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

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*Canada Basin
Arctic Ocean might be older
The old water in the Pacific Deep Water layer

Silicate (μmol/kg) 28.01 $\gamma^N$ (kg/m³)

$\Delta^{14}C$ (mille) 28.01 $\gamma^N$ (kg/m³)

Depth (m) 28.01 $\gamma^N$ (kg/m²)

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
• 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

10/6/16 Talley (2016)
Hydrographic sections P16N: 7 occupations

P16N to 20°S

http://cchdo.ucsd.edu
CCHDO data base

1. Overview

GO-SHIP 2015

CLIVAR Repeat Hydro (GO-SHIP) 2006

WOCE 1991

Pre-WOCE 1984

Talley (2016)
# 1. Overview

Hydrographic sections P16N: 7 occupations

## CCHDO data base

### GO-SHIP 2015

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### CLIVAR Repeat Hydro (GO-SHIP) 2006

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### WOCE 1991

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P16N to 20°S

[http://cchdo.ucsd.edu](http://cchdo.ucsd.edu)

Talley (2016)
Quick results from latest P16N

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

Anthropogenic Carbon (Carter et al.)

Anthropogenic Carbon Estimates along P16

Dissipation which is related to diapycnal diffusivity (divide by $N^2$) (Thurnherr)

Talley (2016)
North Pacific Ocean has only mid-latitude heat loss.

NE Pacific has slight net heating.

Surface heat flux

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
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
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.
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/m²) (vectors) and wind-stress curl (×10⁻⁷ N/m³) (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
Surface geostrophic circulation schematic

10/6/16
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Surface dynamic topography and current names (geostrophic flow)

Talley (2016)

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

The NE Pacific is quiet

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

P16 has low vertical diffusivity in upper ocean

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

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

3 Upper ocean

Subducted salinity maximum water: Subtropical Underwater

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).*

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3 Upper ocean

Oxygen Minimum Zone (OMZ)
Oxygen at 200 m depth
(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
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

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Talley (2016)
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?
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
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)
Talley (2016)
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)

Talley (2016)
Johnson et al. (2008) OMP analysis using just 2 end members.

Fraction of NADW in the deep water layer

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

Fraction of AABW in the bottom layer
4 Deep and Bottom Water

Global deep water potential temperature-salinity

Worthington, 1982

Pacific Deep Water
(or Common Water)

Antarctic Bottom Water

Indian Deep Water

North Atlantic Deep Water

Talley (2016)

DPO 4.17b
4 Deep and Bottom Water

Relate this diagram to the vertical sections that follow

After Schmitz (1995)

DPO Fig. 14.11b
Deep and abyssal circulation and properties

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

P16 WOCE/GO-SHIP

AABW or LCDW

Antarctic Intermediate Water

N. Pacific Intermediate Water

Salinity

Talley (2016)
Salinity in mid-Pacific (150W)

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Talley (2016)

(1) Upper
(2) AAIW and NPIW
(3) PDW
(4) LCBW (AABW)
Oxygen in mid-Pacific (150W)

(1) Upper AAIW and NPIW
(2) PDW
(3) LCBW (AABW)
Nitrate in mid-Pacific (150W)

- (1) Upper AAIW and NPIW
- (2) AAIW and NPIW
- (3) PDW
- (4) LCBW (AABW)
CFC-11 in mid-Pacific (150W)
Silicate in mid-Pacific (150W)

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Talley (2016)

(1) Upper AAIW and NPIW
(2) AAIW and NPIW
(3) PDW
(4) LCBW (AABW)
Δ¹⁴C in mid-Pacific (150W)

Very negative - oldest water

Talley (2016)
Total CO$_2$ in mid-Pacific (150W)
δ³He in mid-Pacific (150W)
4 Deep ocean circulation


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

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Talley (2016)

DPO Fig. 14.4a
Below depth of NADW in S. Atlantic

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


FIGURE 10.17
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.
4 Intermediate, deep and abyssal properties

Pacific Deep Water: (aka “Common Water”)

Isopycnal at 2600-2800 m

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

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

10/6/16

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)
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.

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

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

Extra slides follow: maps from the WHP Pacific atlas
Depth (m) 28.01 $\gamma^n$ (kg/m$^3$)

Depth (m) 28.10 $\gamma^n$ (kg/m$^3$)
Δ¹⁴C (/mille) 28.01 γₙ (kg/m³)

Δ¹⁴C (/mille) 28.10 γₙ (kg/m³)