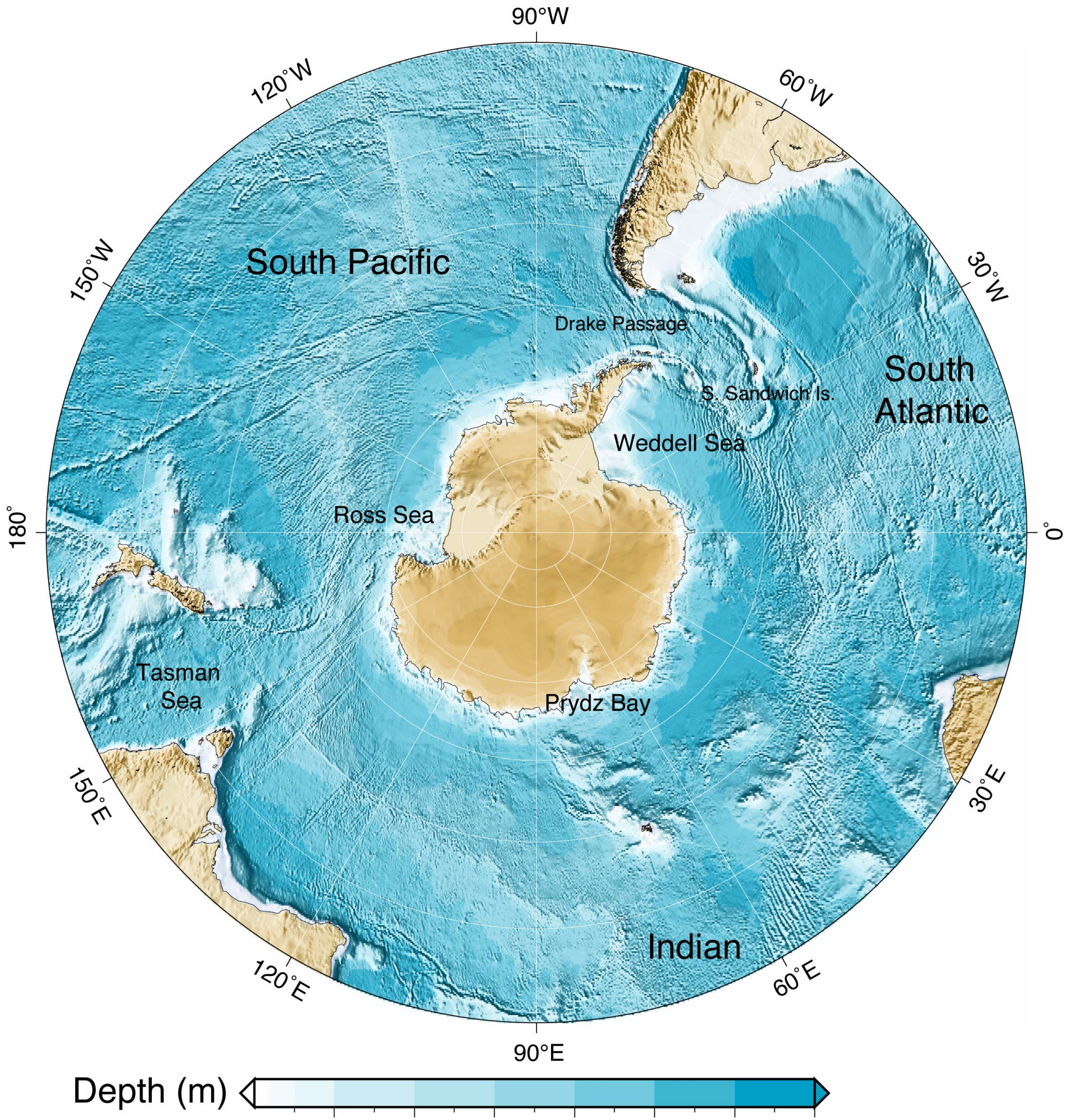
SIO 210: Southern Ocean circulation.
Dynamics X: Southern Ocean
L. Talley Fall, 2015

- Geography:open at Drake Passage
- Circulation: much more like atmosphere (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

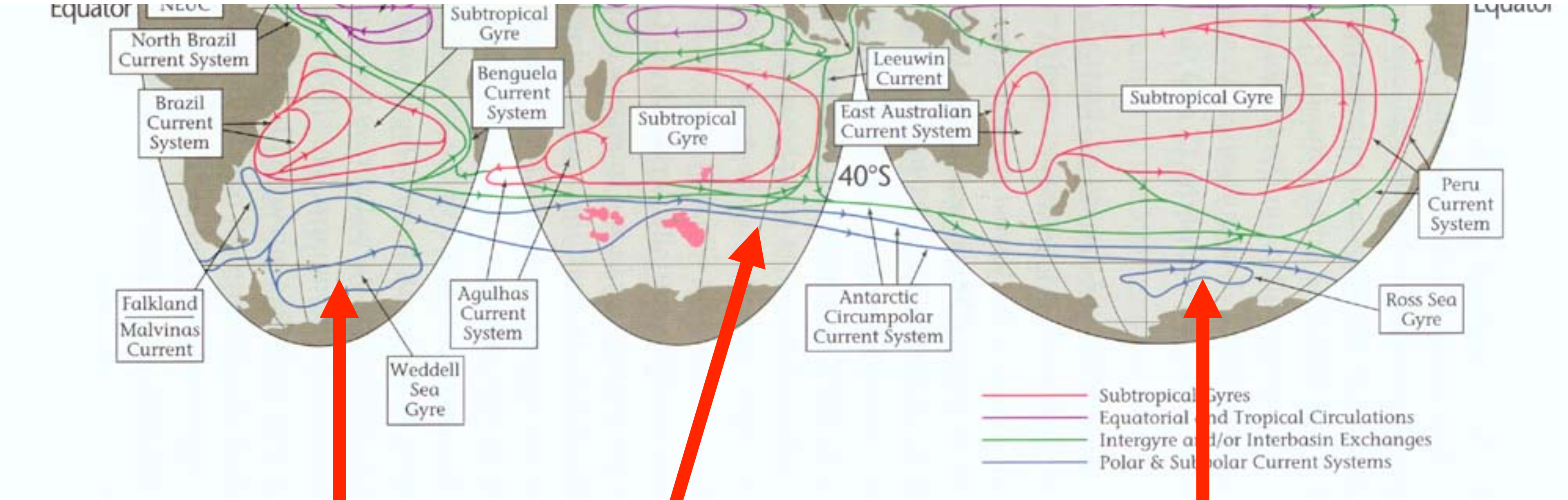
  - Some animations http://ryan.actualscience.net/



Talley SIO 210 (2015)

Southern Ocean geography

Schematic of surface circulation (Schmitz, 1995)

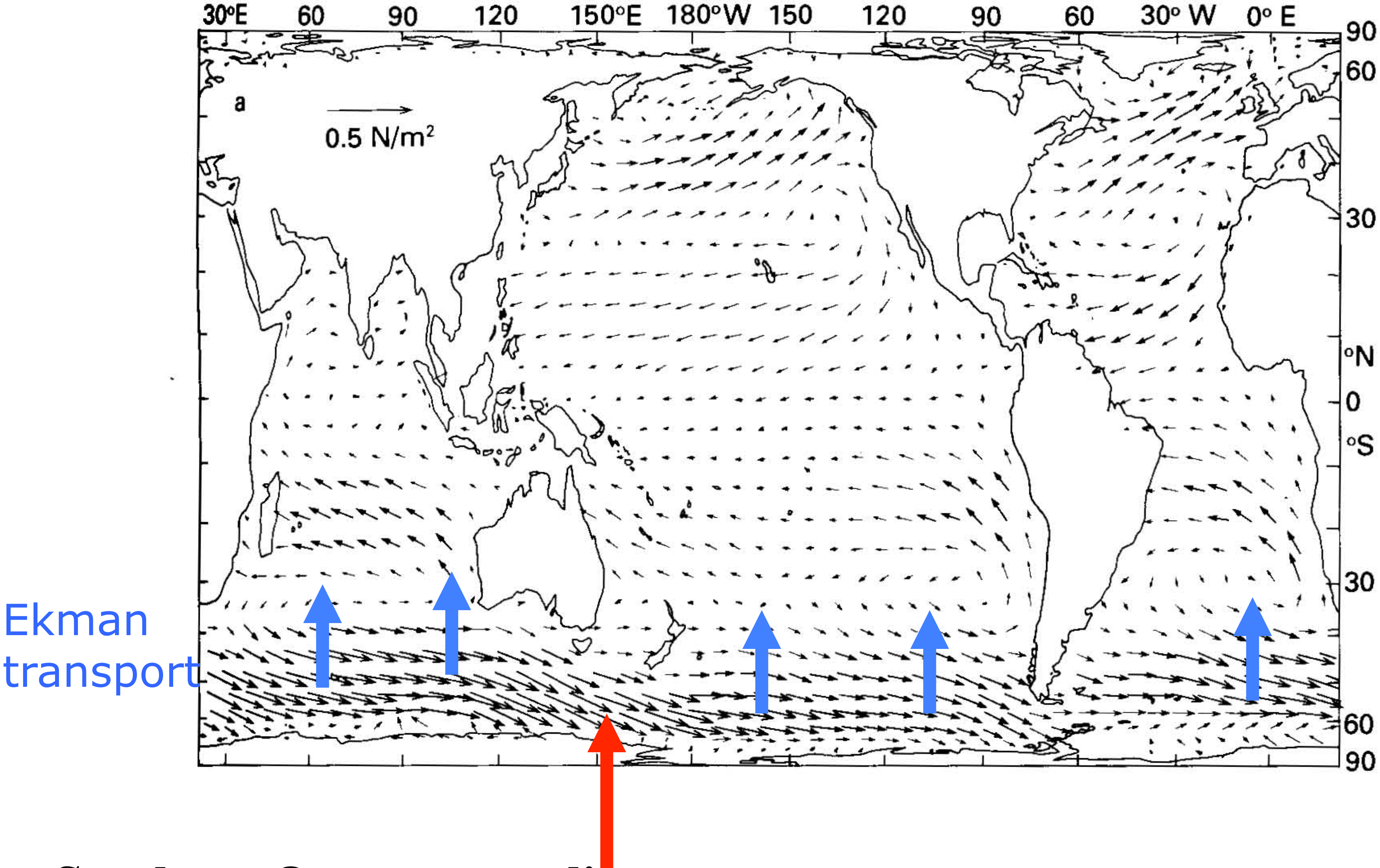


Weddell Sea gyre
(cyclonic)

Ross Sea gyre
(cyclonic)

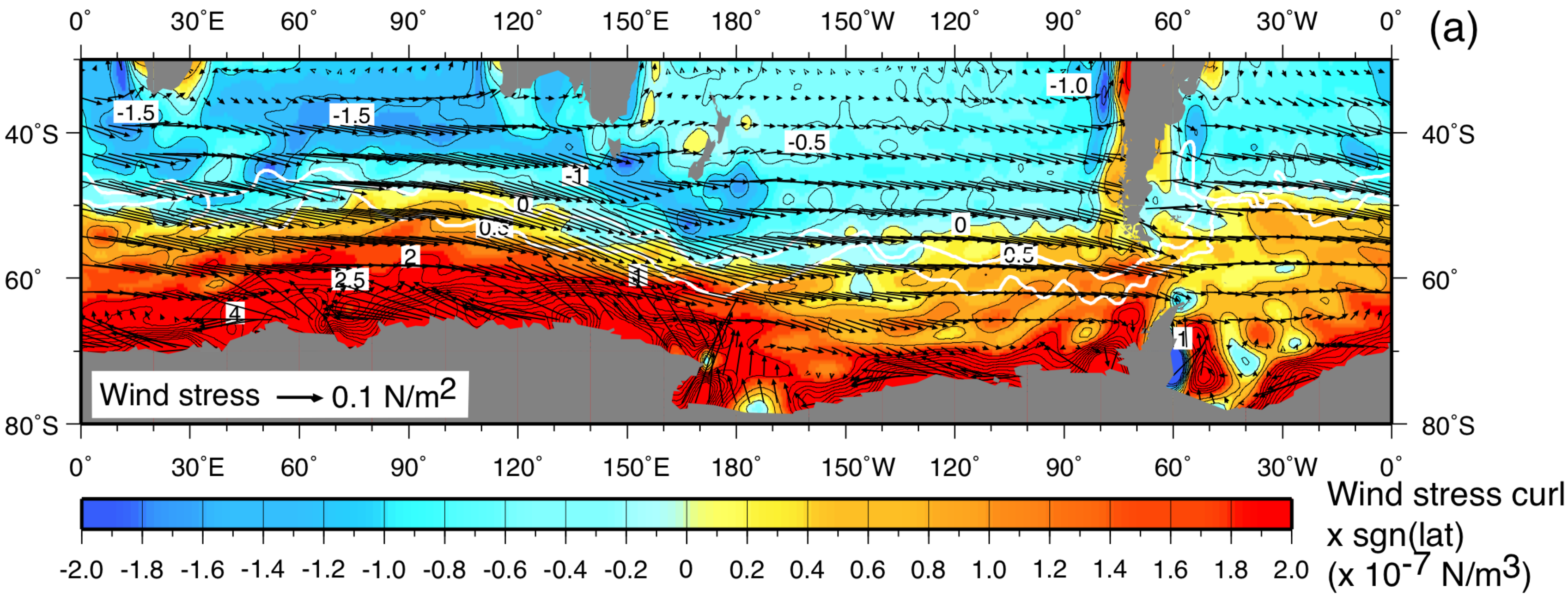
Antarctic Circumpolar Current encircling Antarctica, starting farthest north off S. America as the Malvinas/Falkland Current, shifting southward as it moves eastward until it flows through Drake Passage

Dynamics: Annual mean wind stress, Ekman stress



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

Dynamics: Ekman pumping



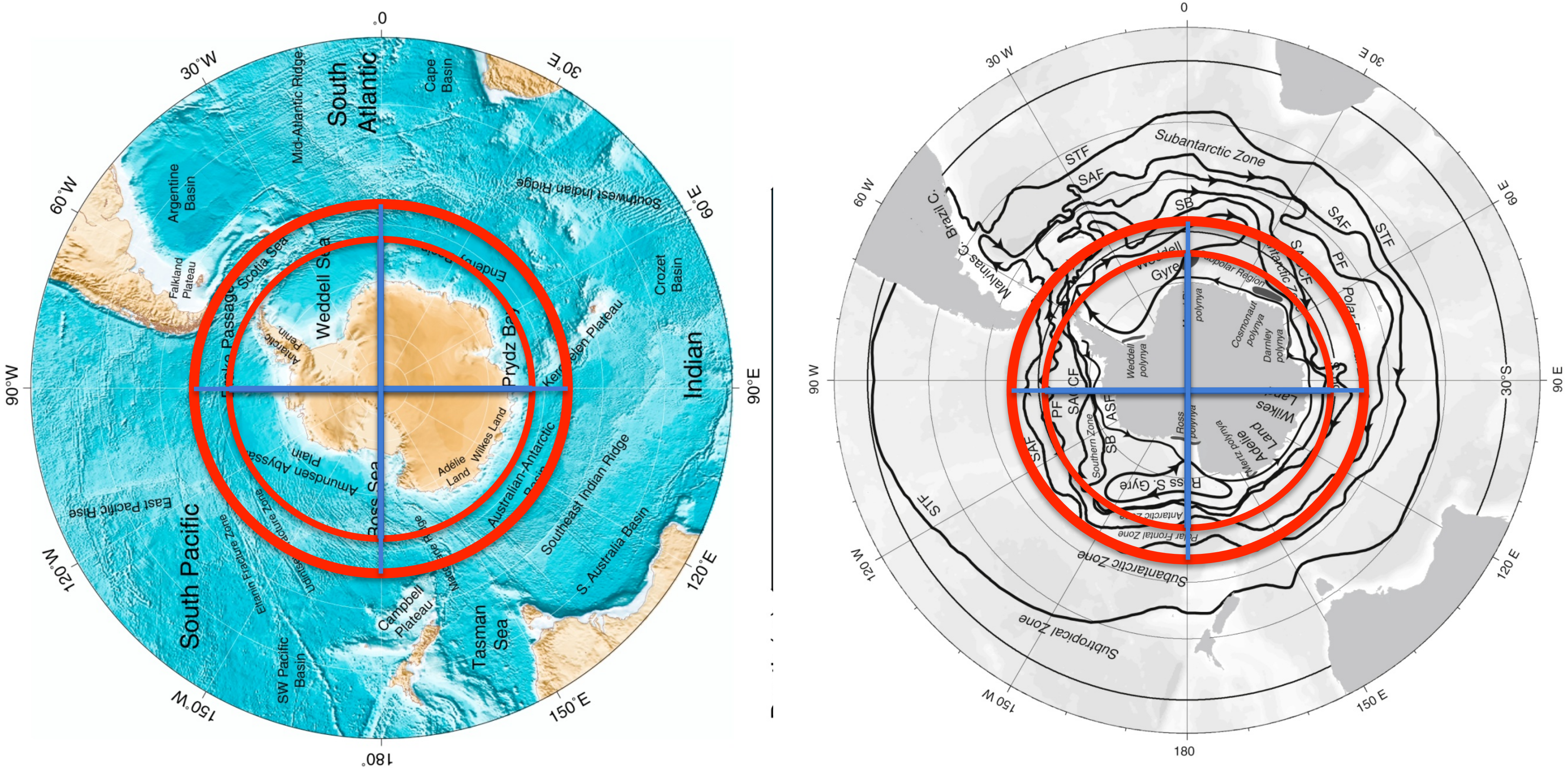
Westerly winds, which decrease in strength towards Antarctica and become easterlies and “katabatic” winds (very cold, continental winds)

→equatorward Ekman transport, Ekman downwelling north of ACC

→AND Ekman upwelling south of the maximum westerly winds

DPO Fig. 13.2

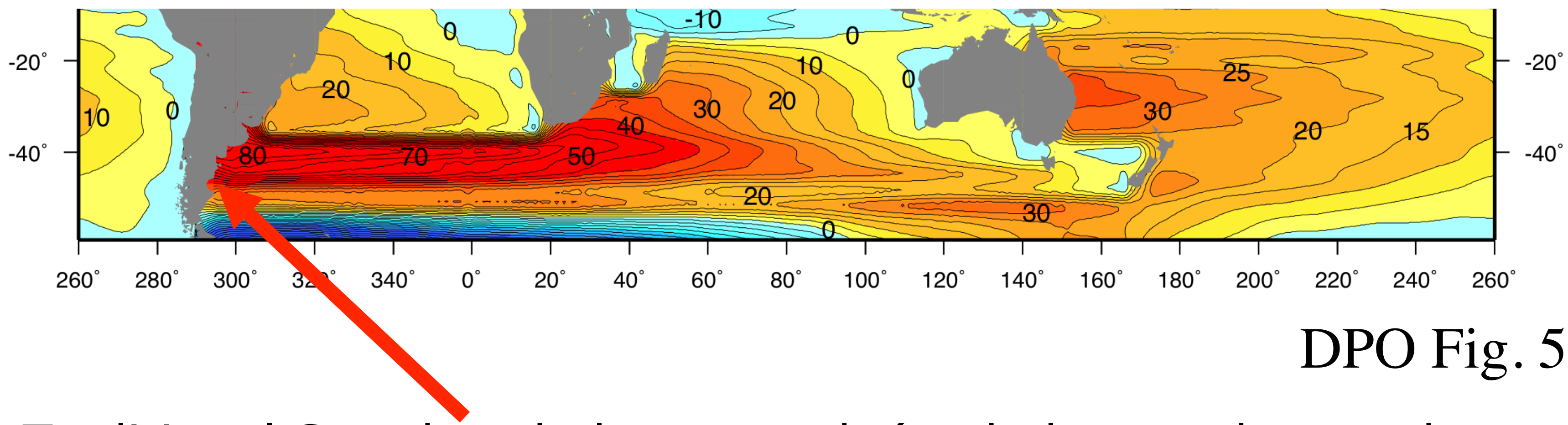
Drake Passage latitudes: bathymetry and circulation



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.

Dynamics: Antarctic Circumpolar Current



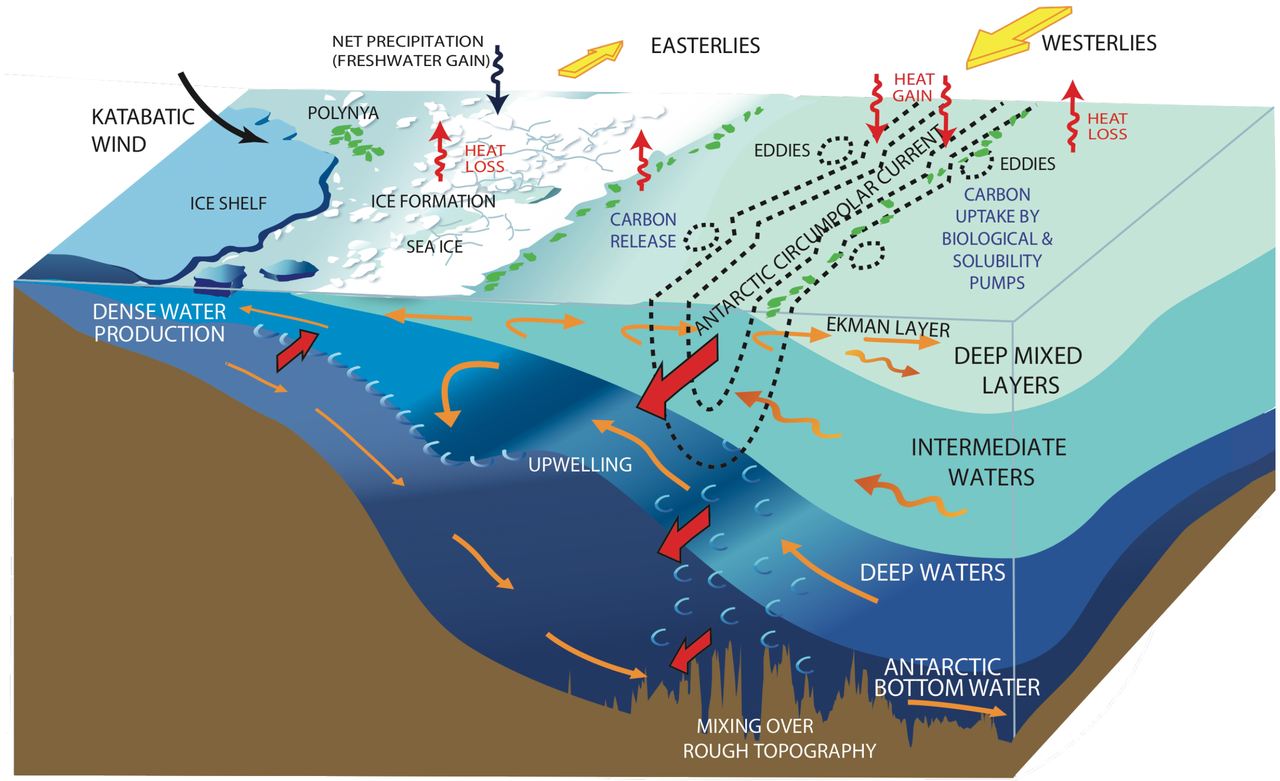
DPO Fig. 5.17

1. Traditional Sverdrup balance north (and also south, not shown here) of latitude of Drake Passage. Western boundary current is the Malvinas (Falkland) Current off S. America. Shift of whole ACC southwards from this location towards the east in response to Ekman upwelling.

2. BUT open Drake Passage from surface to 2000m means that Sverdrup balance does not hold throughout (no western boundary above sill depth).

ACC has additional zonal jet dynamics; outside the scope of SIO 210

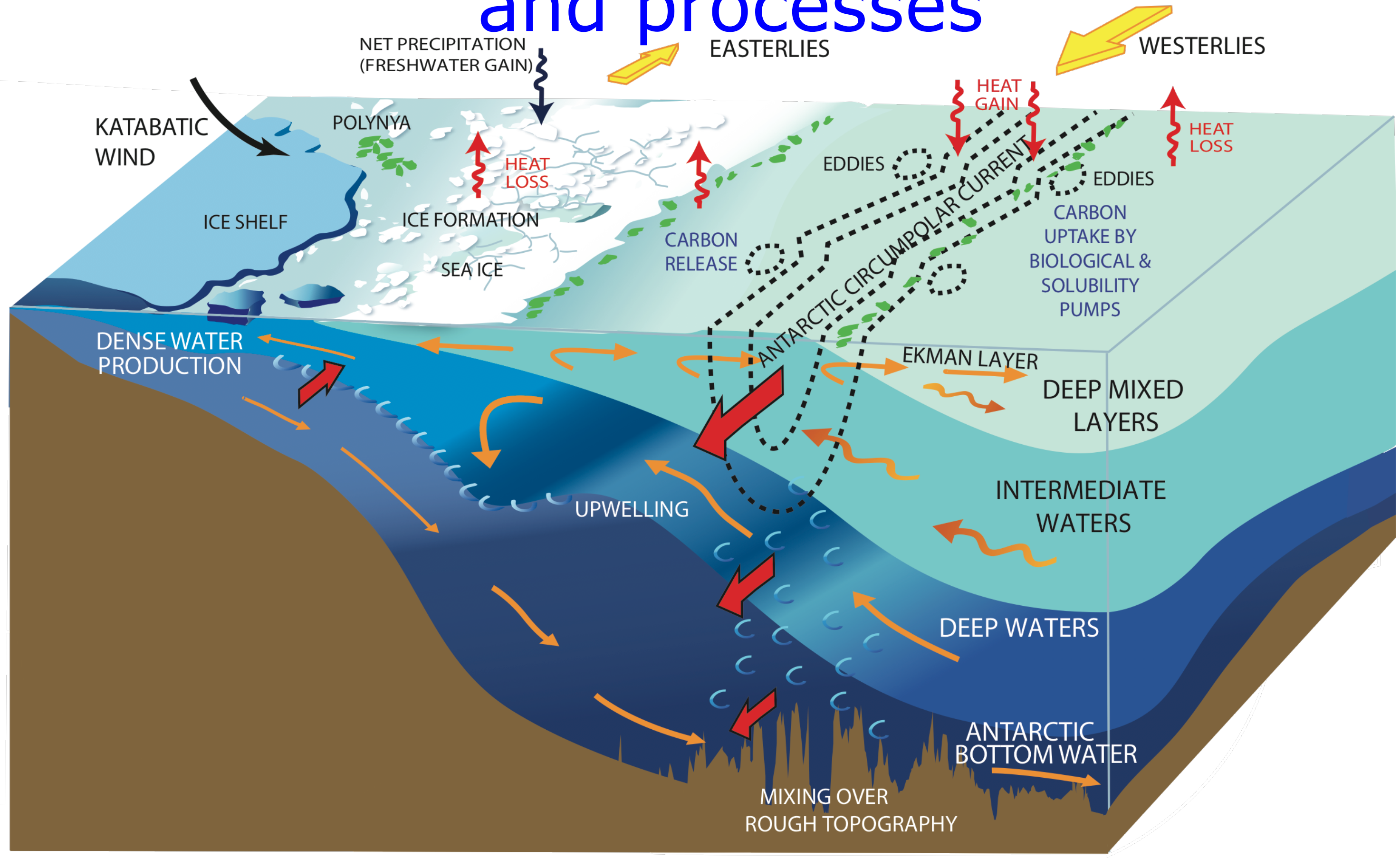
Dyamics: deep to surface upwelling



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

Dynamically this is due to the open Drake Passage latitude band.

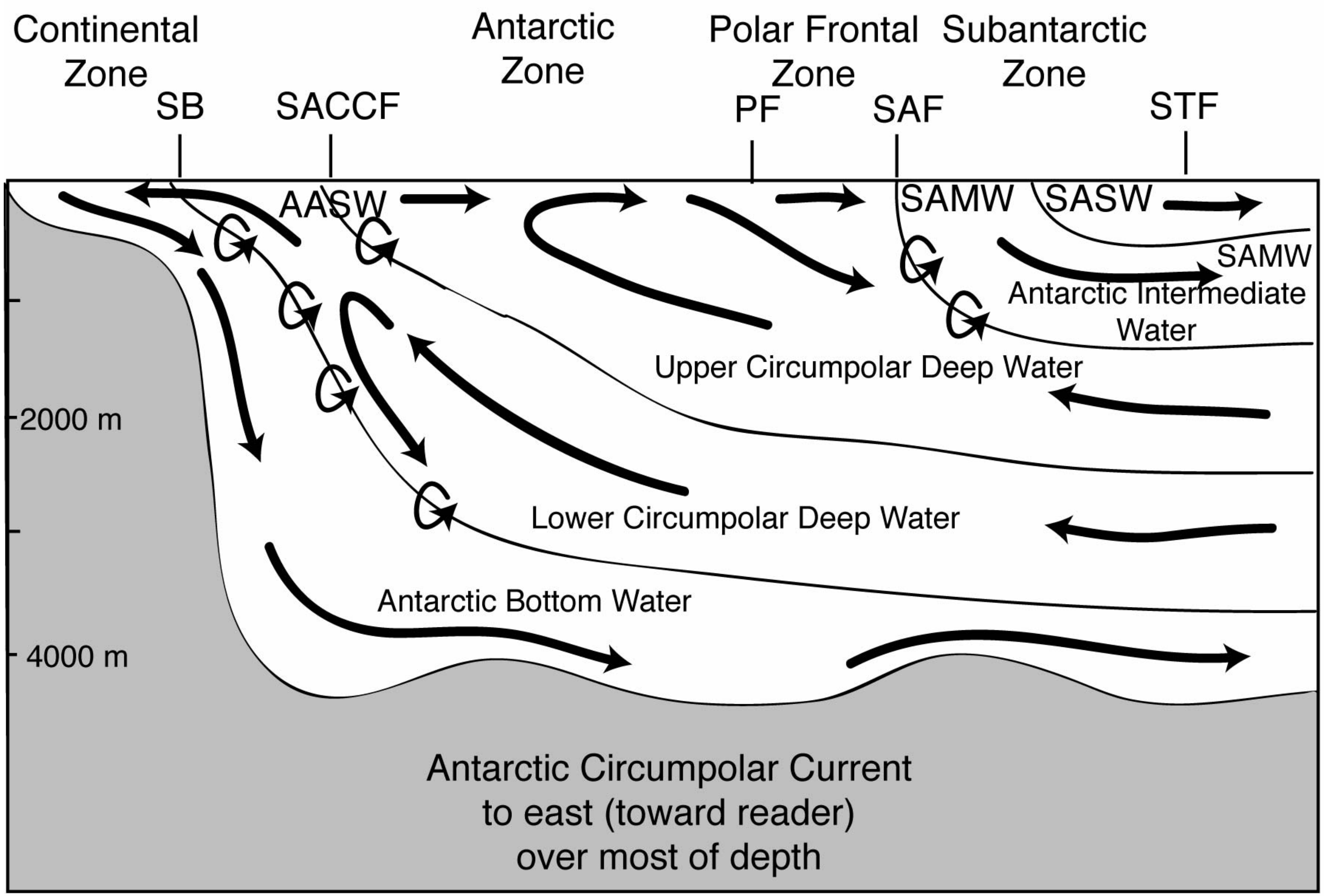
Zonally-averaged overturning circulation and processes



Winds (stress and curl) – upwelling and circulation
Air-sea heat loss and gain
Air/ice-sea freshwater fluxes (here due to ice processes)
Diapycnal mixing

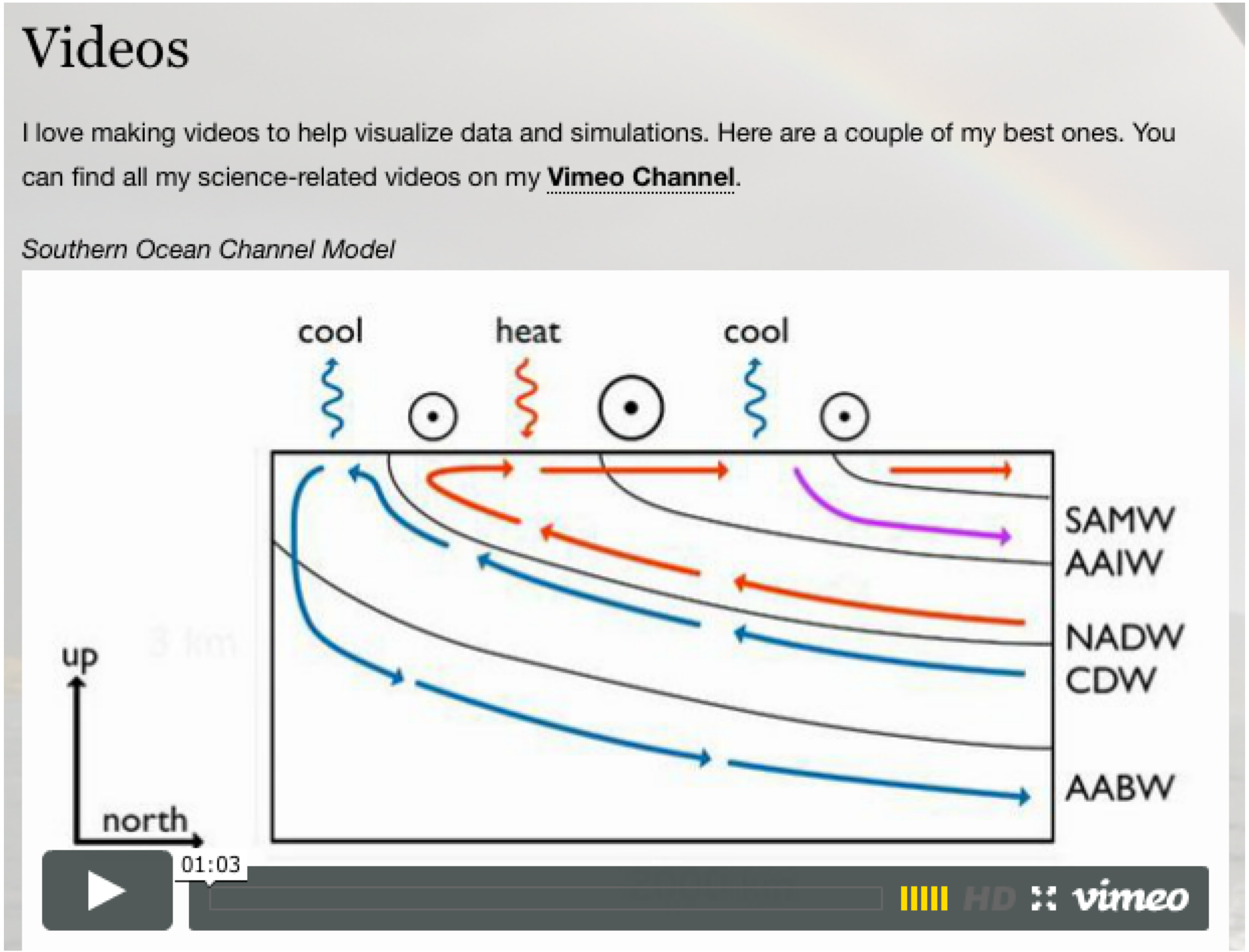
[Schematic has evolved from Speer, Rintoul and Sloyan (JPO 2000)]

Dynamics: Ekman, upwelling, bottom water formation, eastward ACC



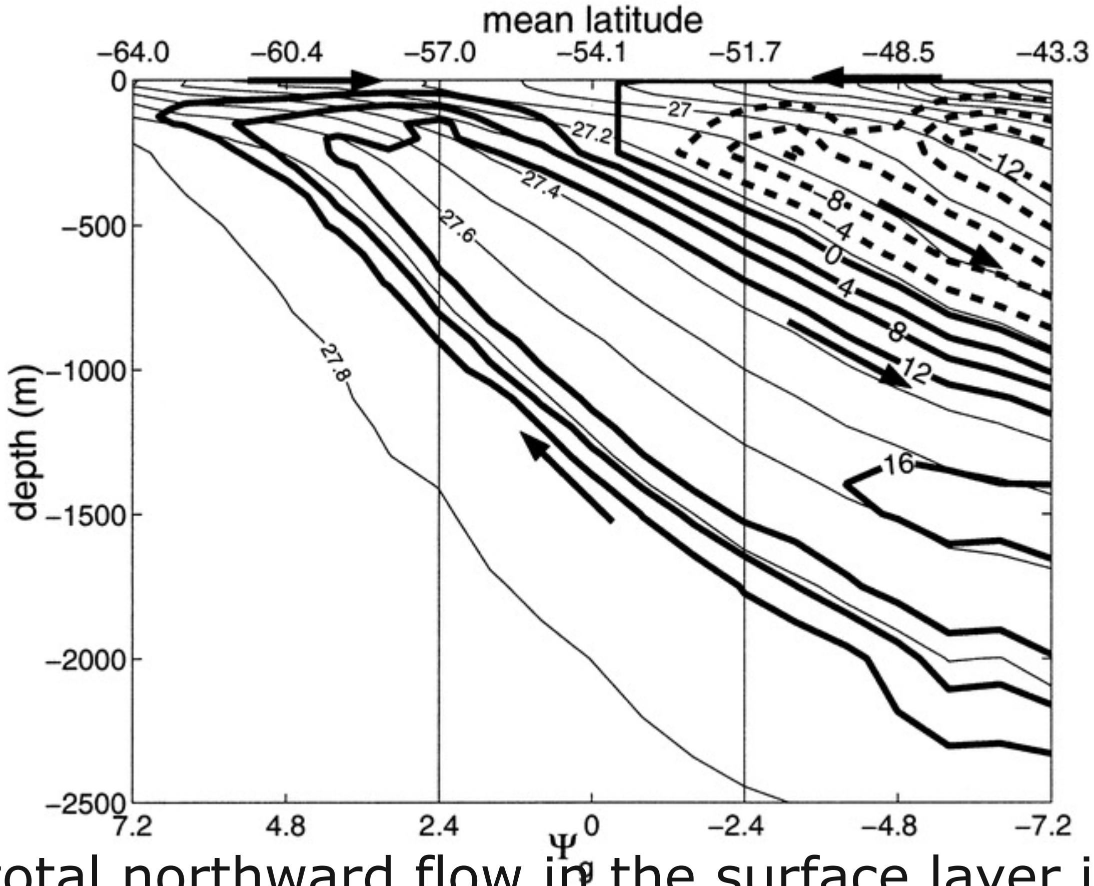
DPO Fig. 13.4 (after Speer et al. 2000)

Dynamics: Ekman, upwelling, bottom water formation, eastward ACC



http://ryan.actualscience.net/videos/

Dynamics: (more advanced) "residual circulation"

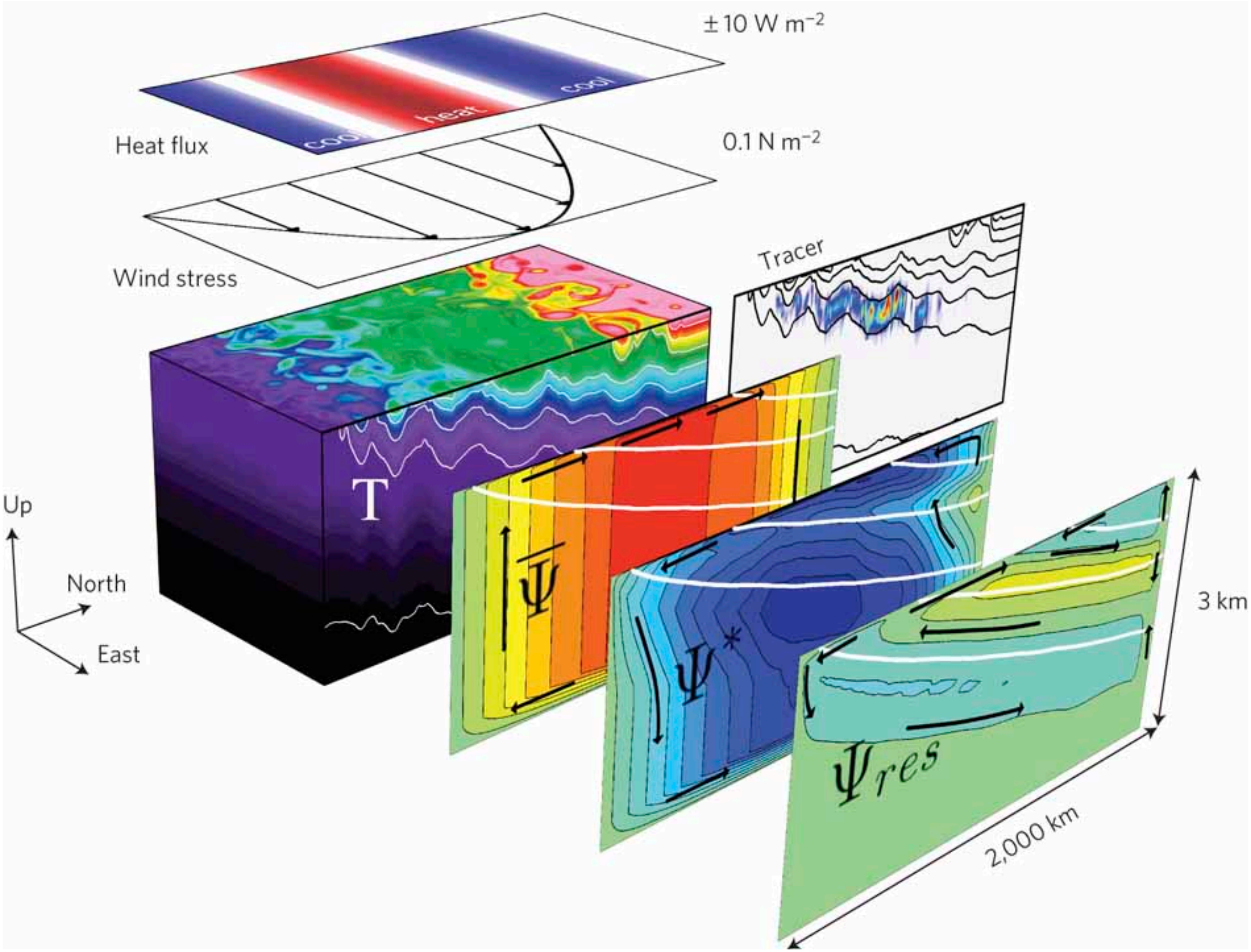


Karsten and Marshall (JPO, 2002)

The total northward flow in the surface layer is the sum of northward Ekman and southward eddy flux that tries to flatten the isopycnals (due to baroclinic instability)

("Residual circulation" is the flow along isopycnals.)

Dynamics: re-entrant channel flow



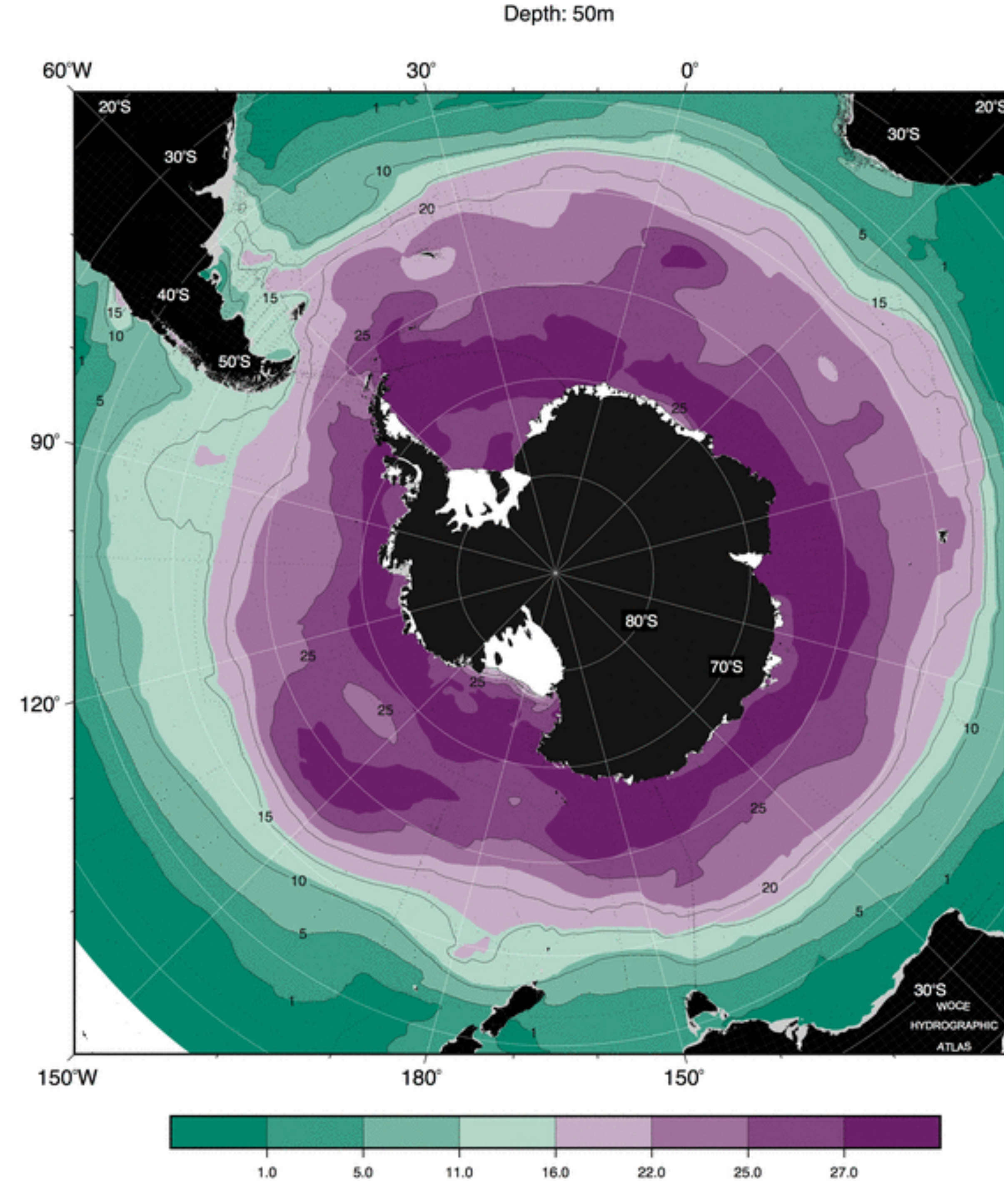
Marshall and Speer (Nat. Geos., 2012)

Based on Abernathey et al. (2011)

Evidence of upwelling: Near-surface nitrate

High surface values reflect upwelling.

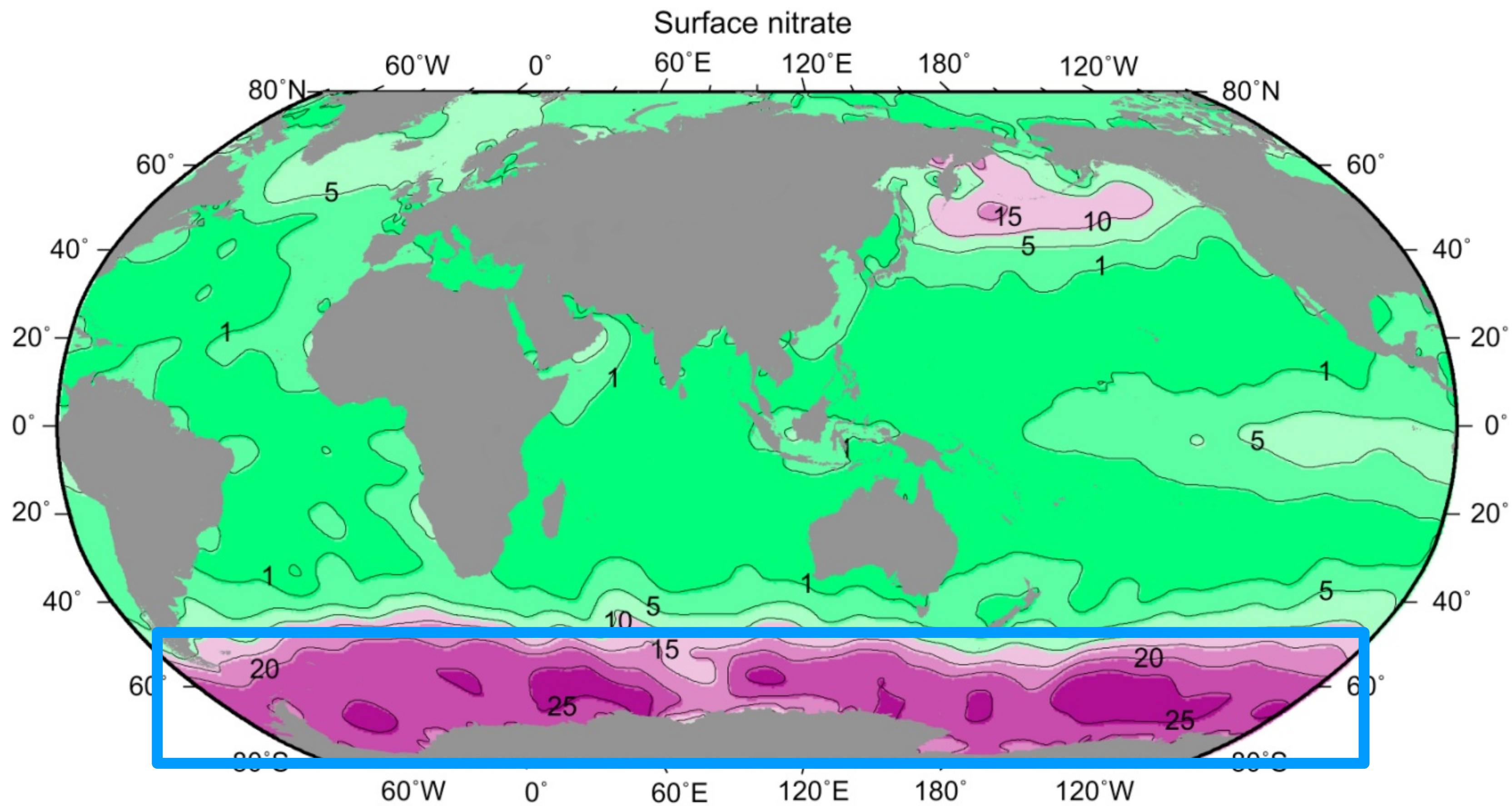
Driven by Ekman suction.



http://woceatlas.tamu.edu

(Orsi and Whitworth, 2005)

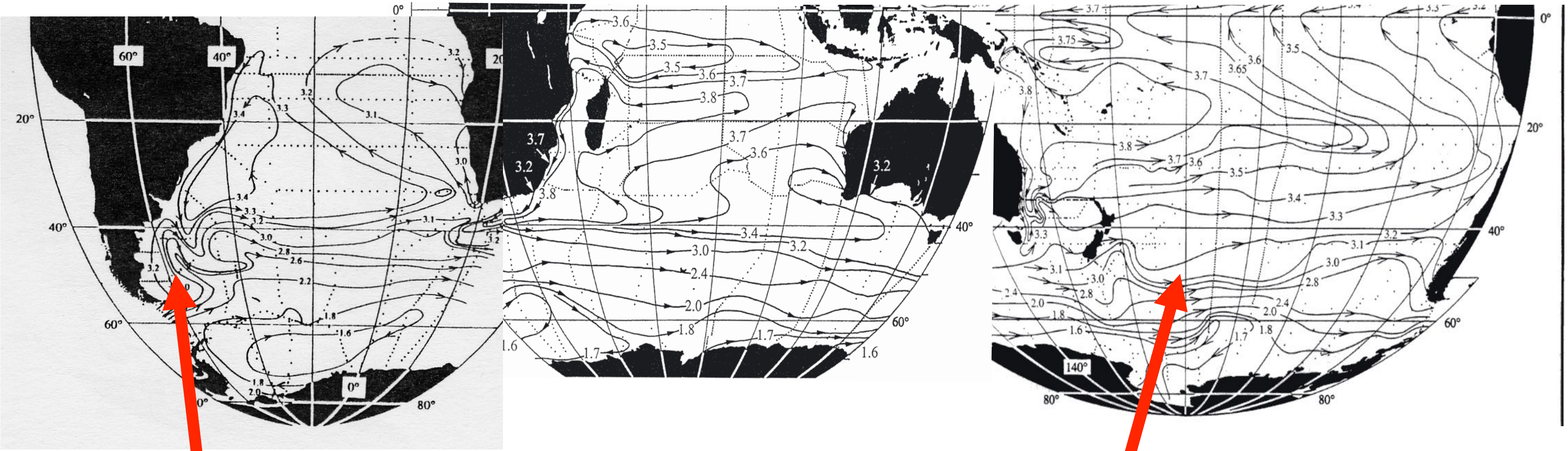
High surface nutrients due to upwelling of deep water



Nitrate (μmol/L) at the sea surface, from the climatological data set of Conkright, Levitus, and Boyer (1994).

Southern Ocean surface circulation: ACC

Asymmetry of the ACC:
- farthest north at Argentina
- farthest south entering Drake Psg from Pacific



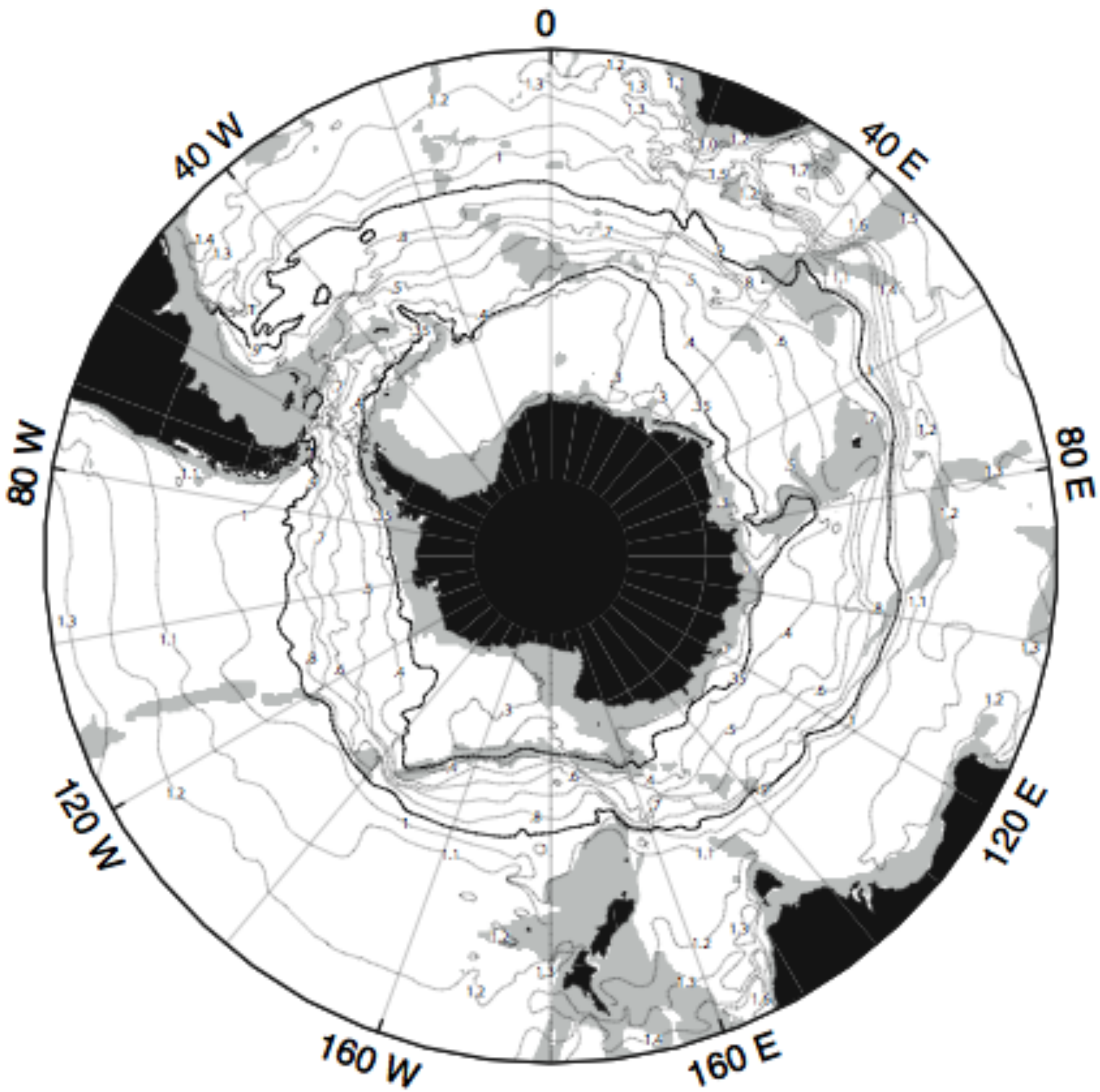
Malvinas (Falkland Current): semi-western boundary current for the ACC

(Similar effect of Campbell Plateau on ACC)

(Reid, 1994, 1997, 2003)

Antarctic Circumpolar Current

- No meridional boundary at Drake Passage latitudes
- Different dynamics from normal gyres (which have western and eastern boundaries)
- 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

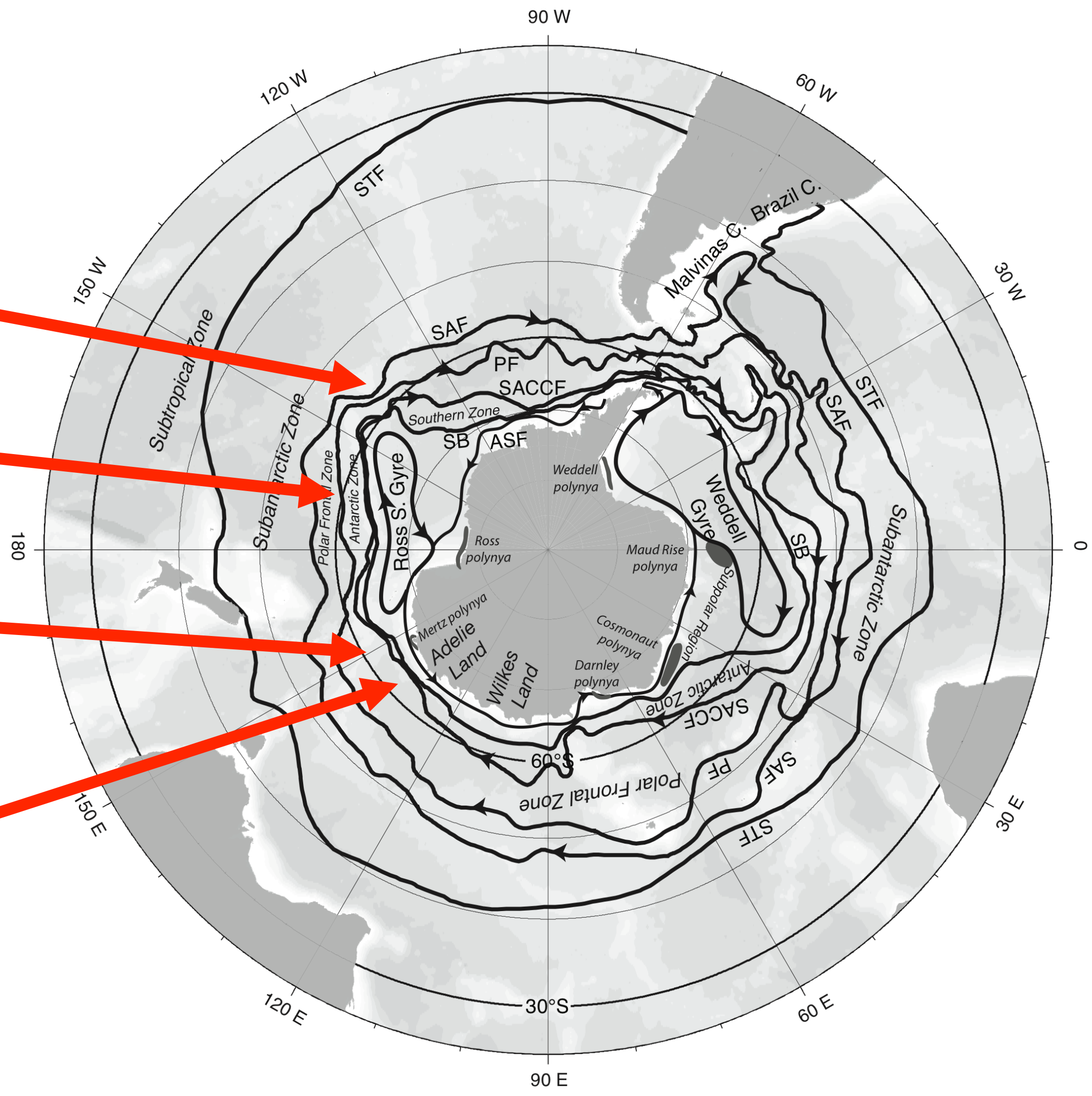
(Orsi et al., 1995)   DPO Fig. 13.8

Antarctic Circumpolar Current: banded (jet-like) structure

Fronts of the Antarctic Circumpolar Current

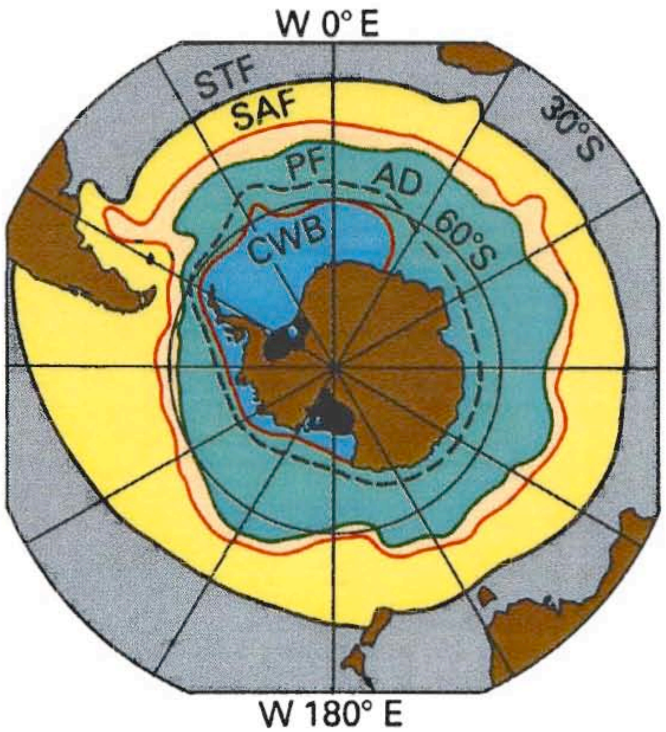
1. Subantarctic Front on north side
2. Polar Front in middle
3. Southern ACC Front to south
4. Southern Boundary or continental shelf front

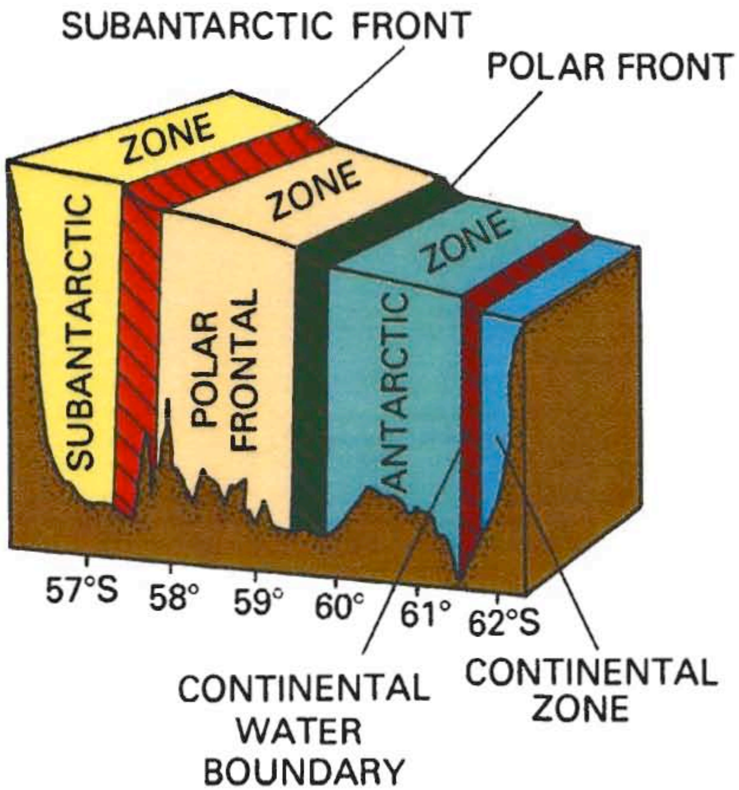
Antarctic Slope Front (westward flow along continental slope)



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

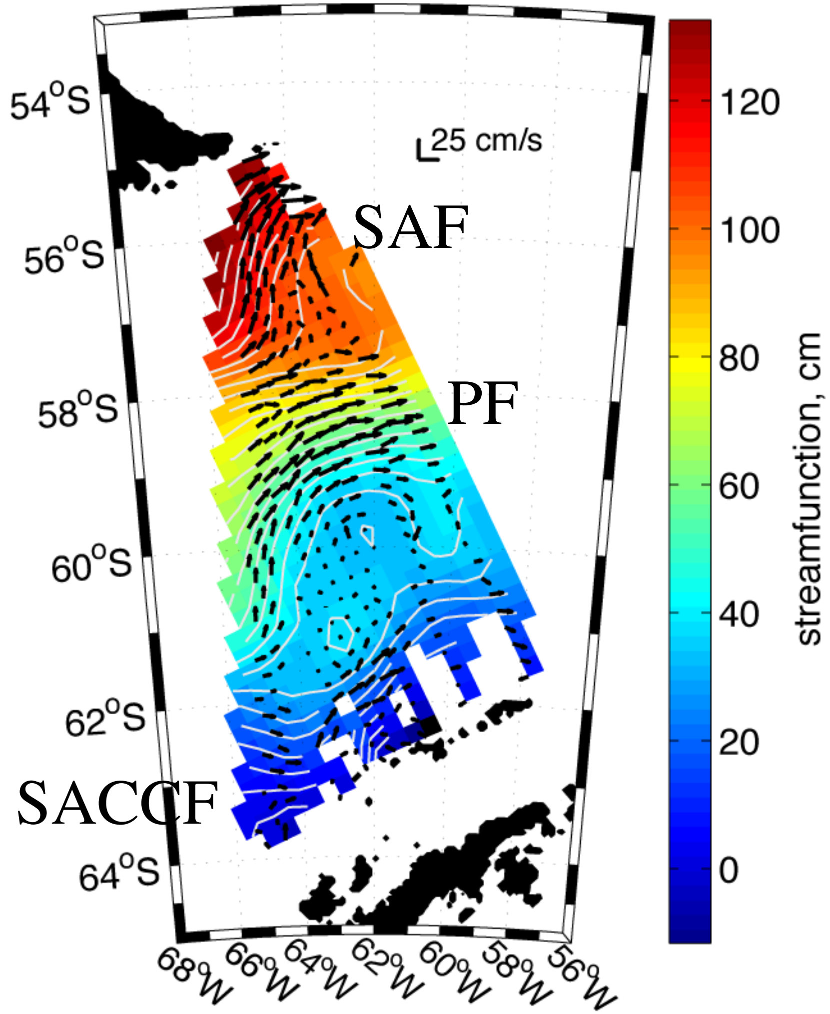
Geostrophic calculations, current meters and ADCP measurements in Drake Passage suggest:

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



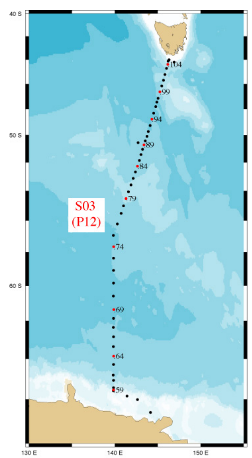
DPO Fig. 13.19

(Lenn et al., 2007)

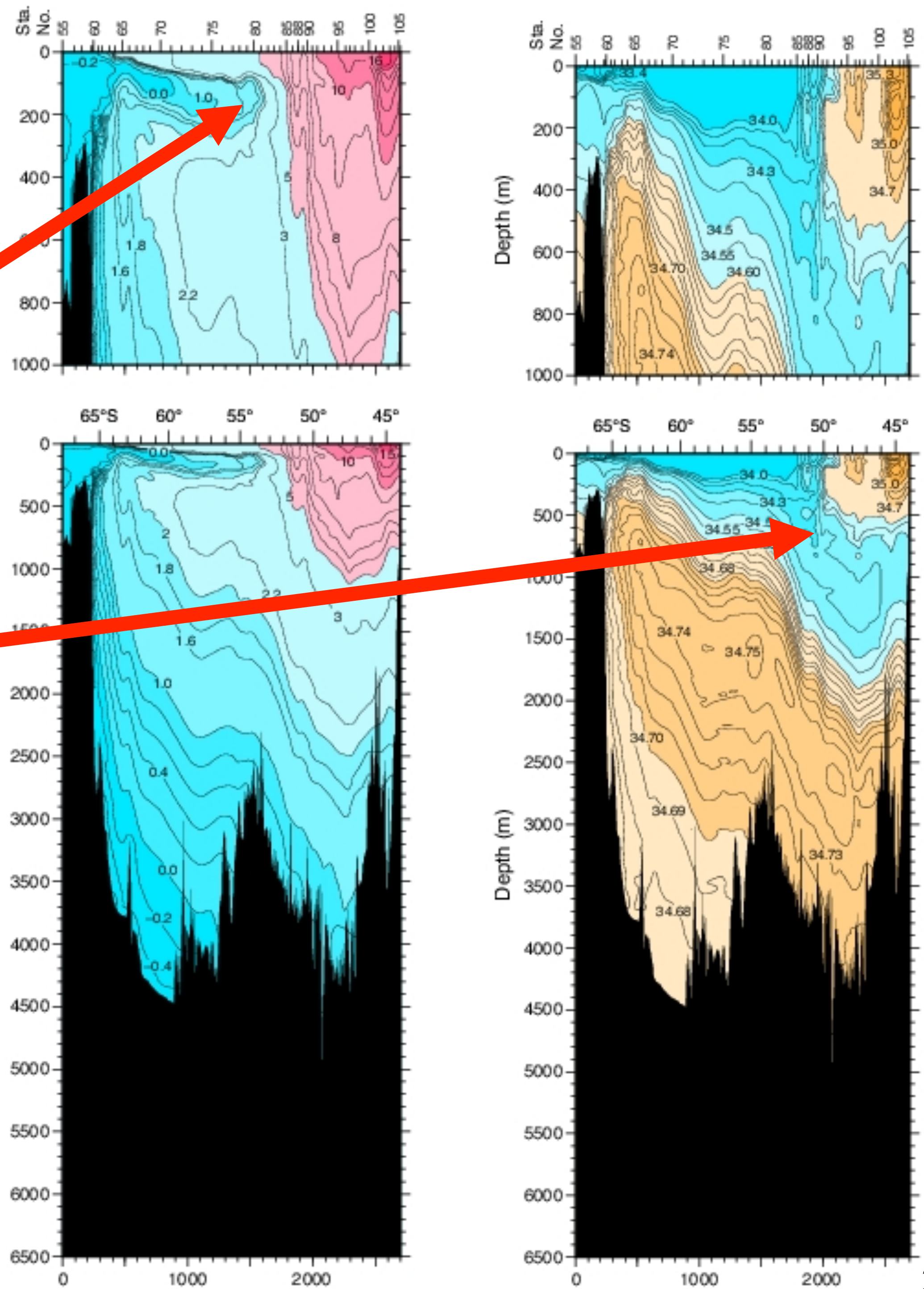
Polar and Subantarctic Fronts in temperature and salinity sections

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

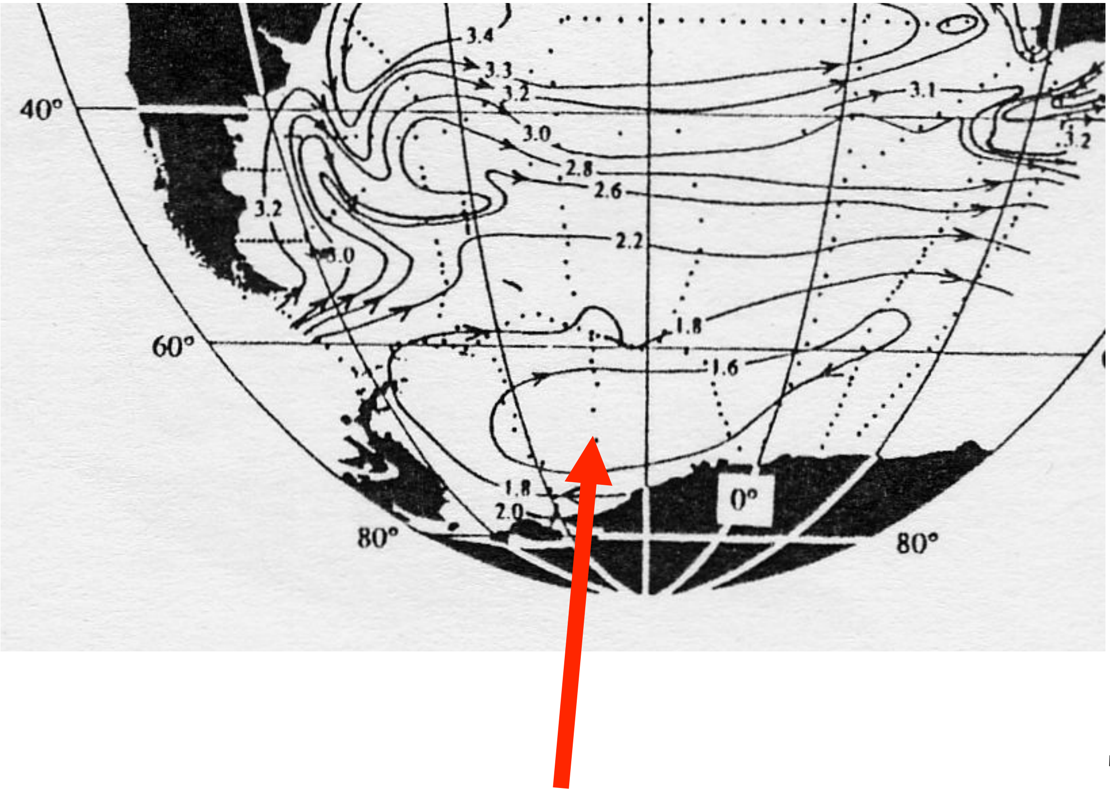
Subantarctic Front: onset of salinity minimum to north of front



Vertical section from Antarctica to Tasmania



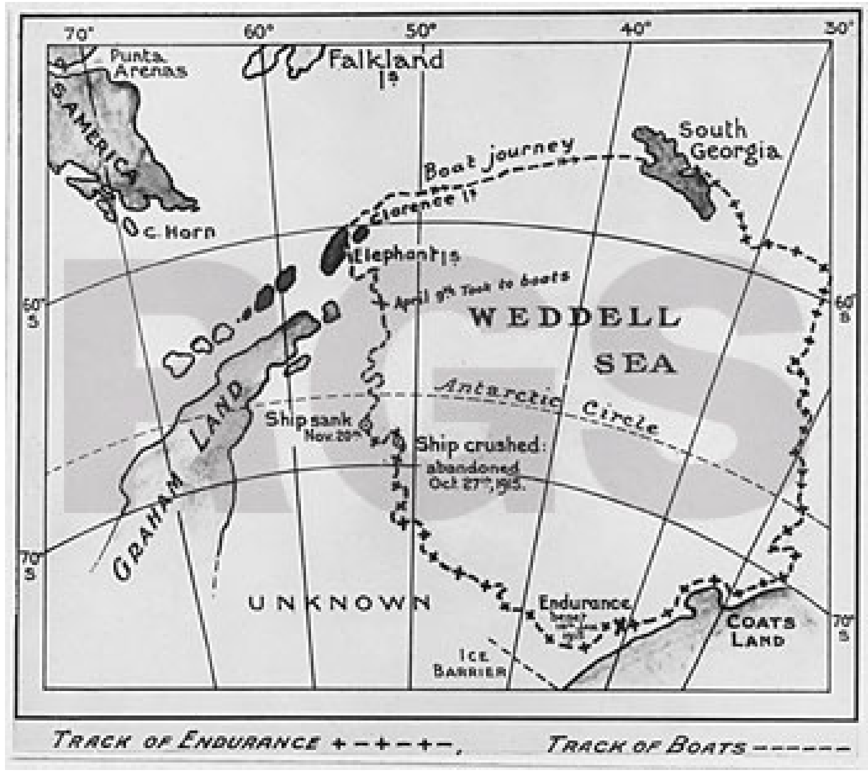
Southern Ocean surface circulation: cyclonic subpolar (polar) gyres – Weddell Sea gyre



Weddell Sea gyre

(Reid, 1994)

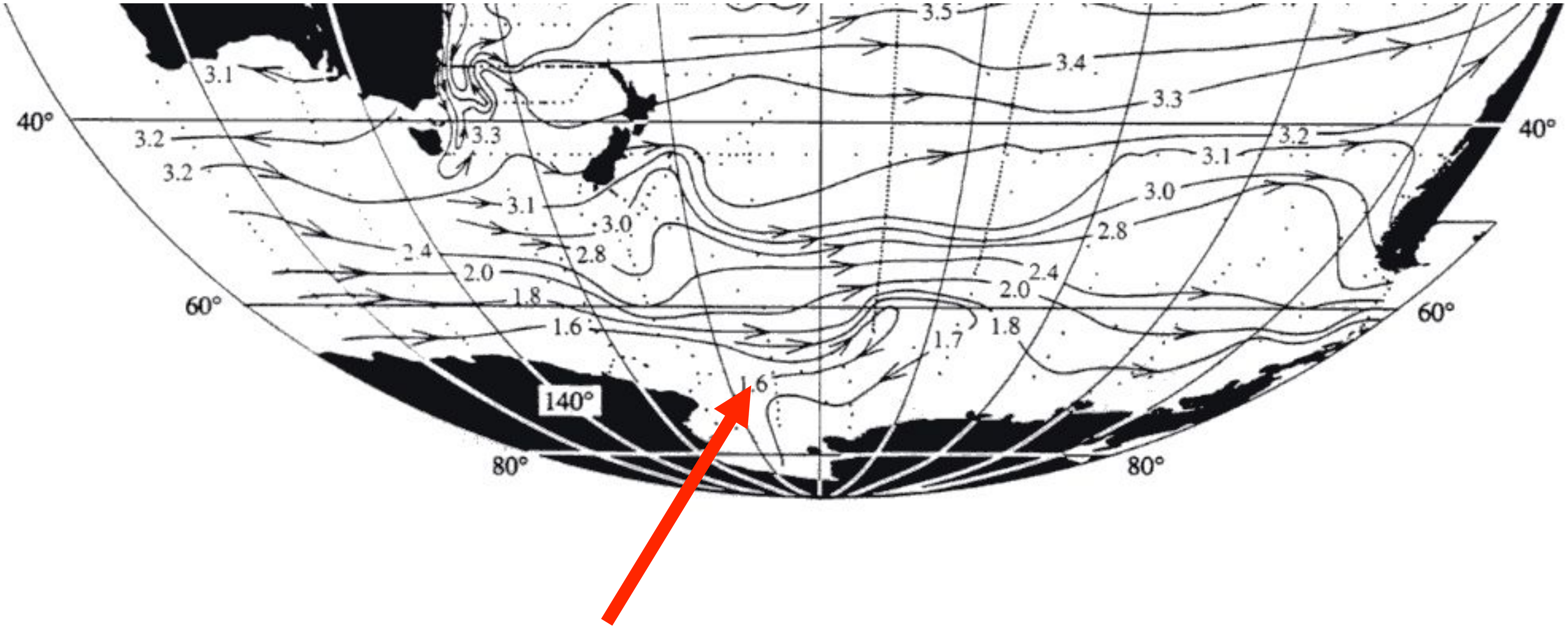
DPO Fig. 9.2a



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

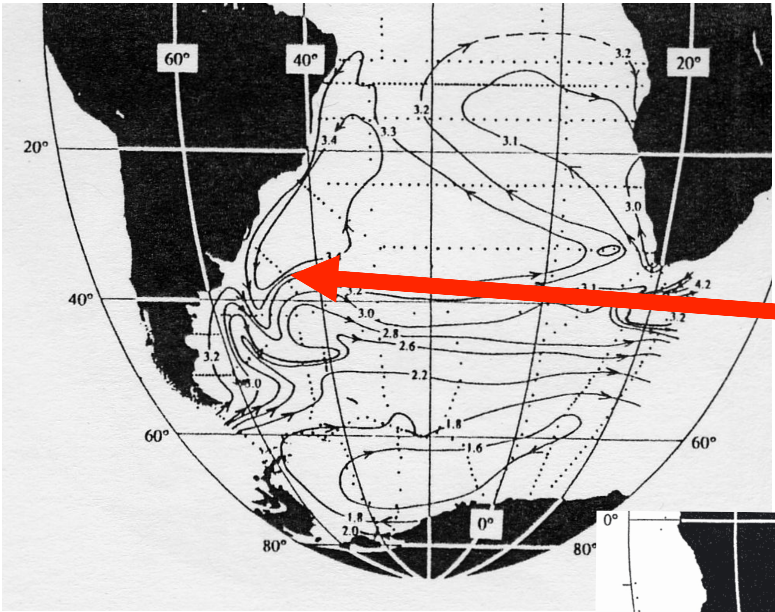
DPO Fig. 13.10

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



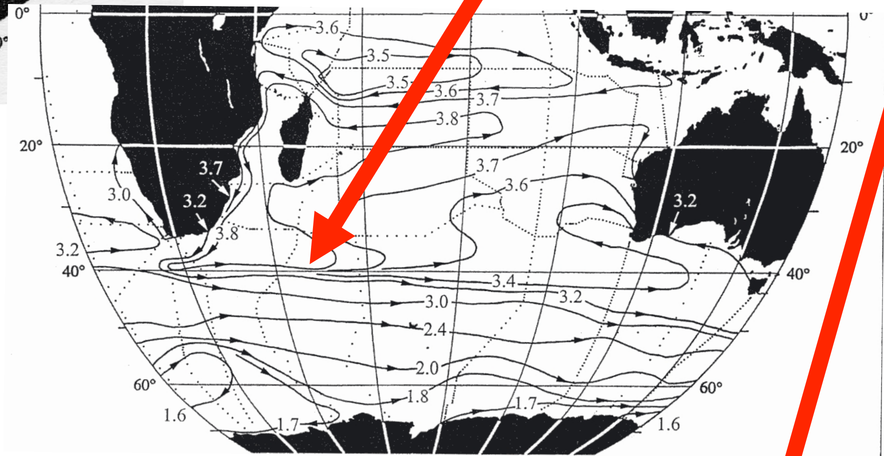
Ross Sea gyre (Reid, 1997)

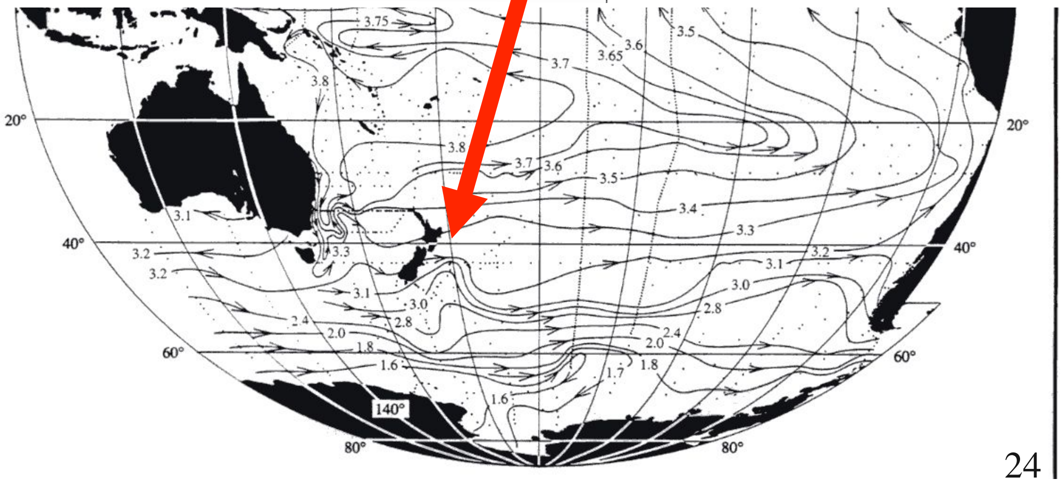
DPO Fig. 10.2a



Southern Ocean surface circulation

Connection to anticyclonic subtropical gyres

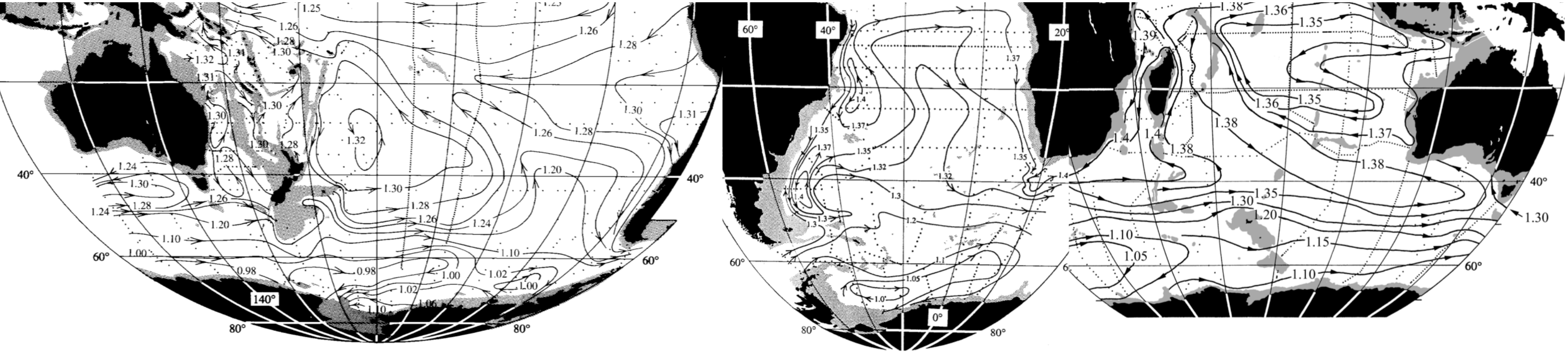




Adjusted steric height

(Reid, 1994, 1997, 2003)

Southern Ocean deep circulation



2000 dbar

At 2000 dbar:

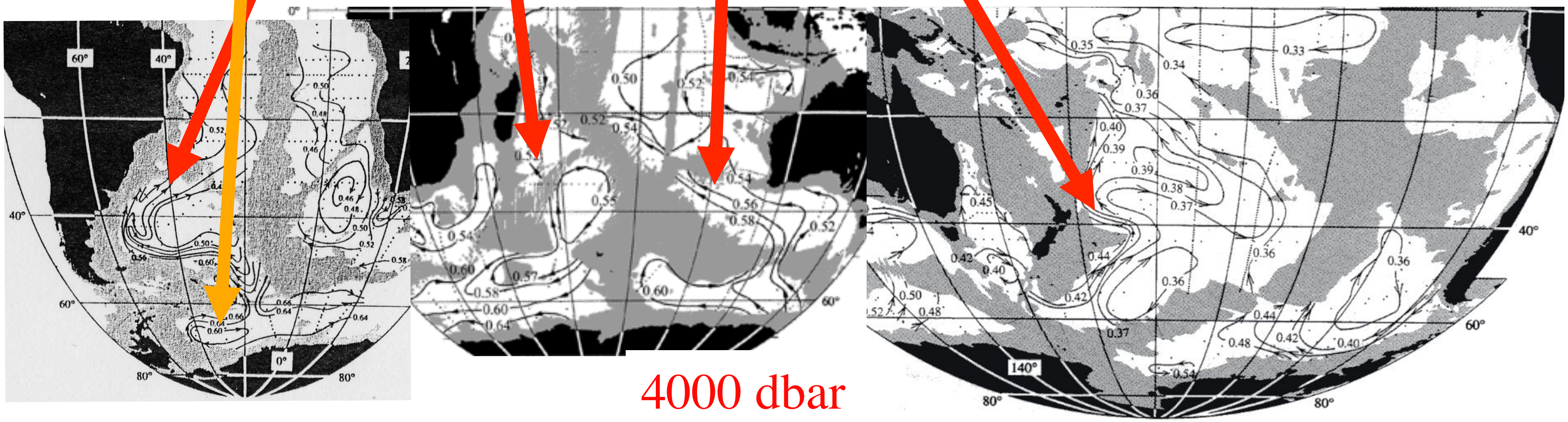
- very similar direction as surface circulation (ACC, Weddell and Ross Sea gyres)
  "equivalent barotropic": "barotropic" = same top to bottom; "equivalent" means there's vertical shear but flow is in same direction at all depths
- weaker currents

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

Southern Ocean abyssal circulation

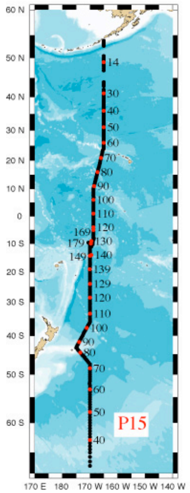
At 4000 dbar:

- 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)

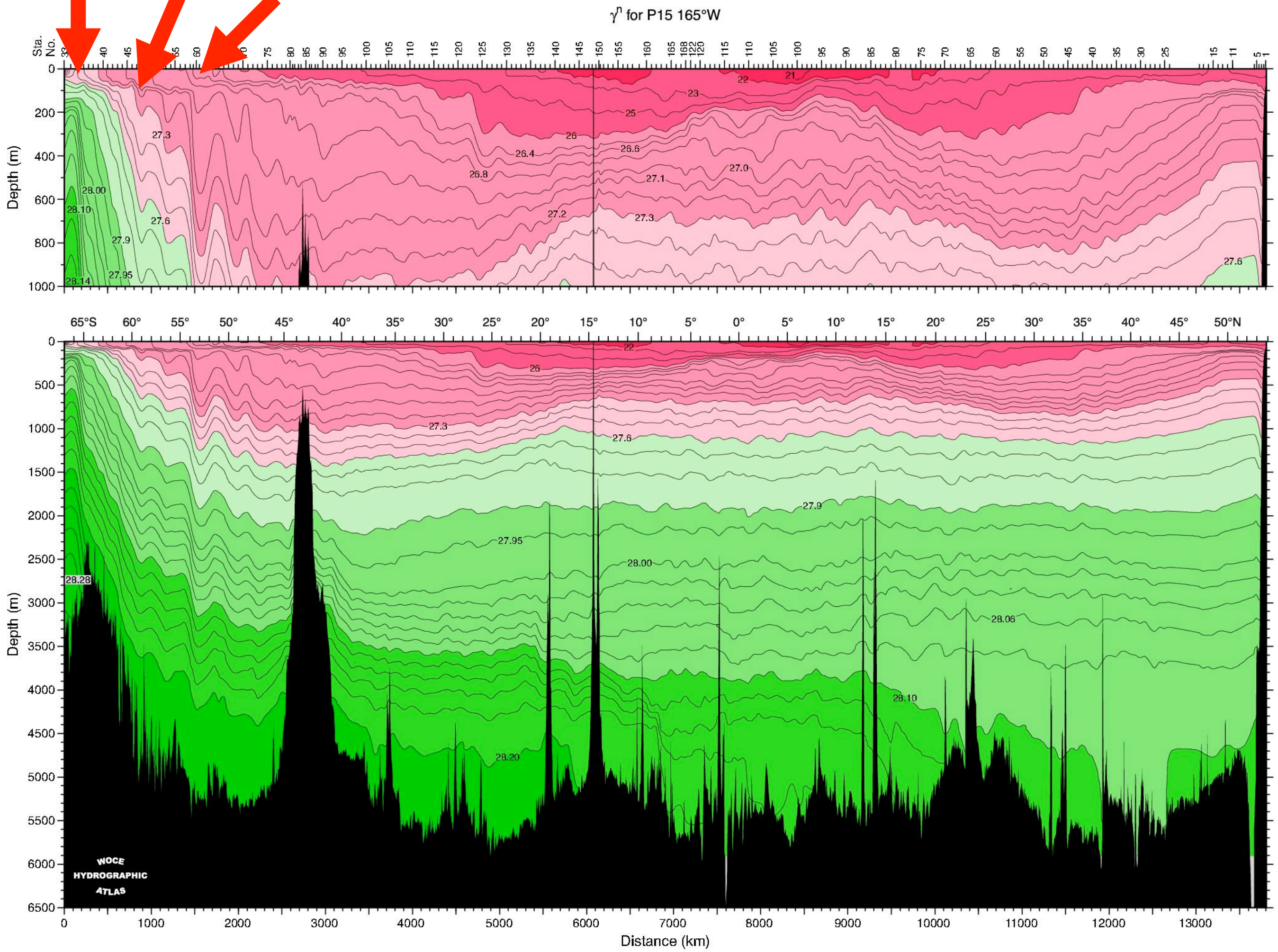
DPO Fig. 14.4b



Geostrophic flow of ACC: (Pacific)

Antarctic Circumpolar Current

SACCF PF SAF (locations determined from theta and salinity)



Geostrophic calculation: sloping isopycnals indicate 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

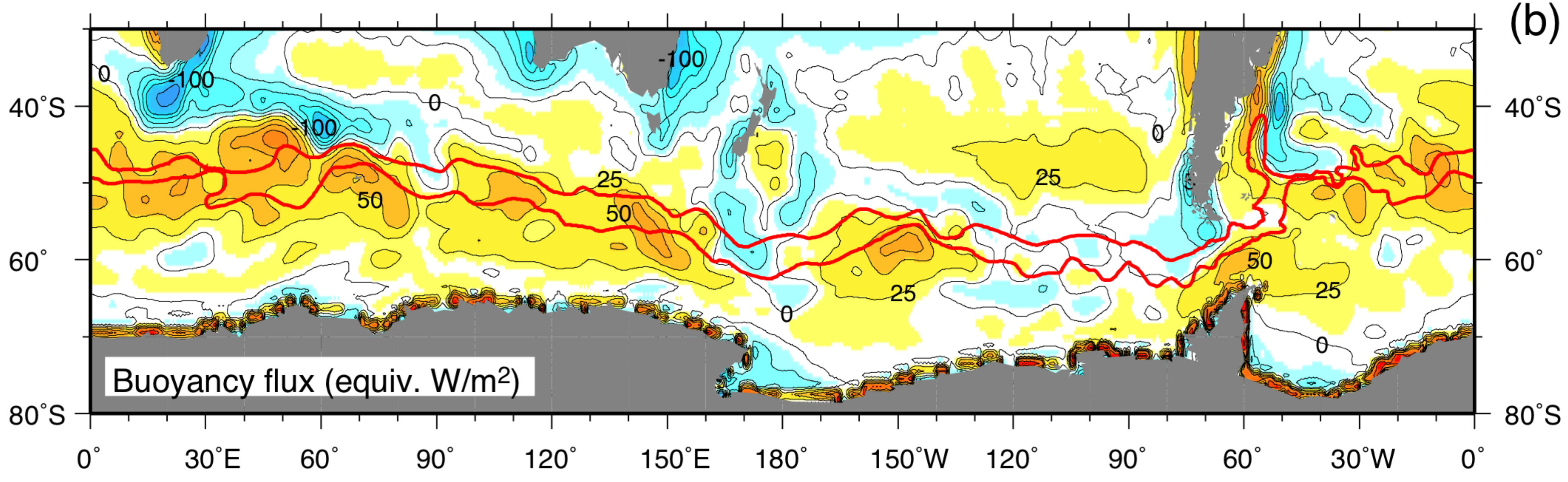
Major processes

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

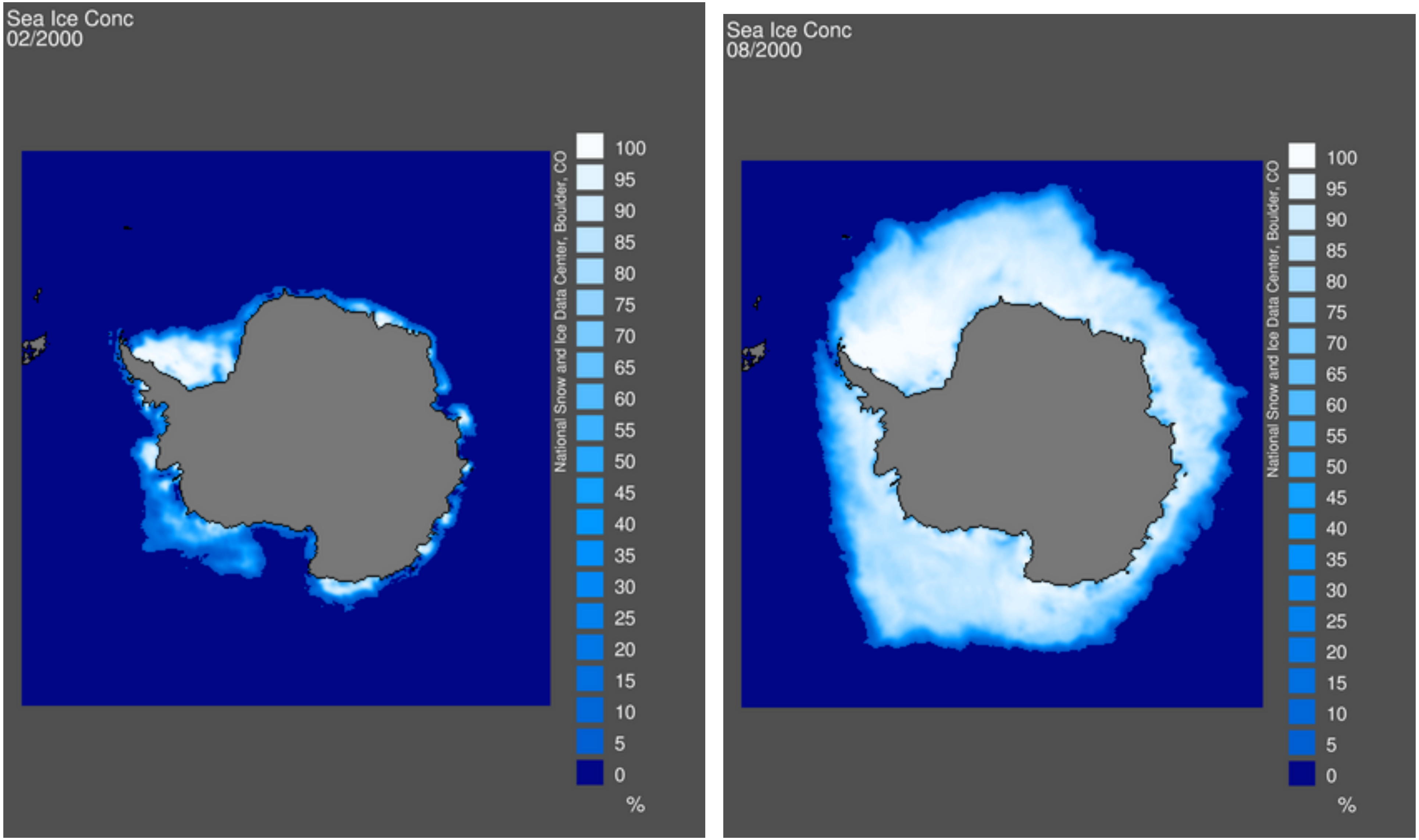
Southern Ocean buoyancy flux



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

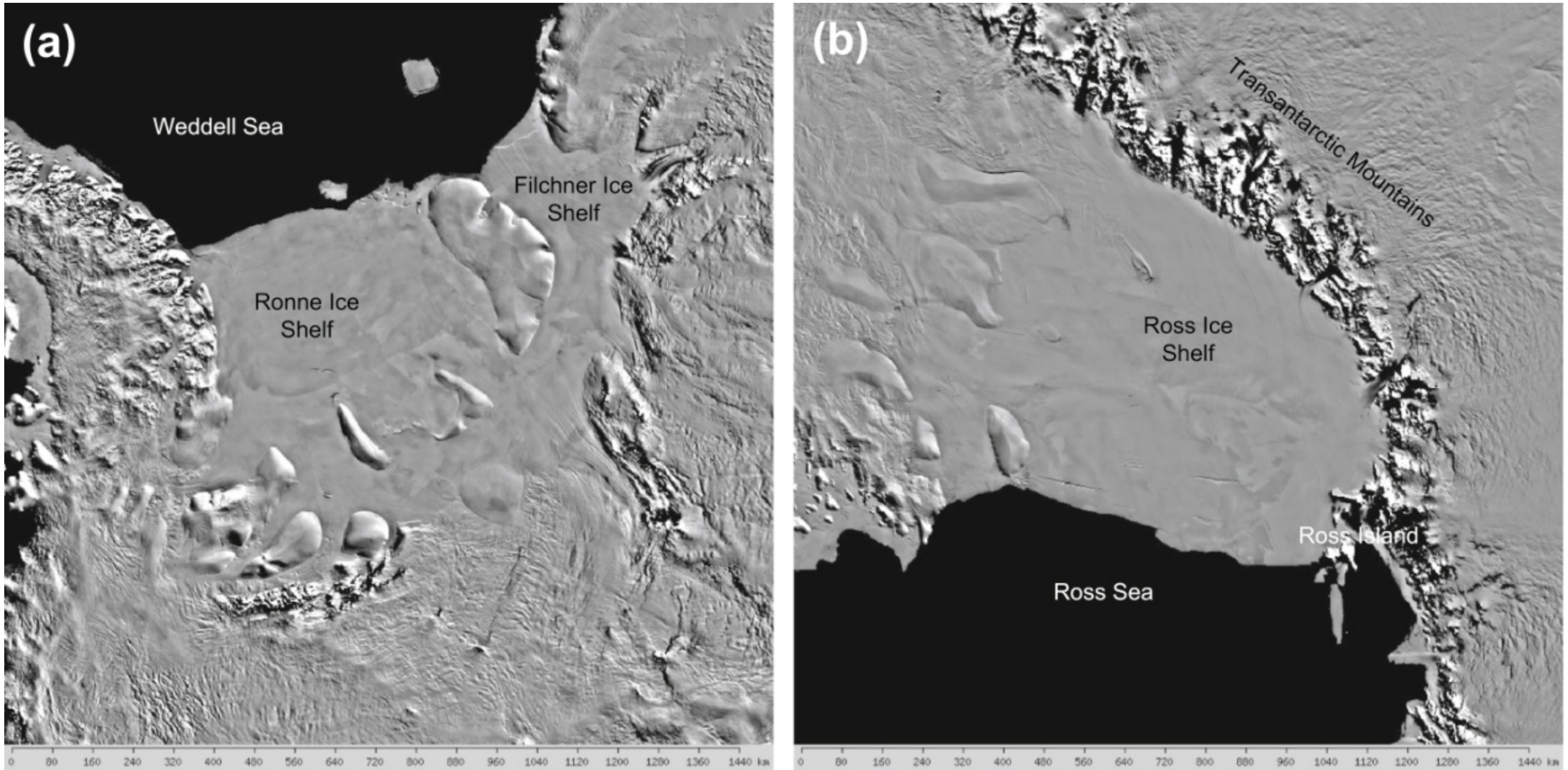
DPO Fig. 13.2b

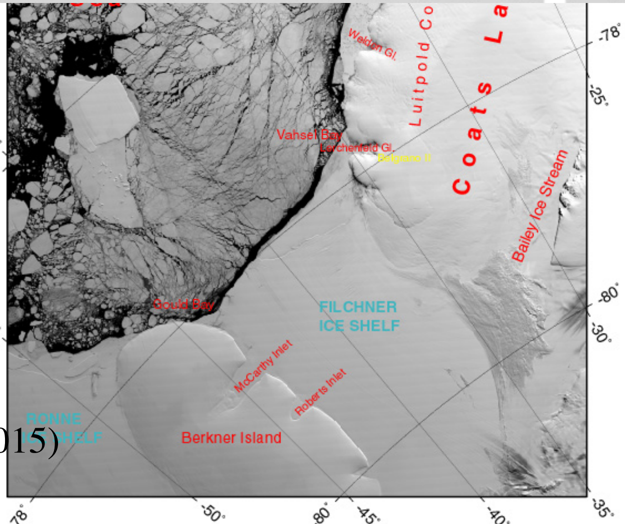
Antarctic ice distribution: sea ice concentration



After DPO Fig. 13.19

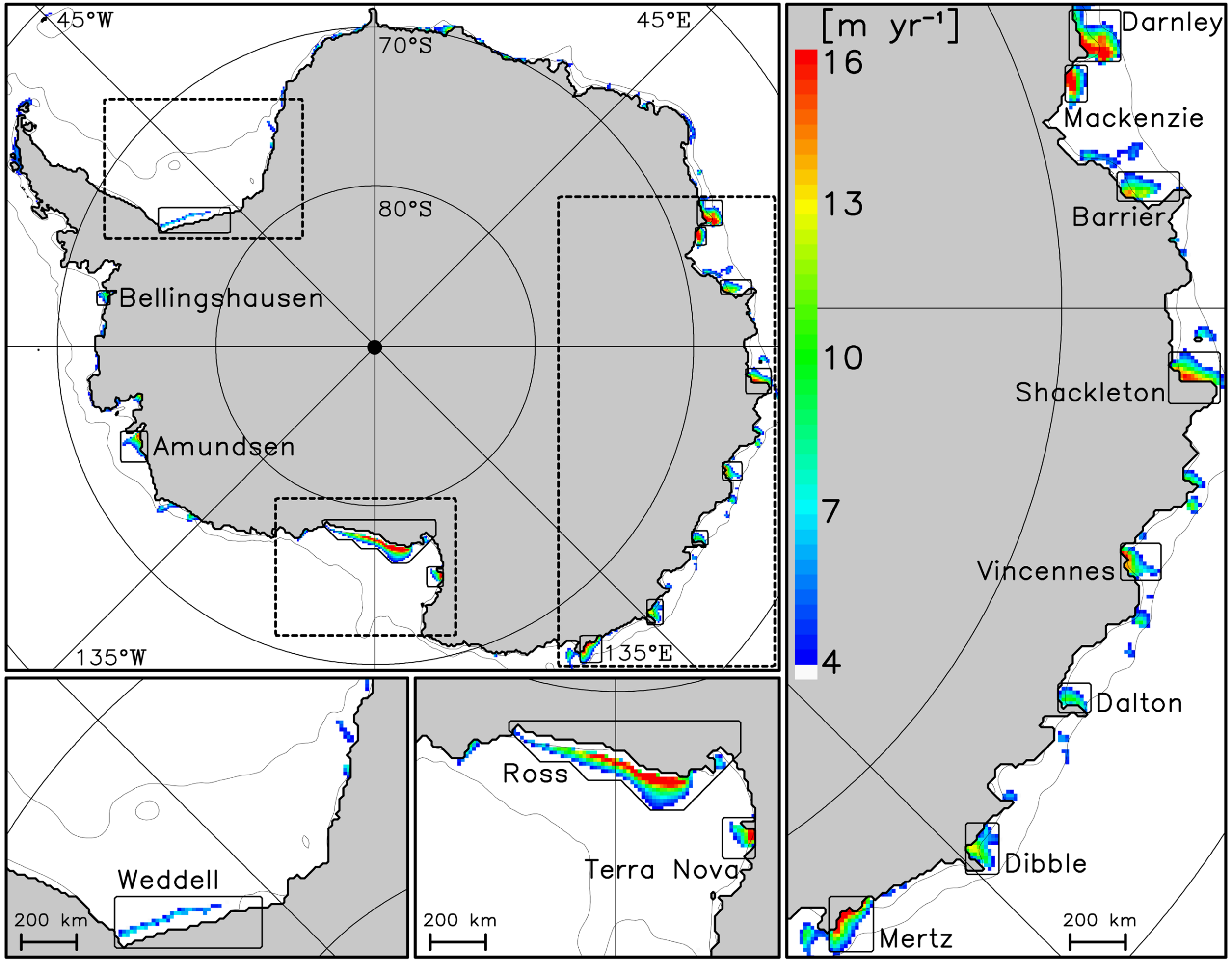
Antarctic ice shelves





Open areas (black) are polynyas and leads. Coastal polynyas especially can lead to large ice and brine production.

Antarctic polynyas

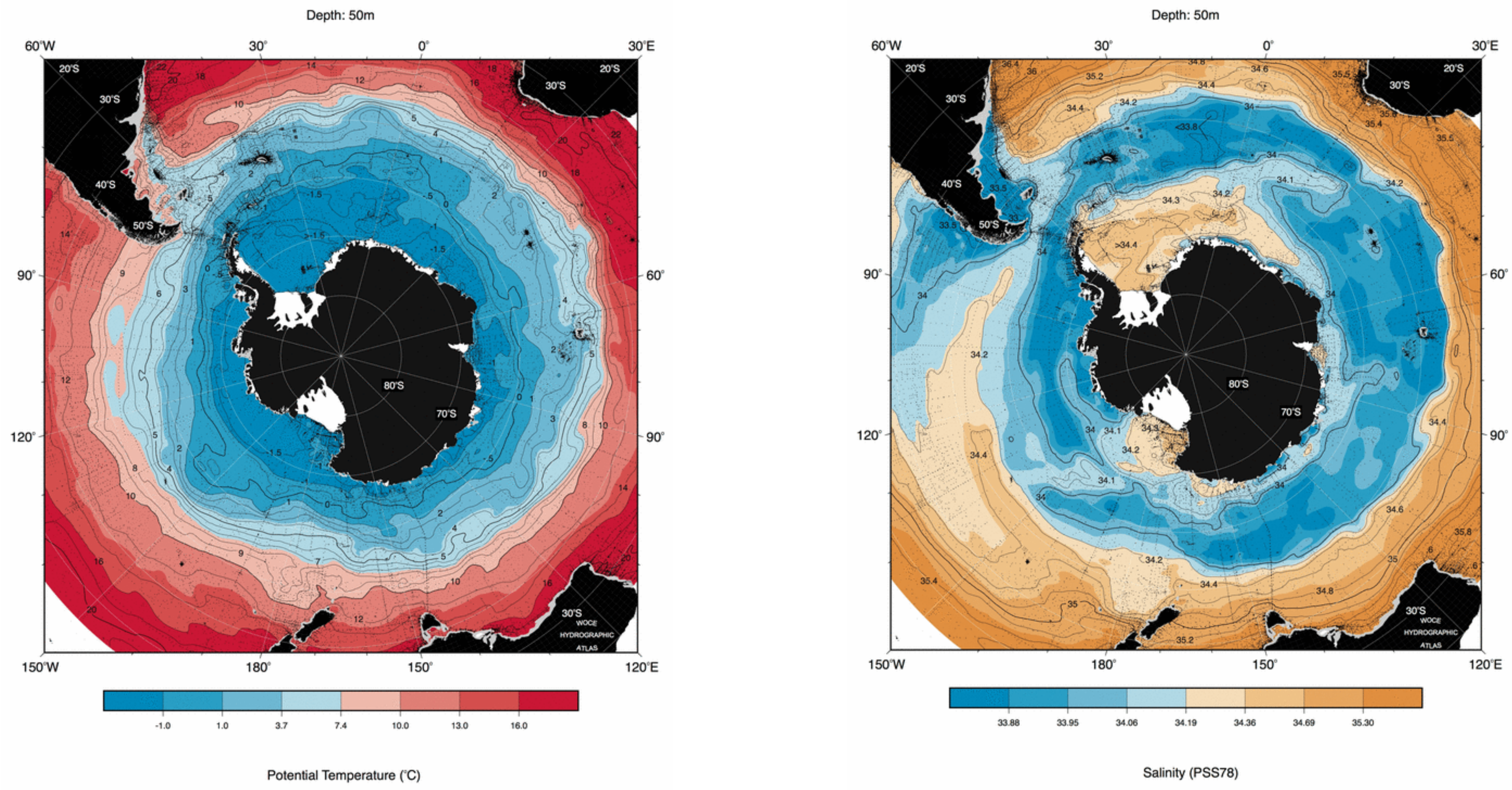


Coastal polynyas: regions characterized by high winds, open water, and large heat fluxes, hence major brine rejection sources.

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

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

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)

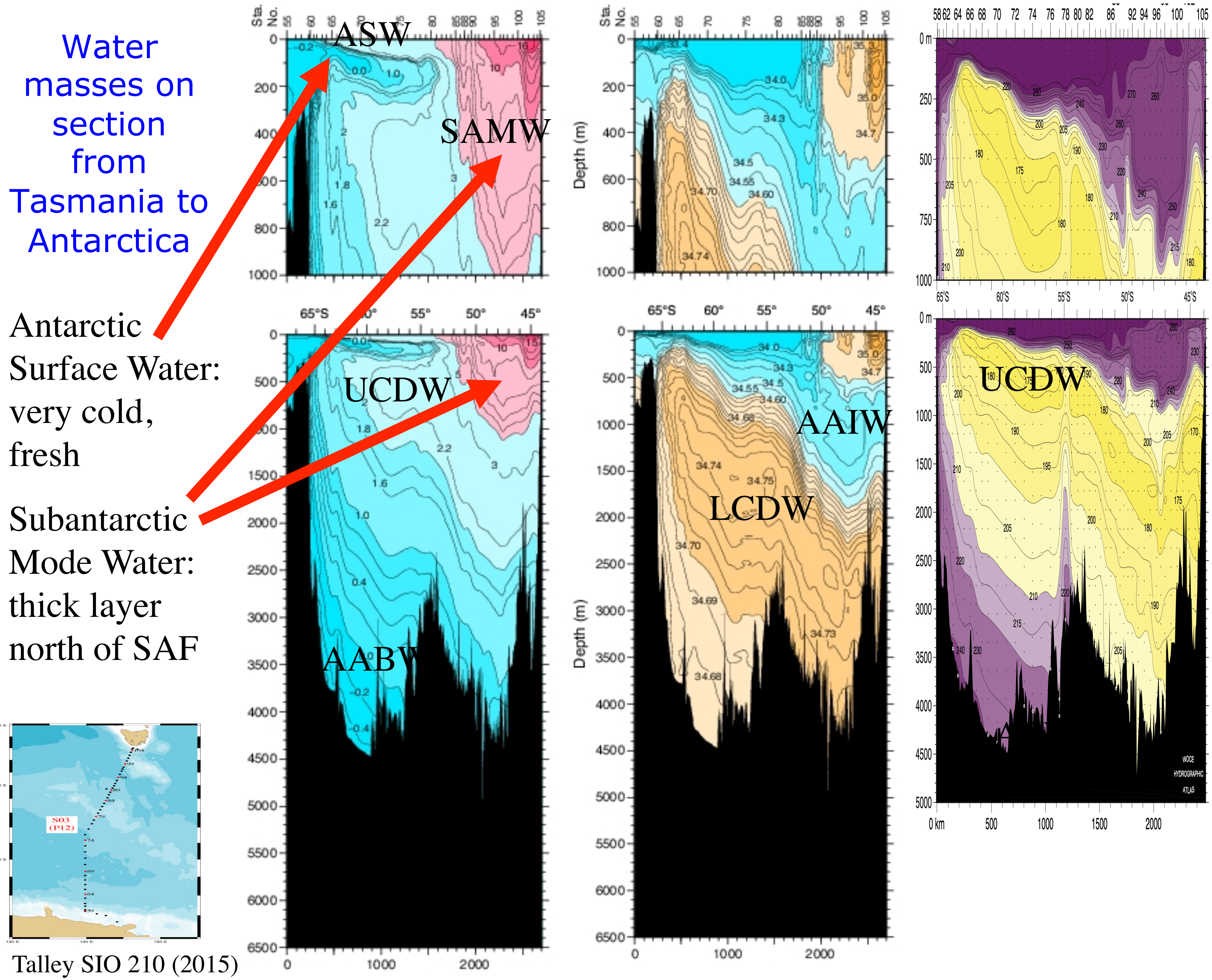
Antarctic Bottom Waters:

brine rejection in coastal polynyas and leads in ice

Water masses on section from Tasmania to Antarctica

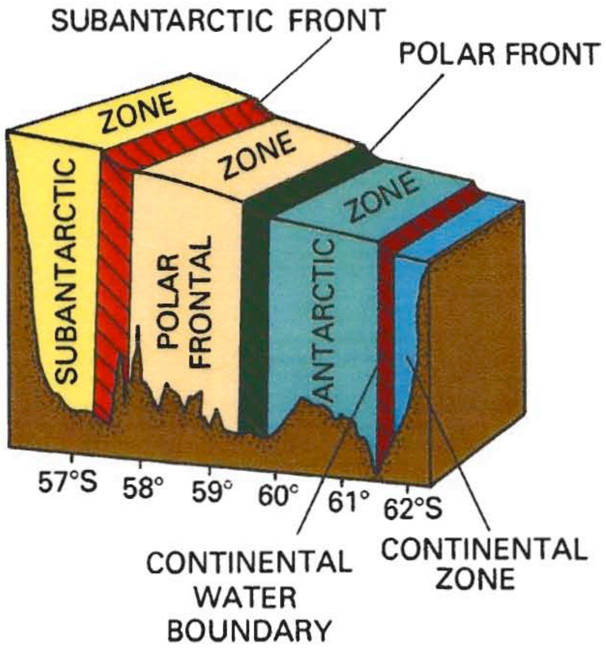
Antarctic Surface Water: very cold, fresh

Subantarctic Mode Water: thick layer north of SAF

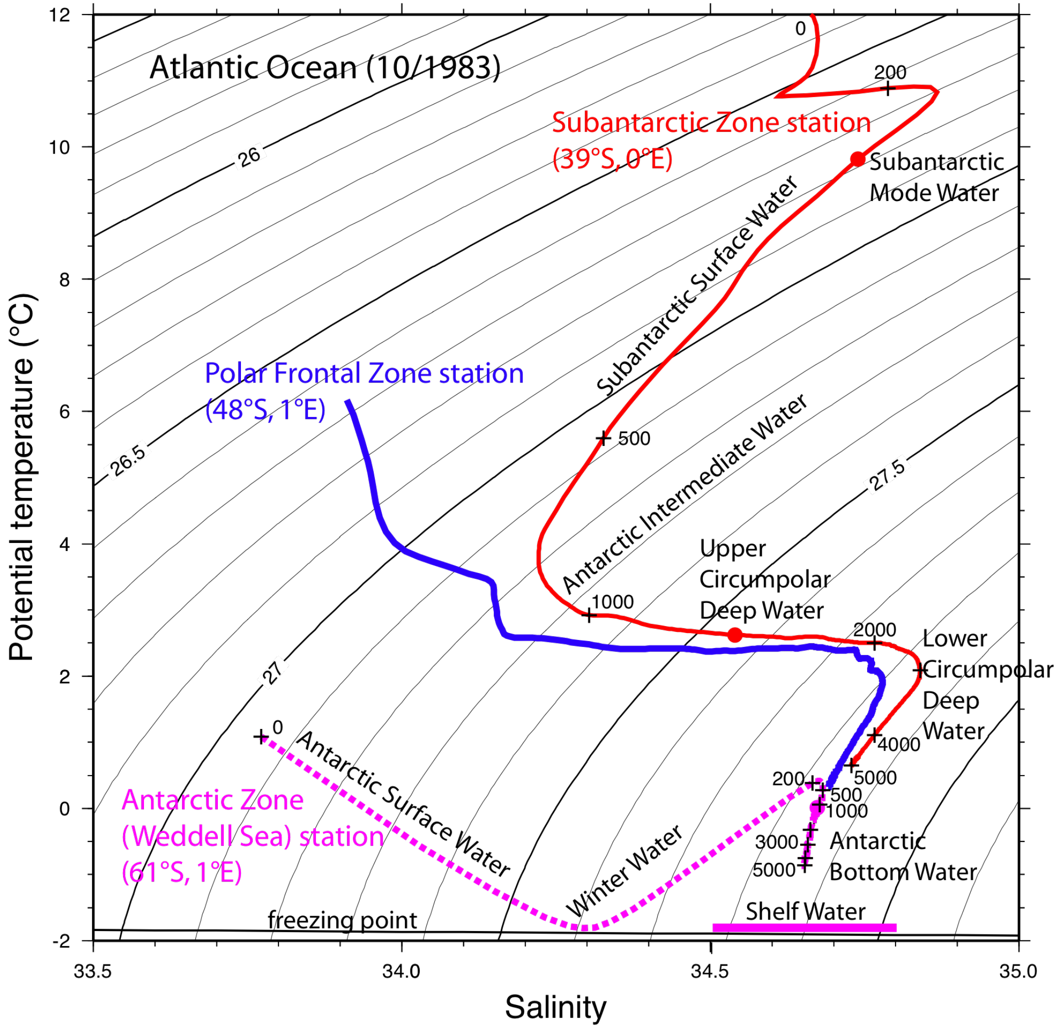


Talley SIO 210 (2015)

Potential temperature - salinity profiles in ACC

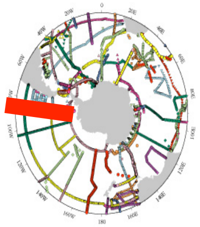


Tomczak and Godfrey Chap. 6



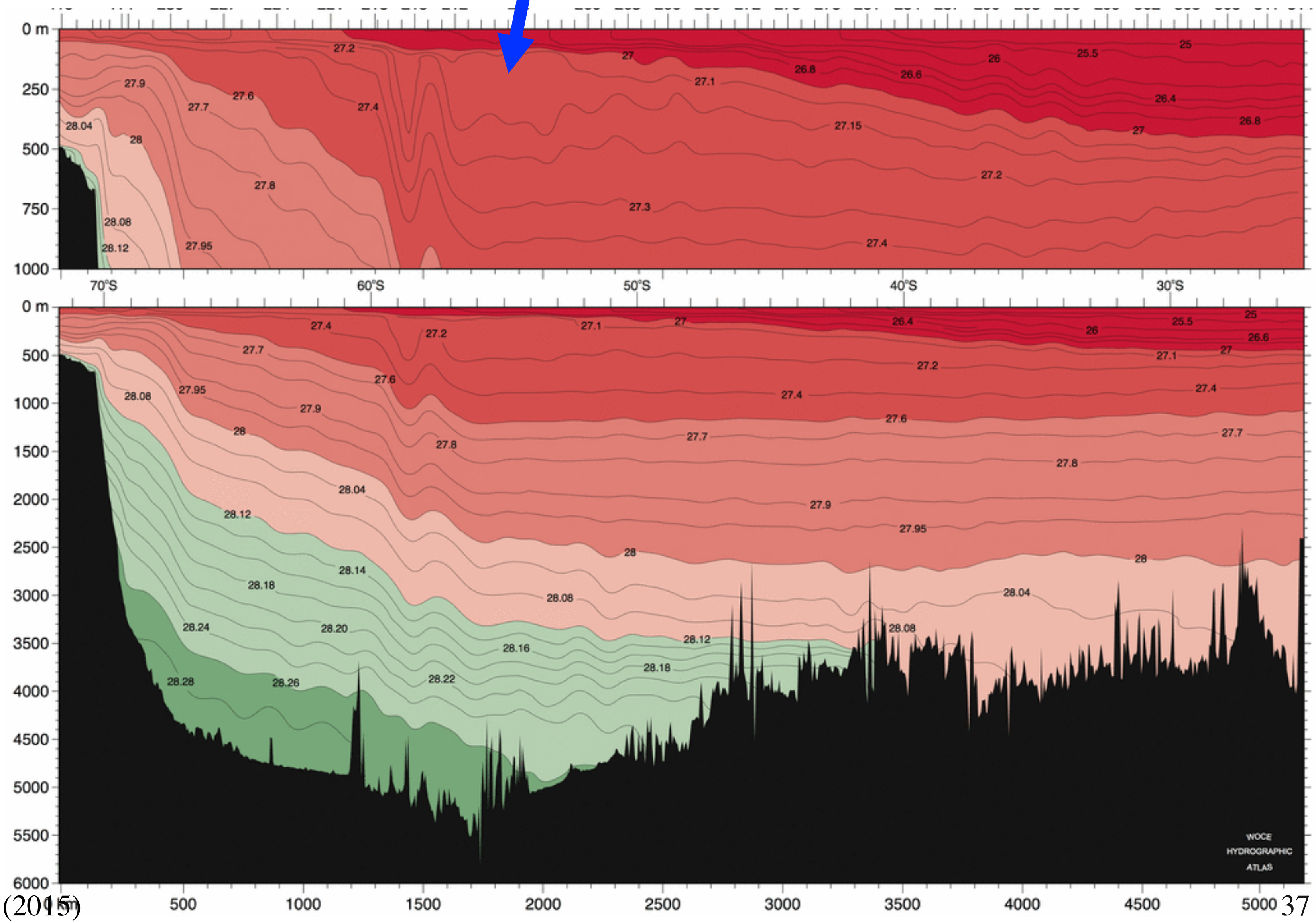
DPO Fig. 13.13

Subantarctic Mode Water: identification

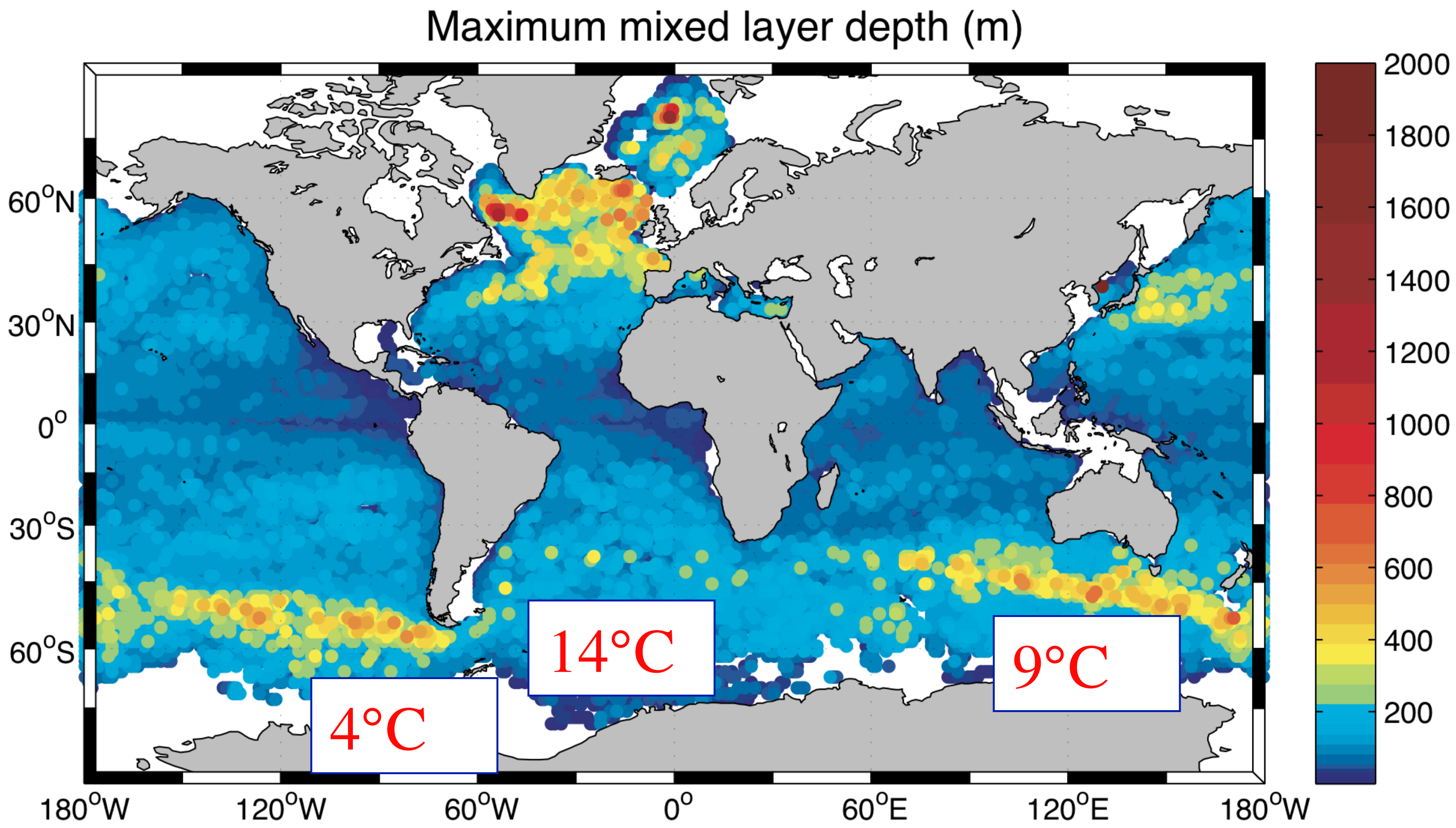


http://
woceatlas
.tamu.edu

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.

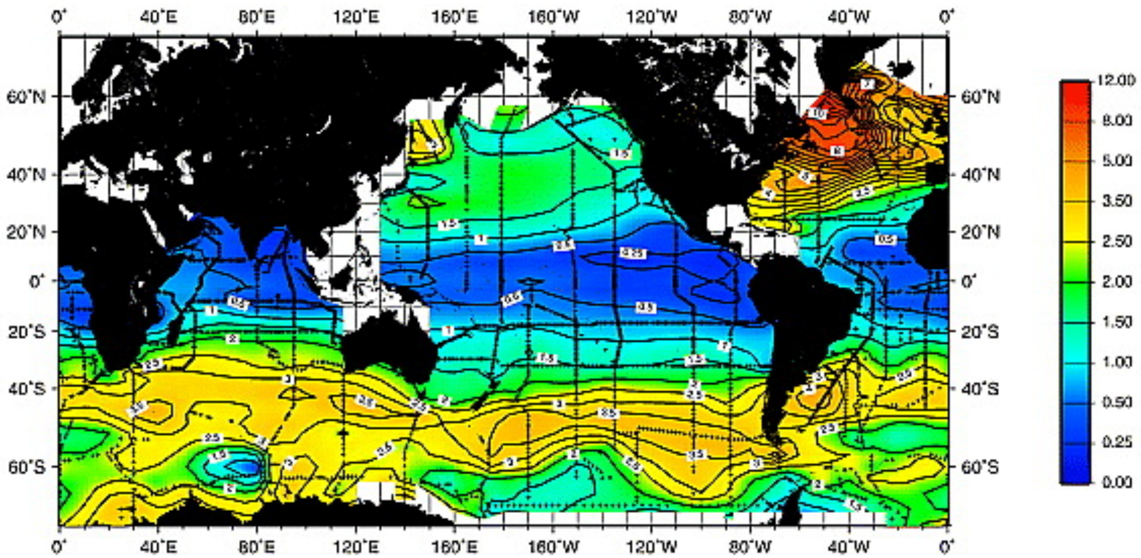
Just north of Subantarctic Front.

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

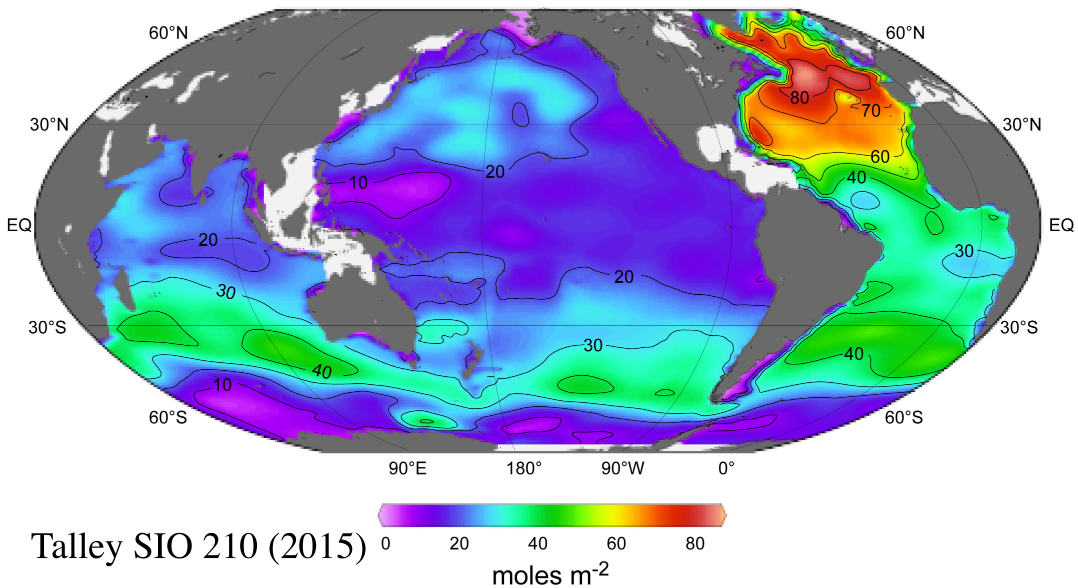
Holte et al (2010) DPO Fig. 4.4c

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

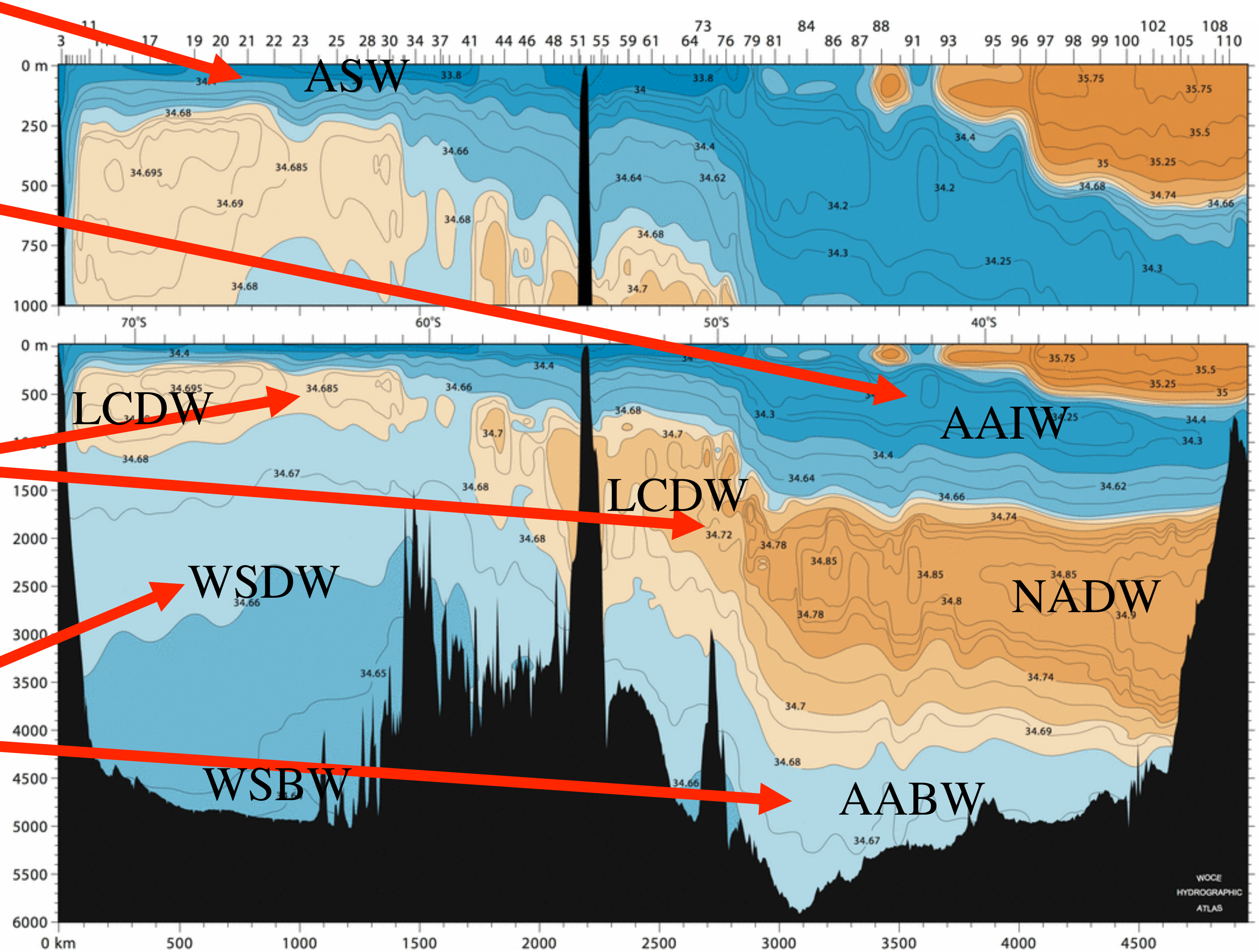
Salinity section at 20W (Atlantic): water masses

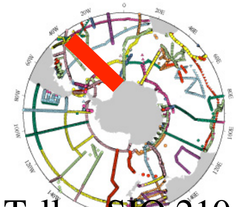
Antarctic Surface Water

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)



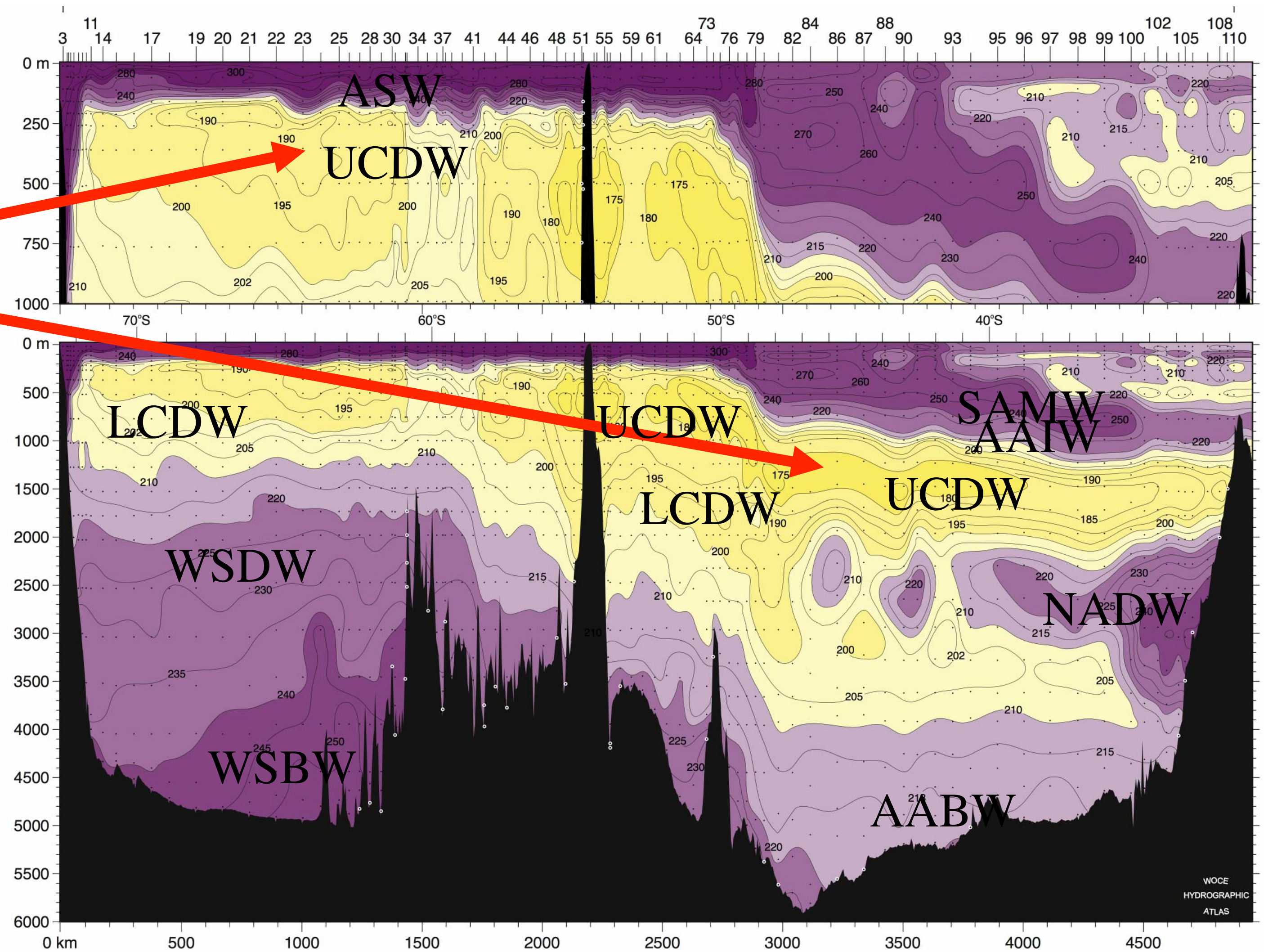


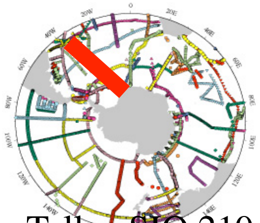
http://woceatlas.tamu.edu

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)





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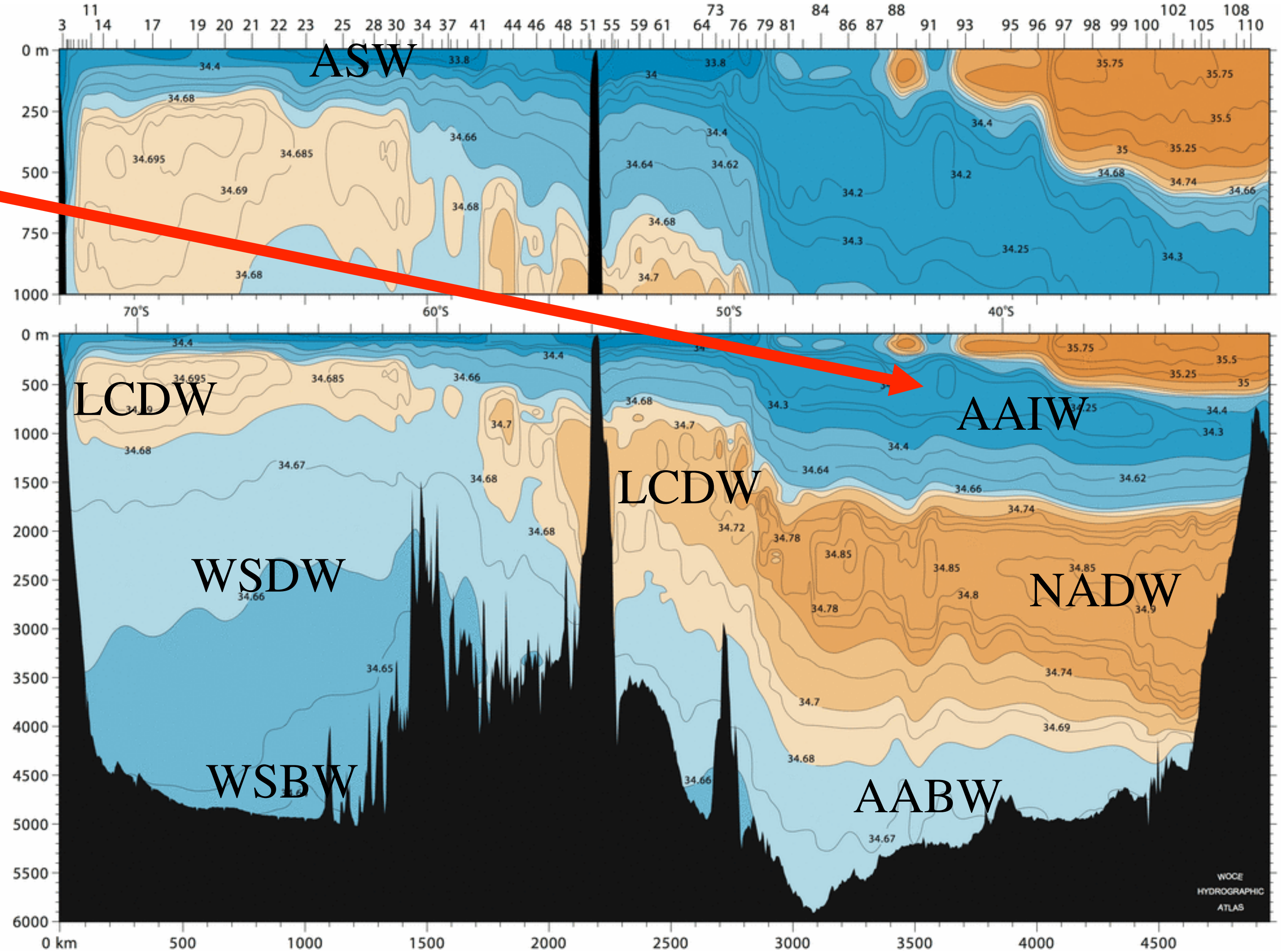
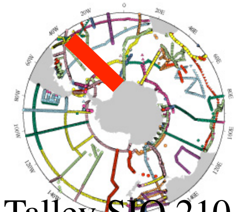
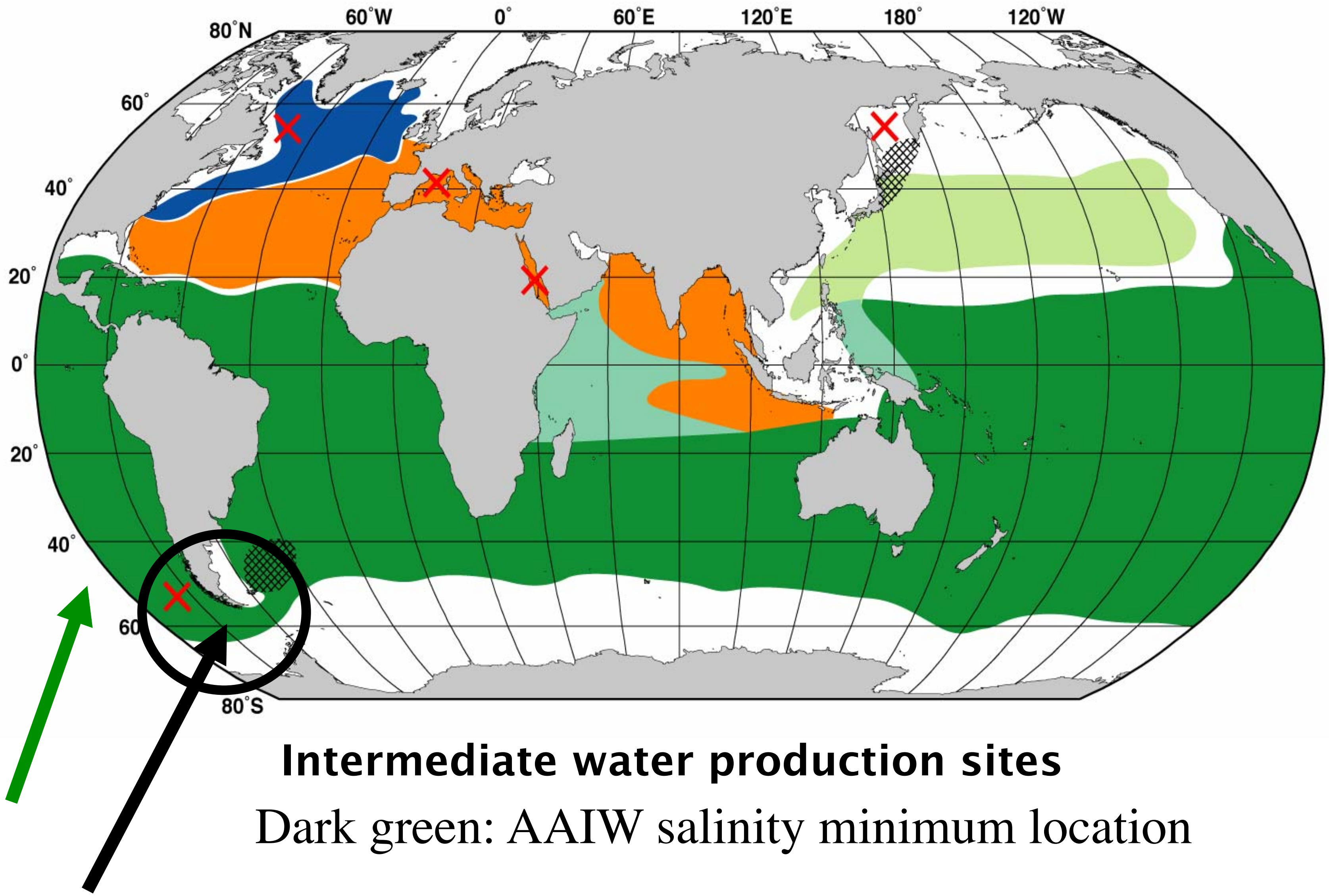
Salinity section at 20W (Atlantic): water masses

Antarctic Intermediate Water (salinity minimum north of SAF in all oceans)





Antarctic Intermediate Water: source as densest, freshest SAMW?



Intermediate water production sites

Dark green: AAIW salinity minimum location

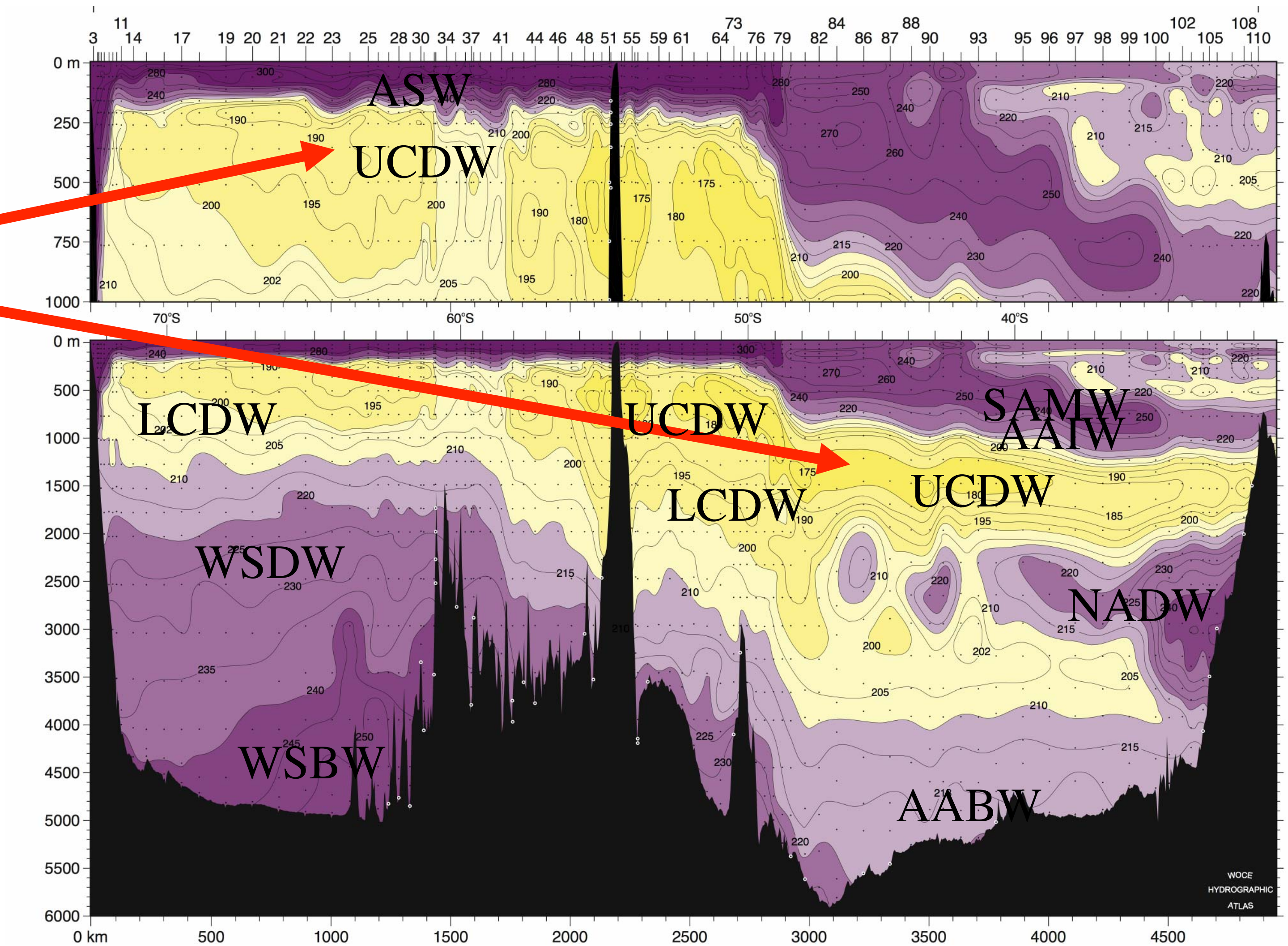
Formation site: west, in, east of Drake Passage

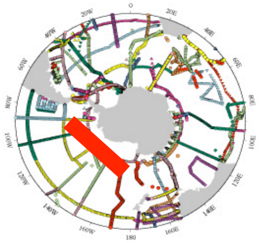
Talley SIO 210 (2015)

Upper Circumpolar Deep Water

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

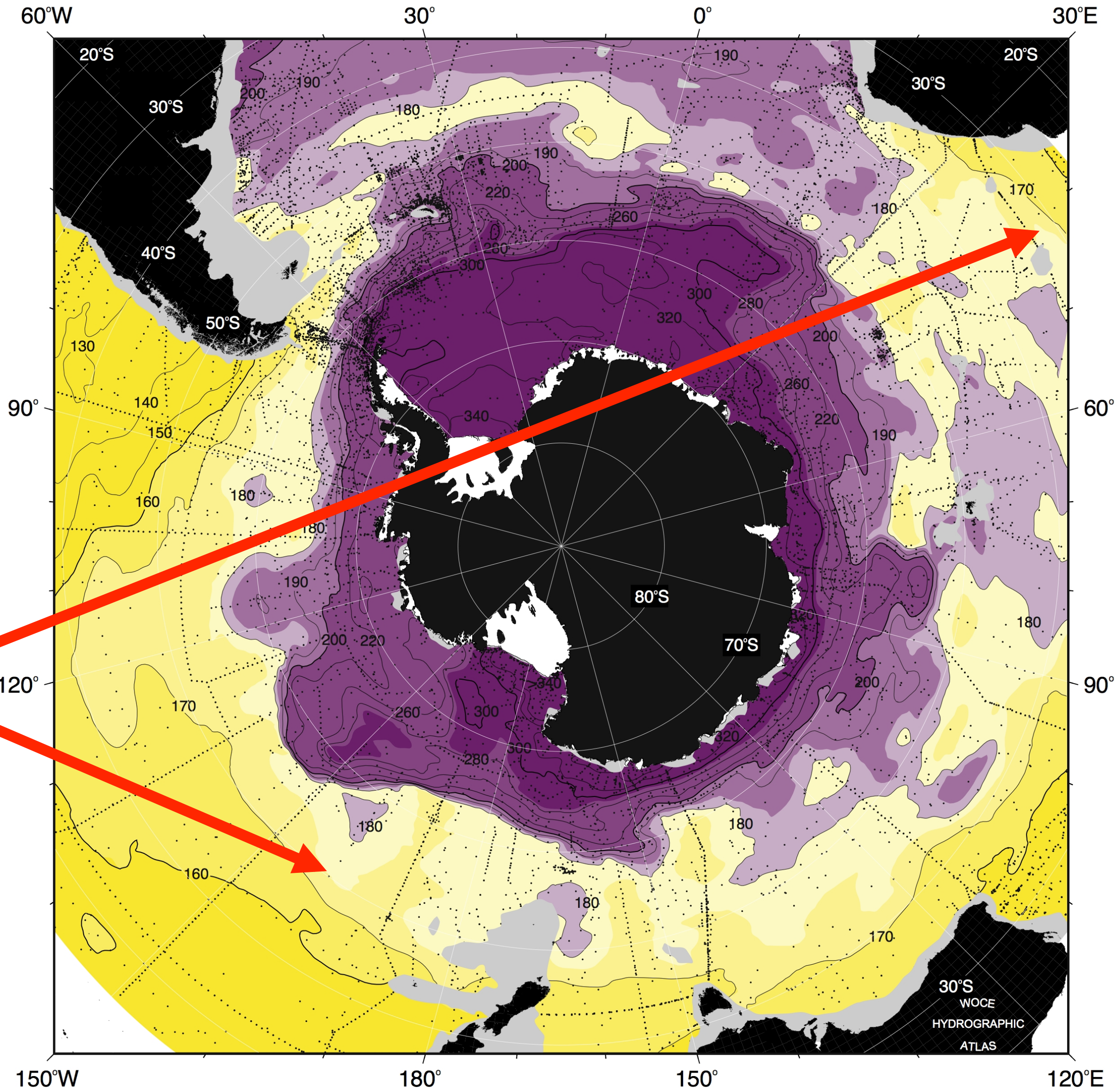
Oxygen at

neutral density 27.84

Low oxygen from IDW, PDW

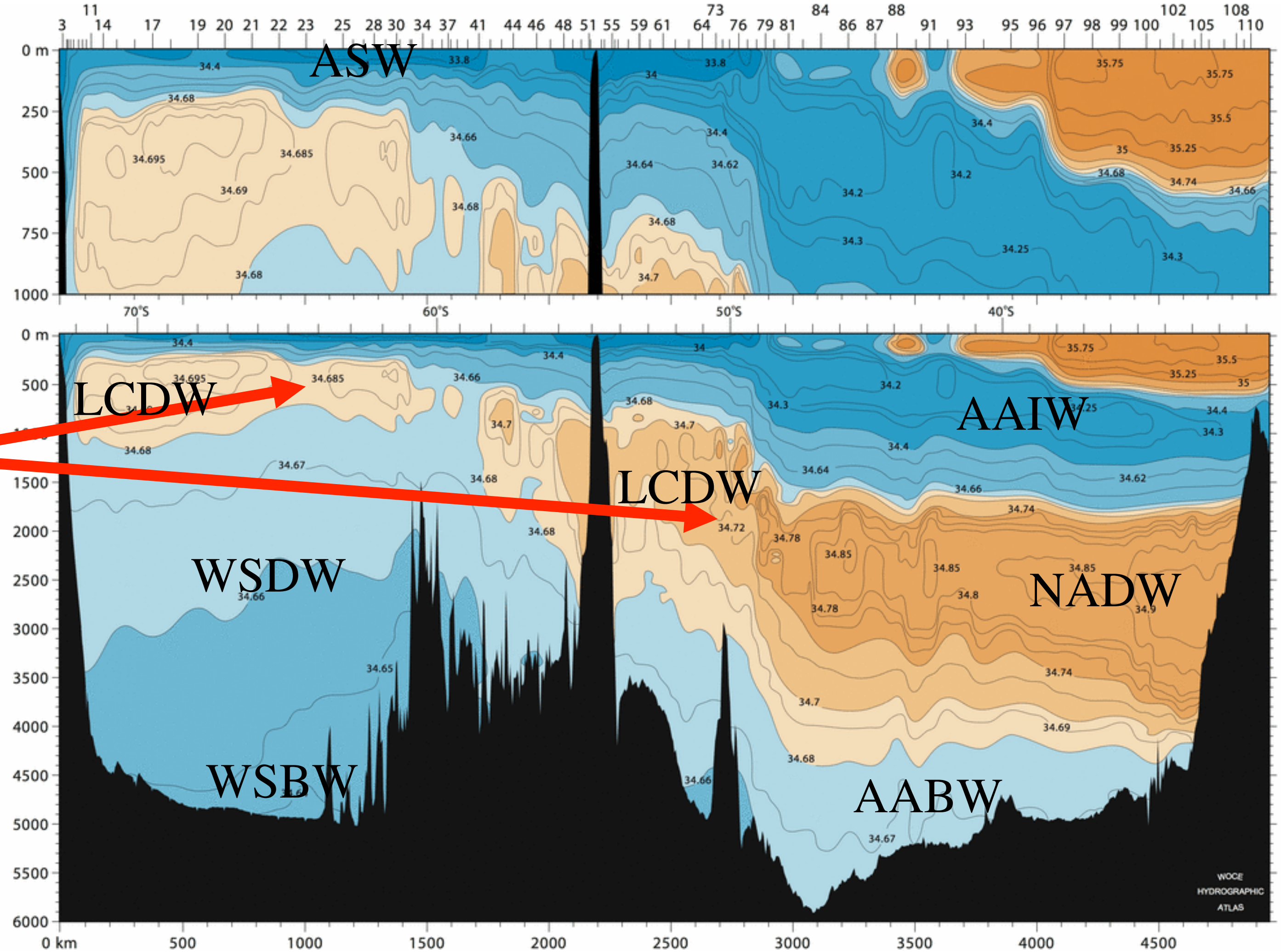
Highest oxygen from S.O. ventilation

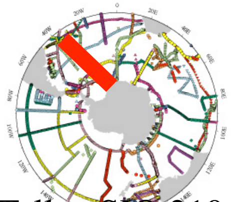
http://woceatlas.tamu.edu



Lower Circumpolar Deep Water

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





Talley SIO 210 (2015)

http://woceatlas.tamu.edu

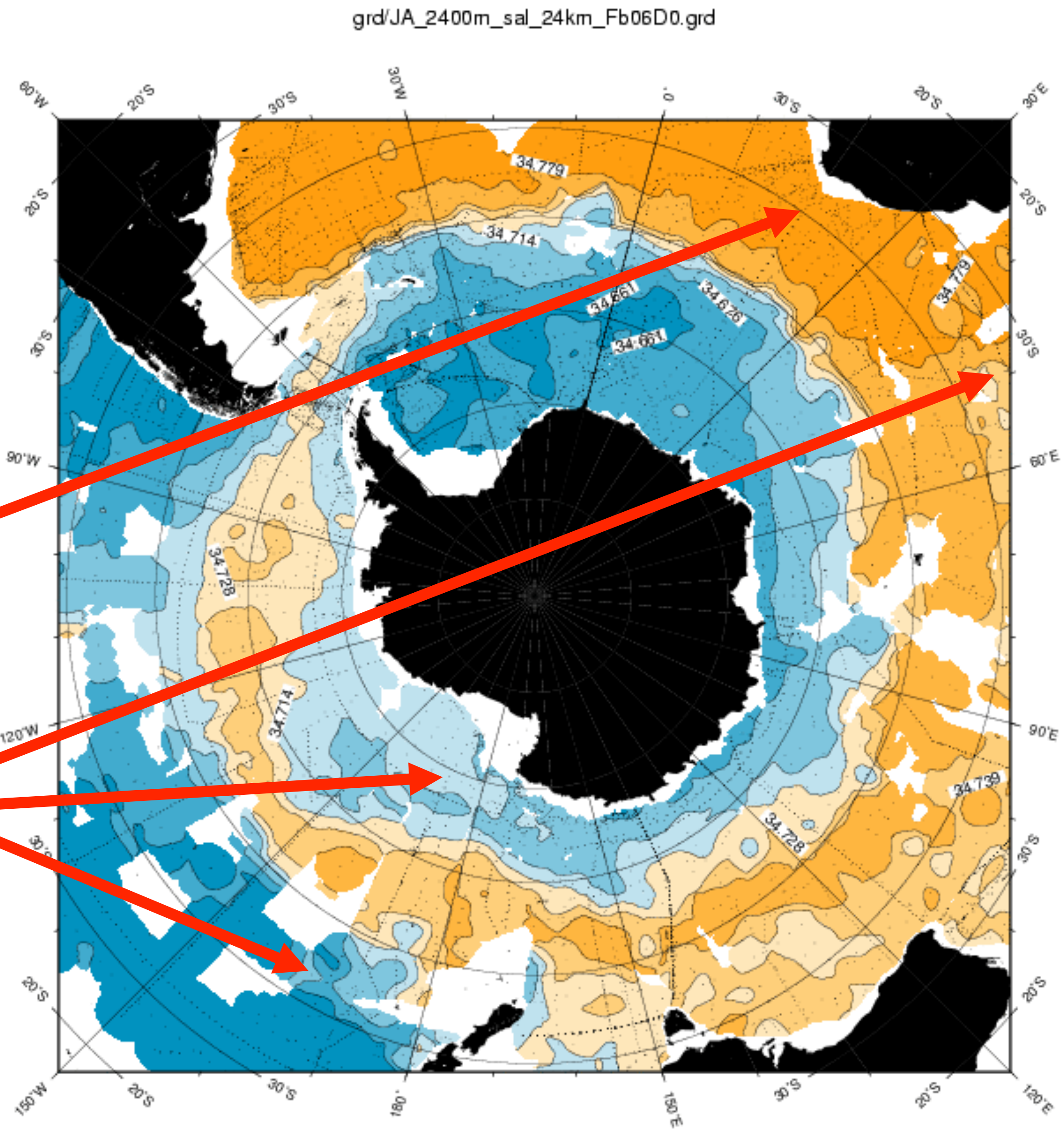
Lower Circumpolar Deep Water: high salinity comes from NADW

Salinity at

2400 meters

High salinity input from NADW

Fresh input from IDW, PDW, diluting the high salinity



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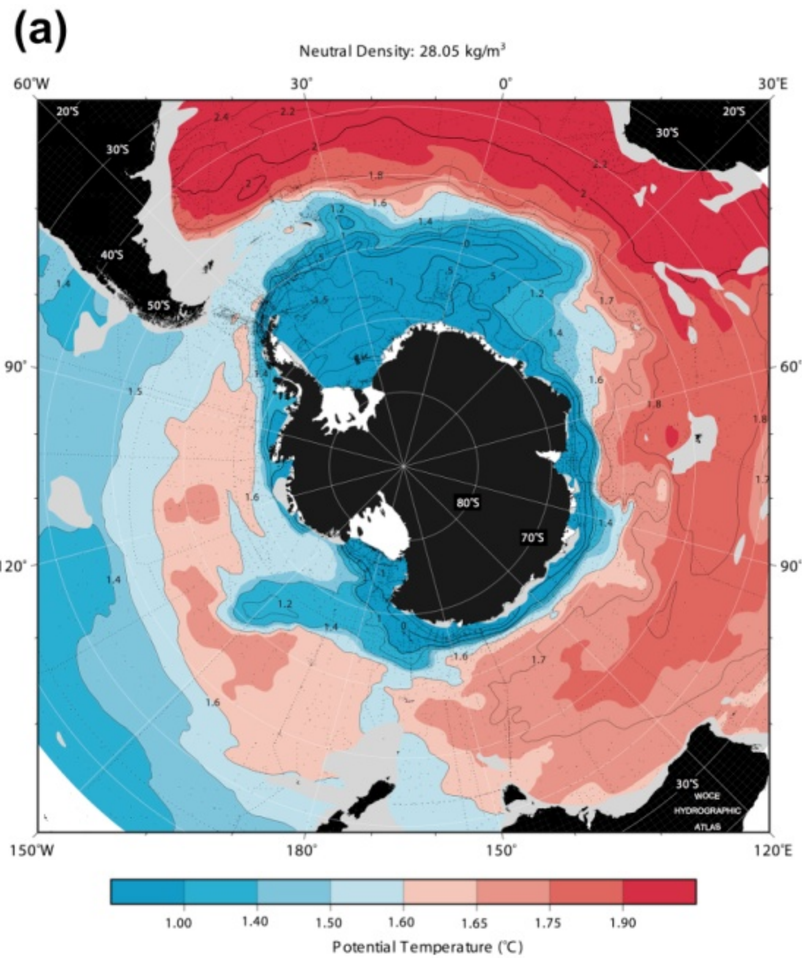
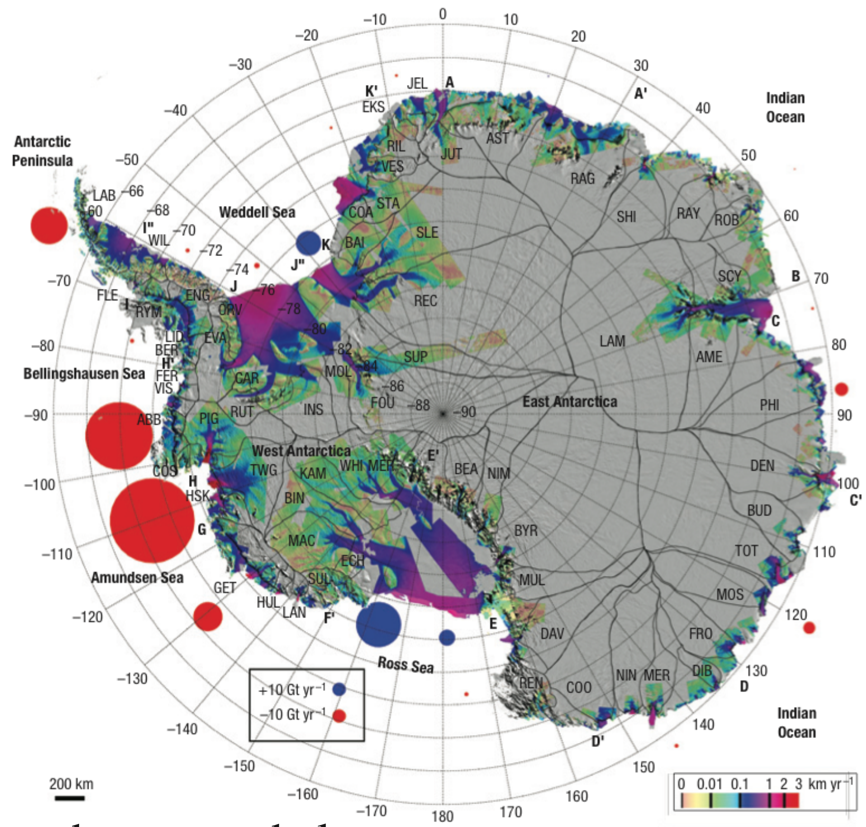
LCDW warm water upwells and comes close to Antarctic ice shelves

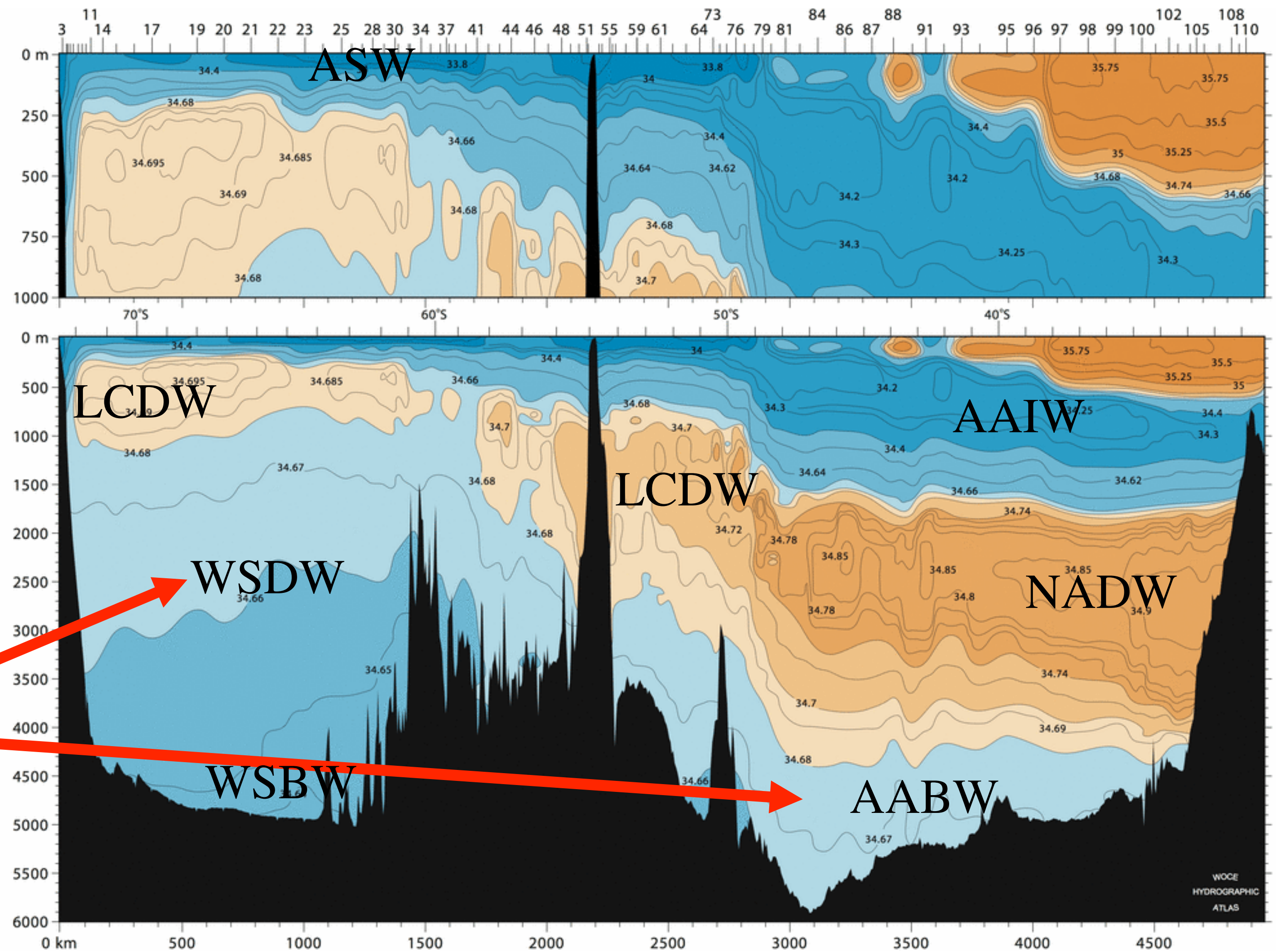


Orsi and Whitworth (2005)



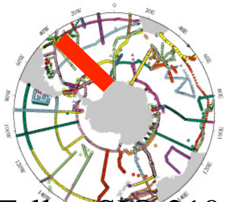
Ice sheet mass balances
→ sea level (Rignot et al.,)

Antarctic Bottom Water



Weddell Sea Deep Water

Antarctic Bottom Water (low salinity, cold bottom layer)



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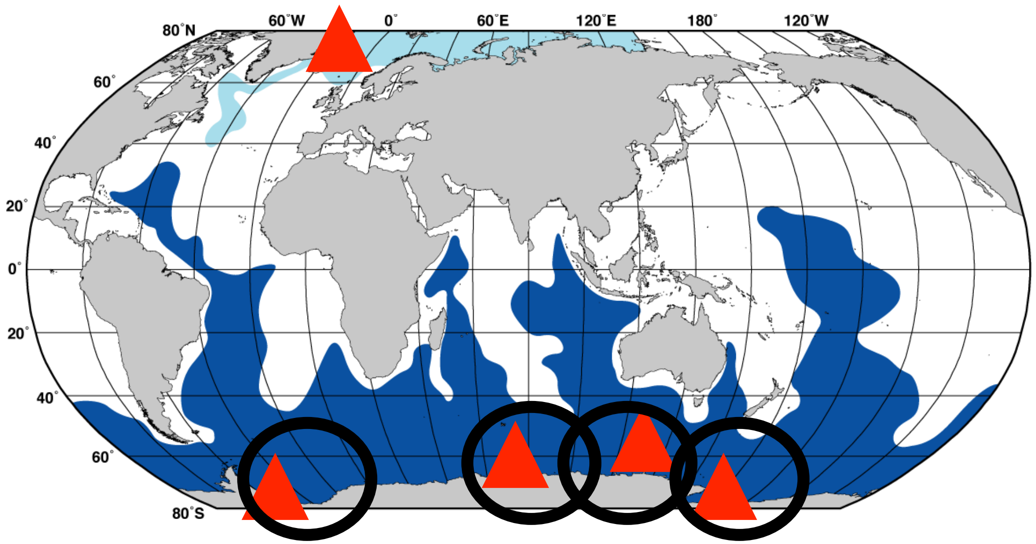
Antarctic Bottom Water



Deep and bottom water production sites: brine rejection in polynyas

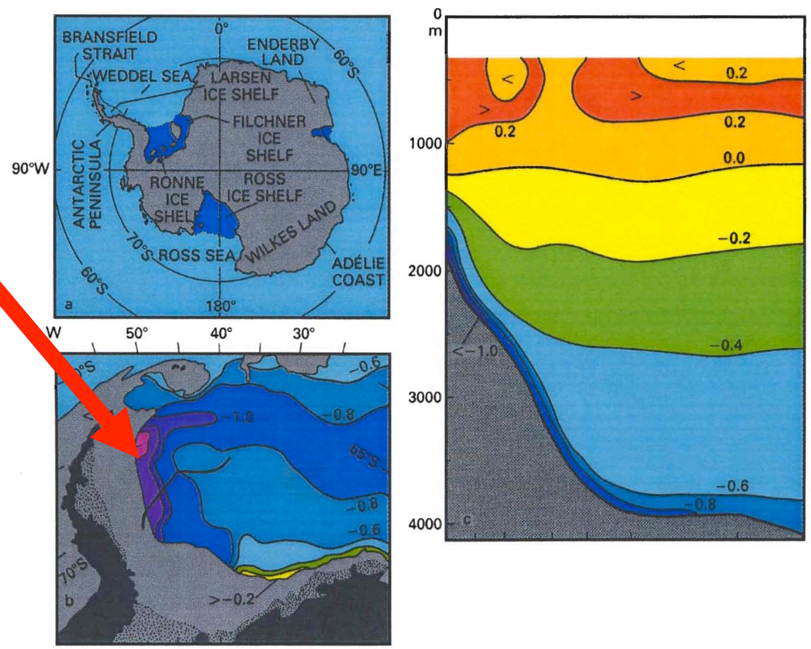
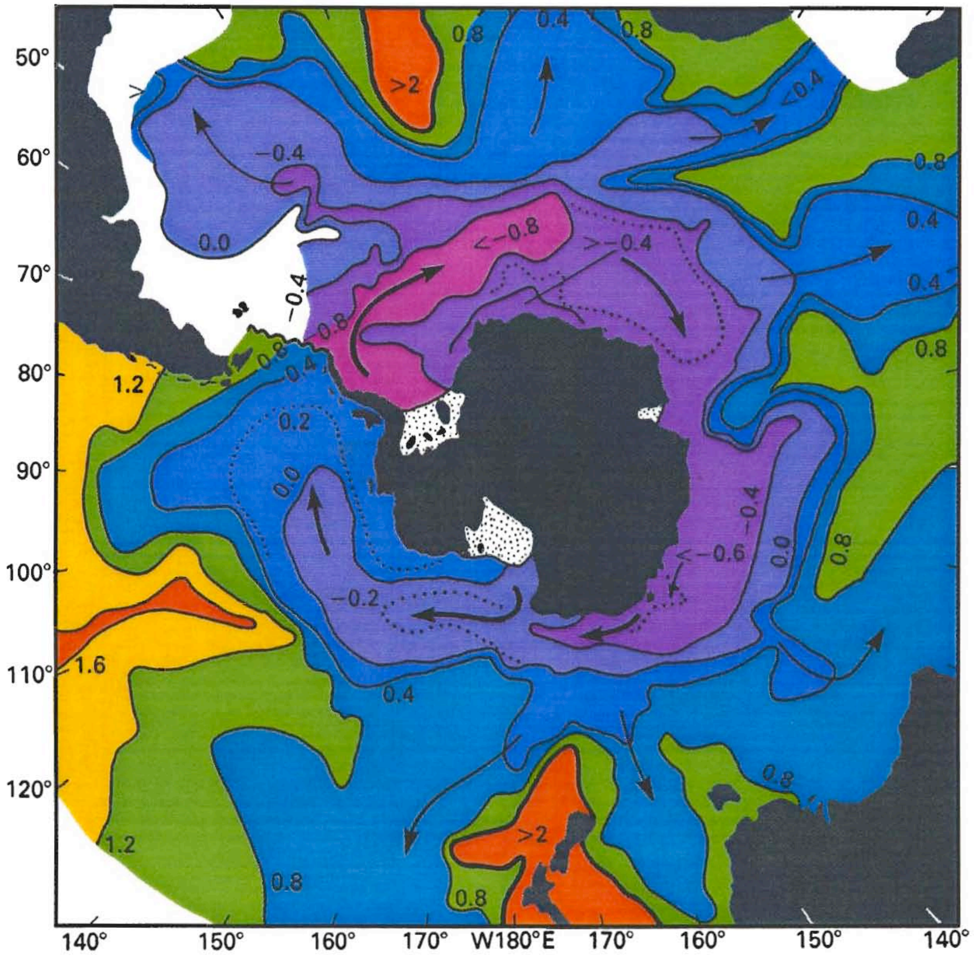
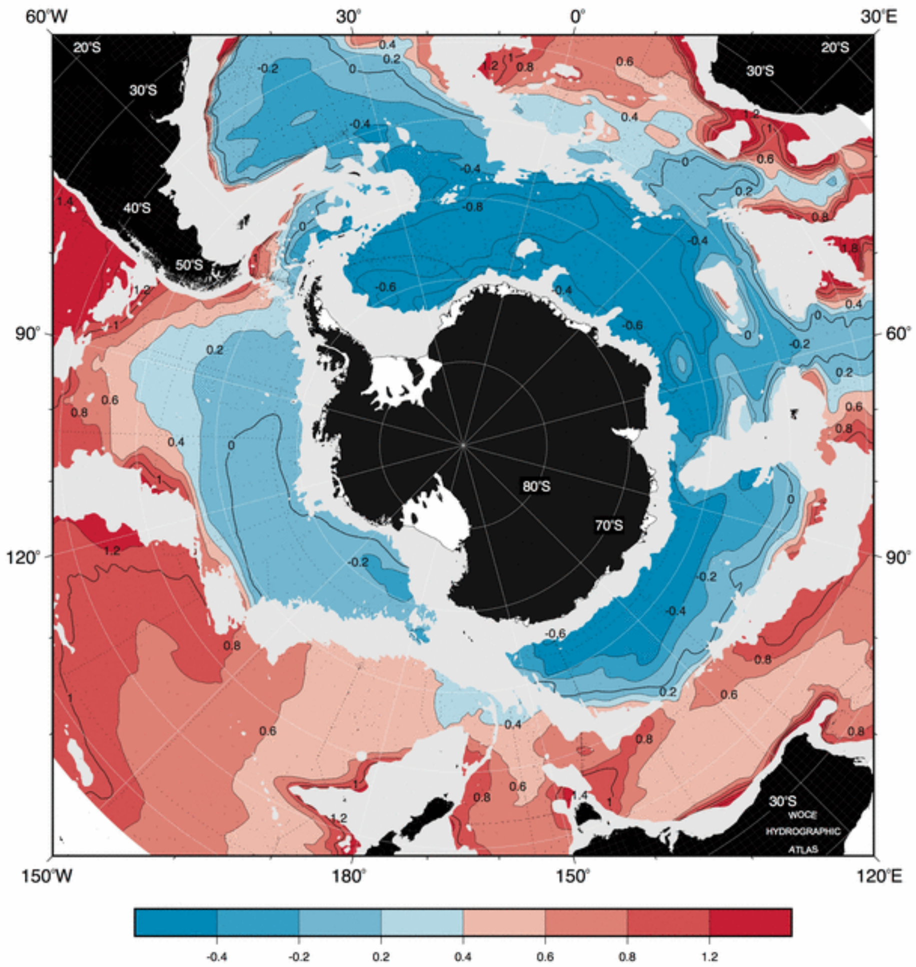


Fig. 6.14. Formation of Antarctic Bottom Water. (a) Locality map, including the regions where deep convection occurs, (b) bottom potential temperature (°C) in the Weddell Sea - the stippled area indicates ice shelf, and the edge of the shaded region is the approximate 3000 m contour, (c) a vertical section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



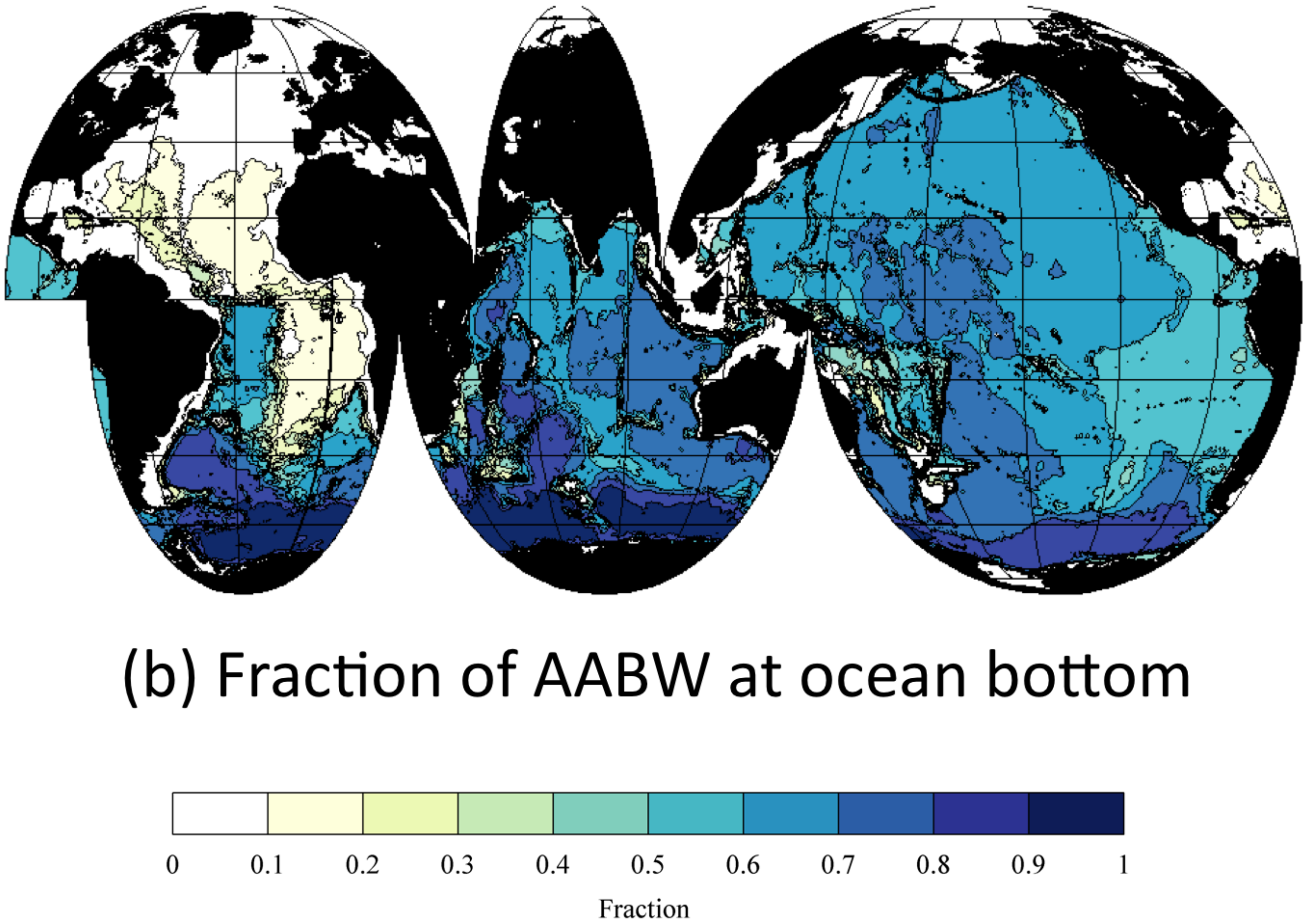
Bottom potential temperature, showing pathways of densest shelf waters around and away from Antarctica
(Tomczak & Godfrey)



Bottom potential temperature

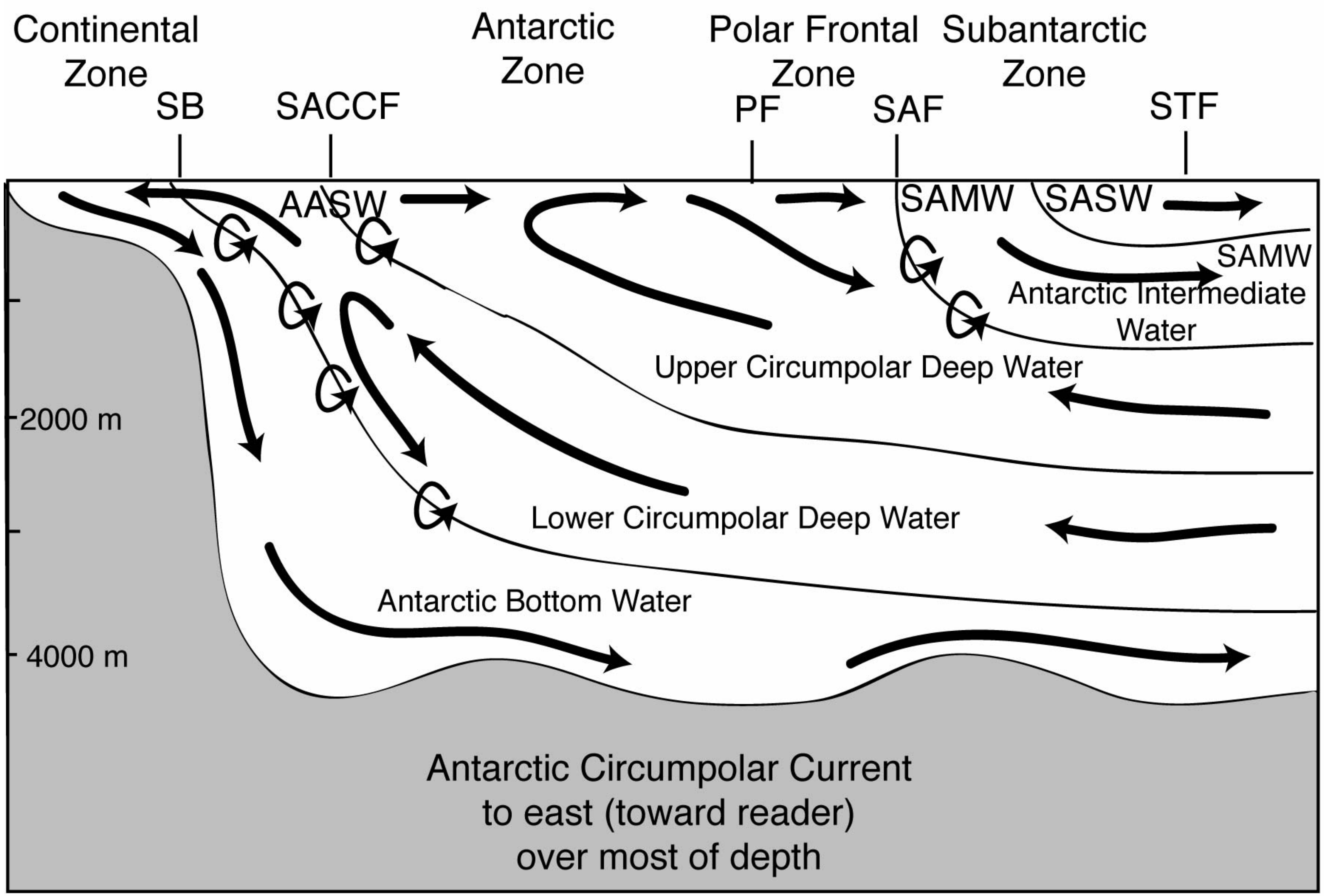
http://woceatlas.tamu.edu

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)