Subantarctic Mode Water and Antarctic Intermediate Water processes from winter observations in the southeast Pacific and from the Southern Ocean State Estimate

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del Pacífico Sur Oriental

Outline

Background: SE Pacific cruises (2005-2006) and
Southern Ocean State Estimate

Antarctic Intermediate Water (AAIW) distribution
Subantarctic Intermediate Water (SAMW) distribution

SAMW and AAIW in the global overturning circulation
Global impacts of SAMW and AAIW

SAMW and AAIW formation
Southeast Pacific SAMW/AAIW cruise results

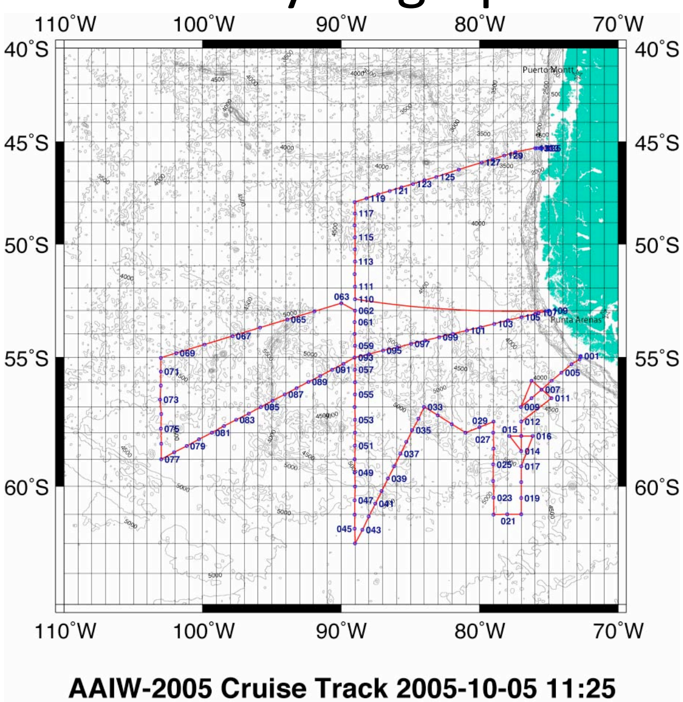
Formation rates using different approaches

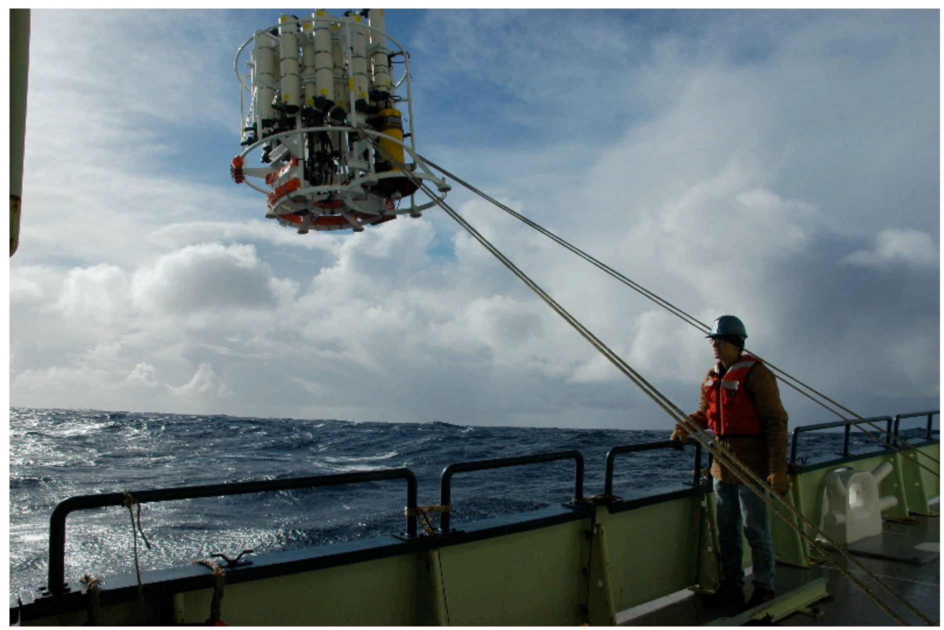
Hydrographic surveys

Southeast Pacific: AAIW and SAMW formation experiment

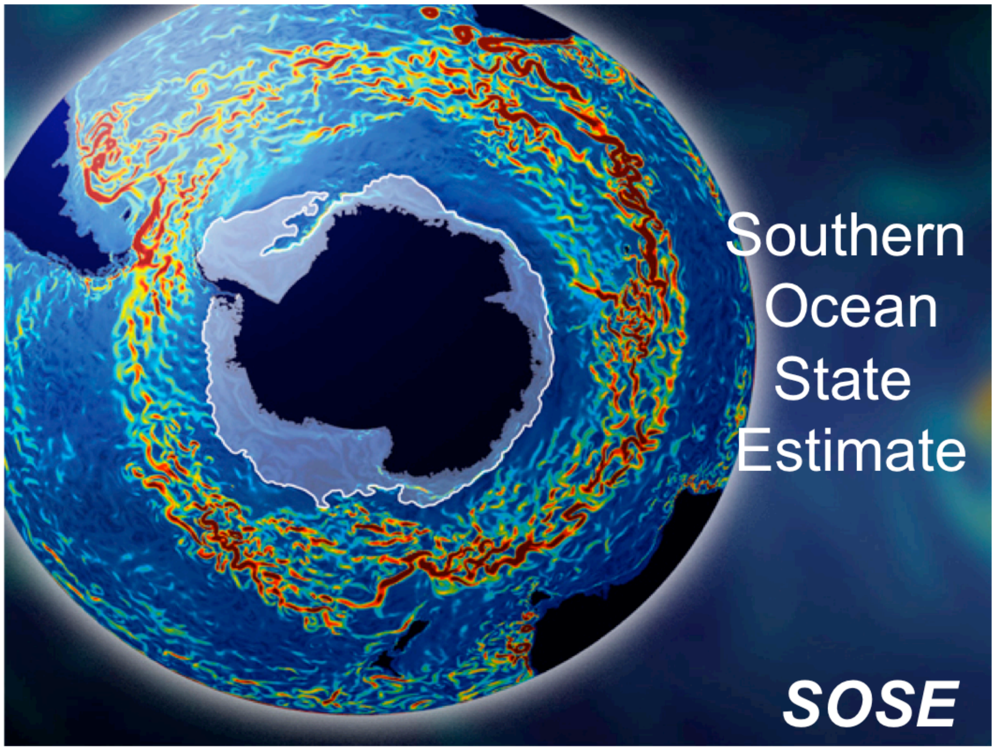
- 2005 Austral Winter Hydrographic Survey
- 2006 Austral Summer Hydrographic Survey
- Complete CTD/rosette profiles of T, S, oxygen, nutrients, carbon, velocity, CFCs
- XCTD deployments between CTD profiles

Also WOCE Hydrographic Programme Data (1990s)





Southern Ocean State Estimate



Matt Mazloff, Scripps Inst. Oceanography
http://sose.ucsd.edu

What is a state estimate?

•Model with initial and boundary conditions, and forcing fields, run for the period of the observations
•Use misfit of model with all data inputs to adjust all ICs, BCs and forcing to better match data.

This provides dynamically consistent analysis (interpolation) of the fields of interest

SOSE:

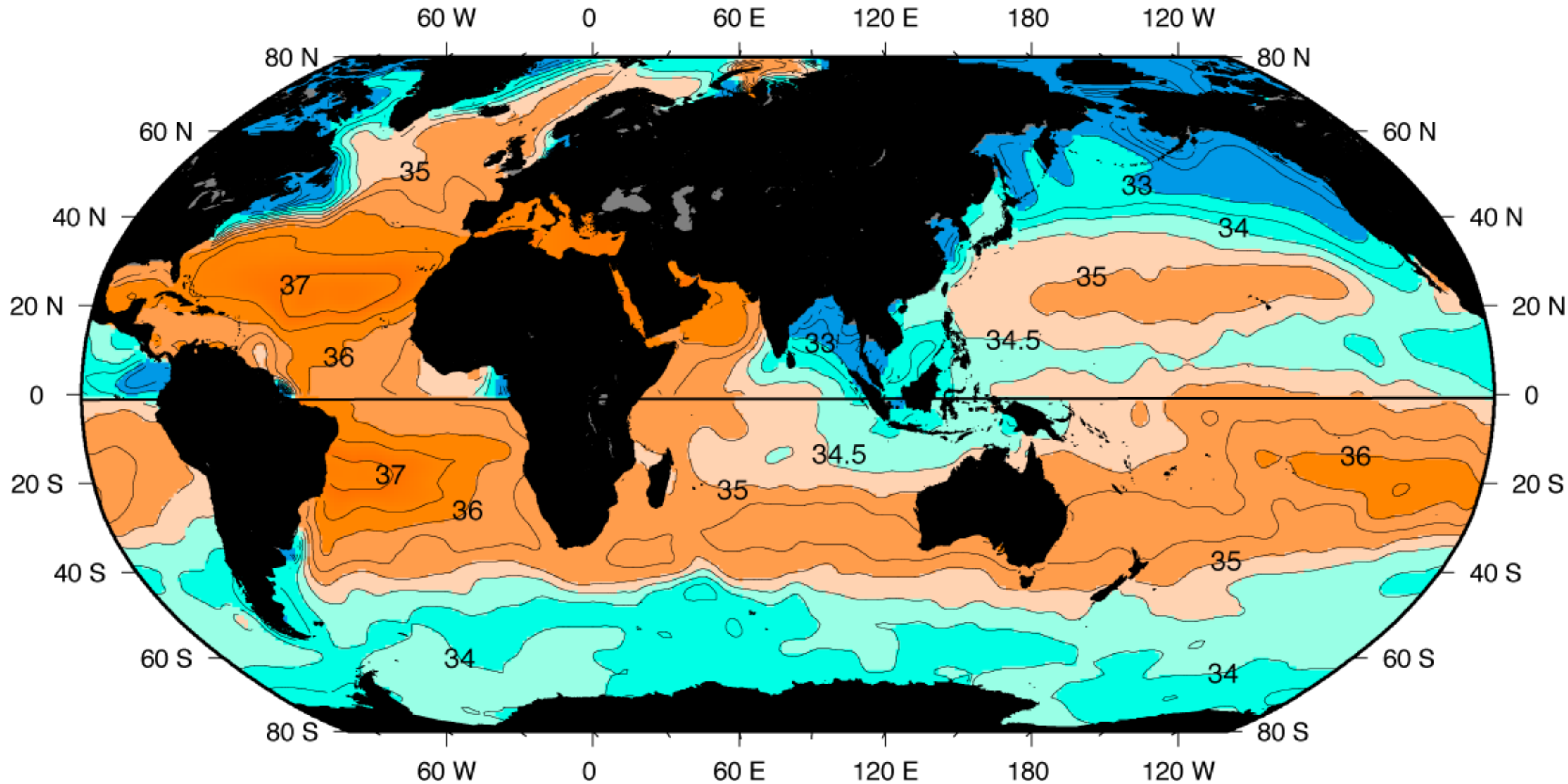
- MIT ocean general circulation model
- 1/6°horizontal resolution
- Temperature, salinity, wind stress, heat fluxes, circulation
- 2005-2007 and 2008-2010

Definitions and distributions of SAMW and AAIW

What are mode and intermediate waters?

What is their role in the global circulation?

Antarctic Intermediate Water (AAIW) distribution



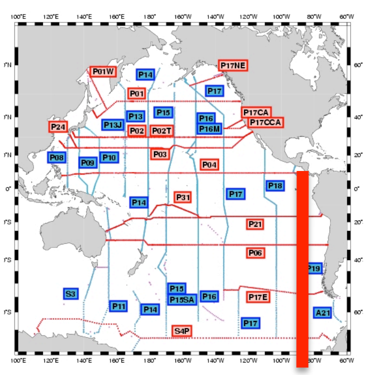
Surface salinity (psu) in winter (January, February, and March north of the equator; July, August, and September south of the equator) based on averaged (climatological) data from Levitus et al. (1994b).

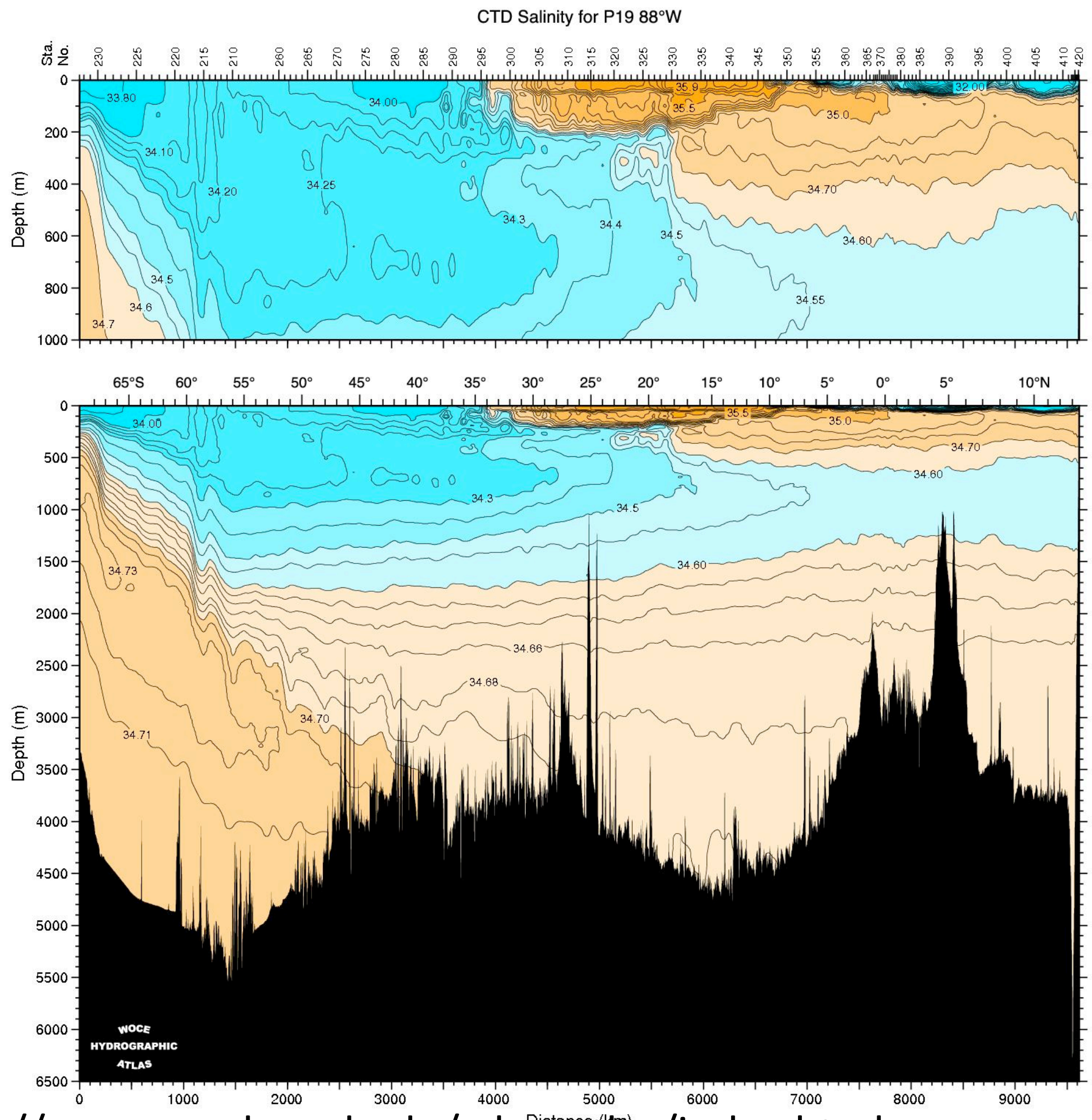
Talley et al. (2011) Descriptive Physical Oceanography Figure 4.15

Antarctic Intermediate Water (AAIW) distribution

Salinity minimum (blue)

Everywhere in Southern Hemisphere north of the Antarctic Circumpolar Current





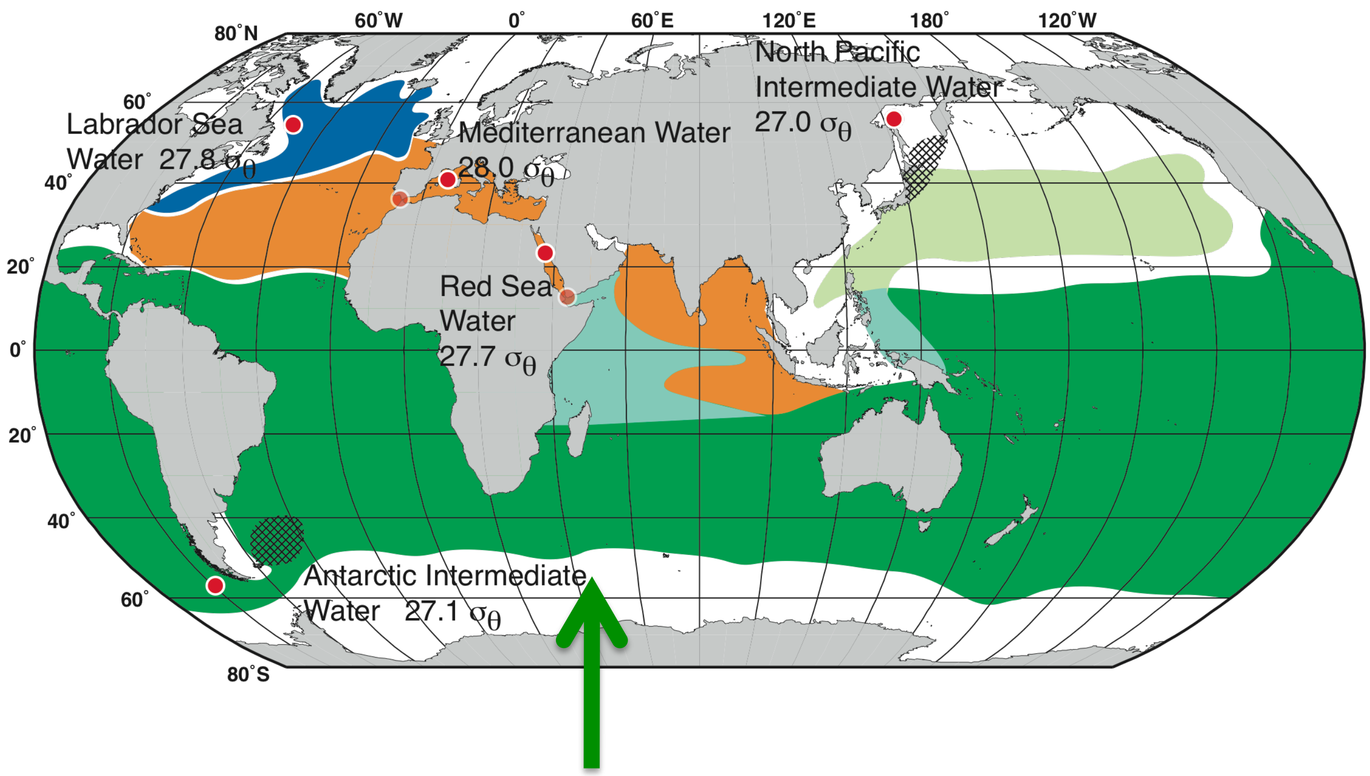
Talley (WHP Pacific Atlas, 2007) http://www-pord.ucsd.edu/whp_atlas/index.html

Antarctic Intermediate Water (AAIW) distribution

Location of intermediate waters

Vertical salinity minima – green and blue

Vertical salinity maxima – orange/ teal

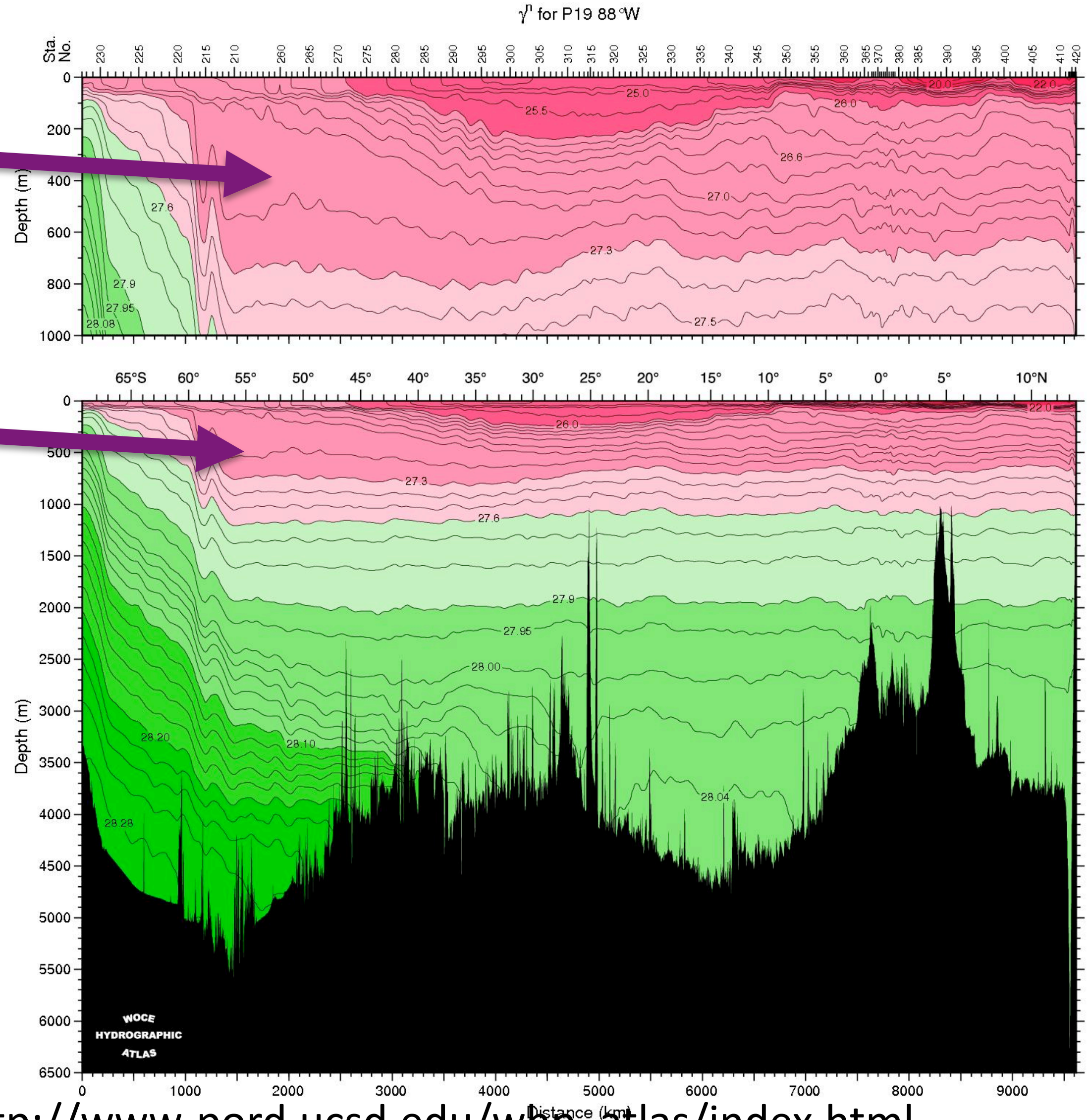


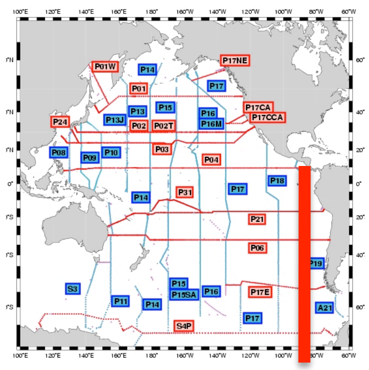
AAIW (dark green)

Talley (2011) Descriptive Physical Oceanography DPO Fig. 14.13

Subantarctic Mode Water (SAMW) distribution

Spreading of density contours, indicating layer with low stratification.



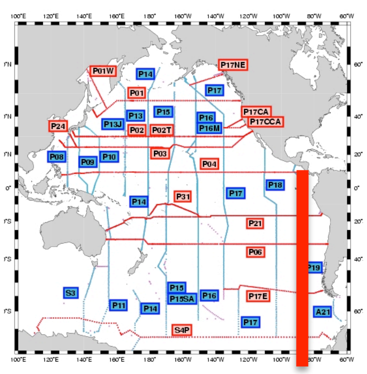


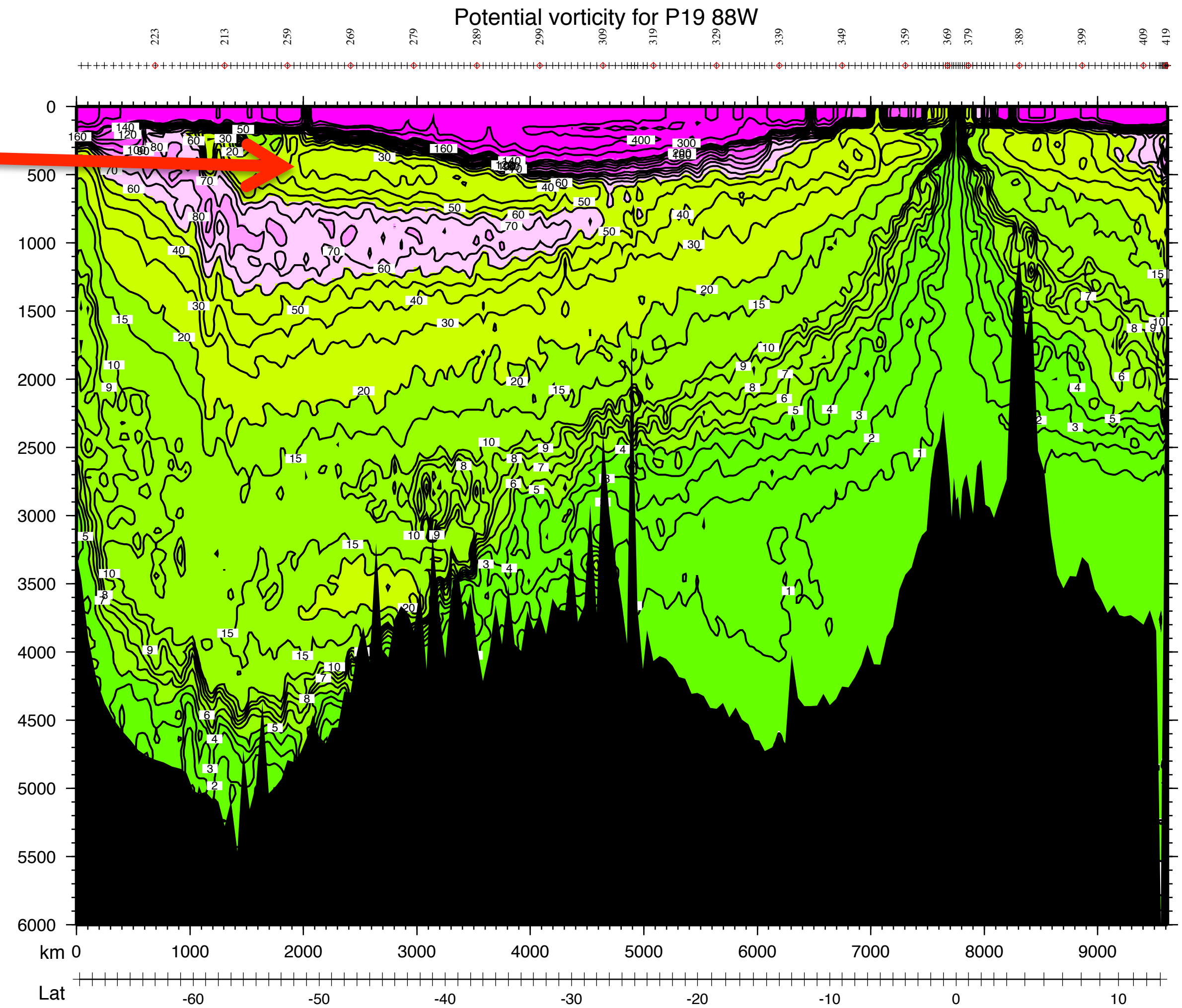
Talley (WHP Pacific Atlas, 2007) http://www-pord.ucsd.edu/whp_atlas/index.html

SAMW distribution

Low stratification is related to low potential vorticity PV.

$$PV = \left| \frac{f}{\rho} \frac{\partial \rho}{\partial z} \right|$$





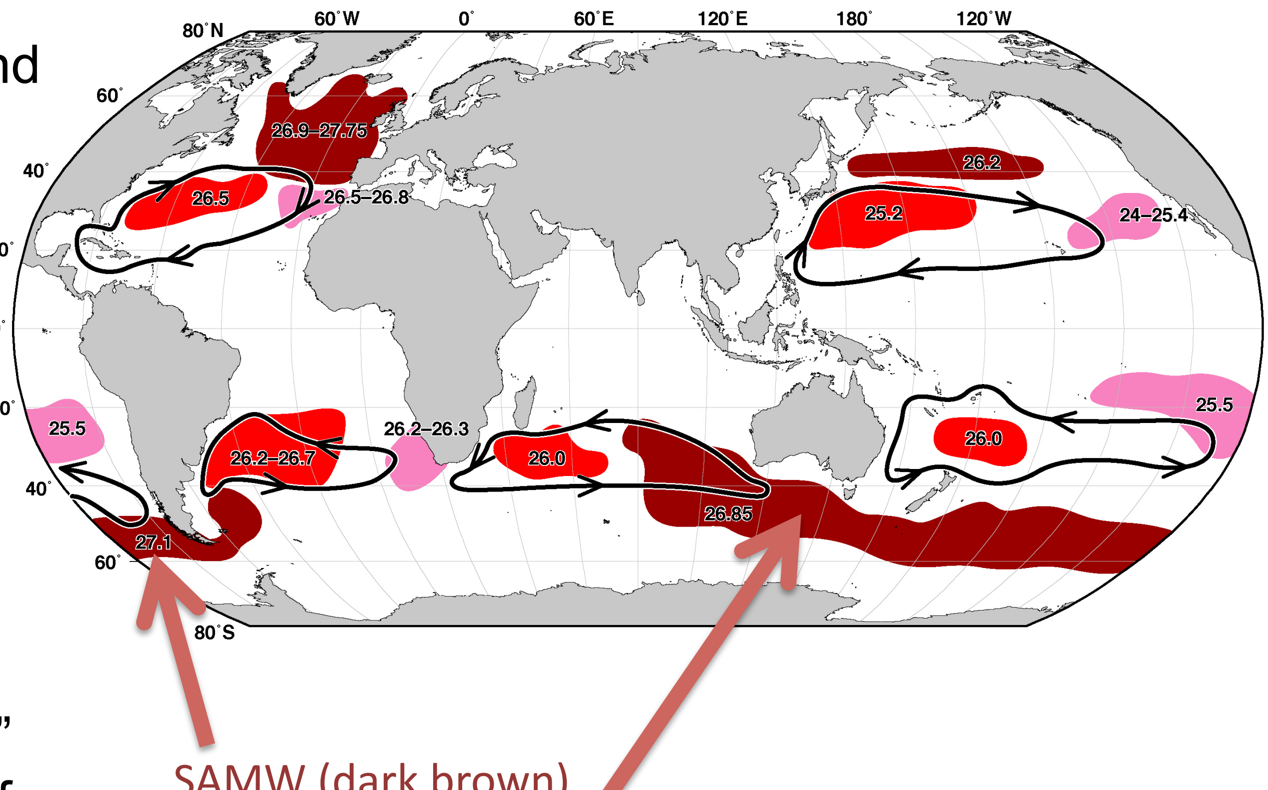
Location of SAMW and other mode waters

Mode Waters:

Layers of very low PV found over broad regions, on warm side of strong currents.

Originate as thick winter mixed layers that spread into the interior along isopycnals (subduction)

“Subantarctic Mode Water” is the low PV layer north of the Antarctic Circumpolar current



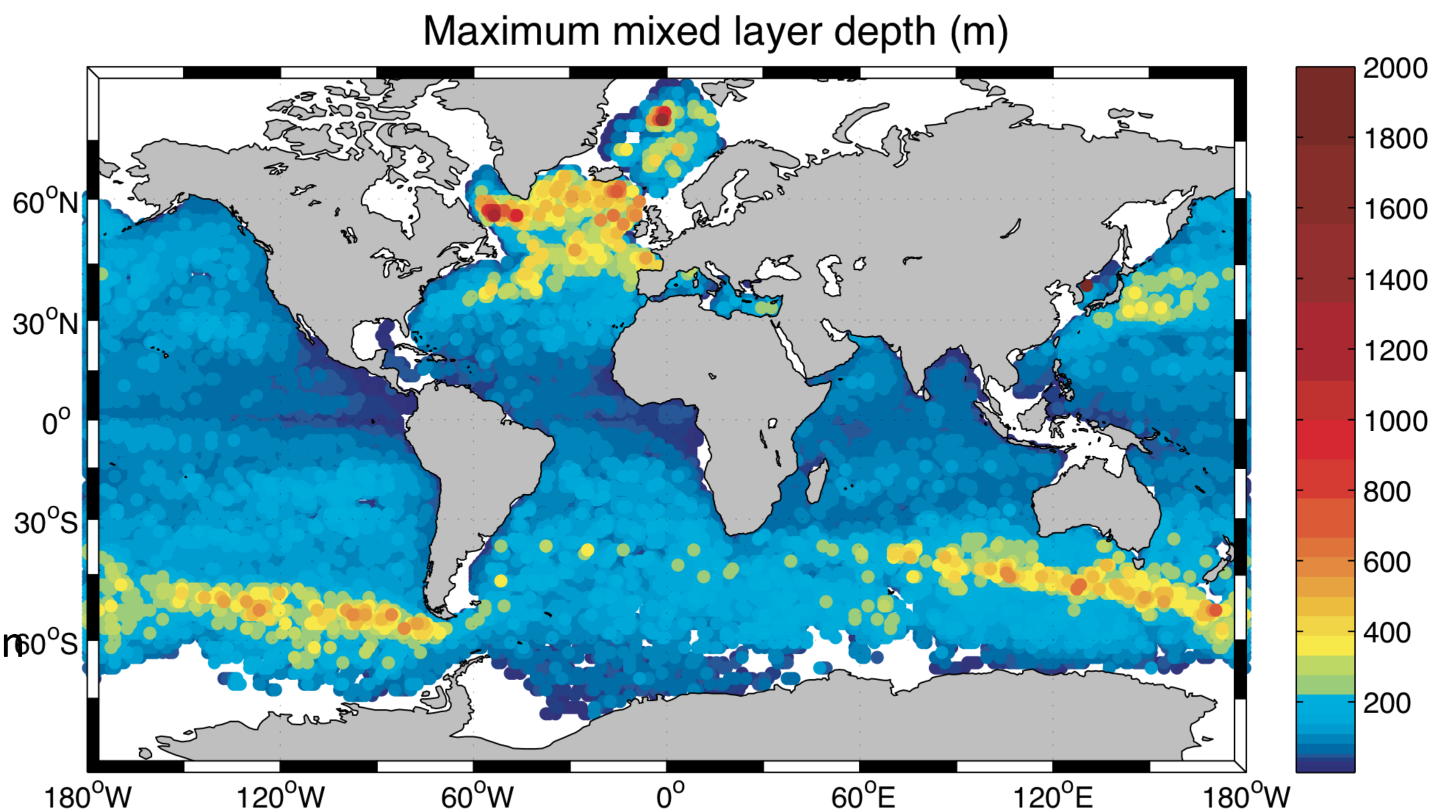
SAMW (dark brown)

Hanawa and Talley (2001); DPO 14.12

SAMW and large mixed layer depths

Mode waters originate where winter mixed layers are very deep.

Thicker (> 500) in some special locations, notably in
(1) band in the Southern Ocean and (2) northern North Atlantic



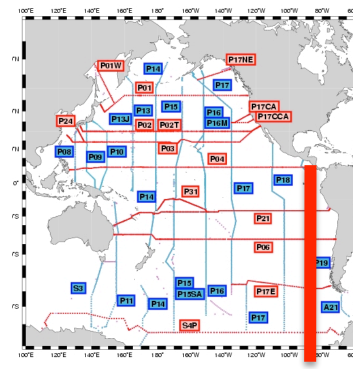
Data set: all profiles from Argo floats

Holte et al website

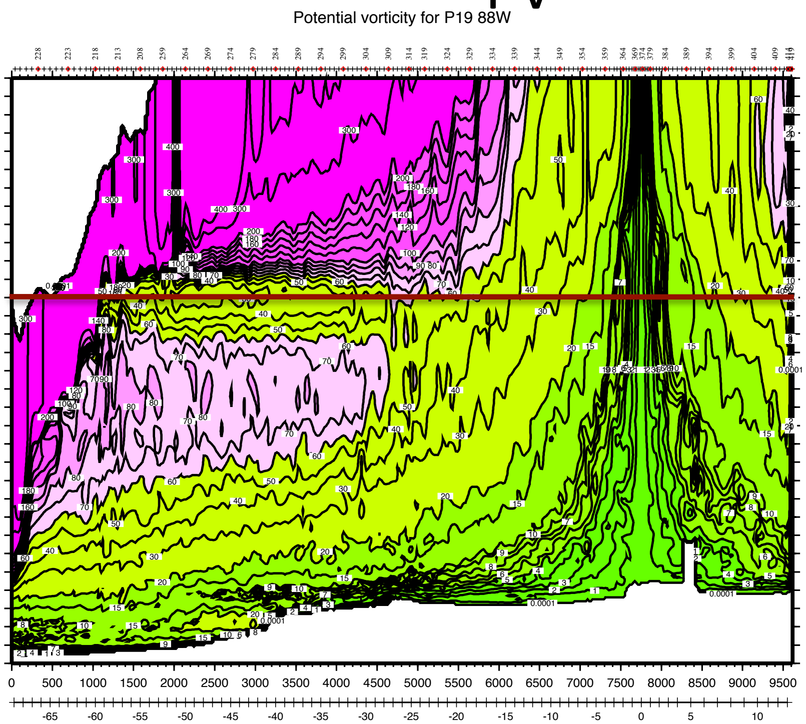
http://mixedlayer.ucsd.edu

SAMW and AAIW distributions

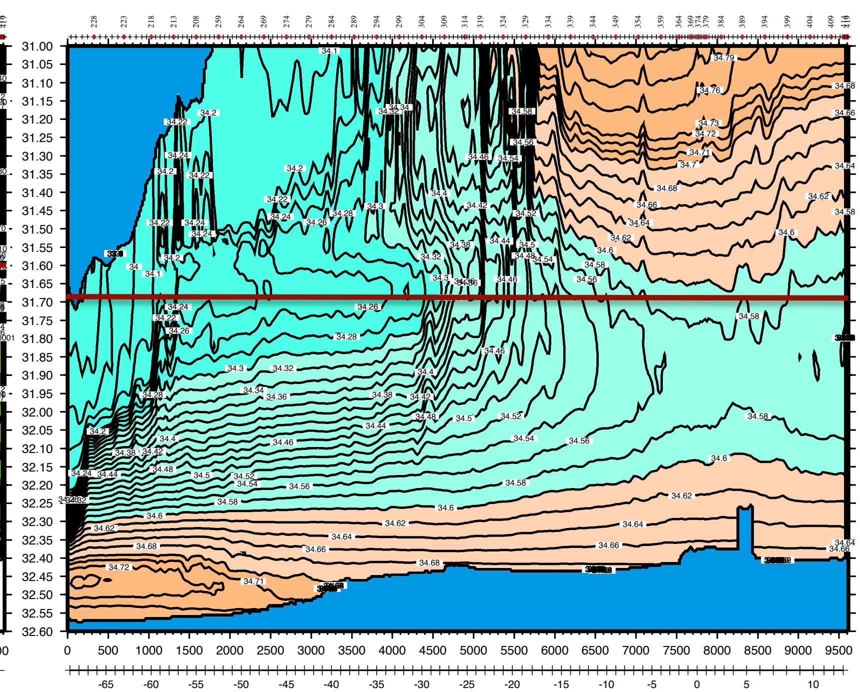
After they form at the sea surface, the low PV water (SAMW) and the low salinity water (AAIW) advect into the ocean interior mostly along isopycnals.



PV



Salinity



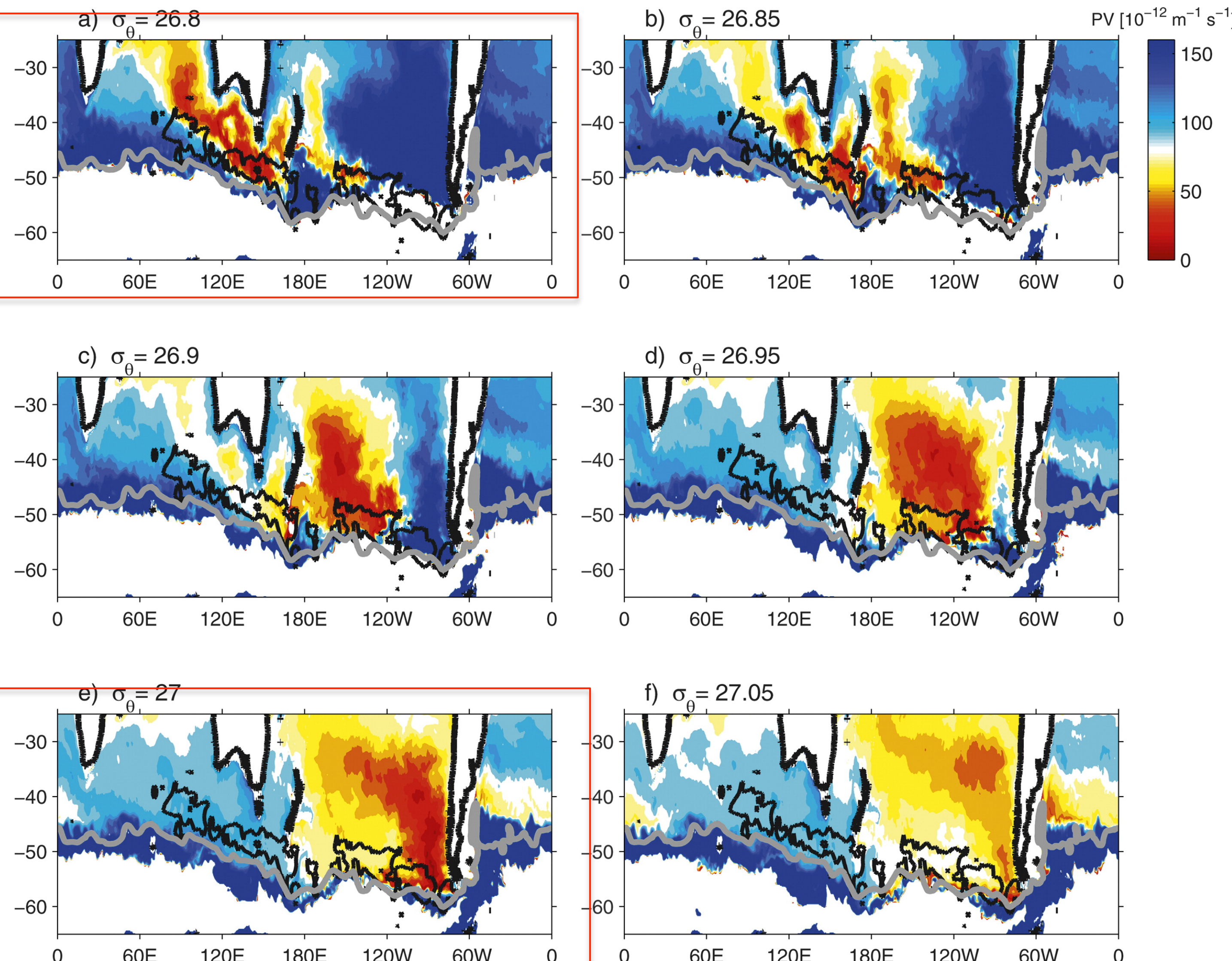
Potential density

Latitude

Latitude

SAMW distribution – PV on isopycnals

Southeast Indian SAMW

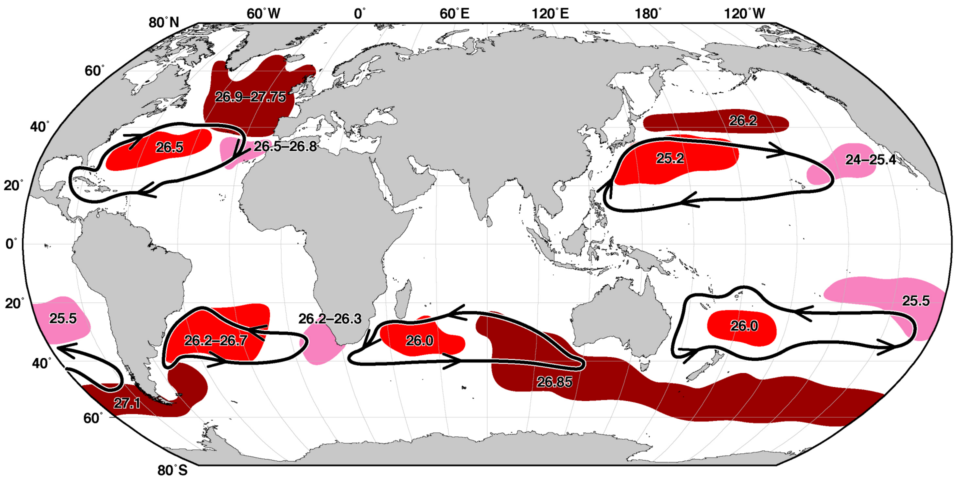


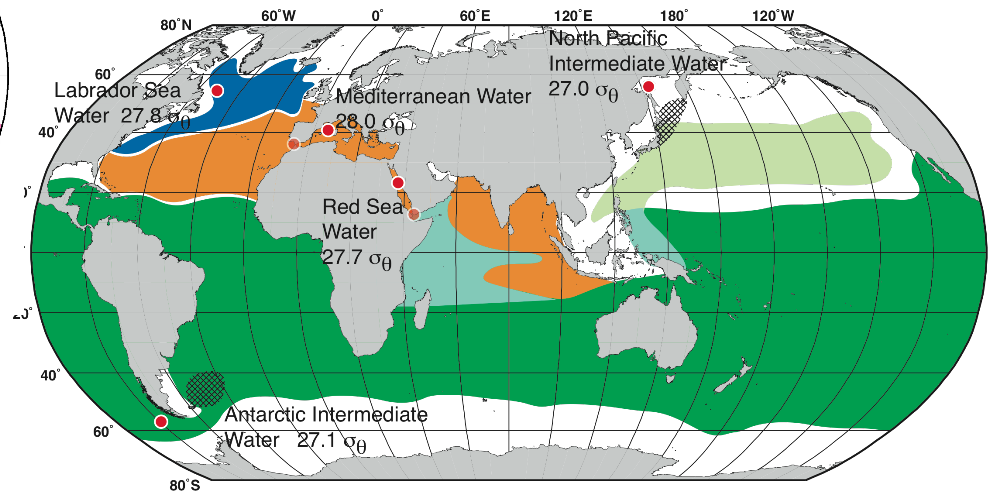
Potential vorticity on isopycnal surfaces (SOSE).
Red: Low PV
Black contours: MLD > 300 m

Southeast Pacific SAMW

Cerovecki et al. (JPO, 2012)

SAMW/AAIW formation hypothesis



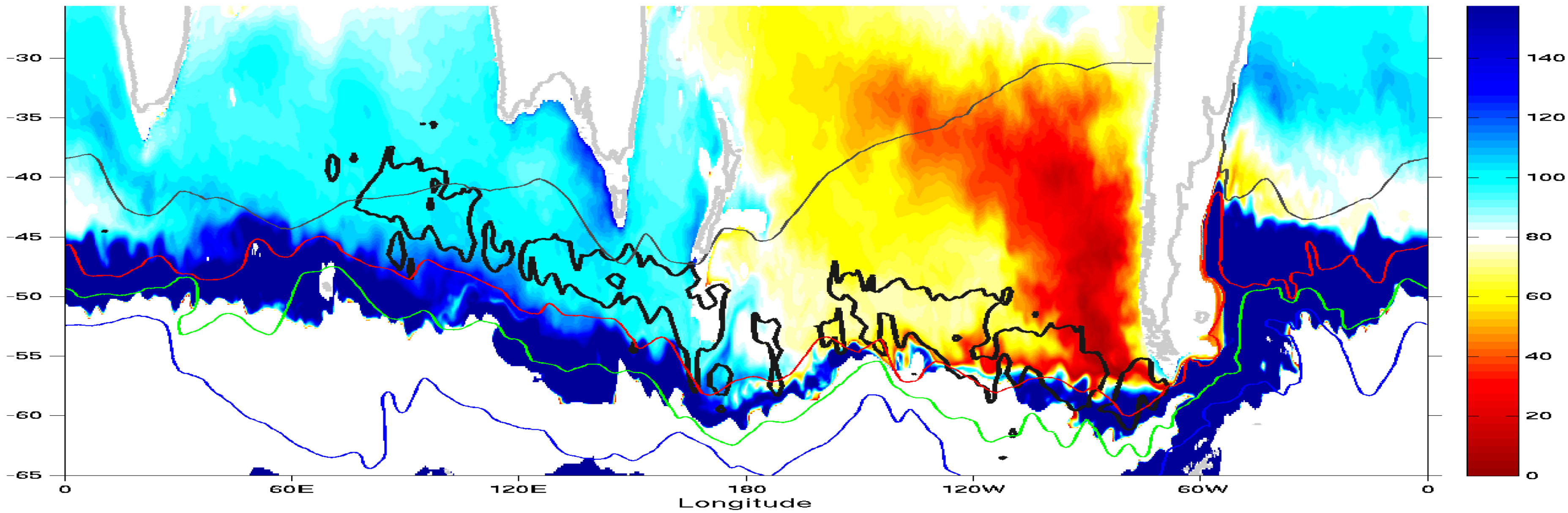


Initial hypothesis for SAMW and AAIW properties and formation from McCartney (1977, 1982):

1. SAMW cools, freshens and densifies from west to east along its circumpolar pathway, with several major detrainments northward into the subtropical gyres
2. AAIW is the coldest, freshest, densest form of SAMW, which thereby is central to the northward transport of freshwater from the Antarctic

SAMW distribution

Southeast Pacific SAMW



The clear source of low PV on this 27.0 isopycnal in the southeast Pacific, as well as clear indications that lowest salinity, highest oxygen AAIW originates here, led to our winter surveys in search of new SAMW and AAIW.

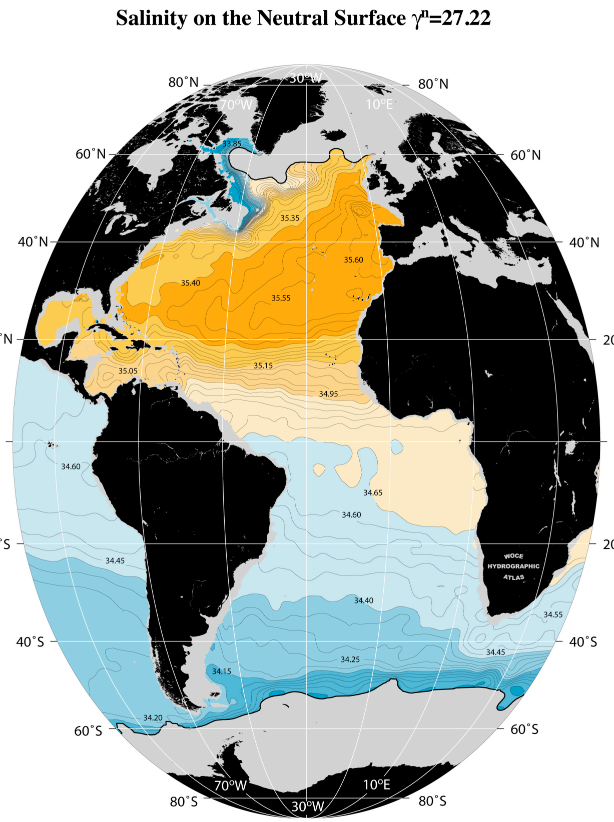
Cerovecki et al. (JPO, 2012)

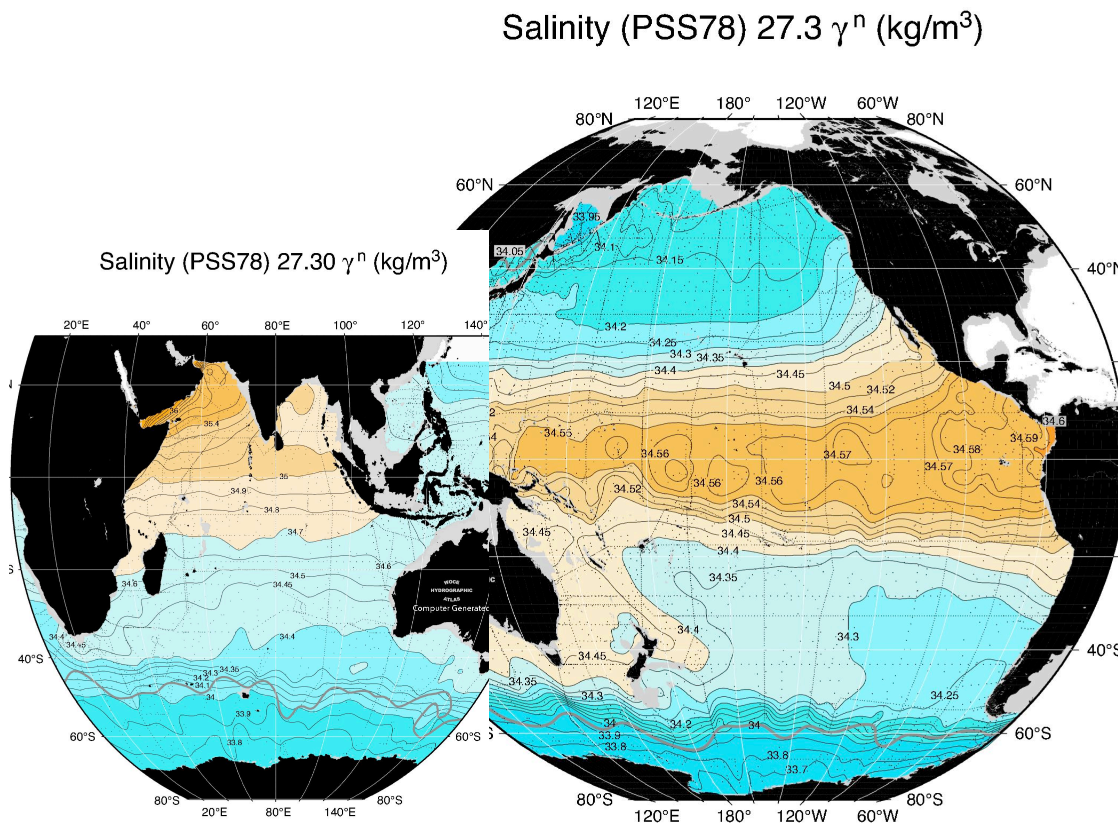
Global view of SAMW and AAIW

What are some of their impacts on global property distributions?

What is their role in the global circulation?

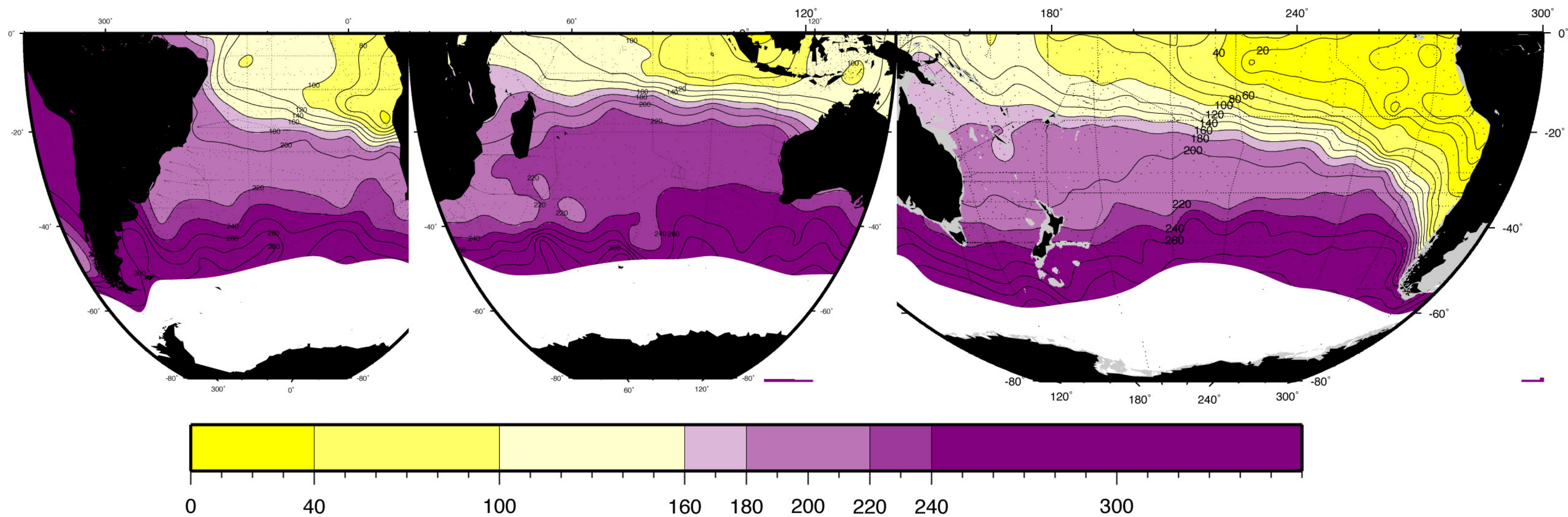
Global impact of AAIW on salinity (freshwater export in SH)





WOCE Hydrographic Programme Atlases http://www-pord.ucsd.edu/whp_atlas/index.html

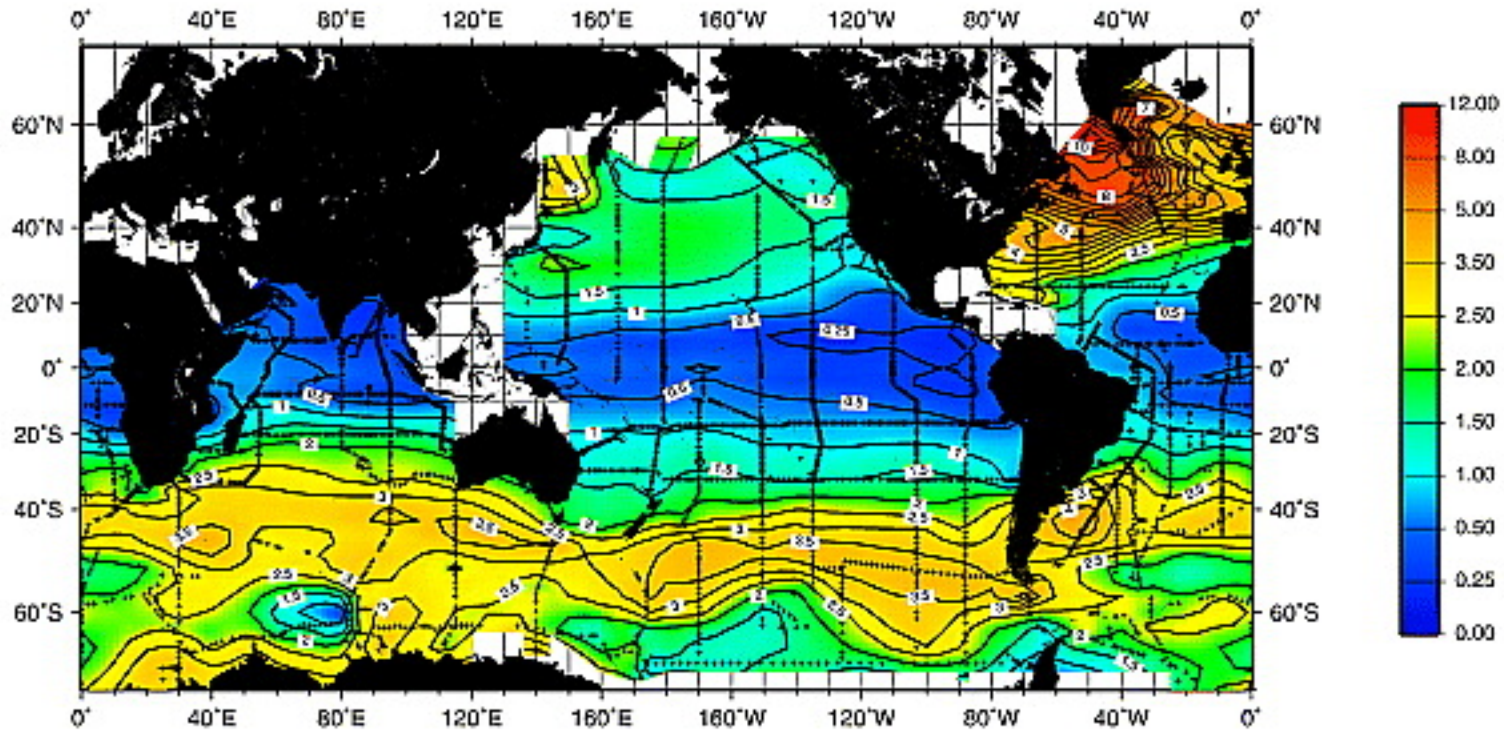
Global impact of SAMW on oxygen



Oxygen 26.75 γ_n (center of SE Indian SAMW)

Global impact of SAMW on dissolved gases

The Southern Hemisphere absorbs atmospheric gases in the SAMW band (yellow)

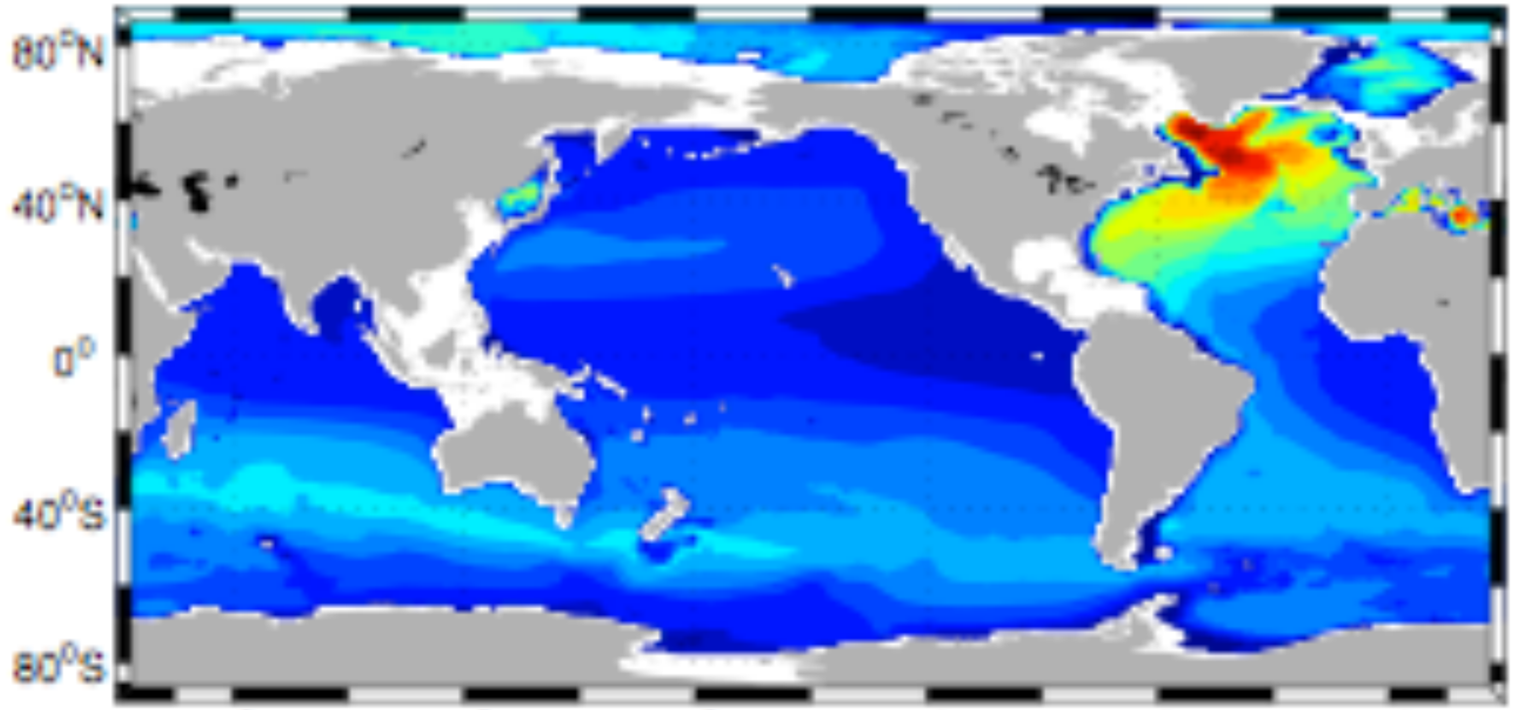


Chlorofluorocarbon (CFC) water column inventory (conservative anthropogenic tracer)

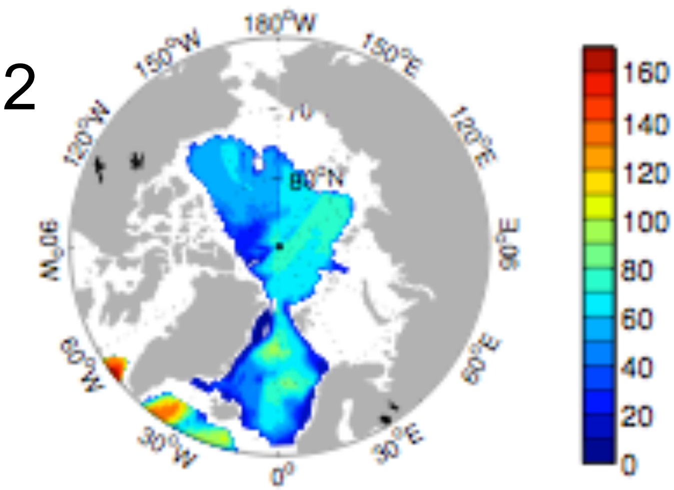
Willey et al. (GRL 2004)

Global impact of SAMW on dissolved gases

The Southern Hemisphere absorbs atmospheric gases in the SAMW band (light blue)



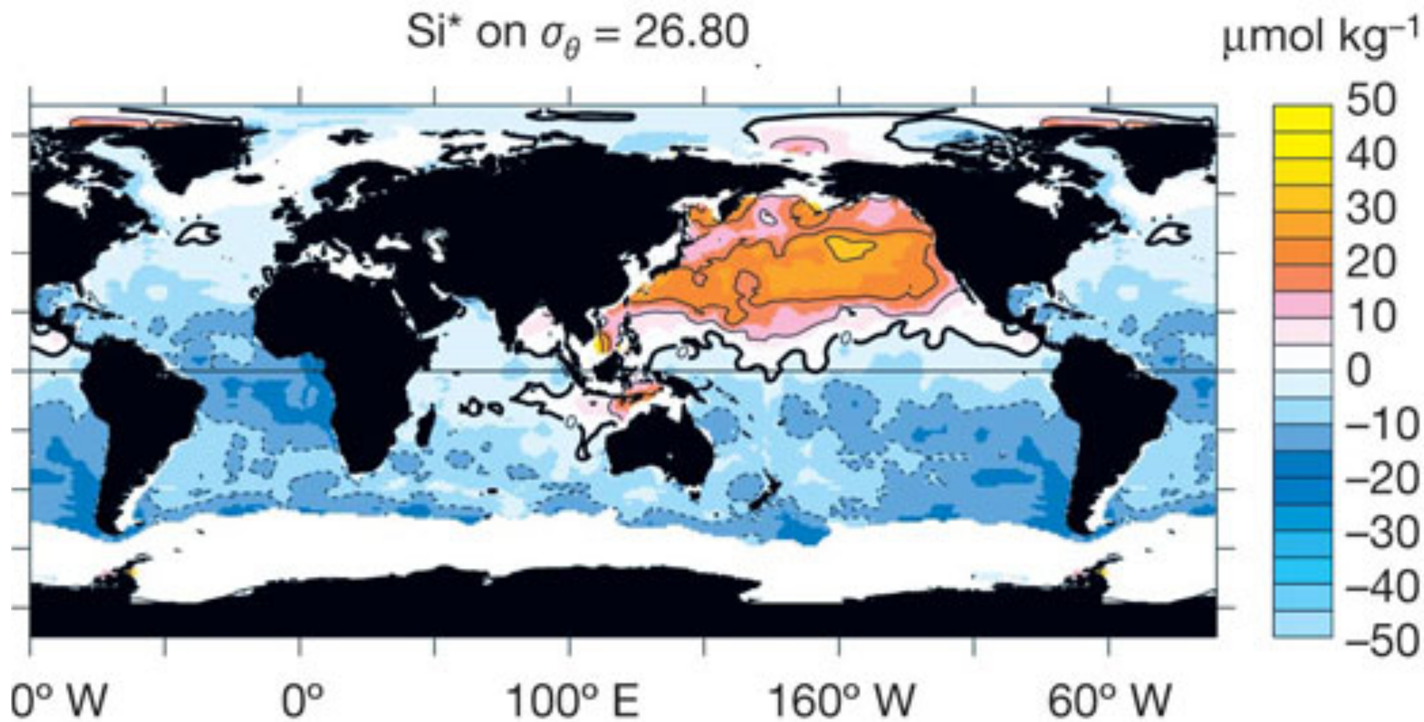
Anthropogenic CO_2



Khatiwala et al. (Biogeosciences 2013)

Global impact of SAMW on nutrients/productivity

The SAMW exports nutrients northward out of the ACC region. The nutrients come from upwelled deep waters (Indian and Pacific DW).

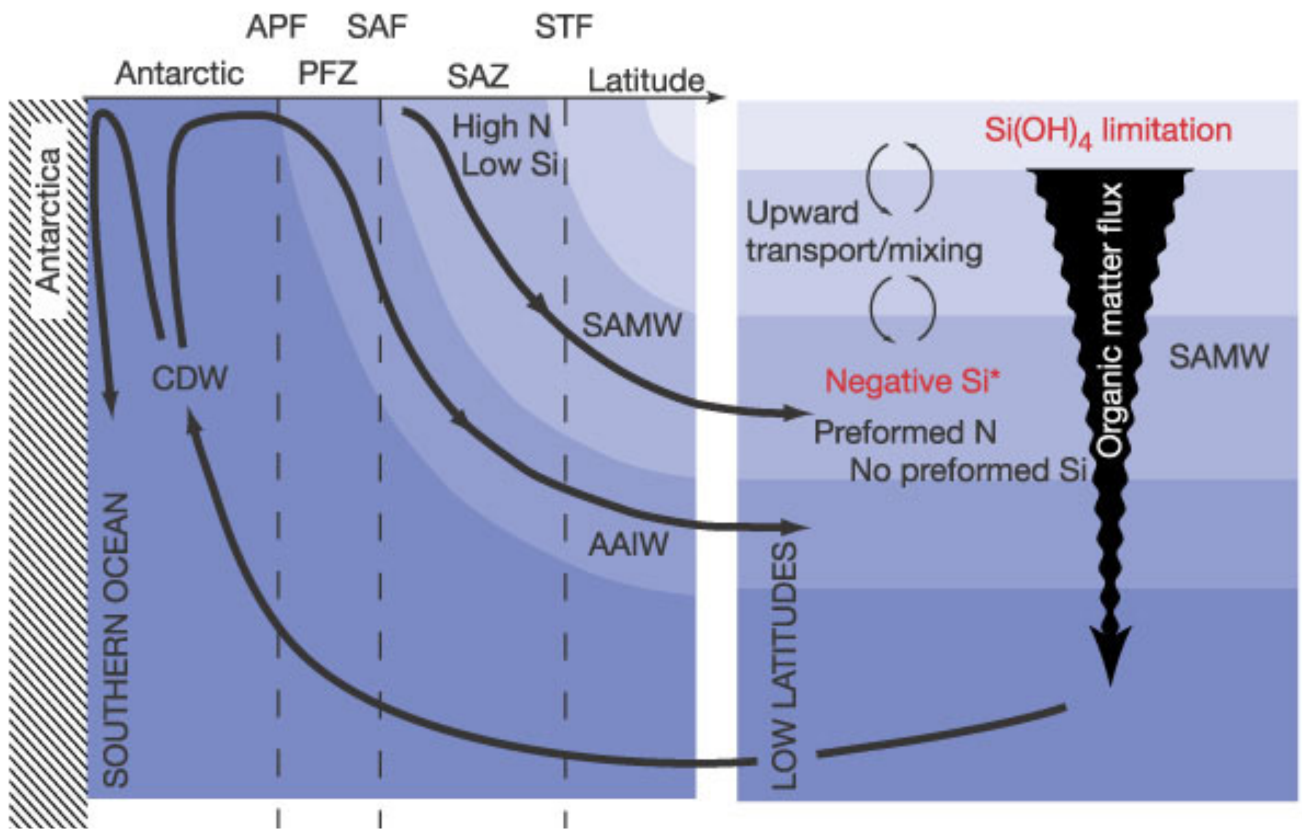


Blue tracer indicates SAMW influence on nutrients within the thermocline (see next slide for why low Si* means high nitrate)

Sarmiento et al. (Nature 2004)

Global impact of SAMW on nutrients/productivity

The nutrient distribution in the Southern Hemisphere thermocline suggests a mechanism for SAMW formation and export: upwelling of deep water in the Southern Ocean, northward transport at the surface joined by subtropical surface water, and subduction northward into the Southern Hemisphere gyres.

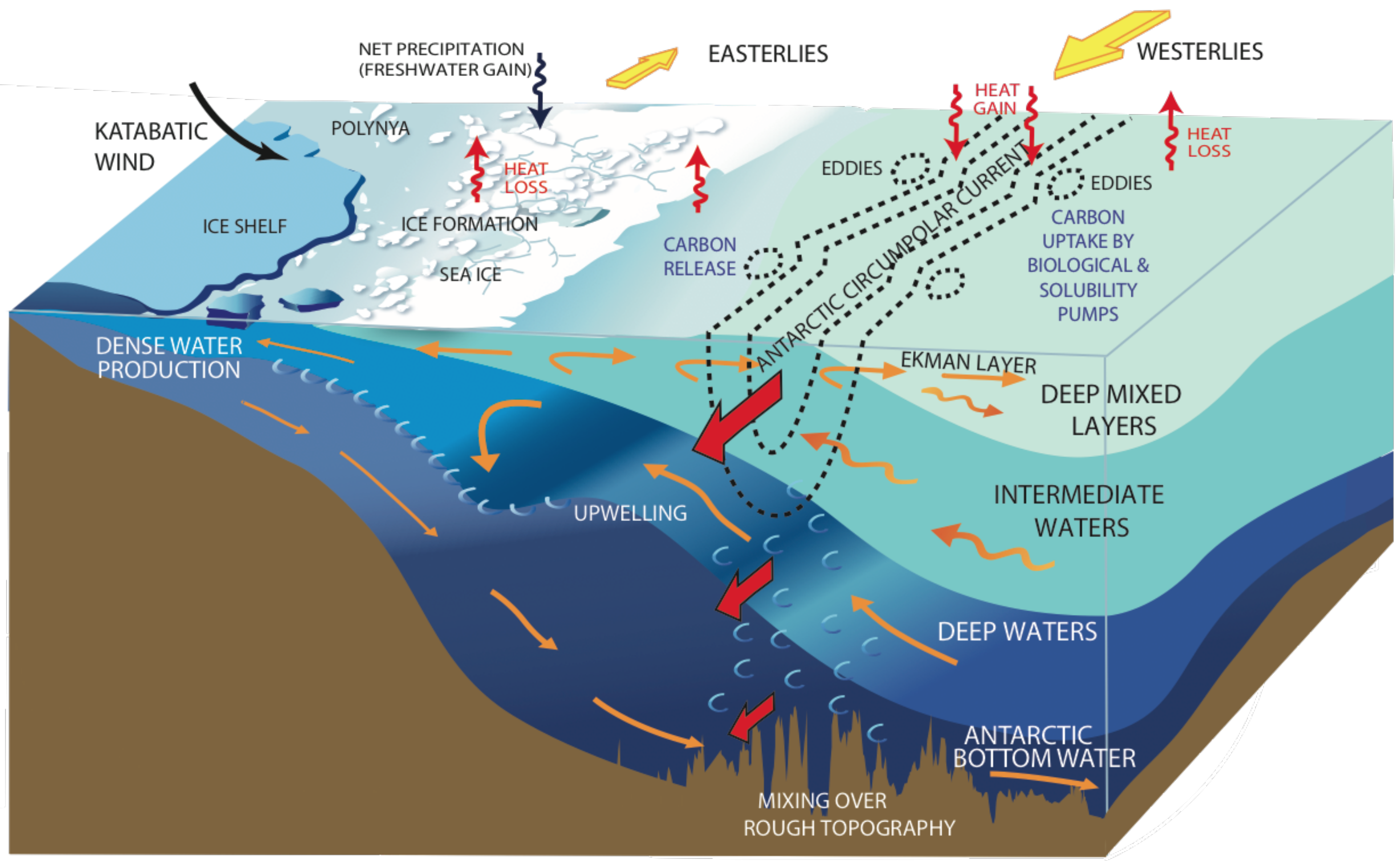


Sarmiento et al. (Nature 2004)

Southern Ocean overturning schematic

Zonally-averaged: deep waters upwell to sea surface.

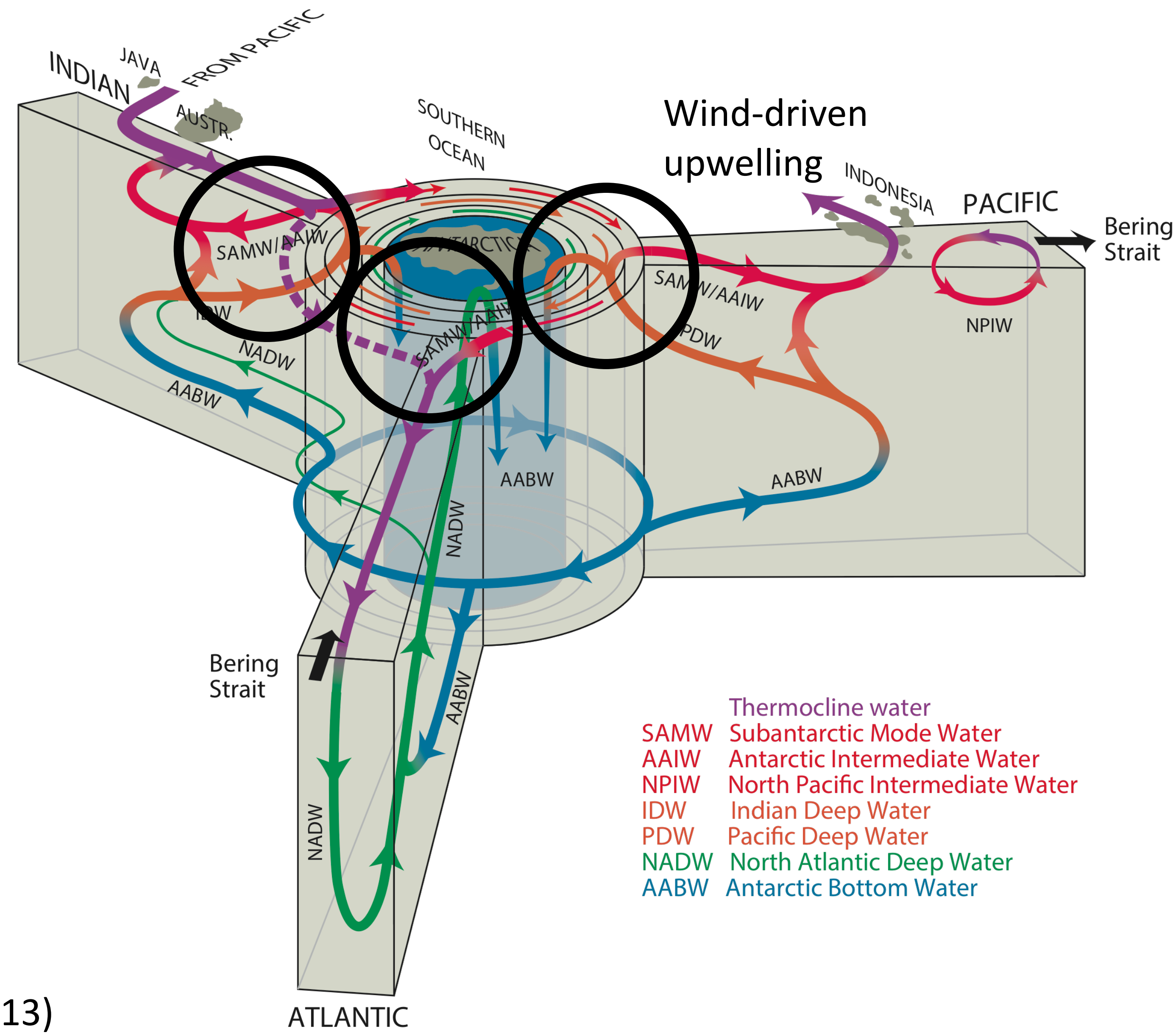
The lighter ones are pushed northwards across the ACC. They feed into the deep mixed layers (SAMW) and then ventilate the surface gyres to the north.



Talley adaptation of NRC (2011) figure

Global overturning circulation schematic

SAMW/AAIW outflow arise, at least partially, from deep waters (originating in the Pacific and Indian Oceans) that upwell to the sea surface in the Southern Ocean, and are pushed northward across the ACC and enter the thermocline

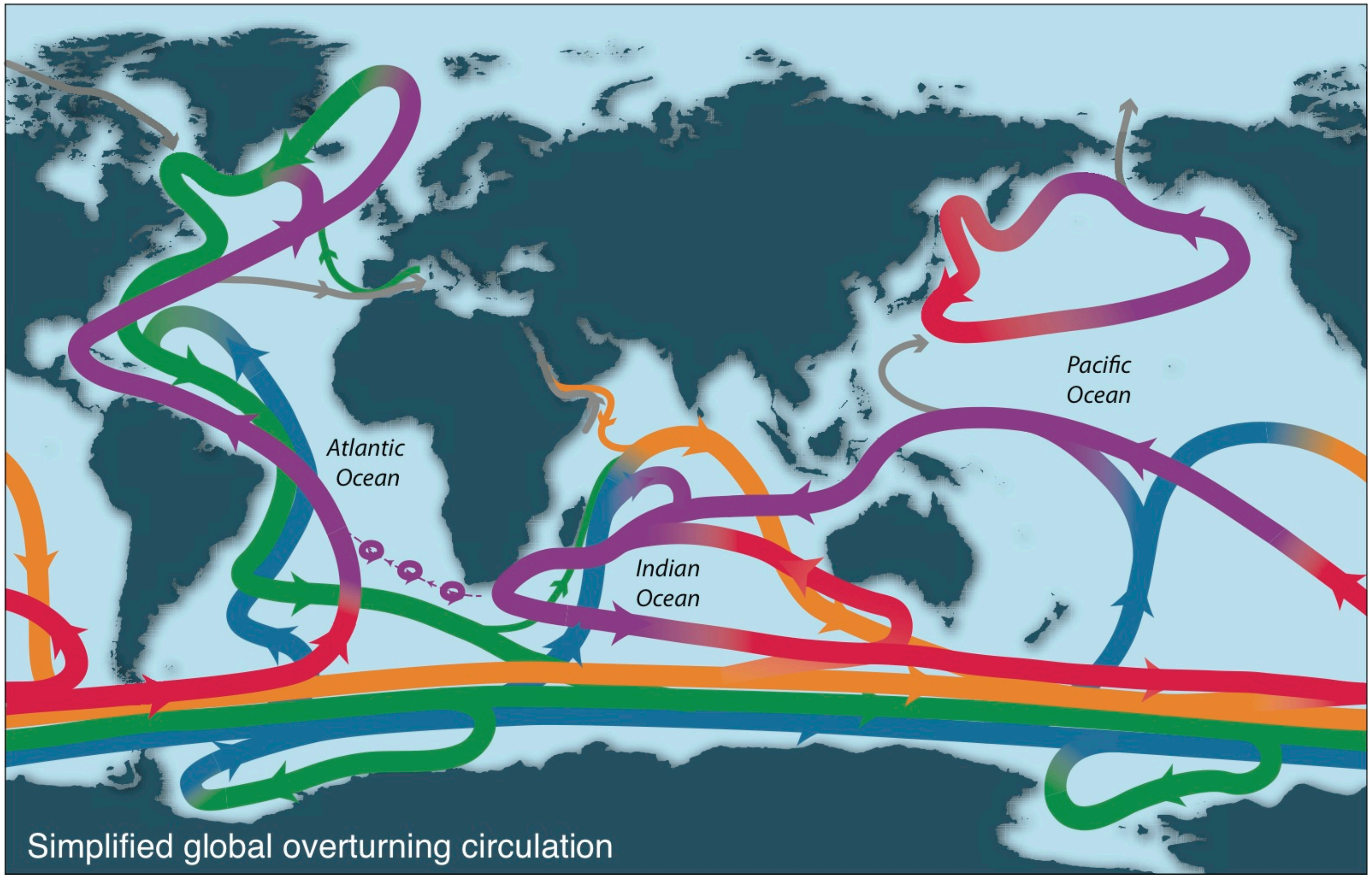


Talley (Oceanography, 2013)

Global overturning circulation schematics

SAMW and AAIW follow the RED pathways northward from the Antarctic Circumpolar Current (ACC).

They are the principal connection from the ACC to the Southern Hemisphere thermoclines/gyres



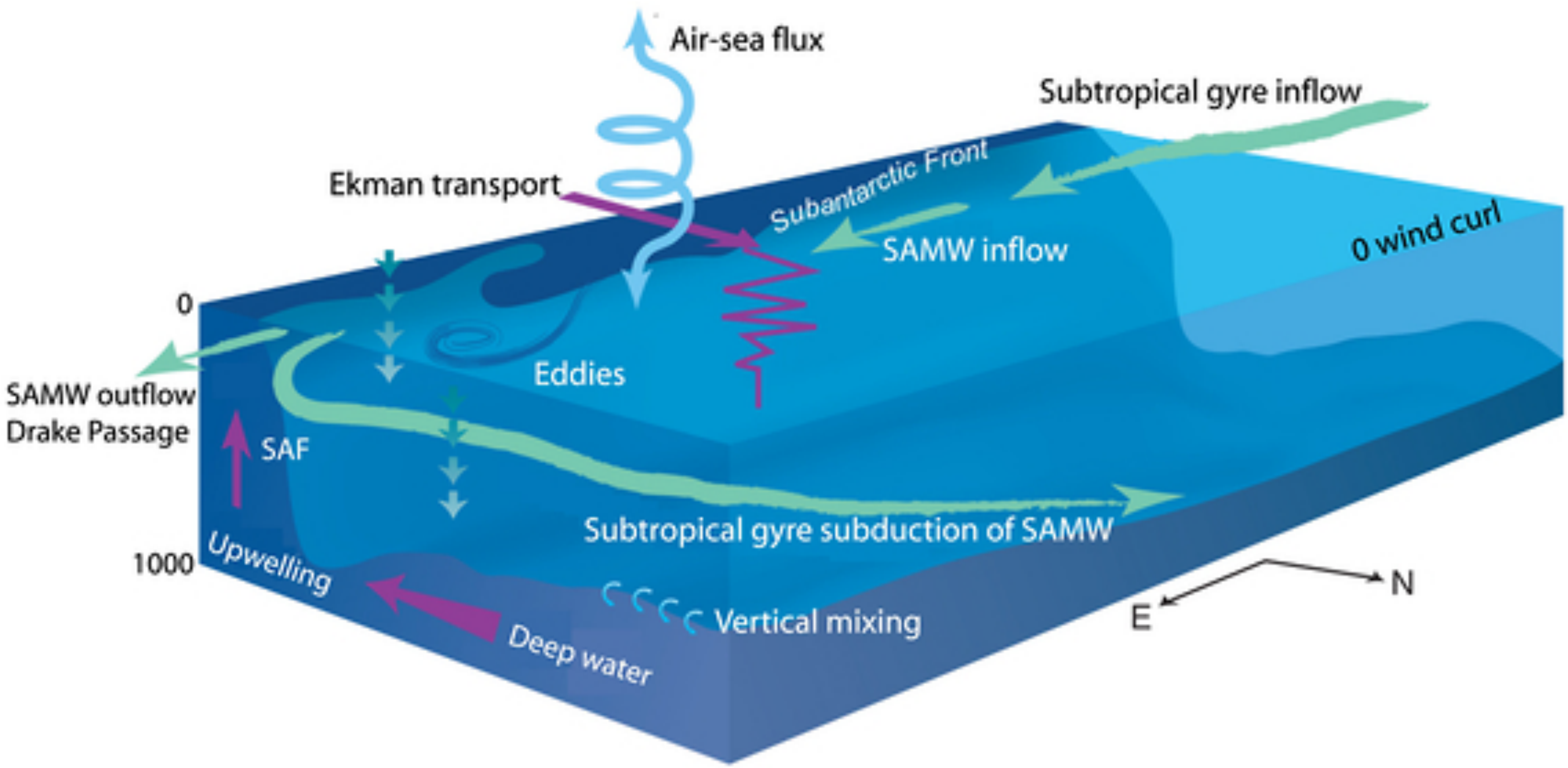
Talley (Oceanography, 2013), edited from Talley et al. 2011 (Descriptive Physical Oceanography, 6th ed.)

Formation of SAMW and AAIW

Where do SAMW and AAIW form?

What are the formation processes?

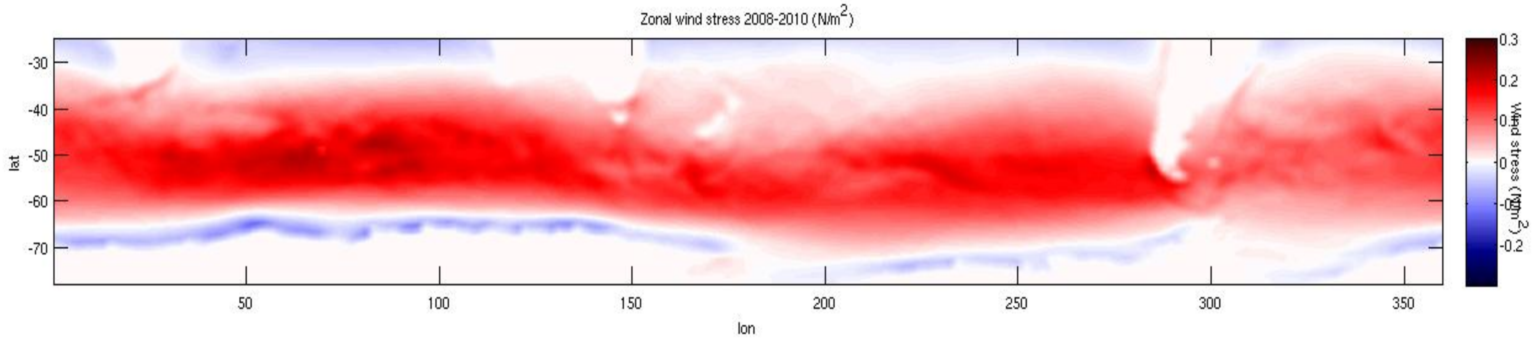
SAMW formation processes



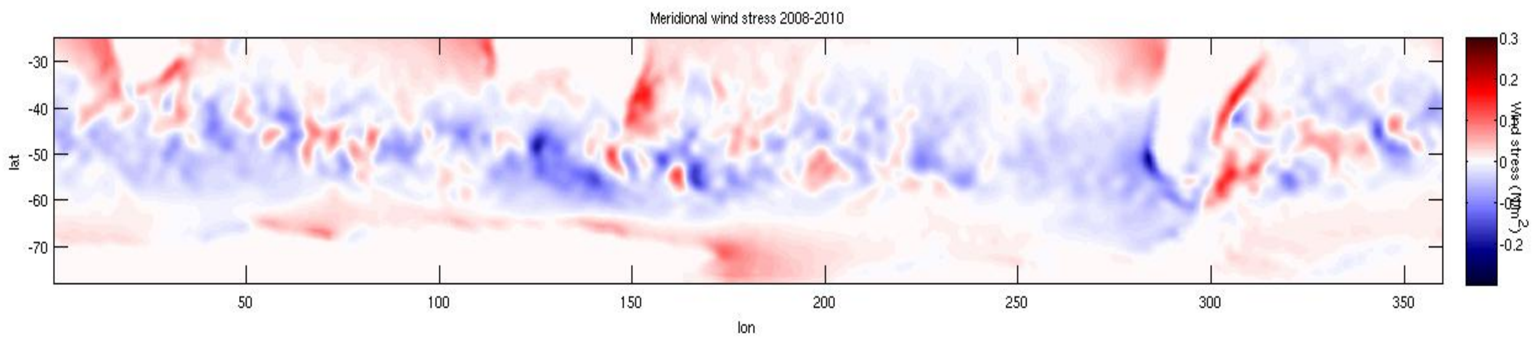
Holte et al. (JPO, 2012)

SAMW formation processes: winds and upwelling

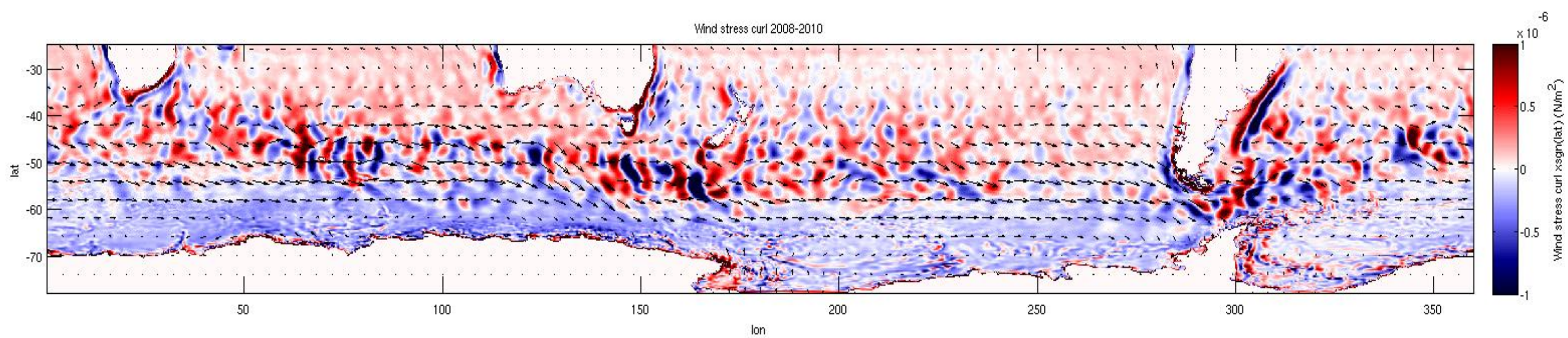
Zonal wind (SOSE): creates mostly northward Ekman transport



Meridional wind (SOSE)

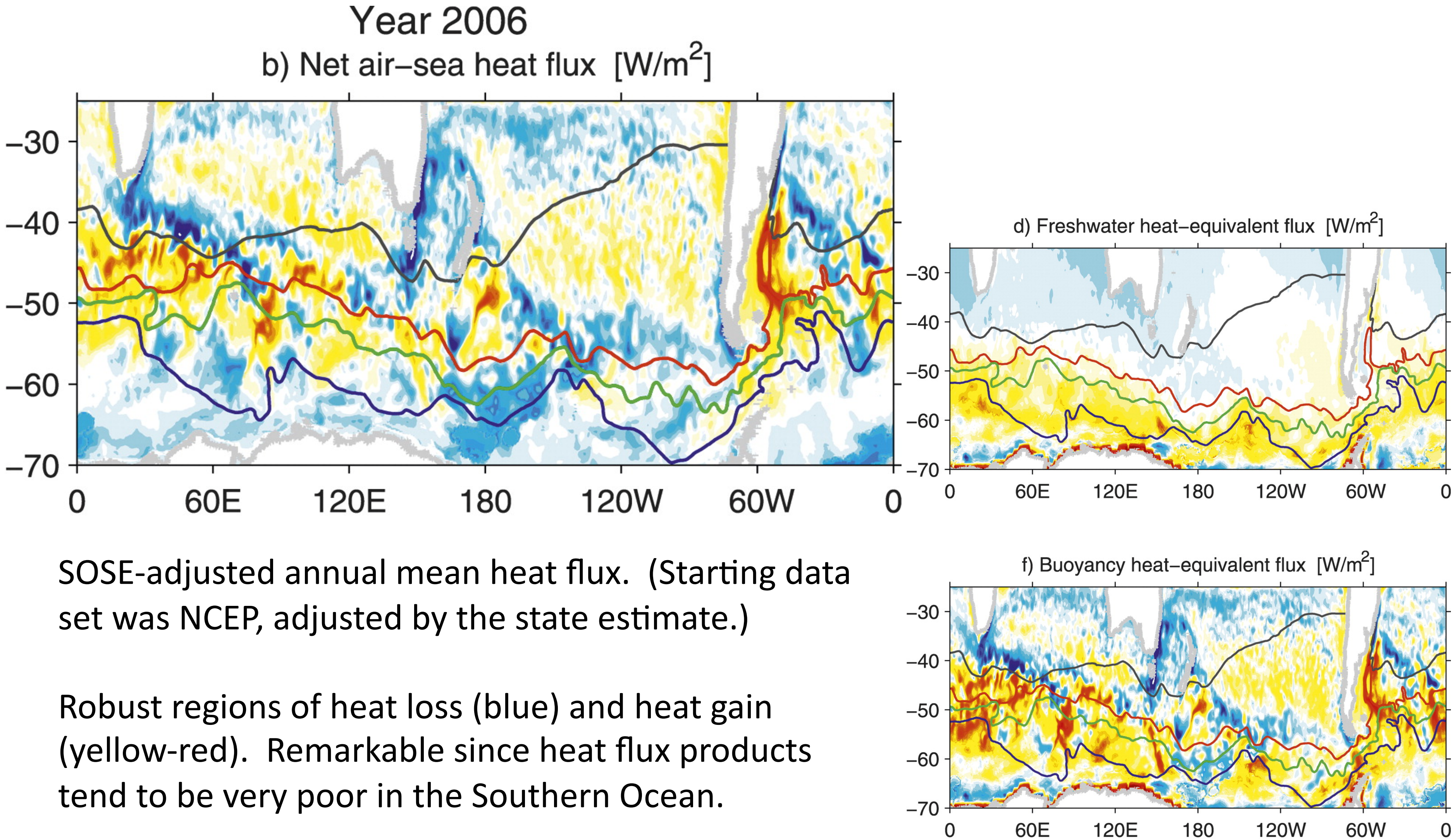


Wind stress curl: red is downwelling, blue is upwelling



SOSE output (Tamsitt, Mazloff & Talley)

SAMW formation processes: air-sea heat and freshwater fluxes



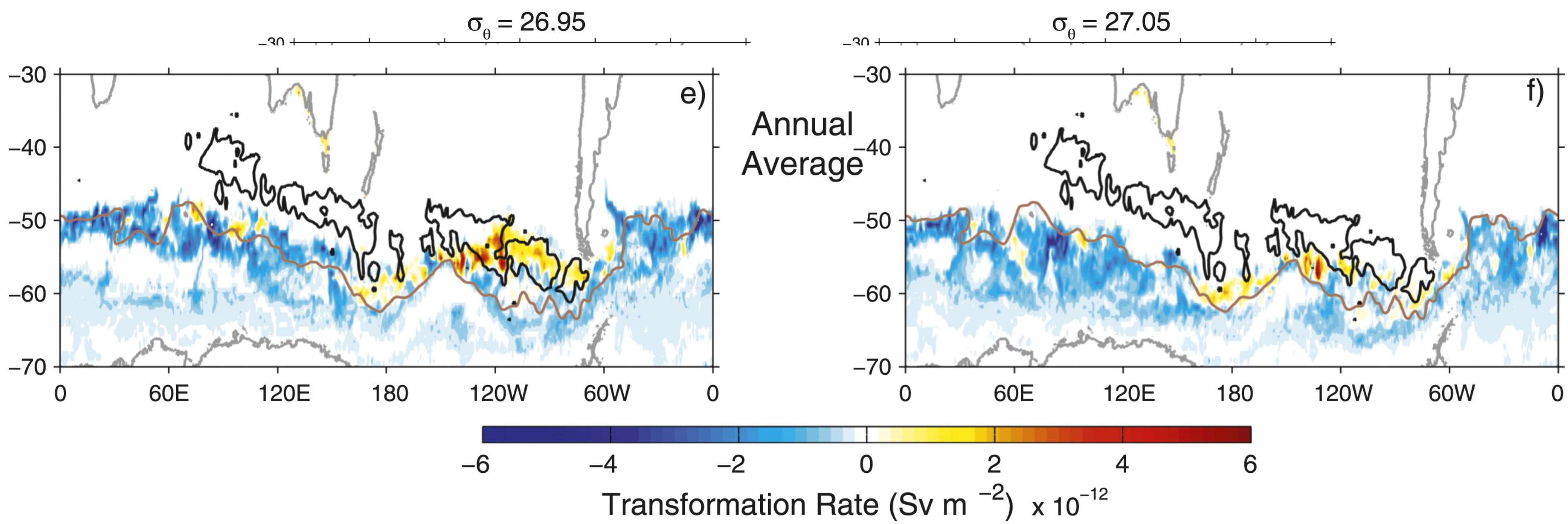
SOSE-adjusted annual mean heat flux. (Starting data set was NCEP, adjusted by the state estimate.)

Robust regions of heat loss (blue) and heat gain (yellow-red). Remarkable since heat flux products tend to be very poor in the Southern Ocean.

Similarly for freshwater and net buoyancy input

Cerovecki et al. (JPO, 2012)

SAMW formation processes: air-sea heat and freshwater fluxes



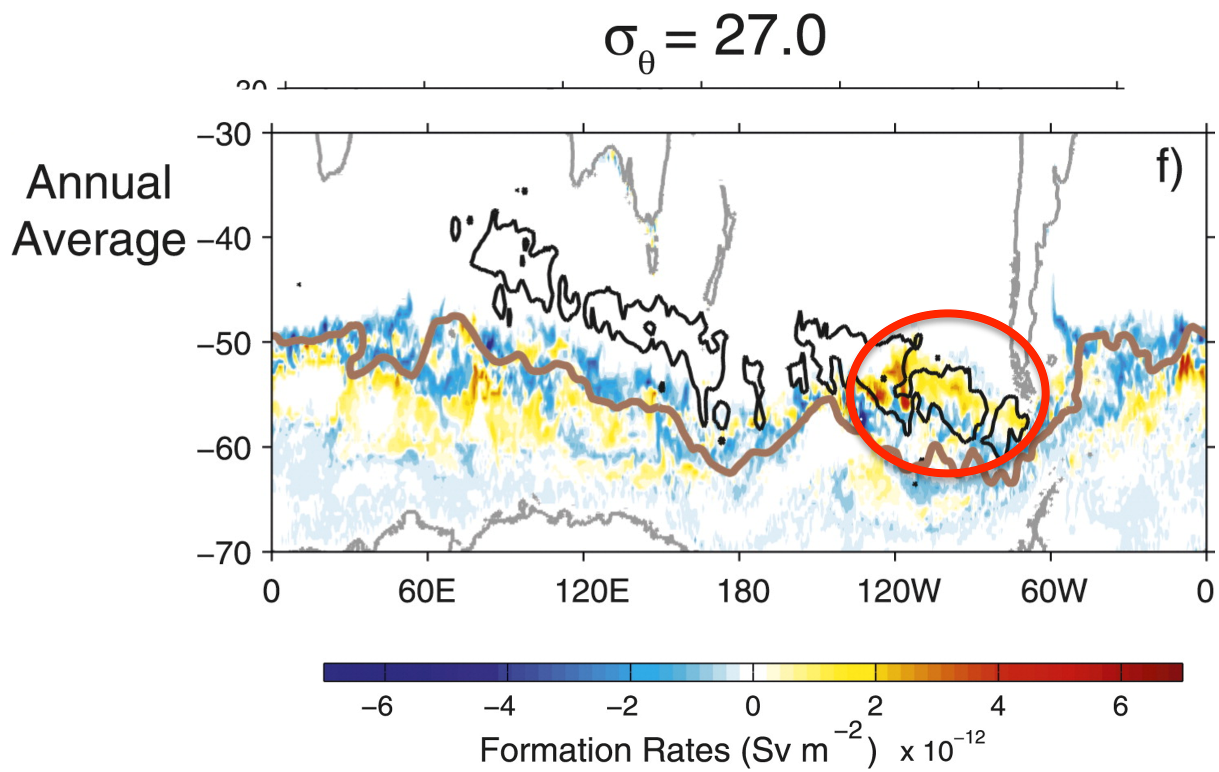
Calculate "transformation": how much water gets denser (yellow/red) and how much gets lighter (blue), using buoyancy fluxes and the location of the isopycnal outcrops at the sea surface (Walin, 1982 method).

Black contour is the 300 m winter mixed layer depth.

Cerovecki et al. (JPO, 2012)

SAMW formation processes: air-sea heat and freshwater fluxes

The Southeast Pacific is a region where water is formed at 27.0, through significant heat loss. This creates the SAMW.

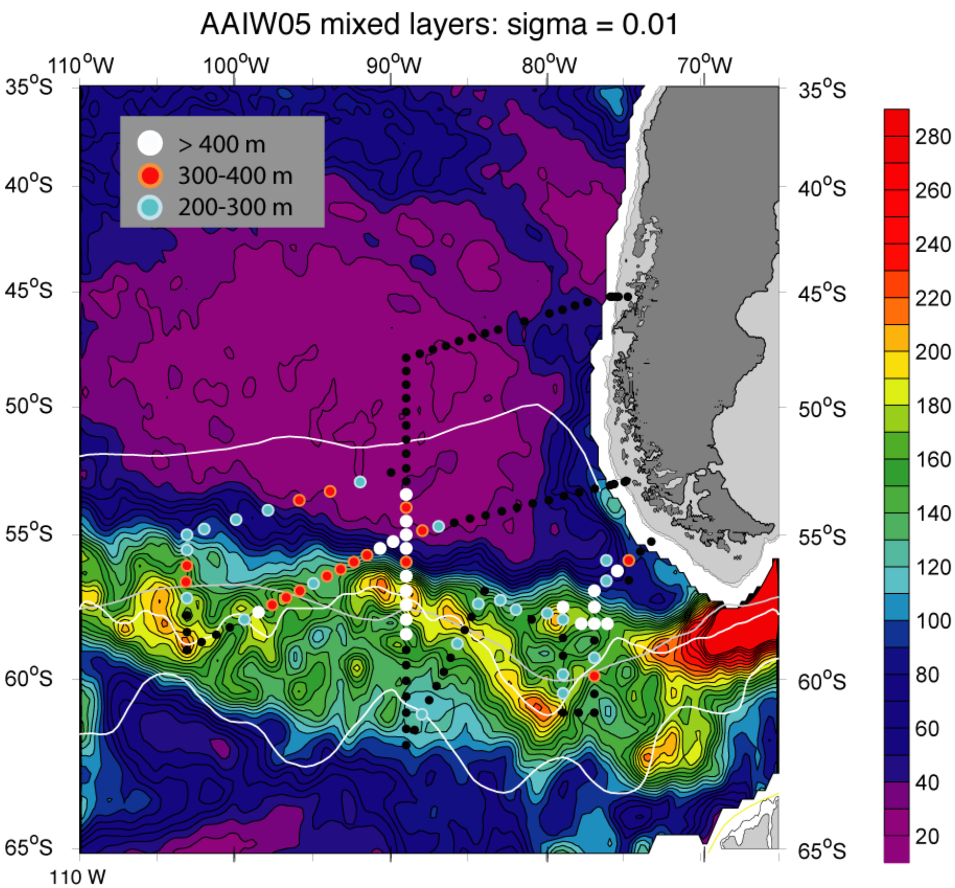


Calculate "formation" from transformation: difference between what enters and leaves at each grid point. Yellow-red is formation of new water. Blue is loss of water. (extension of Walin 1982 method, following Maze et al. 2009)

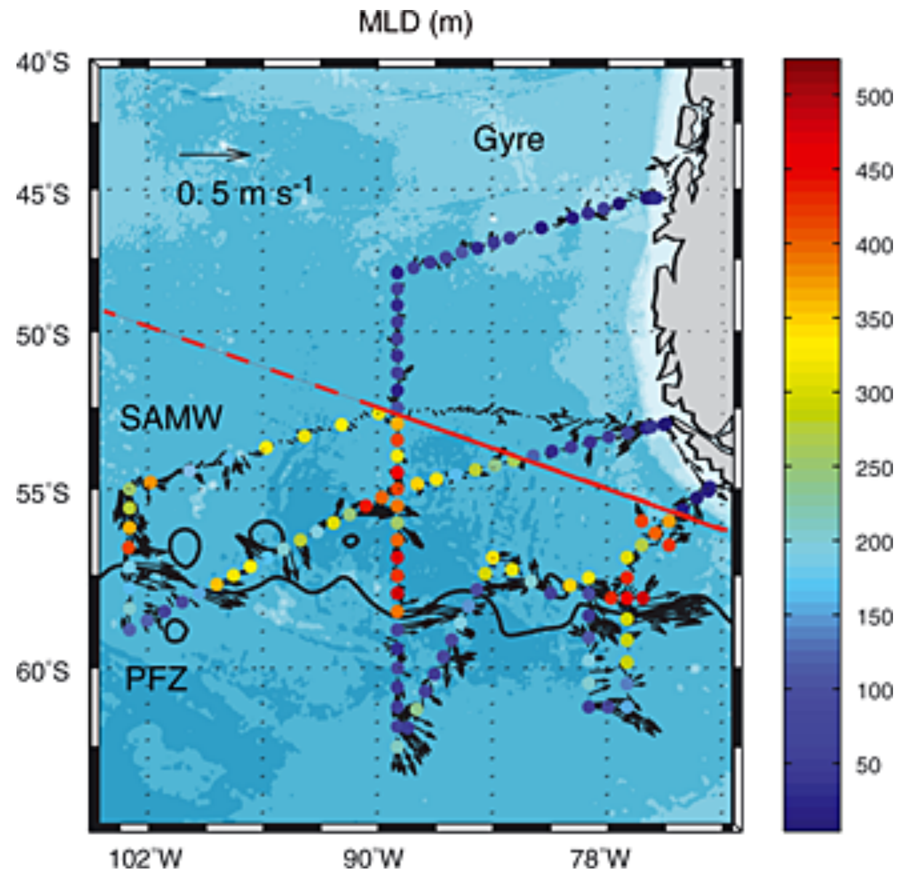
Black contour is the 300 m winter mixed layer depth.

Cerovecki et al. (JPO, 2012)

Southeast Pacific SAMW formation: winter 2005



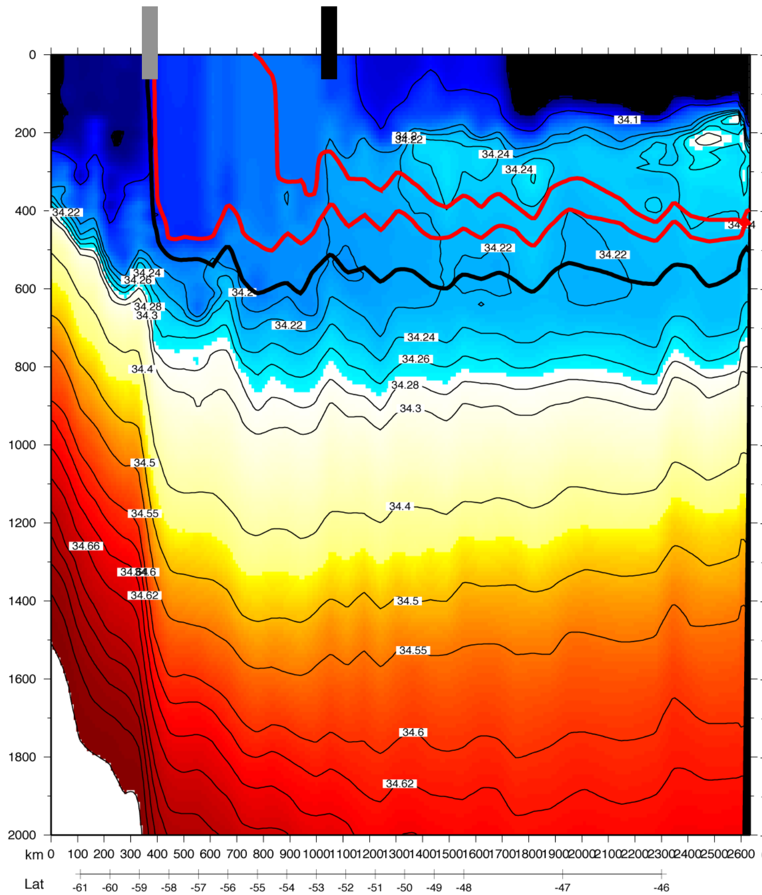
Mixed layer depth (Aug-Oct 2005)
With mean altimetric EKE
(Hormazabal)



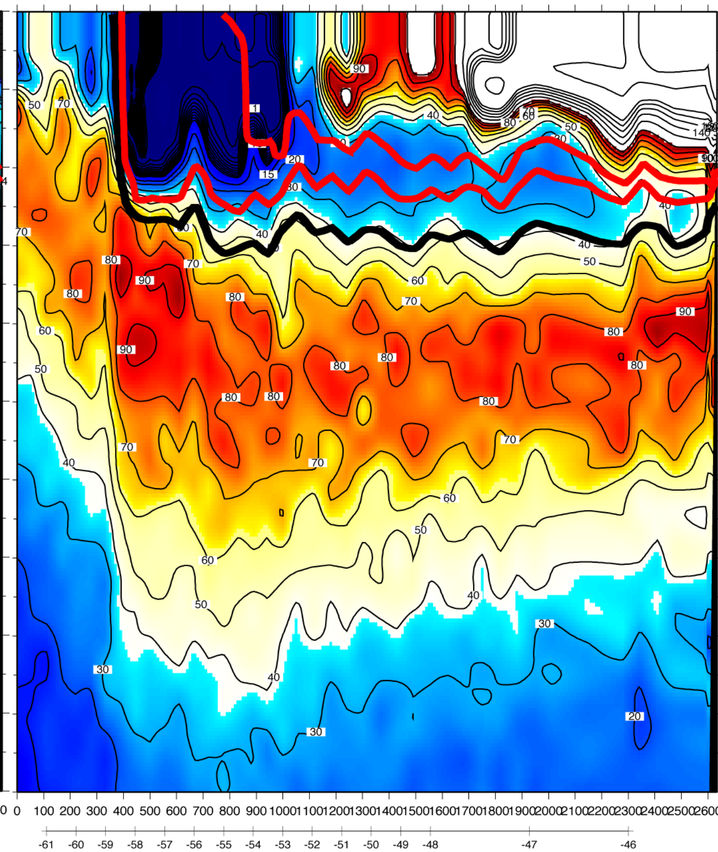
Mixed layer depth with
Subantarctic Front (black)
Aug-Oct 2005

Holte et al. (JPO, 2012)

Southeast Pacific SAMW formation: winter 2005



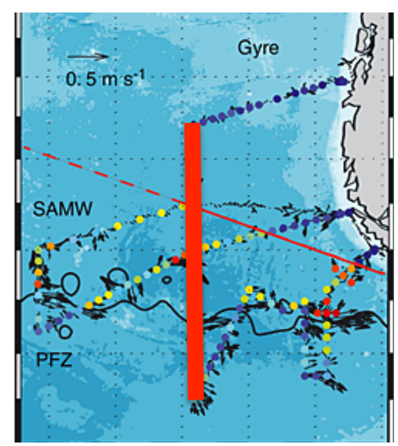
Salinity



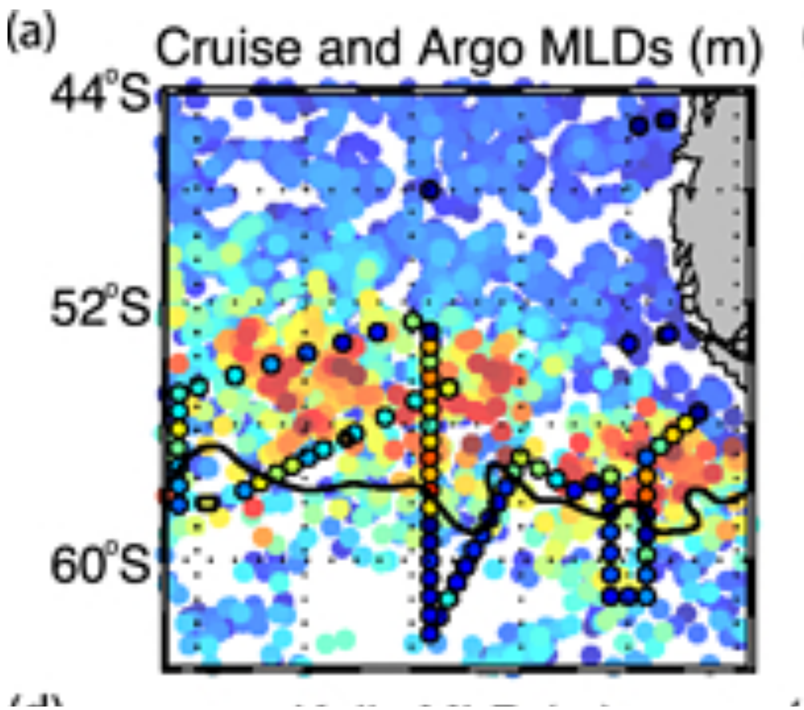
Potential vorticity

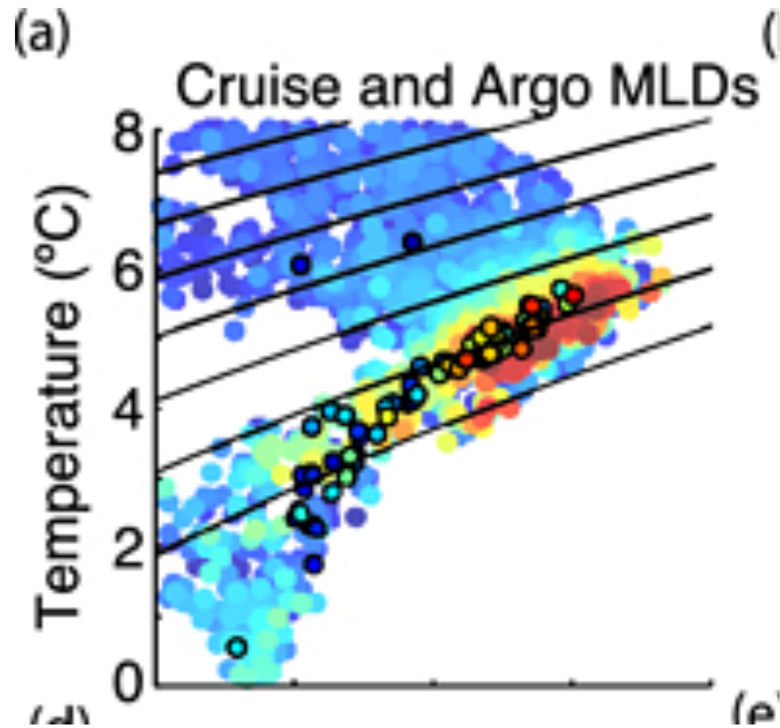
SAMW PV minimum (red) originates in higher salinity deepest mixed layers

AAIW salinity minimum (black) originates at the Subantarctic Front



Southeast Pacific SAMW formation: winter 2005





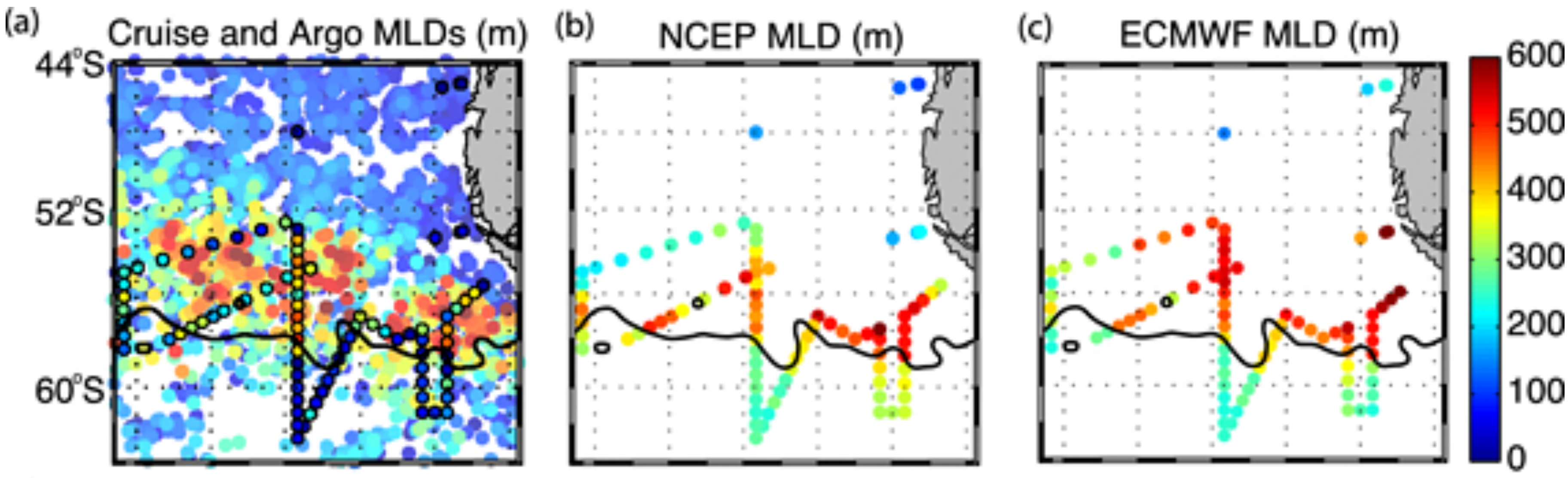
Deep mixed layers formed in 500-600 km region north of SAF
Properties from saltiest water down towards colder, fresher at SAF

High salinity advection from west preconditions for deeper mixed layers

Holte et al. (JPO, 2012)

Journal of Geophysical Research: Oceans
[Volume 117, Issue C3,](#) C03040, 29 MAR 2012 DOI: 10.1029/2011JC007798
http://onlinelibrary.wiley.com/doi/10.1029/2011JC007798/full#jgrc12439-fig-0010

Southeast Pacific SAMW formation: winter 2005



One-dimensional mixed layer model run with NCEP winds and using the observed summer stratification as starting point:

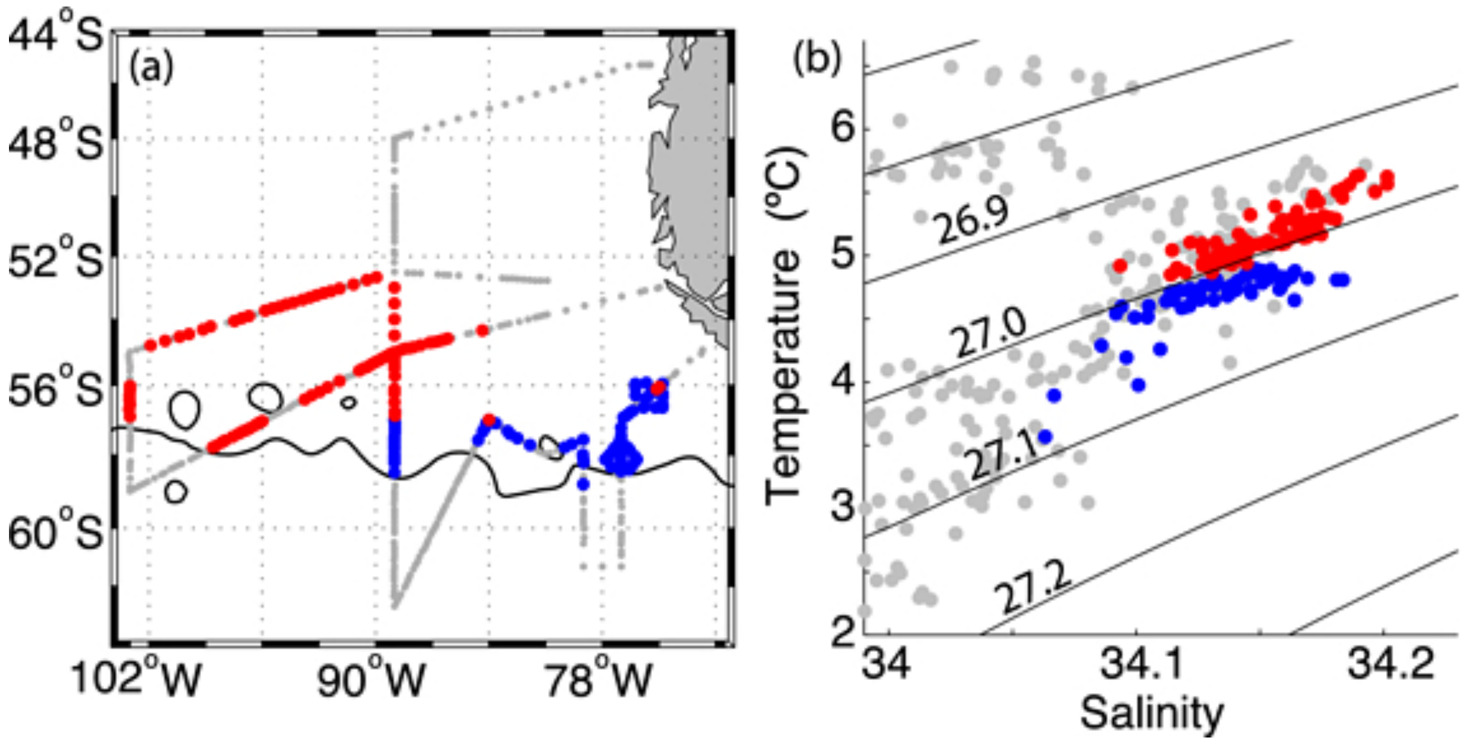
1-D mixed layer model can account for the observed mixed layer depth distribution; NCEP is best of the 5 products tested.

But it cannot account for the downstream change in SAMW salinity.

Holte et al. (JPO, 2012)

Journal of Geophysical Research: Oceans
Volume 117, Issue C3, C03040, 29 MAR 2012 DOI: 10.1029/2011JC007798
http://onlinelibrary.wiley.com/doi/10.1029/2011JC007798/full#jgrc12439-fig-0010

Southeast Pacific SAMW formation: winter 2005



Winter mixed layer properties: two distinct SAMW pools

Eastern pool (blue) is fresher, cooler, denser

Holte et al. (JPO, 2013)

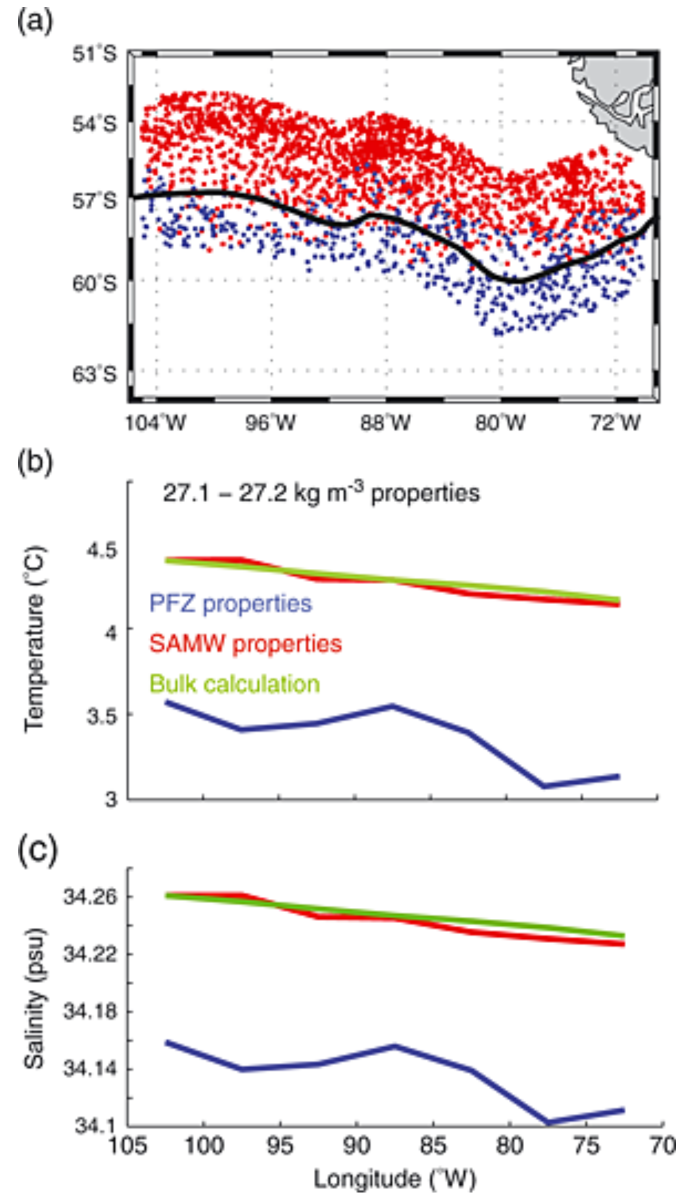
Southeast Pacific SAMW formation: winter 2005

A formal water mass analysis shows that there is water coming northward across the Subantarctic Front: more PFZ water contribution in the east.

The downstream freshening is due to cross-frontal flux (not local net precipitation).

Cross-frontal flux of 10% Polar Frontal Zone water per every 15° longitude.

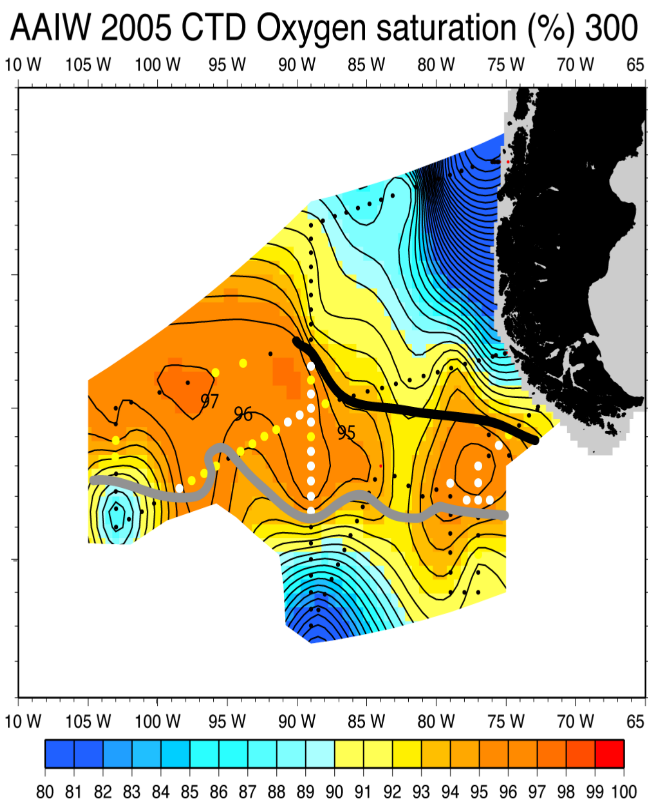
Speculation for future work:
Circumpolar pathlength is 360°. If just half of this has such cross-frontal mixing, then most of the AAIW layer north of SAF (27.1 to 27.5σ_θ) could be refreshed through cross-frontal processes.



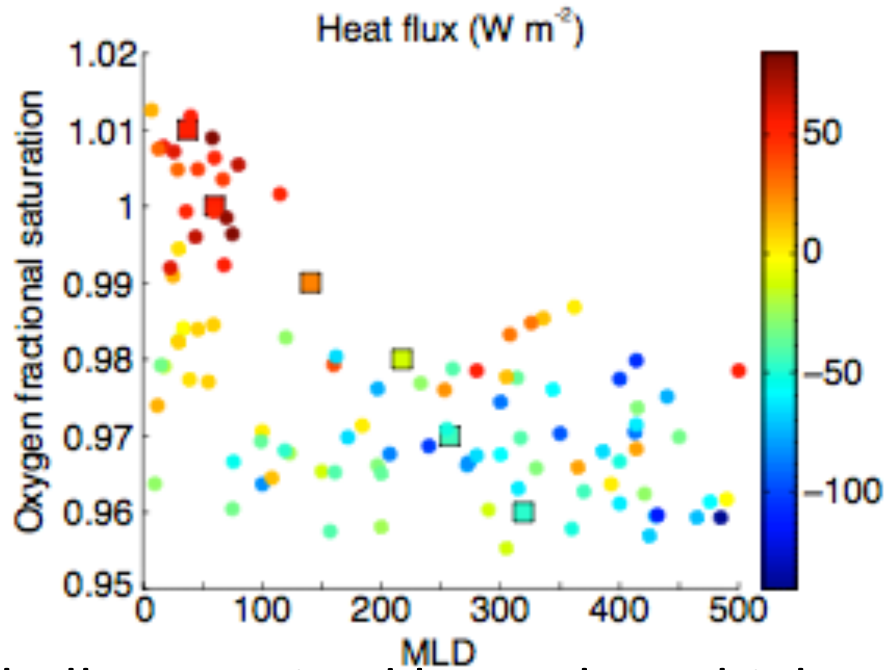
Holte et al. (JPO, 2013)

Journal of Geophysical Research: Oceans
Volume 118, Issue 4, pages 2052-2066, 23 APR 2013 DOI: 10.1002/jgrc.20144
http://onlinelibrary.wiley.com/doi/10.1002/jgrc.20144/full#jgrc20144-fig-0011

Southeast Pacific SAMW formation: winter 2005



Oxygen saturation is > 95% in deep mixed layers at 300 m depth



Shallower mixed layers have higher oxygen and minimal heat loss (or gain)

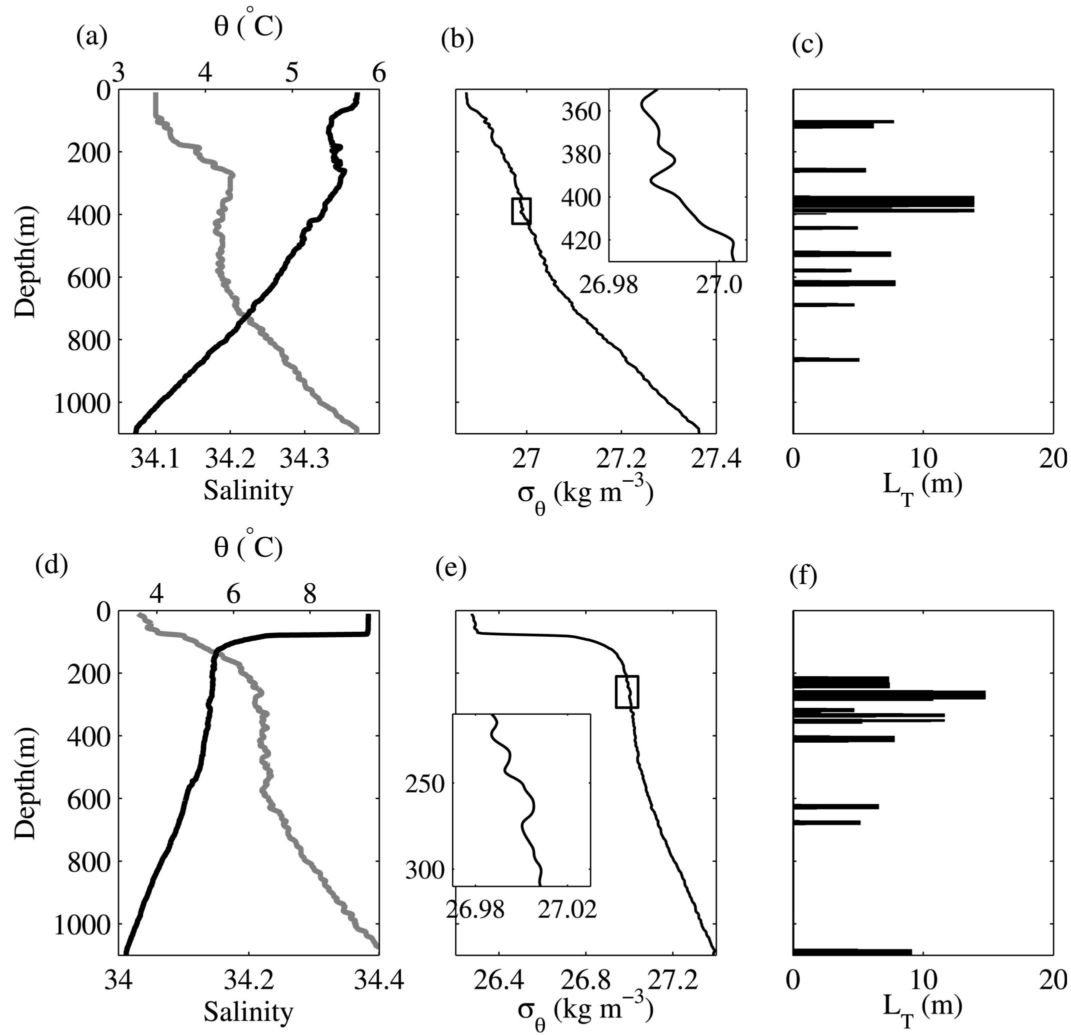
Deep mixed layers have ~ low oxygen and high heat loss - hence entraining lower oxygen waters from below mixed layer, but not extremely rapidly

Holte et al. (JPO, 2012)

Southeast Pacific SAMW formation: winter 2005 and summer 2006

Diapycnal mixing within the SAMW and below:

High diffusivity, up to 10^{-4} to 10^{-3} m^2, suggests that the low stratification may be partly maintained by mixing outside the winter



Use of Thorpe overturn scales to estimate diapycnal diffusivity

Sloyan et al. (JPO, 2010)

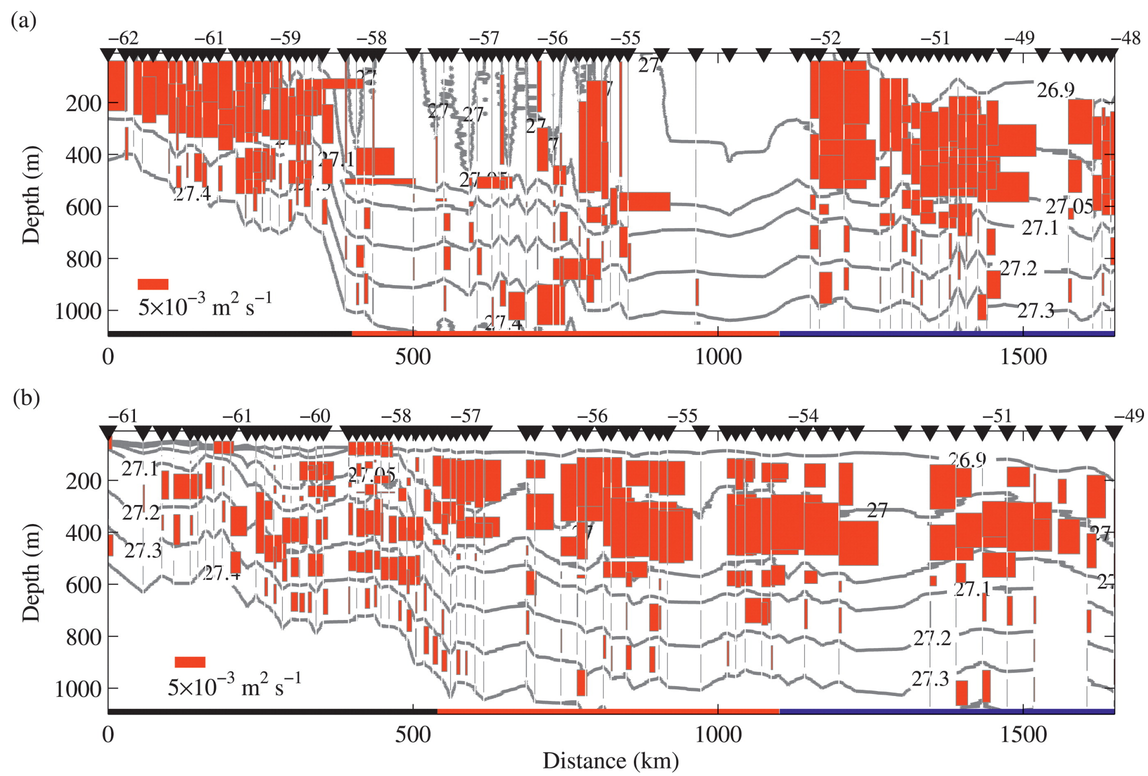
Southeast Pacific SAMW formation: winter 2005 and summer 2006

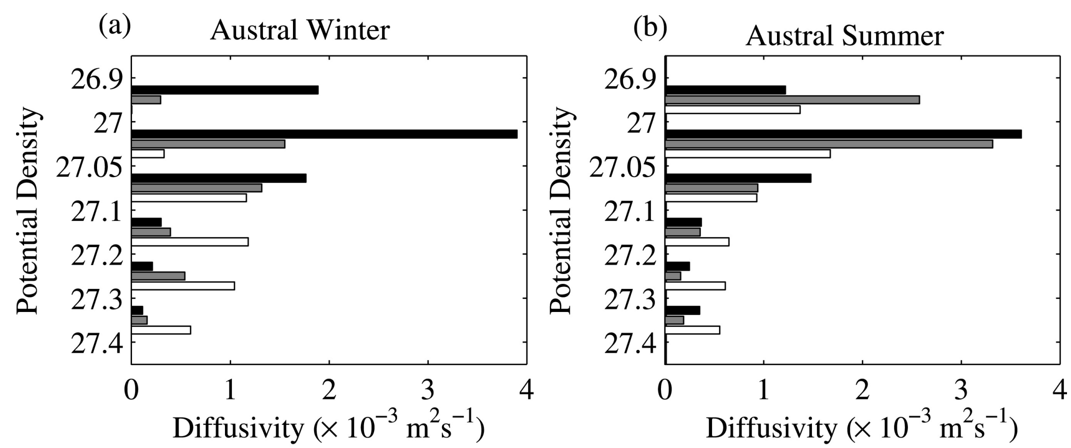
Diapycnal mixing within the SAMW and below:

High diffusivity, up to 10^{-4} to 10^{-3} m^2, suggests that the low stratification may be partly maintained by mixing outside the winter

The high diffusivity may also indicate vigorous cross-frontal mixing in the remnant mixed layer (SAMW), whose signature is obliterated in winter by deep convection.

Sloyan et al. (JPO, 2010)

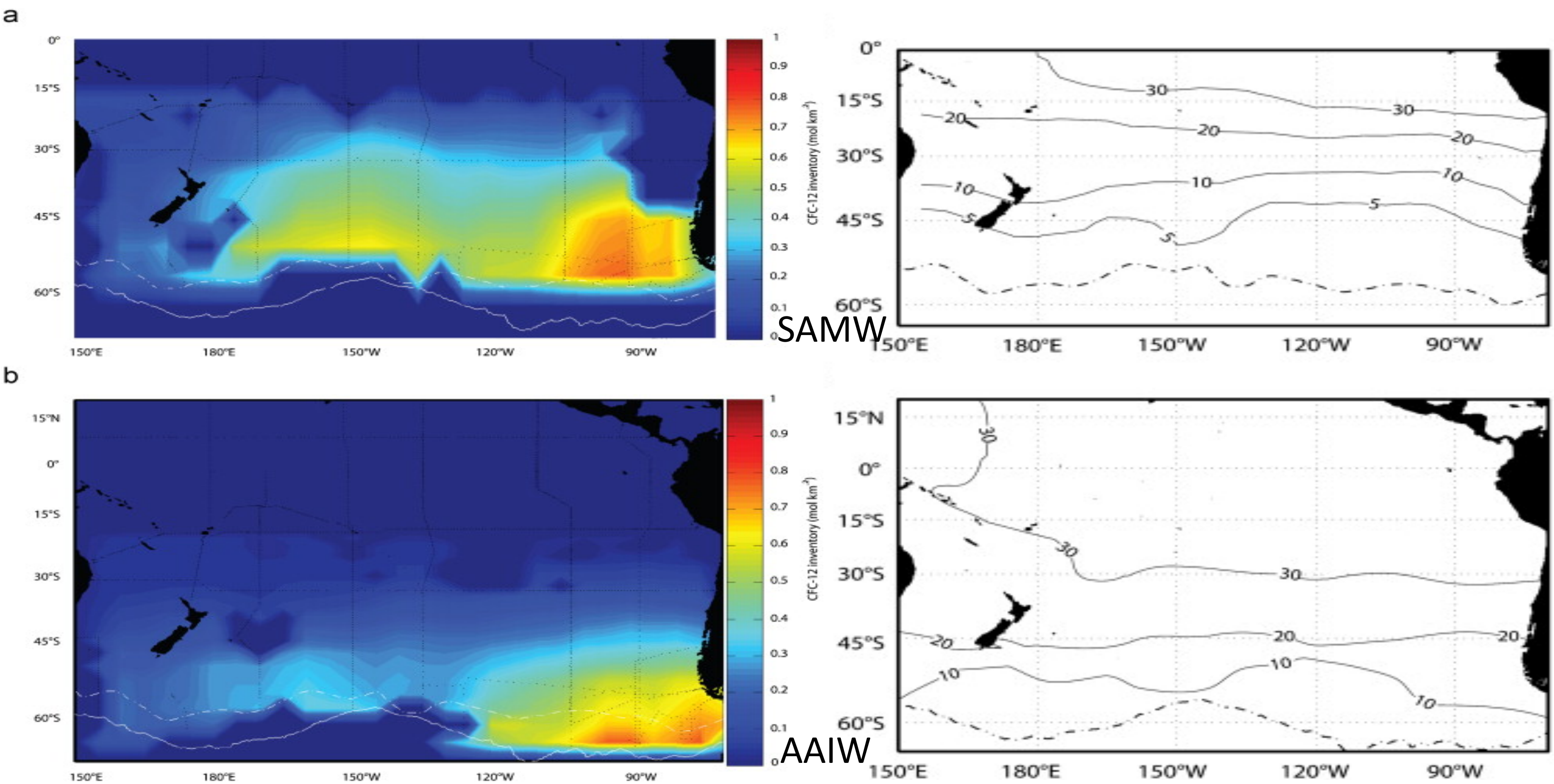




Formation rates of SAMW and AAIW

What are some estimates of SAMW and AAIW formation rates?

Southeast Pacific SAMW and AAIW ages and formation rates



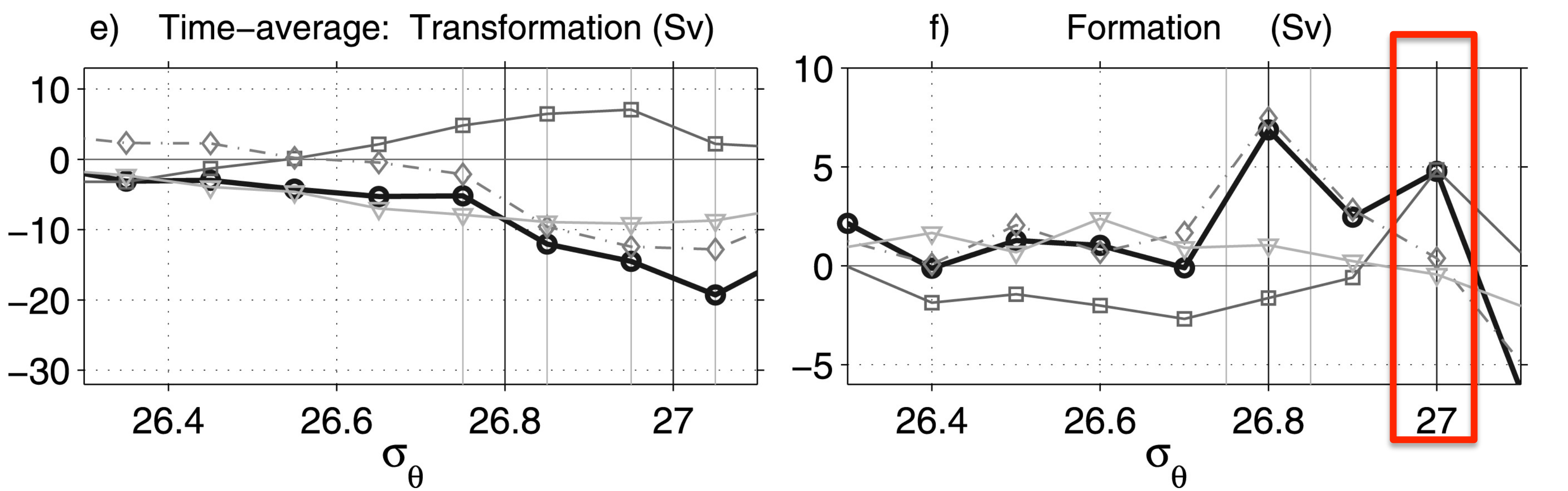
CFC-12 inventory

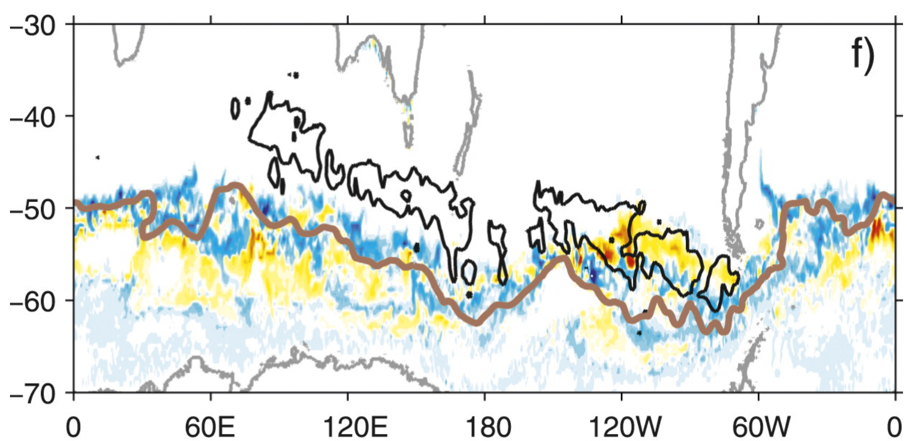
CFC "relic" age (yrs)

Formation rates from CFC data: 11.7 Sv (SEPSAMW) and > 5.8 Sv (AAIW)

Hartin et al. (DSR, 2011)

SAMW formation rates in SOSE: air-sea fluxes





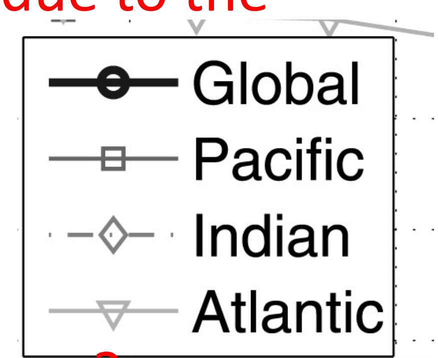
SEPSAMW density has peak in surface formation, due to the Pacific.

Rate is 5 Sv.

Lower than Hartin.

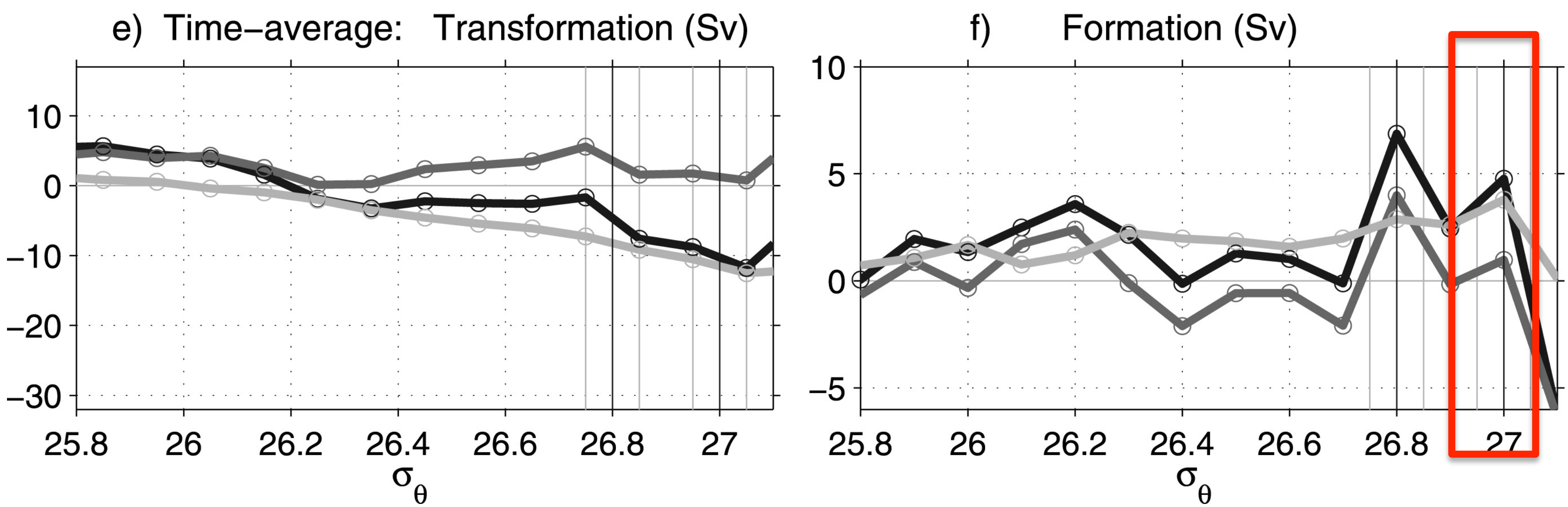
Interannual?

Destruction elsewhere?



Cerovecki et al. (JPO, 2012)

SAMW formation rates in SOSE: air-sea fluxes



SEPSAMW density has peak in surface formation, due to freshwater gain and heat loss

Cerovecki et al. (JPO, 2012)

Summary 1

•AAIW has a dramatic low salinity signature at the TOP of its layer.

•SEPSAMW has a dramatic low PV signature; ventilation source for entire South Pacific south of 30°S; SAMW is nutrient source for most of globe except N. Pacific.

•SEPSAMW includes (1) subtropical water that is cooled and (2) fresh surface water from south of the Subantarctic Front.

•Southeast Pacific SAMW/AAIW winter survey:

Very deep mixed layers well north of SAF -> SAMW

Deep, freshest mixed layers at the SAF -> AAIW salinity minimum

Air-sea heat loss creates the deep mixed layers

Cross-frontal mixing freshens the deep mixed layers to east

Elevated diapycnal mixing at base of mixed layer and through summer may keep layer more stratified

•SEPSAMW formation rate is between 5 and 12 Sv, and likely has large interannual variability (SOSE result, not shown).

•AAIW formation could be > 6 Sv

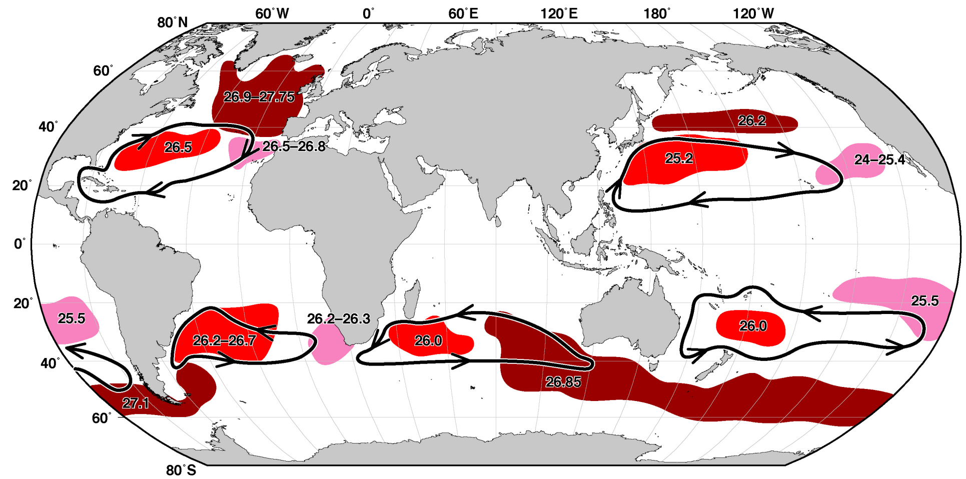
Summary 2

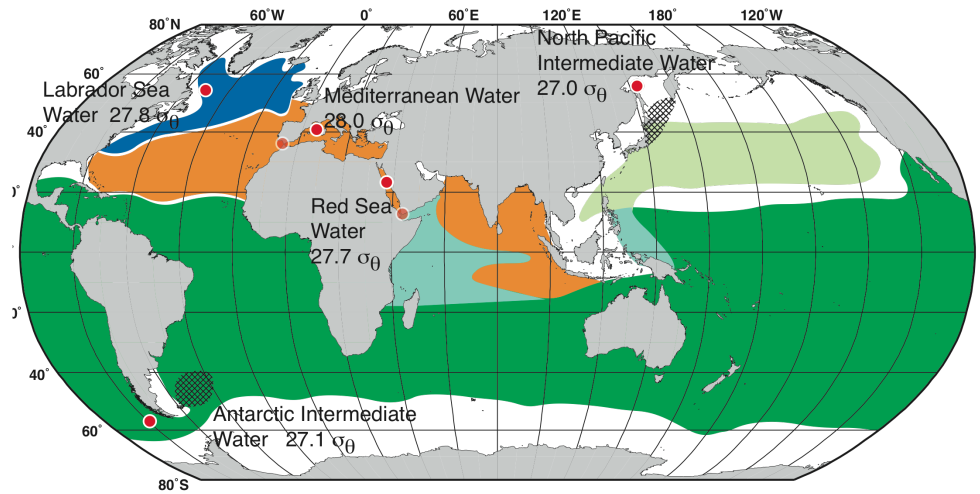
An observation:
When we proposed the work in the SE Pacific 10 years ago, I was convinced that the most important issue was formation of AAIW, with secondary importance for SEPSAMW.

Now we understand the great importance of SAMW in general, and also specifically the Southeast Indian SAMW in addition to SEPSAMW, for thermocline ventilation processes.

Secondly, I was convinced that the McCartney model for AAIW formation was correct. Now I think it is correct only for the S minimum, but that cross-frontal flux is important for the rest of the layer beneath that. (DIMES work, Naveira-Garabato et al., other SOSE analyses). The lack of high oxygen signature for the "new" AAIW is in keeping with such flux, whose source is upwelled, low-oxygen Indian and Pacific Deep Water.

Revisit SAMW/AAIW formation hypothesis





Initial hypothesis for SAMW and AAIW properties and formation from McCartney (1977, 1982):

1. SAMW cools, freshens and densifies from west to east along its circumpolar pathway, with several major detrainments northward into the subtropical gyres OK – GREAT HYPOTHESIS
2. AAIW is the coldest, freshest, densest form of SAMW, which thereby is central to the northward transport of freshwater from the Antarctic NOT QUITE ACCURATE – OK for just the topmost definition of AAIW (S minimum) but not clearly accurate for the remainder of the layer below. Cross-frontal processes could be very important for the full AAIW layer. -> future work/synthesis

Publications

Based on hydrographic surveys:

Carter, B.R., L. D. Talley and A. G. Dickson, 2013. Mixing and remineralization in waters detrained from the surface into Subantarctic Mode Water and Antarctic Intermediate Water in the southeastern Pacific. Submitted to J. Geophys. Res. Oceans.

Chereskin, T. K., L. D. Talley and B. M. Sloyan, 2010. Nonlinear vorticity balance of the Subantarctic Front in the southeast Pacific. J. Geophys. Res., 115, C06026,doi:10.1029/2009JC005611.

Hartin, C.A., R. A. Fine, B. M. Sloyan, L. D. Talley, T. K. Chereskin, J. Happell, 2011. Formation rates of Subantarctic Mode Water and Antarctic Intermediate Water within the South Pacific. Deep-Sea Res. I, 58, 524-534.

Holte, J. and L. Talley, 2009. A new algorithm for finding mixed layer depths with applications to Argo data and Subantarctic Mode Water formation. J. Atm. Oceanic Tech., 26, 1920-1939, DOI: 10.1175/2009JTECHO543.1.

Holte, J.W., L. D. Talley, T. K. Chereskin, and B. M. Sloyan, 2012. The role of air-sea fluxes in Subantarctic Mode Water formation. J. Geophys. Res., 117, C03040, doi:1029/2011JC007798.

Holte, J.W., L. D. Talley, T. K. Chereskin, and B. M. Sloyan, 2013. Subantarctic mode water in the southeast Pacific: Effect of exchange across the Subantarctic Front. J. Geophys. Res., 118, doi:10.1002/jgrc.20144, 15 pp.

Sloyan, B., L. D. Talley, T. Chereskin, R. Fine and J. Holte, 2010. Antarctic Intermediate water and Subantarctic Mode water formation in the southeast Pacific: the role of turbulent mixing. J. Phys. Oceanogr., 40, 1558-1574.

Publications

Based on our own funded SOSE analyses:

Bourassa, M.A., S.T. Gille, C. Bitz, D. Carlson, I. Cerovecki, C.A. Clayson, M. F. Cronin, W.M. Drennan, C. W. Fairall, R. Hoffman, G. Magnusdottir, R. T. Pinker, I. A. Renfrew, M. Serreze, K. Speer, L. Talley, G. A. Wick, 2013. High-Latitude Ocean and Sea-Ice Surface Fluxes: Challenges for Climate Research. Bull. Amer. Met. Soc., 94, 403-423.

Cerovecki, I., L. D. Talley, M. R. Mazloff and G. Maze, 2013. Subantarctic Mode Water formation, destruction and export in the eddy-permitting Southern Ocean State Estimate. J. Phys. Oceanography, 43, 1485-1511

Cerovecki, I., L. D. Talley and M. R. Mazloff, 2011. A comparison of Southern Ocean air-sea buoyancy flux from an ocean state estimate with five other products. J. Climate, 24, 6283-6306.

Matt Mazloff has many, many more publications, many as collaborations with many different investigators. The SOSE output is freely available and he encourages you to download it and analyze!