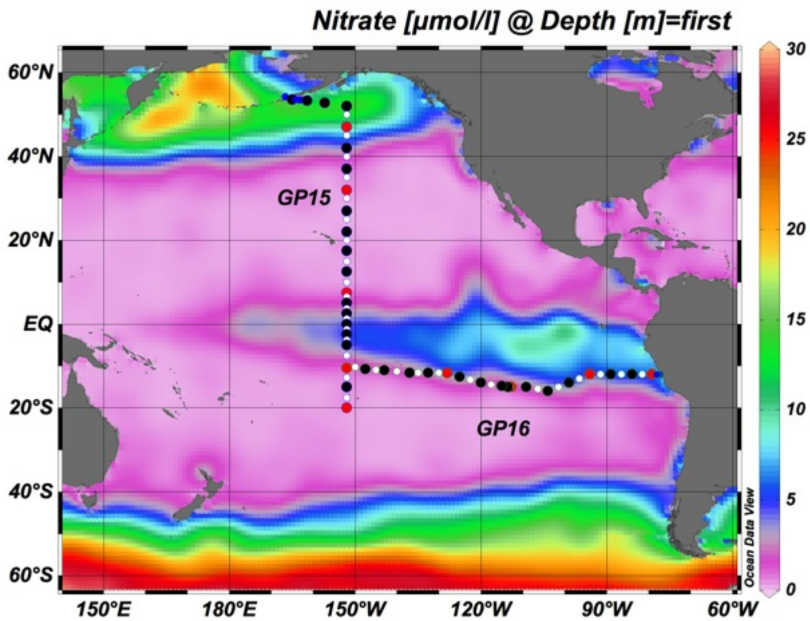
Circulation and hydrography in the NE and eastern Pacific: expedition to the oldest* waters on Earth



Lynne Talley, Scripps Institution of Oceanography

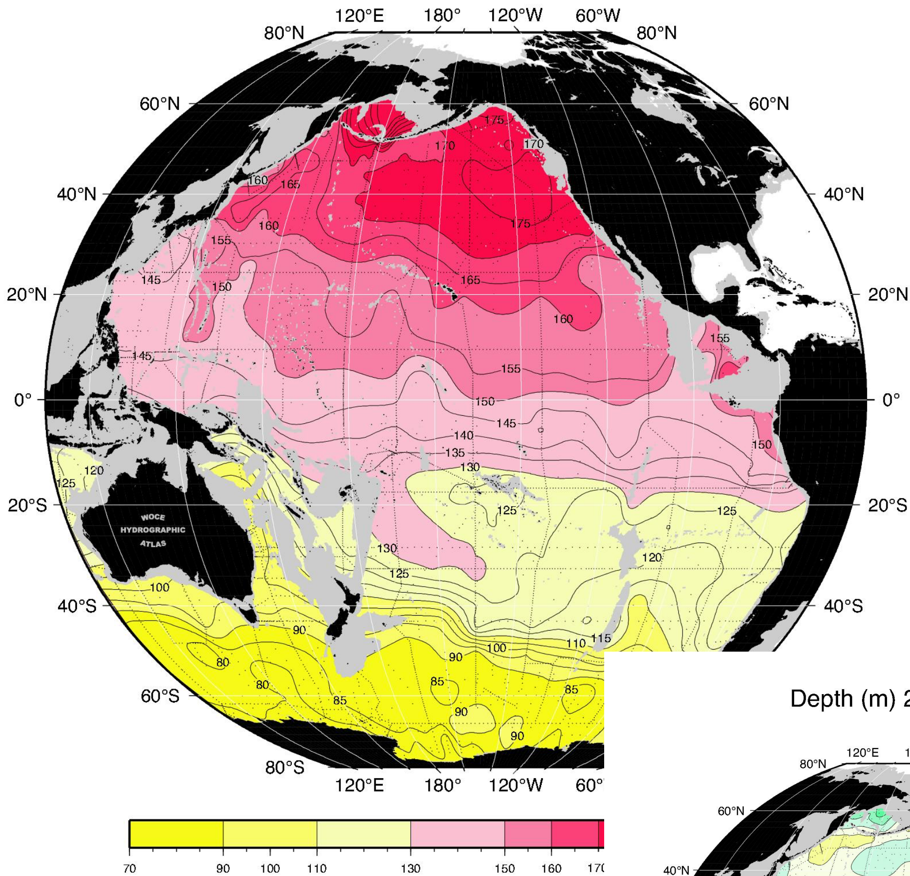
GEOTRACES meeting, La Jolla CA

October 6, 2016

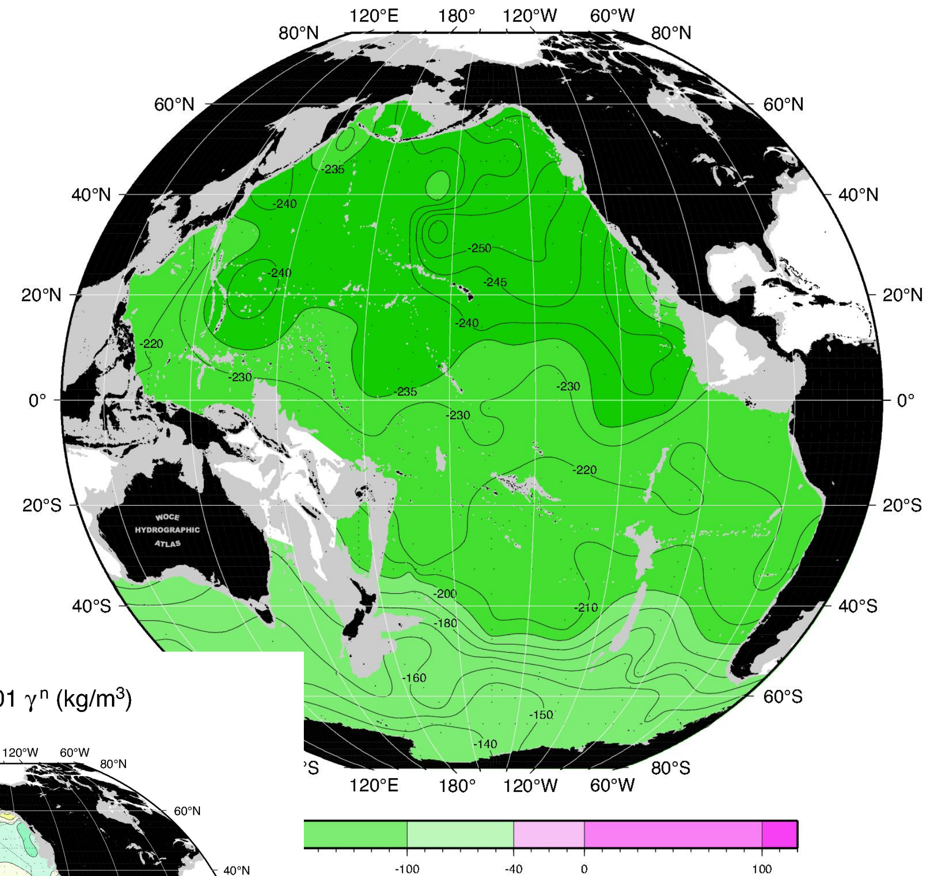
*Canada Basin Arctic Ocean might be older

The old water in the Pacific Deep Water layer

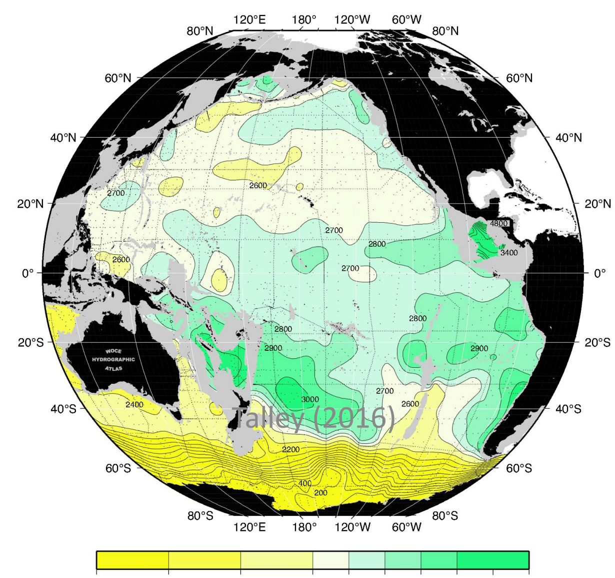
Silicate (μmol/kg) 28.01 γ^n (kg/m^3)



Δ^{14}C (/mille) 28.01 γ^n (kg/m^3)



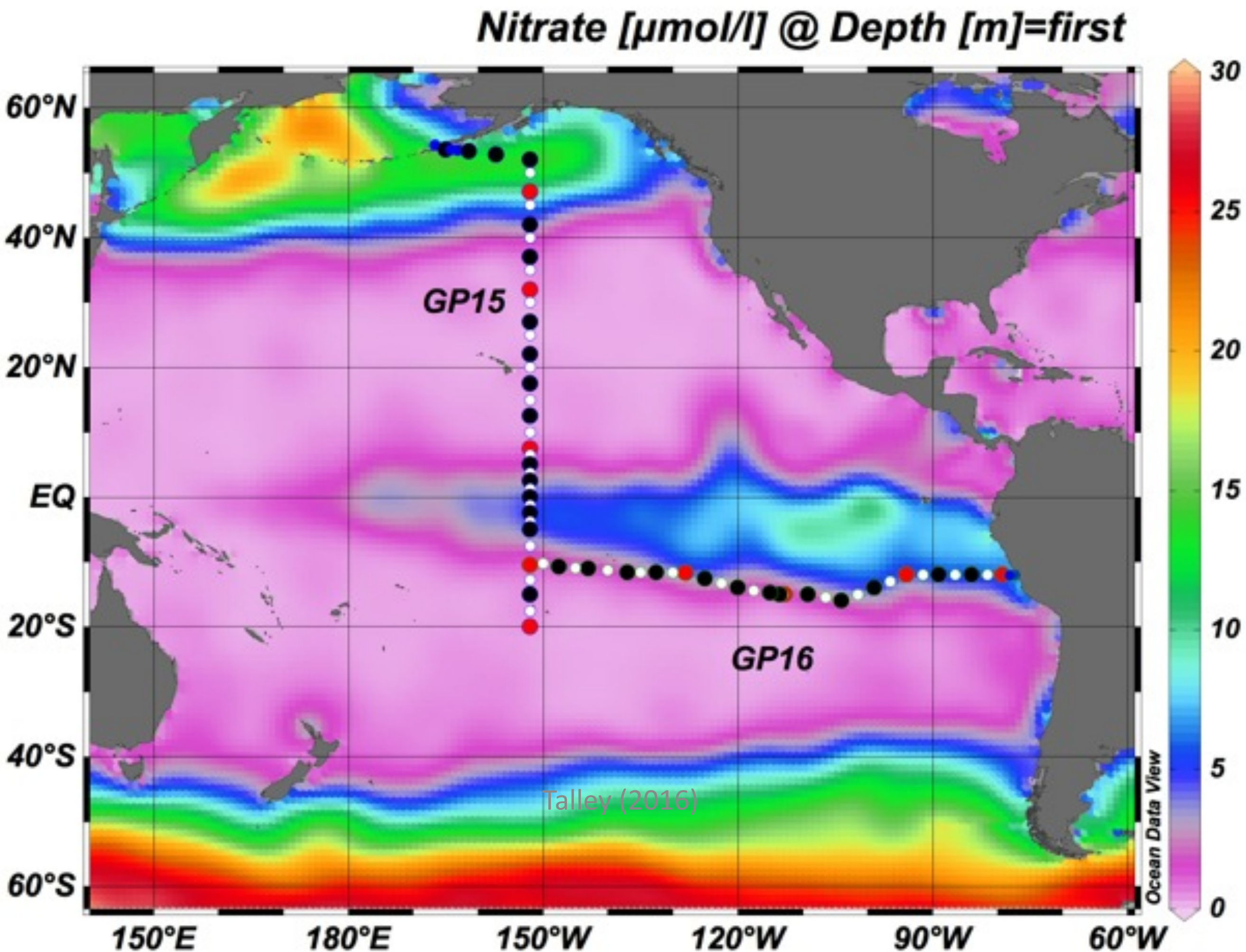
Depth (m) 28.01 γ^n (kg/m^3)



WHP Pacific Atlas
(Talley, 2007)

Outline

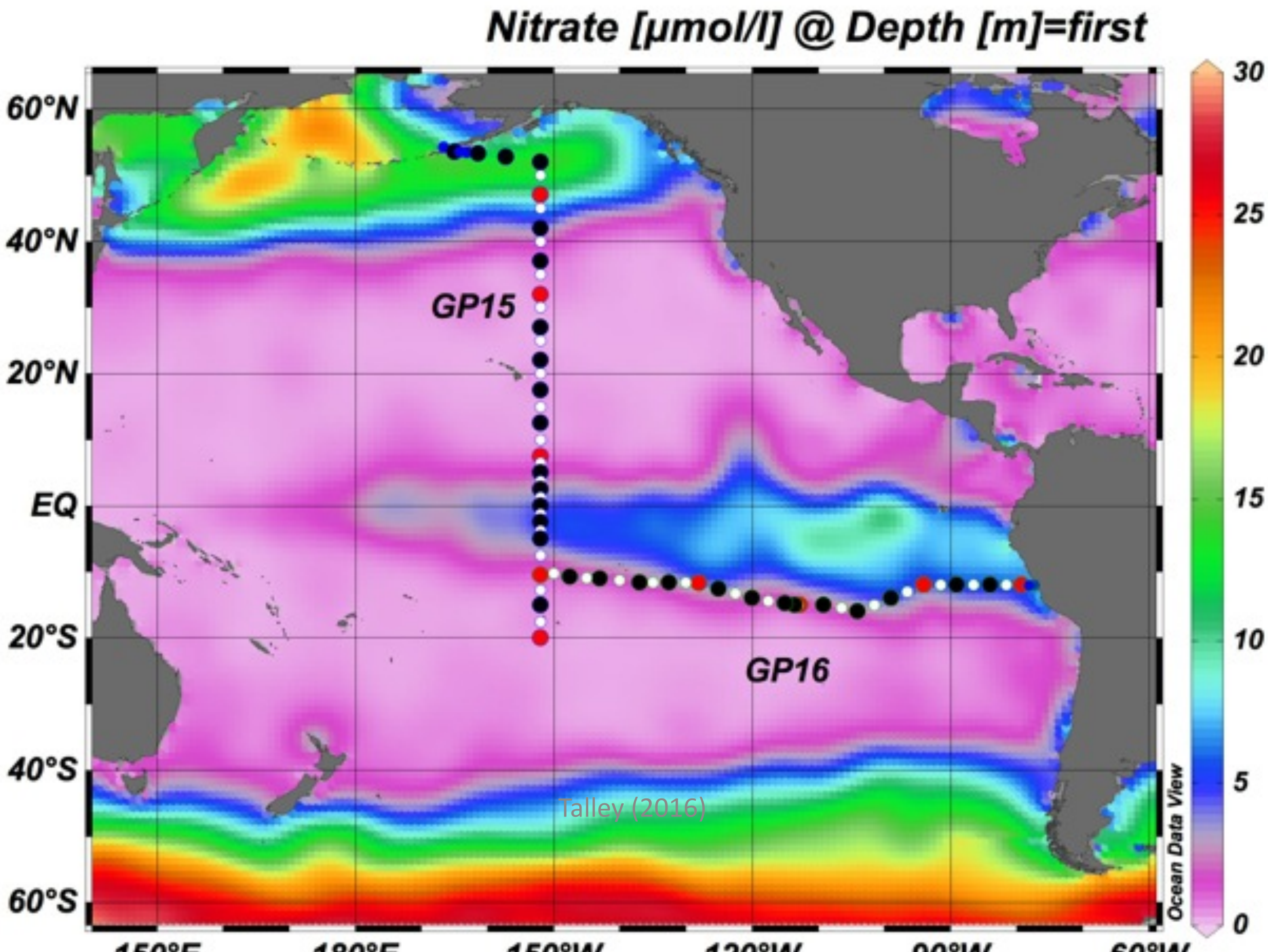
1. Overview: previous occupations of P16
2. Surface forcing and global overturn in brief
3. Upper ocean: subpolar, subtropical, tropical
4. Intermediate, deep and abyssal ocean



Talley (2016)

Outline

- P16 150°W section
- Property maps from the WHP Pacific Atlas (Talley, 2007)



1 Overview: some P.O. resources

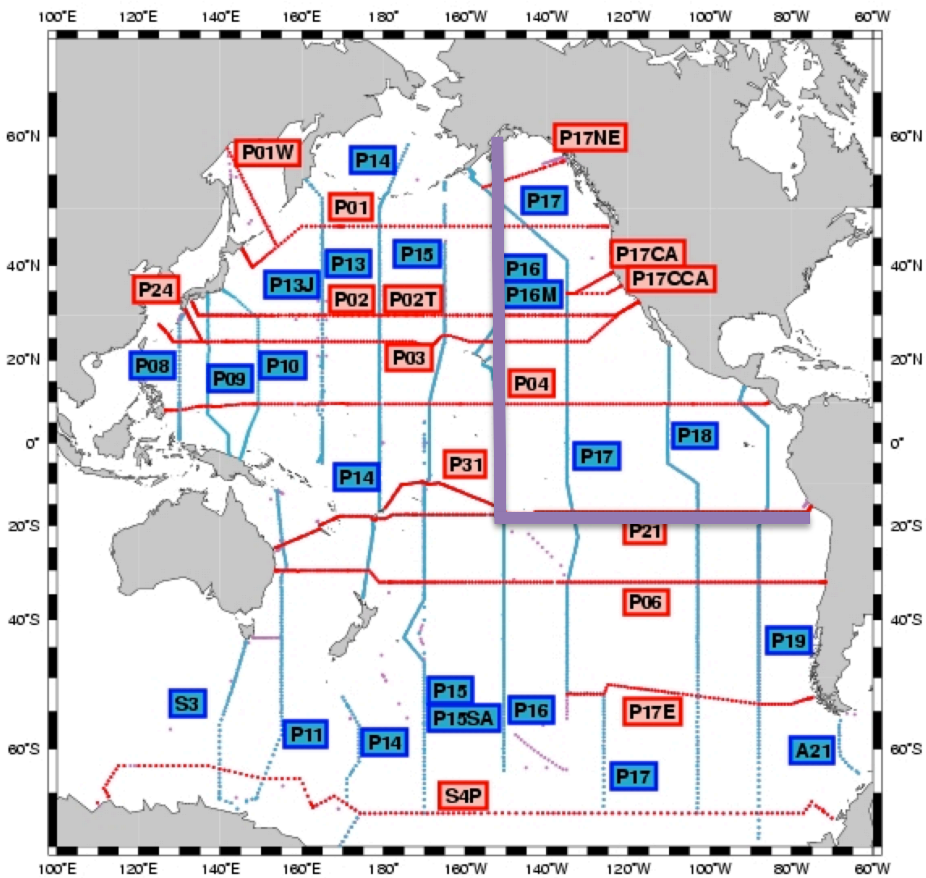
- WOCE Pacific atlas (Talley, 2007): http://www-pord.ucsd.edu/whp_atlas/pacific_index.html
- WOCE Global Hydrographic Climatology (Gouretski and Koltermann, 2004)
- TAO array (to 10°S) http://www.pmel.noaa.gov/tao/disdel/disdel.html

- Circulation: Reid (1997) Progress in Oceanography
- Overview of Pacific circulation and water properties: Chapter 10 in Descriptive Physical Oceanography, 6th edition (2011)
- Overview of properties in upper ocean (Fiedler and Talley, 2006)

WOCE and GO-SHIP

1. Overview

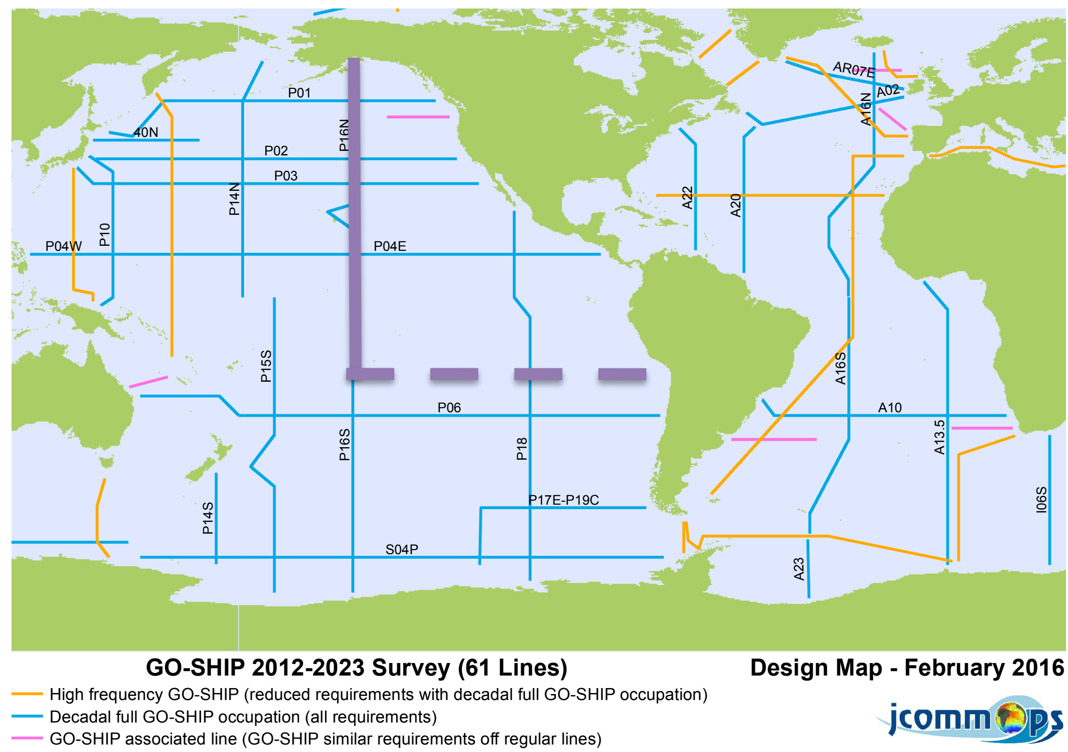
P16N to 20°S and P21E



http://woceatlas.ucsd.edu

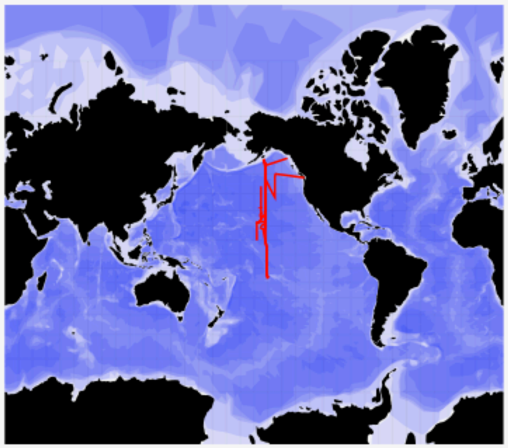
WHP Pacific Atlas

P16N to 20°S and P21E



Hydrographic sections P16N: 7 occupations

P16N to 20°S



http://cchdo.ucsd.edu

CCHDO data base

Search Results

Expocode	Line(s)	Ship	Country	Start Date	End Date	PI
33RO20150525	• P16N • P16	RONALD H. BROWN	US	2015-05-25	2015-06-25	• Alison Macdonald
33RO20150410	• P16C • P16N • P16	Ronald H. Brown	US	2015-04-10	2015-05-13	• Jessica Cross
325020080826	• P16 • P16N	THOMAS THOMPSON	US	2008-08-26	2008-09-17	• Steven Emerson
325020060213	• P16 • P16C • P16N	THOMAS G. THOMPSON	US	[illegible]	[illegible]	• Richard A. Feely • Christopher L. Sabine
325019971101	• P16 • P16N	THOMAS G. THOMPSON	US	1997-11-01	1997-11-23	• Paul Quay • Steven Emerson
31WTTUNES_3	• P16 • P16N • P16C	THOMAS WASHINGTON	US	1991-08-31	1991-10-01	• Lynne Talley
31DSCGC91_1	• P16 • P16N	DISCOVERER	US	1991-02-14	1991-04-08	• John L. Bullister
31WTMARAII	• P16 • P16N	THOMAS WASHINGTON	US	1984-05-04	1984-06-04	• Roland A. de Szoeke
32NM19800810	• P16 • P16N	NEW HORIZON	US	1980-08-10	1980-09-03	• Thomas Hayward

GO-SHIP 2015

CLIVAR Repeat Hydro (GO-SHIP) 2006

WOCE 1991

Pre-WOCE 1984

Filter Table:

Bulk Download Options

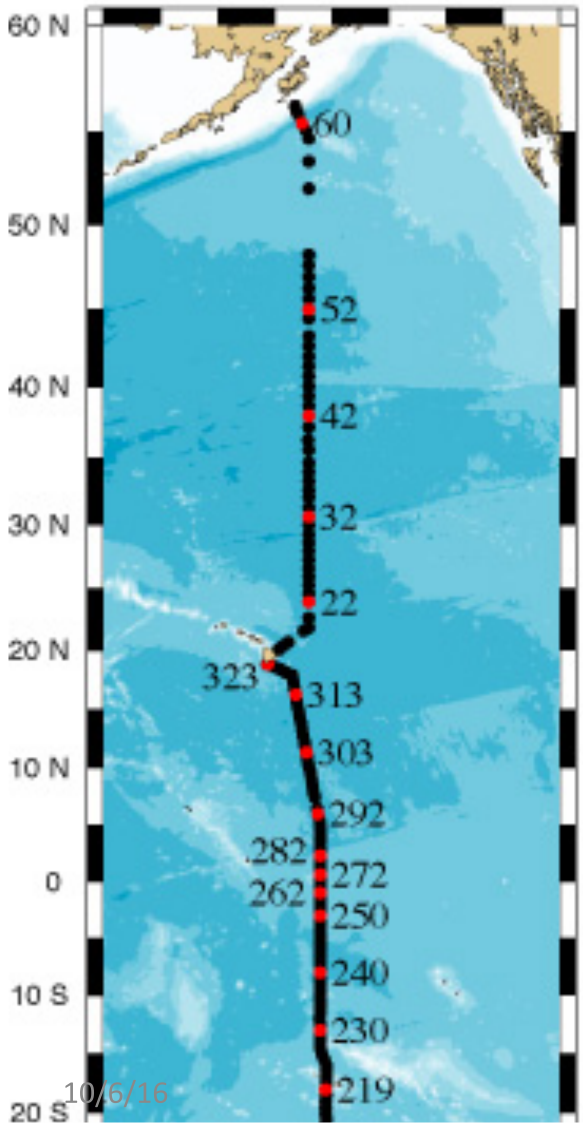
Results: 9

Search Tips:

- Click the table headings to sort the results, again to reverse the order.
- Type text in the box above to further filter the results shown in the table.
- To do a new search, use the search box at the top of the page.

Hydrographic sections P16N: 7 occupations

P16N to 20°S



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GO-SHIP 2015

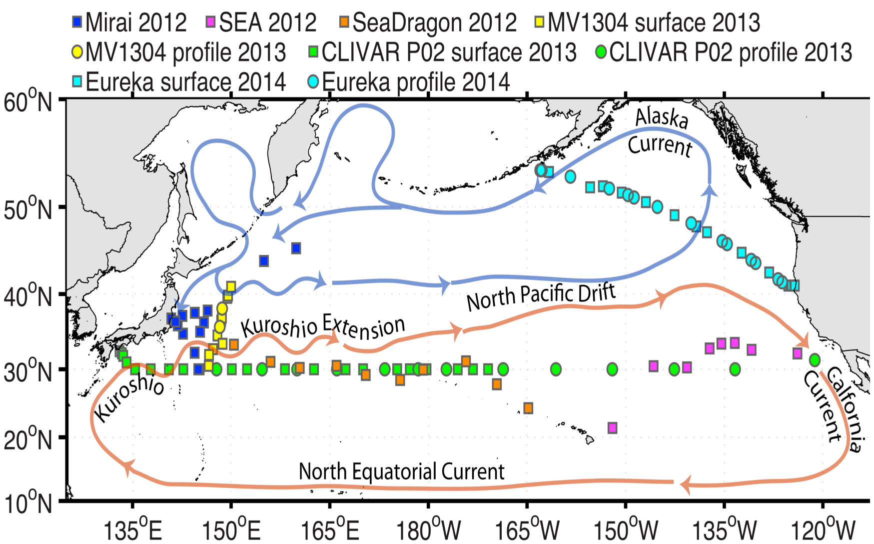
CLIVAR Repeat Hydro (GO-SHIP) 2006

WOCE 1991

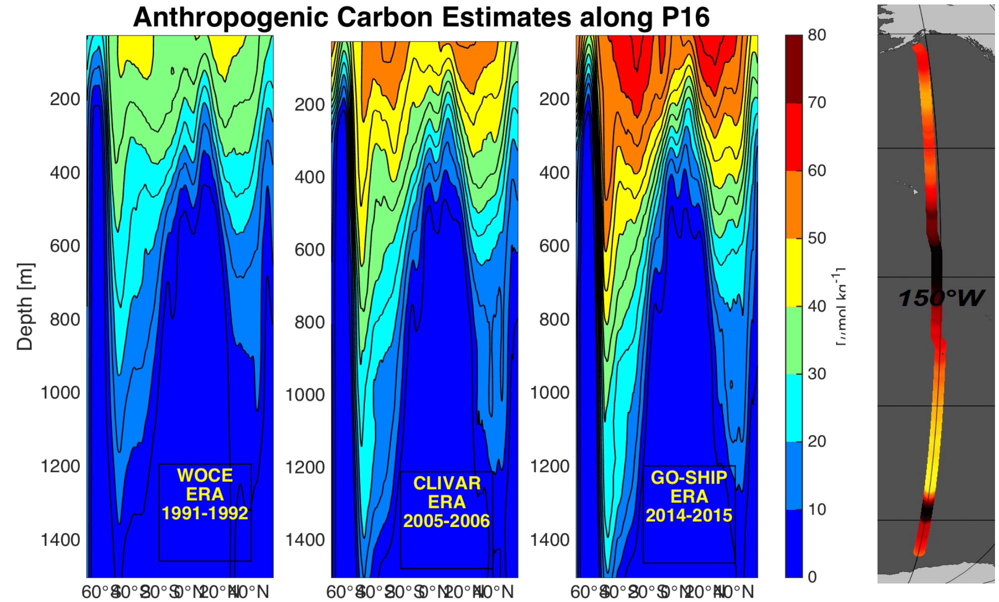
Pre-WOCE 1984

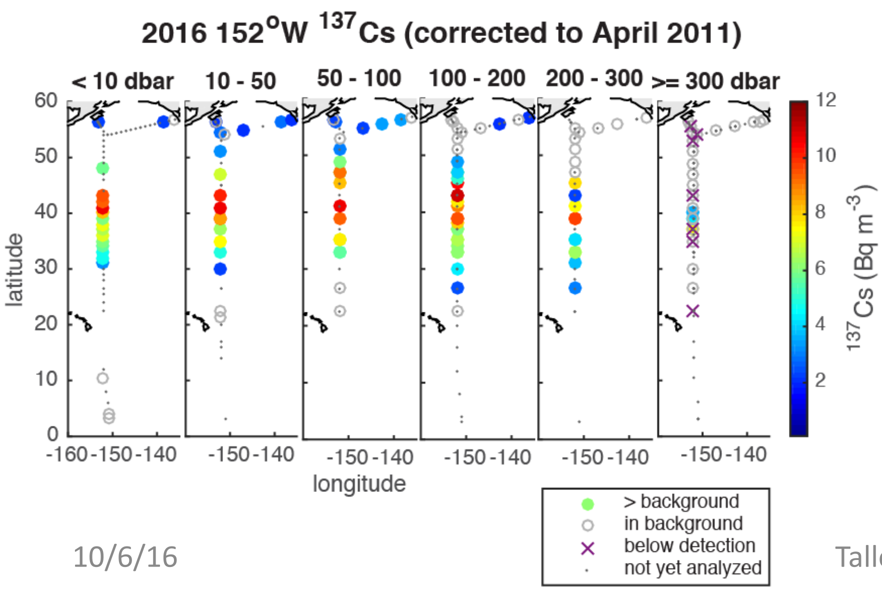
Quick results from latest P16N

Tracking Fukashima radionuclides (Macdonald, Yoshida, Buesseler, et al)

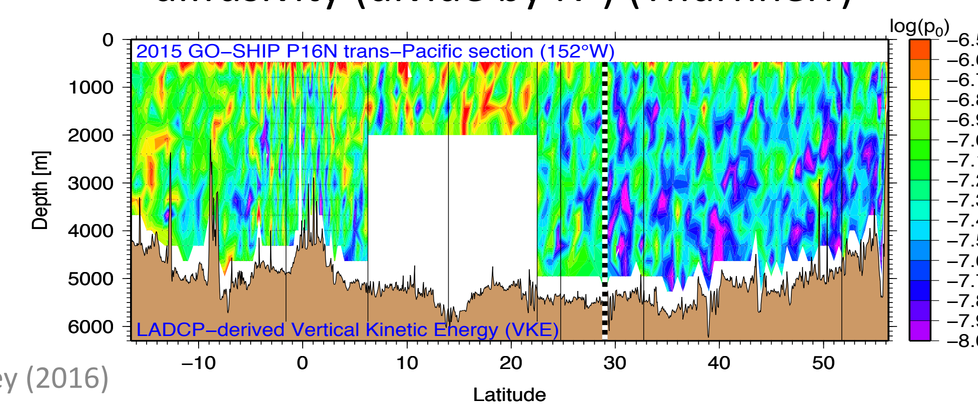


Anthropogenic Carbon (Carter et al.)

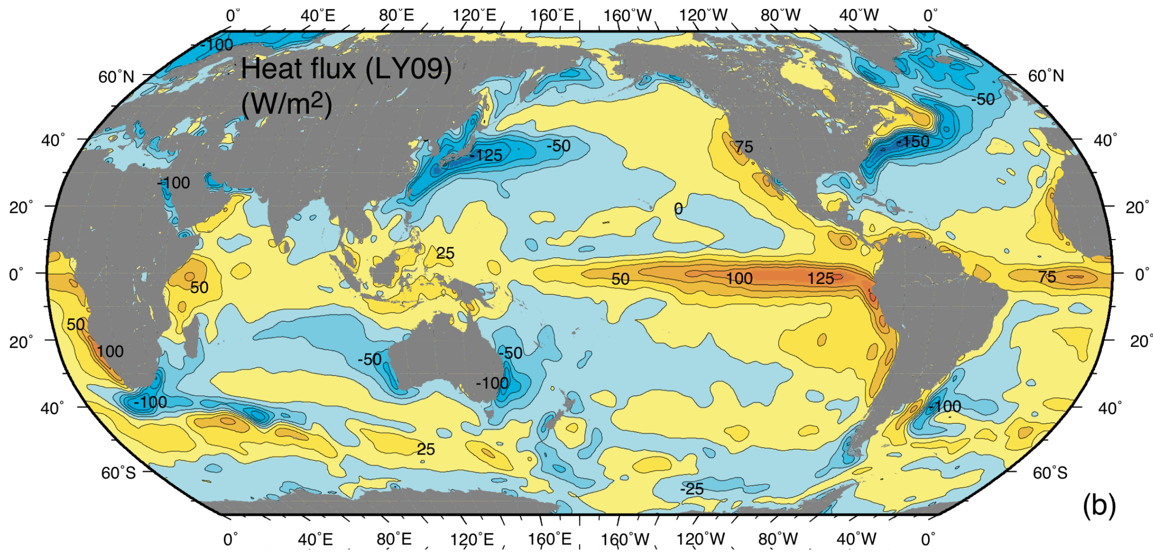




Dissipation which is related to diapycnal diffusivity (divide by N²) (Thurnherr)



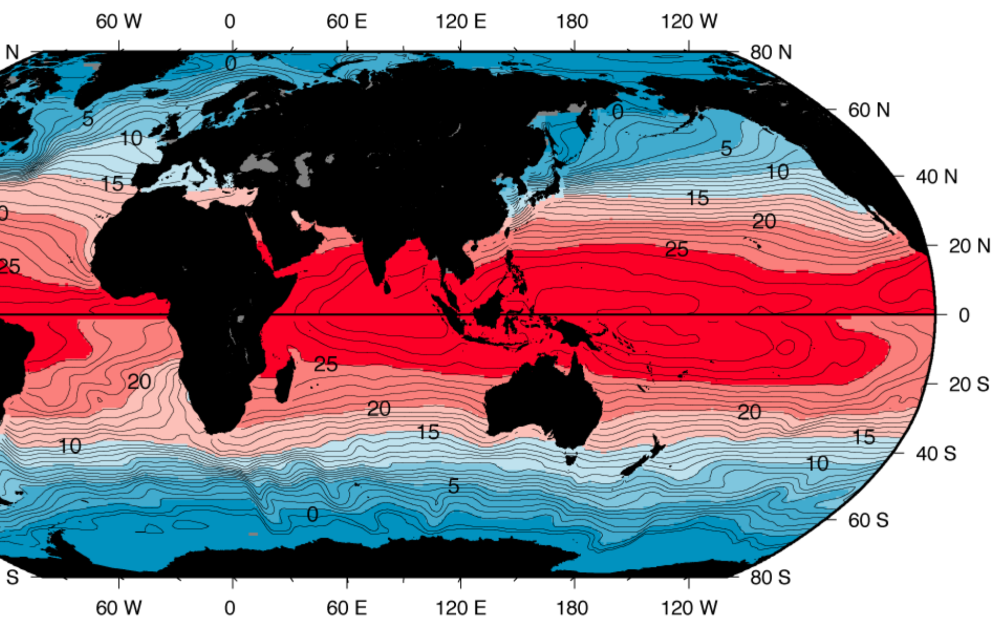
2 Heat flux and surface temperature



Surface heat flux

North Pacific Ocean has only mid-latitude heat loss.

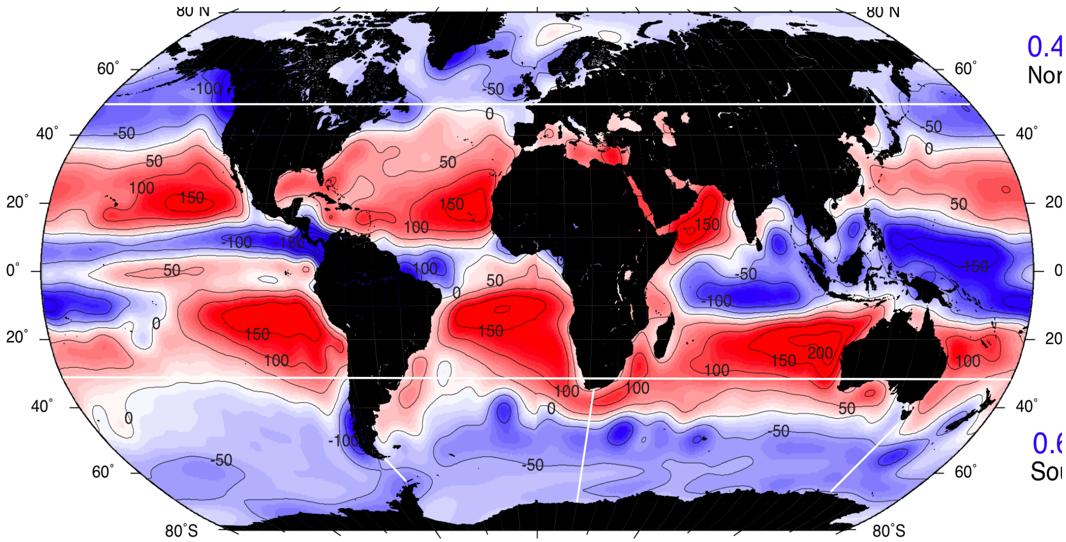
NE Pacific has slight net heating.



Surface temperature (winter)

DPO Figure 4.1: Winter data from Levitus and Boyer (1994)

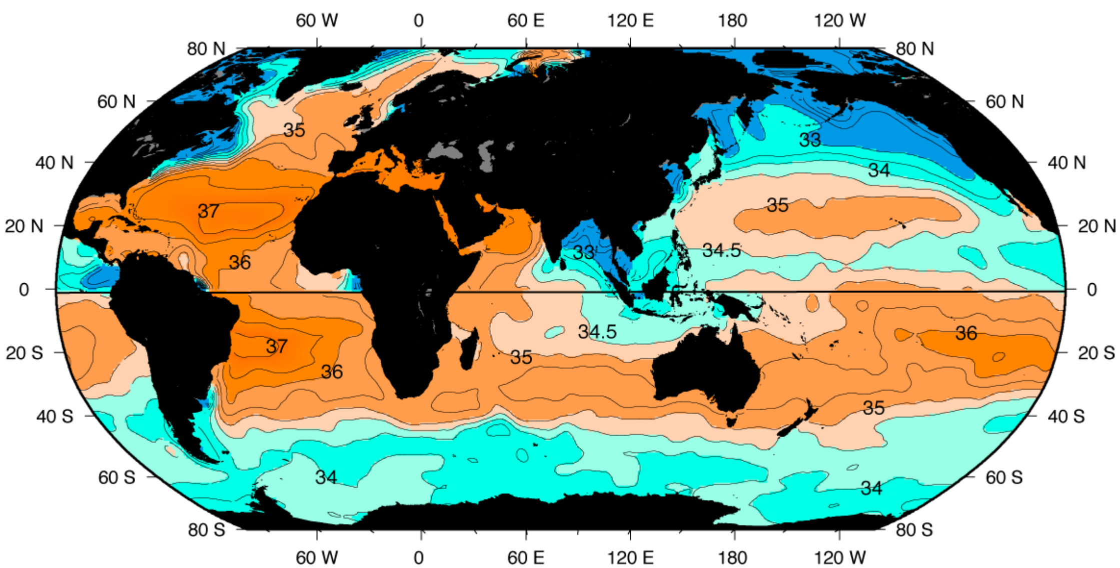
2 Freshwater forcing and surface salinity



Evaporation minus precipitation

North Pacific Ocean is fresh compared with other oceans due to excess P-E.

This prevents deep water formation

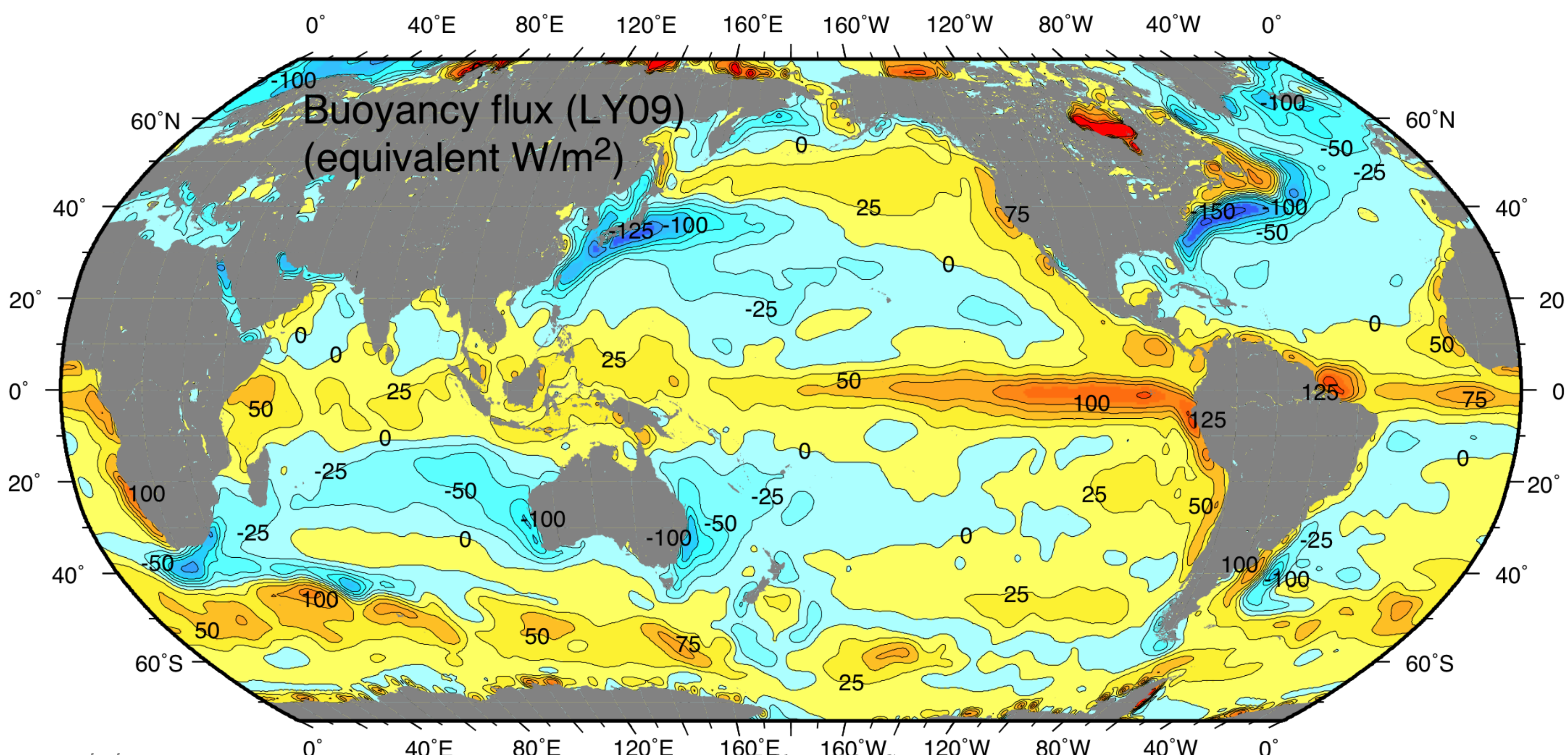


Surface salinity

Talley (2016)

2 Buoyancy flux

- Density is changed by buoyancy flux, which is the sum of heat and freshwater flux (changing temperature and salinity)
- Map is mostly related to heat flux, little impact from E-P except at high latitudes
- NE Pacific is a region of buoyancy gain

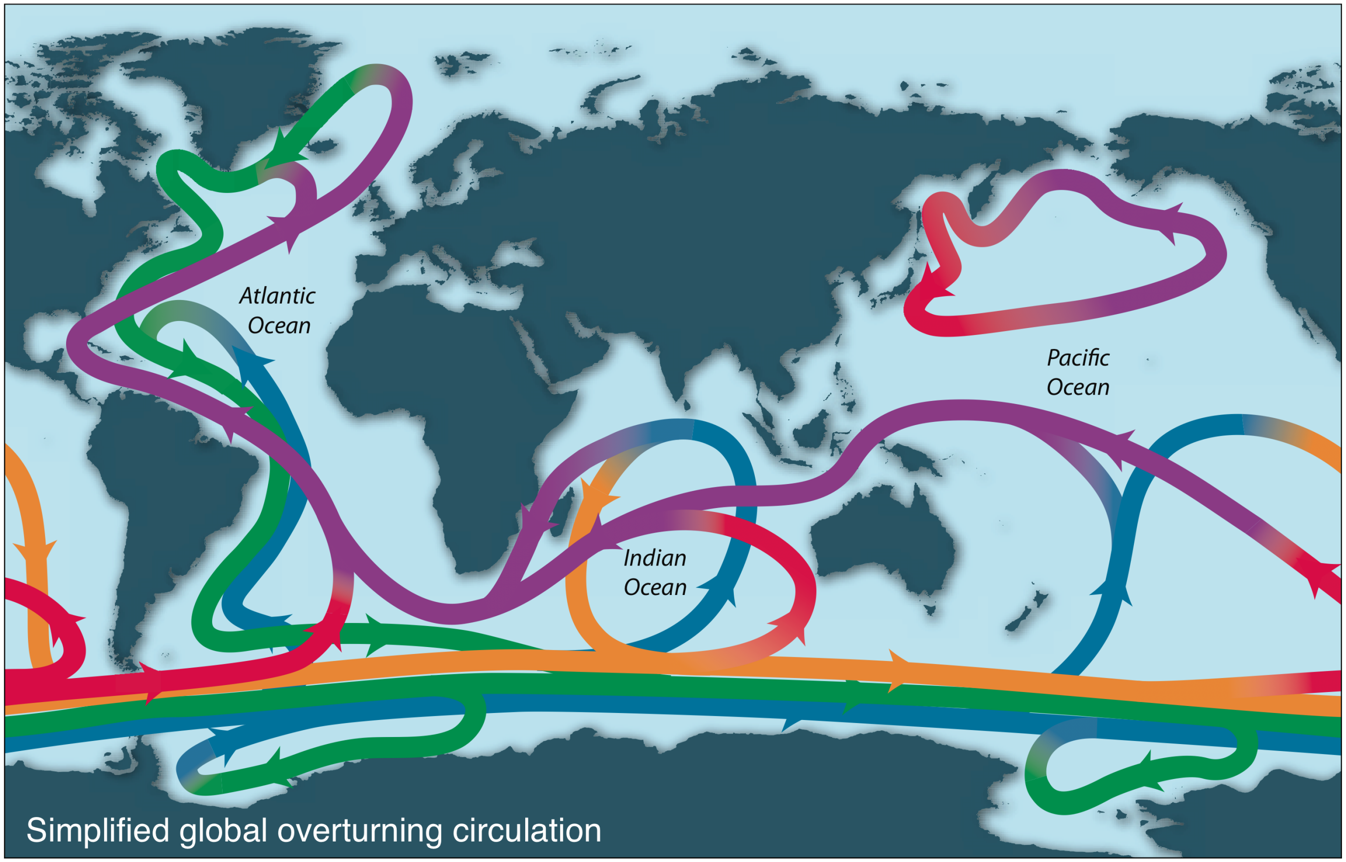


Talley (2016)
DPO Figure 5.15

2 Global overturning schematic

No deep water formation in N. Pacific.
NPIW formation is the weak analog of NADW formation.
The global overturning circulation bypasses much of the N. Pacific.

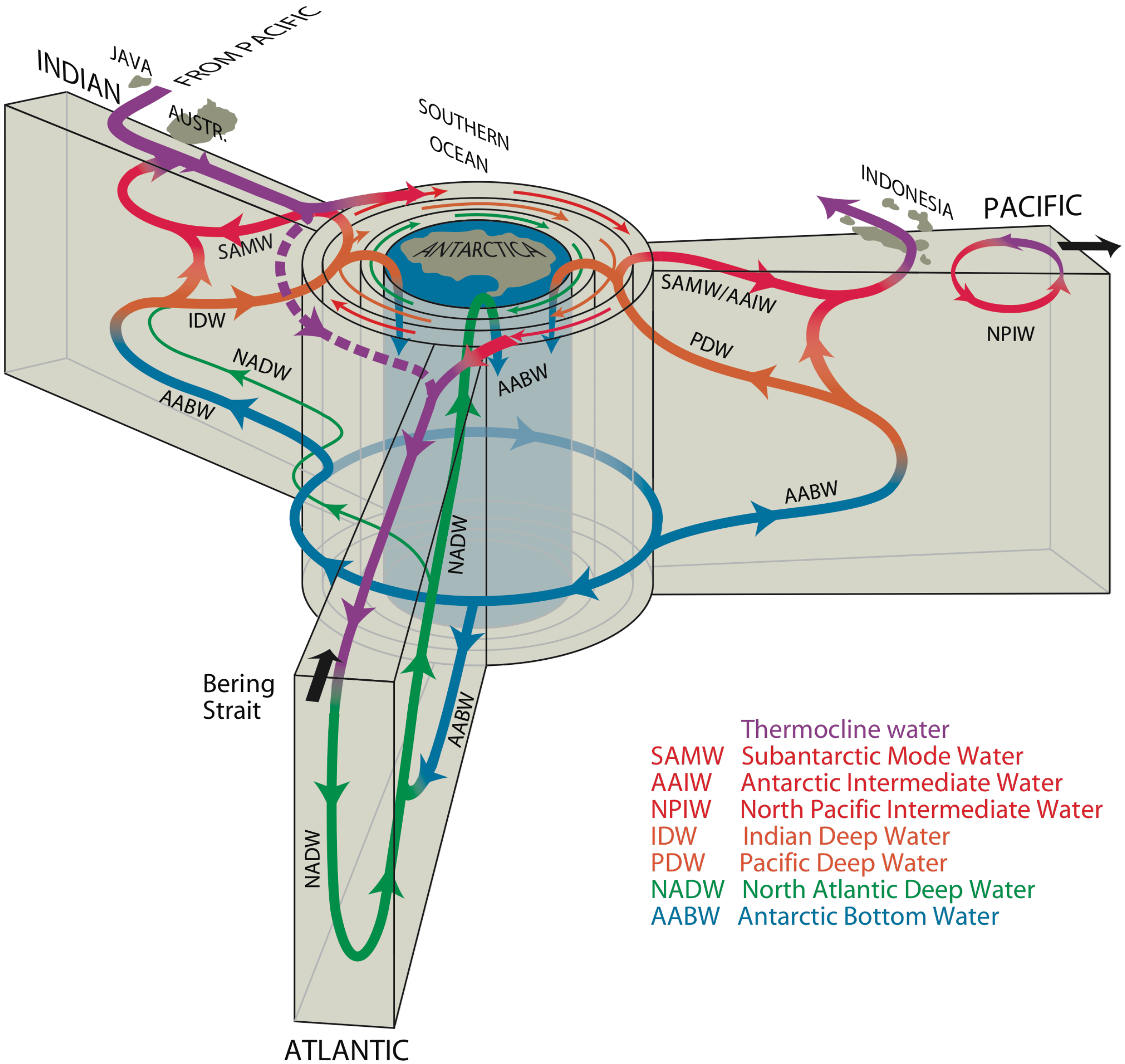
Most of the upwelling of bottom waters occurs south of 24N, and likely is in the tropics.
There is a much weaker overturning contribution in the northern N. Pacific.



Talley (2016)

DPO Fig. 14.11a

2 Global overturning with Southern Ocean perspective



No deep water forms in the N. Pacific.

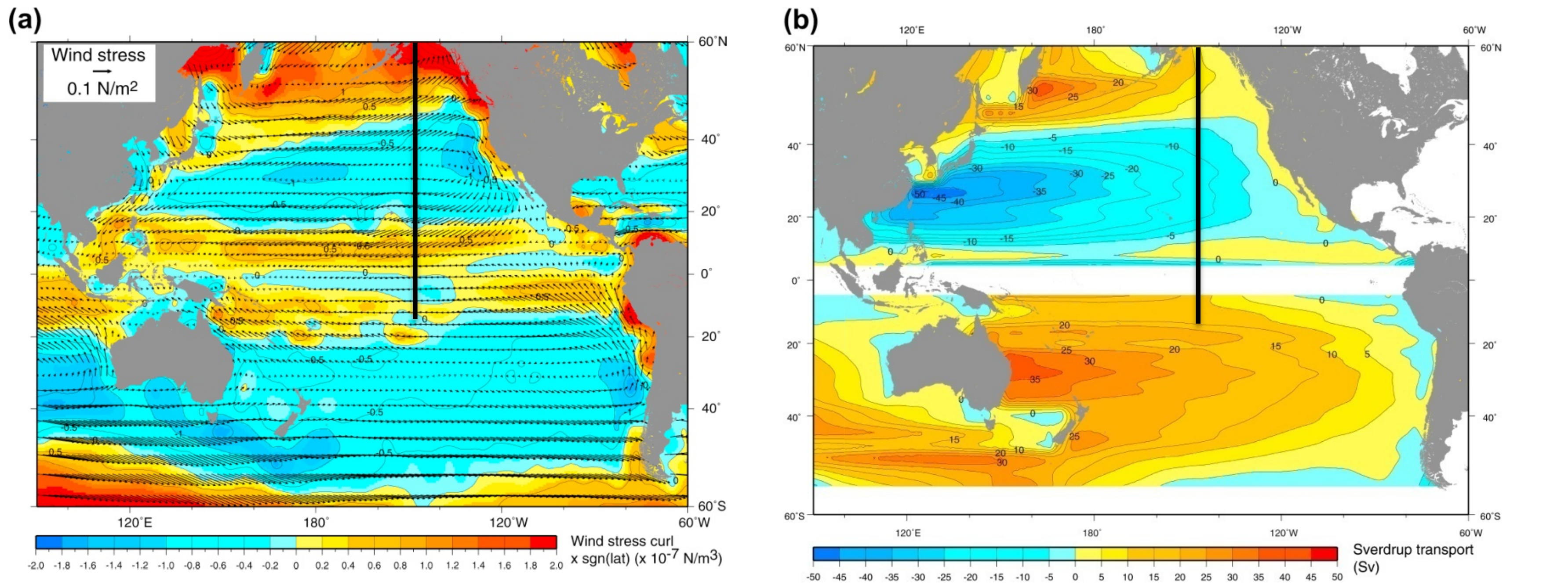
It has almost no role in the global overturning circulation: weak diffusive upwelling

Hence very old deep waters here.

After Schmitz (1995)

DPO Fig. 14.11b

2 Wind forcing

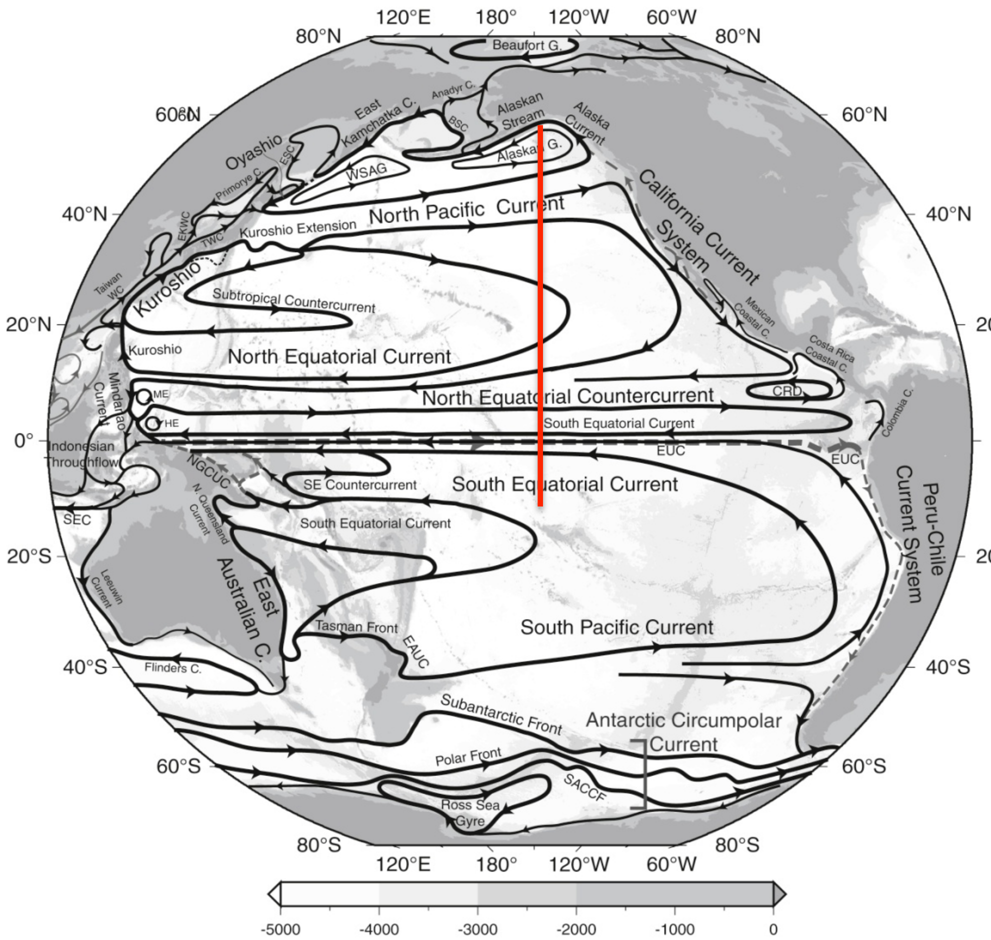


Annual mean winds. (a) Wind stress (N/m^2) (vectors) and wind-stress curl (×10^{-7} N/m^3) (color), multiplied by –1 in the Southern Hemisphere. (b) Sverdrup transport (Sv), where blue is clockwise and yellow-red is counterclockwise circulation. *Data from NCEP reanalysis (Kalnay et al.,1996).*

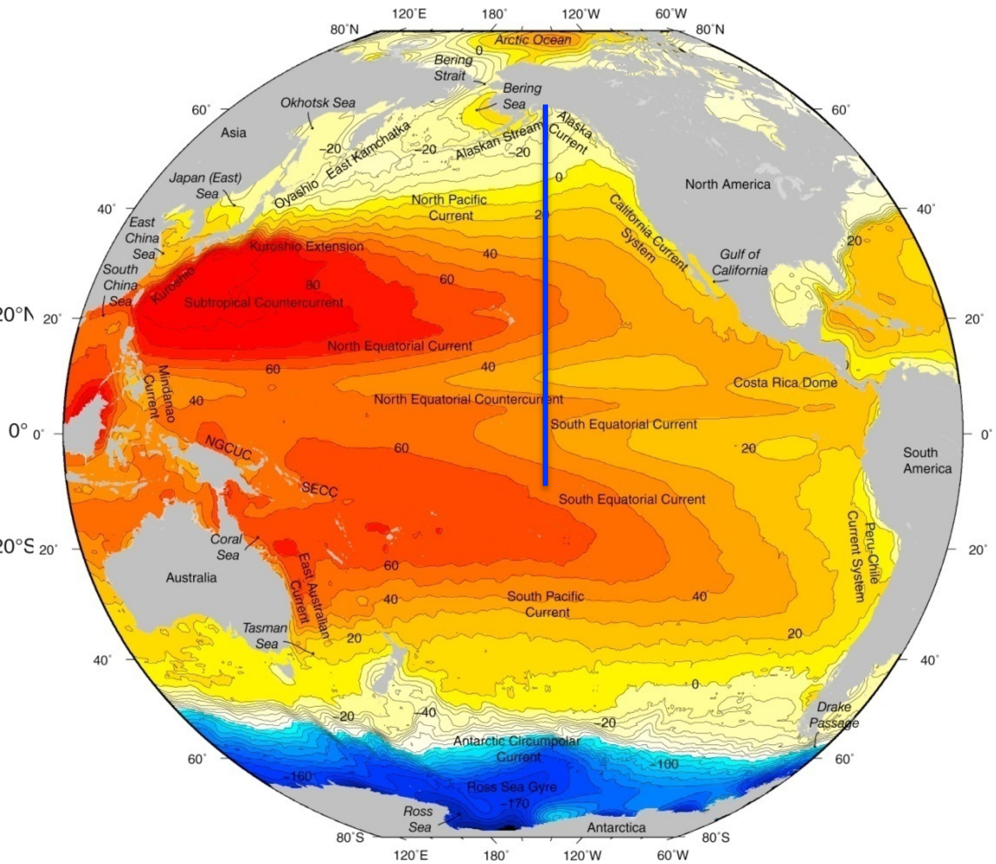
Wind forcing: Subpolar upwelling, subtropical downwelling, ITCZ upwelling

Circulation regimes: Subpolar gyre (cyclonic), subtropical gyre (anticyclonic), equatorial circulation, and into northern part of S. Pacific subtropical gyre

1 2 Upper ocean circulation 3 4



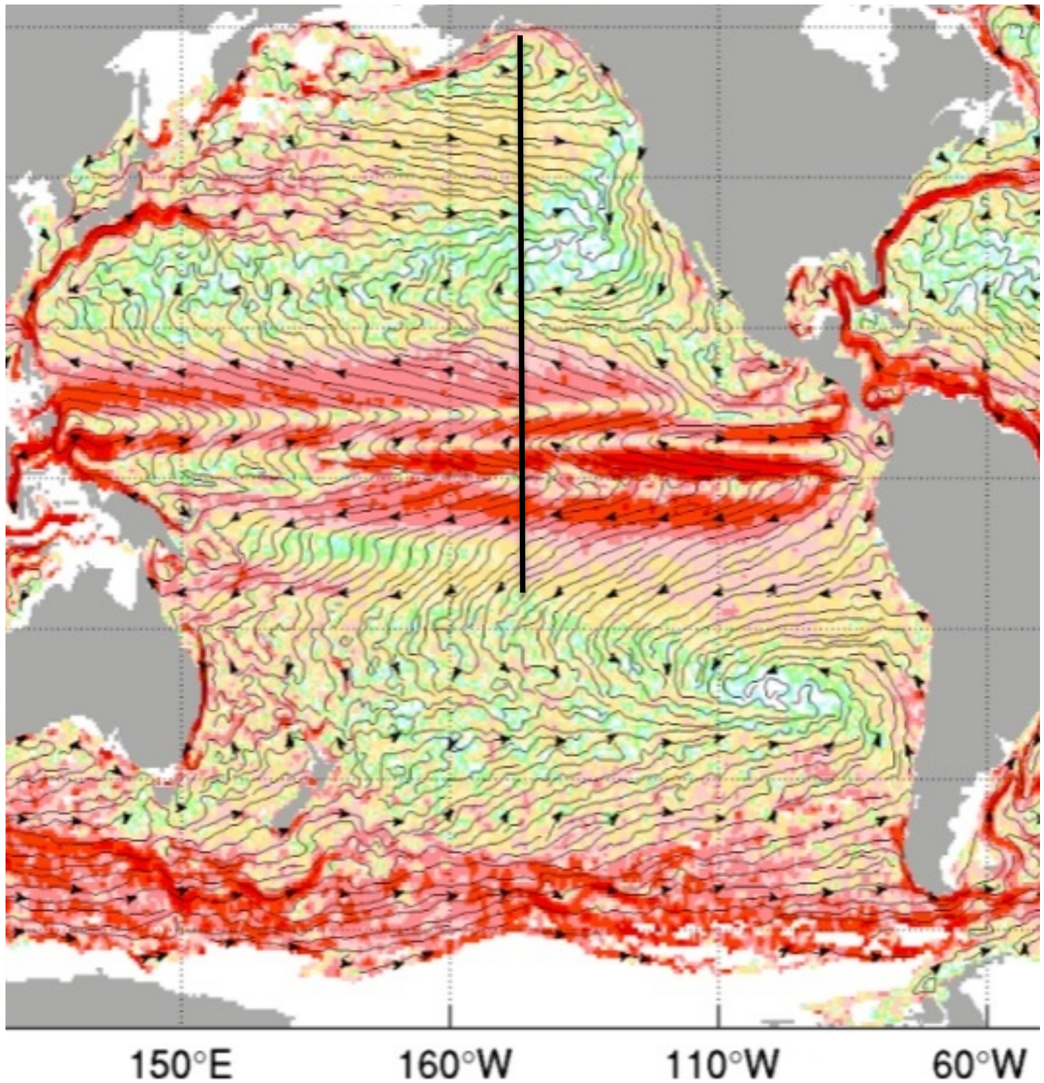
Surface geostrophic circulation schematic



Surface dynamic topography and current names (geostrophic flow)

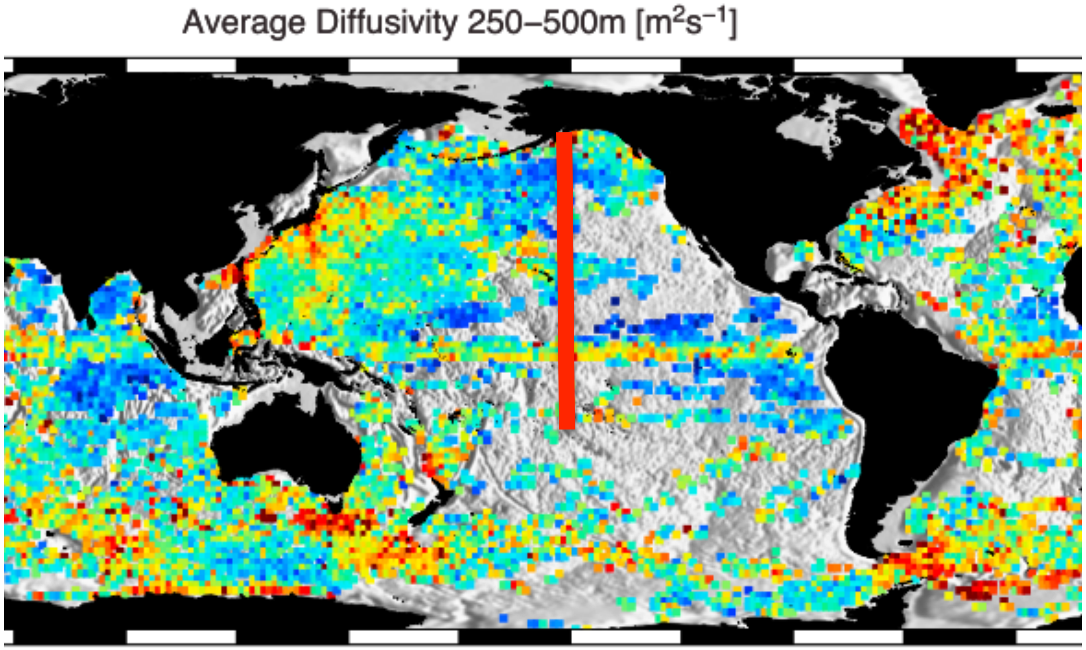
Talley (2016)

1 2 Upper ocean circulation 3 4



Surface circulation including Ekman and geostrophic flows (Maximenko et al., 2009)

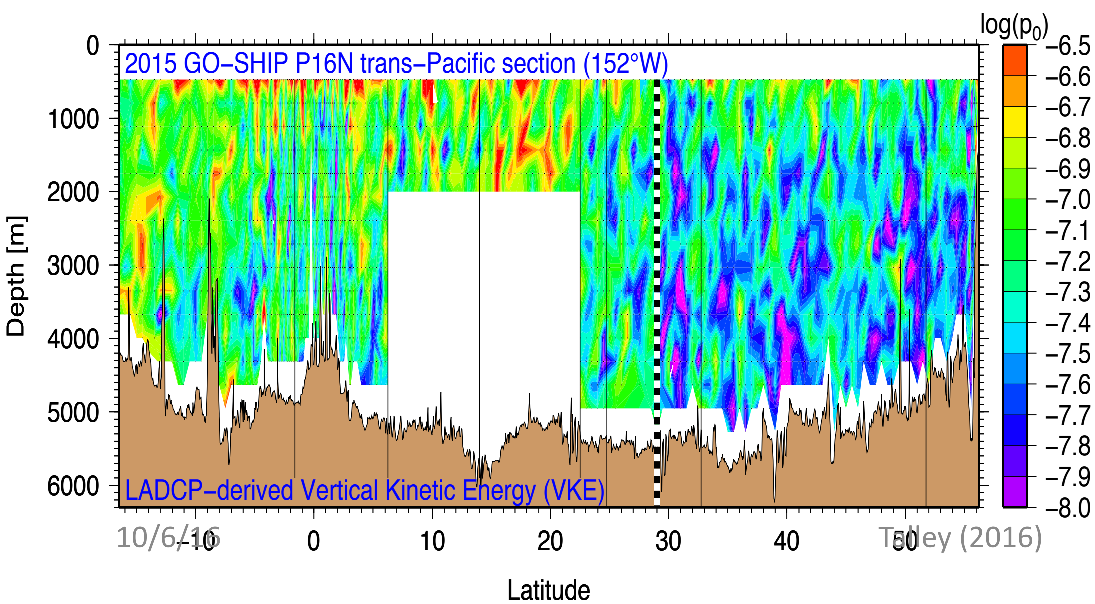
3 Upper ocean to 4 Deep



The NE Pacific is quiet

Diapycnal diffusivity 250-500 m from Argo
(Whalen et al., 2012)

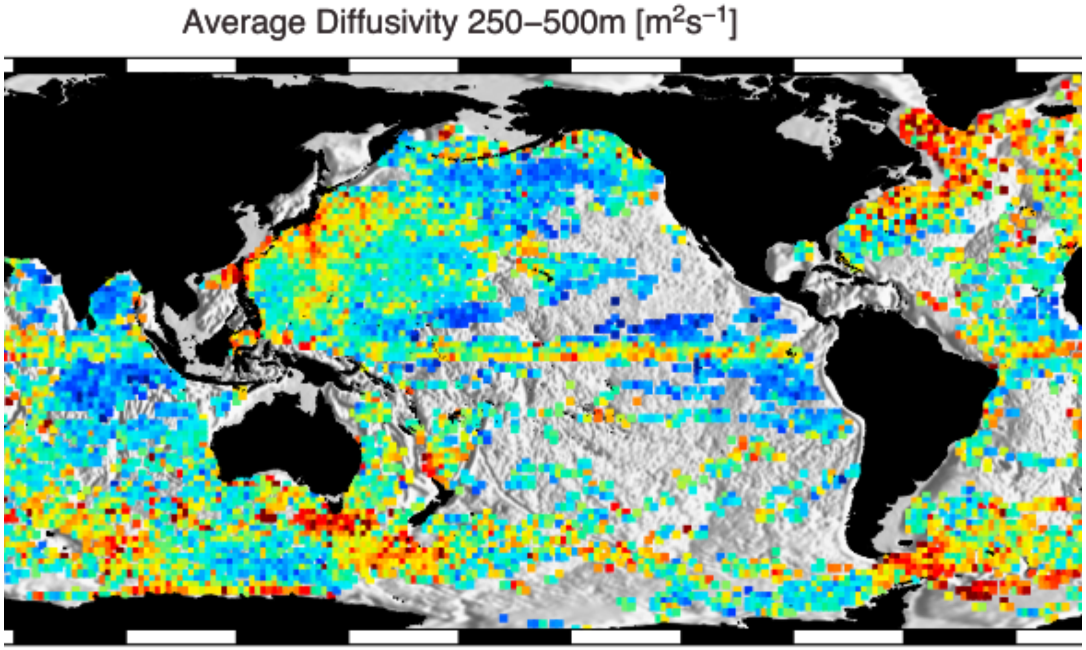
P16 has low vertical diffusivity in upper ocean



Vertical kinetic energy on P16 (Thurnherr, pers comm), which is related to diffusivity (Thurnherr, 2011)

NE Pacific has low vertical kinetic energy in deep ocean.
(Need plot of diffusivity to say anything about it, but dissipation is more directly related to the actual mixing.)

3 Upper ocean to 4 Deep



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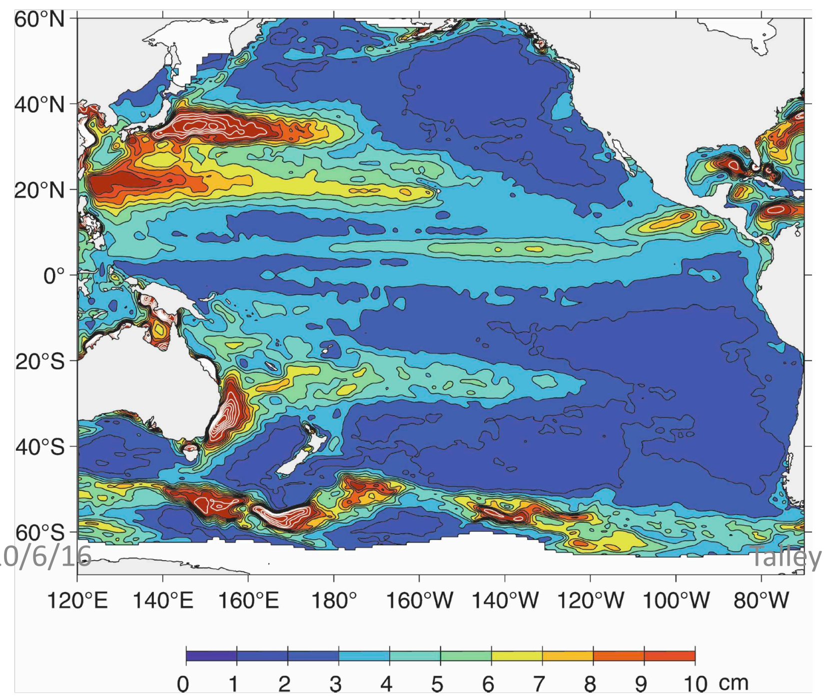
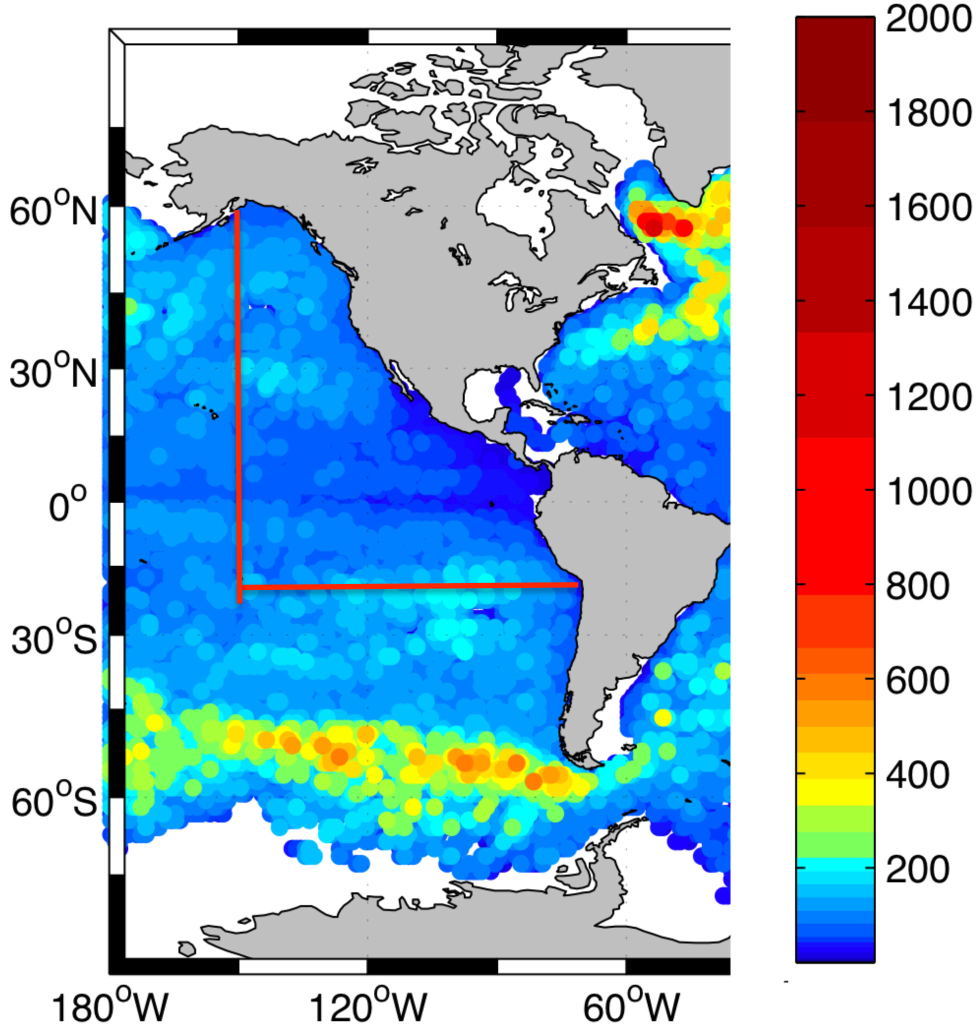


Eddy kinetic energy
(altimetric SSH)
(Qiu et al., 2008)

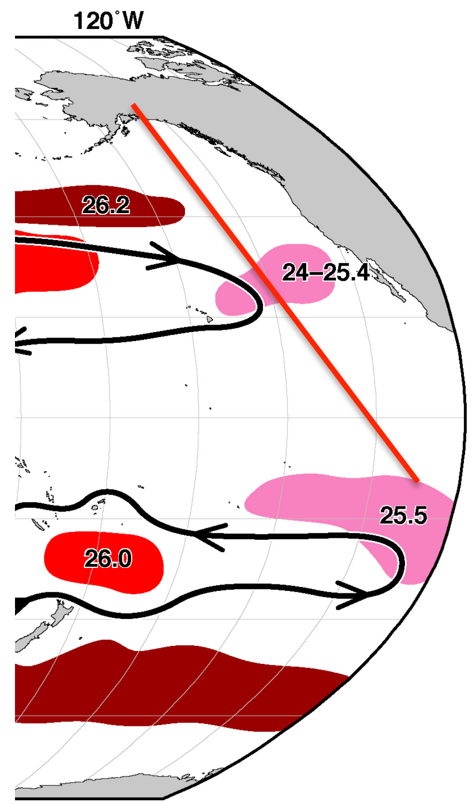
P16 is in an eddy desert except in NECC (TIWEs)

3 Upper ocean



Maximum mixed layer depth from all Argo profiles.

http://mixedlayer.ucsd.edu
(Holte, Gilson, Talley, Roemmich, 2010)



Mode waters:
P16 crosses Central Mode Water and NEPSTMW
(Hanawa and Talley, 2011)

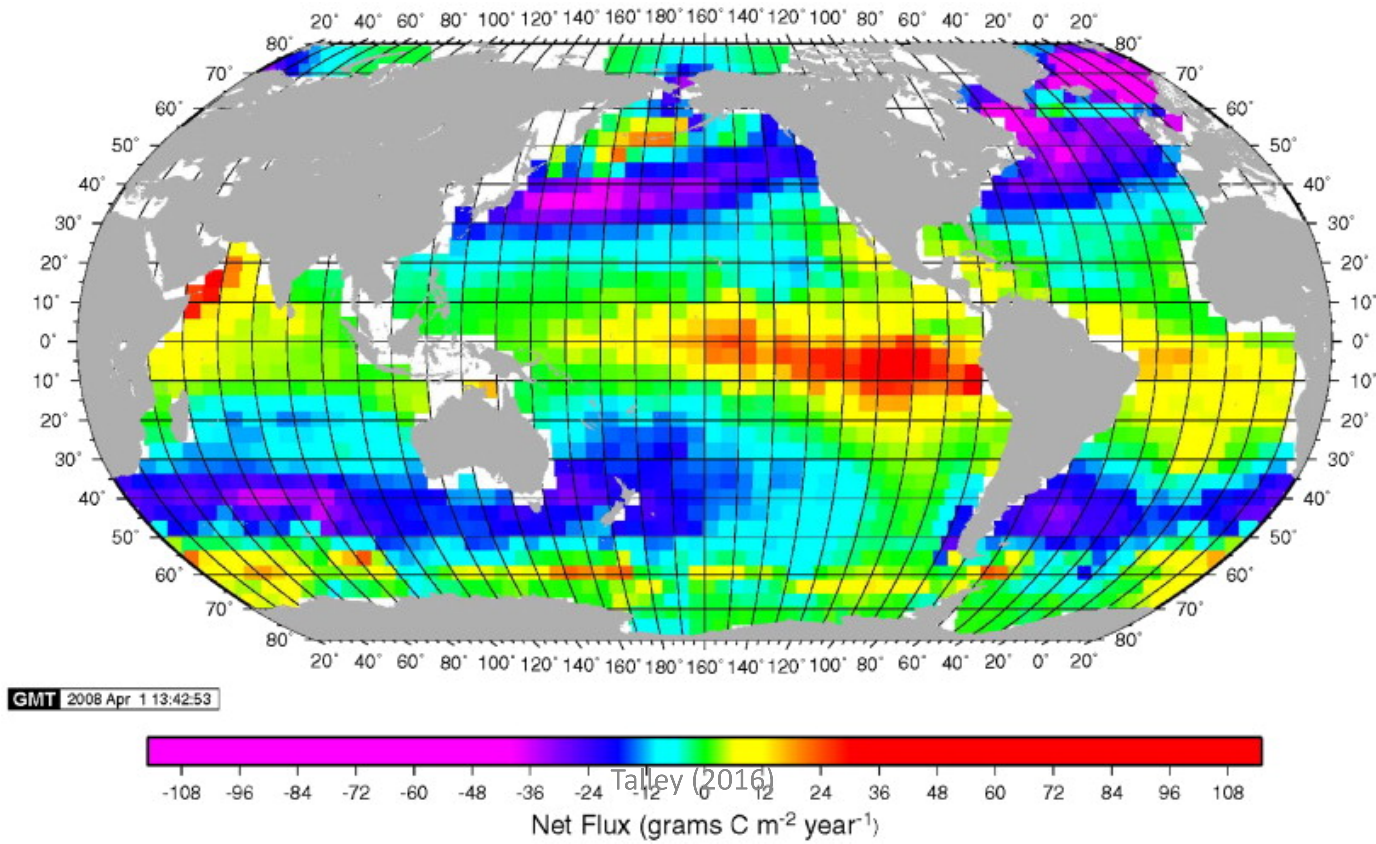
3 Upper Ocean

Air-sea CO2 flux (Takahashi et al. 2009)

Subtropical outgassing, stretching to Pacific northwest

Subpolar uptake, largest along the Aleutian Islands where there is large upwelling and drawdown of gas (evidenced in oxygen depletion in surface waters)

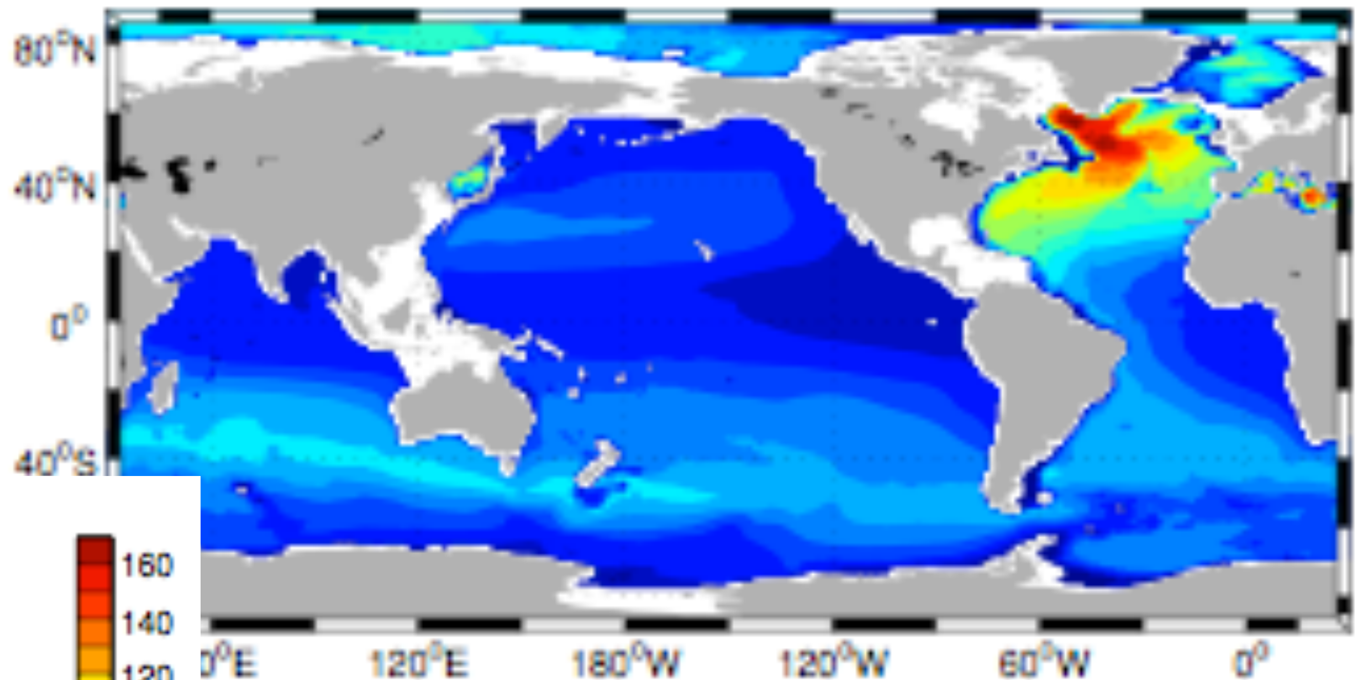
High tropical uptake associated also with upwelling

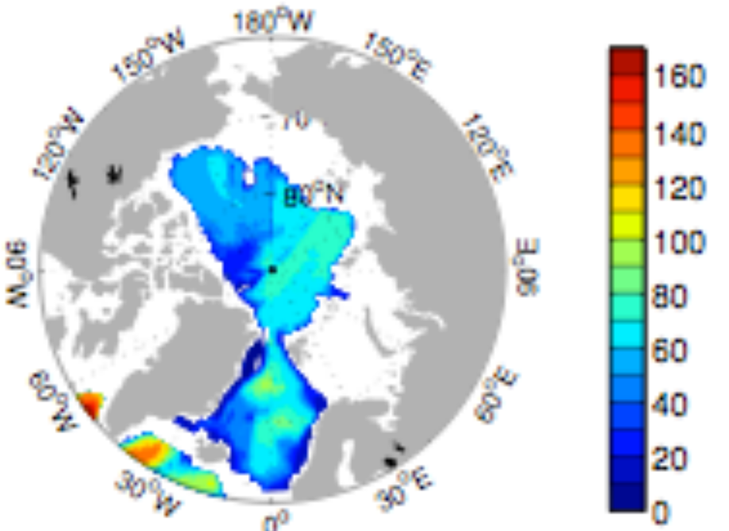


3 Upper Ocean and 4 Deep Ocean

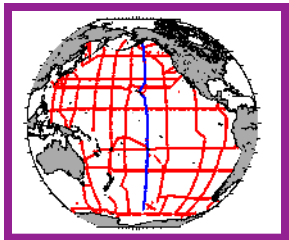
Anthropogenic CO_2

NE Pacific has little ACO_2; what there is is in the ST gyre, where the net CO_2 flux is into the ocean

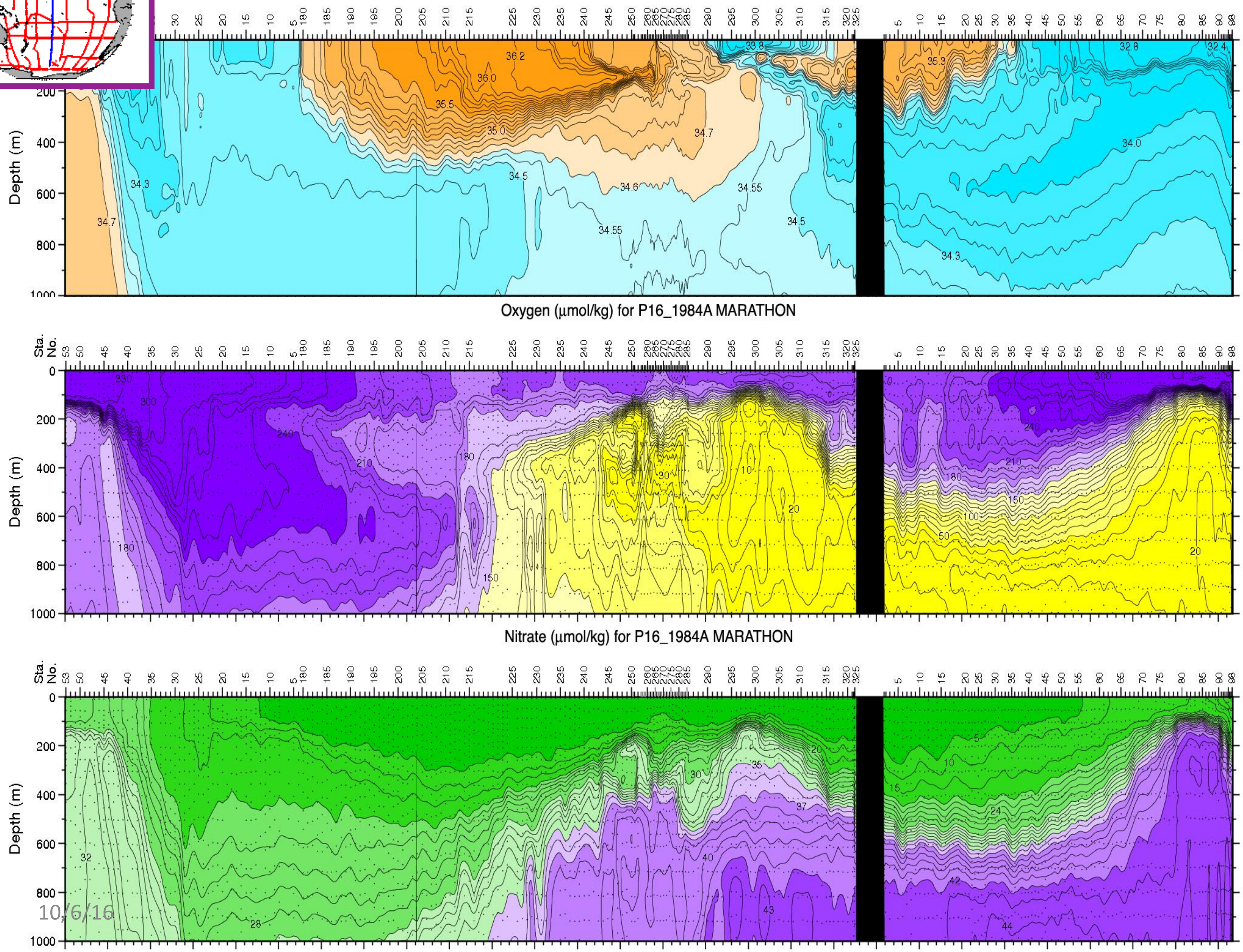




Khatiwala et al. (Biogeosciences 2013)

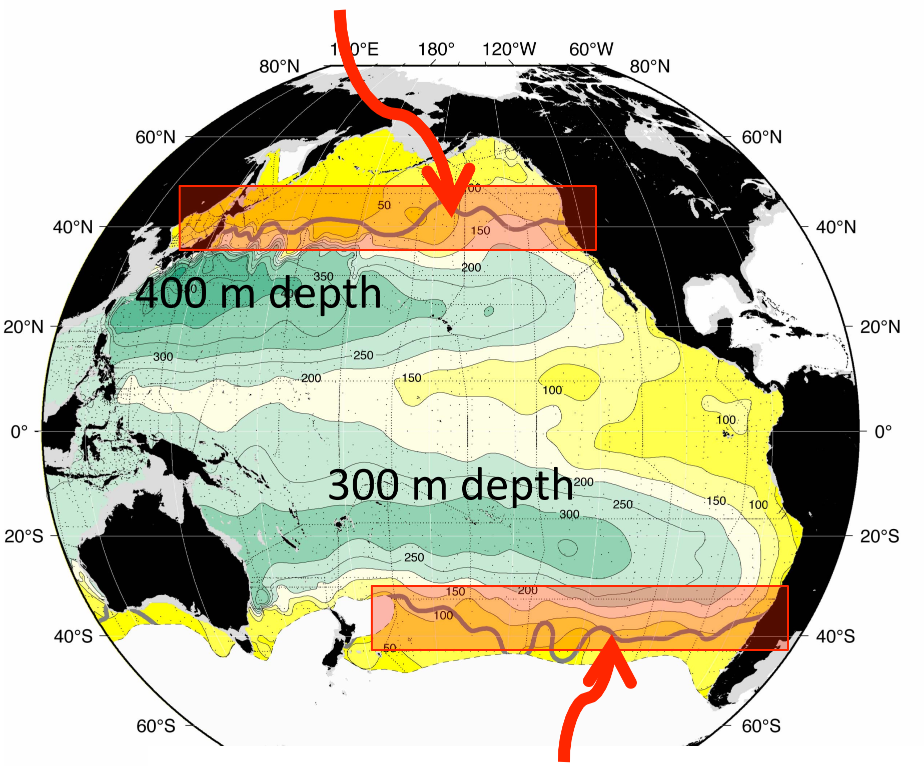


3 Upper ocean water mass descriptions

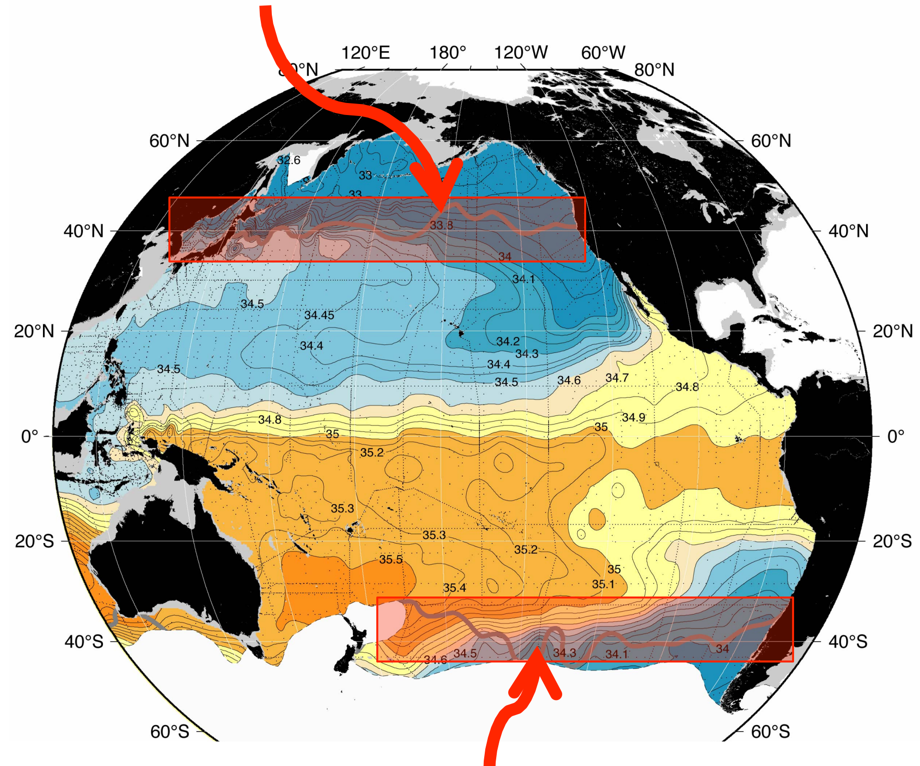


3 Upper ocean ventilation concepts

Depth (m) 26.0 γ^n (kg/m^3)



Salinity (PSS78) 26.0 γ^n (kg/m^3)



Surface outcrop: source of water for the this shallow isopycnal

Water in ocean interior originates at surface outcrops. (There is no interior source of high density.)

The water mostly flows into the ocean interior along isopycnals (presuming only weak diapycnal mixing).

Talley (2016)

WOCE Pacific Atlas (2007)

Subducted salinity maximum water: Subtropical Underwater

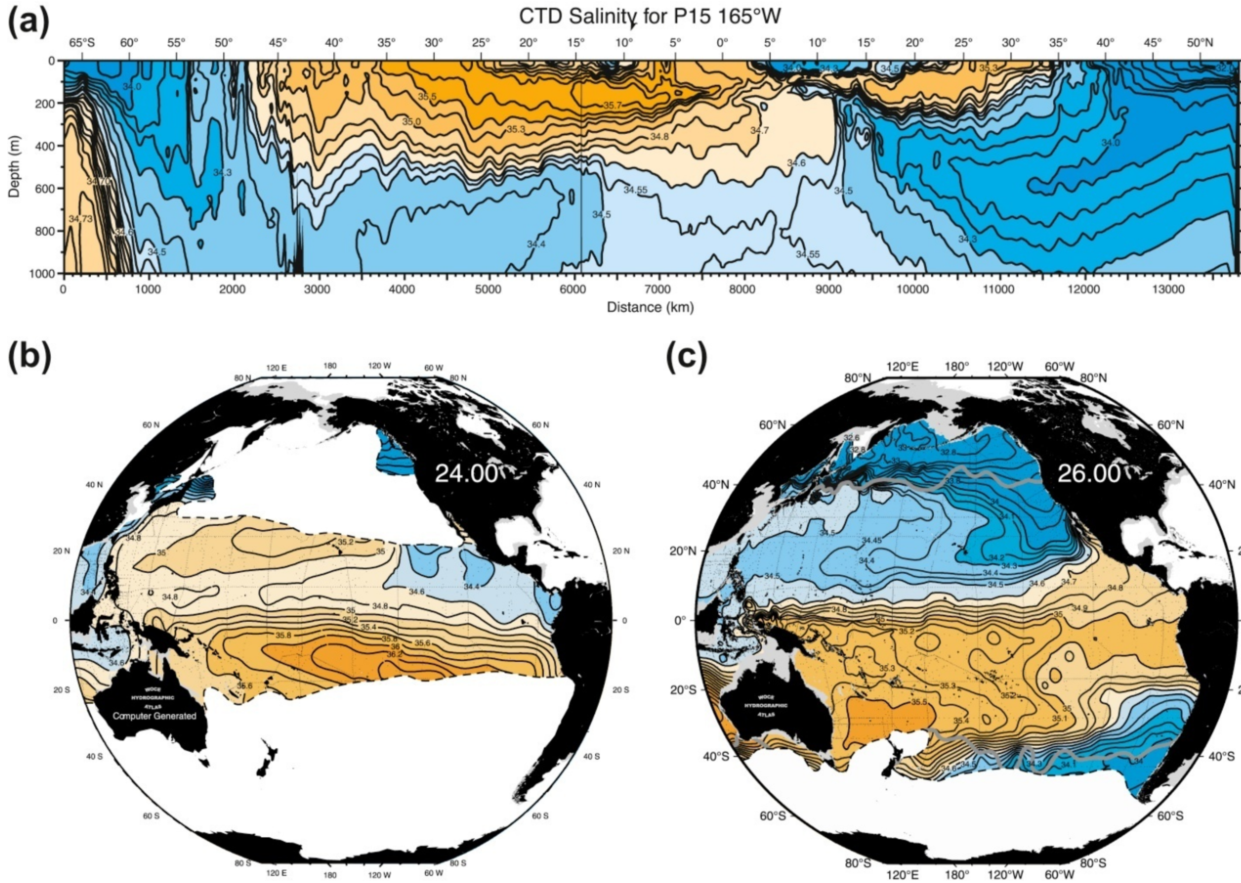
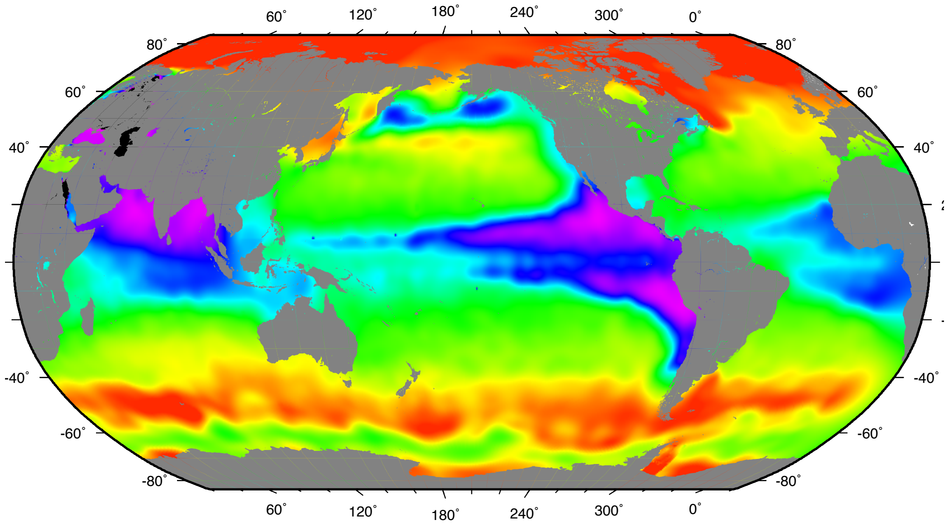


FIGURE 10.30

Salinity: (a) along 165°W (WOCE P15); (b) at neutral density 24.0 kg/m^3, characteristic of STUW; and (c) at neutral density 26.00 kg/m^3, characteristic of SPSTMW. The isopycnals intersect the surface along the dashed contours Gray contours in (c) indicate winter outcrops. *Source: From WOCE Pacific Ocean Atlas, Talley (2007).*

3 Upper ocean

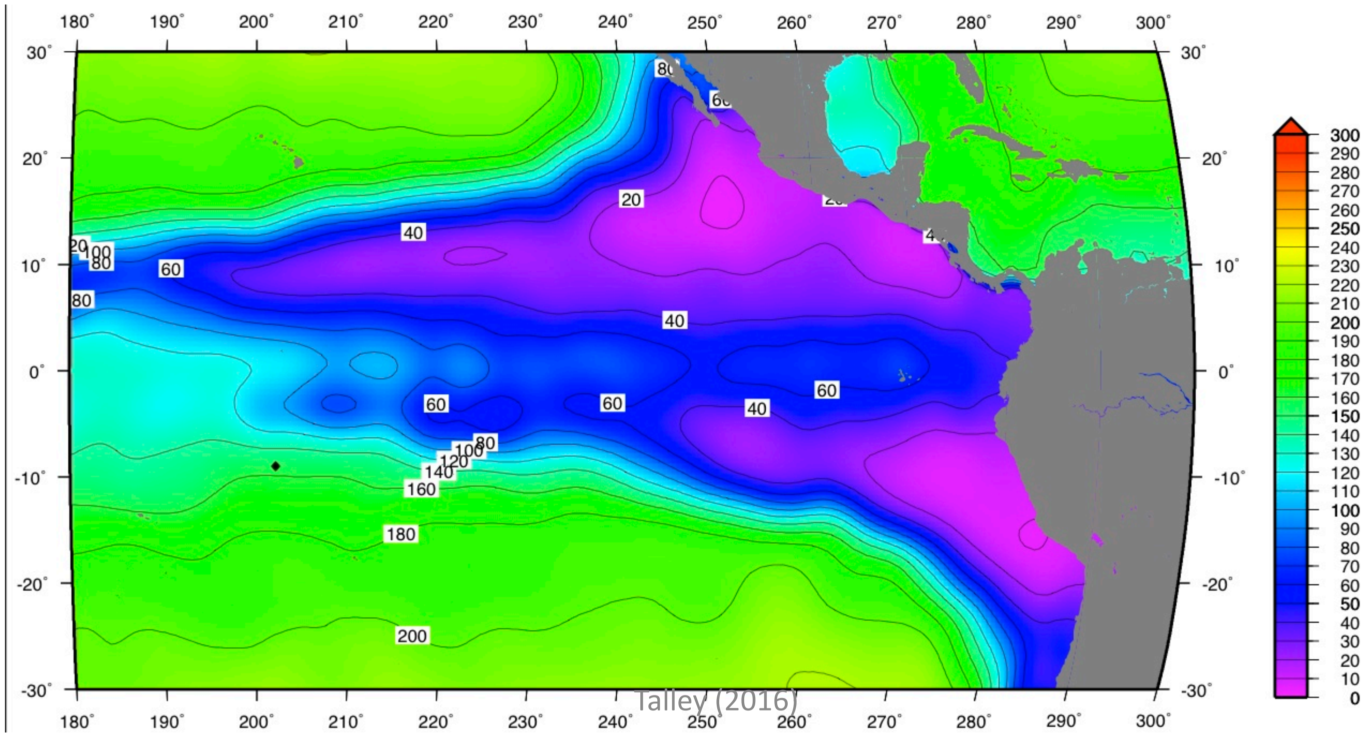
Oxygen (µmol/kg) at 200 m



Oxygen Minimum Zone (OMZ)

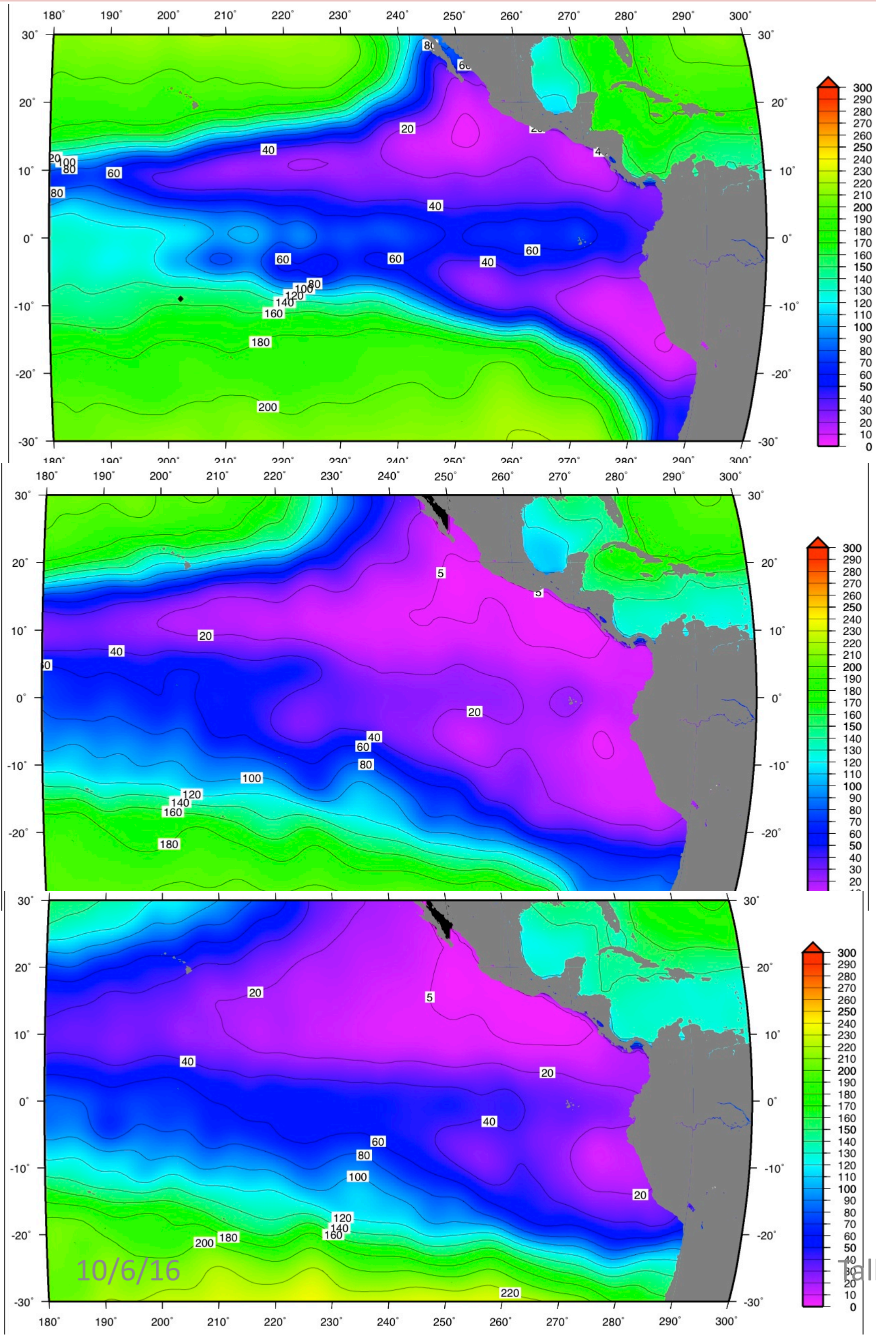
Oxygen at 200 m depth

(WOCE Global Hydrographic Climatology, Gouretski and Koltermann, 2004)



Talley (2016)

3 Upper ocean



Oxygen at

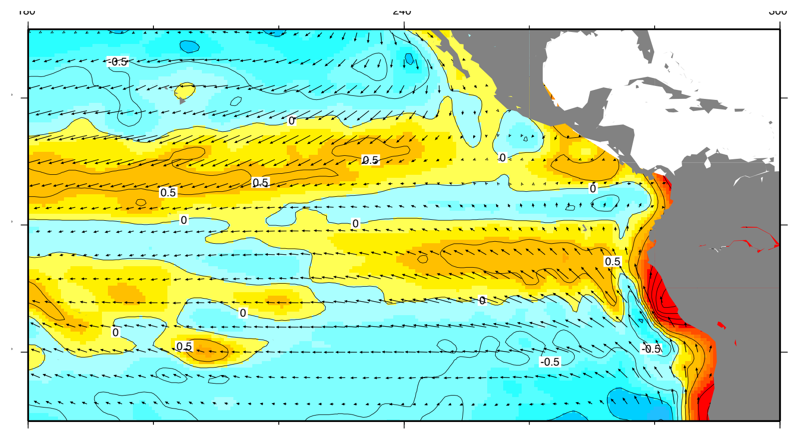
200 m

400 m

600 m

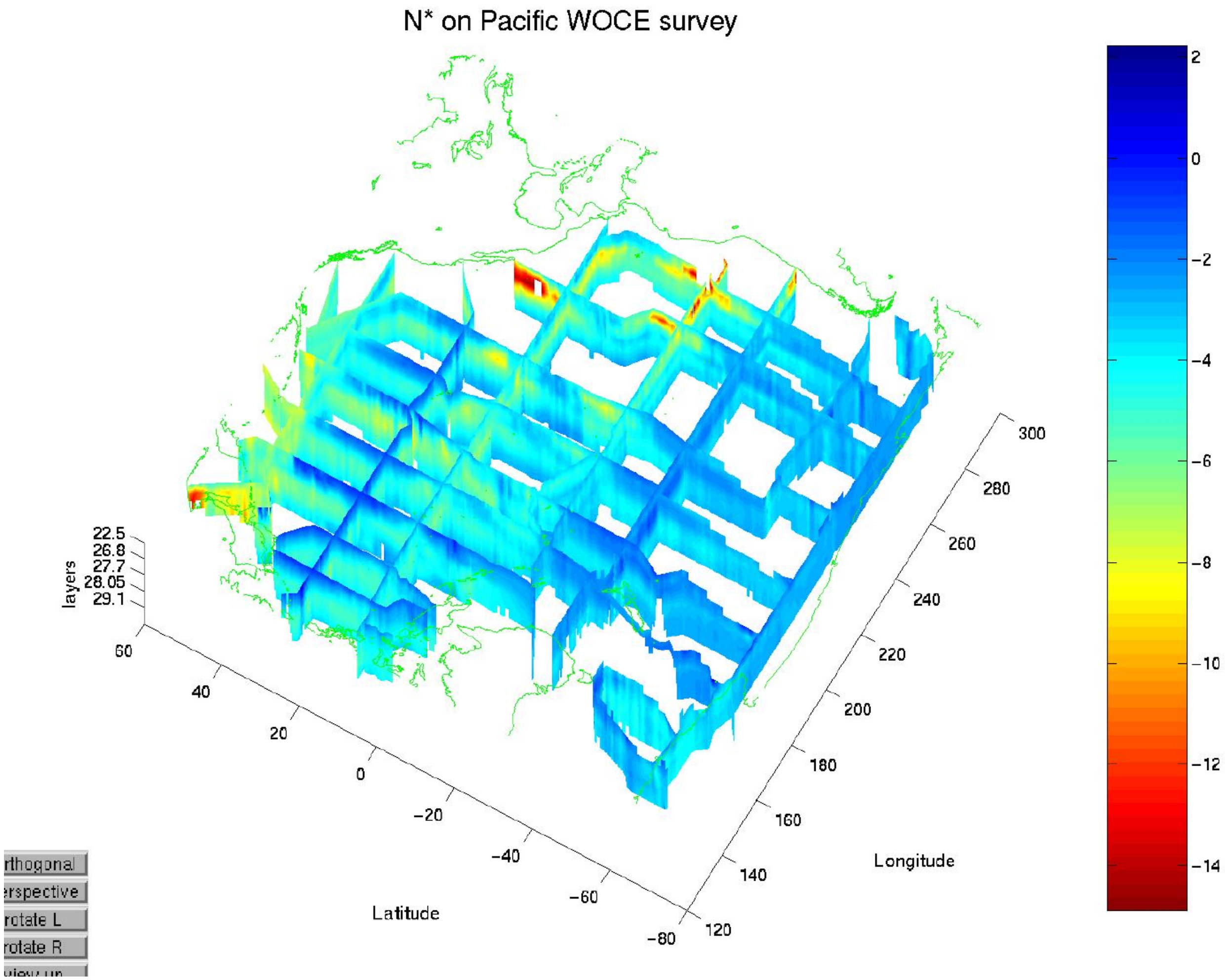
(WOCE Global Hydrographic Climatology, Gouretski and Koltermann, 2004)

OMZ associated with **open ocean upwelling**; stronger N.Pacific OMZ due to lack of nearby vigorous ventilation at and below the OMZ compared with S. Pacific



Wind stress curl (oranges = upwelling; blues = downwelling)

3 Upper ocean and 4 Deep ocean



N* from the Pacific WHP survey

(Robbins and Talley, unpublished)

Low N* in the denitrification region of the OMZ

Low N* in subpolar gyre, principal source Okhotsk Sea – sedimentary denitrification

3 Upper ocean

Summary:

Upper ocean circulation is in the subducted, ventilated layer

Characteristic water mass distributions:
Examined only two – Subtropical Underwater and the oxygen minimum zone

Much more detail to be presented: frontal locations especially and how the subpolar and subtropical gyres interact, details about equatorial circulation, etc

Why there is net heat gain in the eastern subpolar gyre: horizontal advection vs. large-scale upwelling?

4 Intermediate, deep and abyssal ocean

Vertical sections of properties assist with understanding directions of deep meridional transports

Deep circulation pathways from

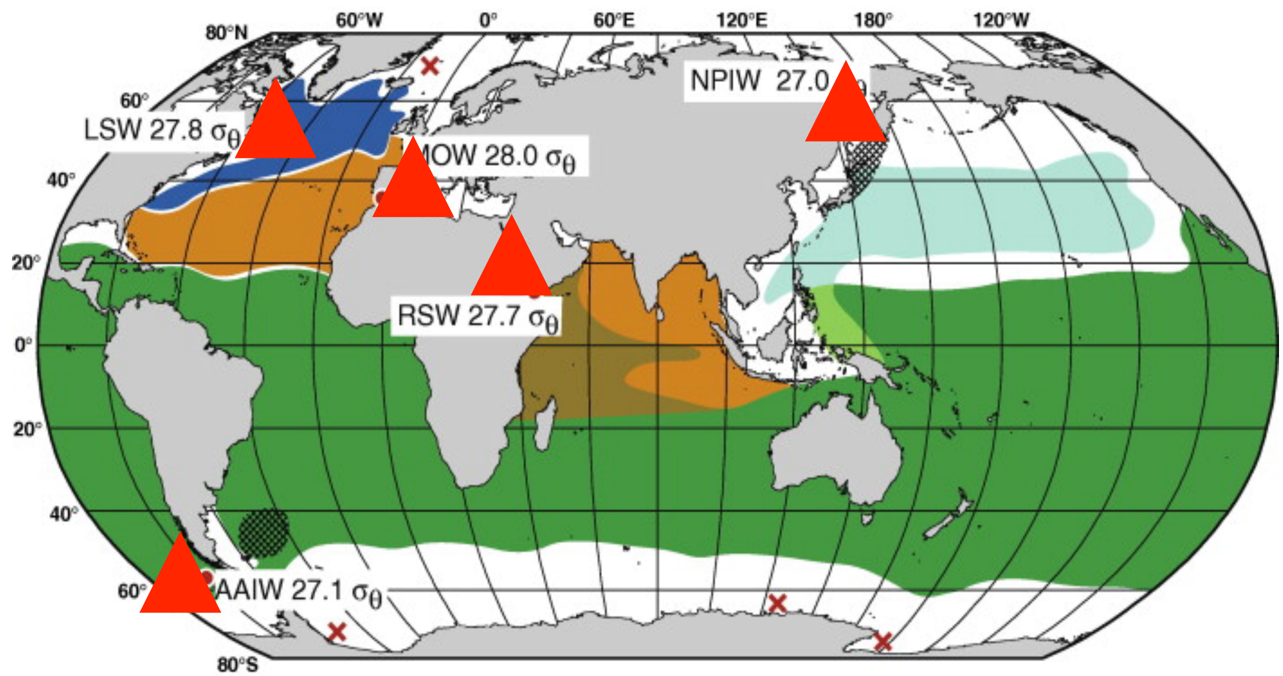
Isopycnal maps of properties to see result of pathways and sources

- Deep North Pacific is far removed from global overturning circulation: even a reverse deep cell, consistent with diffusivity distribution

4 Intermediate water location

North Pacific Intermediate Water:
Forms through brine rejection in the Okhotsk Sea
Spreads and mixes through Kuril Islands, transporting properties deep
Ventilates subpolar and subtropical North Pacific; salinity minimum in the subtropical gyre

This IS the mode of 'deep' overturn for the N. Pacific.
It has the same role as NADW formation in the N. Atlantic:
- much weaker (2 Sv instead of 20 Sv)
- much less dense and much shallower



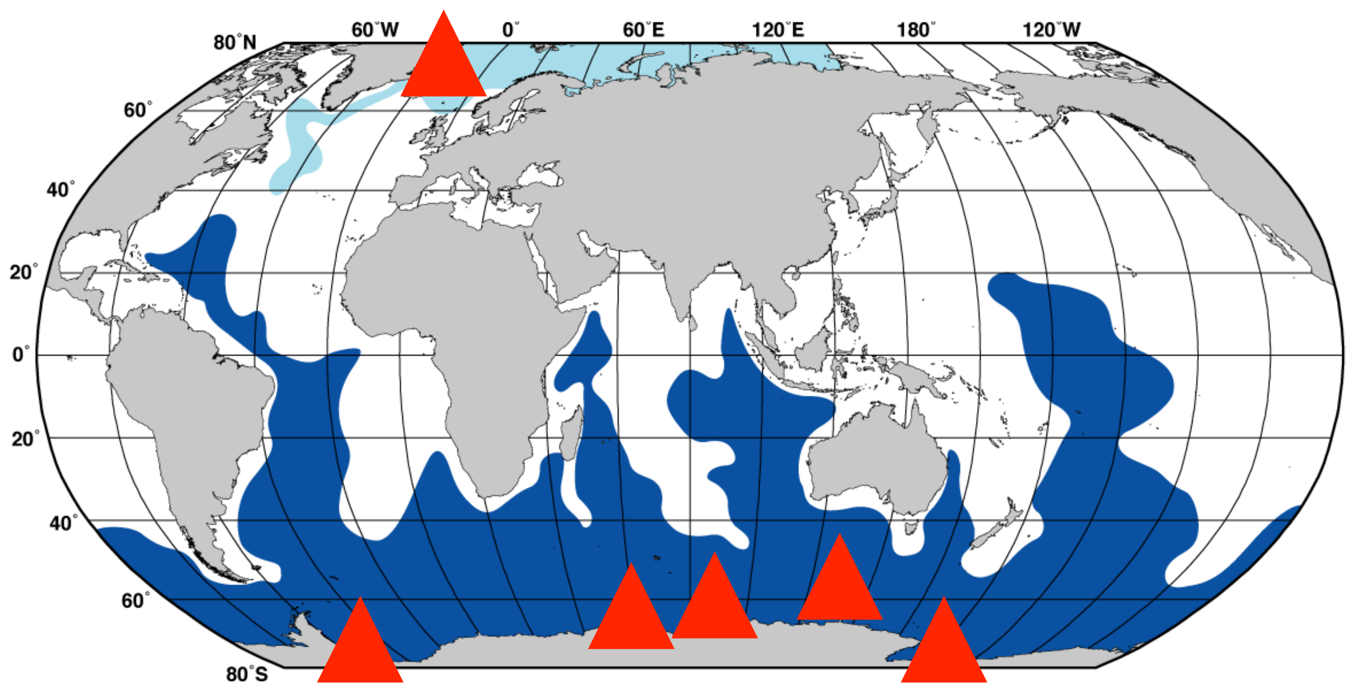
Talley (2008)

4 Deep and Bottom Water

No deep or bottom water are formed through surface processes (convection or brine rejection) in the North Pacific

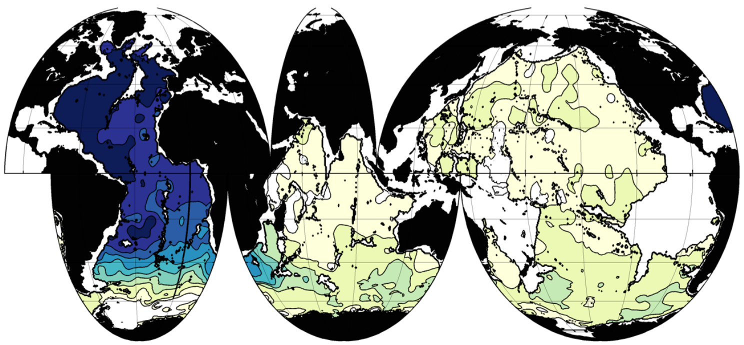
All are formed in the northern N. Atlantic and Antarctic

This is because the Pacific Ocean is much fresher than the other oceans.

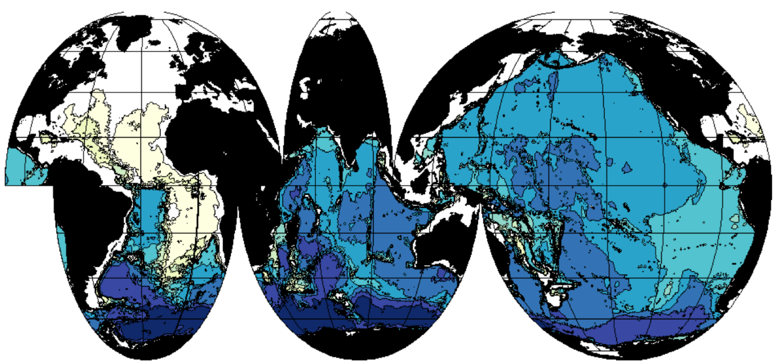


Talley (1997)

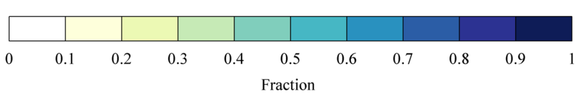
4 Deep and Bottom Water



(a) Fraction of NADW at γ^N=28.06 kg/m^3 (2500-3000 m)



(b) Fraction of AABW at ocean bottom



Johnson et al. (2008) OMP analysis using just 2 end members.

Fraction of NADW in the deep water layer

Fraction of AABW in the bottom layer

What if we added diapycnal processes (downward diffusion of heat) to this OMP and calculate fraction of locally, diffusively formed Pacific Deep Water?

Talley (2016)

4 Deep and Bottom Water

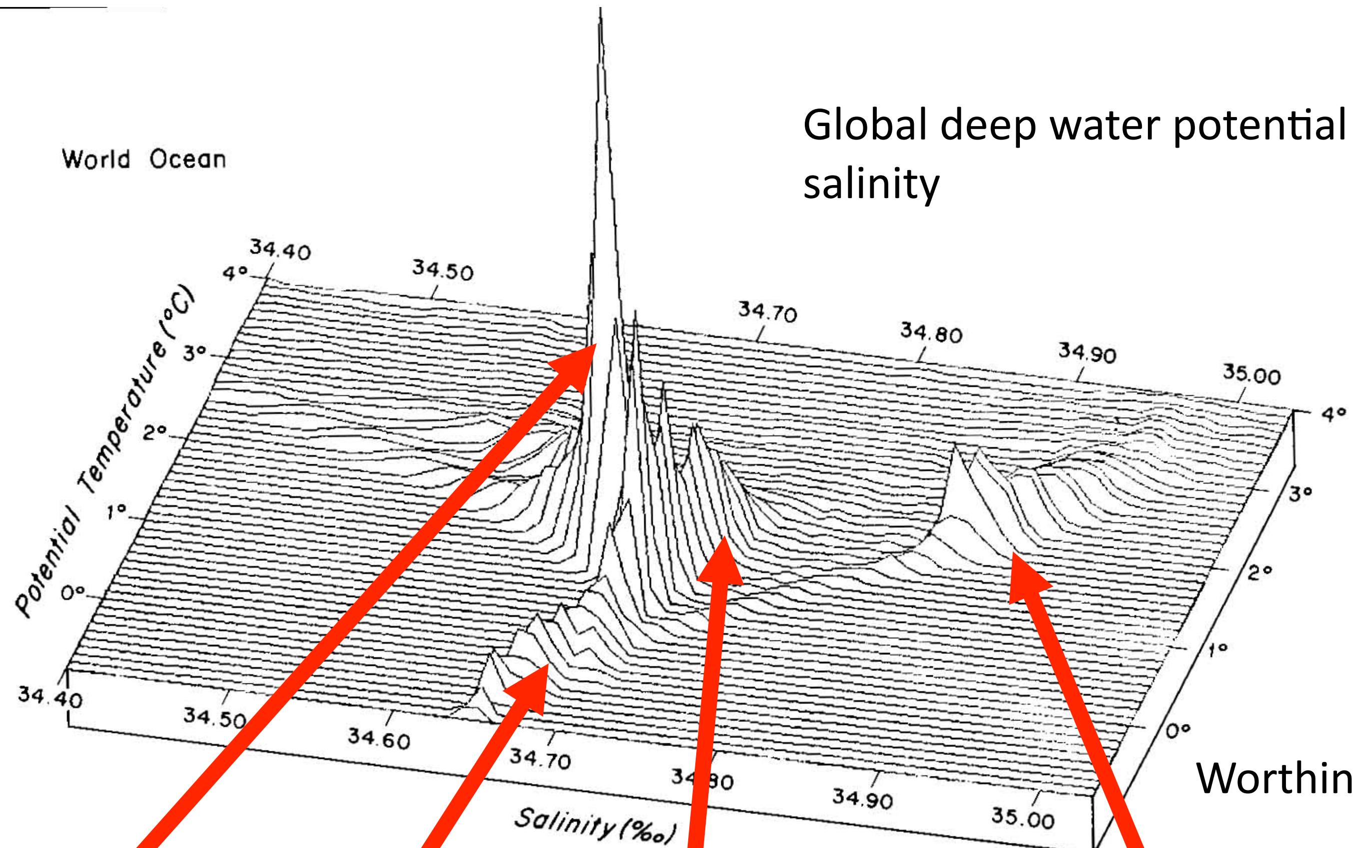


Figure 2.2 Simulated three-dimensional T–S diagram of the water masses of the world ocean. Apparent elevation is proportional to volume. Elevation of highest peak corresponds to 26.0 × 10⁶ km³ per bivariate class 0.1°C × 0.01‰.

Global deep water potential temperature-salinity

Worthington, 1982

Pacific Deep Water

(or Common Water)

Antarctic Bottom Water

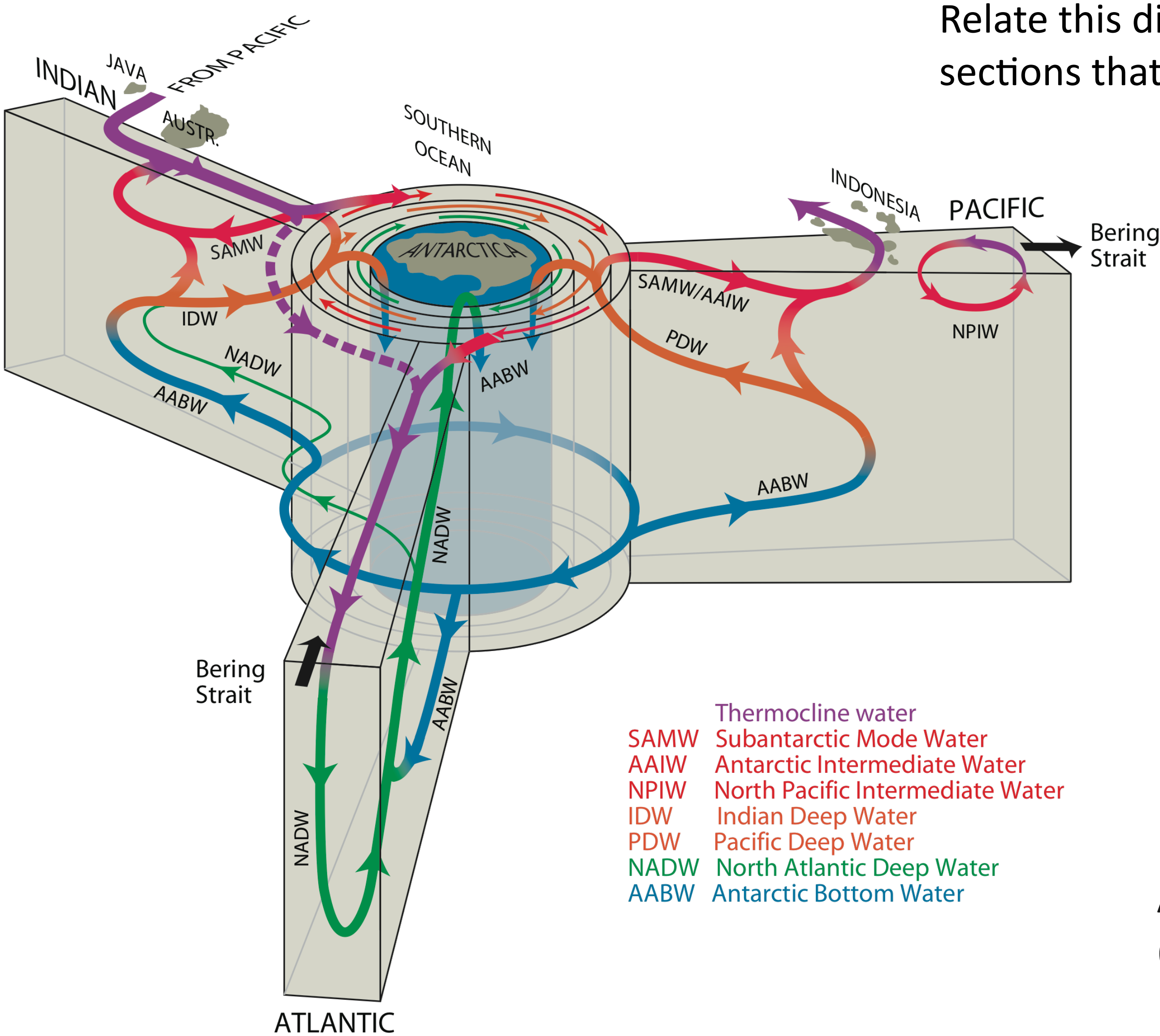
Indian Deep Water

North Atlantic Deep Water

DPO 4.17b

4 Deep and Bottom Water

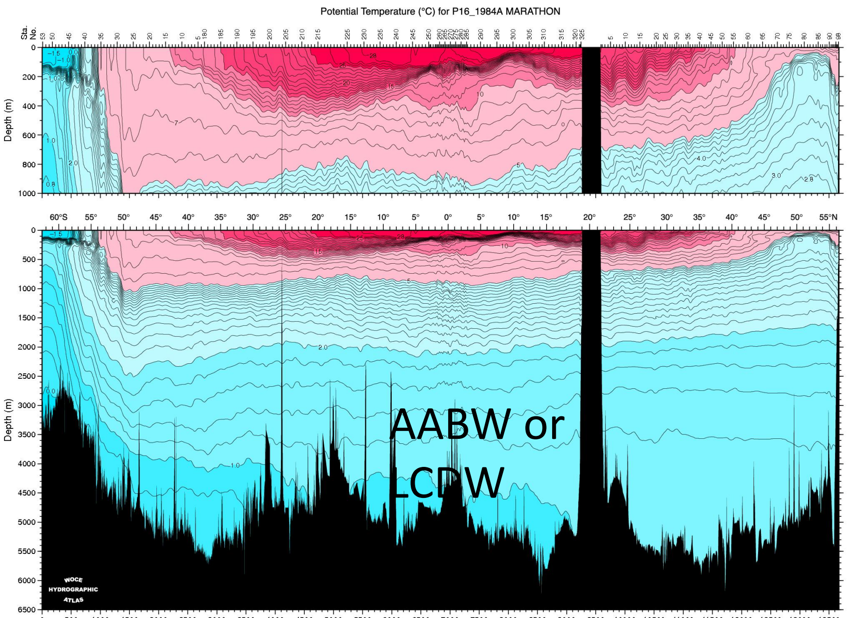
Relate this diagram to the vertical sections that follow



After Schmitz (1995)

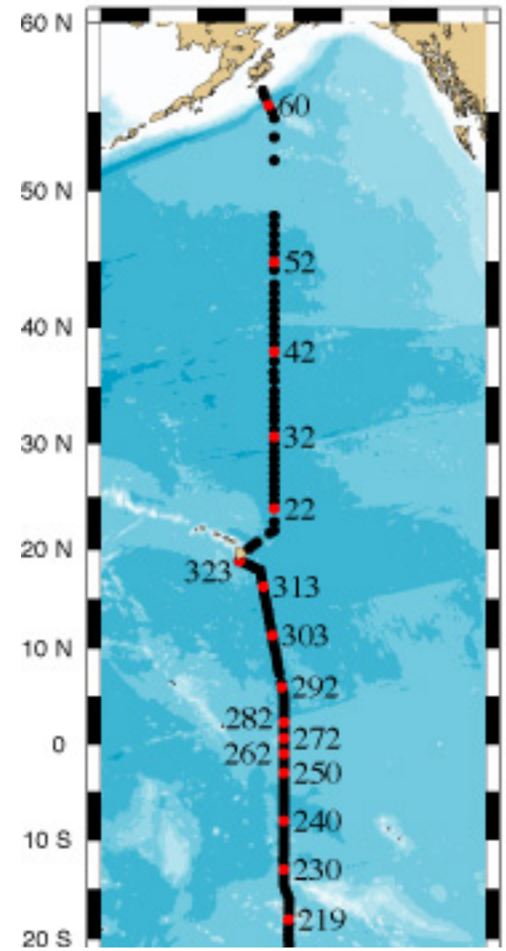
DPO Fig. 14.11b

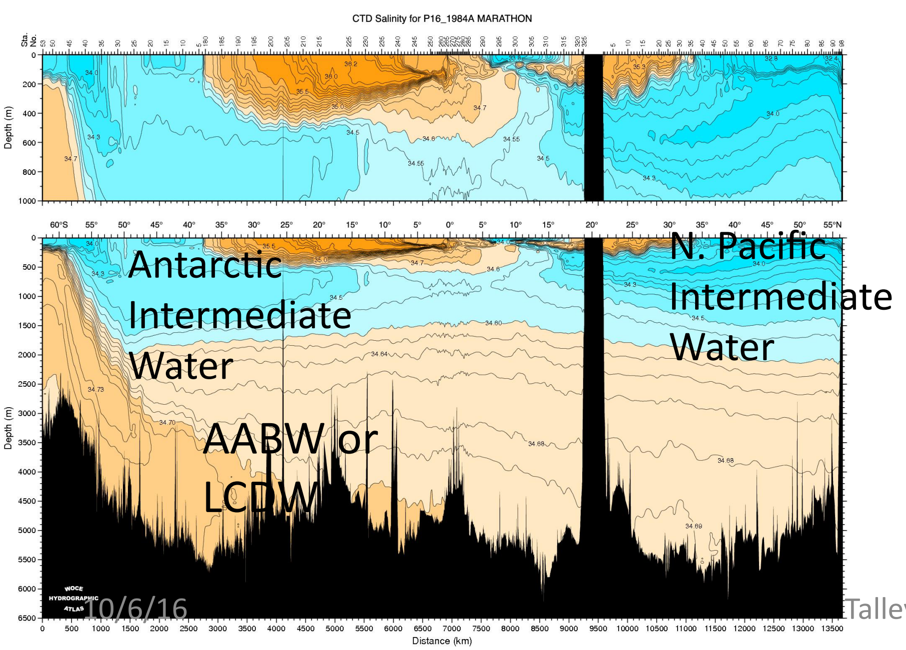
1 2 3 4 Deep and abyssal circulation and properties



P16 WOCE/GO-SHIP

Potential temperature (note dipping of isotherms into the EPR due to geothermal heating and mixing)

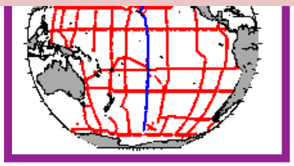


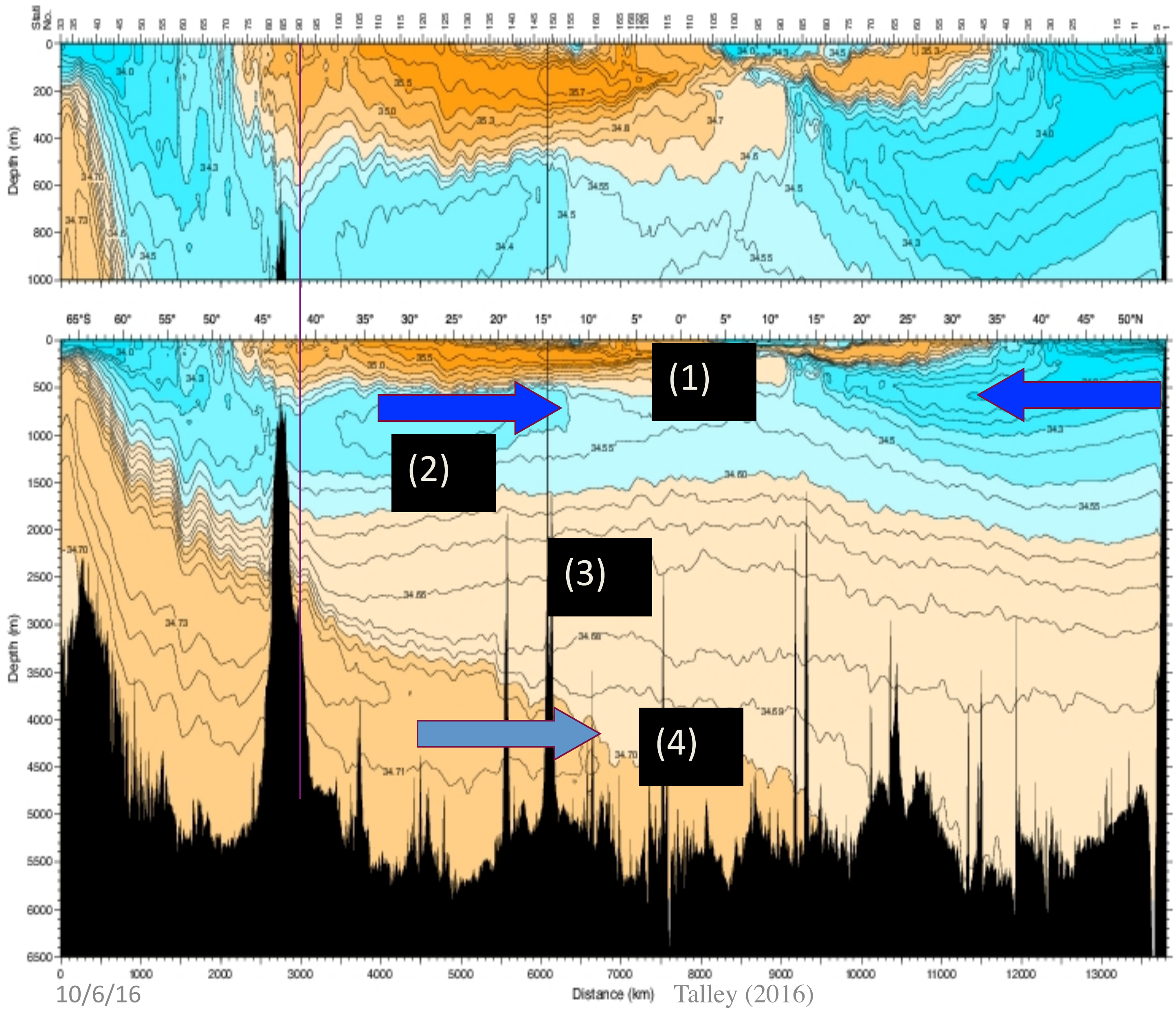


Salinity

Talley (2016)

Salinity in mid-Pacific (150W)

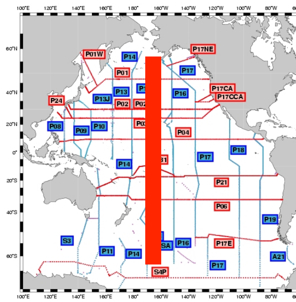


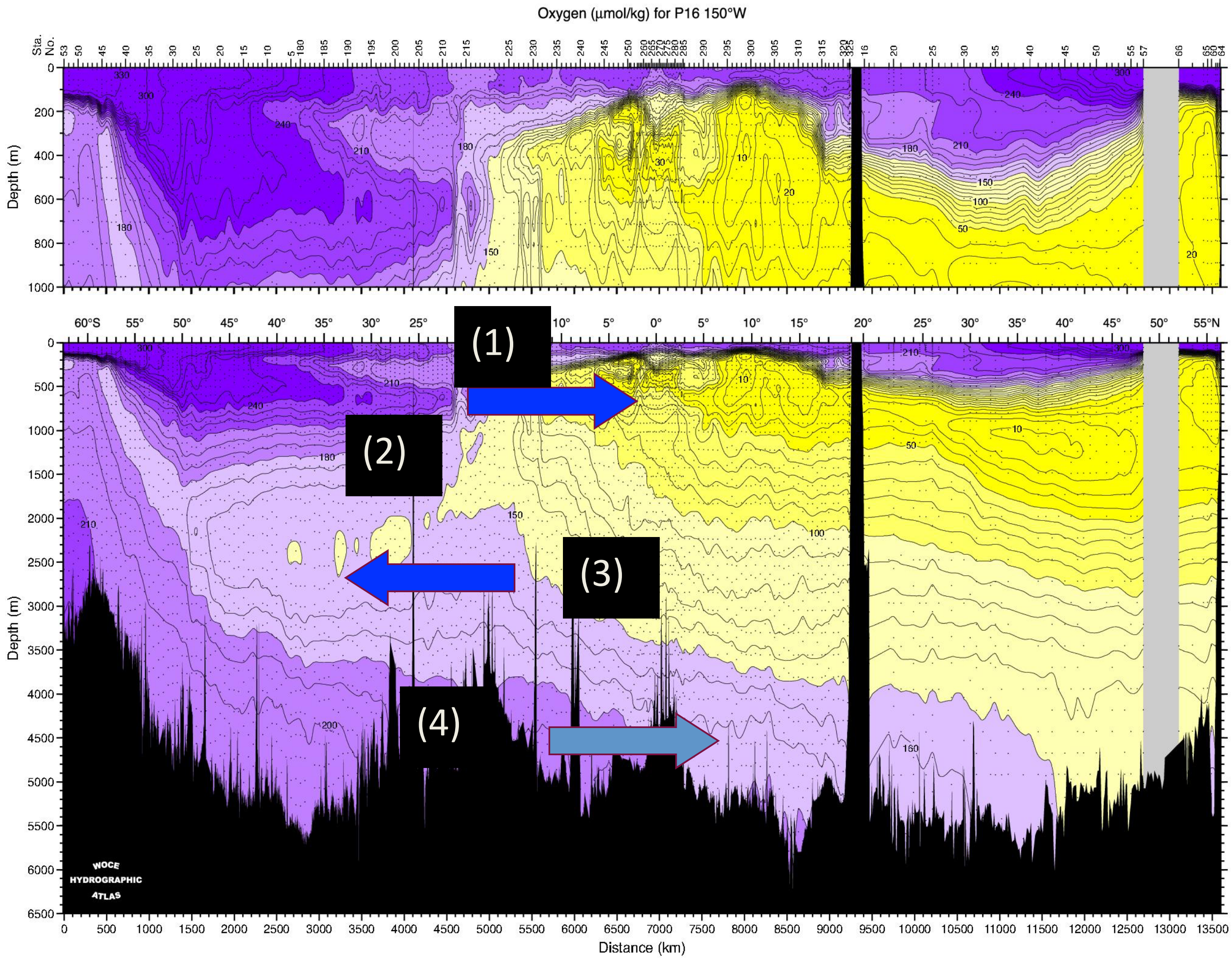


(1) Upper
(2) AAIW and NPIW
(3) PDW
(4) LCBW (AABW)

Talley (2016)

Oxygen in mid-Pacific (150W)





(1) Upper

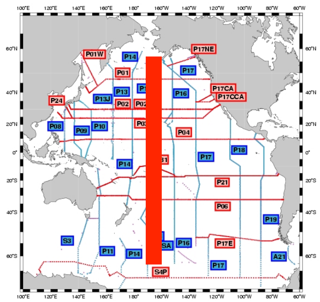
(2) AAIW and NPIW

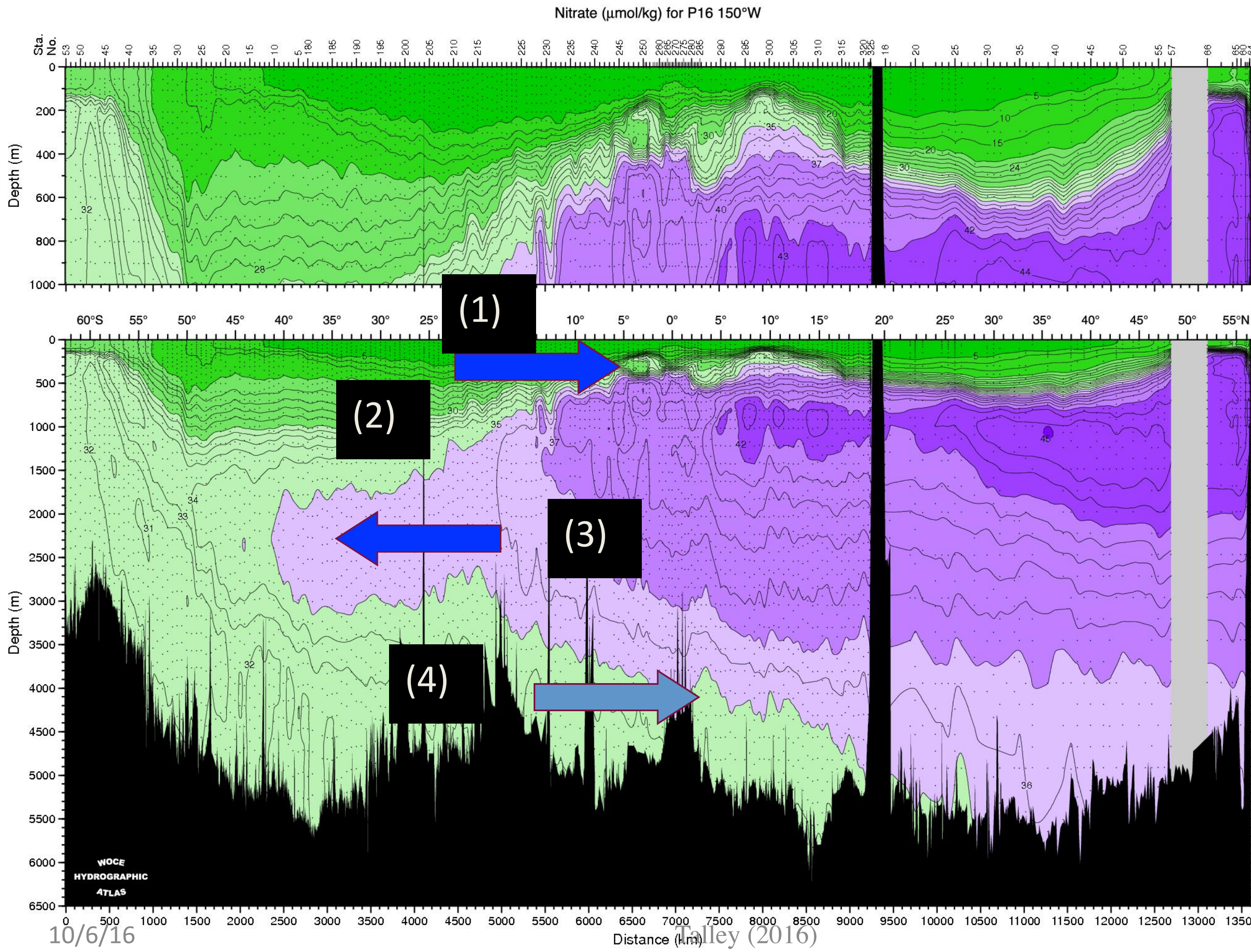
(3) PDW

(4) LCBW (AABW)

Talley (2016)

Nitrate in mid-Pacific (150W)





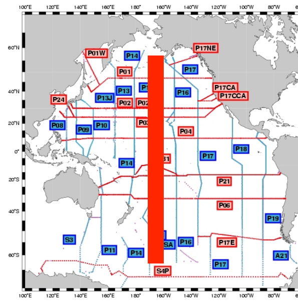
(1) Upper

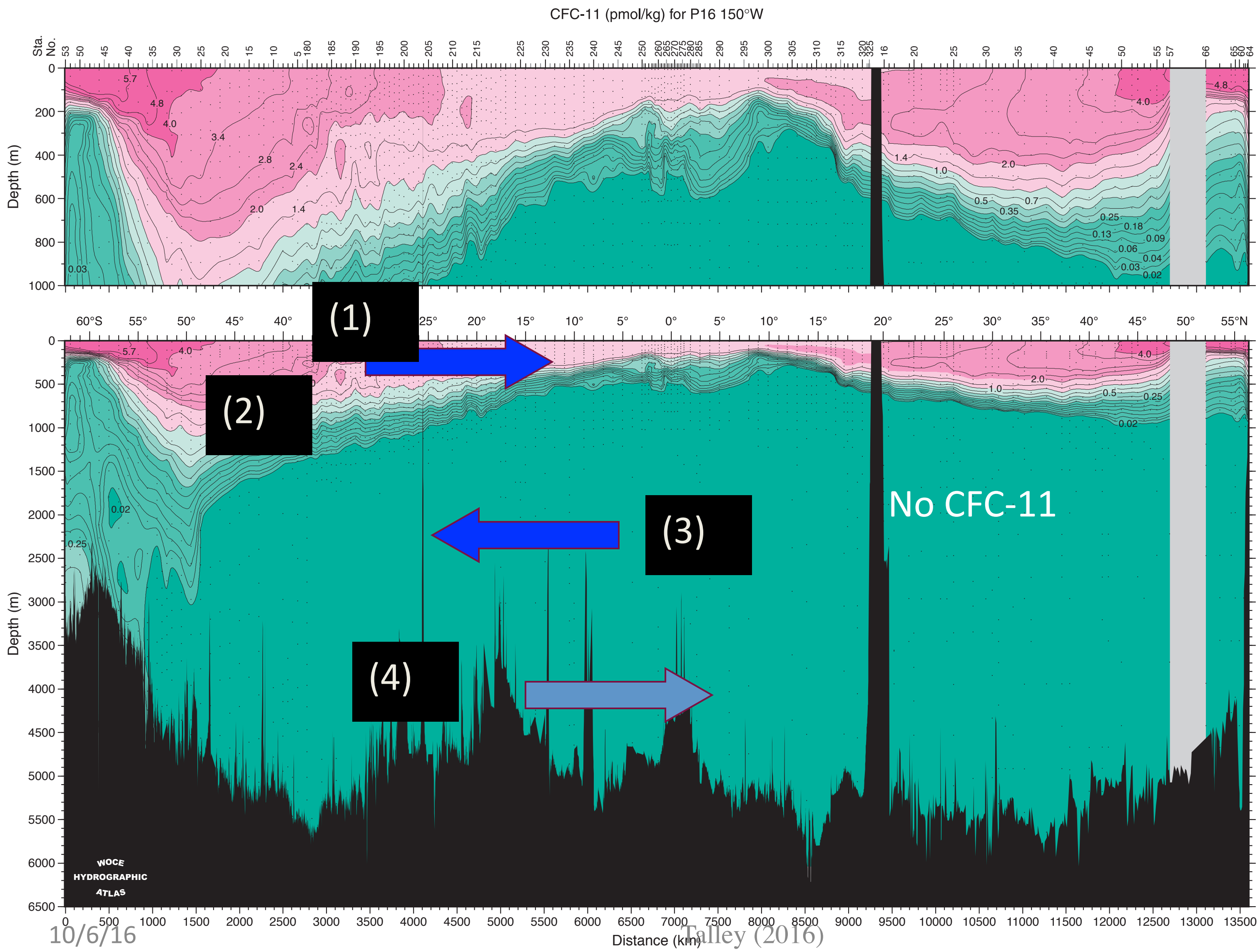
(2) AAIW and NPIW

(3) PDW

(4) LCBW (AABW)

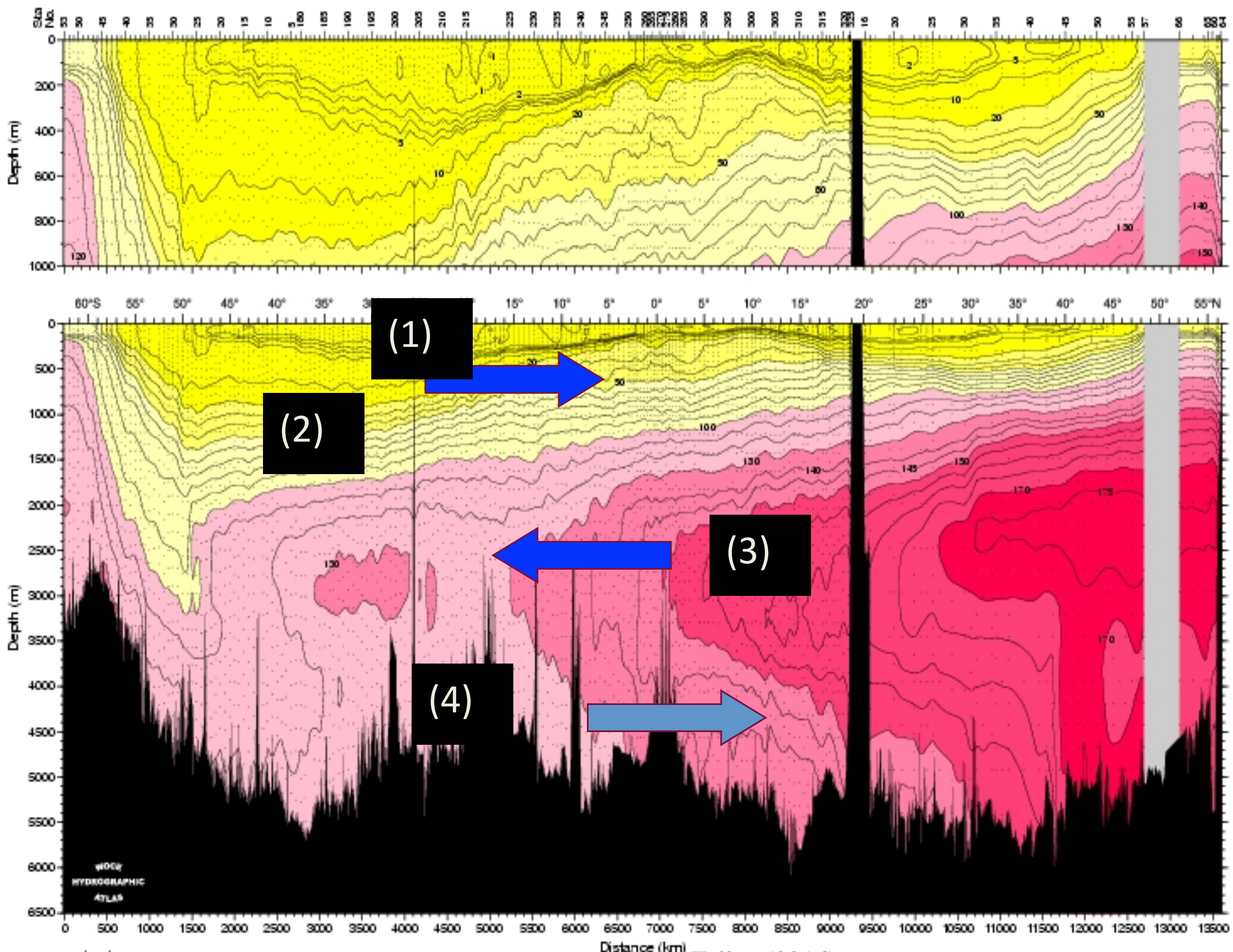
CFC-11 in mid-Pacific (150W)

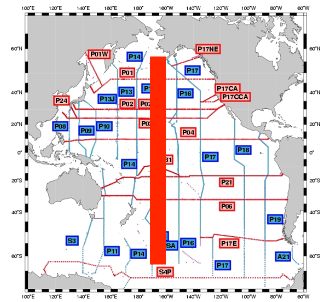




Talley (2016)

Silicate in mid-Pacific (150W)

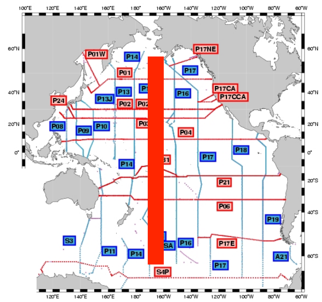


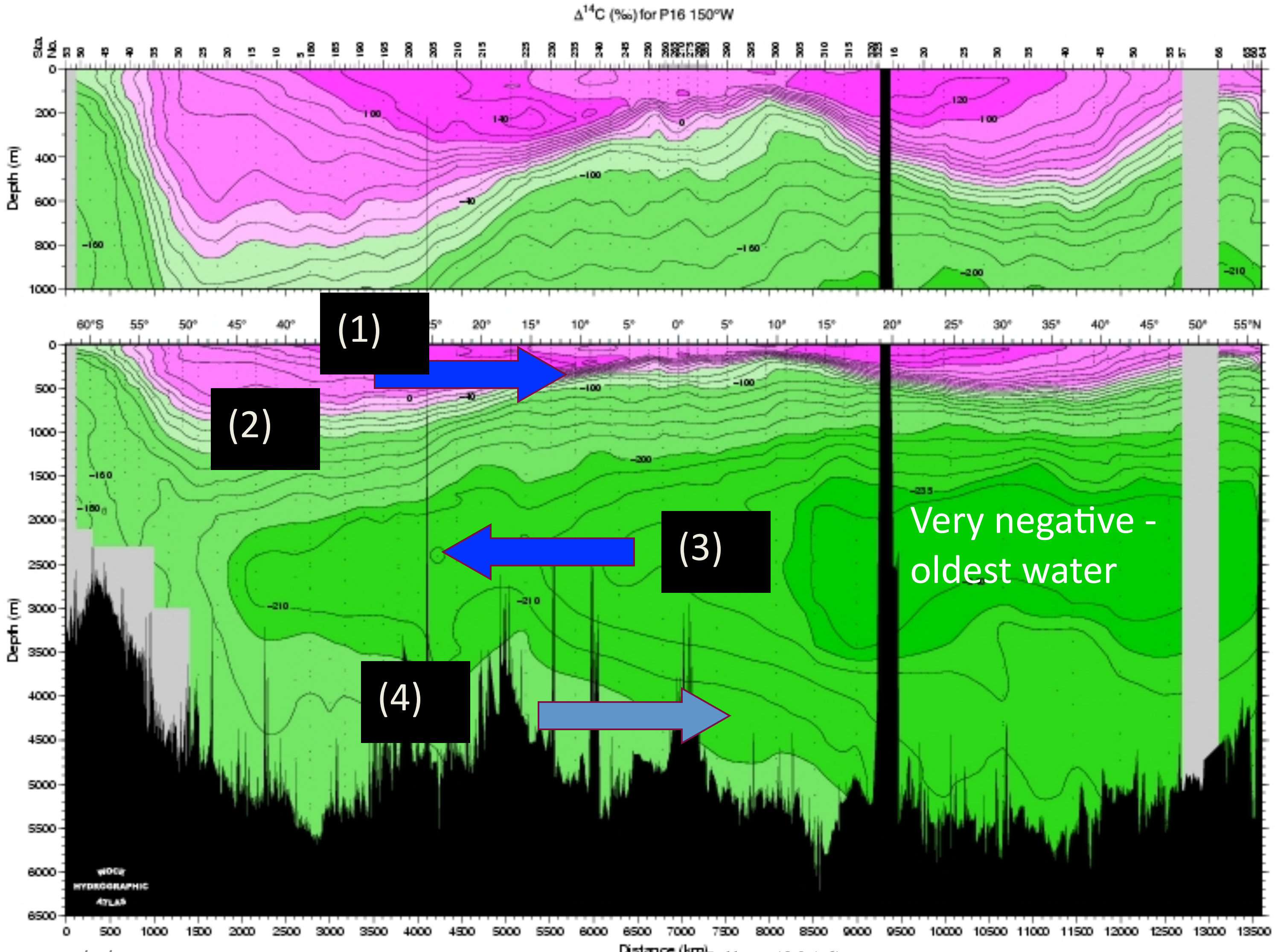


(1) Upper
(2) AAIW and NPIW
(3) PDW
(4) LCBW (AABW)

Talley (2016)

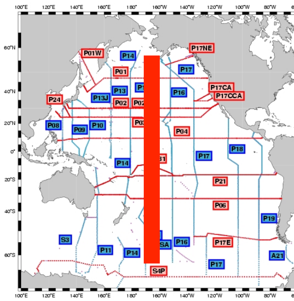
Δ^{14}C in mid-Pacific (150W)

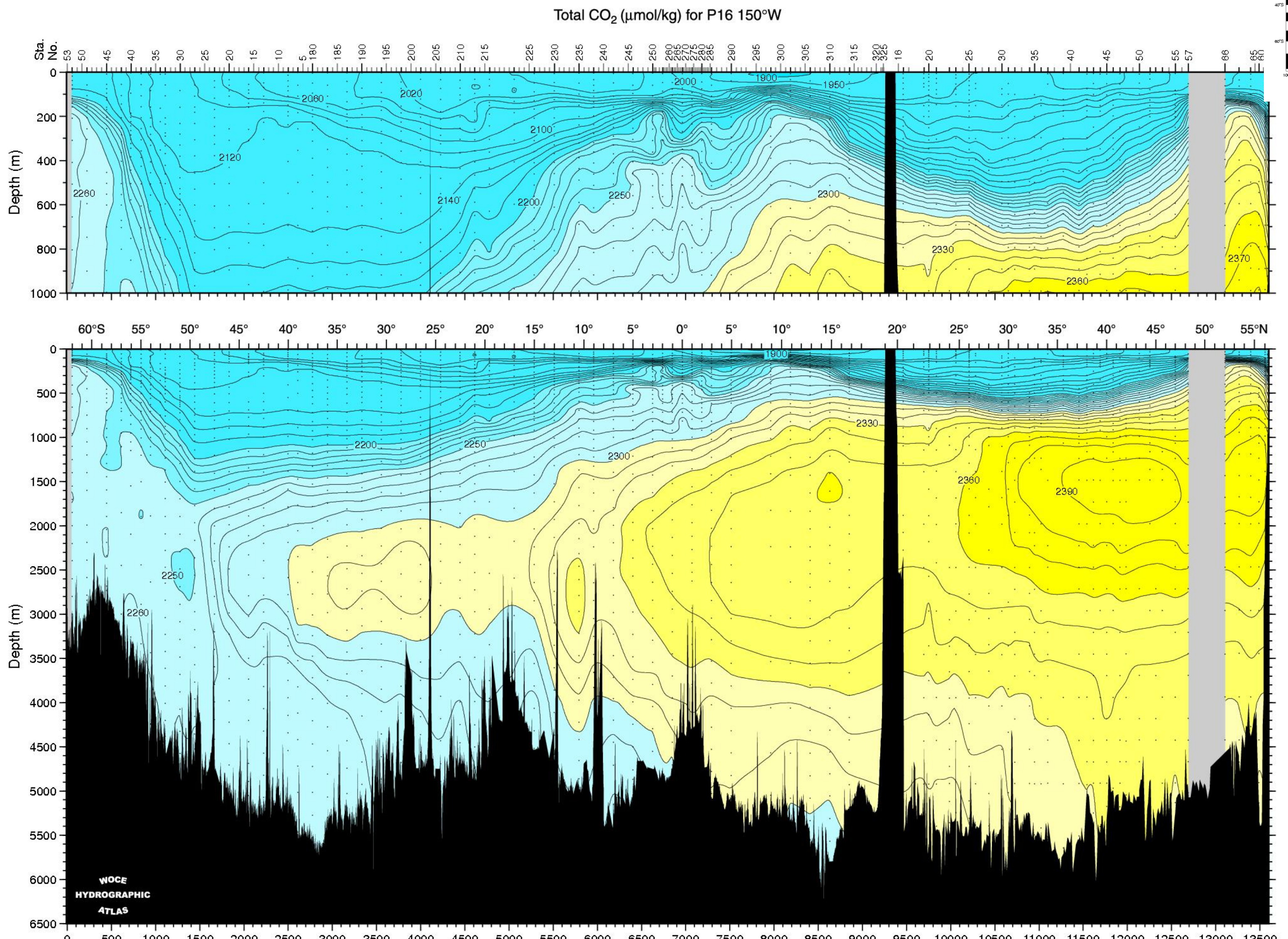




Talley (2016)

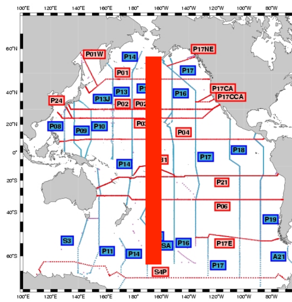
Total CO_2 in mid-Pacific (150W)

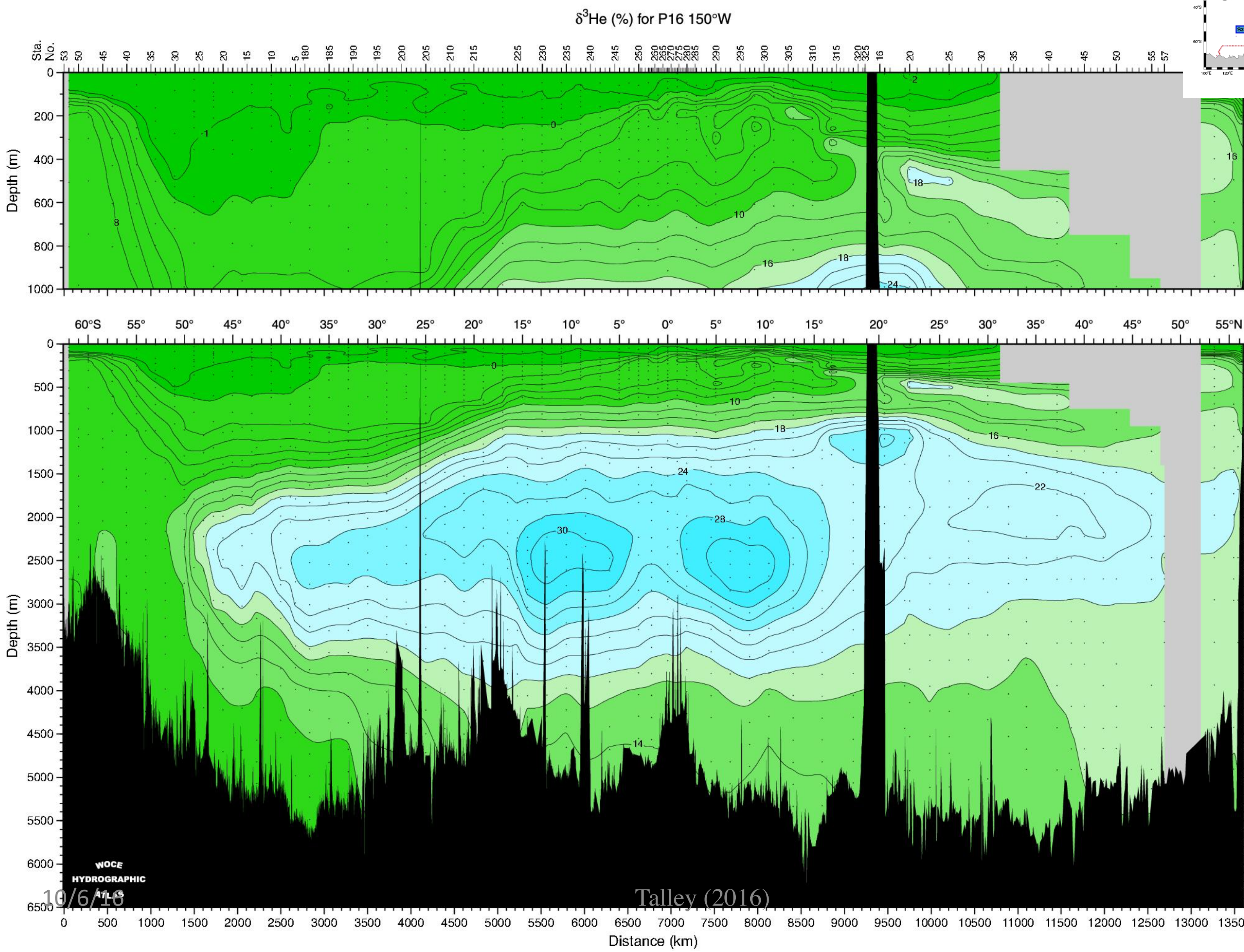




Talley (2016)

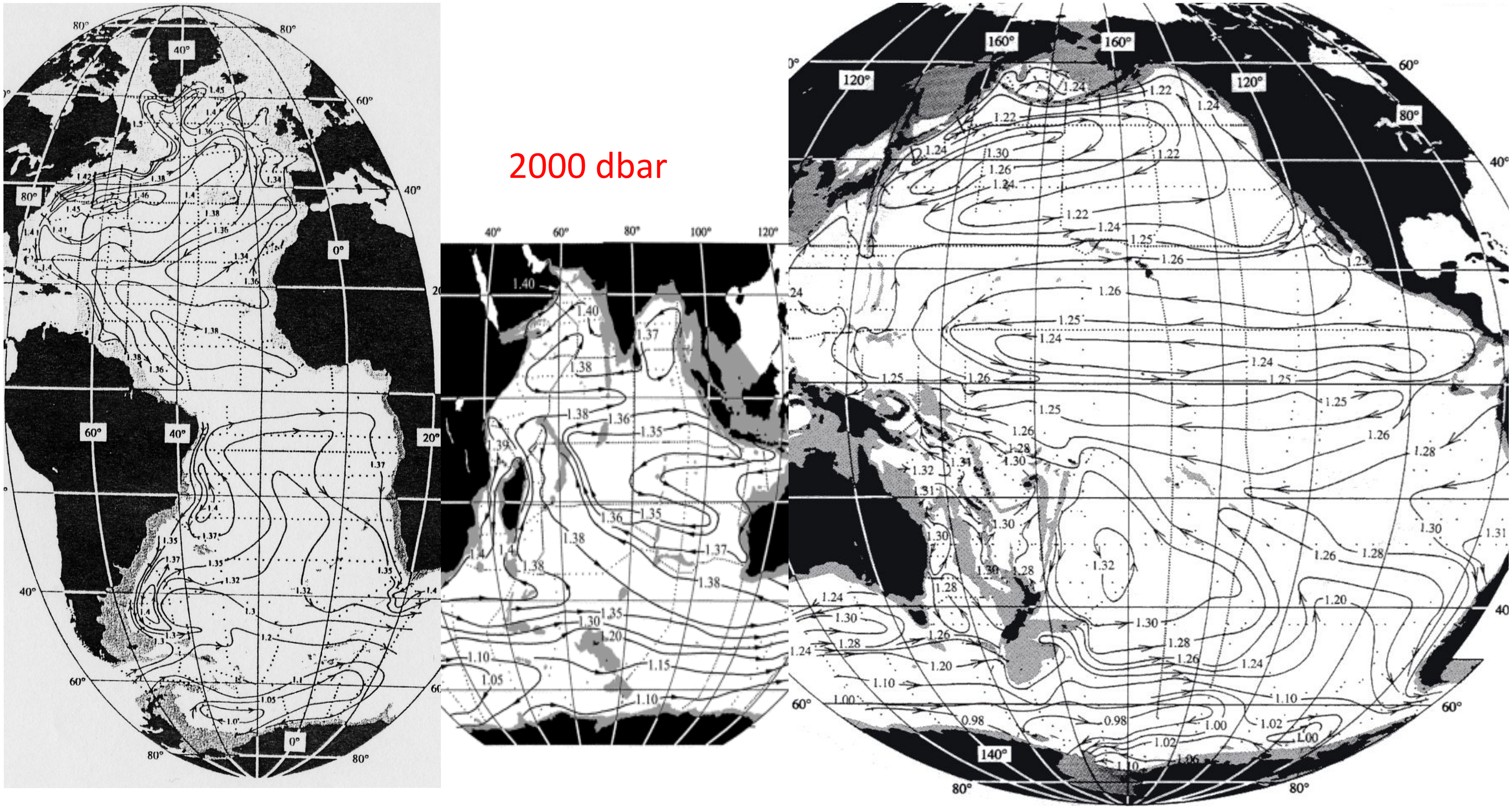
δ^3He in mid-Pacific (150W)





Talley (2016)

4 Deep ocean circulation

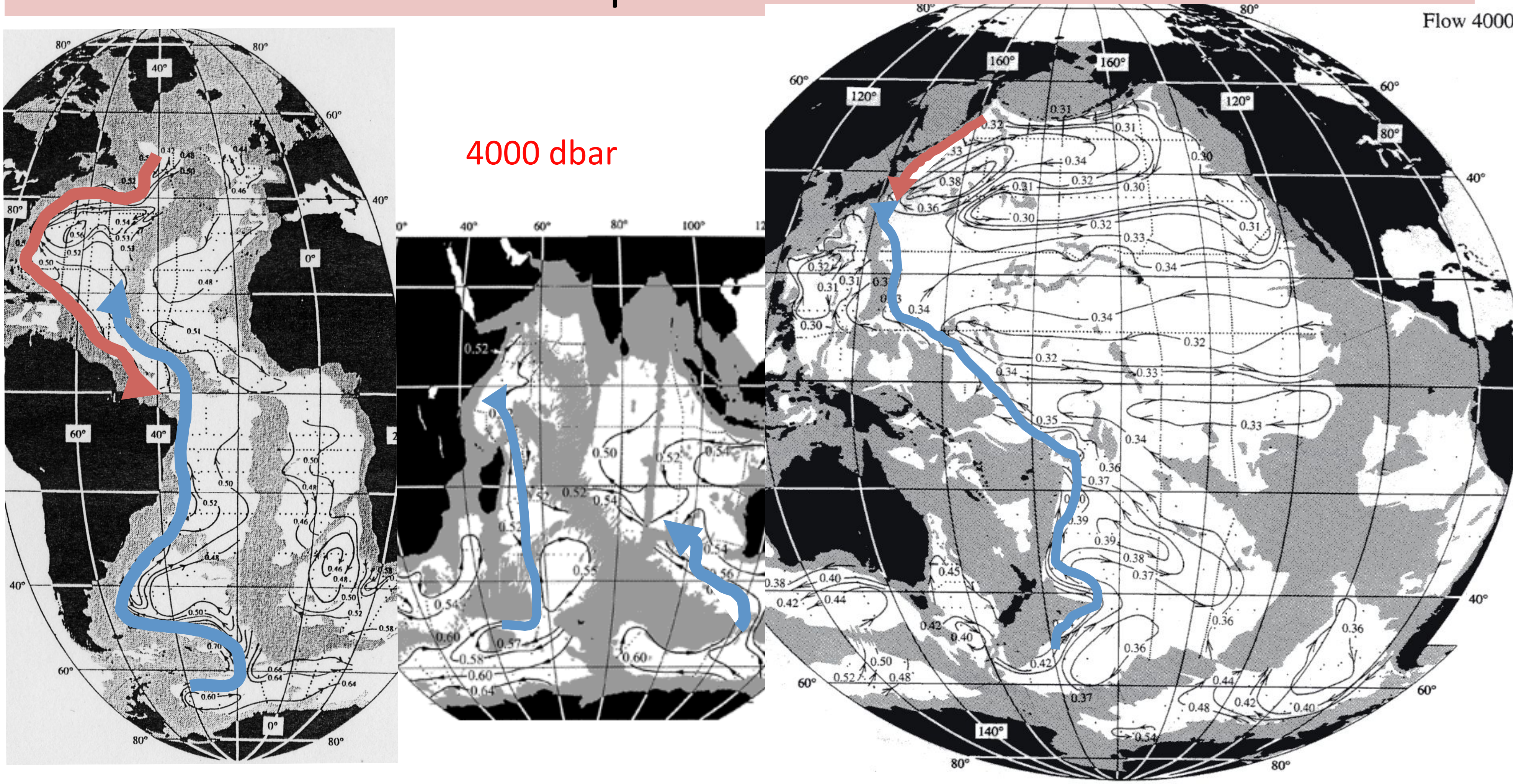


Circulation (adjusted steric height) (Reid, 1994, 1997, 2003)

Greatly reduced subtropical gyres, continued ACC and equatorial zonal flows, weak circulations elsewhere.

DPO Fig. 14.4a

4 Deep ocean circulation



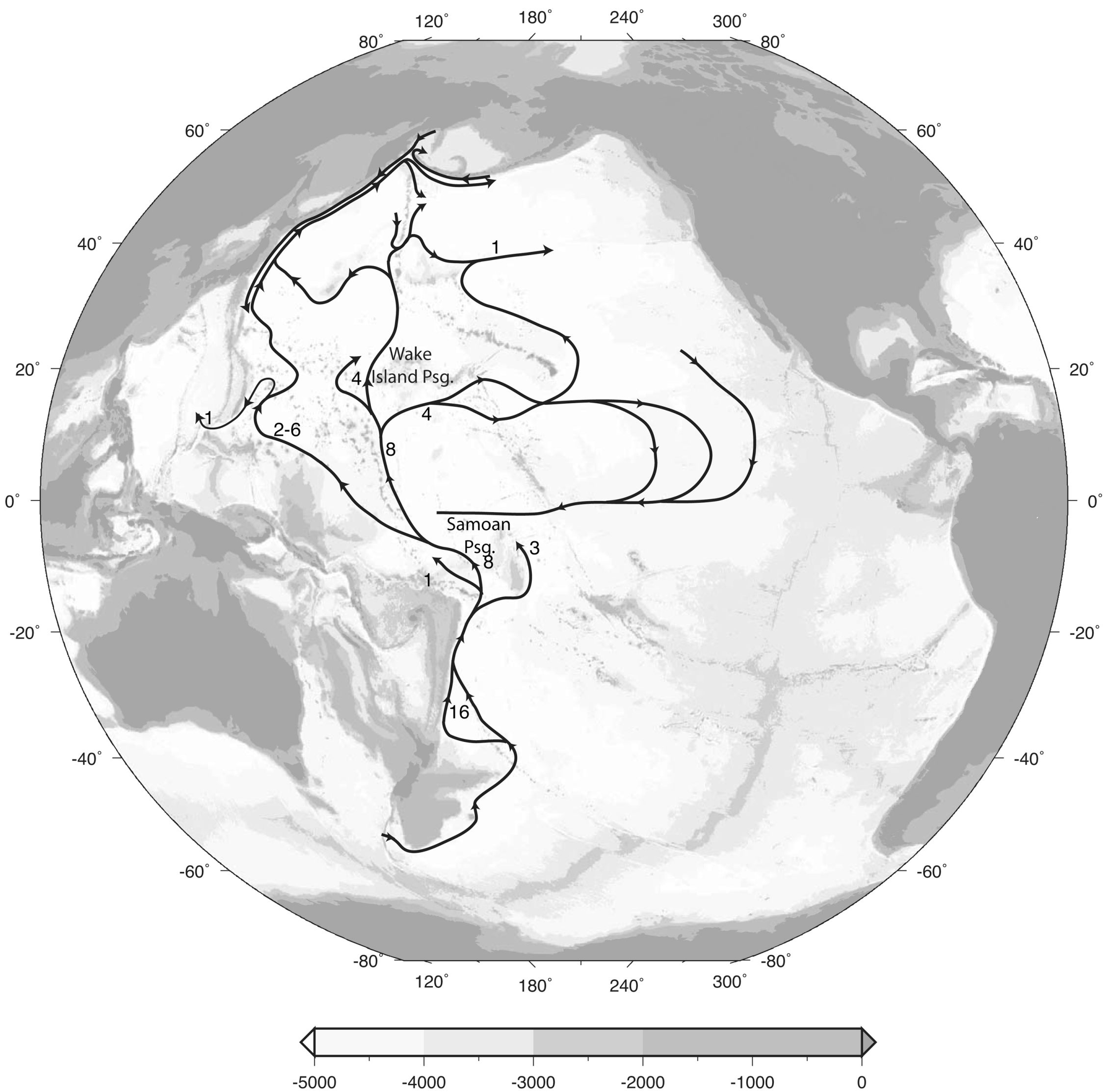
Circulation (adjusted steric height) (Reid, 1994, 1997, 2003)

Below depth of NADW in S. Atlantic

Dominated by topography. Deep Western Boundary Currents, deep cyclonic flows in some isolated basin

DPO Fig. 14.4b

4 Deep ocean circulation



Abyssal circulation schematics. *After: Owens andWarren(2001), JohnsonandToole (1993),Kato andKawabe (2009), Komaki and Kawabe (2009), Yanigomoto, Kawabe, and Fujio (2010), Whitworth et al. (1999), and Roemmich, Hautala, and Rudnick (1996).*

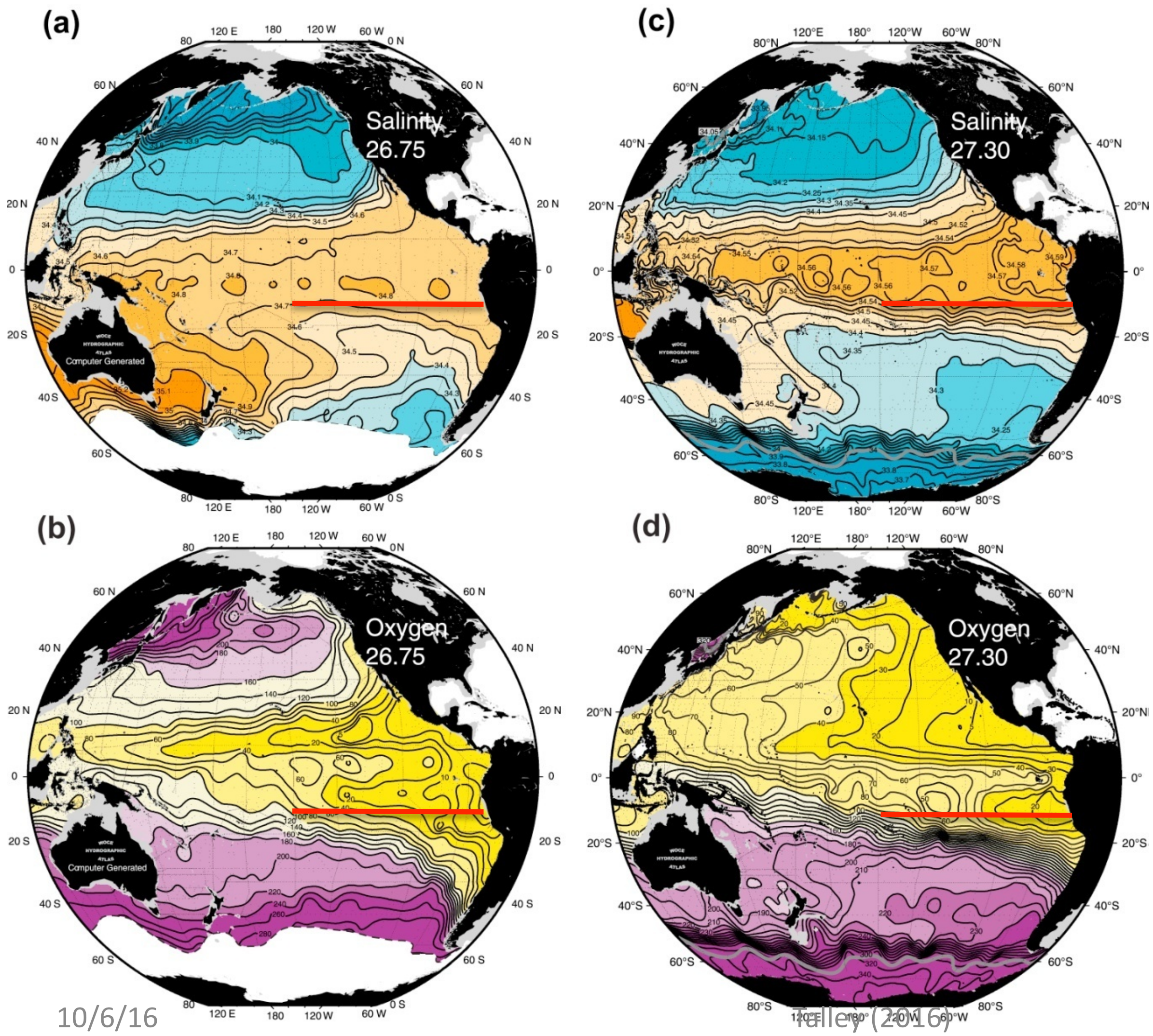
FIGURE 10.17

TALLEY

4 Intermediate, deep and abyssal properties

North Pacific Intermediate Water
~400 m depth

Antarctic Intermediate Water
~700 m depth

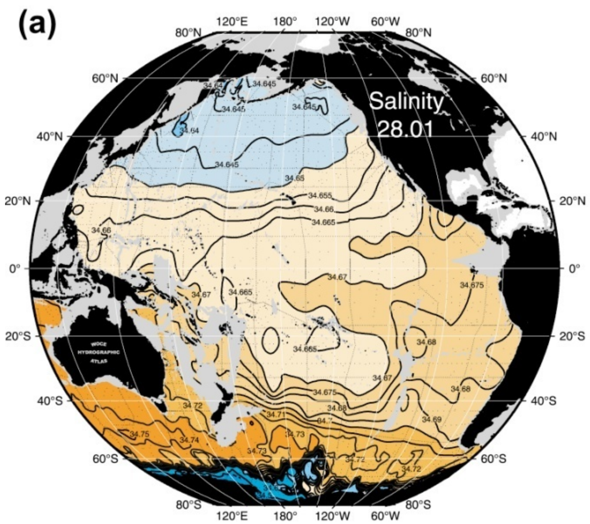


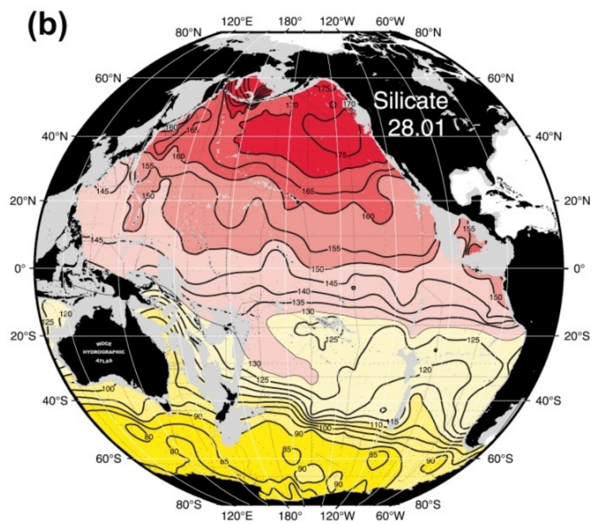
Bottom of pycnocline: flow is like the subtropical gyres and tropical zonal currents.

Note strong contrast in tropical vs. subtropical properties.
Front ("subequatorial front") lies near the GEOTRACES section.
High tropical salinities are all due to diapycnal diffusion from above.

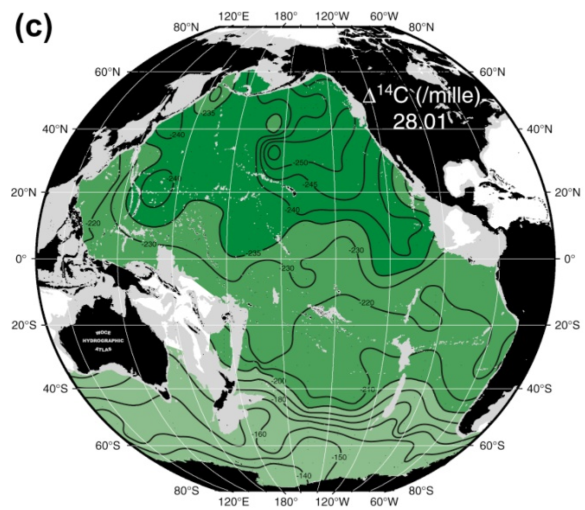
Talley (2016)

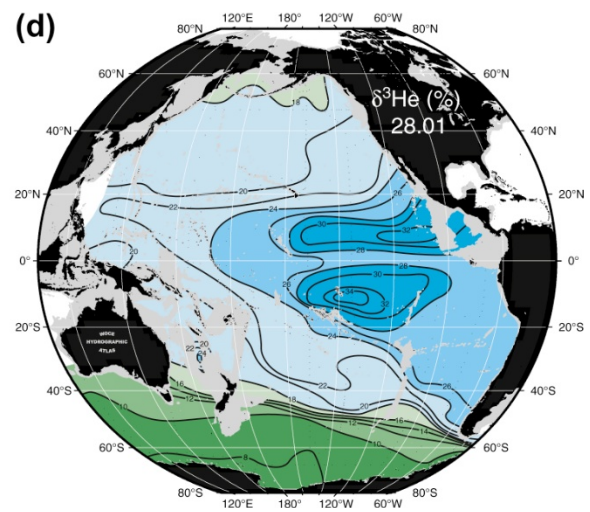
4 Intermediate, deep and abyssal properties





High salinity on isopycnal means WARM water – this is the hydrothermal plume

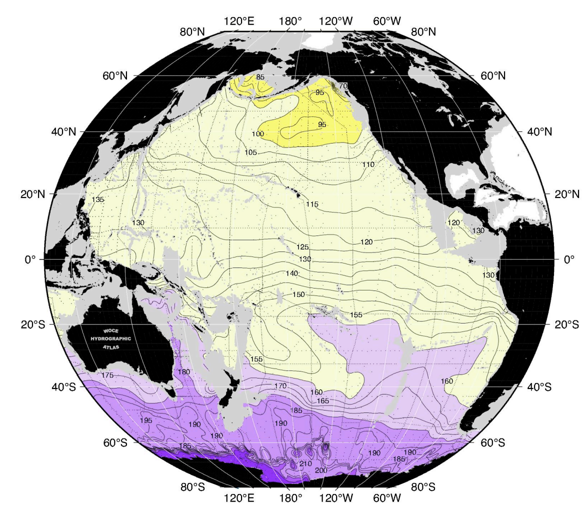




Pacific Deep Water: (aka "Common Water")

Isopycnal at 2600-2800 m

Originates through upwelling of bottom waters, diapycnal mixing of properties.

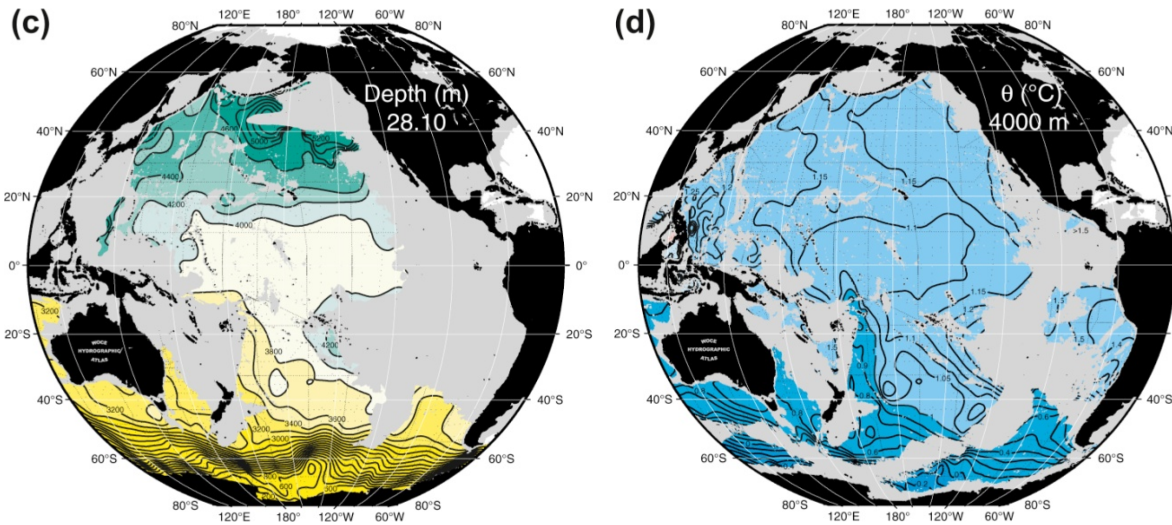


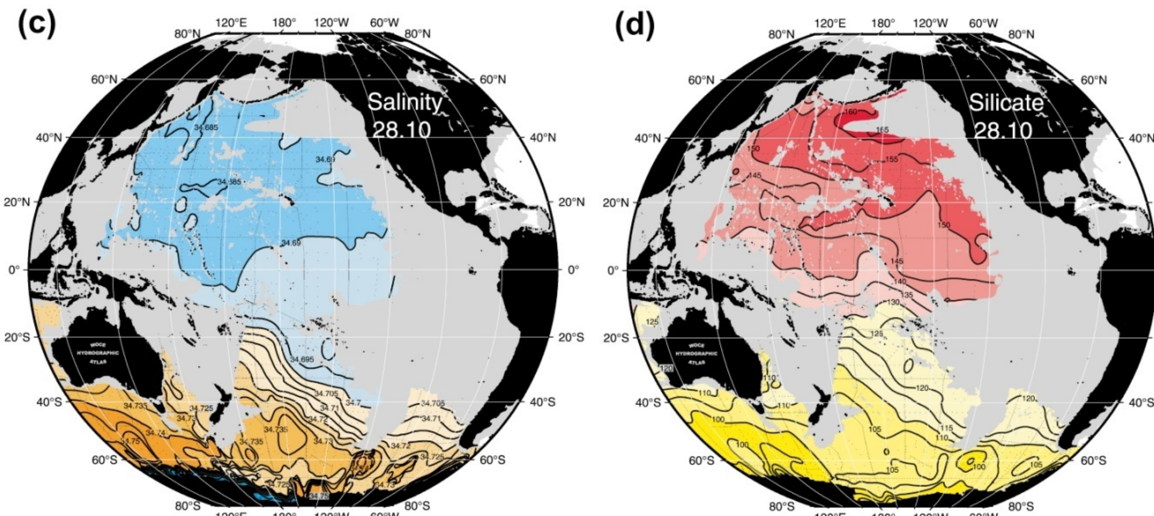
Talley (2016)

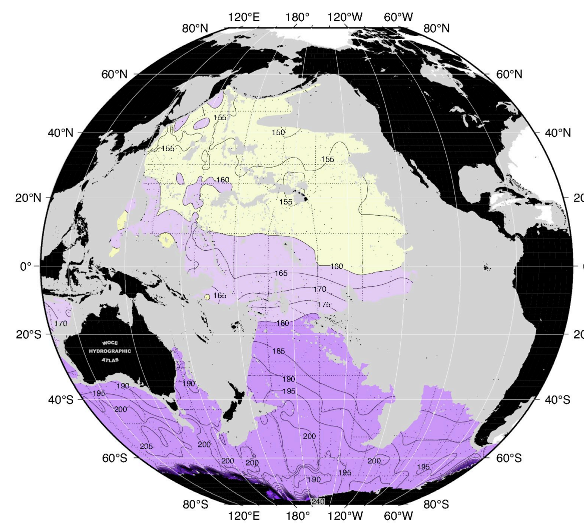
4 Intermediate, deep and abyssal properties

Antarctic Bottom Water (Lower Circumpolar Deep Water) (most of the GEOTRACES cruise will not see this)

Source is from the Antarctic Circumpolar Current region. Diapycnal mixing and BGC processes change its properties as it flows northward.

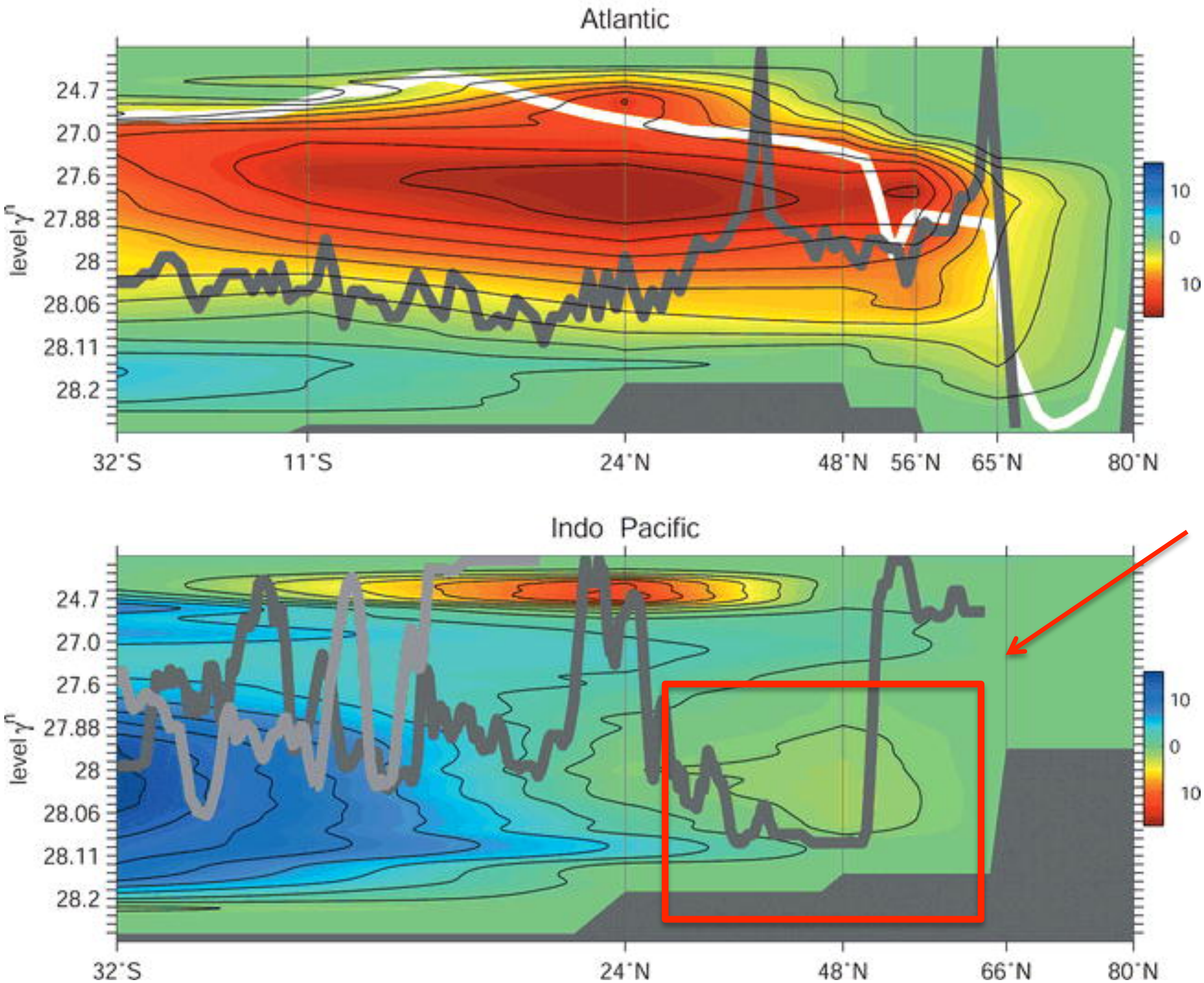






Talley (2016)

4 Overturning circulation



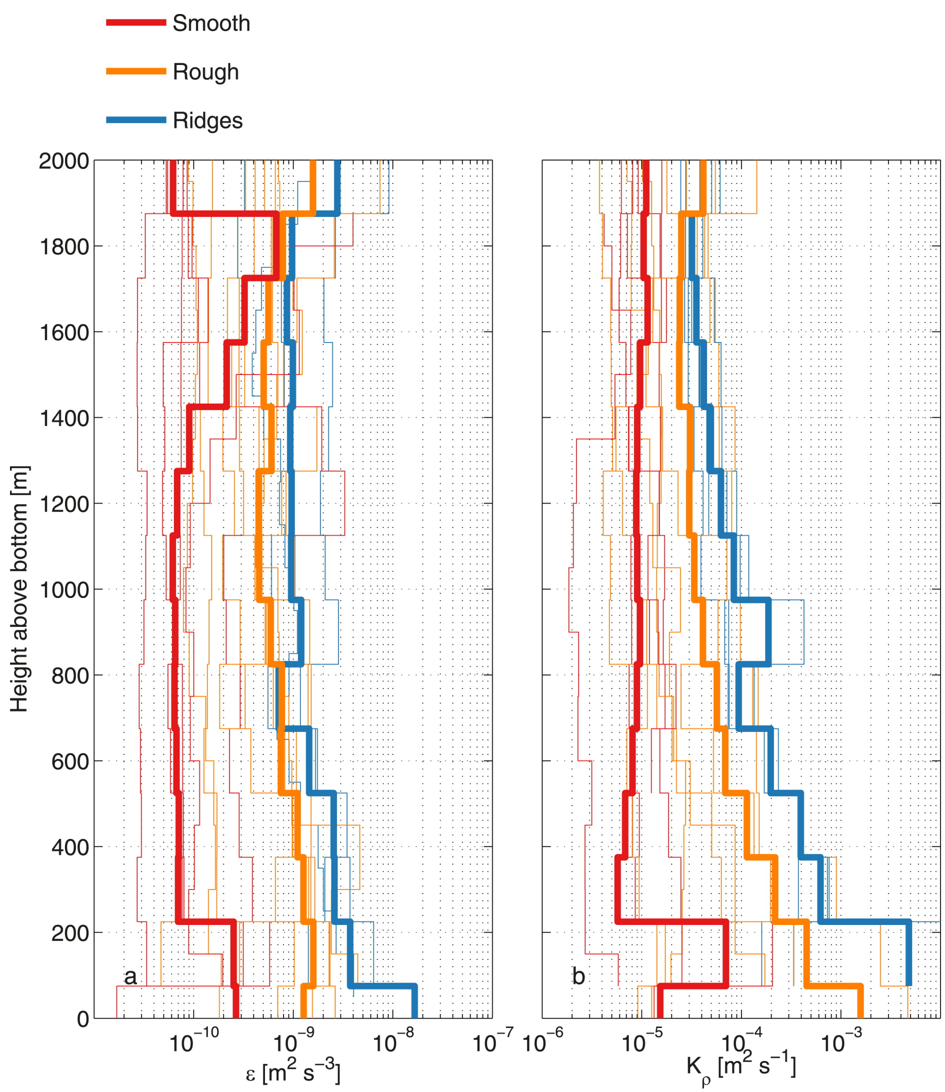
The meridional overturning circulation for the Indo-Pacific shows the AABW to PDW/IDW cell (blue). It also has a reverse cell in the deep north.

This feature is also found in Reid's overturning transports (Talley et al., 2003)

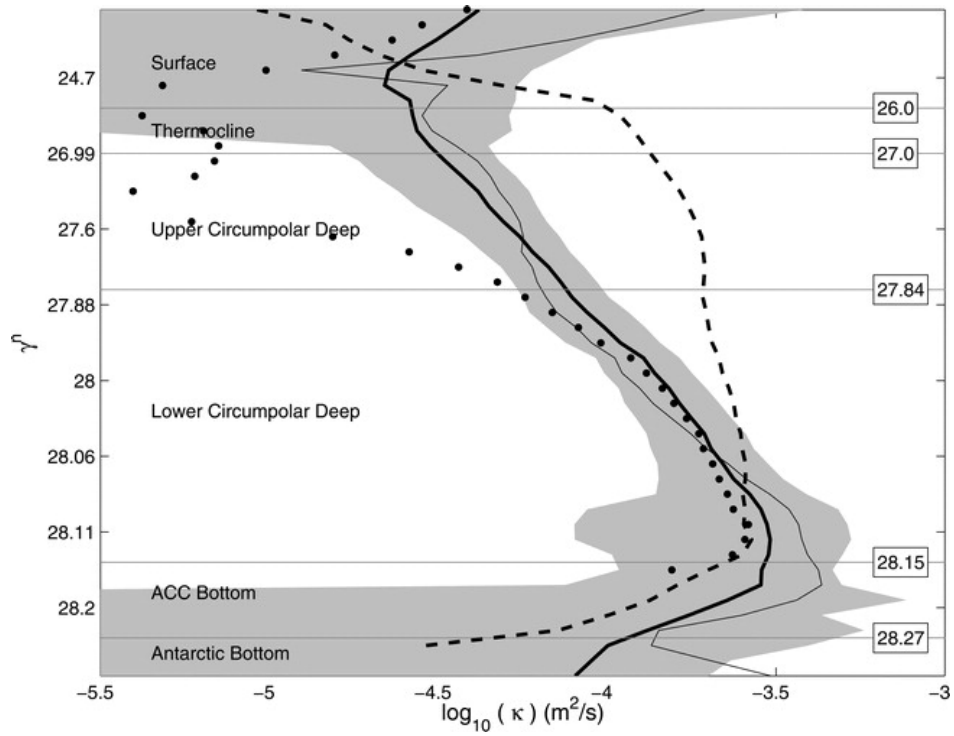
Atlantic and Indian-Pacific

Lumpkin and Speer (2007)

4 Overturning circulation



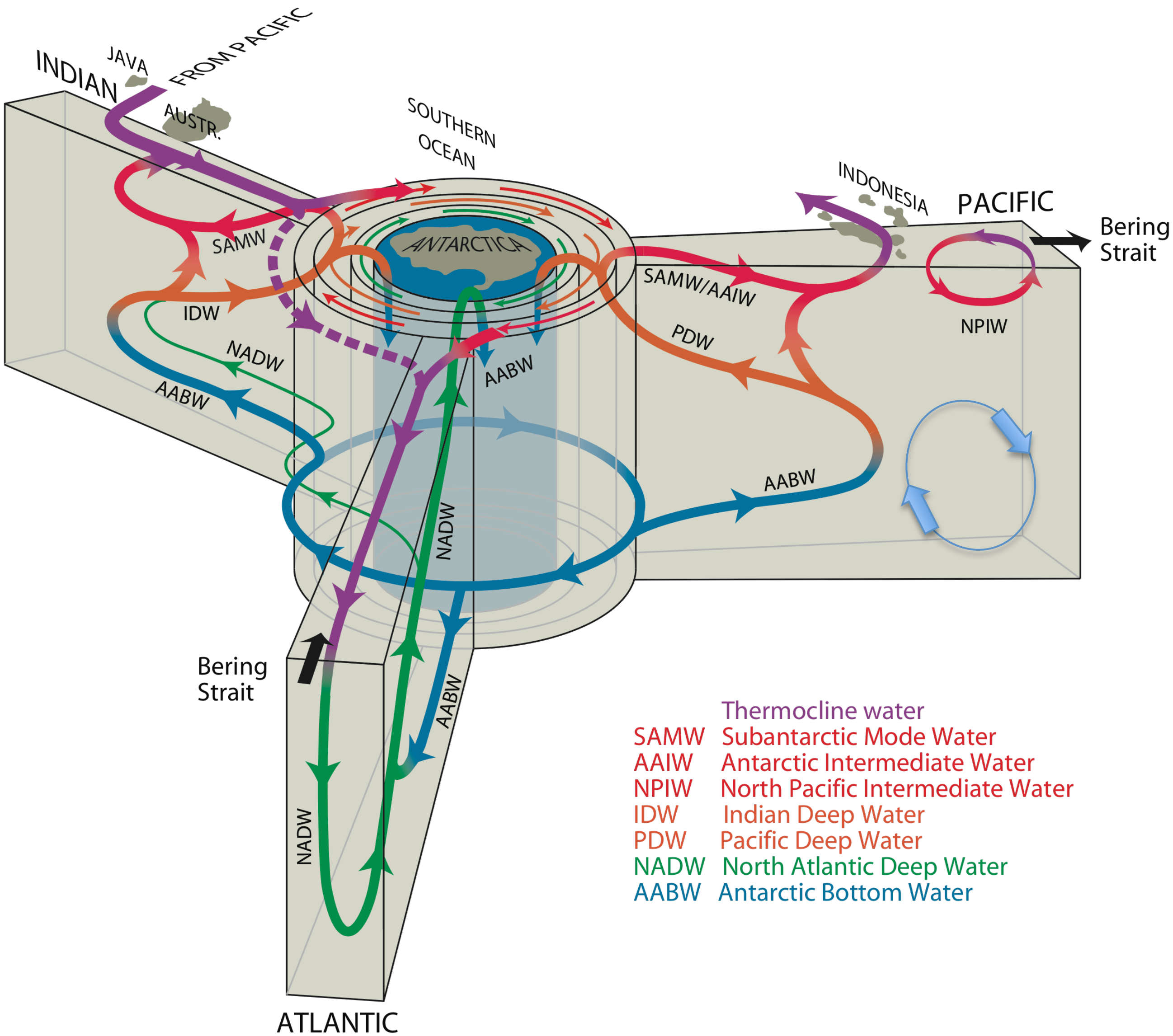
Diffusivity increases towards the bottom since a source of turbulence is internal wave breaking on rough bottom.
This in itself can be consistent with a deep downwelling profile. We see such a deep cell only in the northern N. Pacific.



Lumpkin and Speer (2007)
Dissipation and diffusivity, averaged globally, inferred from volume transports in inverse model

Waterhouse et al. (2015)
Dissipation and diffusivity, averaged globally, based on direct observations

4 Overturning circulation



Should add weak counter cell in the deep N. Pacific?

After Schmitz (1995)

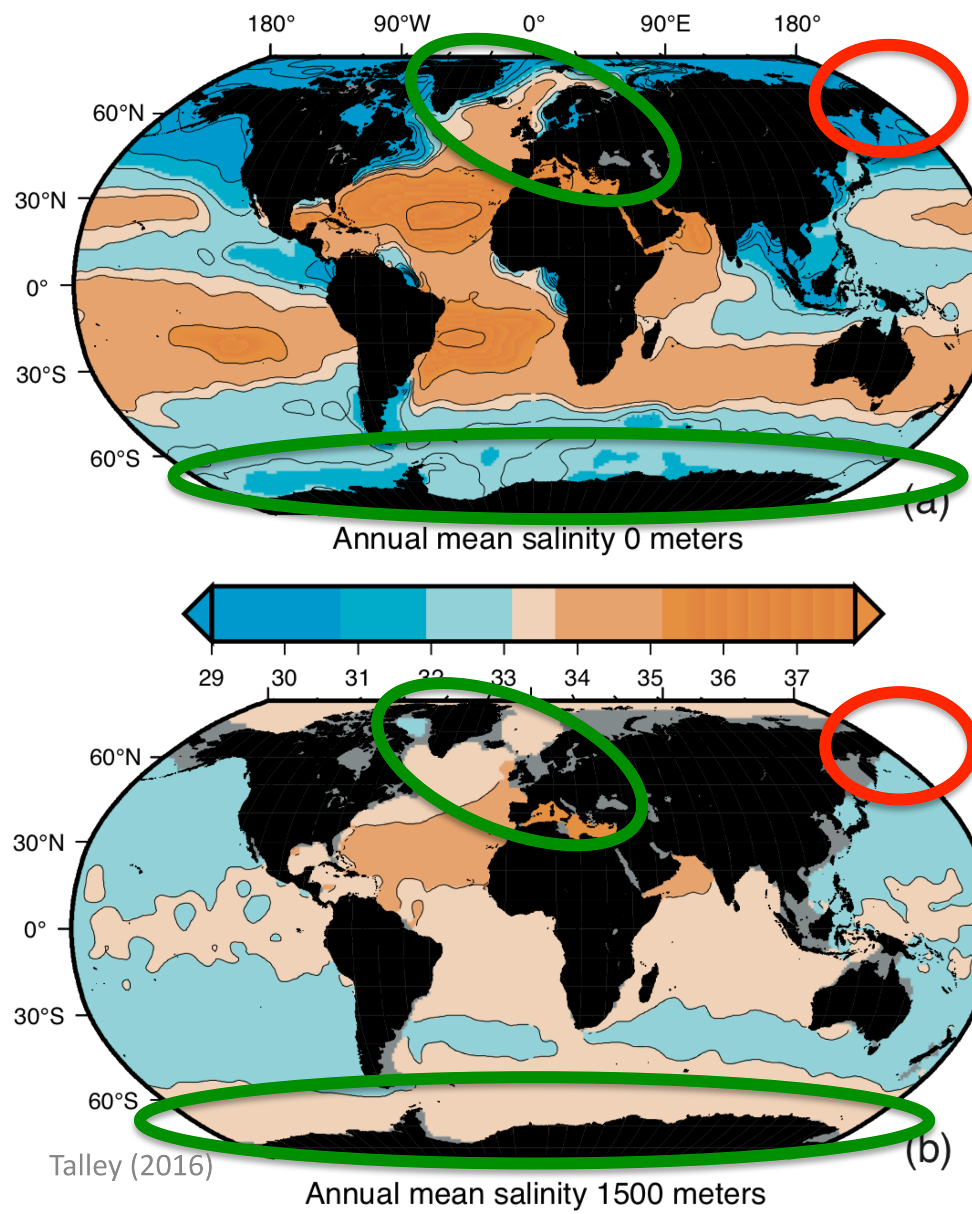
DPO Fig. 14.11b

Future of the GOC in a warming world: Ocean salinity and overturning circulation

The Atlantic and Indian Oceans are salty from top to bottom compared with the fresher Pacific

Dense deep and bottom waters are formed where salinity is highest (North Atlantic) and where salt is produced bountifully as part of the formation process (Antarctic)

Deep/bottom waters are NOT formed in the fresher N. Pacific



Talley (2008) using Levitus

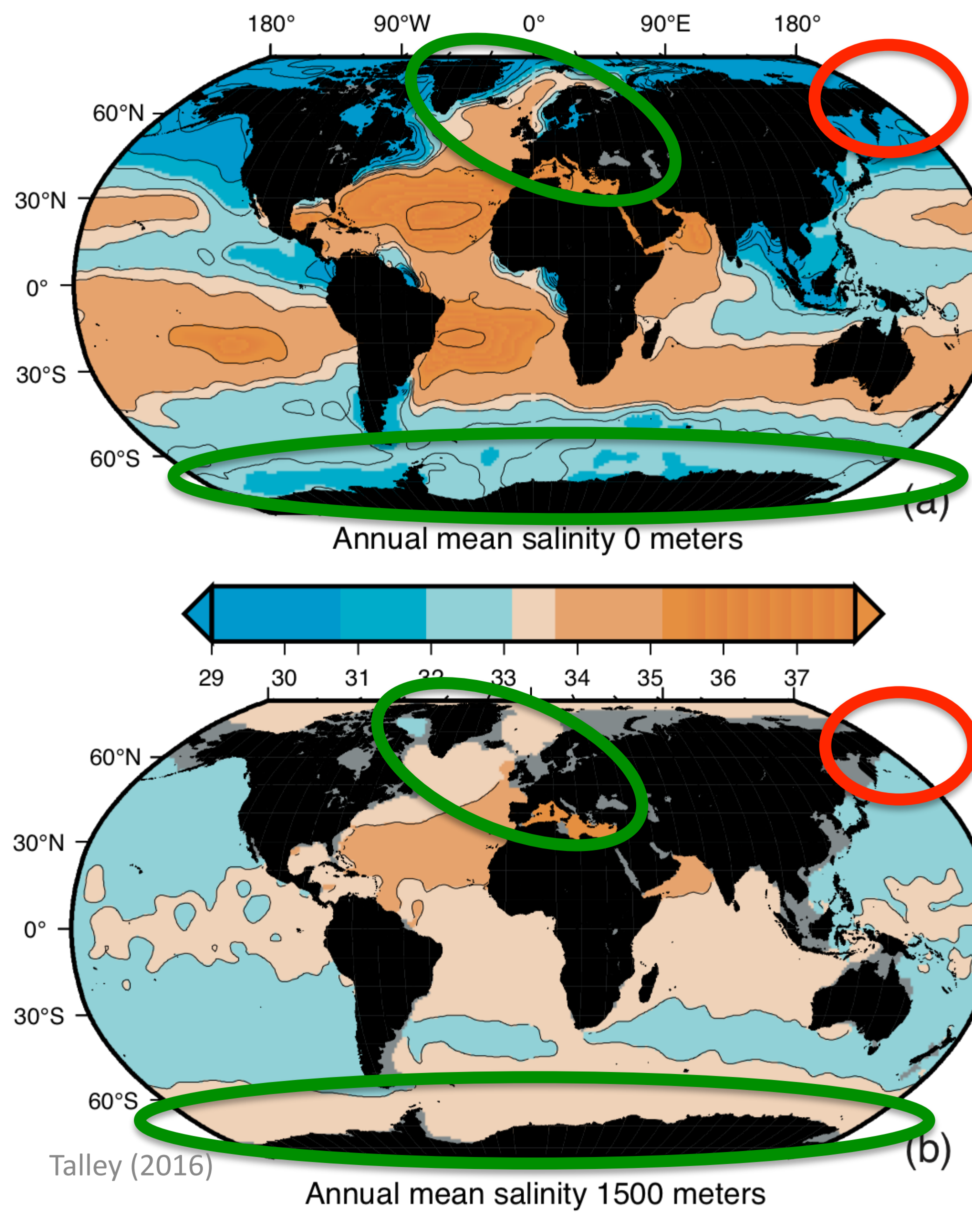
Future? of the GOC in a warming world: Ocean salinity and overturning circulation

Fresh gets fresher
Salty gets saltier

NADW overturn strengthens as Atlantic becomes saltier?

Antarctic overturn weakens as it becomes fresher, including melting ice sheets? Competing with strengthening as wind-driven upwelling strengthens

Pacific role remains only to return water diffusively to mid-depth (and onward to surface in Southern Ocean driven by winds), but diffusivity not likely to vary (tidal)



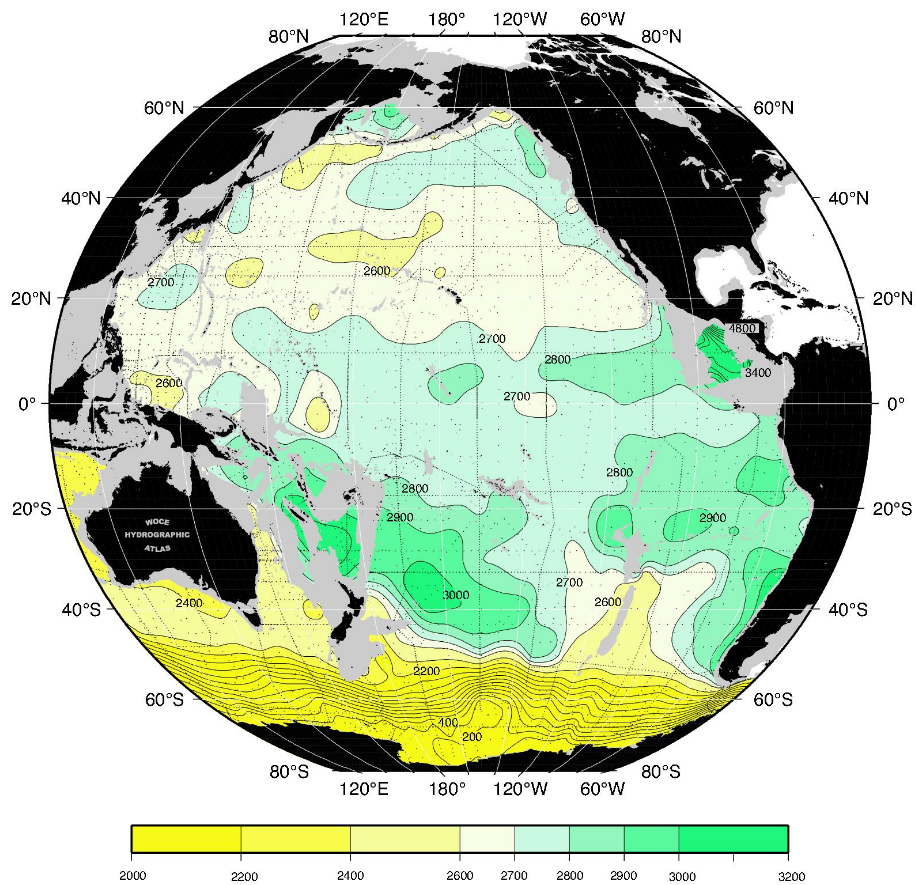
Talley (2016)

Summary

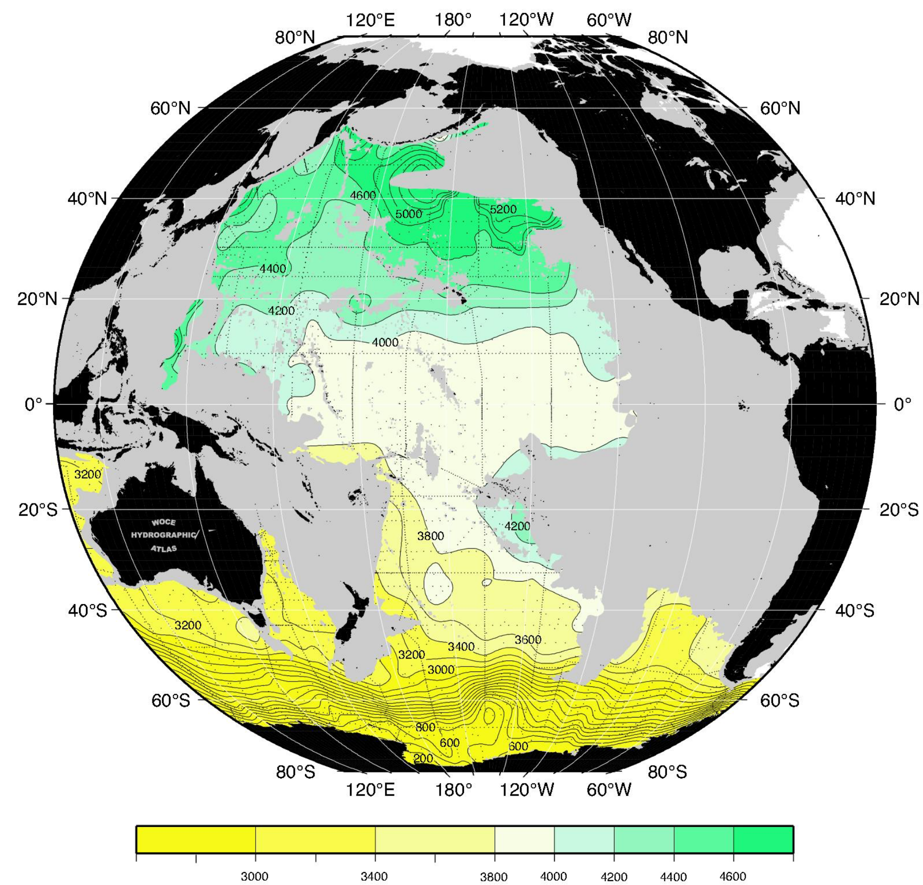
THANKS.

Extra slides follow: maps from the WHP Pacific atlas

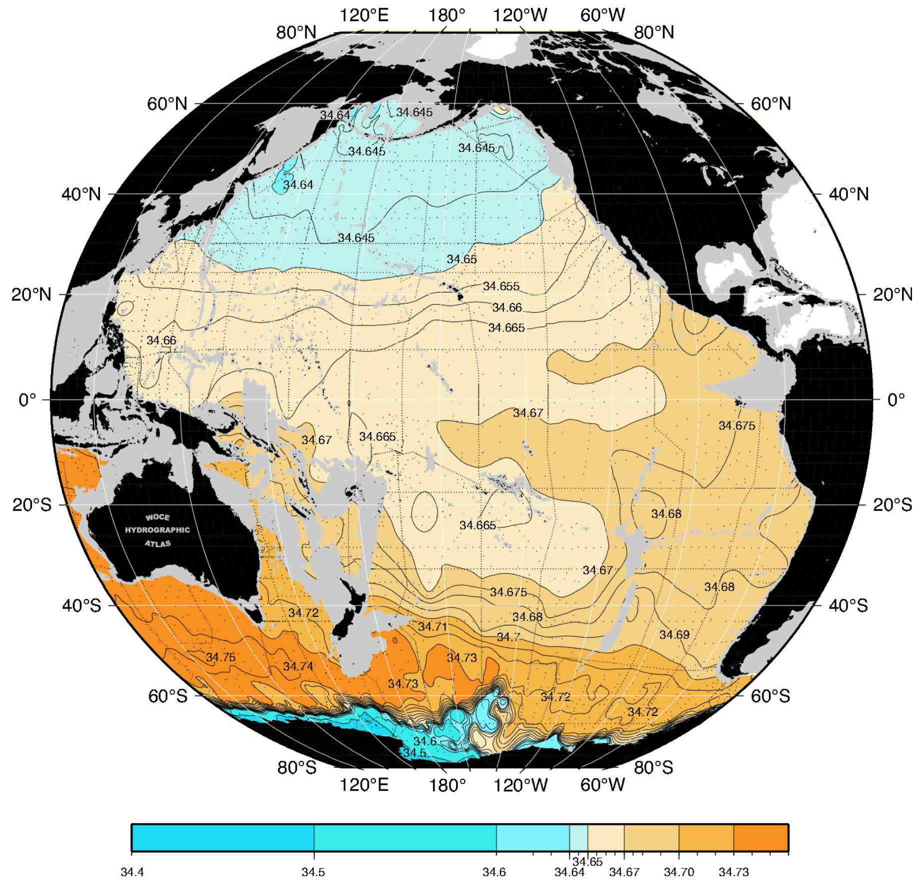
Depth (m) 28.01 γ^n (kg/m^3)



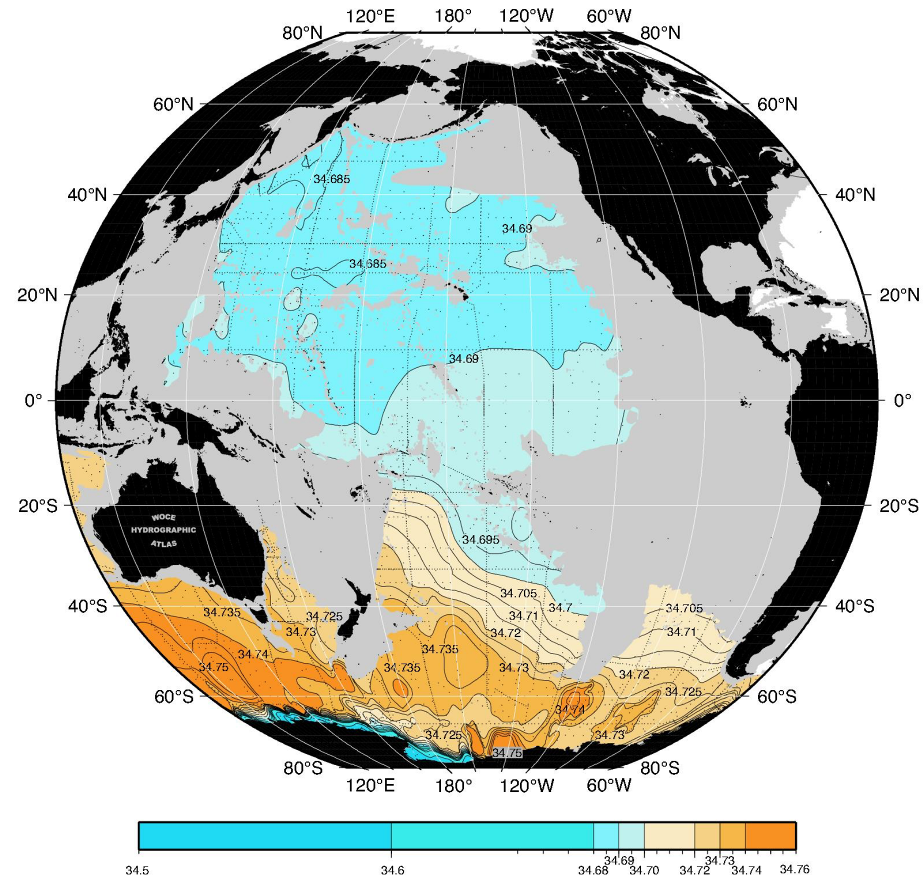
Depth (m) 28.10 γ^n (kg/m^3)



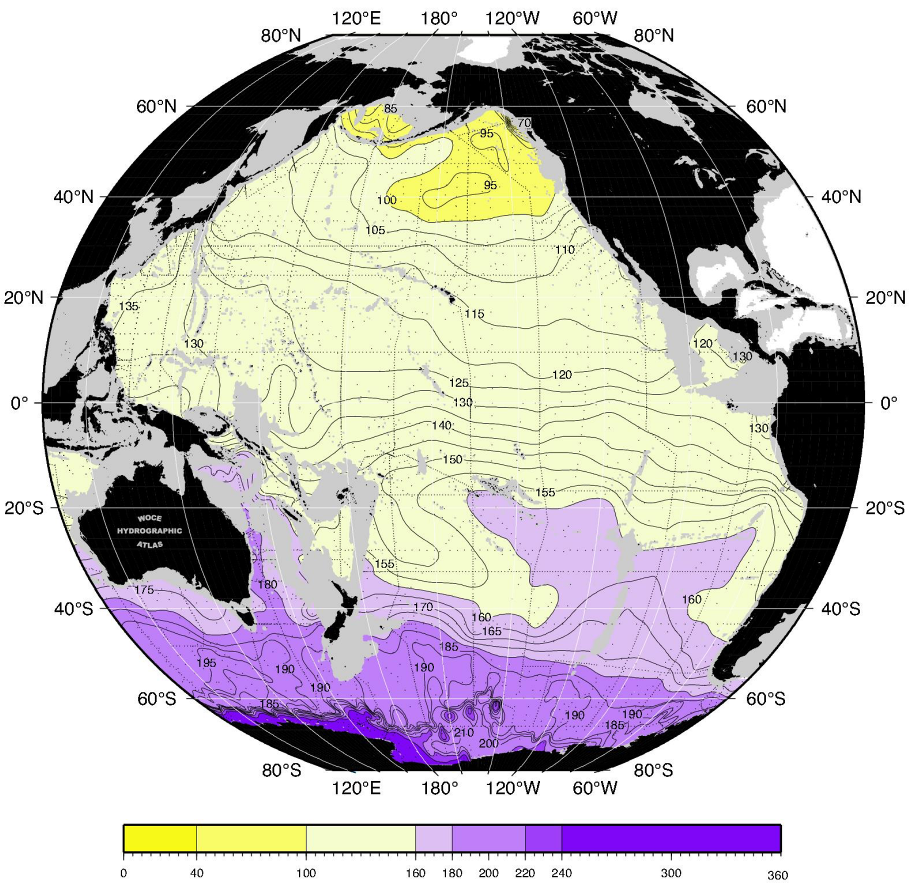
Salinity (PSS78) 28.01 γ^n (kg/m^3)



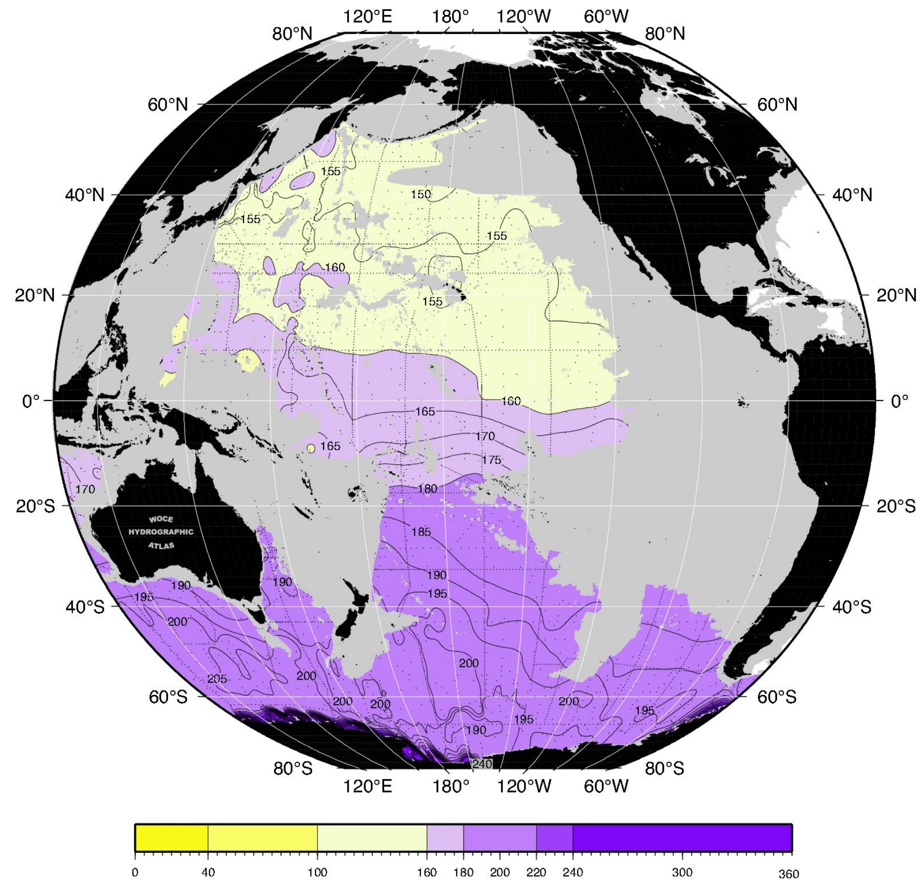
Salinity (PSS78) 28.10 γ^n (kg/m^3)



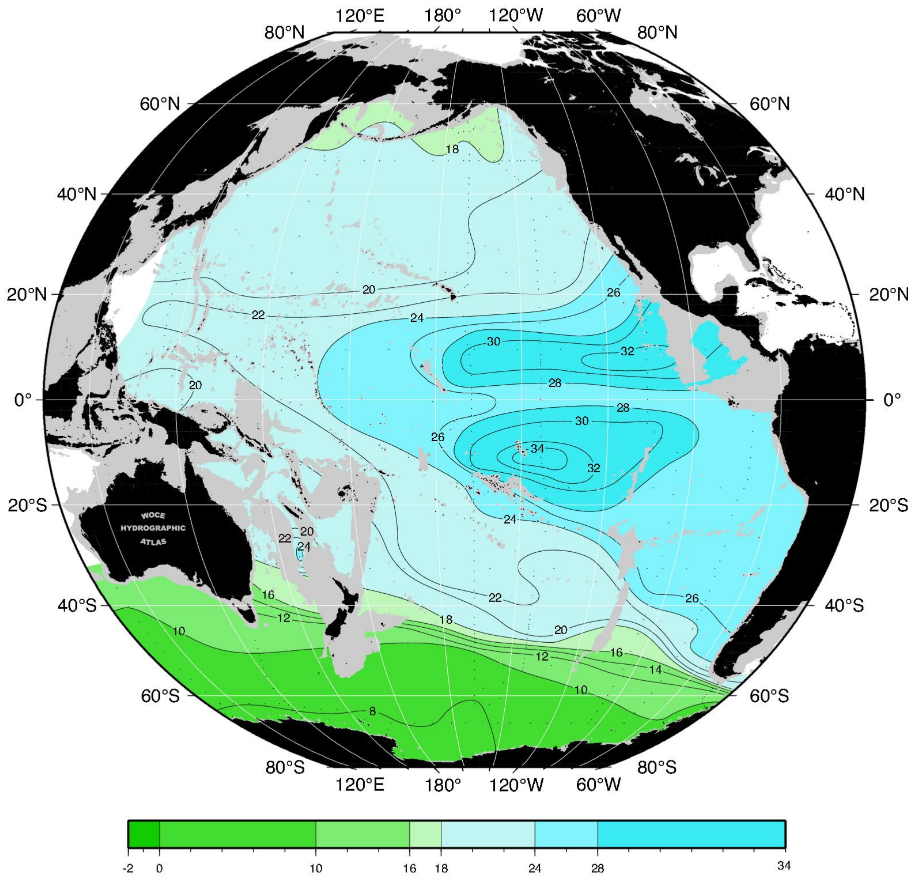
Oxygen (μmol/kg) 28.01 γ^n (kg/m^3)



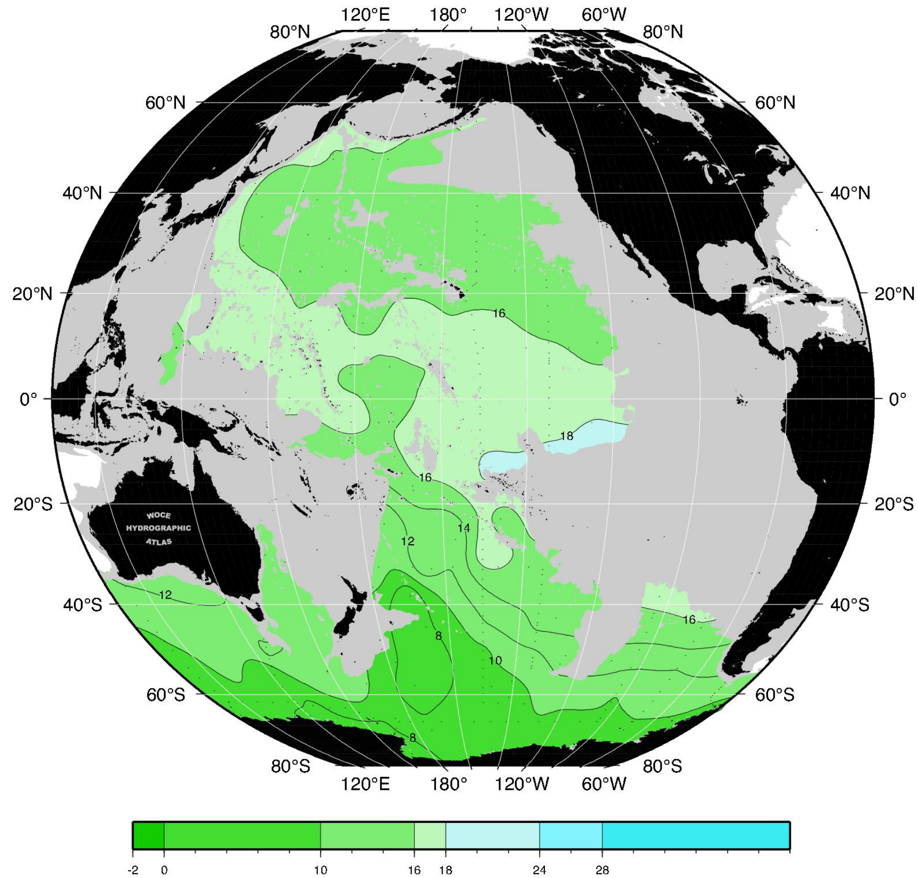
Oxygen (μmol/kg) 28.10 γ^n (kg/m^3)



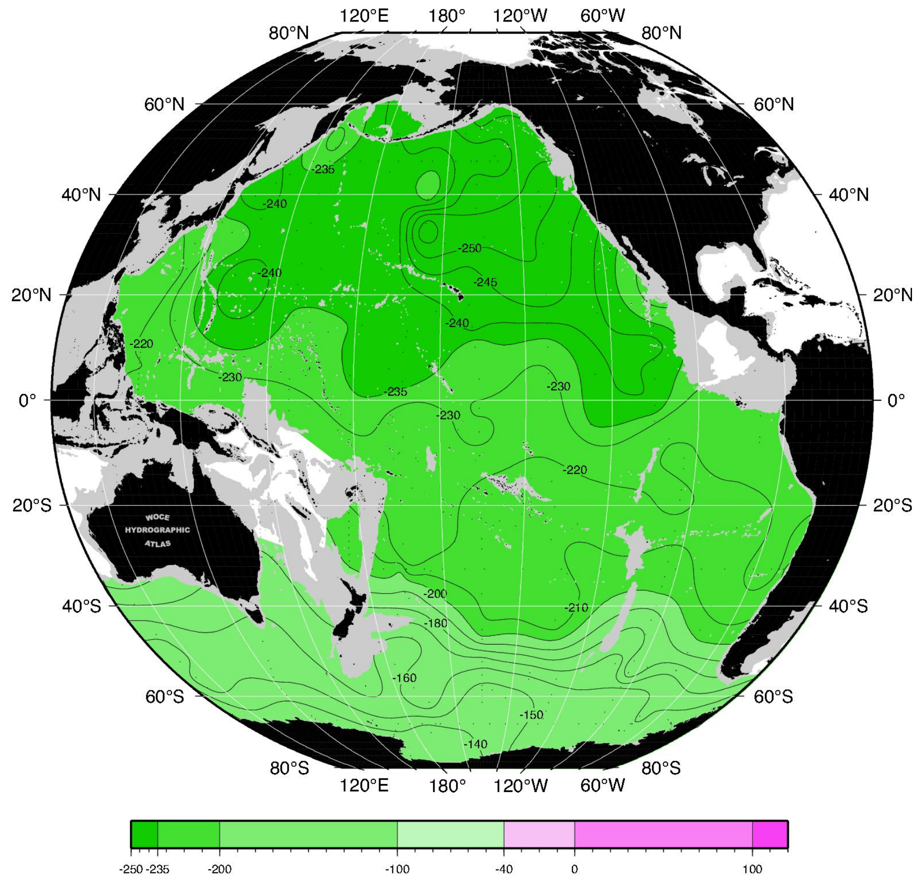
δ^3He (%) 28.01 γ^n (kg/m^3)



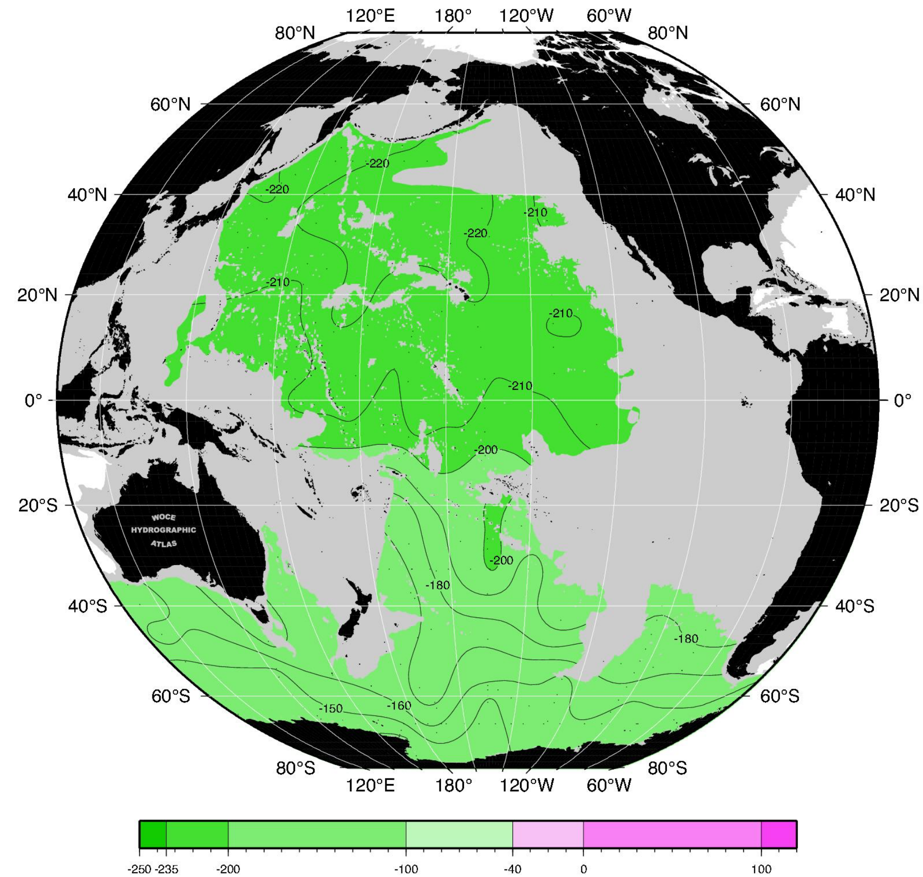
δ^3He (%) 28.10 γ^n (kg/m^3)



$\Delta^{14}C$ (/mille) 28.01 γ^n (kg/m^3)

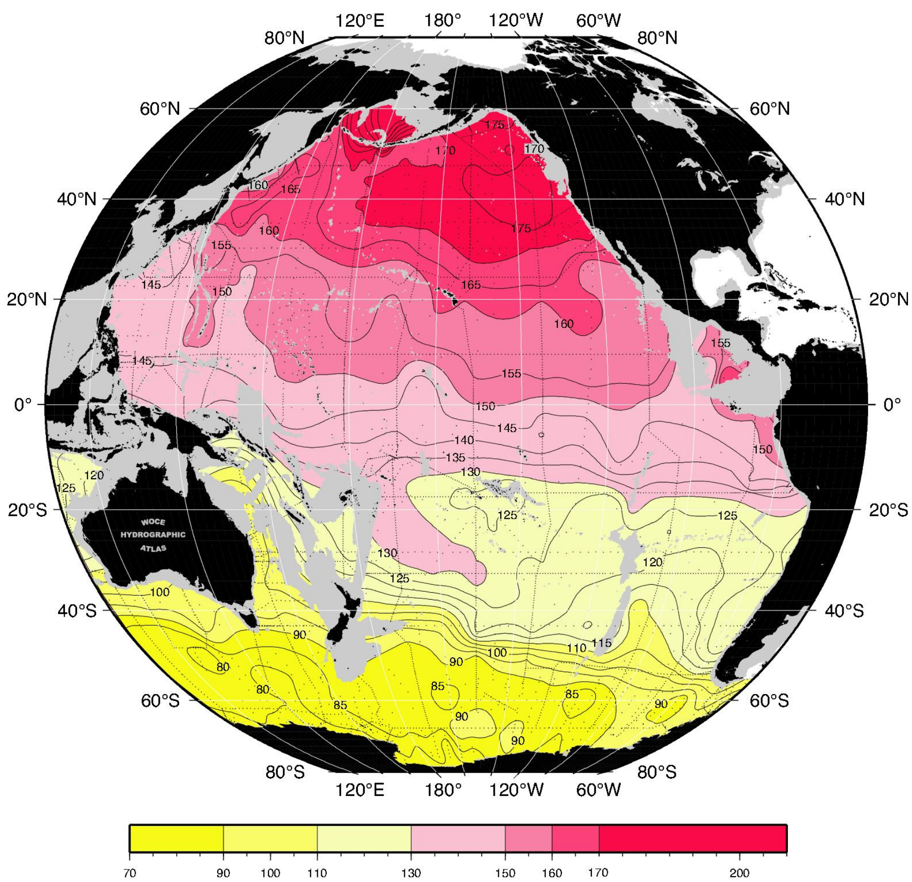


$\Delta^{14}C$ (/mille) 28.10 γ^n (kg/m^3)



Talley (2016)

Silicate (μmol/kg) 28.01 γ^n (kg/m^3)



Silicate (μmol/kg) 28.10 γ^n (kg/m^3)