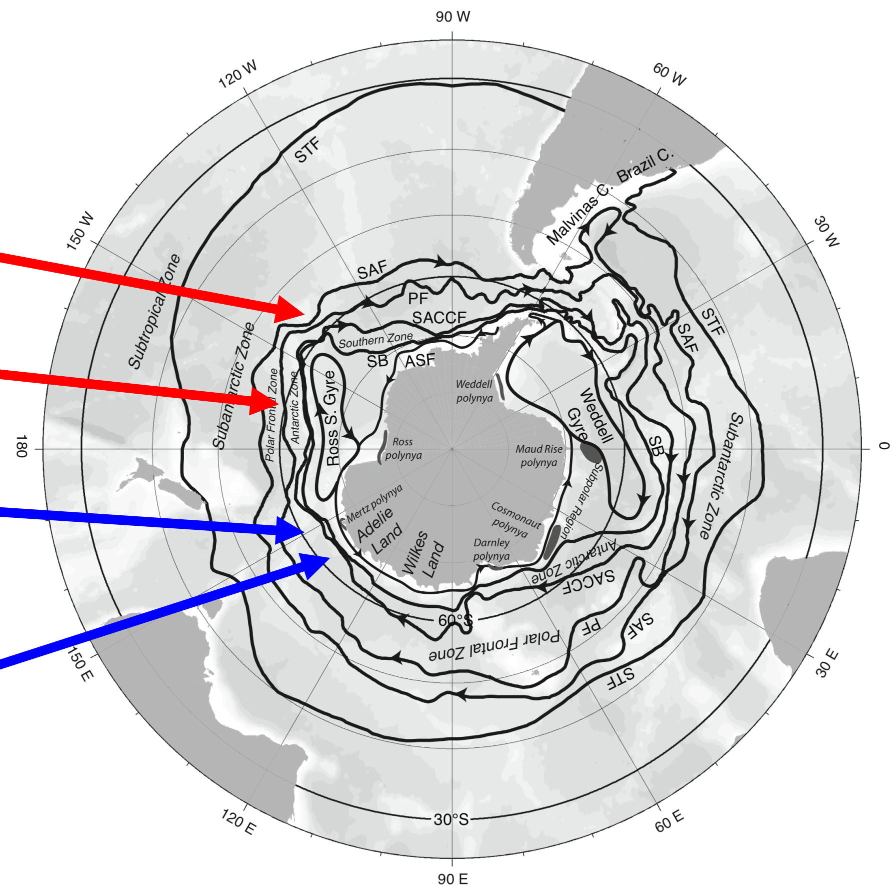
(Reid, 1994, 1997, 2003)

Antarctic Circumpolar Current: banded frontal structure

Fronts of the Antarctic Circumpolar Current

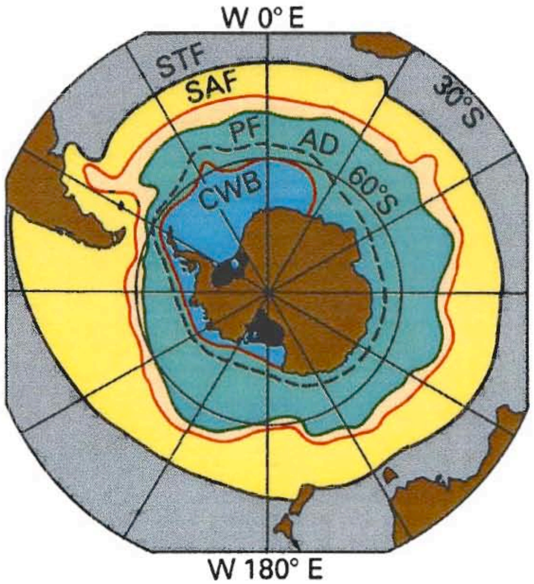
1. Subantarctic Front on north side
2. Polar Front in middle
3. Southern ACC Front to south
4. Southern Boundary or continental shelf front

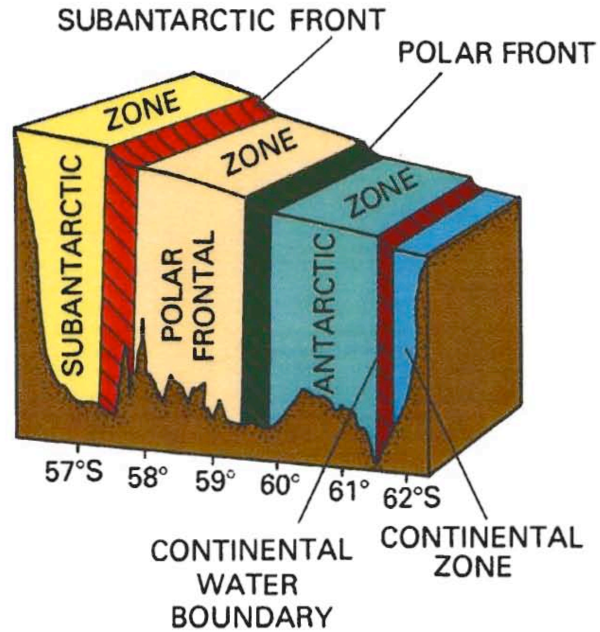
Antarctic Slope Front (westward flow along continental slope)



DPO Figure 13.1 (after Orsi et al., 1995)

Fronts of the Antarctic Circumpolar Current





Tomczak and Godfrey, Ch. 6

Most transport is carried in the fronts

Subantarctic Front and Polar Front most important

Another important front: Southern ACC Front (not shown here)

ACC speeds and transport in Drake Passage

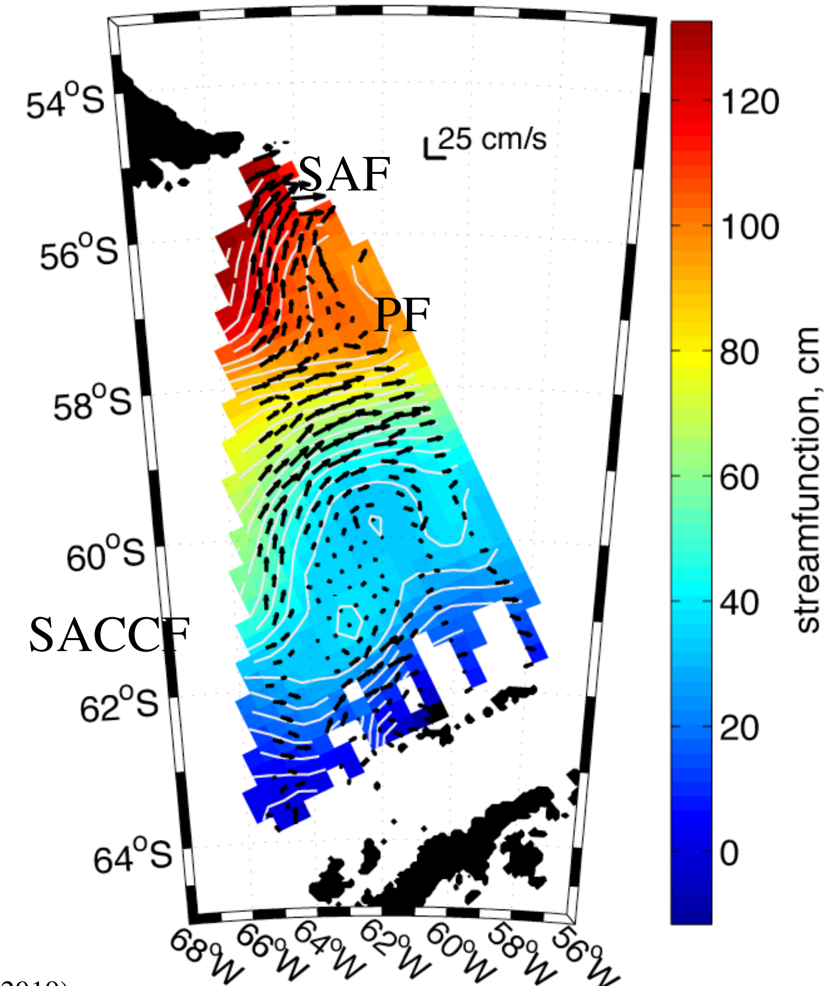
Geostrophic calculations, current meters and ADCP measurements in Drake Passage suggest:

Maximum current speeds: ~50 cm/sec

Maximum currents in the 2 fronts (SAF and PF)

Transport of about 100 Sv, top to bottom, including all fronts (and intervening possible westward recirculations, eddies)

Transports elsewhere up to 150 Sv



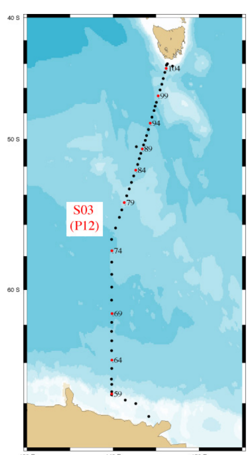
DPO Fig. 13.19

(Lenn et al., 2007)

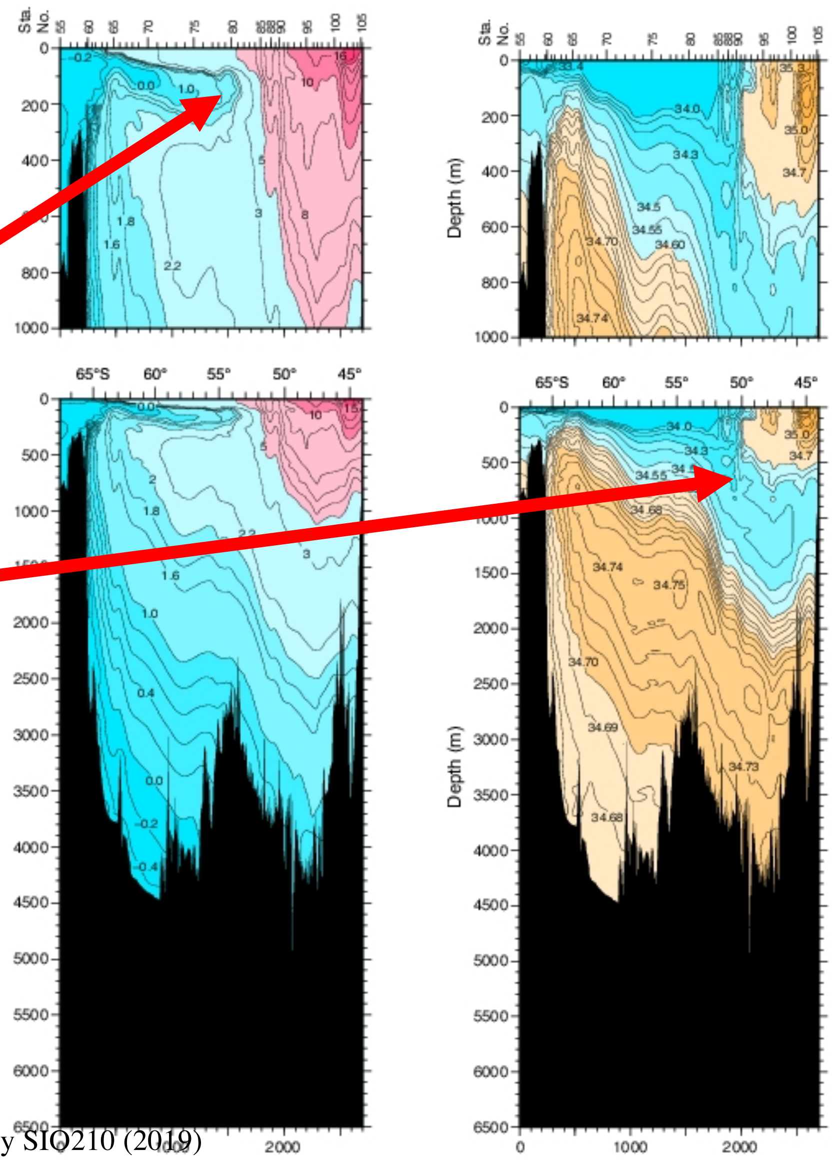
Polar and Subantarctic Fronts in temperature and salinity sections

Polar Front: onset of temperature minimum layer to south of PF

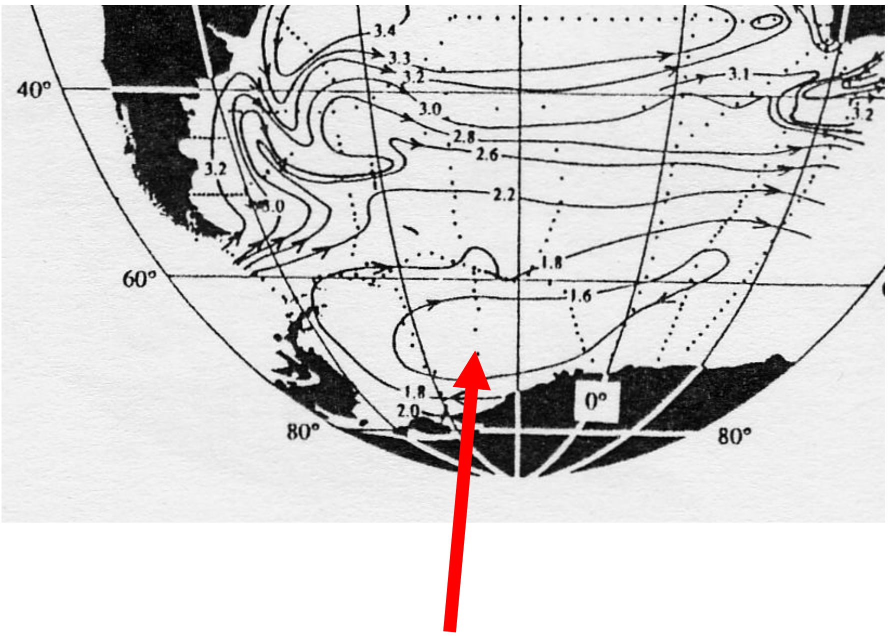
Subantarctic Front: onset of AAIW salinity minimum to north of SAF



Vertical section from Antarctica to Tasmania



Southern Ocean surface circulation: cyclonic subpolar (polar) gyres – Weddell Sea gyre



Weddell Sea gyre

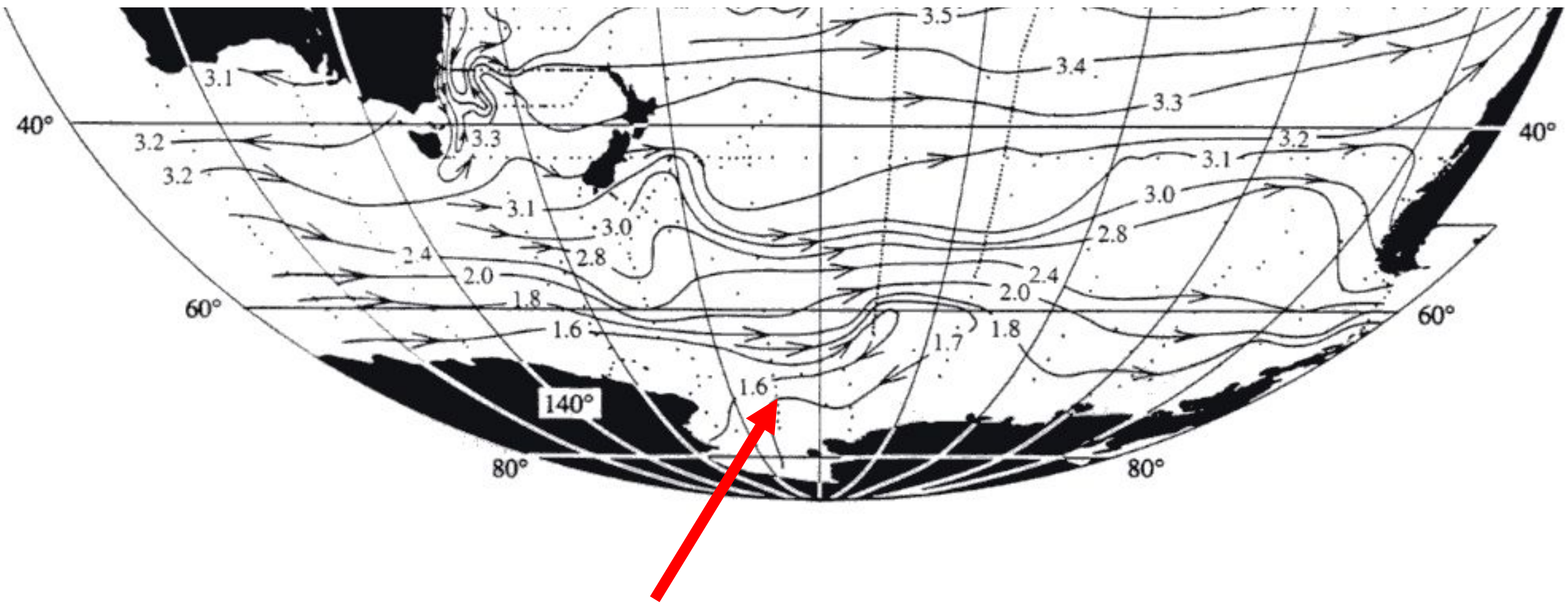
(Reid, 1994)

Track of the Endurance (Shackleton): cyclonic through the Weddell Sea ice pack (Royal Geographic Society)

DPO Fig. 9.2a

DPO Fig. 13.10

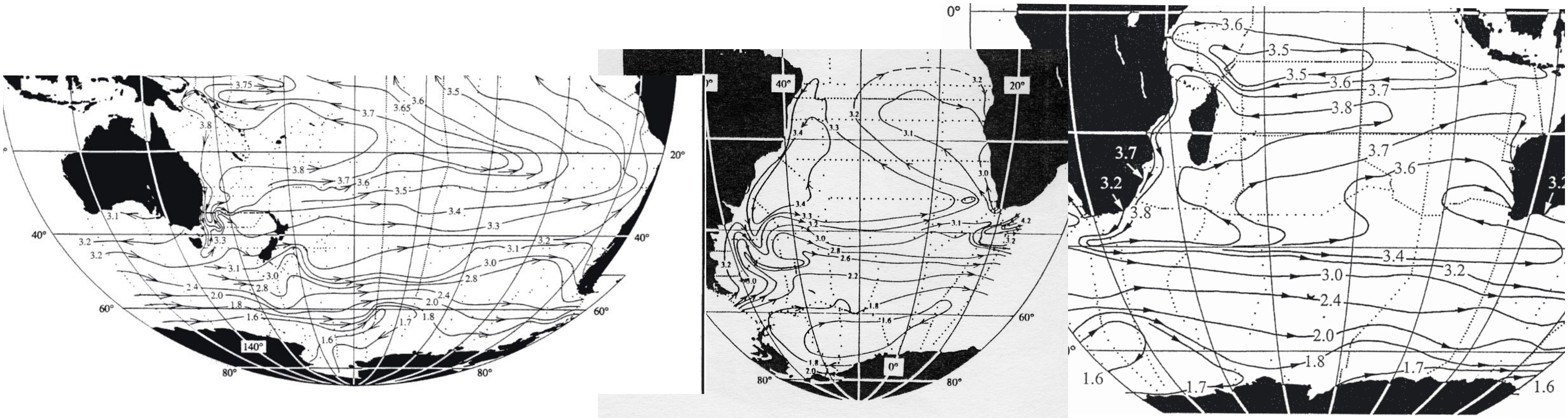
Southern Ocean surface circulation: cyclonic subpolar (polar) gyres – Ross Sea gyre



Ross Sea gyre (Reid, 1997)

DPO Fig. 10.2a

Southern Ocean surface circulation

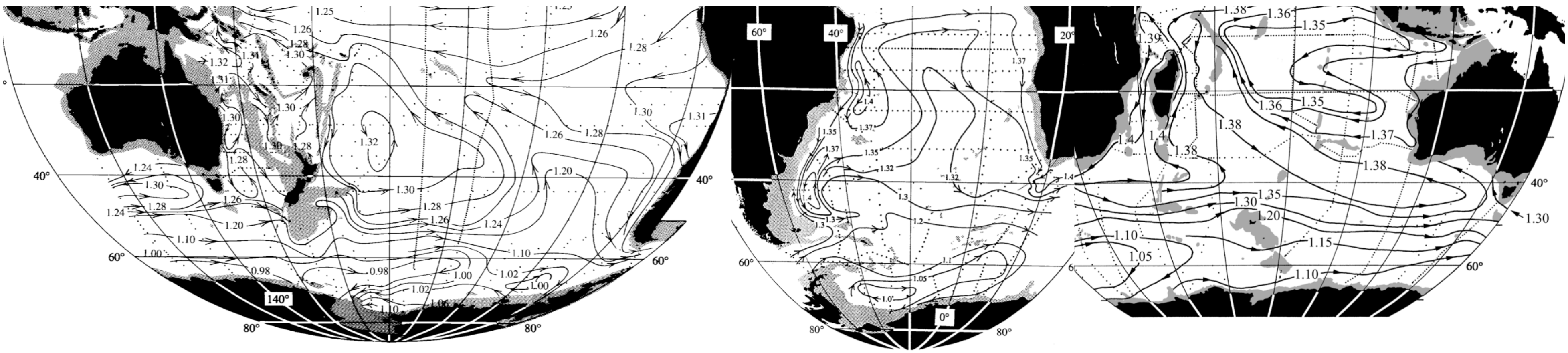


0 dbar

Adjusted steric height

(Reid, 1994, 1997, 2003)

Southern Ocean deep circulation



2000 dbar

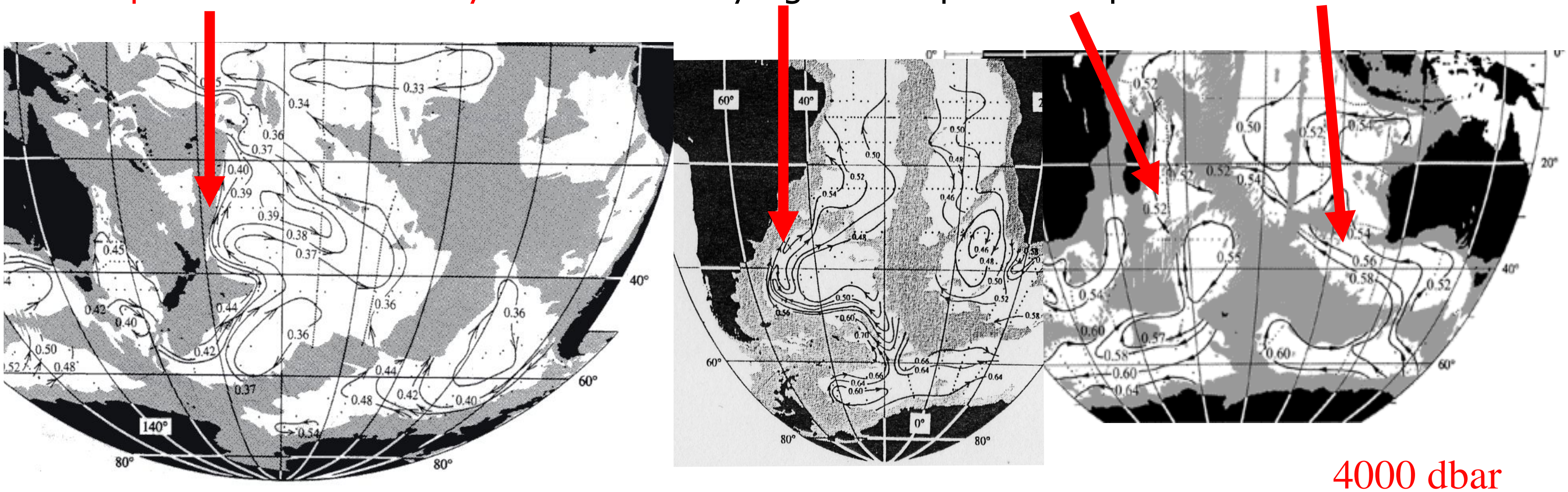
At 2000 dbar:

- very similar direction as surface circulation (ACC, Weddell and Ross Sea gyres) "equivalent barotropic": "barotropic" = same top to bottom; "equivalent" means there's vertical shear but flow is in same direction at all depths
- weaker currents

(Reid, 1994, 1997, 2003) DPO Fig. 14.4a

Southern Ocean abyssal circulation

Strong control by topography
Closed at Drake Passage
Weddell Gyre still apparent
Deep Western Boundary Currents carrying Circumpolar Deep Waters northward



(Reid, 1994, 1997, 2003)

DPO Fig. 14.4b

Geostrophic flow of ACC: (Pacific)

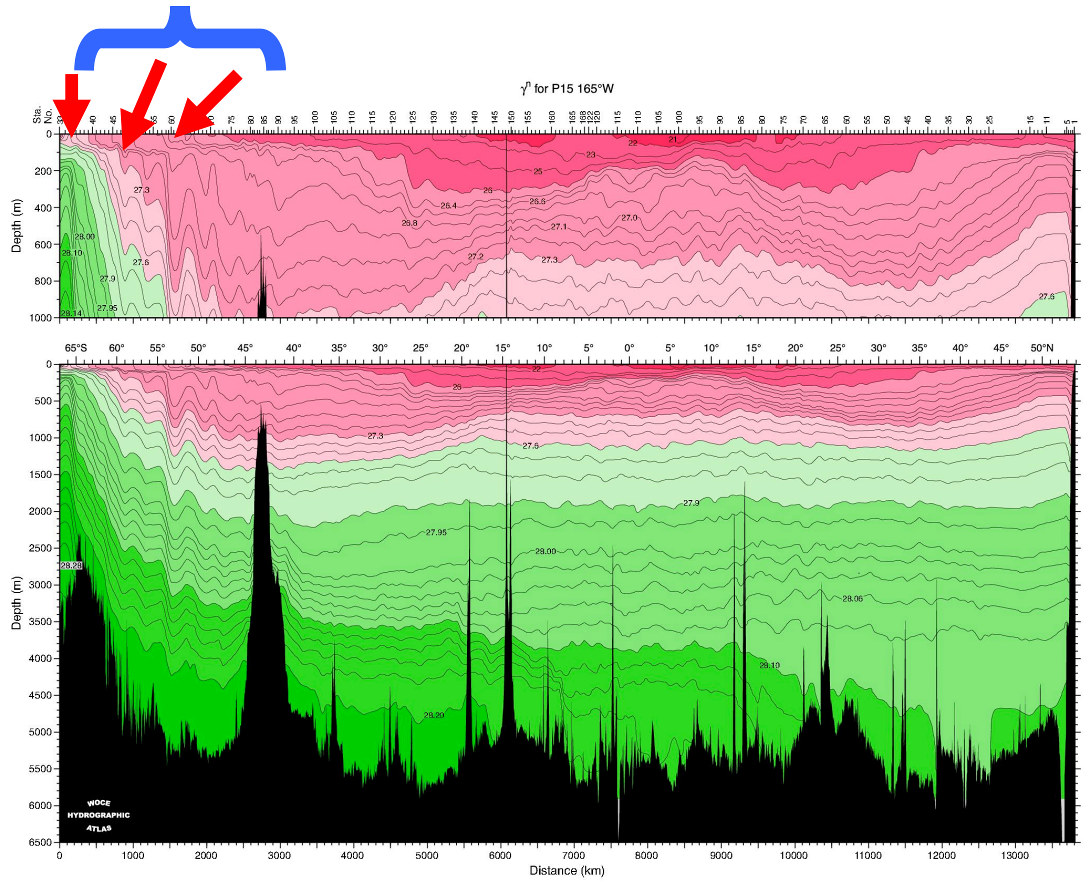
Antarctic Circumpolar Current

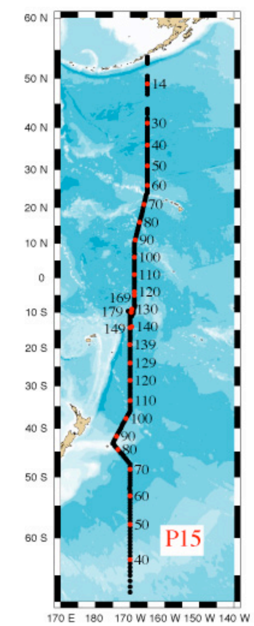
SACCF PF SAF (locations determined from theta and salinity)

Geostrophic (thermal wind) calculation: sloping isopycnals downward towards north, indicates eastward current (out of page) if strongest at surface

Shear reaches to bottom

> 1000 km wide band, but full of wiggles (fronts and eddies)





Neutral density section from http://www-pord.ucsd.edu/whp_atlas/pacific_index.html

Southern Ocean water properties and water masses

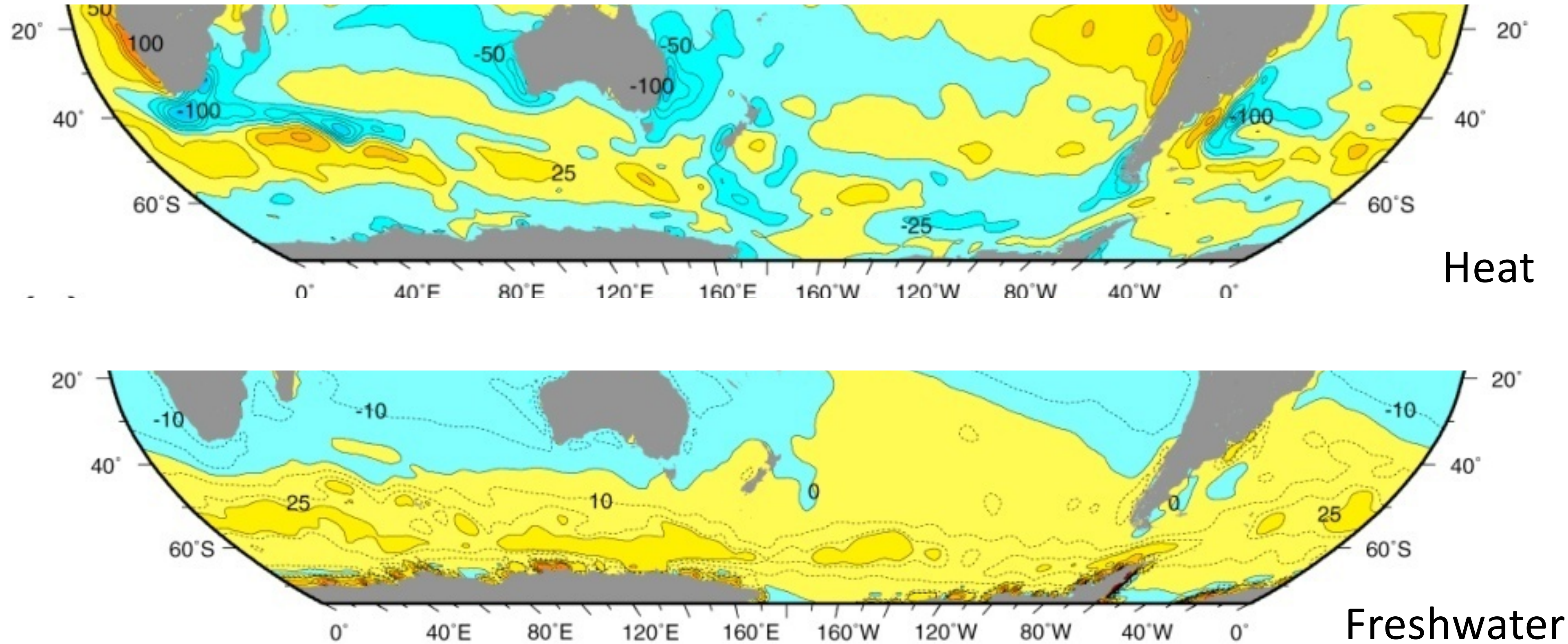
Major processes

Upwelling (from deep water to surface - can see in nutrients)

Buoyancy loss (cooling) and surprising GAIN (freshening)

Sea ice formation: brine rejection creating dense water

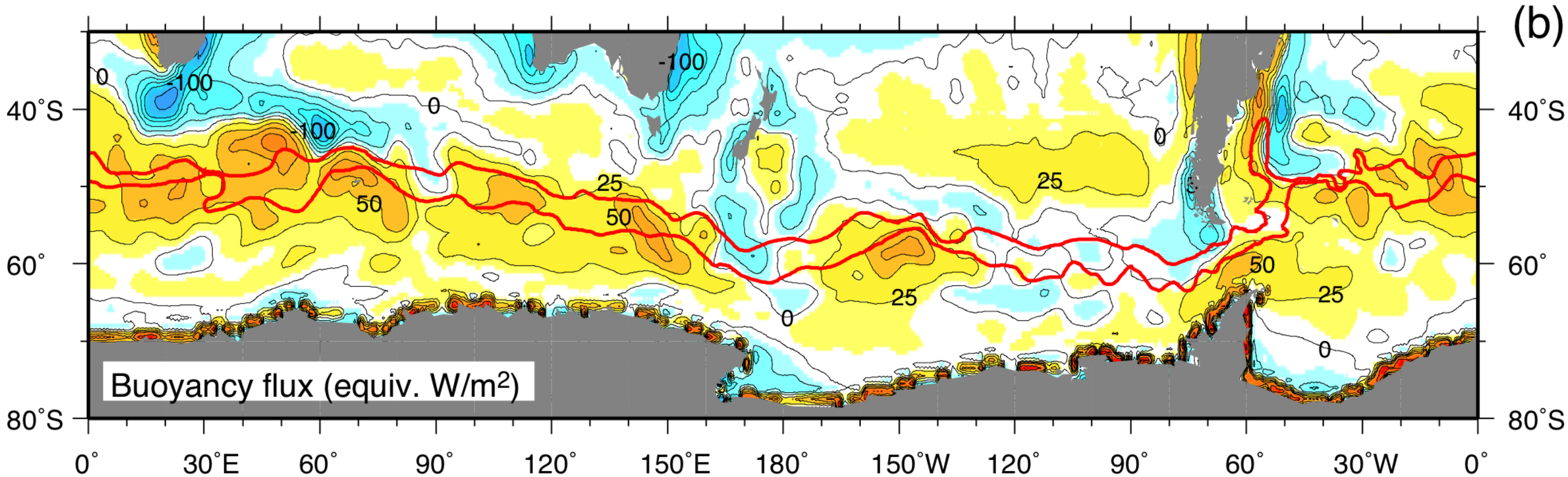
Southern Ocean air-sea heat, freshwater, buoyancy flux



Note the surprising heat gain and the net freshwater input

DPO Fig. 13.2b

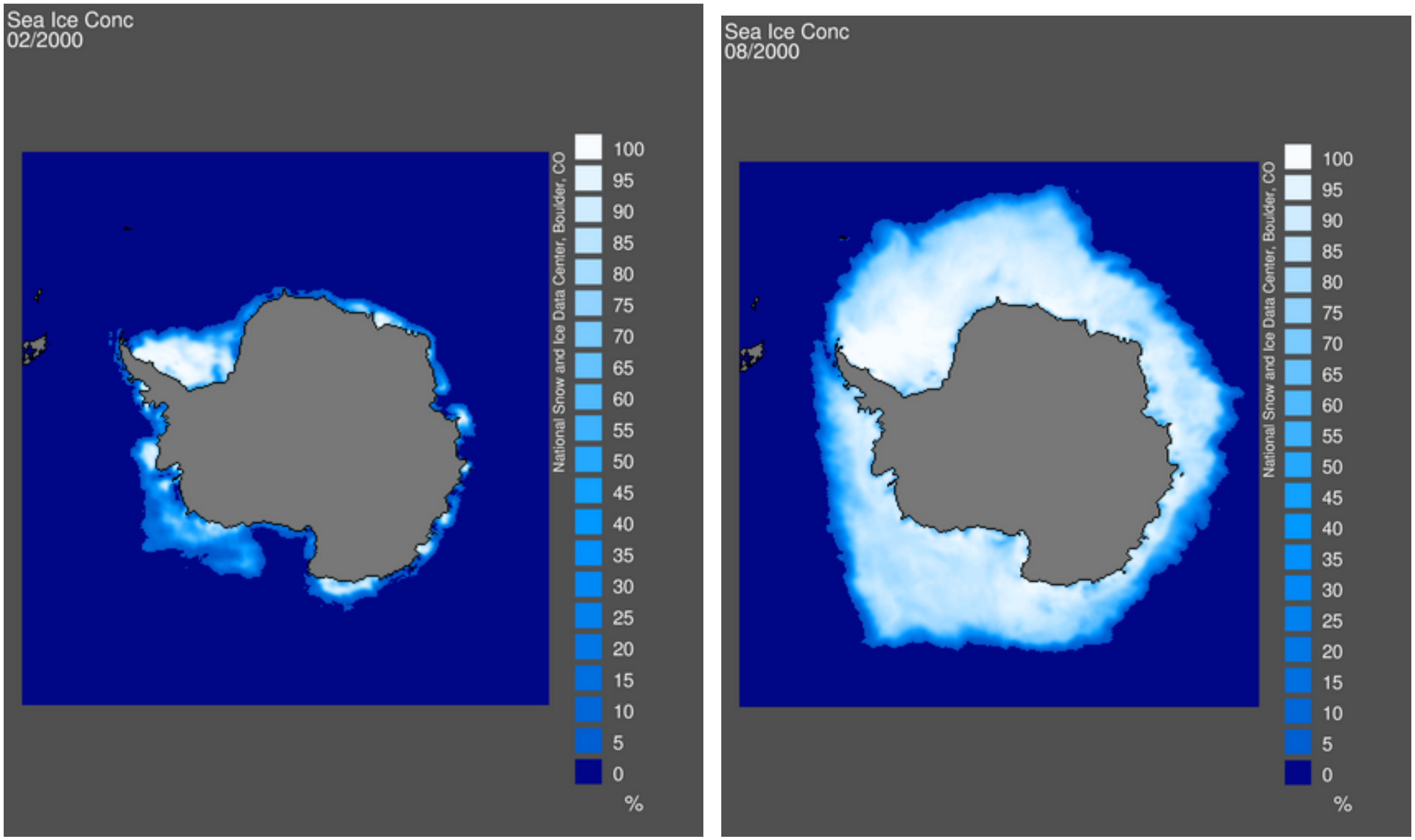
Southern Ocean heat, freshwater, buoyancy flux



Note the surprising net buoyancy gain through most of the Southern Ocean: contributions from both heat gain and net precipitation

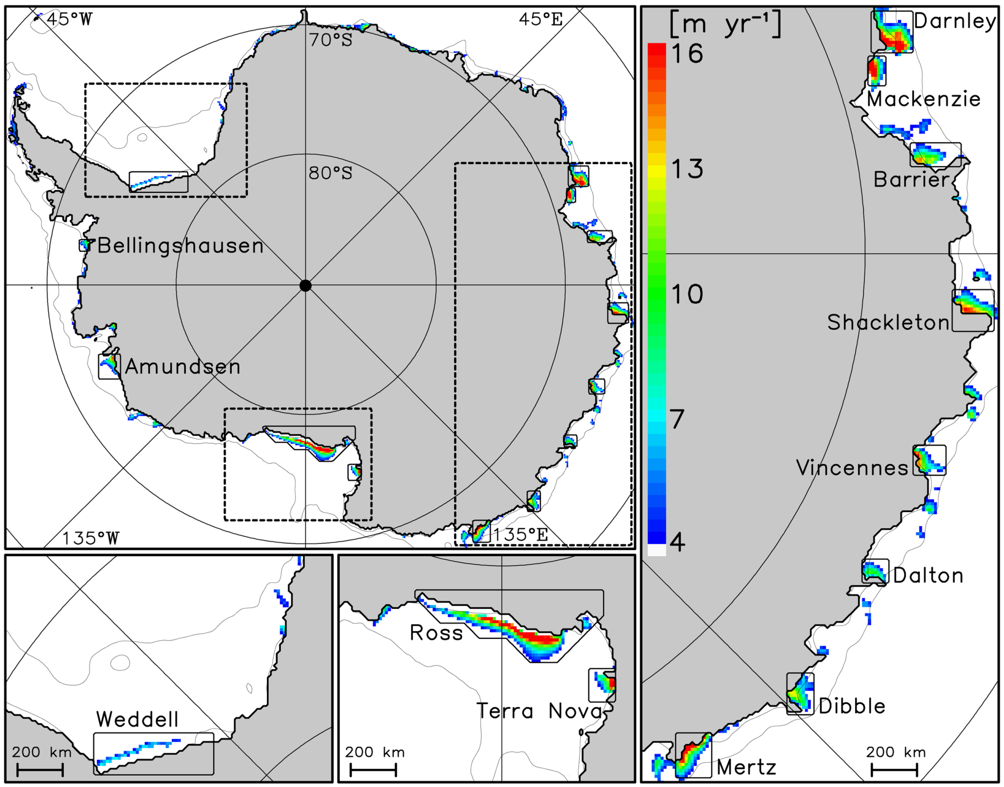
DPO Fig. 13.2b

Antarctic ice distribution: sea ice concentration

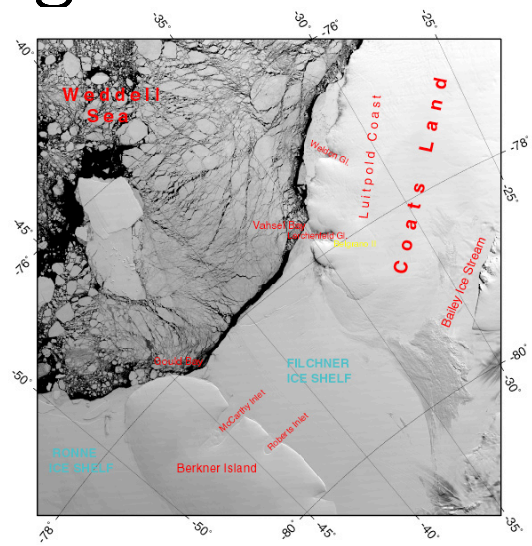


February and August, 2000 National Snow and Ice Data Center
After DPO Fig. 13.19

Antarctic polynyas: surface forcing



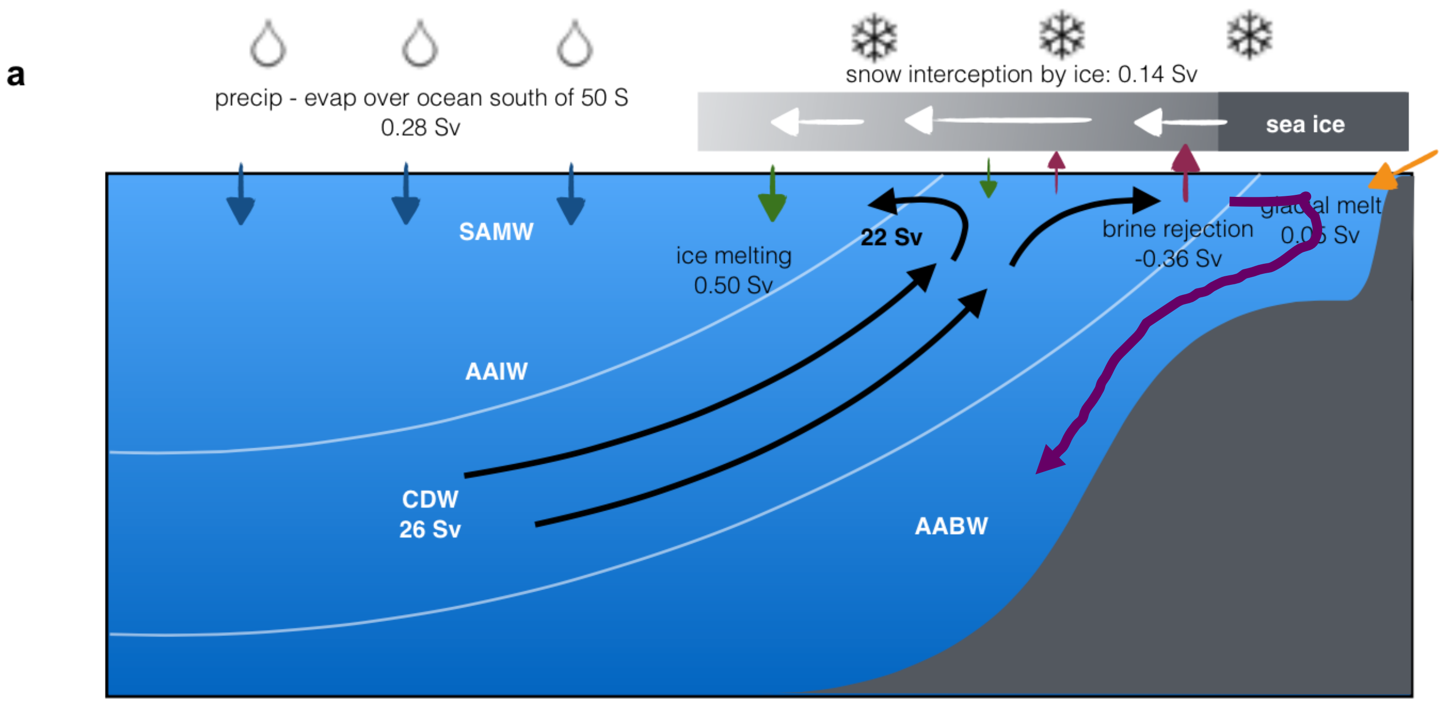
Tamura et al. (2008) (DPO Fig. 13.20)



Coastal polynyas: regions characterized by high winds, open water, and large heat fluxes, hence major brine rejection sources.

Important sites for densest water: Weddell, Ross, Mertz, (Darnley)

Sea ice: dual role in water mass formation



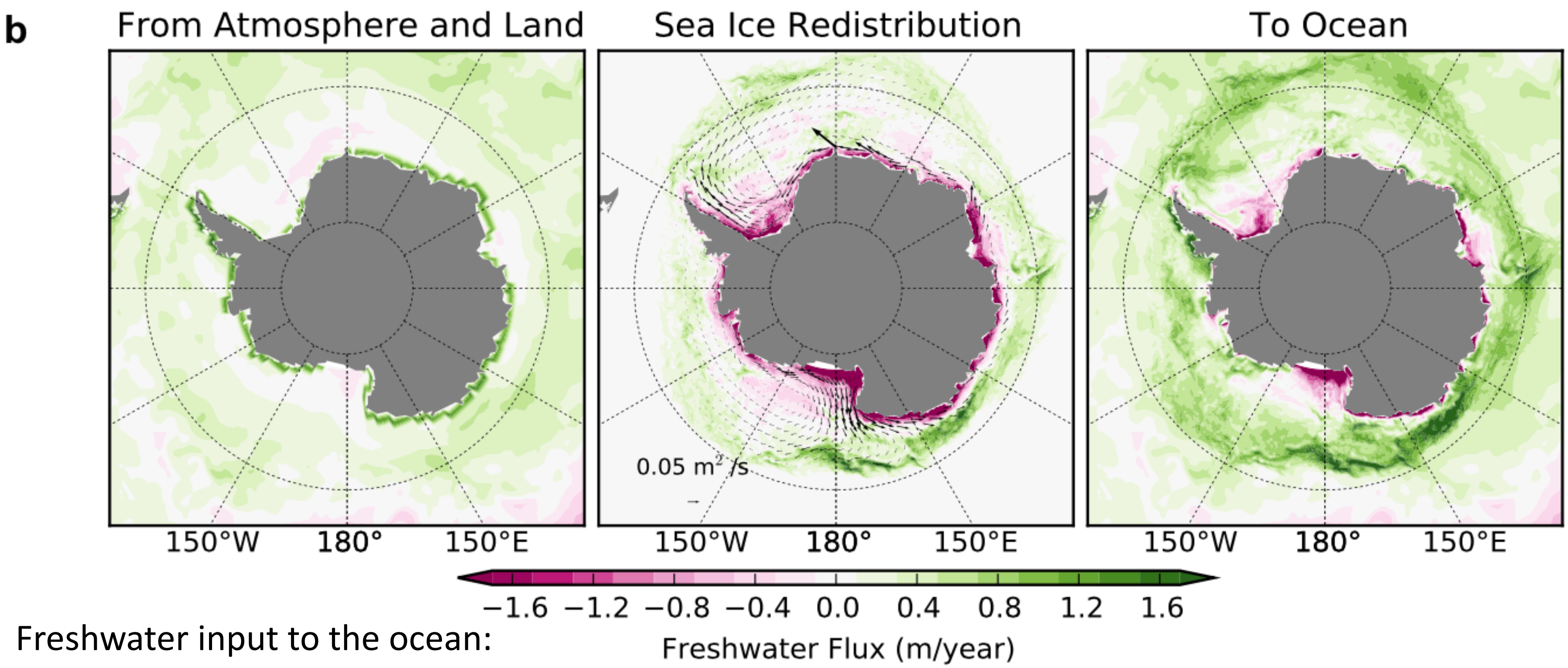
Abernathey et al. (Nat GS 2016)

Brine rejection creates dense AABW

Sea ice melt lowers density of upwelled Deep Waters and inputs into thermocline water (Subantarctic Mode Water)

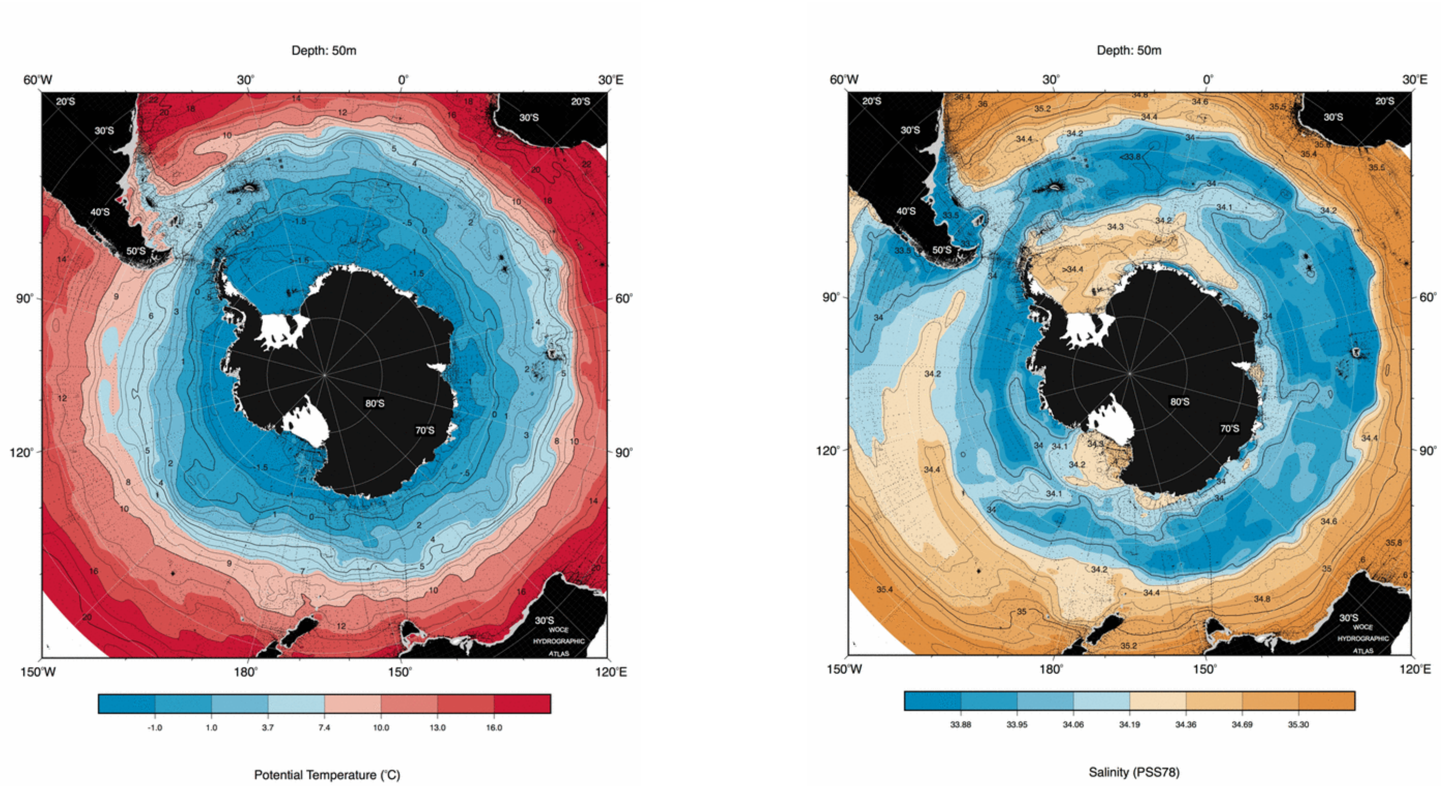
Sea ice: dual role in water mass formation

Abernathey et al. (Nat GS 2016)



Freshwater input to the ocean:
Both from atmosphere and land (precip and runoff) AND
'fractionation' by sea ice:
(a)Brine rejection where sea ice forms, makes ocean saltier (reds above)
(b)Sea ice is pushed away by winds (Ekman) and melts farther north, which freshens the ocean (greens above)

Southern Ocean near-surface properties



Freezing point around Antarctica.   Higher salinity in Weddell, Ross.
Cold, saltier water -> dense water production due to brine rejection from sea ice formation

Orsi and Whitworth (2005) (DPO Fig. 13.3)

Southern Ocean water masses

Major water masses (covered on next slides)

Subantarctic Mode Water (thick surface layers north of SAF)

Antarctic Surface Water (cold, fresh surface layer south of PF)

Antarctic Intermediate Water (subsurface salinity minimum north of SAF)

Circumpolar Deep Water (Upper and Lower CDW):

Inflow of Atlantic, Pacific and Indian Deep Waters, formation of deep water in Weddell (brine rejection)

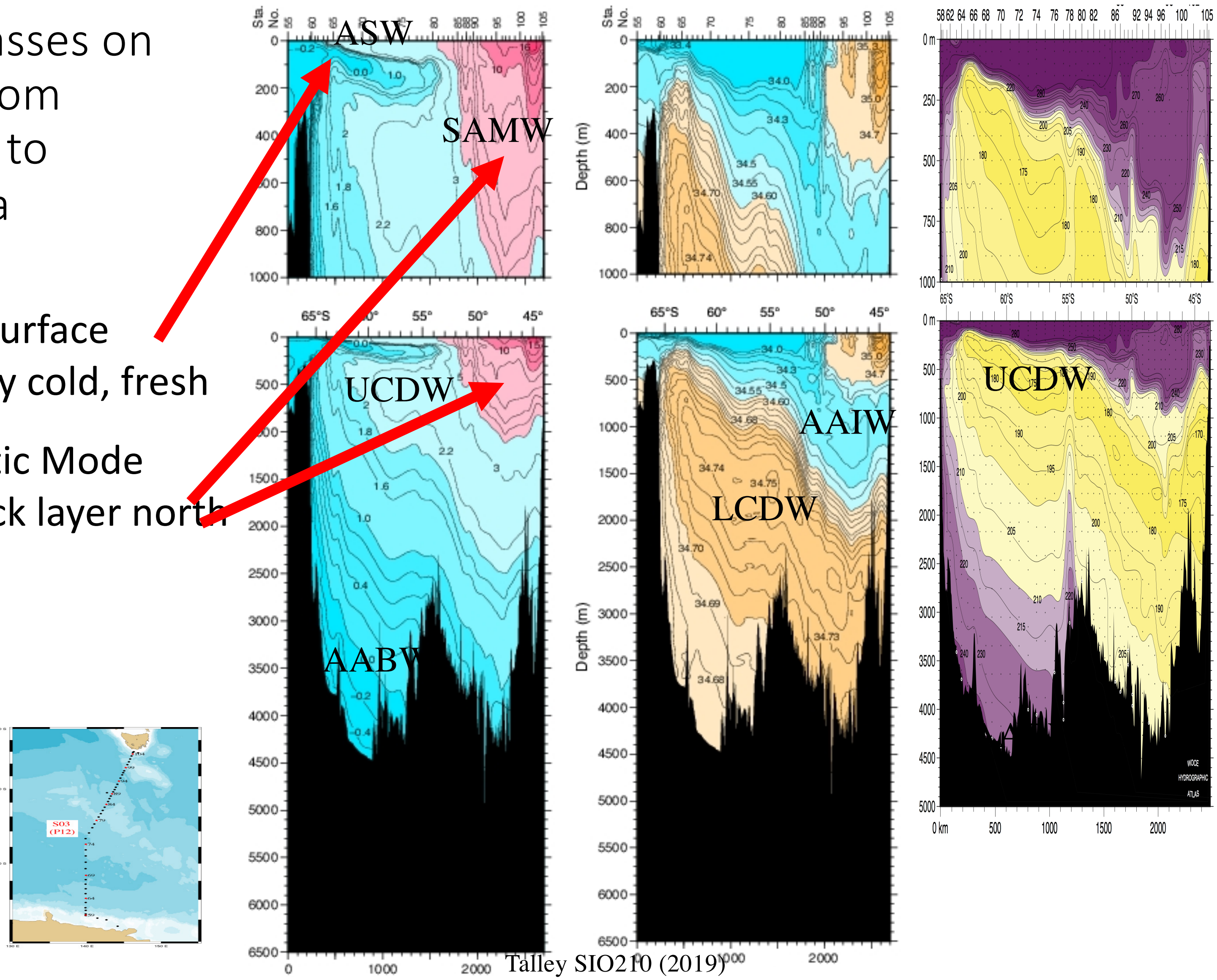
Antarctic Bottom Waters:

brine rejection in coastal polynyas and leads in ice

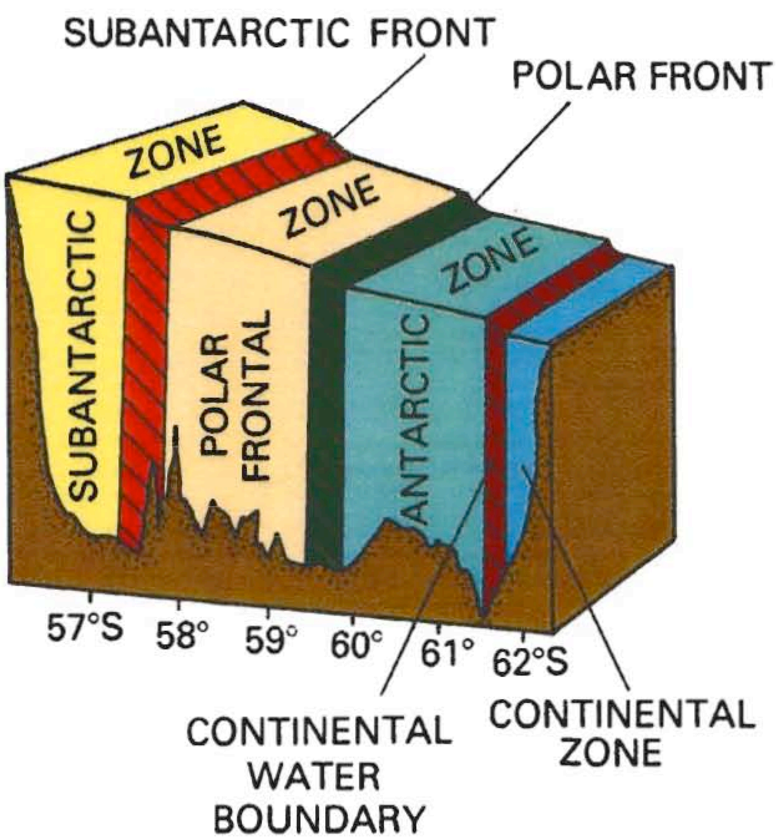
Water masses on section from Tasmania to Antarctica

Antarctic Surface Water: very cold, fresh

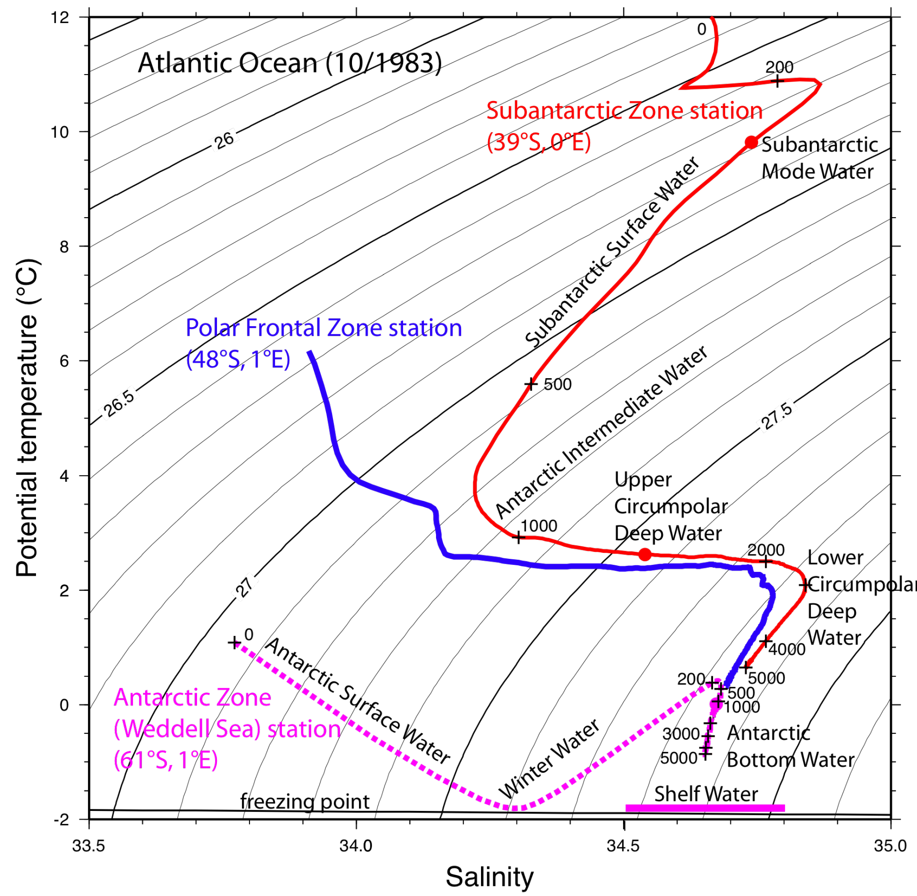
Subantarctic Mode Water: thick layer north of SAF



Fronts and frontal zones of the ACC

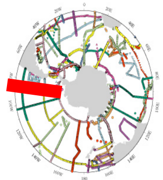


Tomczak and Godfrey Chap. 6



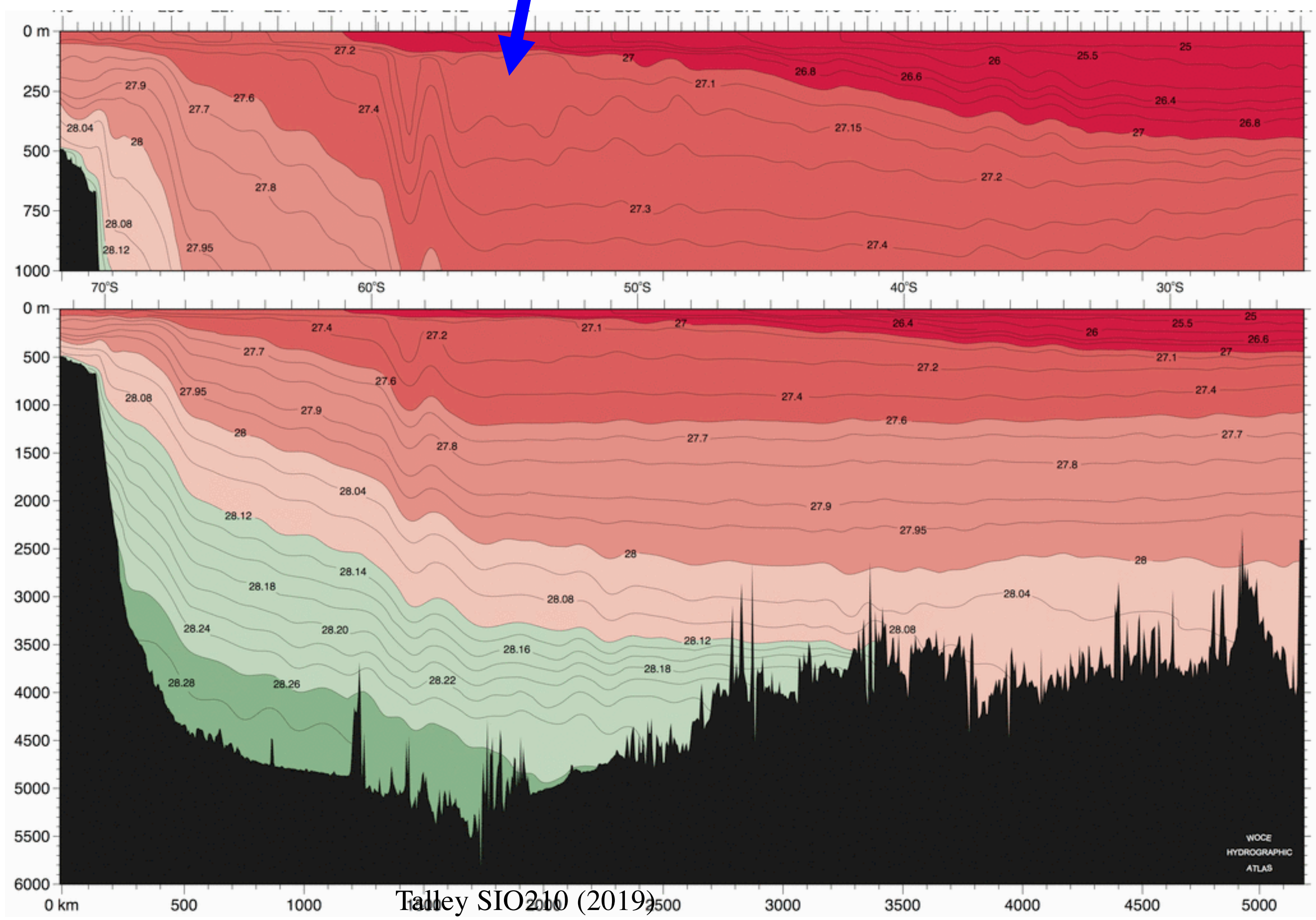
DPO Fig. 13.13

Subantarctic Mode Water: identification

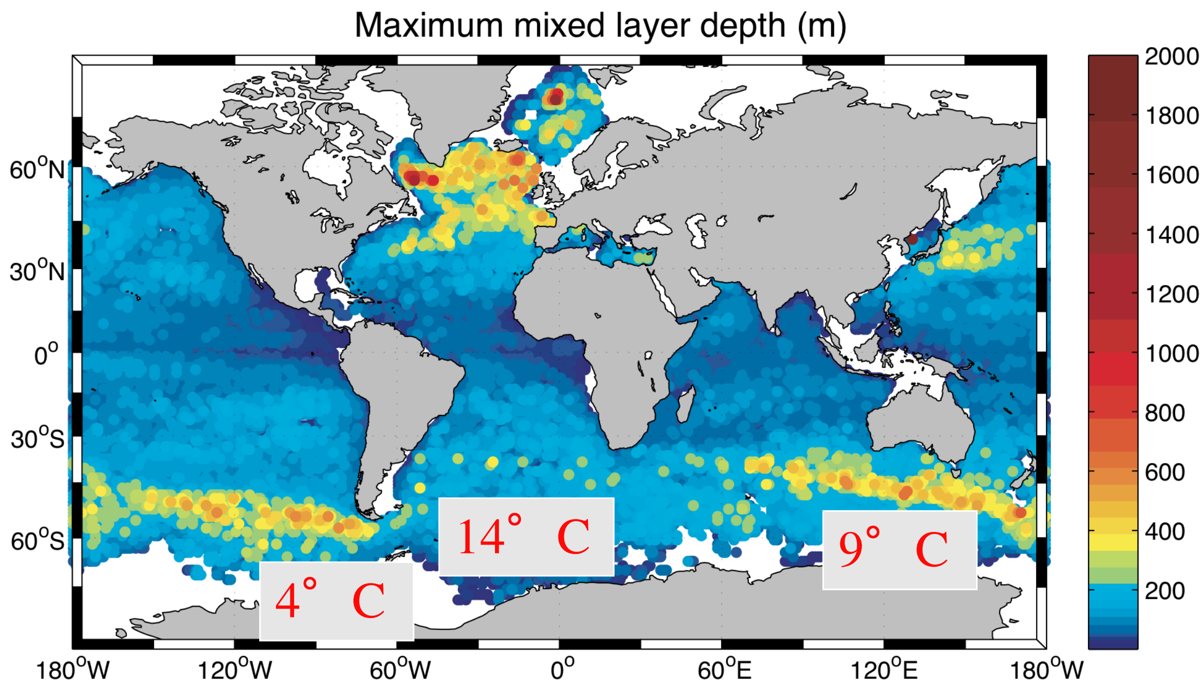


http://woceatlas.tamu.edu

SAMW: thick layer north of Subantarctic Front



Subantarctic Mode Water: source in deep winter mixed layers north of SAF



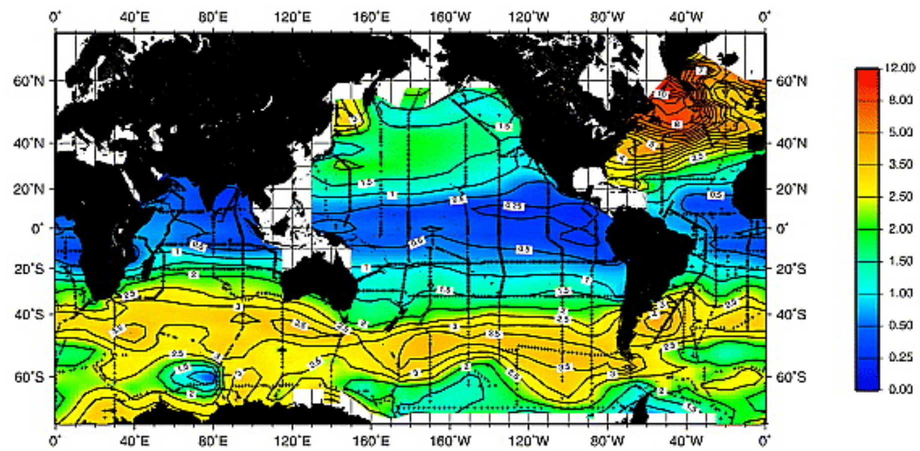
Thick mixed layers in Southern Ocean: remnant subducts and becomes SAMW.

Just north of Subantarctic Front.

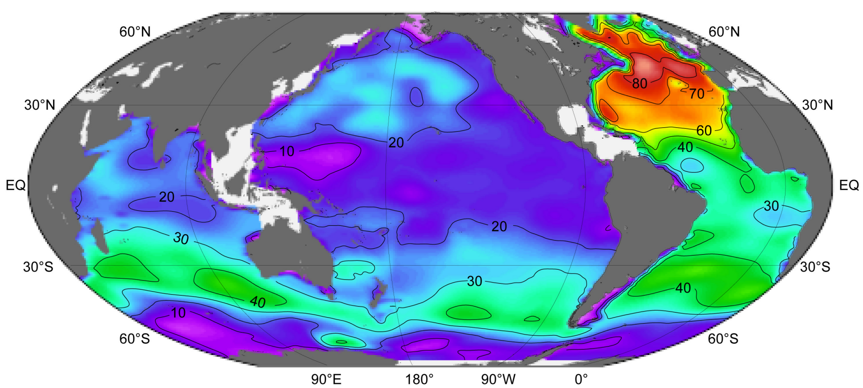
Progress from warmest (least dense) in S. Atlantic to coldest in SE Pacific

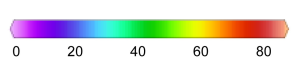
Holte et al (2010) DPO Fig. 4.4c

Subantarctic Mode Water: impact
Chlorofluorocarbon and anthropogenic CO2 water column inventory



CFCs are anthropogenic tracers. Indicate ventilation in the last ~50 years.





Anthropogenic CO_2

Coincidence of high inventories with location of SAMW

Willey et al. 2005

Sabine et al., 2005

Talley SIO210 (2019)

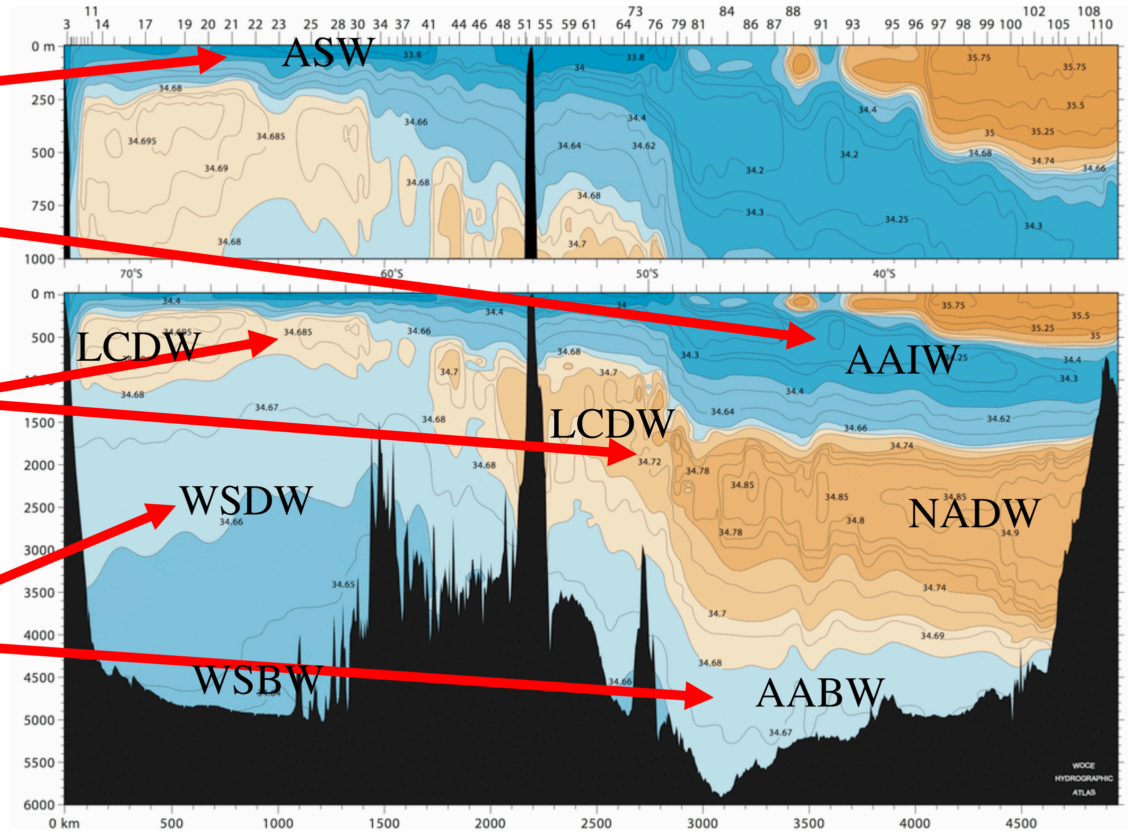
Salinity section at 20W (Atlantic): water masses

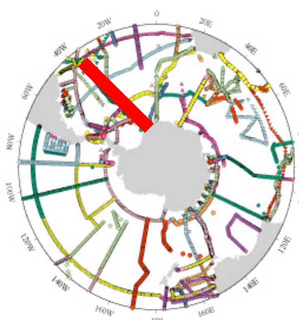
Antarctic Surface Water

Antarctic Intermediate Water (salinity minimum north of SAF)

Lower Circumpolar Deep Water (salinity maximum, arising from North Atlantic Deep Water)

Weddell Sea Deep Water and Antarctic Bottom Water (low salinity, cold bottom layer)

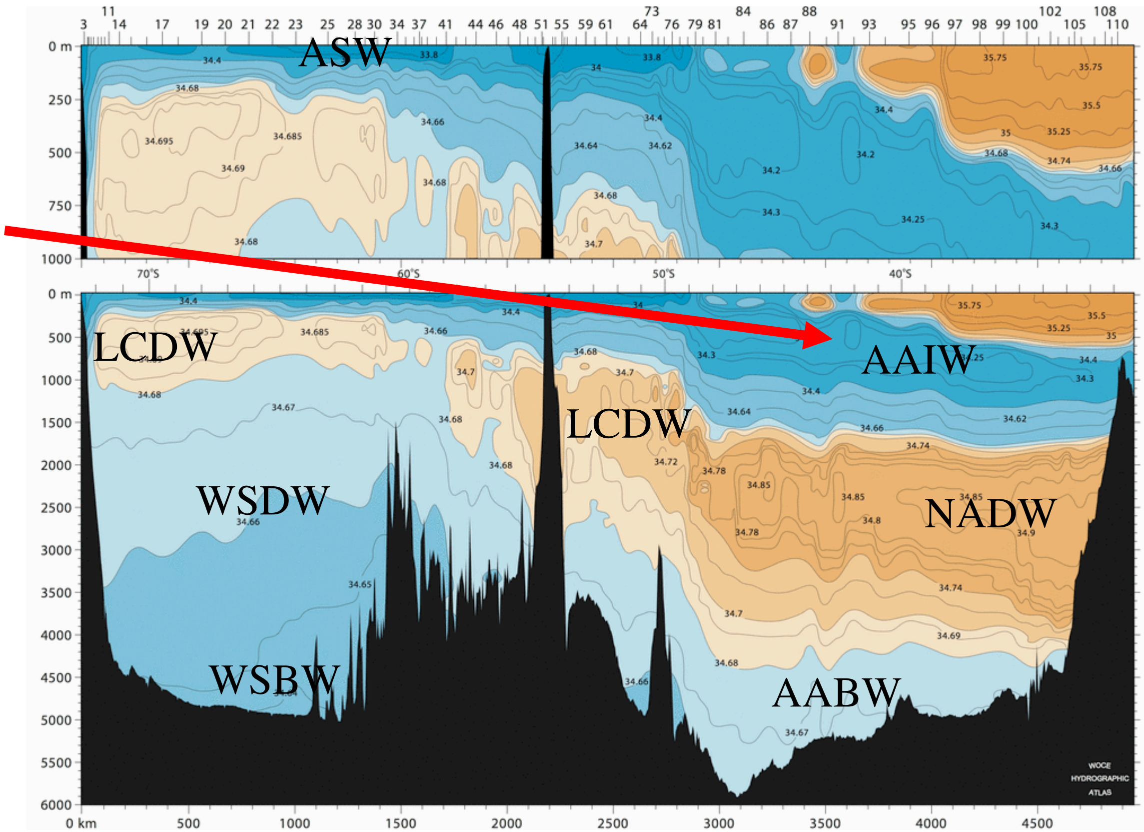


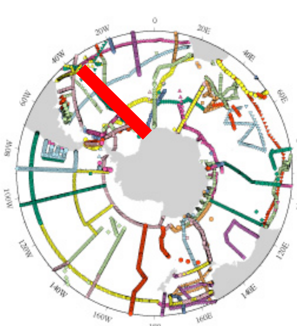


http://woceatlas.tamu.edu

Salinity section at 20W (Atlantic): water masses

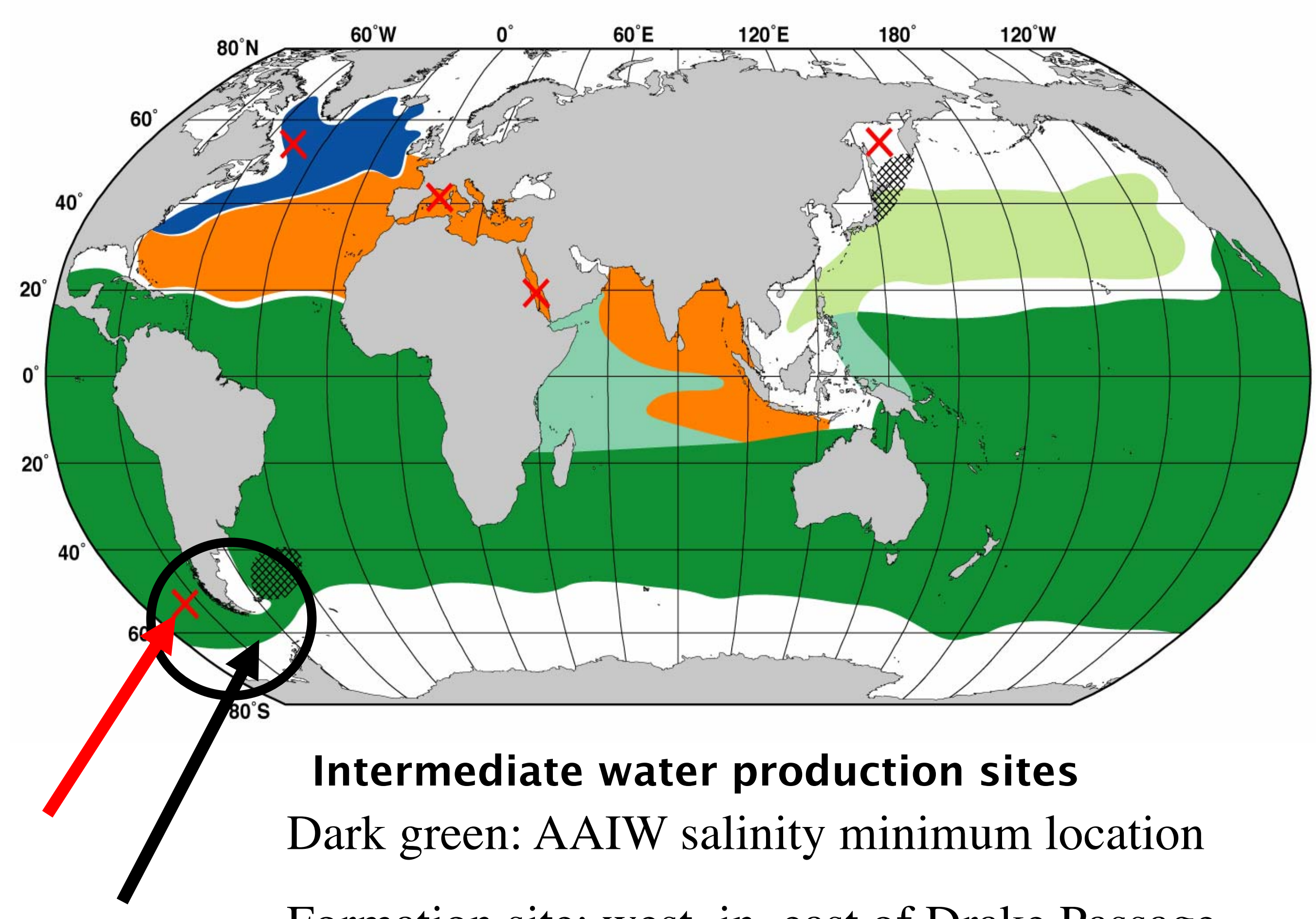
Antarctic Intermediate Water (salinity minimum north of SAF)





http://woceatlas.tamu.edu

Antarctic Intermediate Water: source as densest, freshest SAMW? Or farther south in Polar Frontal Zone.



Intermediate water production sites

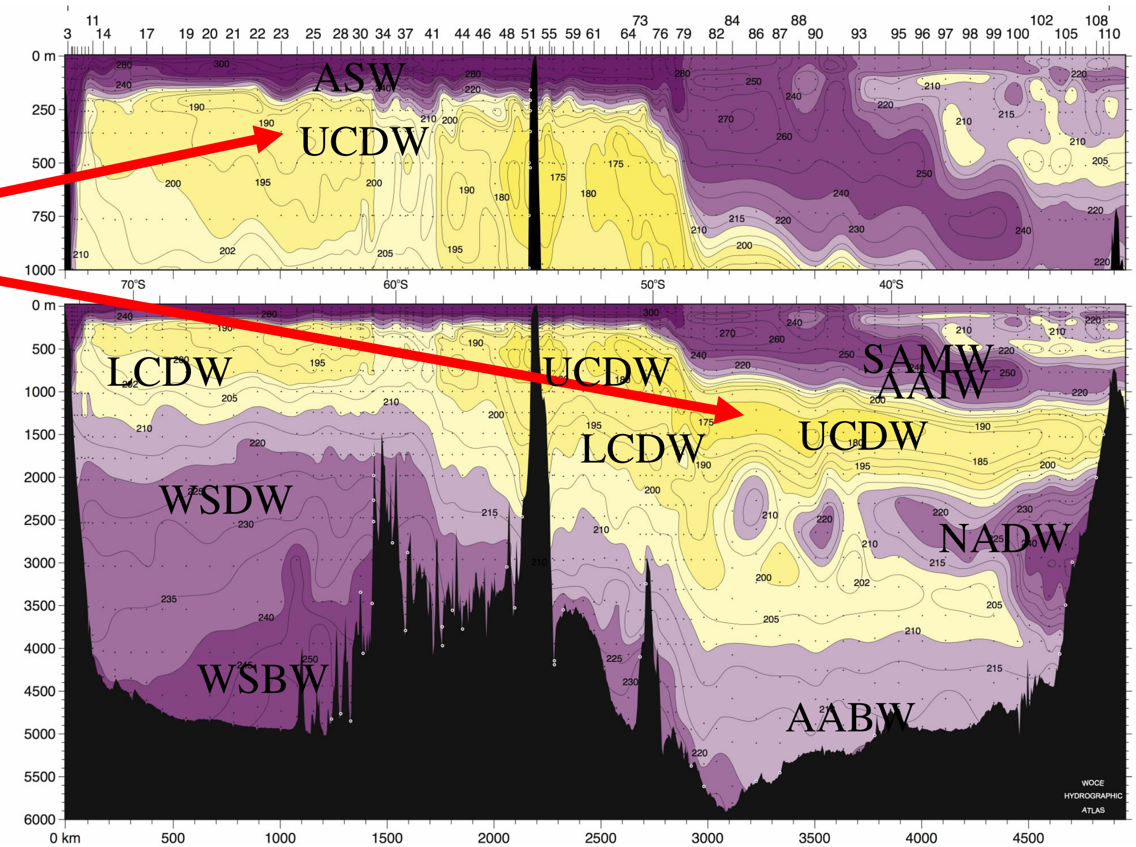
Dark green: AAIW salinity minimum location

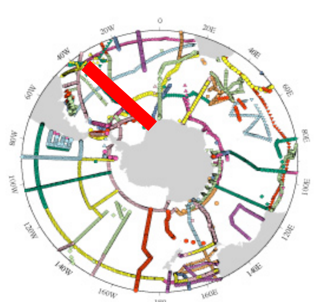
Formation site: west, in, east of Drake Passage

Southern Ocean water masses: Oxygen section at 20W (Atlantic)

Upper Circumpolar Deep Water (oxygen minimum, arising from Pacific and Indian Deep Water)

(also the temperature maximum layer south of Polar Front)





 http://woceatlas.tamu.edu

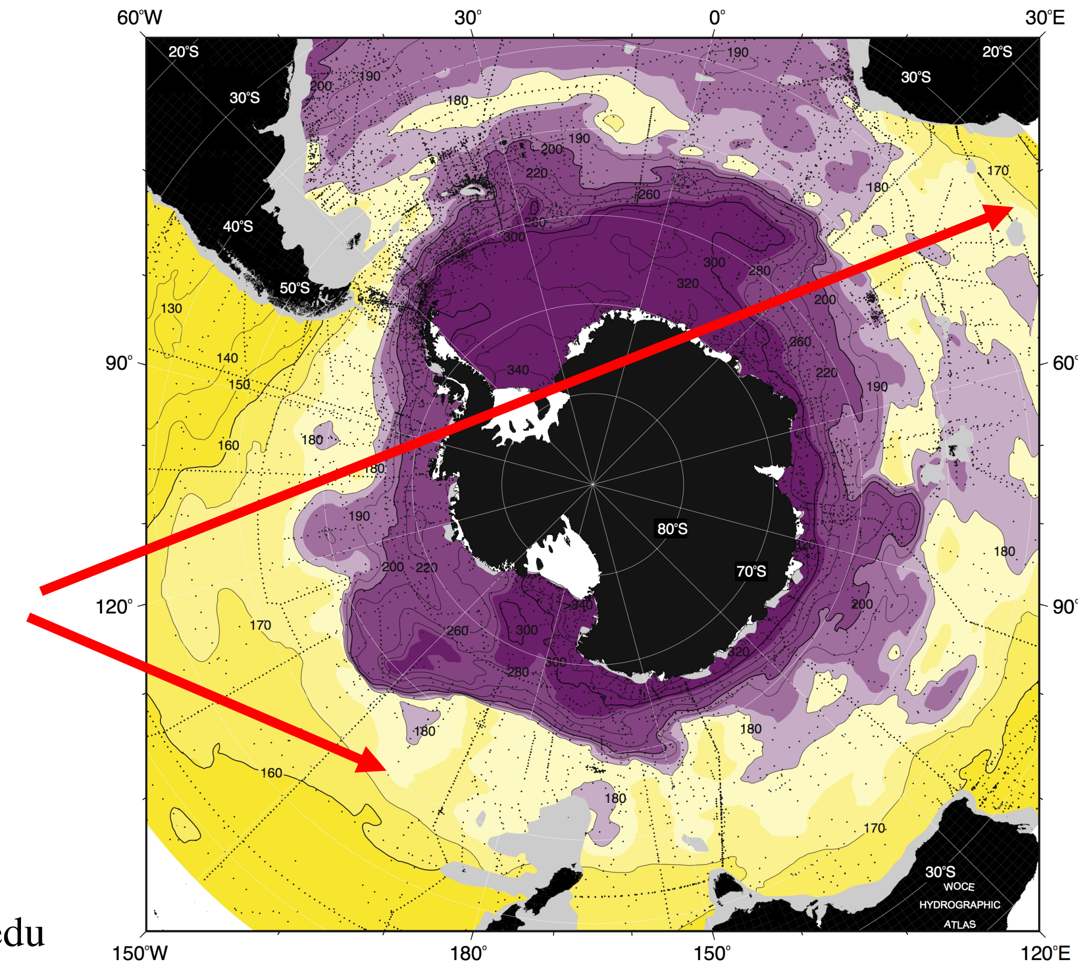
Upper Circumpolar Deep Water:low oxygen from PDW and IDW

Oxygen at

neutral density 27.84

Low oxygen from IDW, PDW

Highest oxygen from S.O. ventilation



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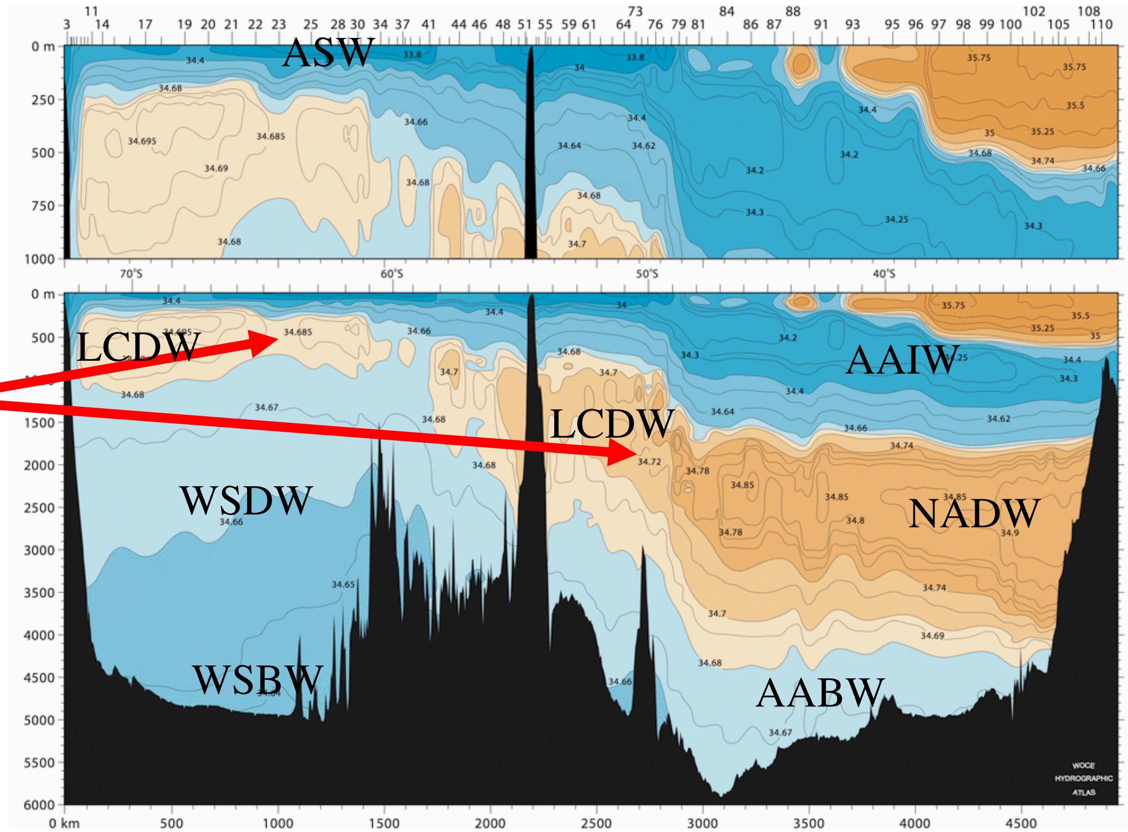
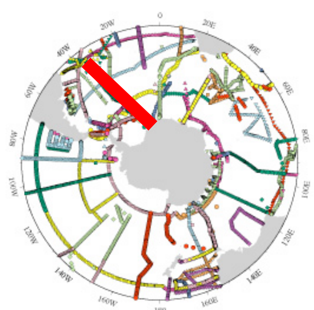
Lower Circumpolar Deep Water: high salinity from NADW

Lower Circumpolar Deep Water (salinity maximum, arising from North Atlantic Deep Water)





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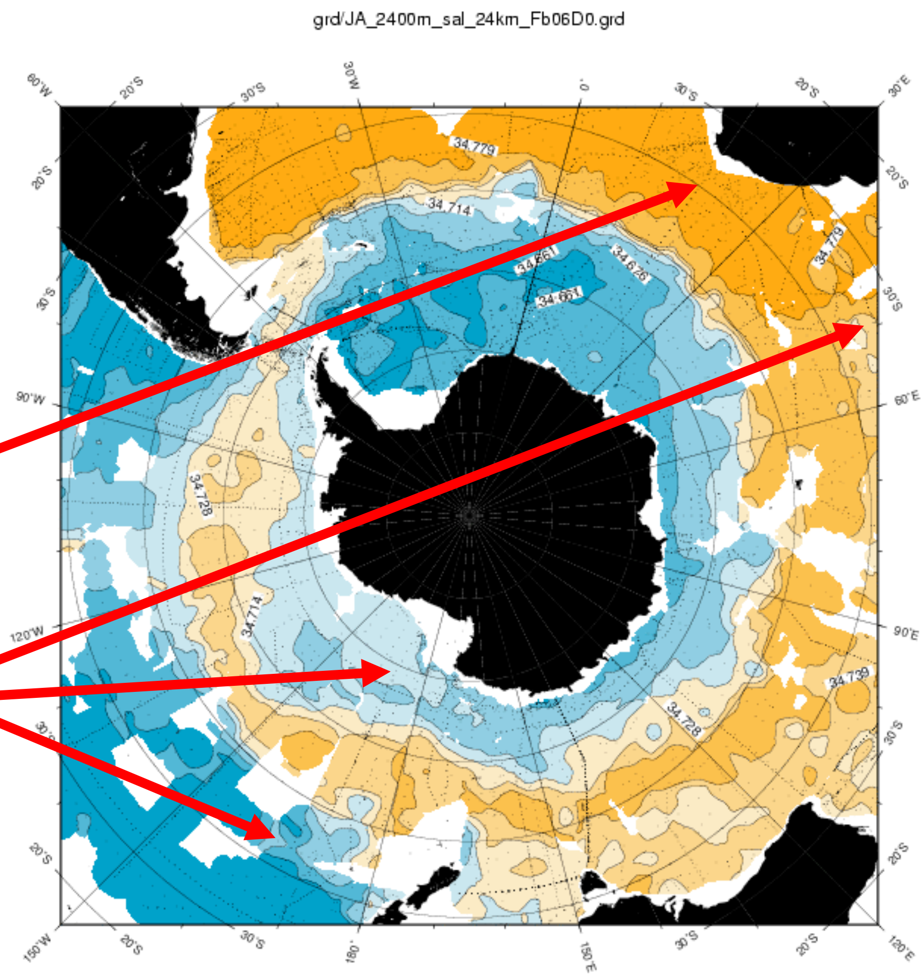
Lower Circumpolar Deep Water: high salinity from NADW

Salinity at

2400 meters

High salinity input from NADW

Fresh input from IDW, PDW, diluting the high salinity



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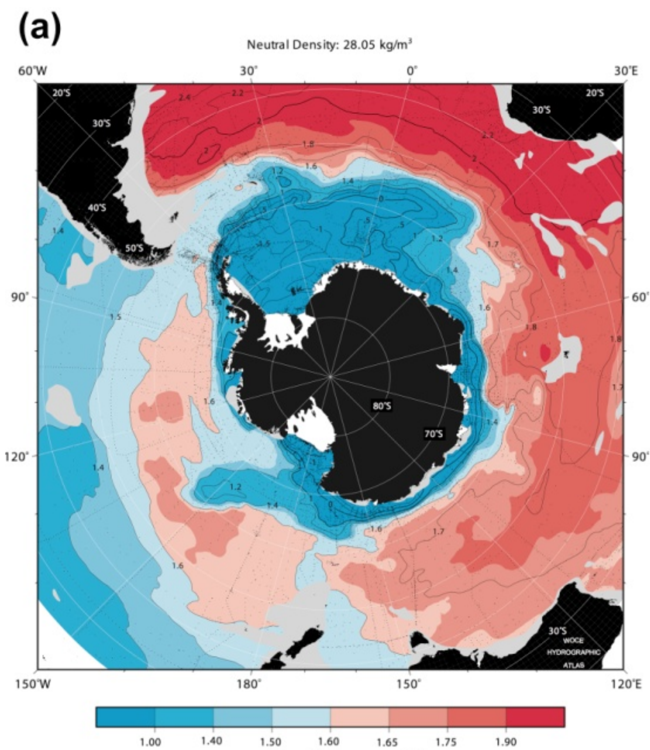
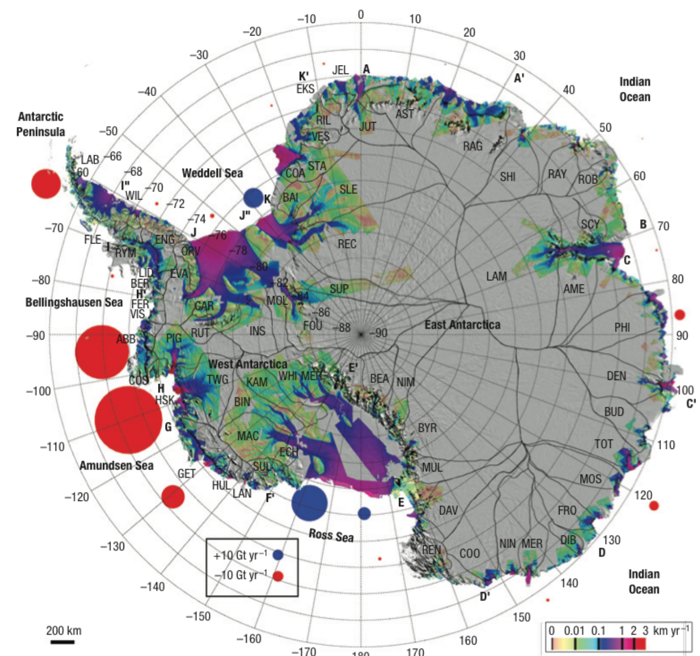
LCDW warm water upwells and comes close to Antarctic ice shelves



Orsi and Whitworth (2005)



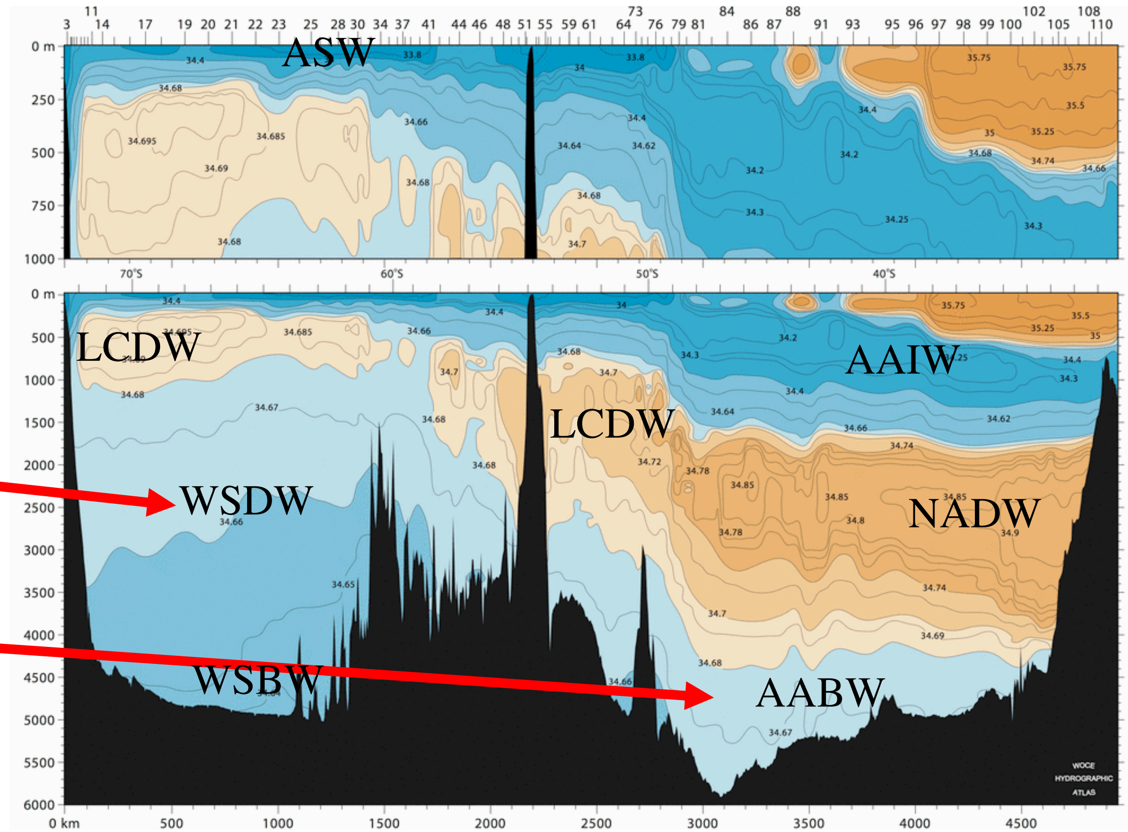
Ice sheet mass balances
→ sea level (Rignot et al. 2008)

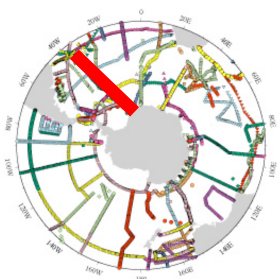
Rignot et al. (2008)

Antarctic Bottom Water

Weddell Sea Deep Water

Antarctic Bottom Water (low salinity, cold bottom layer)





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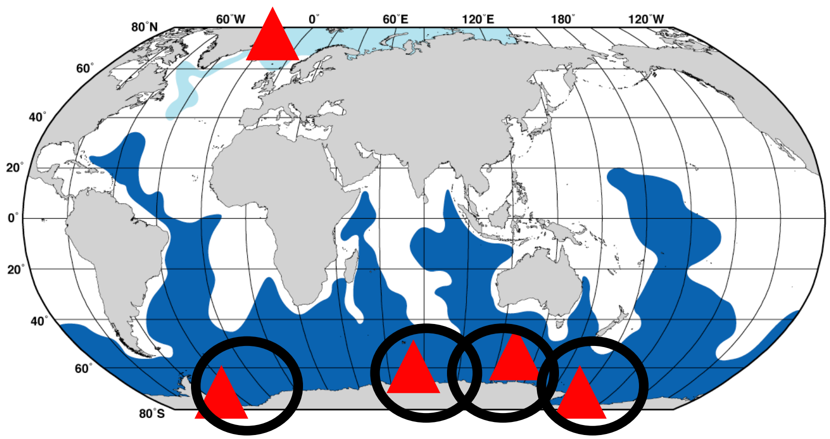
Antarctic Bottom Water



Deep and bottom water production sites: brine rejection in polynyas

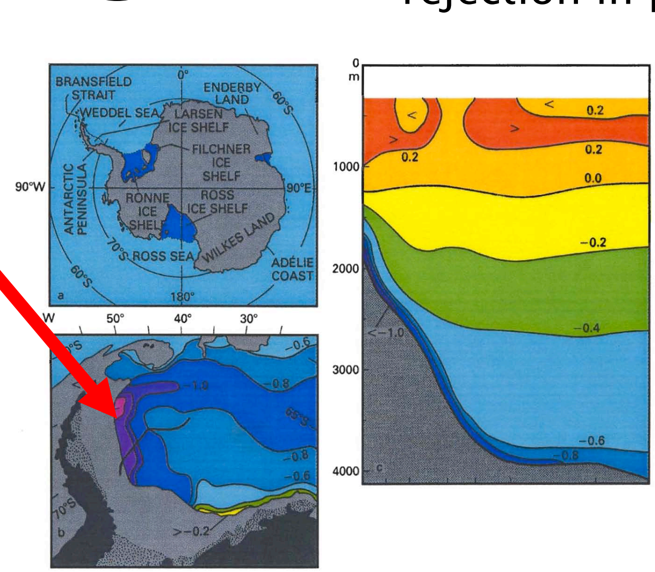
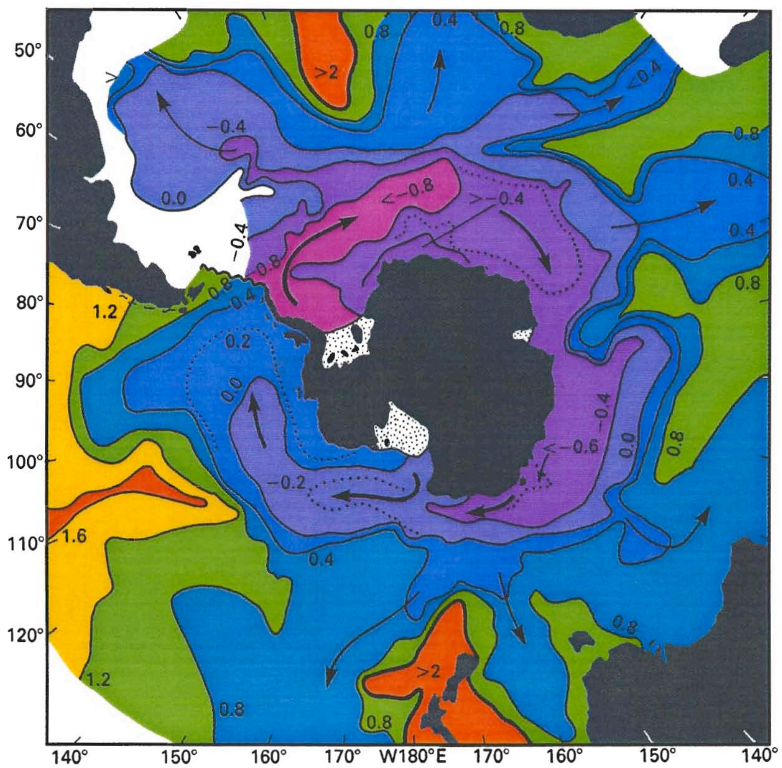
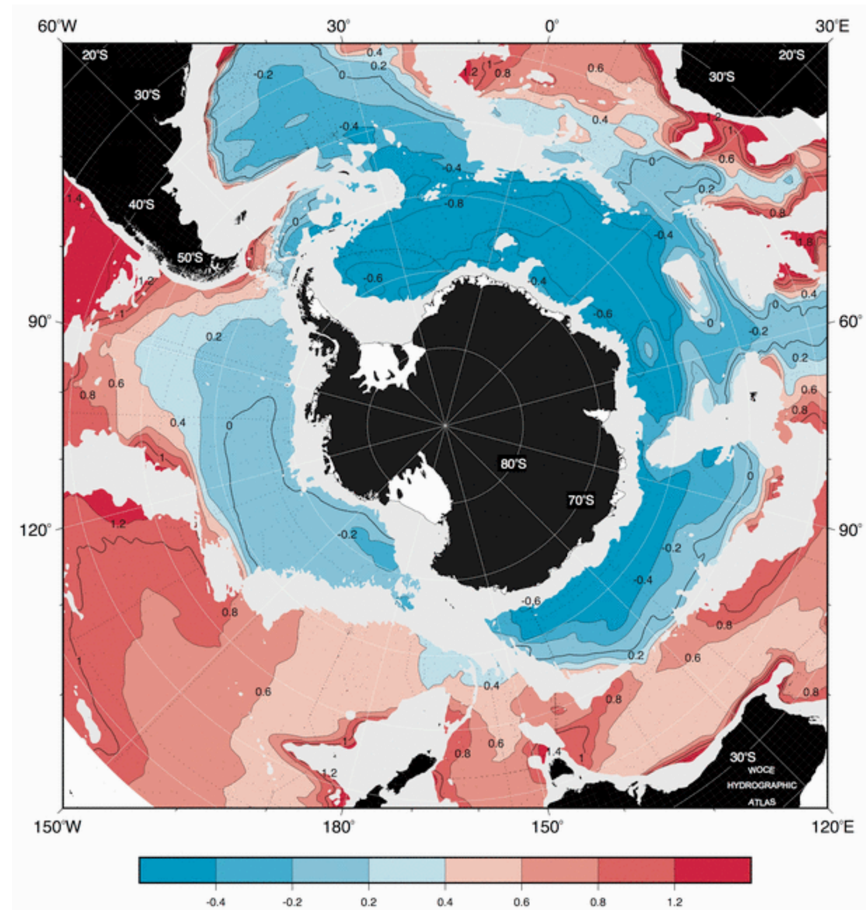


Fig. 6.14. Formation of Antarctic Bottom Water. (a) Locality map, including the regions where deep convection occurs, (b) bottom potential temperature (°C) in the Weddell Sea - the stippled area indicates ice shelf, and the edge of the shaded region is the approximate 3000 m contour, (c) a vertical section of potential temperature (°C) in the Weddell Sea. The position of the section is shown by the heavy line in (b). From Warren (1981a)

Antarctic Bottom Water spread



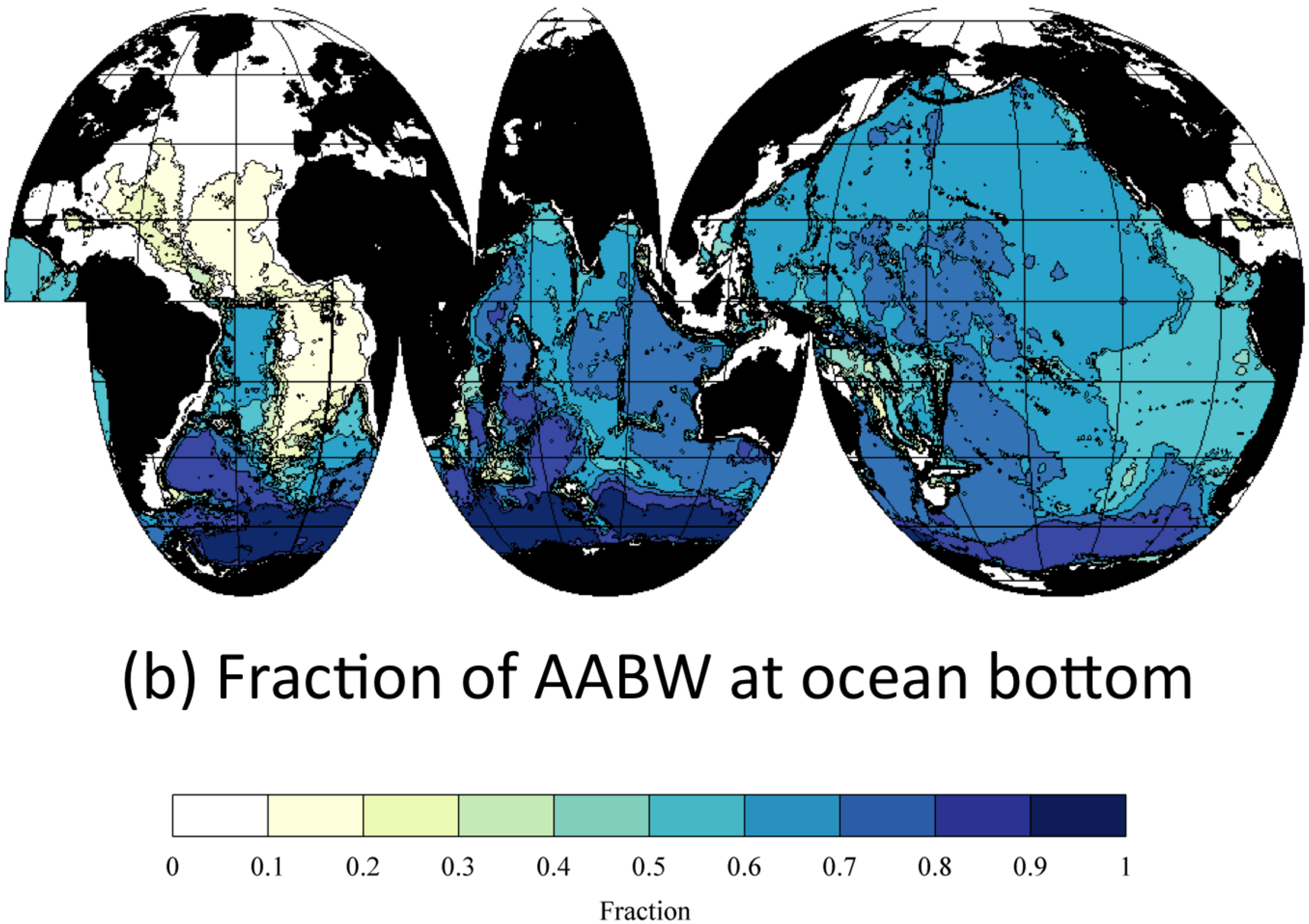
Bottom potential temperature, showing pathways of densest shelf waters around and away from Antarctica (Tomczak&Godfrey)



Bottom potential temperature

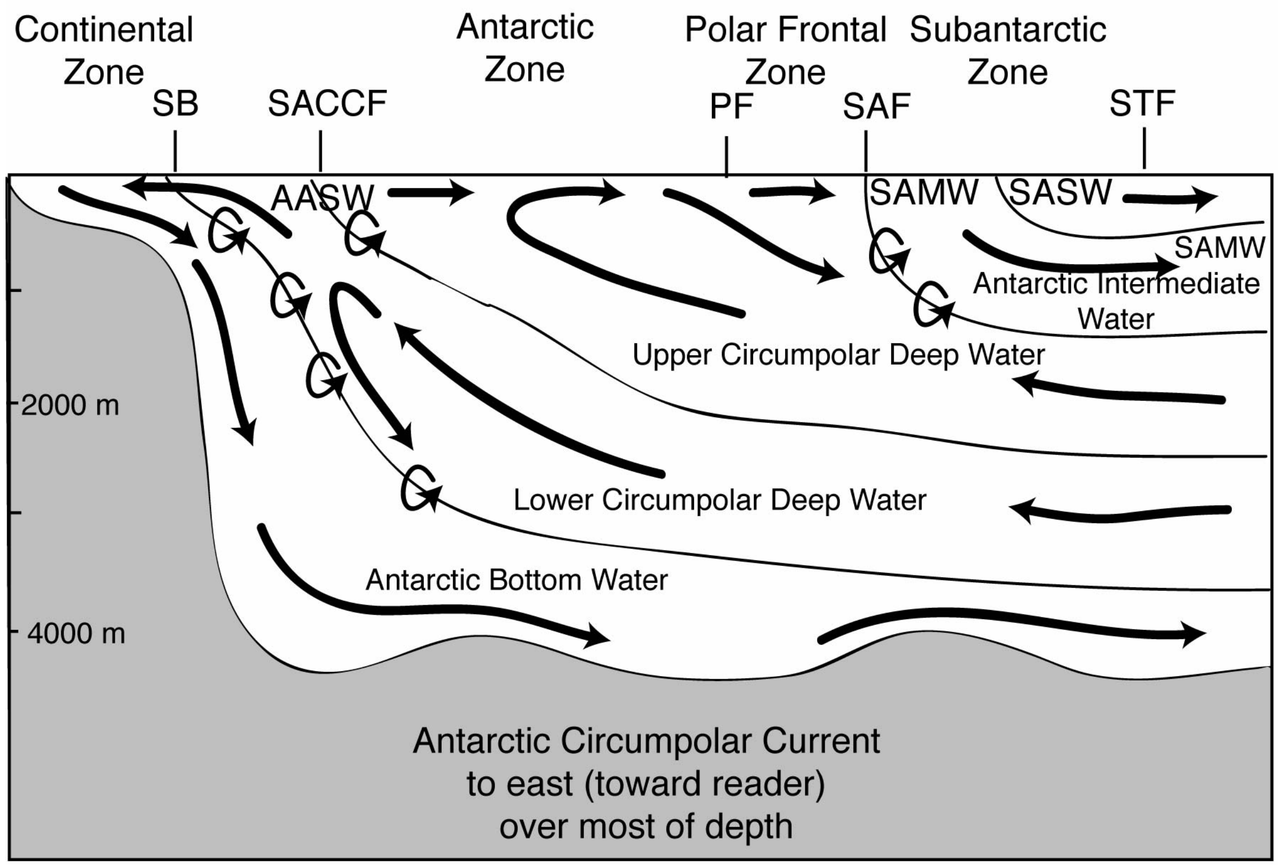
http://woceatlas.tamu.edu

AABW contribution to bottom water



Johnson (2008)
DPO Fig. 14.15

Southern Ocean: meridional view of water masses and overturn



DPO Fig. 13.4 (after Speer et al. 2000)