



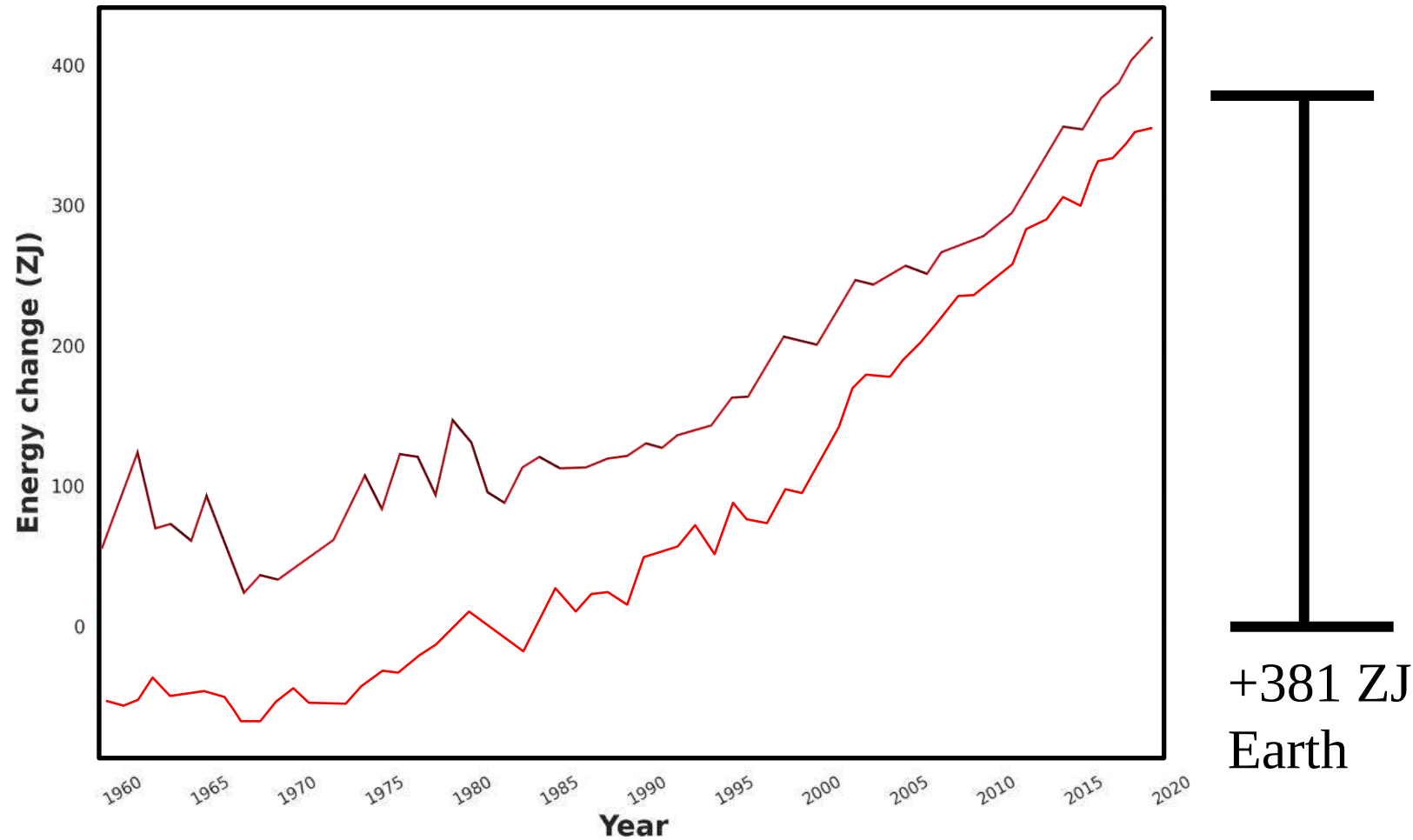
What Ocean Observations Tell Us About Ocean Warming: Surface to the Abyss

Sarah Purkey

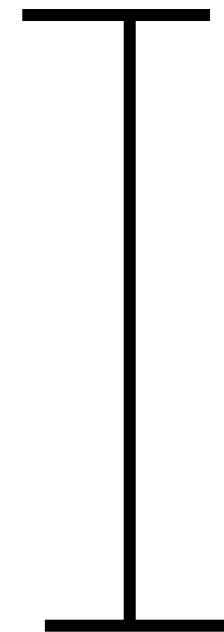
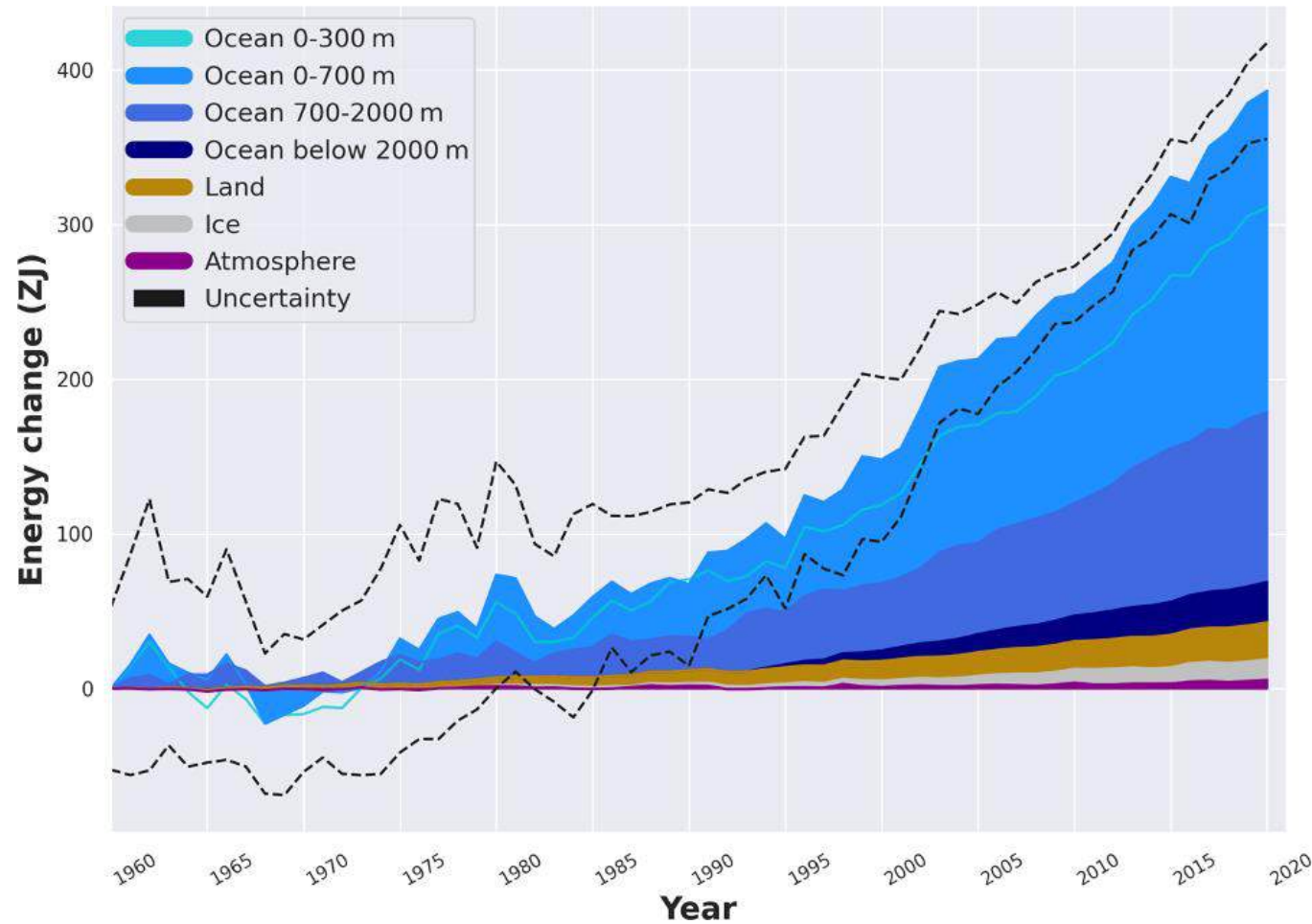
May 21, 2025

ECCO Summer School

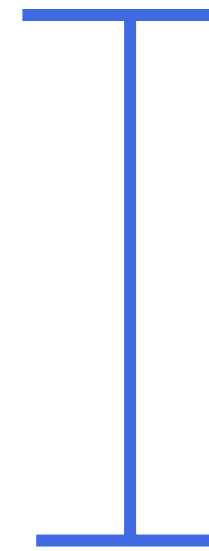
Global Warming



Global Warming



+381 ZJ
Earth



+340 ZJ
Ocean



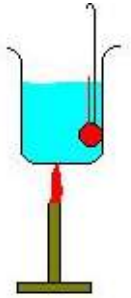
+30 ZJ
Deep
Ocean



<4 ZJ
atm

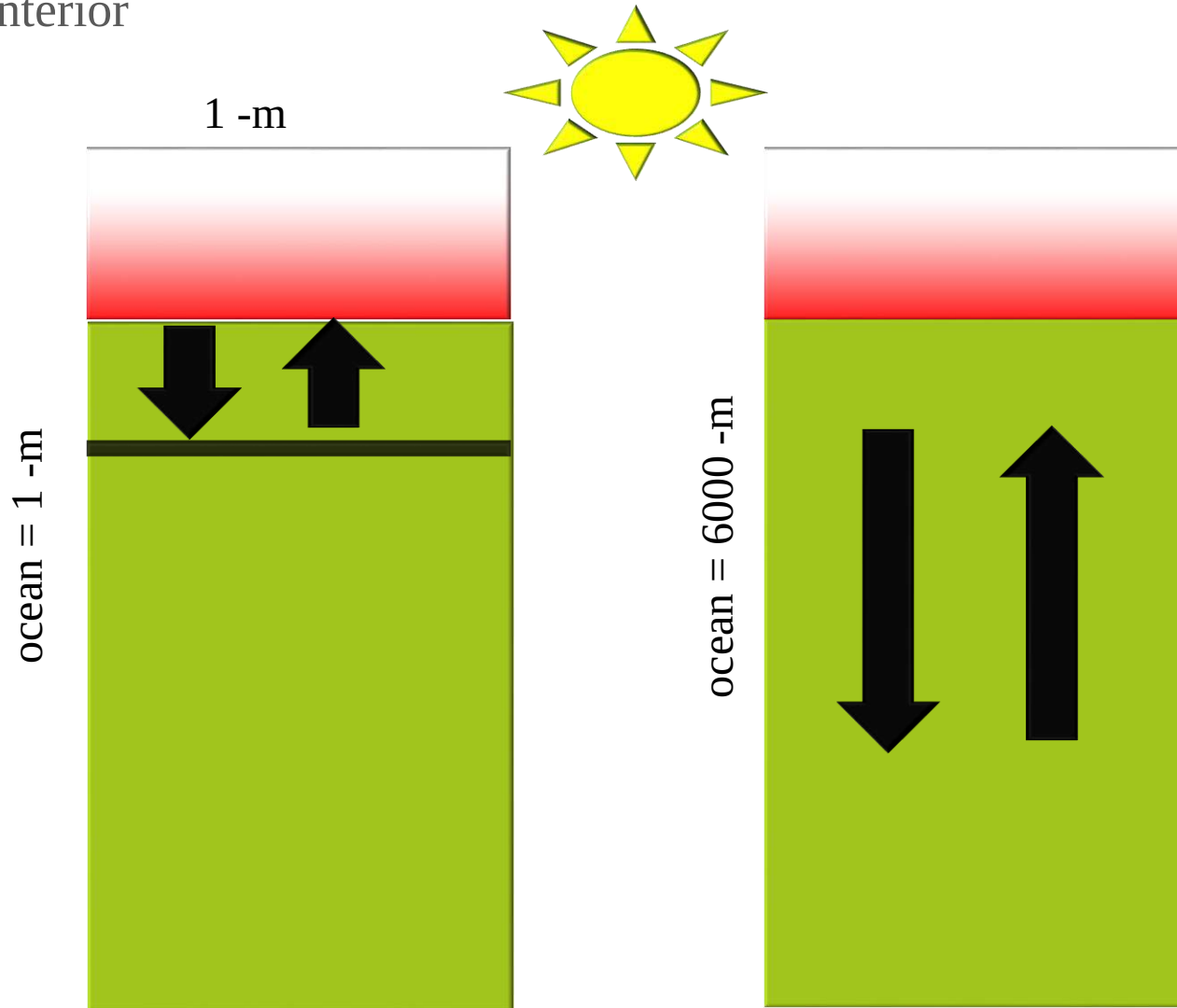
Why is some much heat going into the ocean?

High heat capacity of water **AND** the ocean can transport heat from the surface to the interior

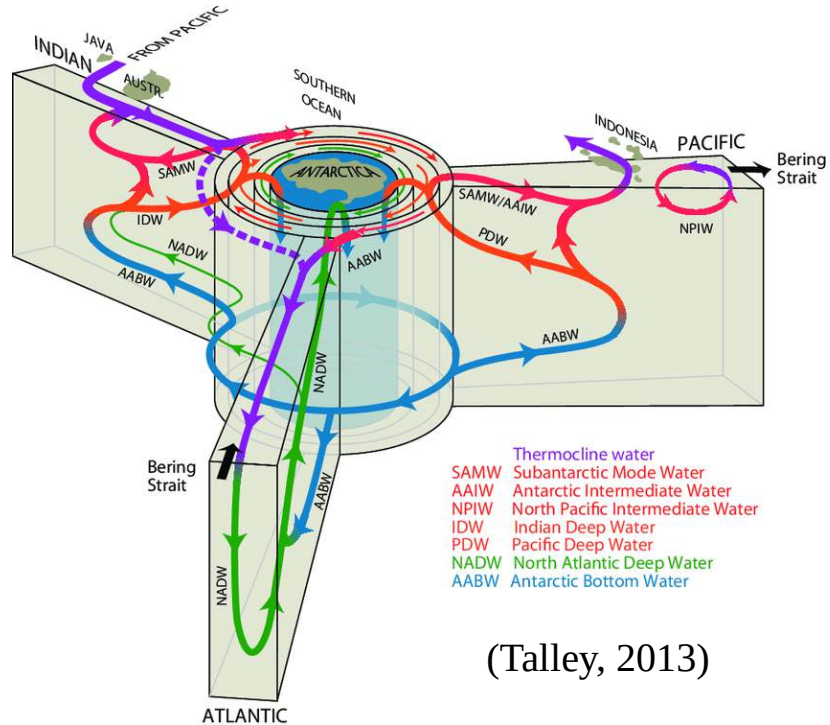


$c = 4,186 \text{ J/kg/C}$
for water at
 $T = 4 \text{ C}$

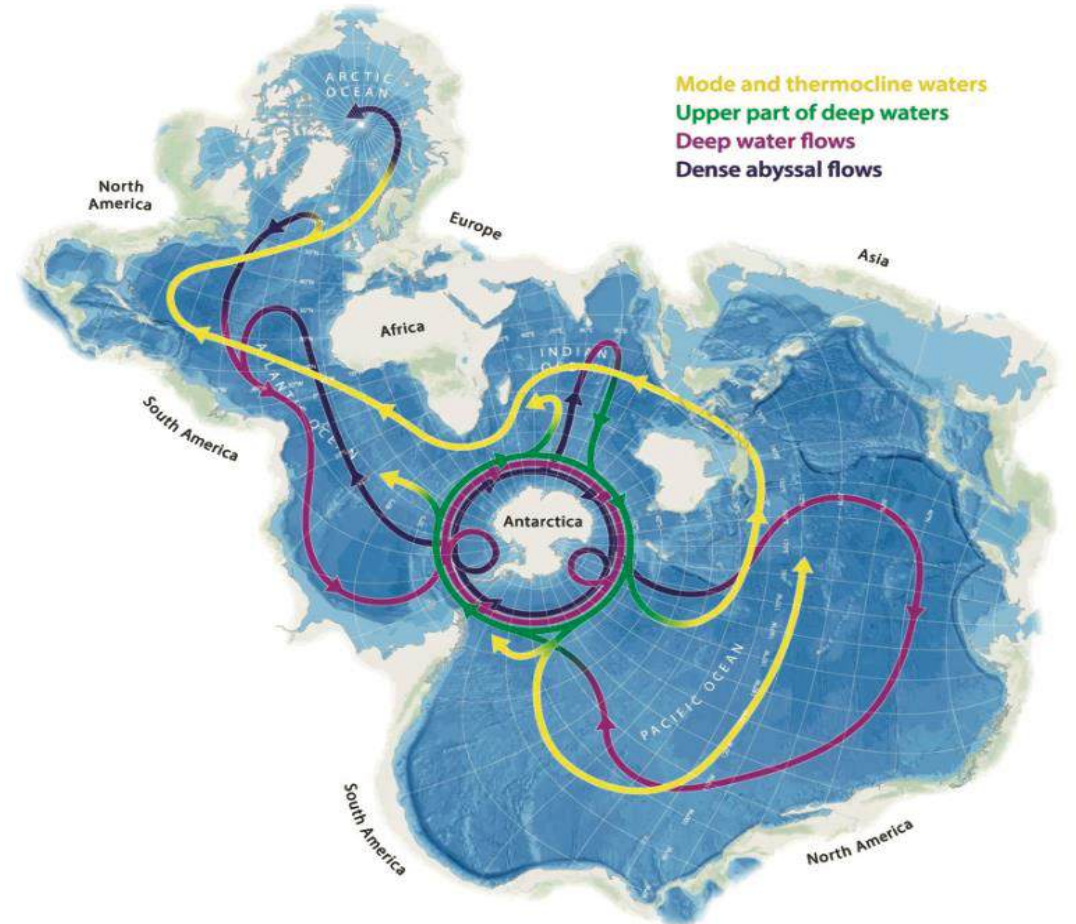
4186 J to raise
1 kg (m^3) of
water by 1
deg C



Meridional Overturning Circulation (MOC)



(Talley, 2013)



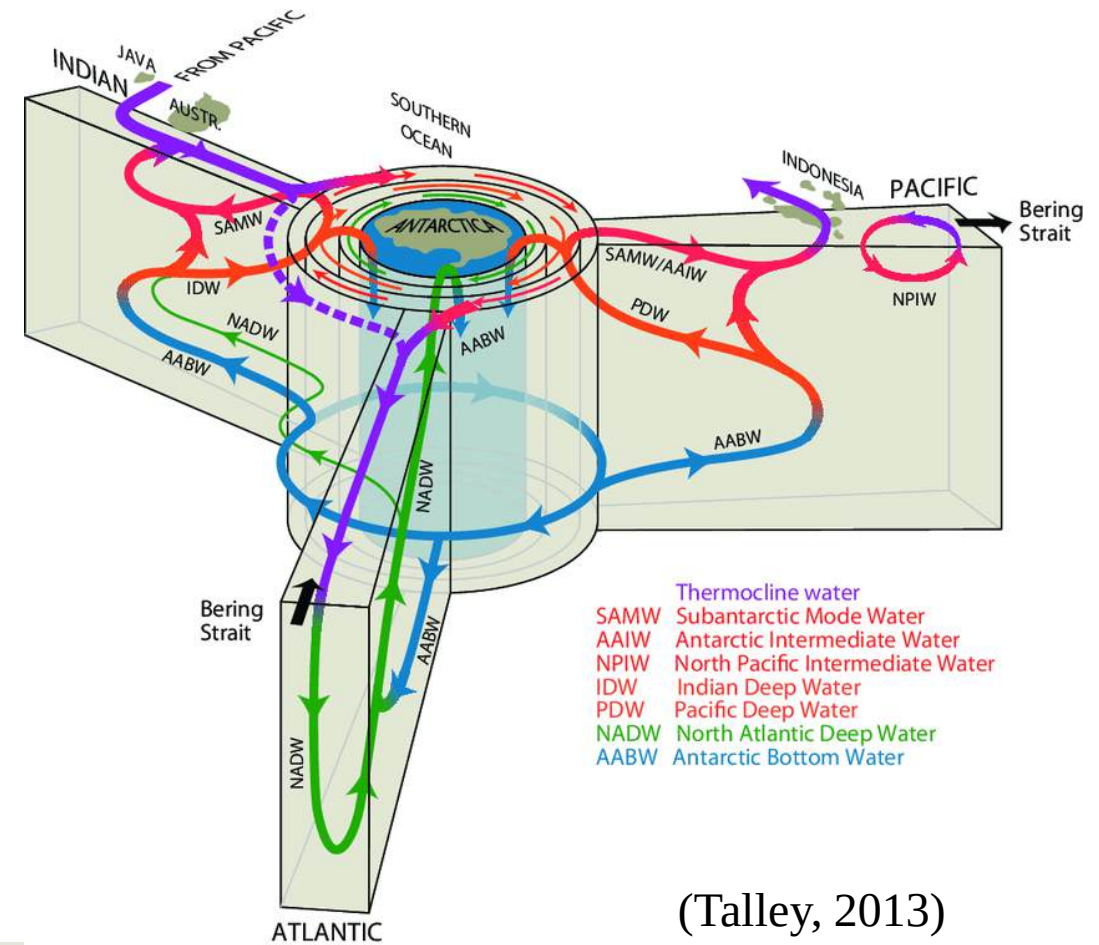
Meredith (Nat. Comm. 2022)

To monitor and predict ocean heat uptake accurately, you must understand ocean ventilation

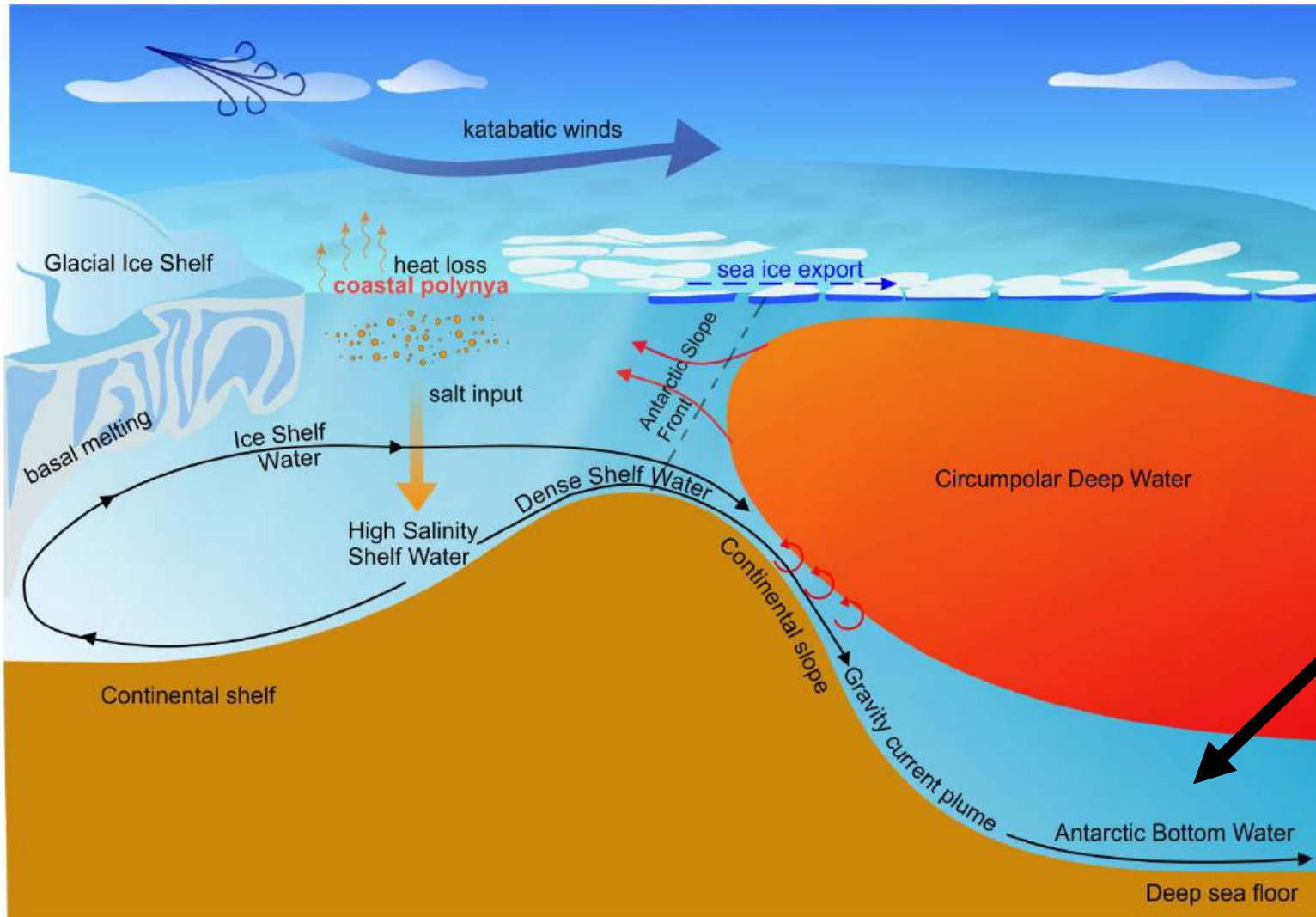
Outline

- ▣ Quick overview of Abyssal ocean circulation (deep MOC 101)
- ▣ Ocean observations (Argo and WOCE follow-ons)
- ▣ Ocean warming and changes in deep ocean circulation

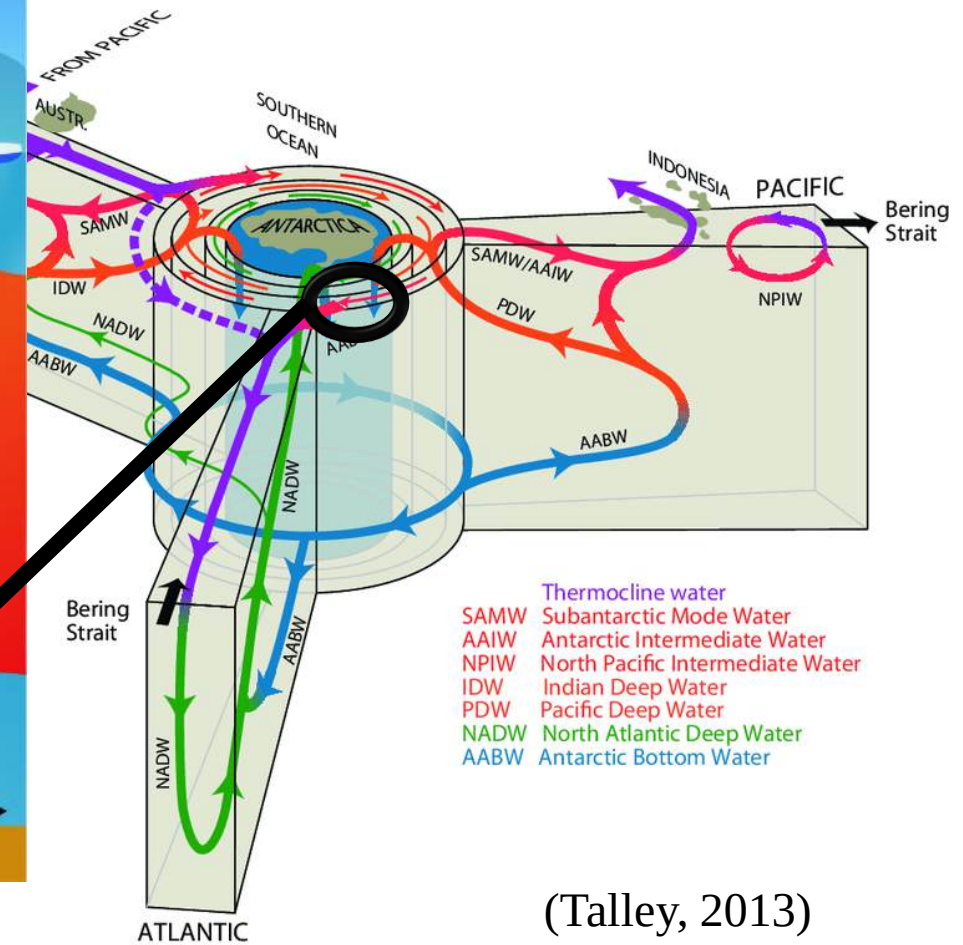
Meridional Overturning Circulation (MOC)



MOC: Antarctic Bottom Water (AABW)

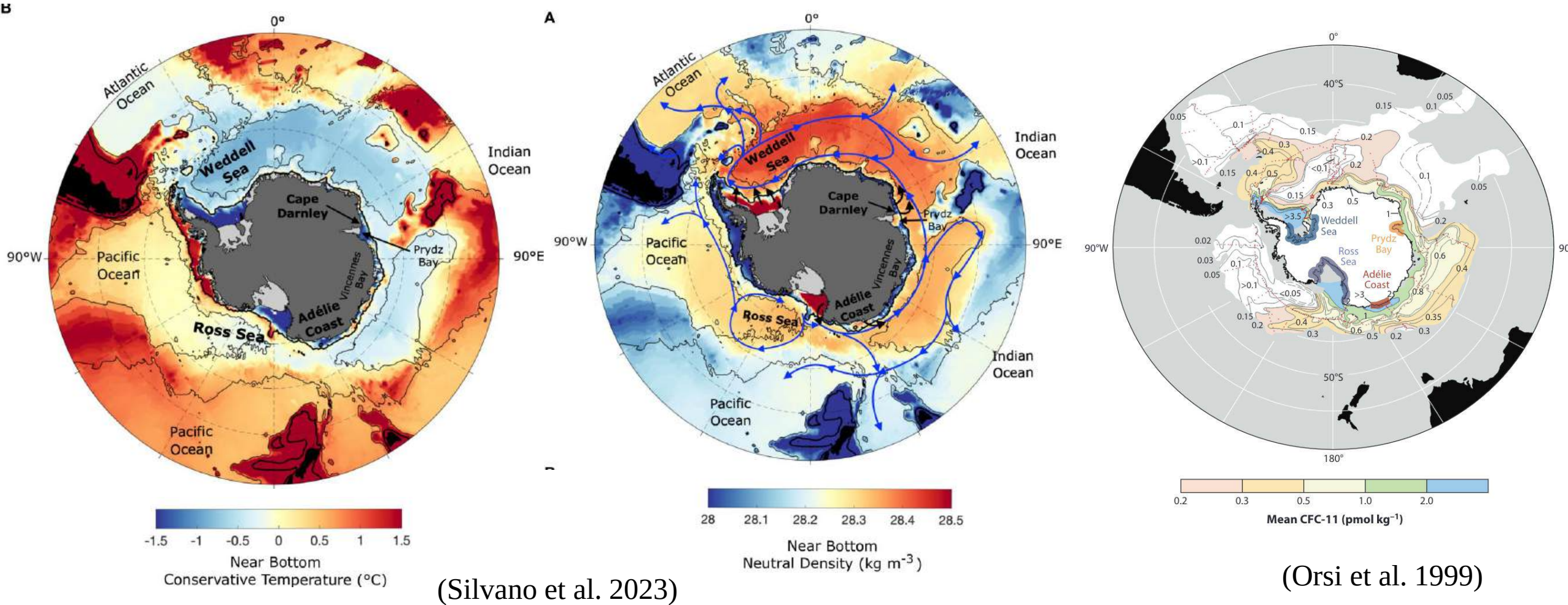


(Silvano et al. 2023)



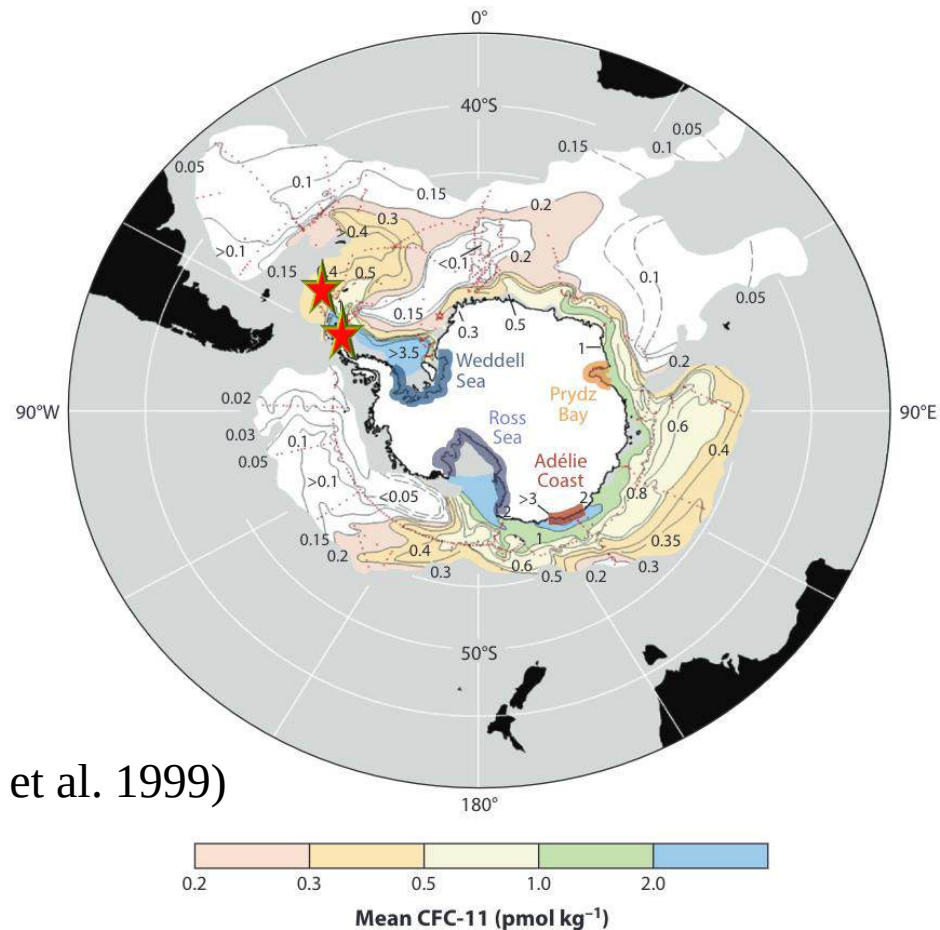
(Talley, 2013)

MOC: Antarctic Bottom Water (AABW)

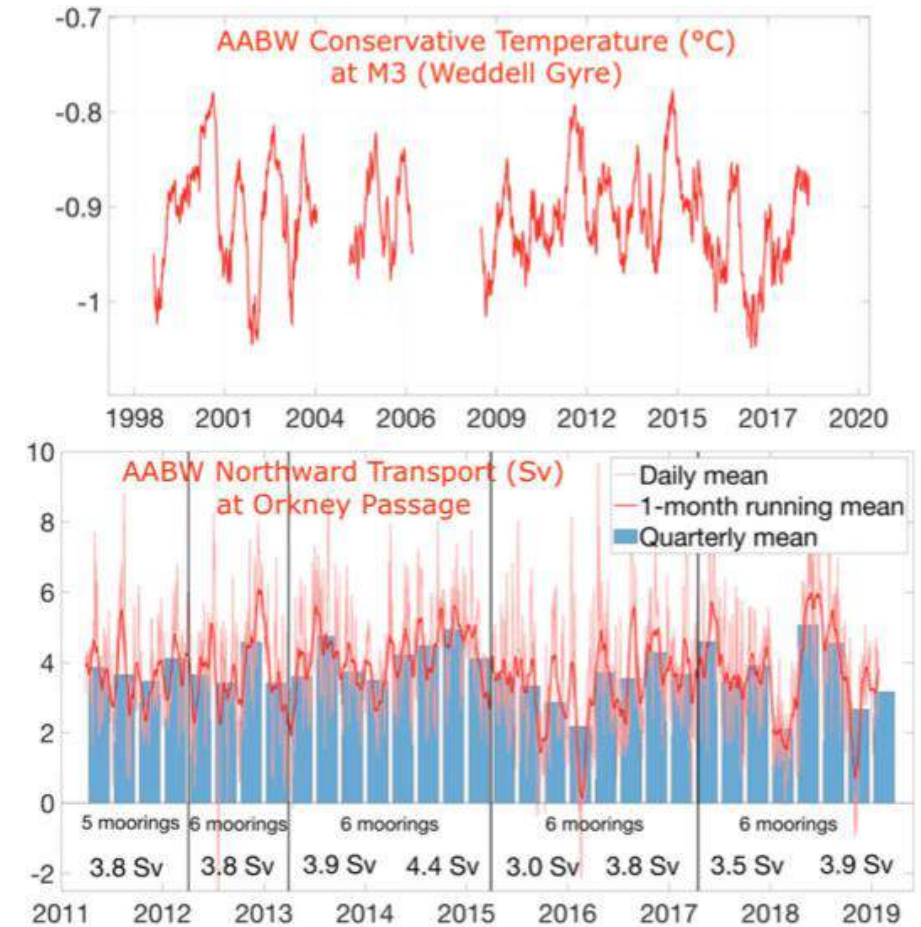


■ AABW is formed in 4 locations around the Antarctic coast

MOC: Antarctic Bottom Water (AABW)

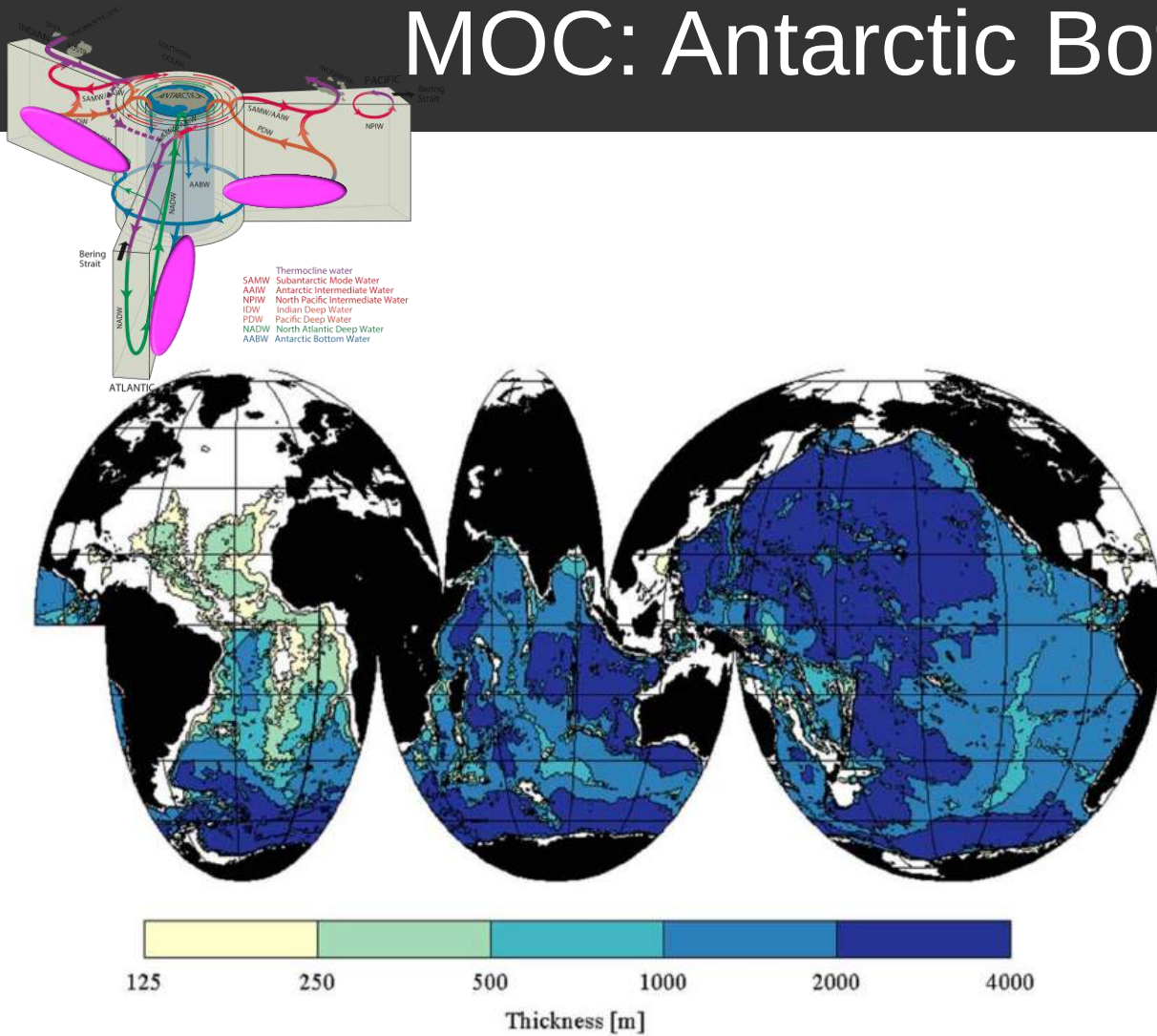


- AABW formation rates have been mostly estimated from ocean properties and tracers

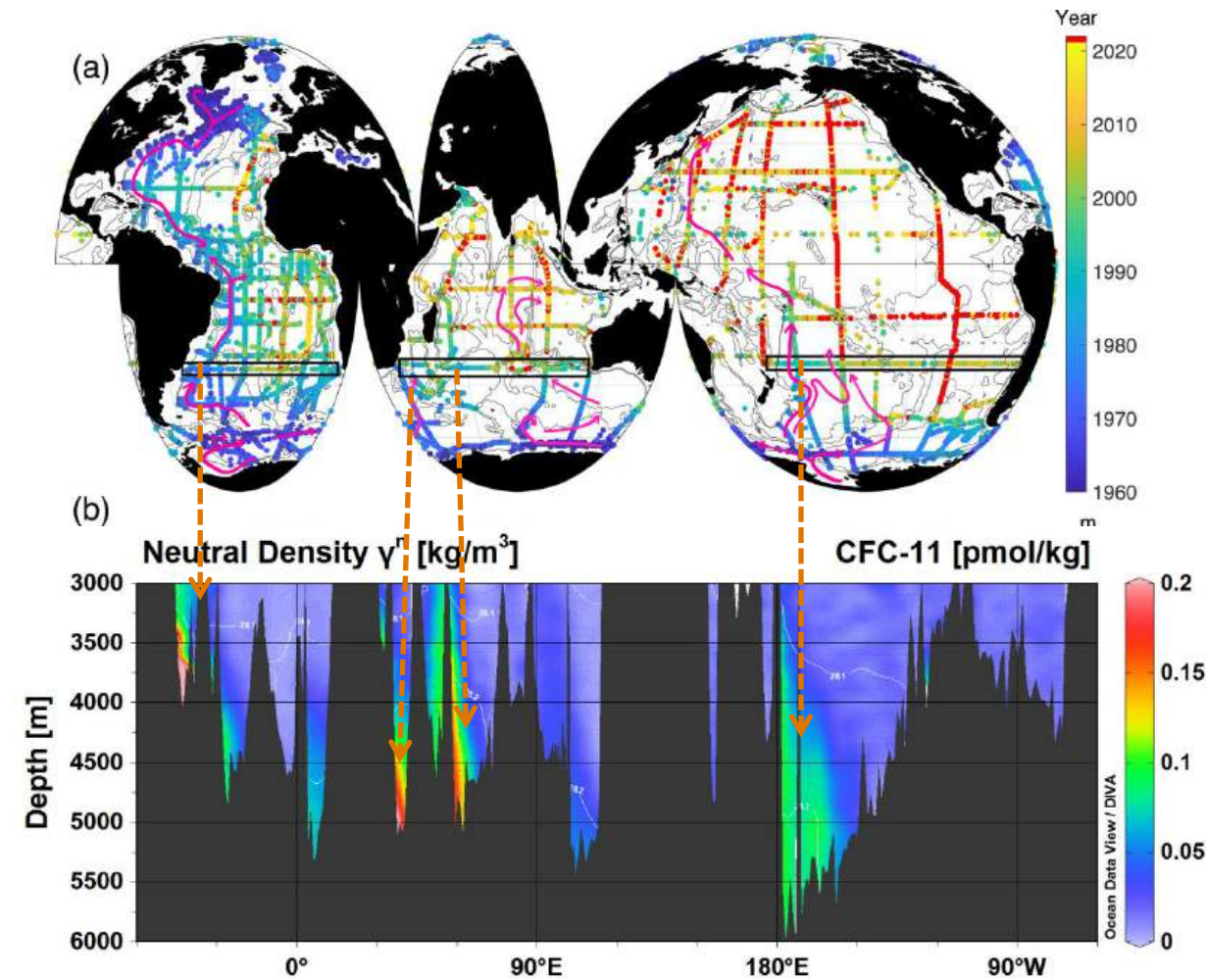


- Limited direct observations of AABW formation show variability in properties and volume (Silvano et al. 2023)

MOC: Antarctic Bottom Water (AABW)



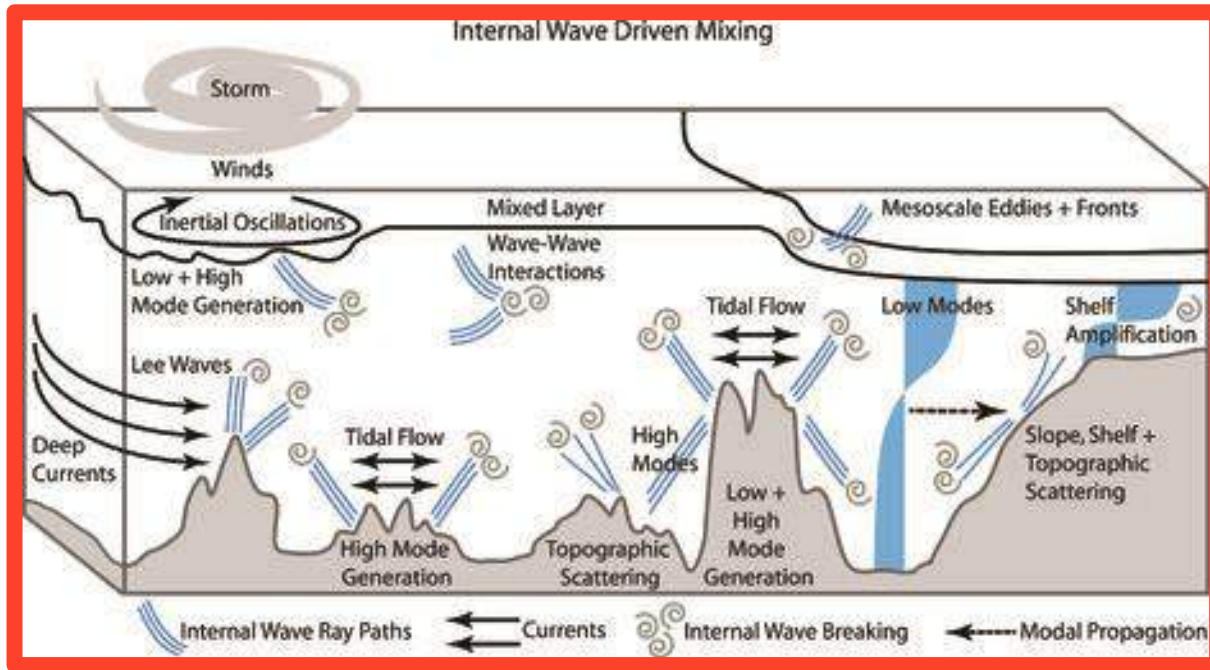
(Johnson 2008)



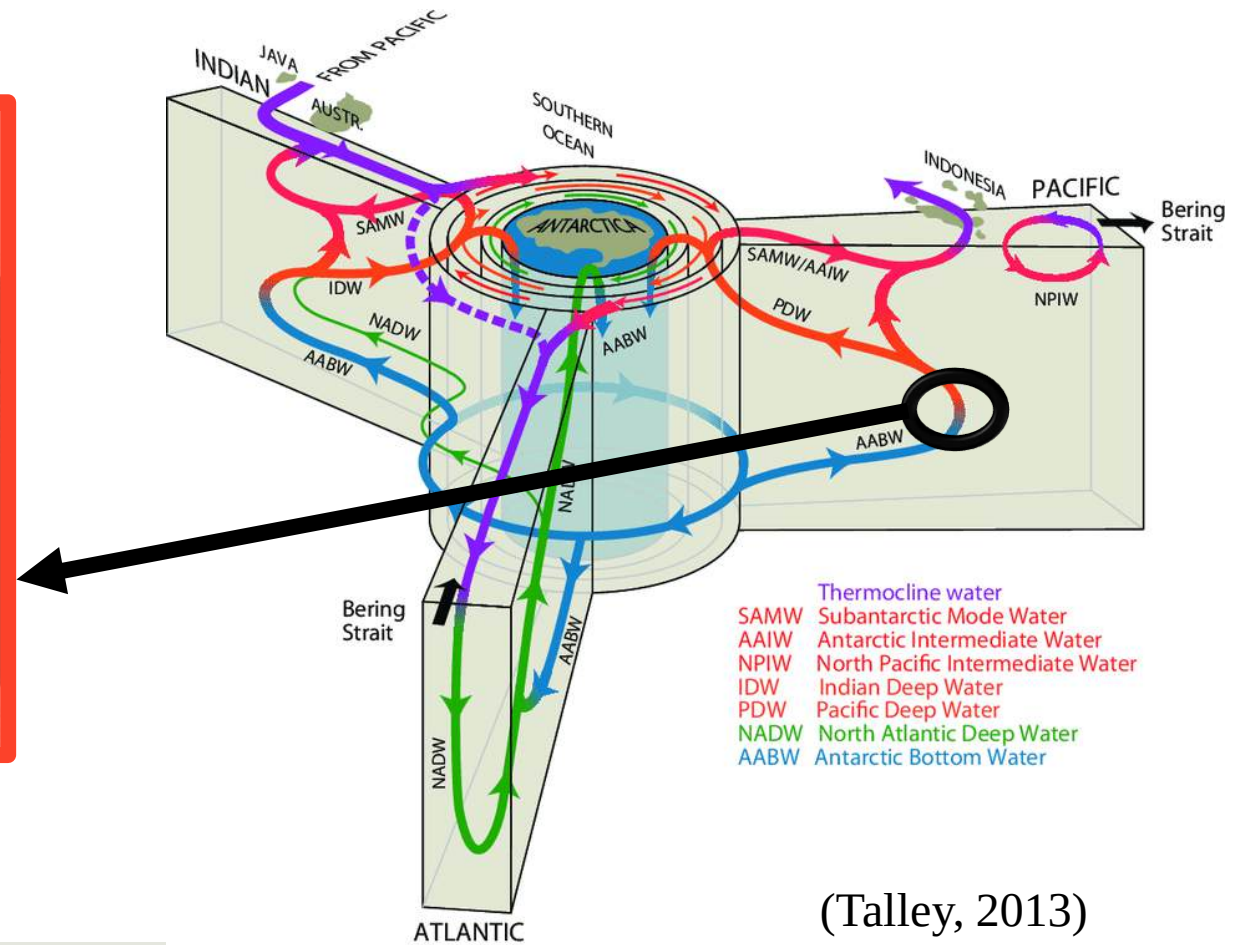
(Purkey et al., 2018)

(Cimoli et al., 2023)

MOC: Mixing

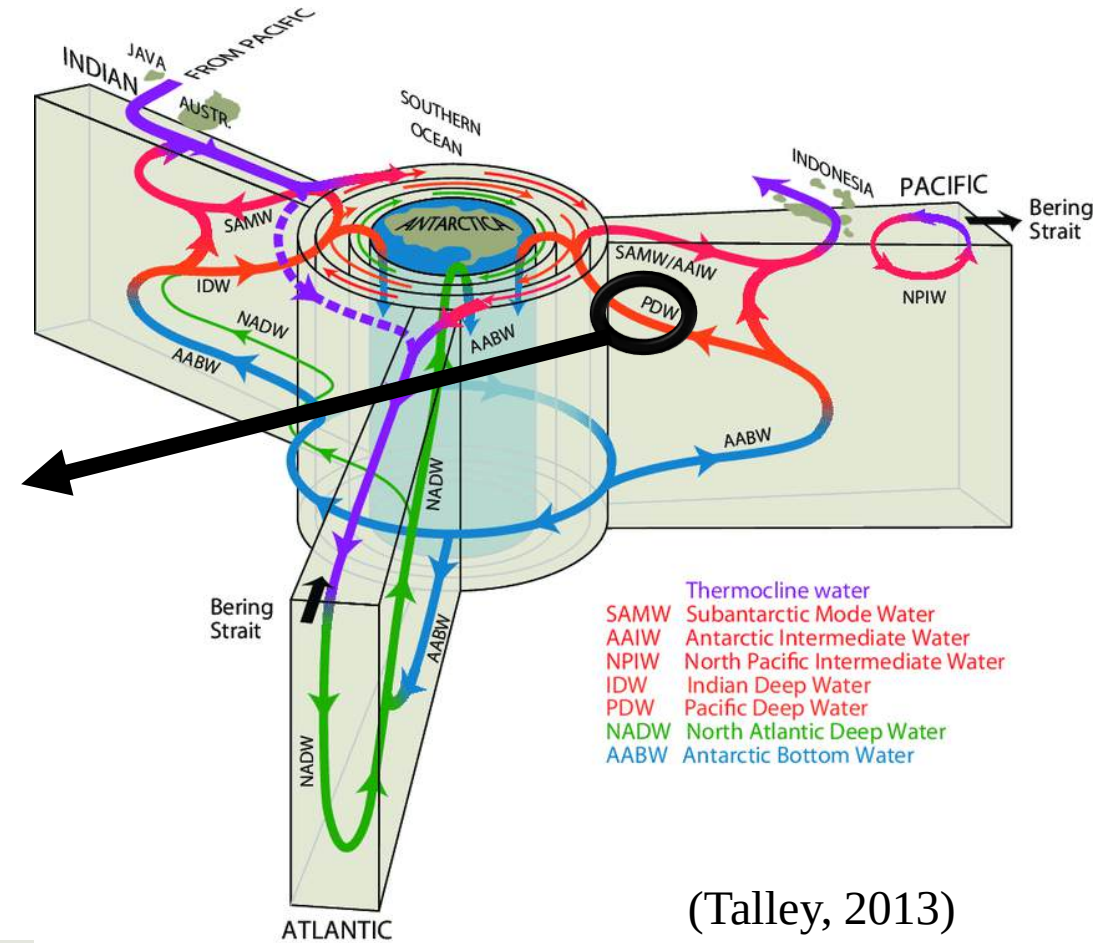
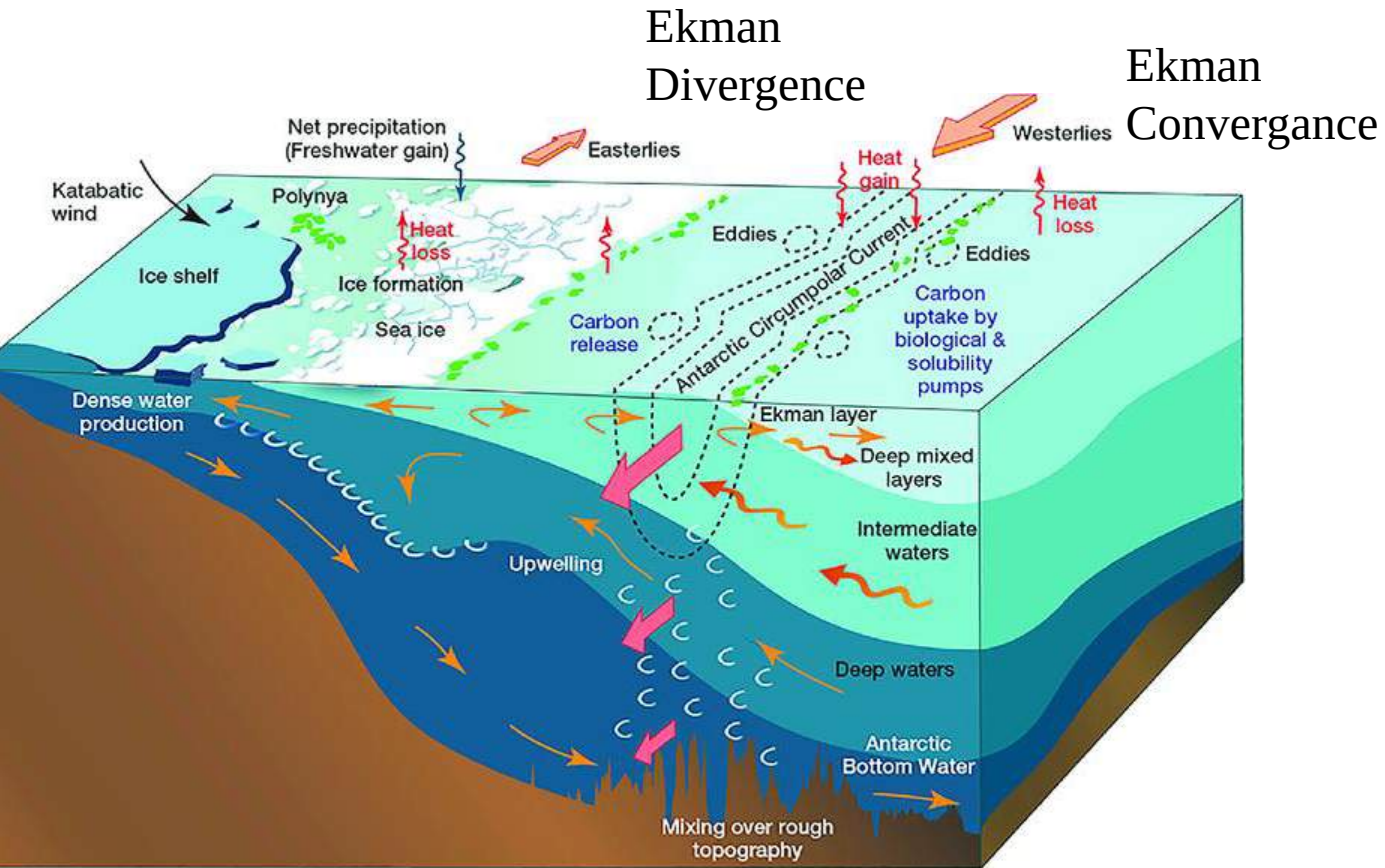


(MacKinnon et al. 2017)



(Talley, 2013)

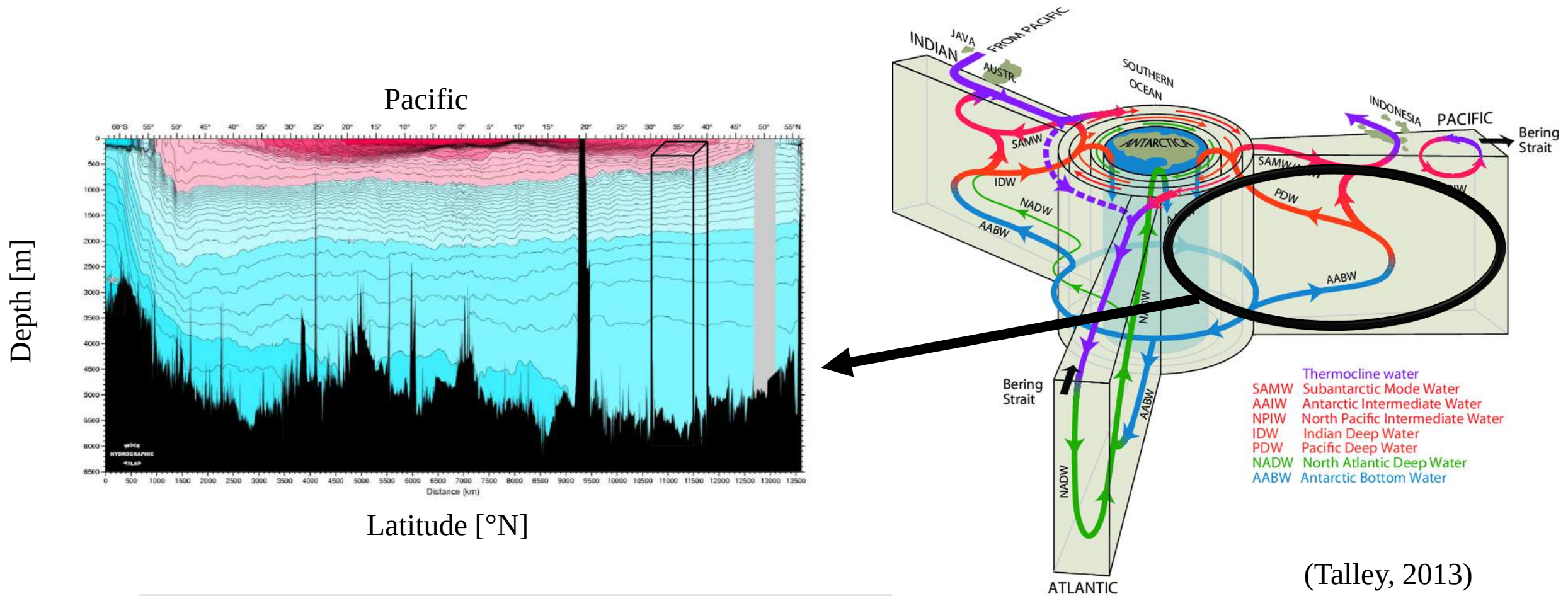
MOC: Upwelling



(Talley, 2013)

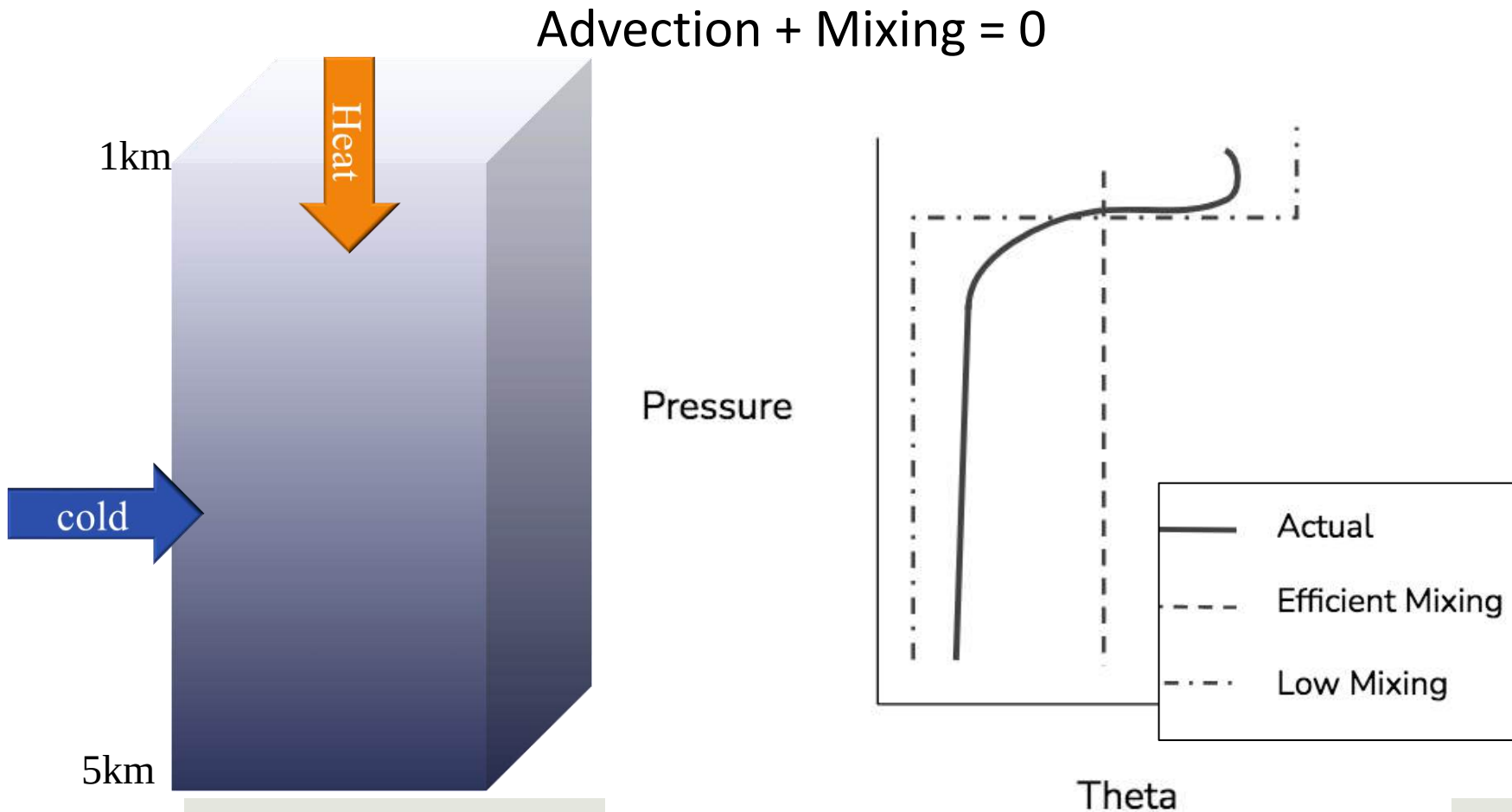
Bottom limb of the MOC

- Bottom water properties are set by the balance between the renewal of deepwater formed around Antarctica and the rate of mixing with overlying water



Deep Ocean Properties

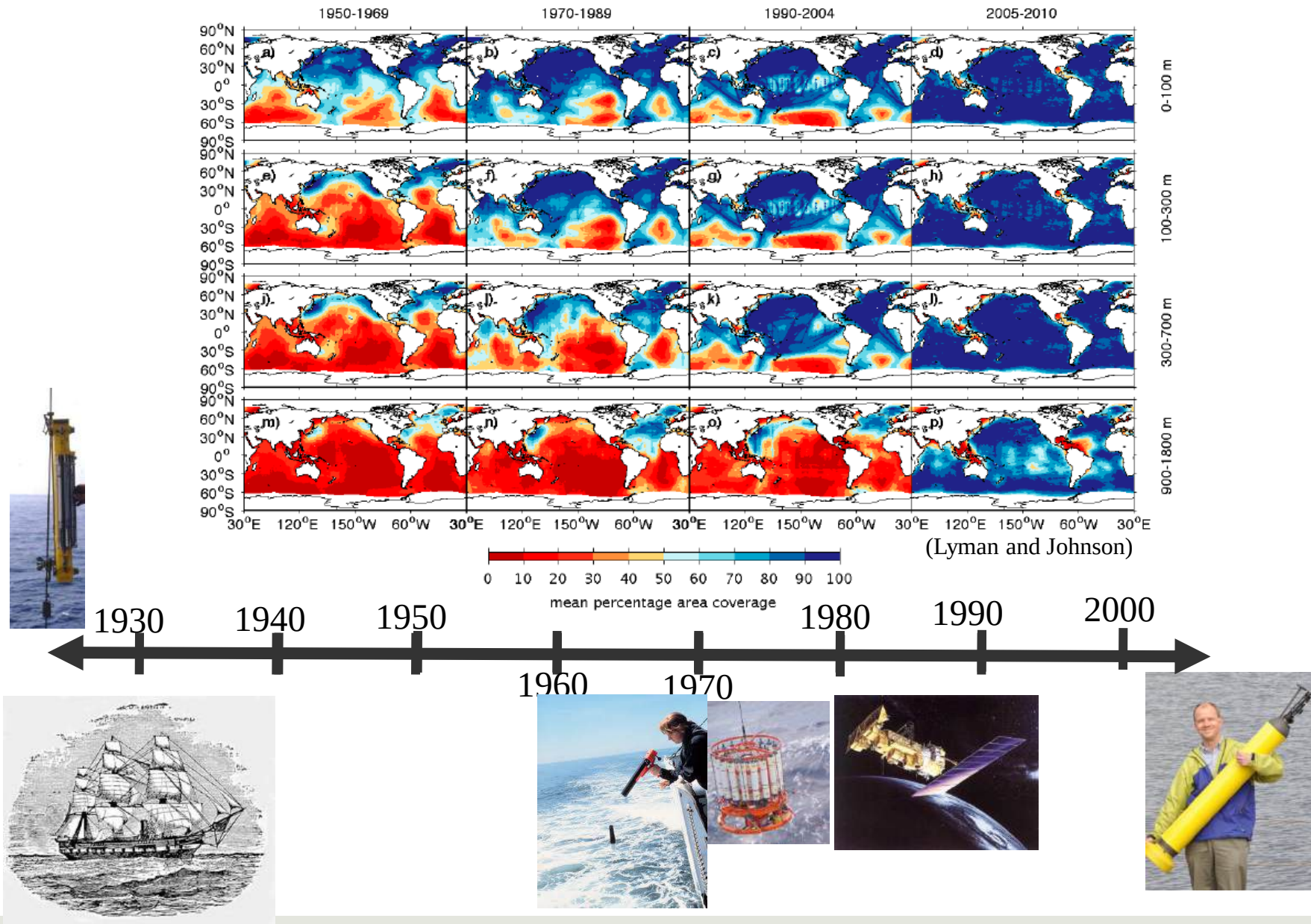
- Bottom water properties are set by the balance **between the renewal of deepwater formed** around Antarctica and the rate of mixing with overlying water



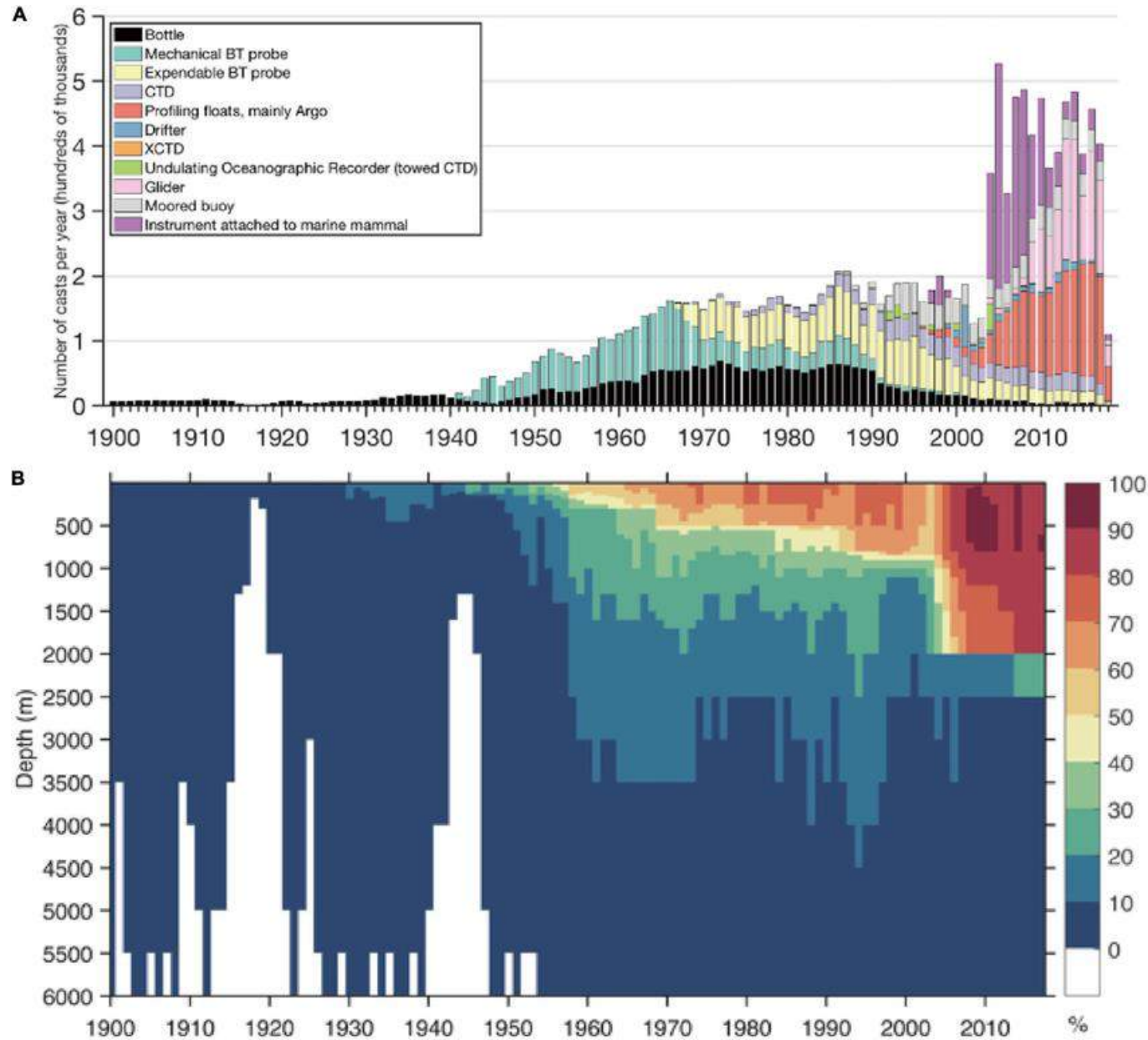
- In steady state, these two processes are equal and bottom temperature is constant in time

Ocean observation

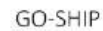
Temperature is the oldest and best measured parameter !



Temperature is the oldest and best measured parameter !

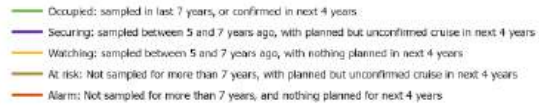


GO-SHIP



Floating status of GO-SHIP (55 Core Lines)

November 2023



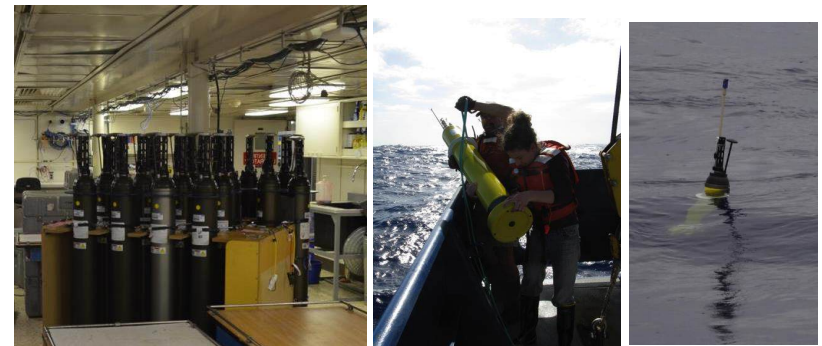
Generated by ocean-ops.org, 2023-11-24
Projection: Plate Carree (-150,0000)



Argo

4126 Operational Floats

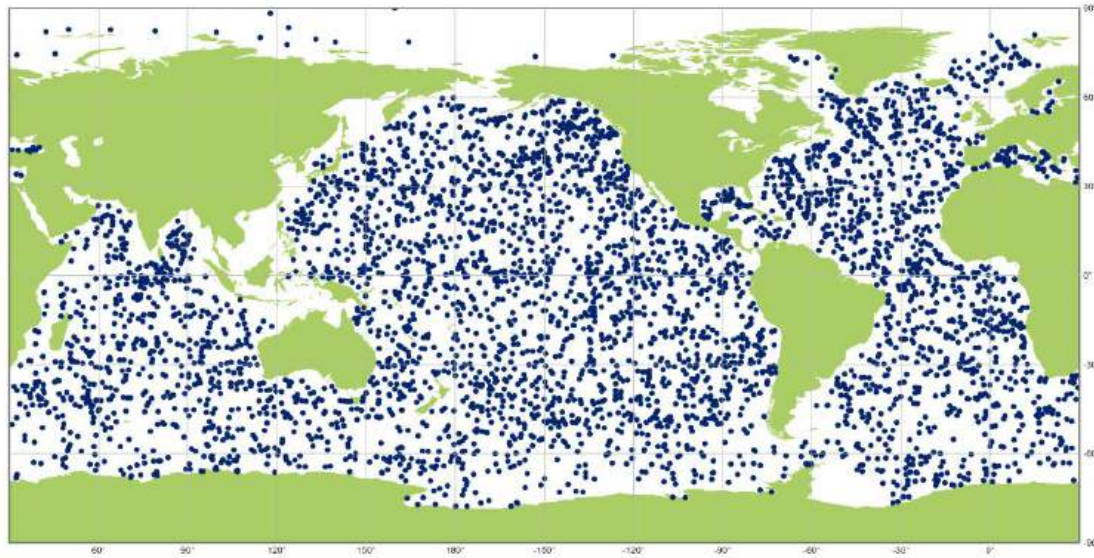
March 2025



Repeat hydrography



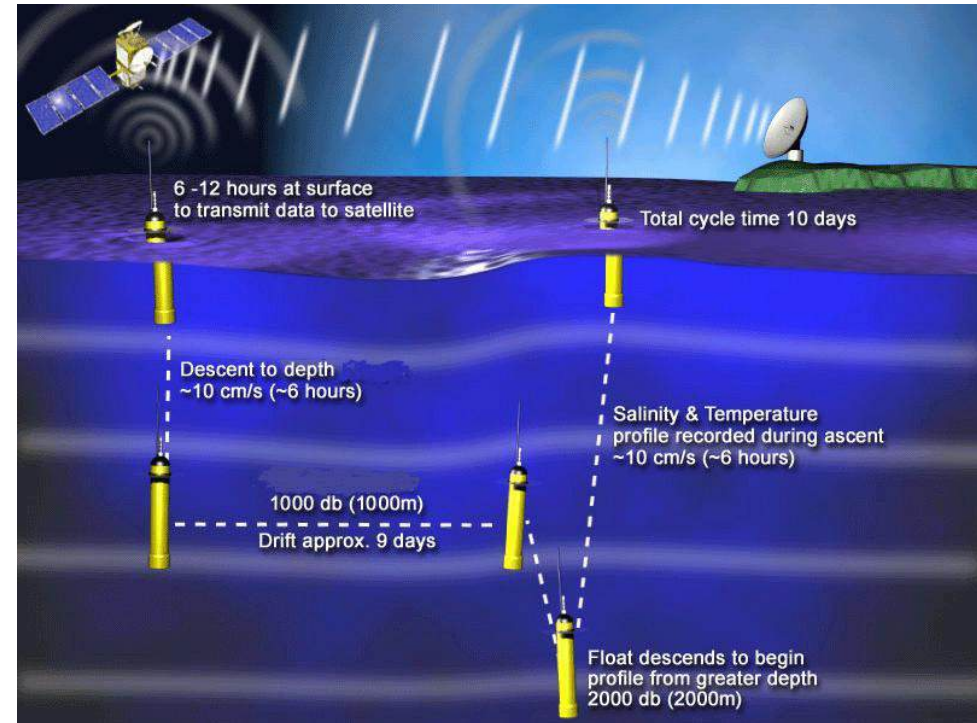
Argo



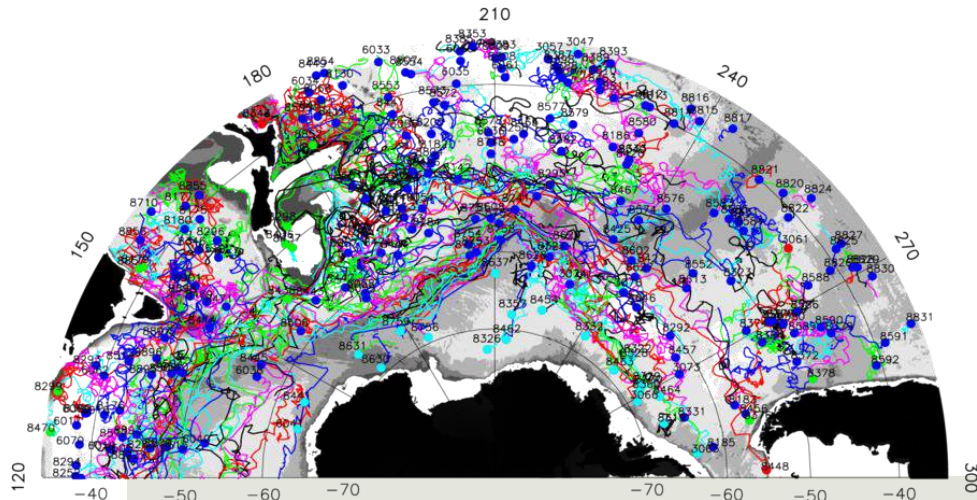
Argo

4126 Operational Floats

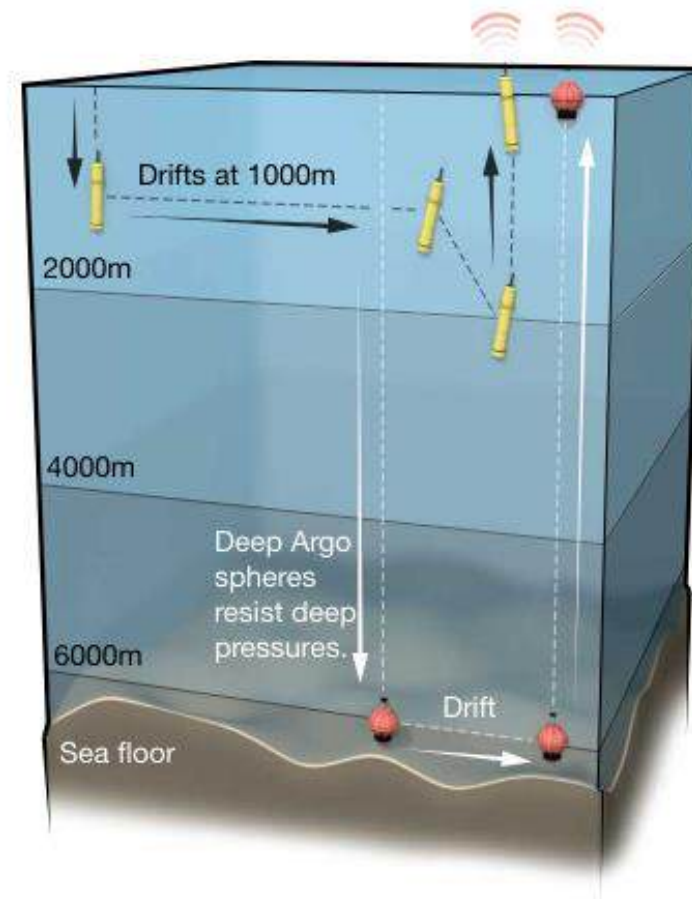
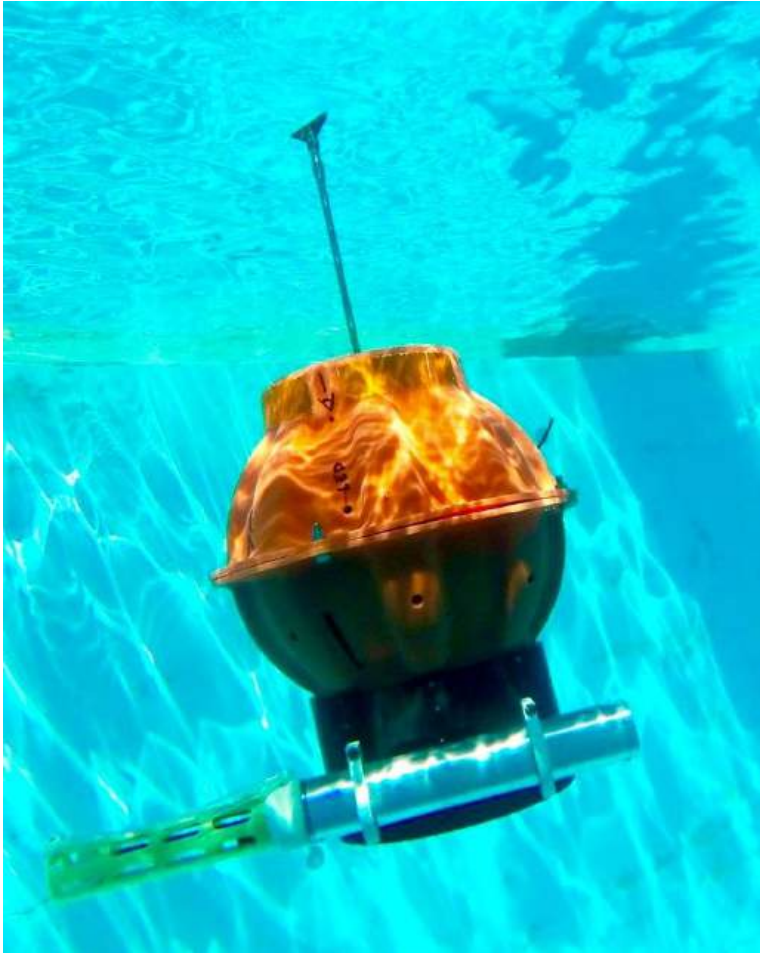
March 2025



~12k profiles randomly distributed throughout the global ocean from 0-2000m, plus 1000m reference velocity



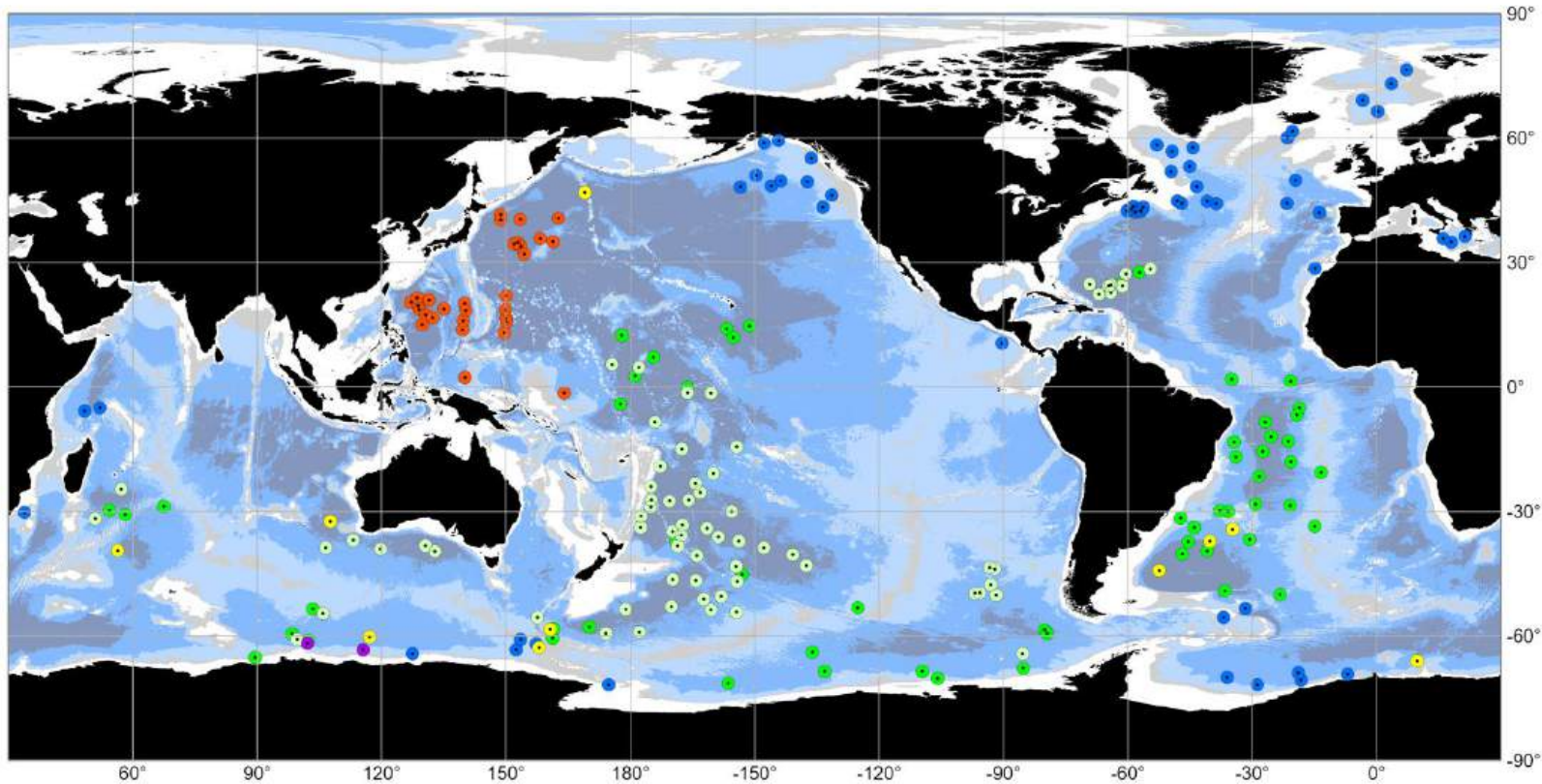
Deep Argo: 3 x deeper



C. Bickel/Science

Deep Argo

- 222 active Deep floats (some 4000 dbar max depth, some 6000 dbar max depth)

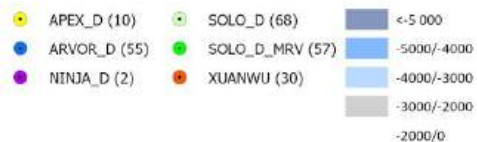


Deep Argo

Deep Float Models

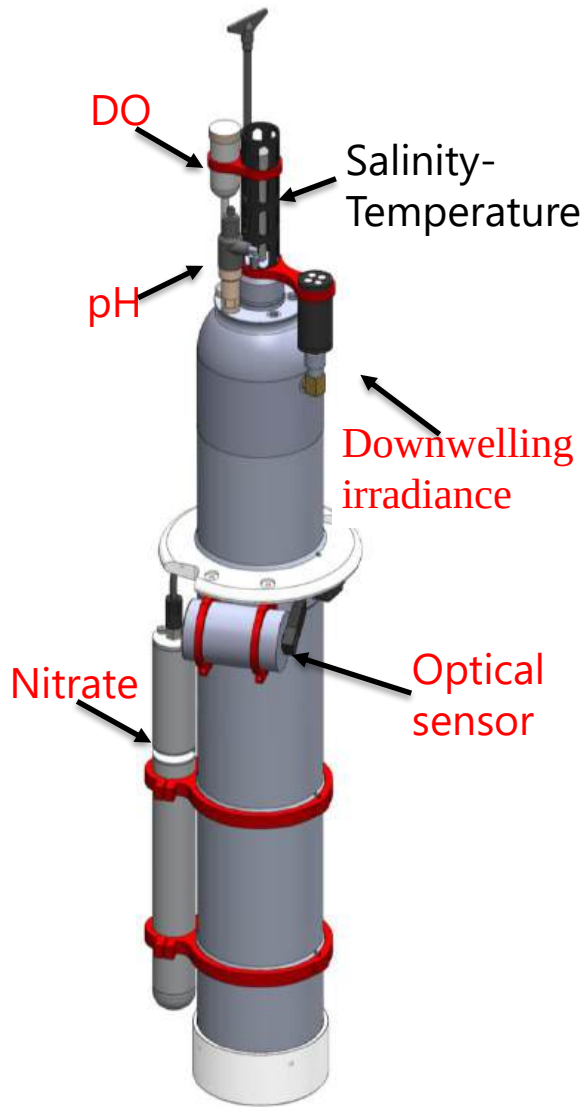
April 2025

Latest location of operational floats (data distributed within the last 30 days),



Generated by ocean-ops.org, 2025-05-06
Projection: Plate Carree [-150,0000]

BGC Argo



Salinity, temperature, depth	Ocean heat, freshwater, and circulation; Steric sea level rise
Oxygen	Deoxygenation; Ocean ventilation rates
pH	Ocean carbon uptake; Ocean acidification
Nitrate	Nutrient availability
Chlorophyll a	Phytoplankton abundance (fisheries); primary production
Backscatter	Suspended particles
Downwelling irradiance	Net primary production; calibrating satellite color

BGC Argo

- 775 Operational BGC floats with varying numbers of BGC sensors, with 74 having all 6 sensors

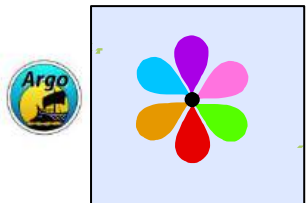


Biogeochemical Argo

Sensor Types

April 2025

Latest location of operational floats (data distributed within the last 30 days)

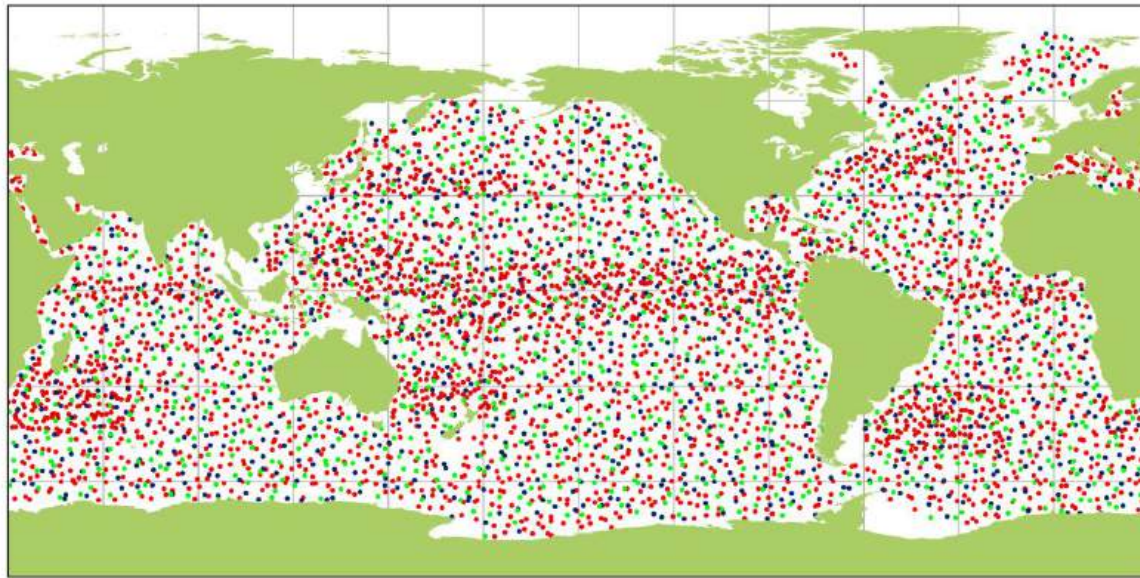


- Operational Floats (775)
- Suspended particles (539)
- Downwelling irradiance (156)
- pH (447)
- Nitrate (440)
- Chlorophyll a (539)
- Oxygen (768)
- Full BGC Floats (74)



Generated by ocean-ops.org, 2025-05-06
Projection: Plate Carree (~150,0000)

Progress towards One Argo



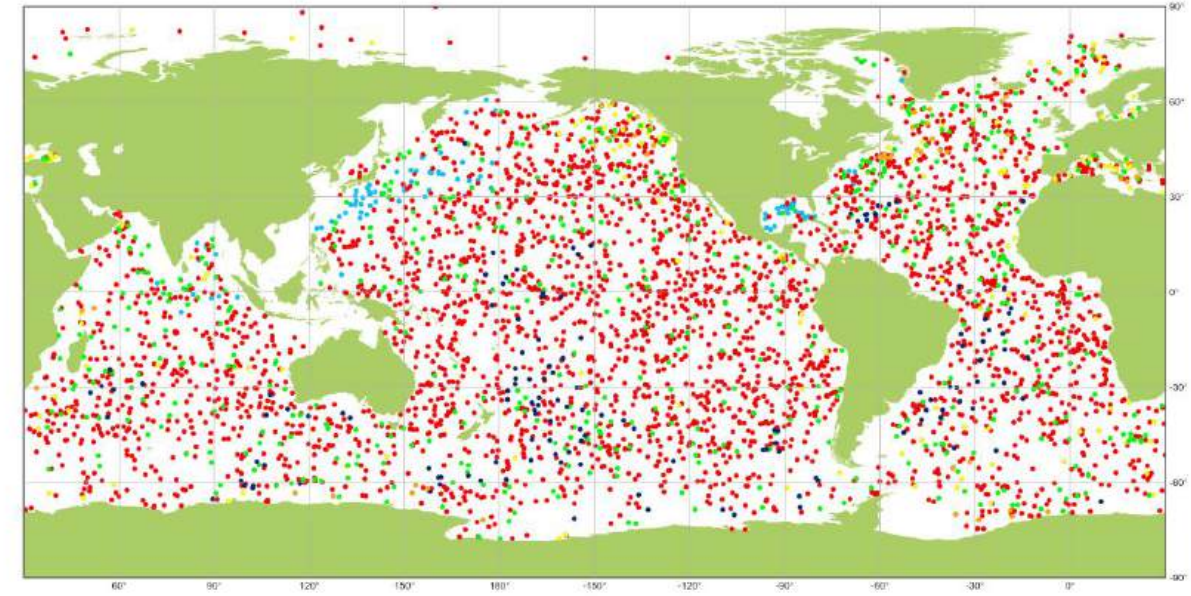
Argo

Argo Distribution - OneArgo simple
Argo global, full-depth, multidisciplinary design: 4700 floats

- Core Floats, 2500
- Deep Floats, 1200
- BGC Floats, 1000



Generated by ocean-ops.org, 2022-03-09
Projection: Plate Carree (-150,0000)



Argo

Networks
4056 operational units

April 2025

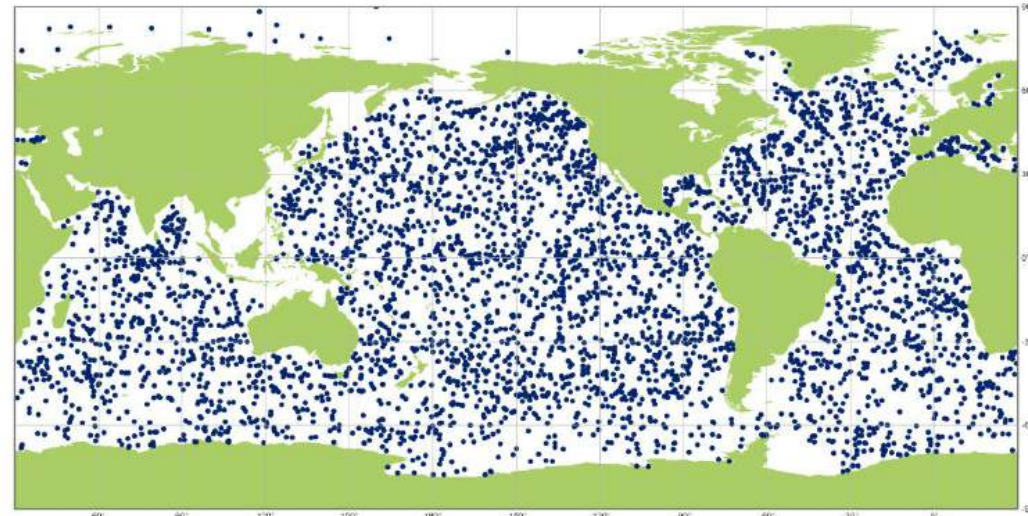
- Deep (TSO only) (55)
- Deep (192)
- BioGeoChemical (without TSO only) (566)
- Core + O2 (TSO) (154)
- Core (3019)
- Equivalent (143)



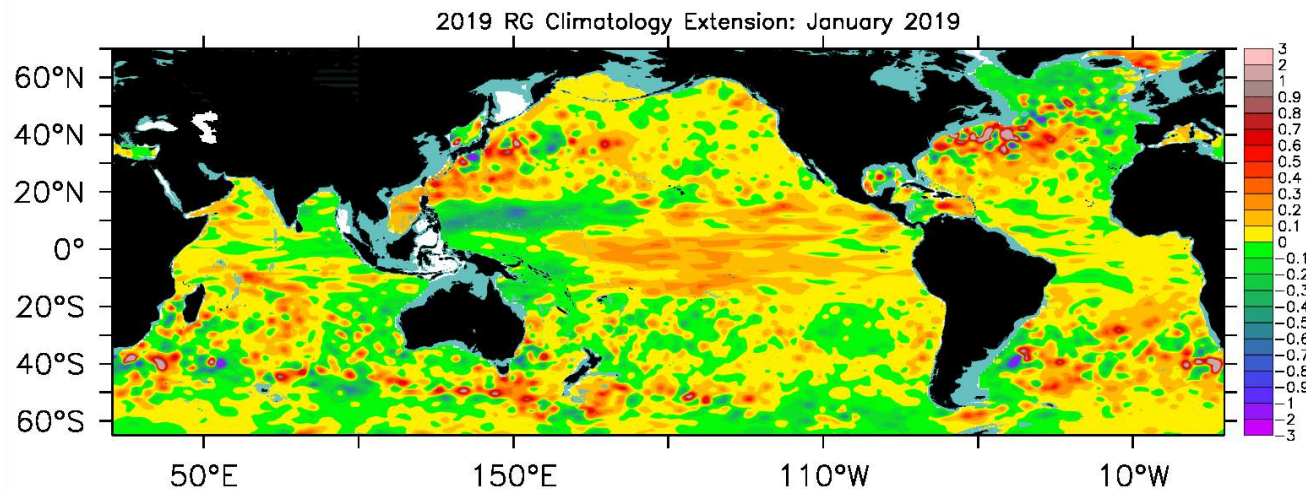
Generated by ocean-ops.org, 2025-05-06
Projection: Plate Carree (-150,0000)

Ocean warming

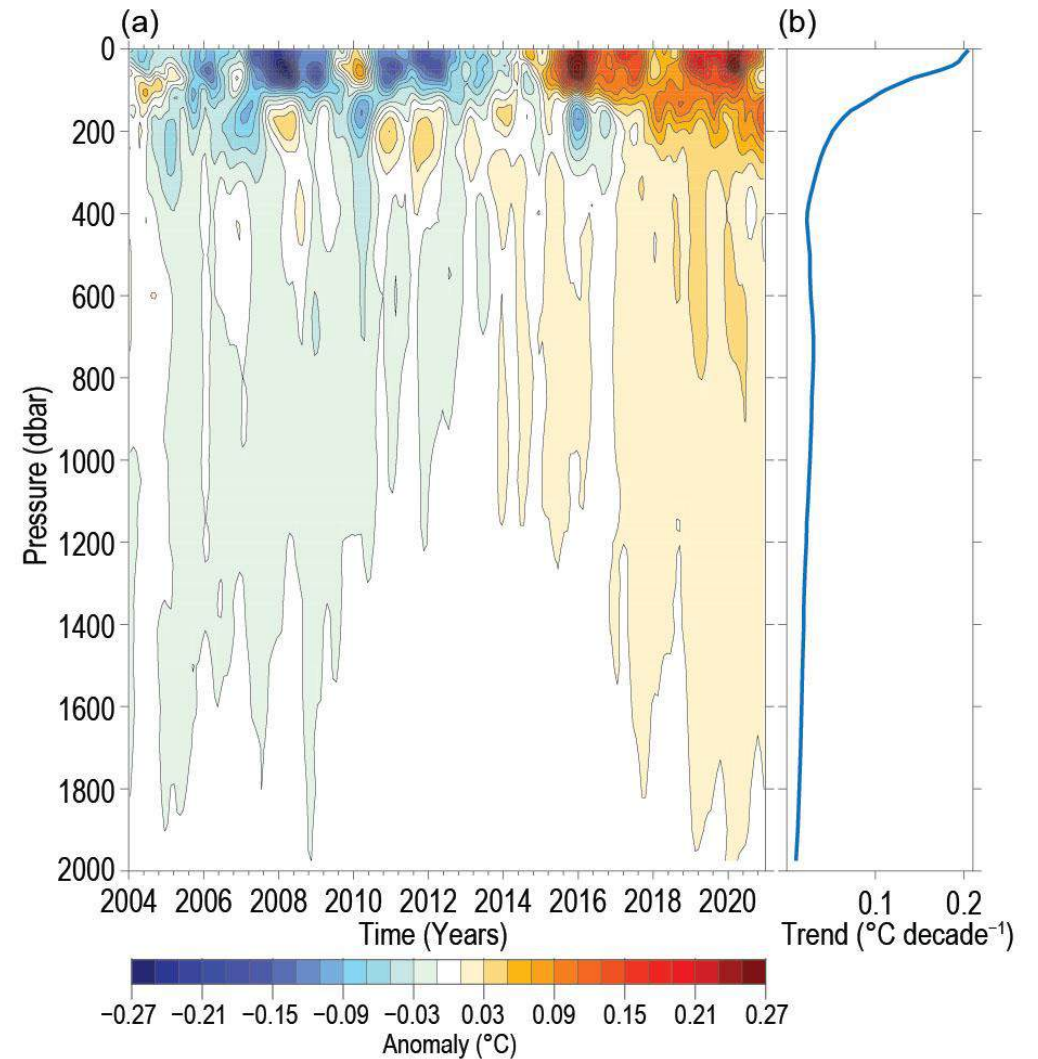
Upper ocean heat content



Argo 4126 Operational Floats March 2025

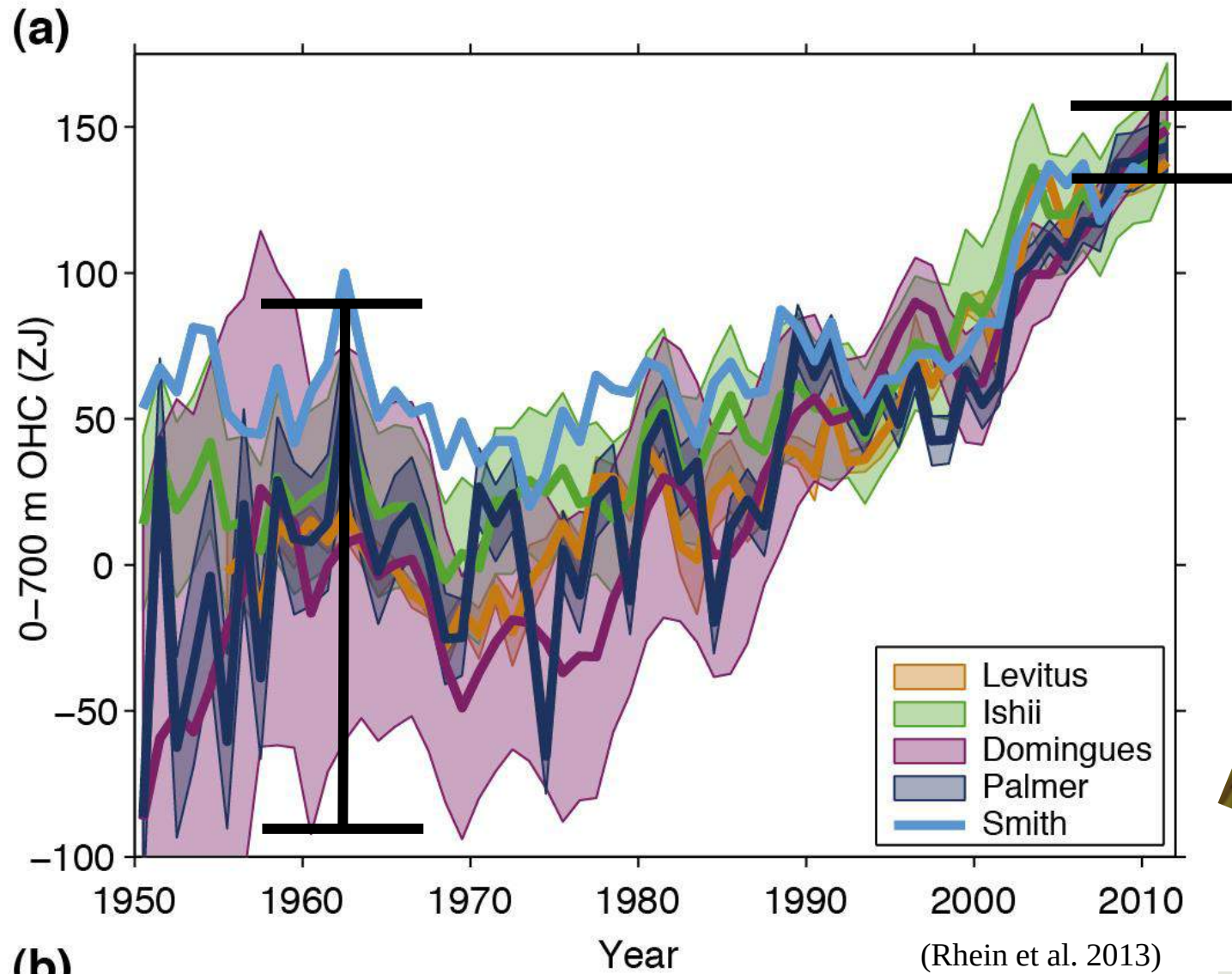


Pressure Averaged Potential Temperature Anomaly (0–2000dbar, °C). The anomaly is defined relative to the RG annual cycle

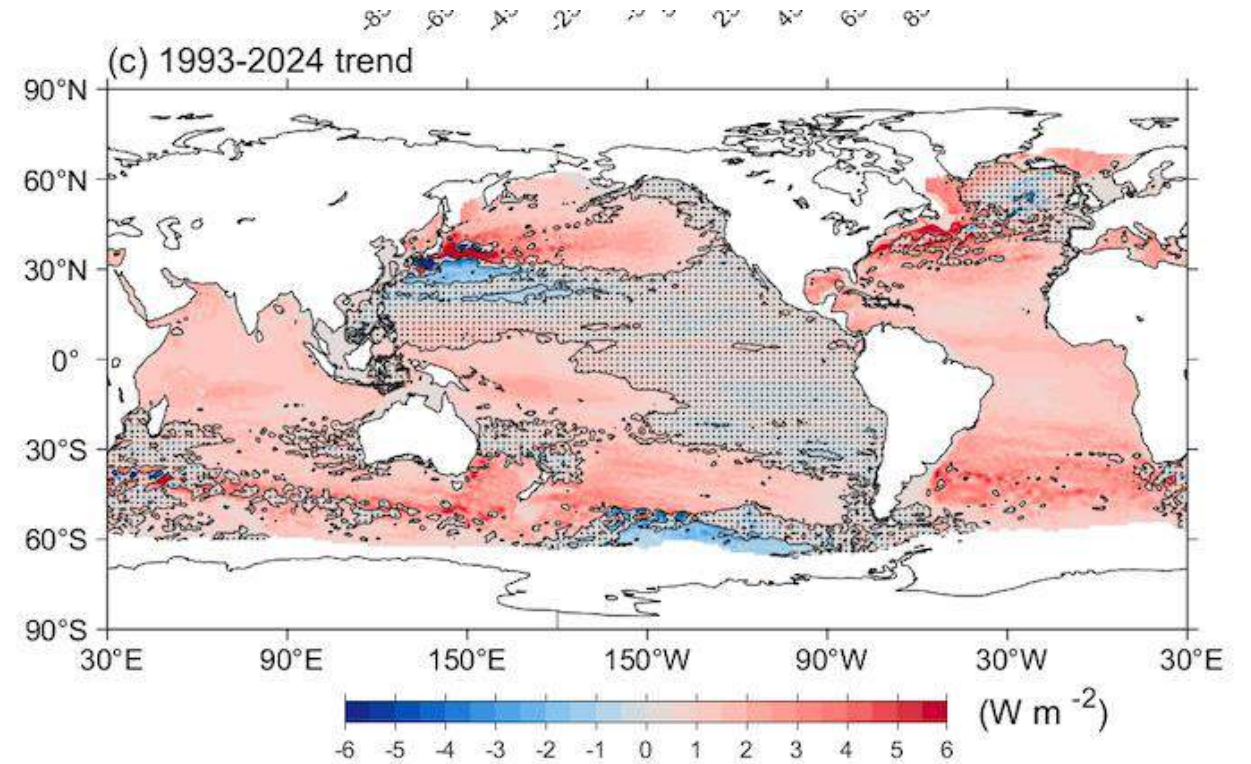
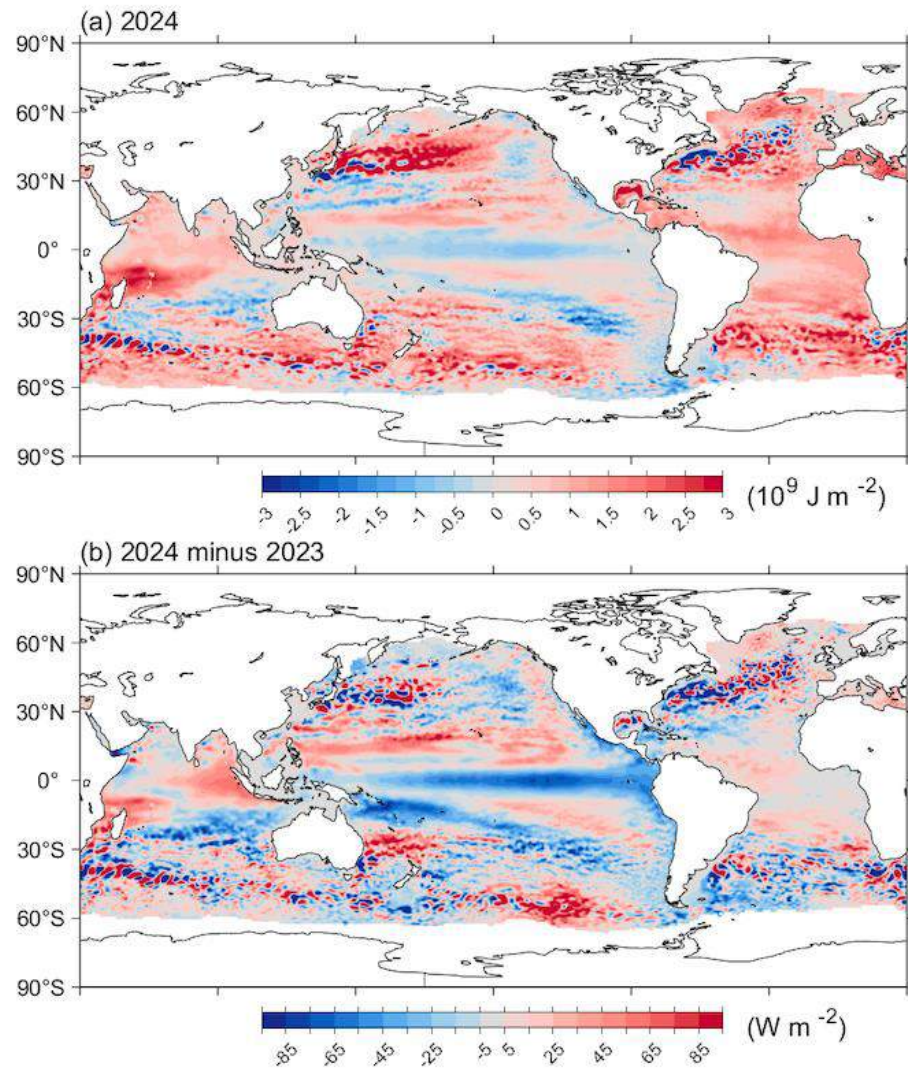


(Roemmich and Gilson)

Upper ocean heat content



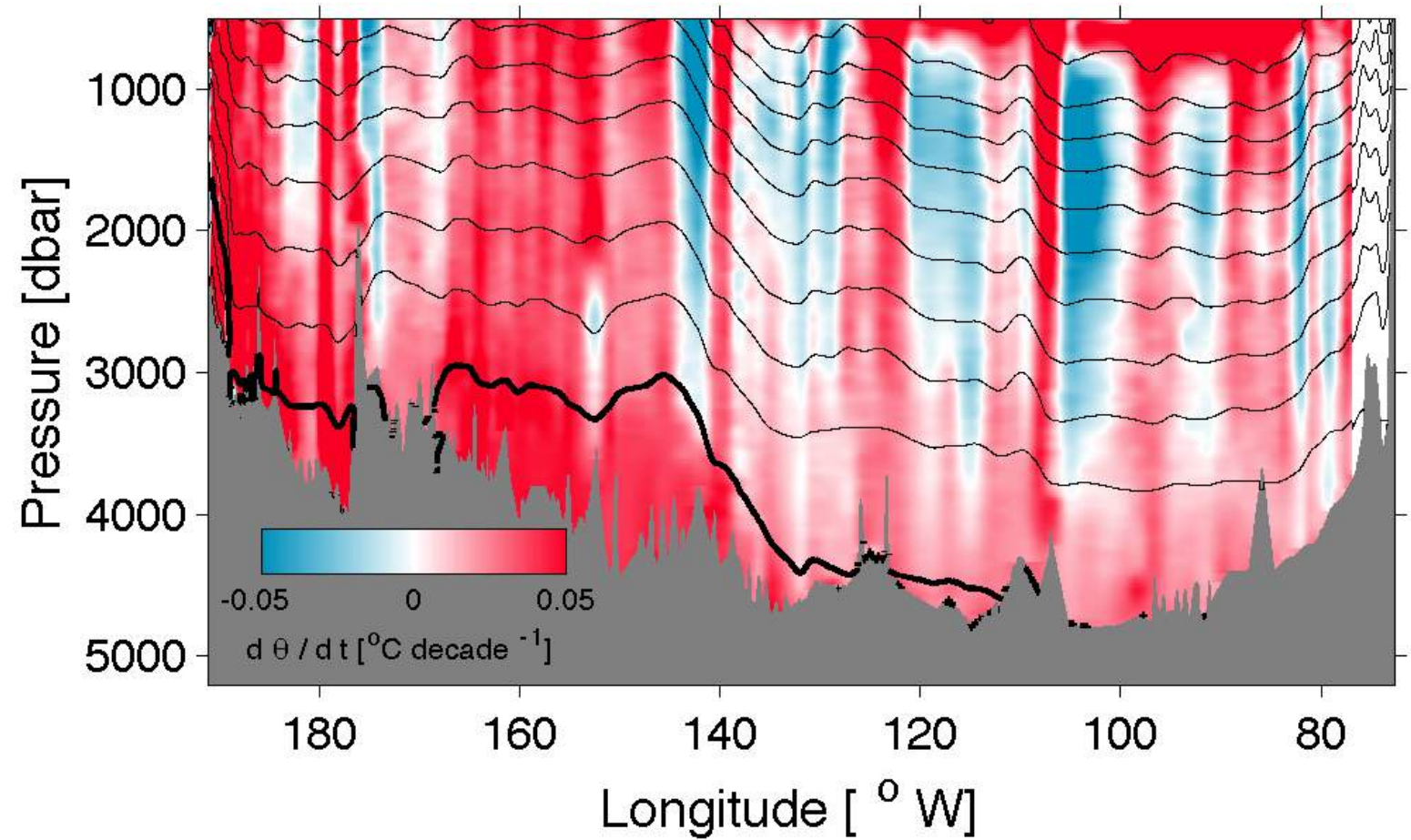
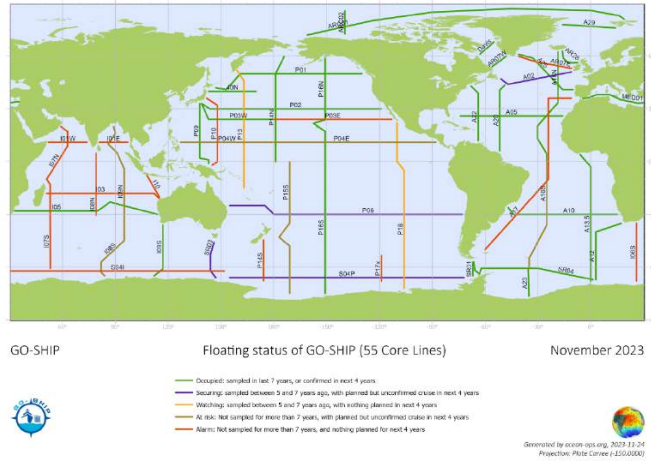
OHC: 0-2000m



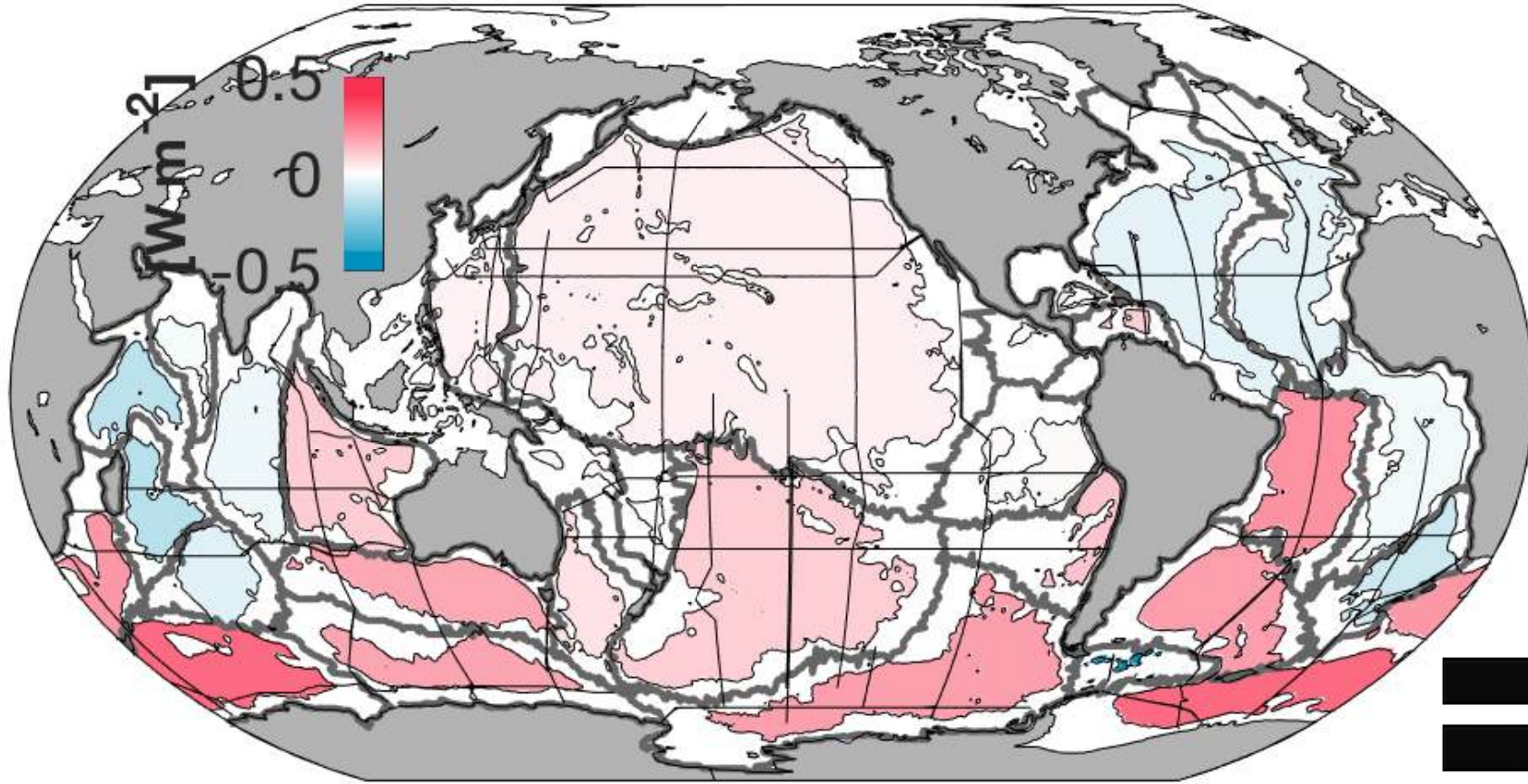
(2024 State of the climate, personal communication Greg Johnson)

Below Argo?

Along WOCE Section



Accumulation of heat below 4000m

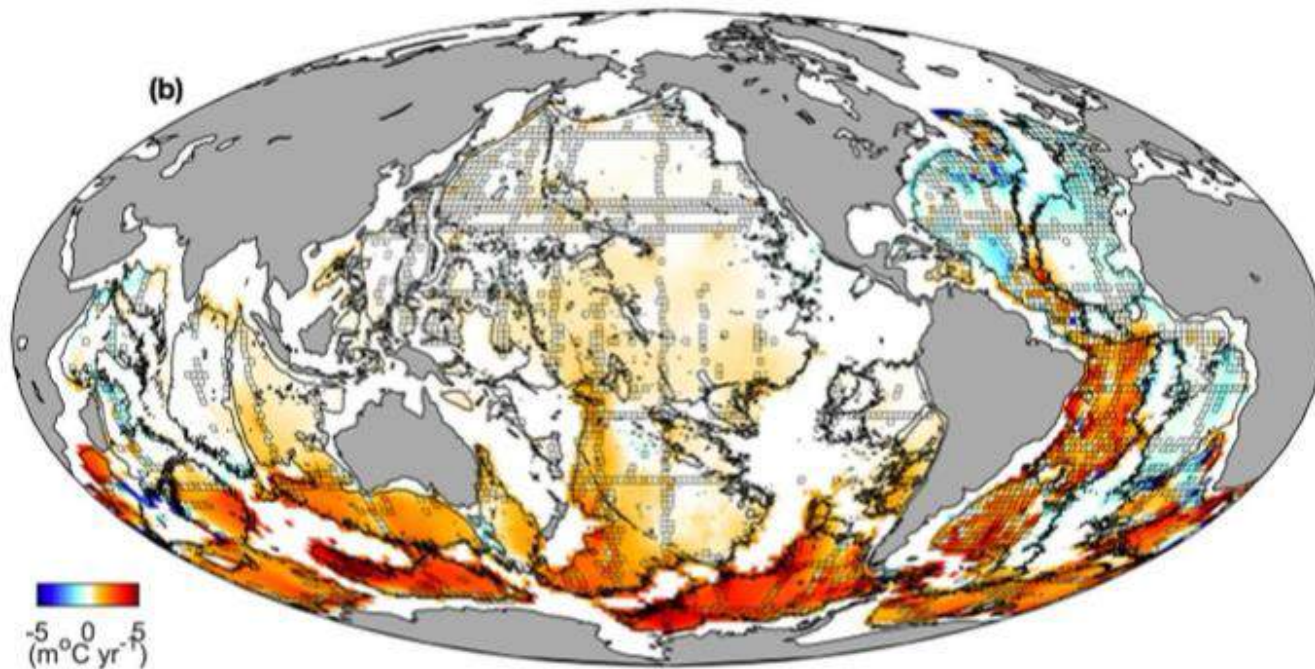


(Updated from Purkey and Johnson, 2010)

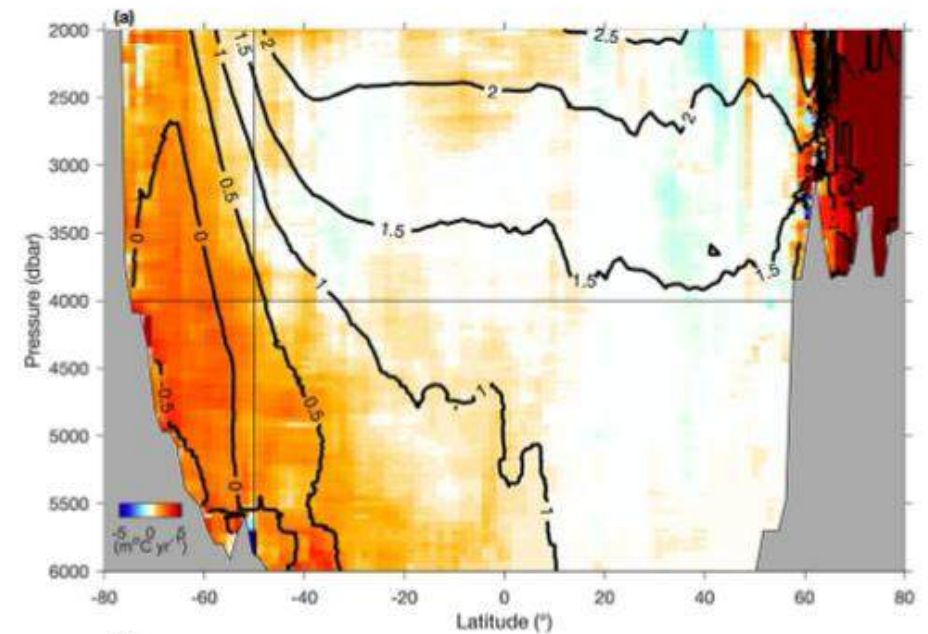
0.7 ZJ/yr

GO-SHIP + Deep Argo: Deep Ocean Warming

Deep Warming below 4000m

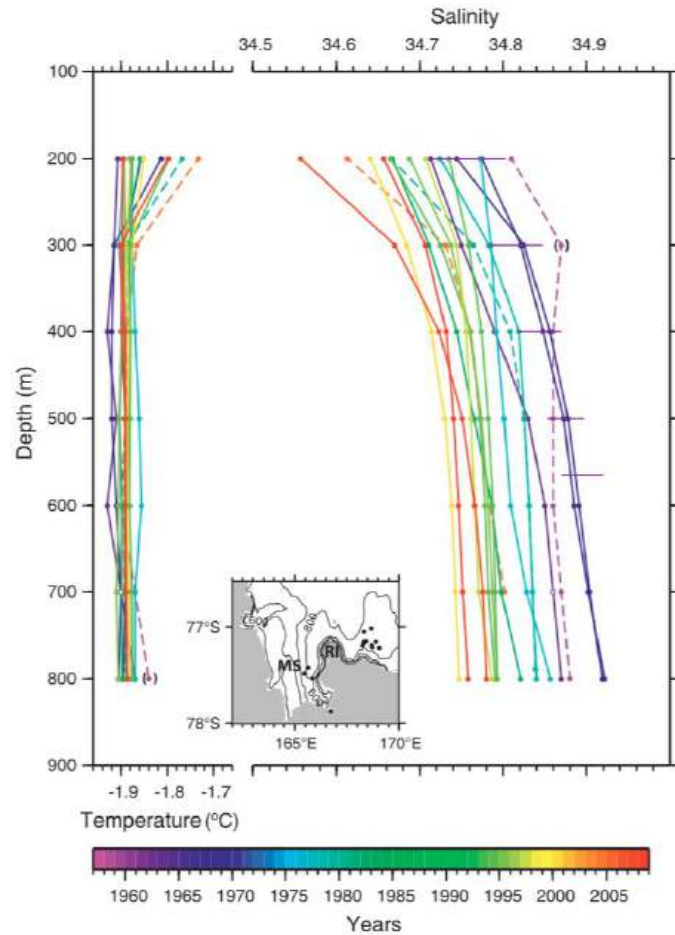


Zonal Mean Deep warming below 2000m

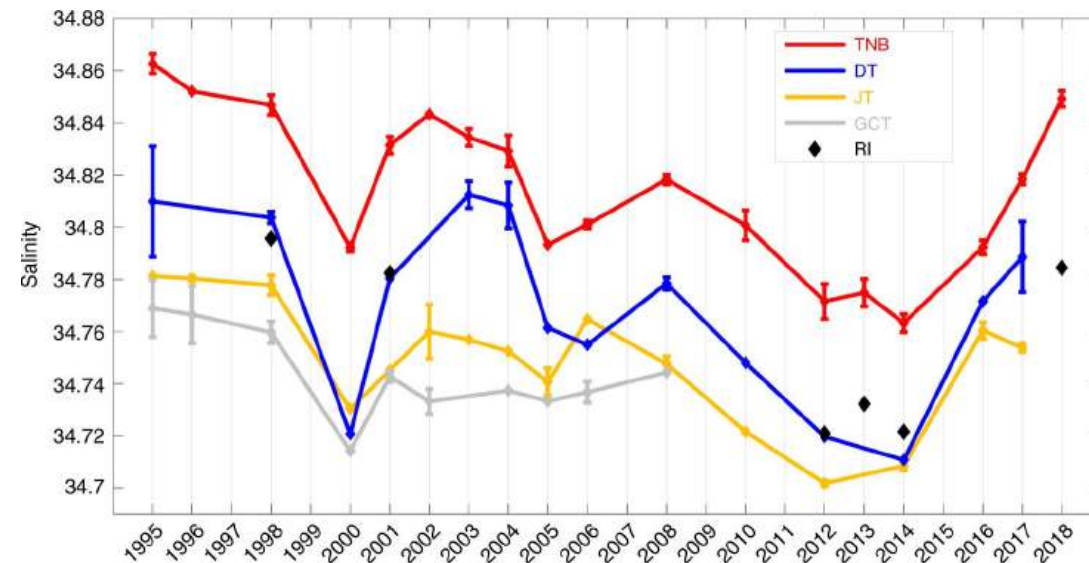
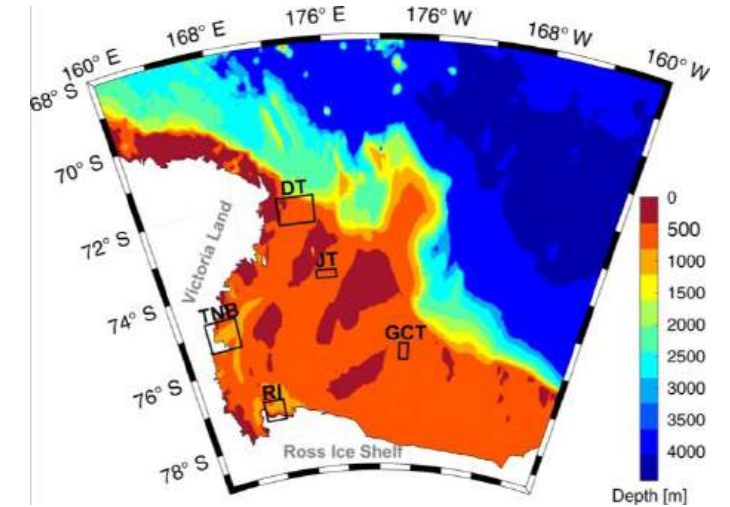
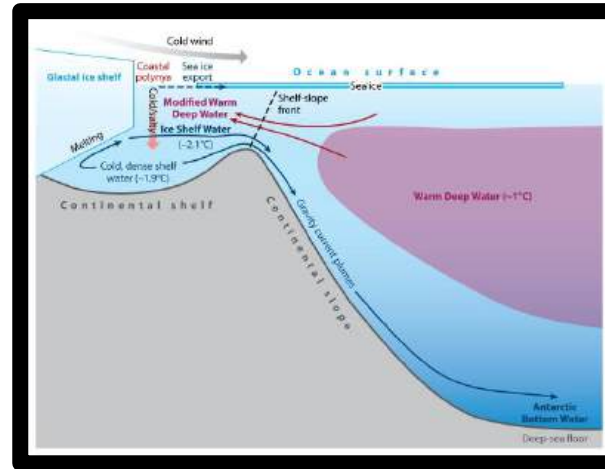


(Johnson and Purkey, 2024)

Ross Sea shelf water salinity variability

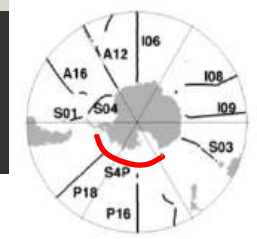


(Jacob and Giulivi, 2010)

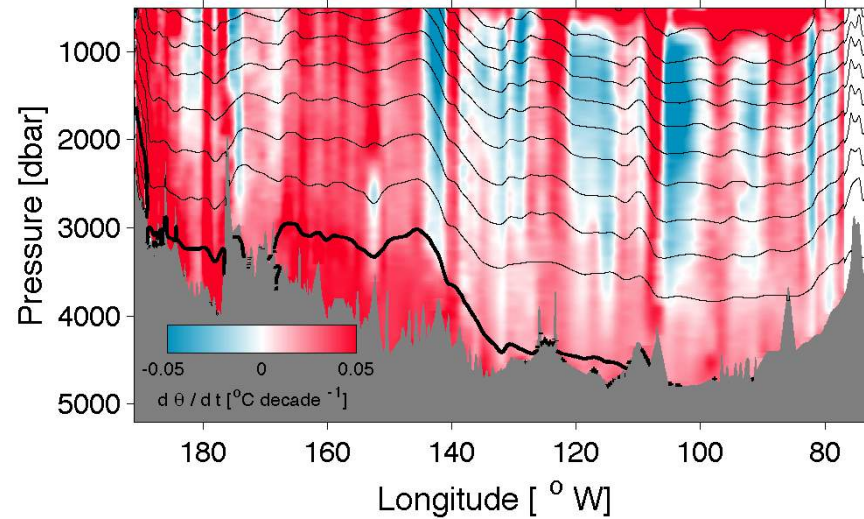


(Castagno et al. 2019)

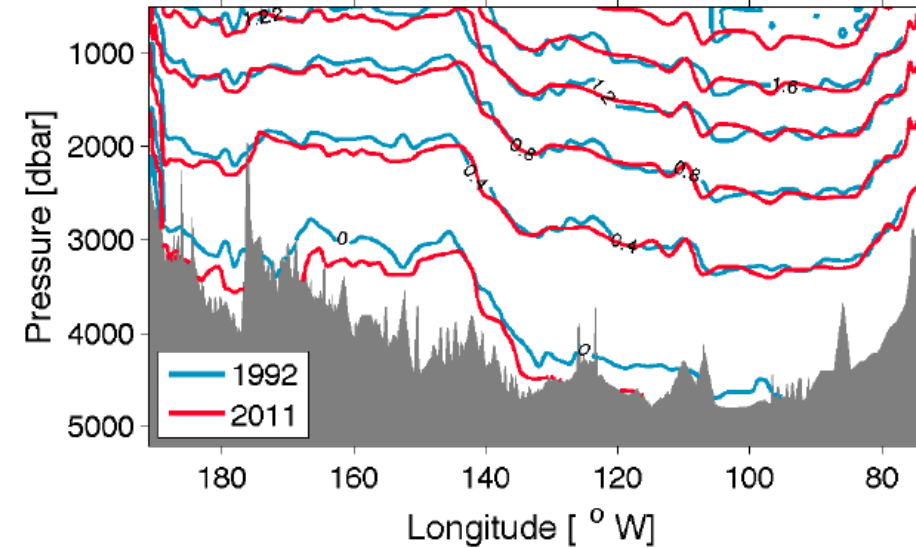
Warming = Isotherm Heave



(Purkey & Johnson 2012)

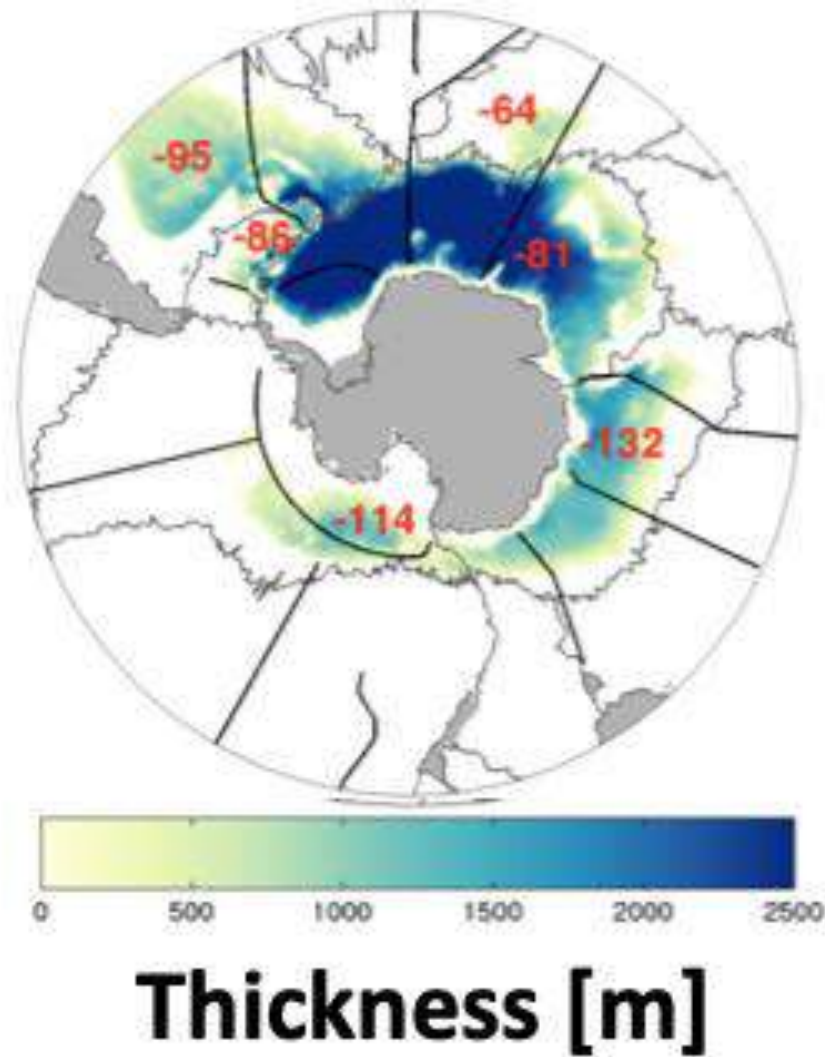


- Warming between 1992 and 2011 occupation of S4P

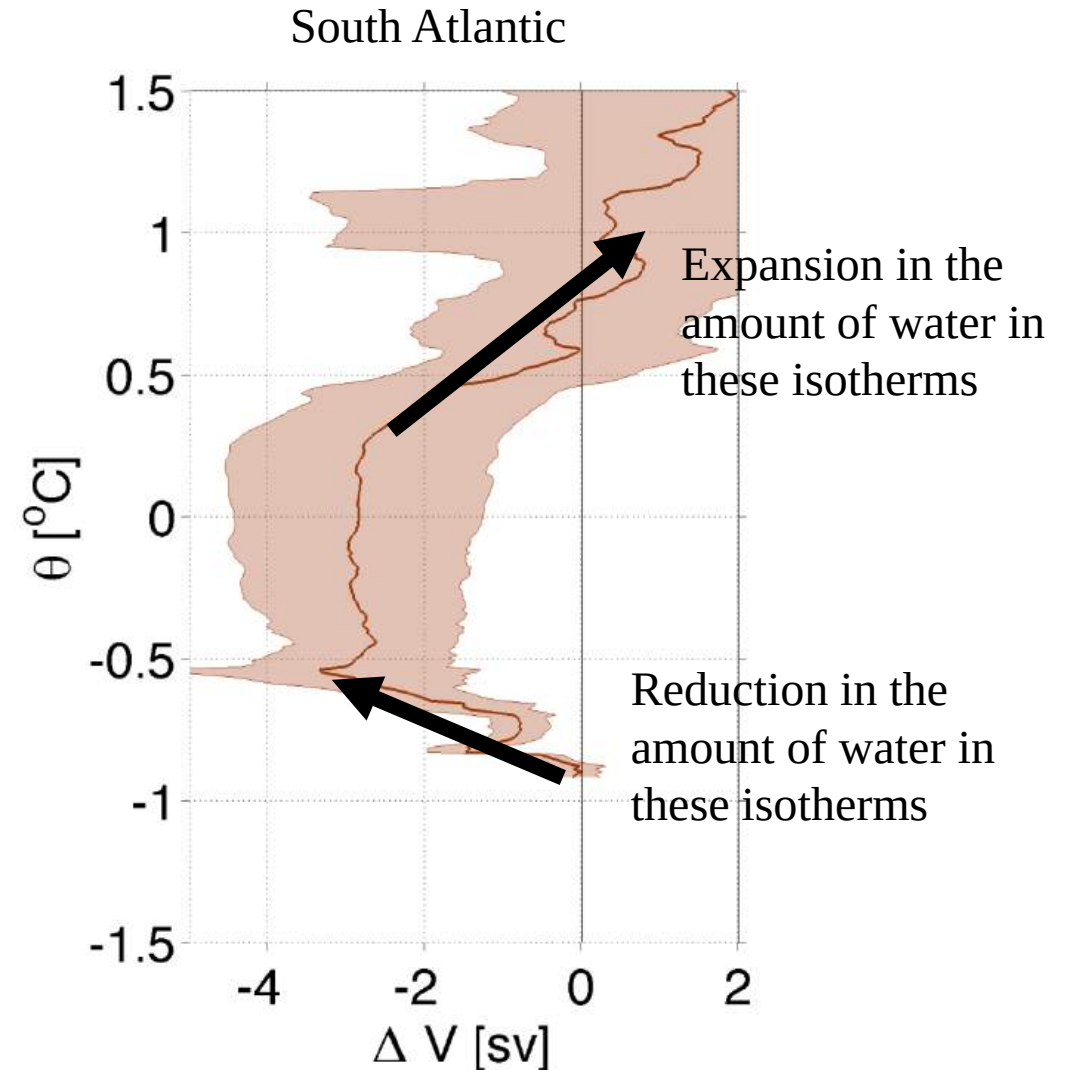


- Warming on isobars is equivalent to descending isotherms

Reduction in AABW compensated by an expansion of CDW?

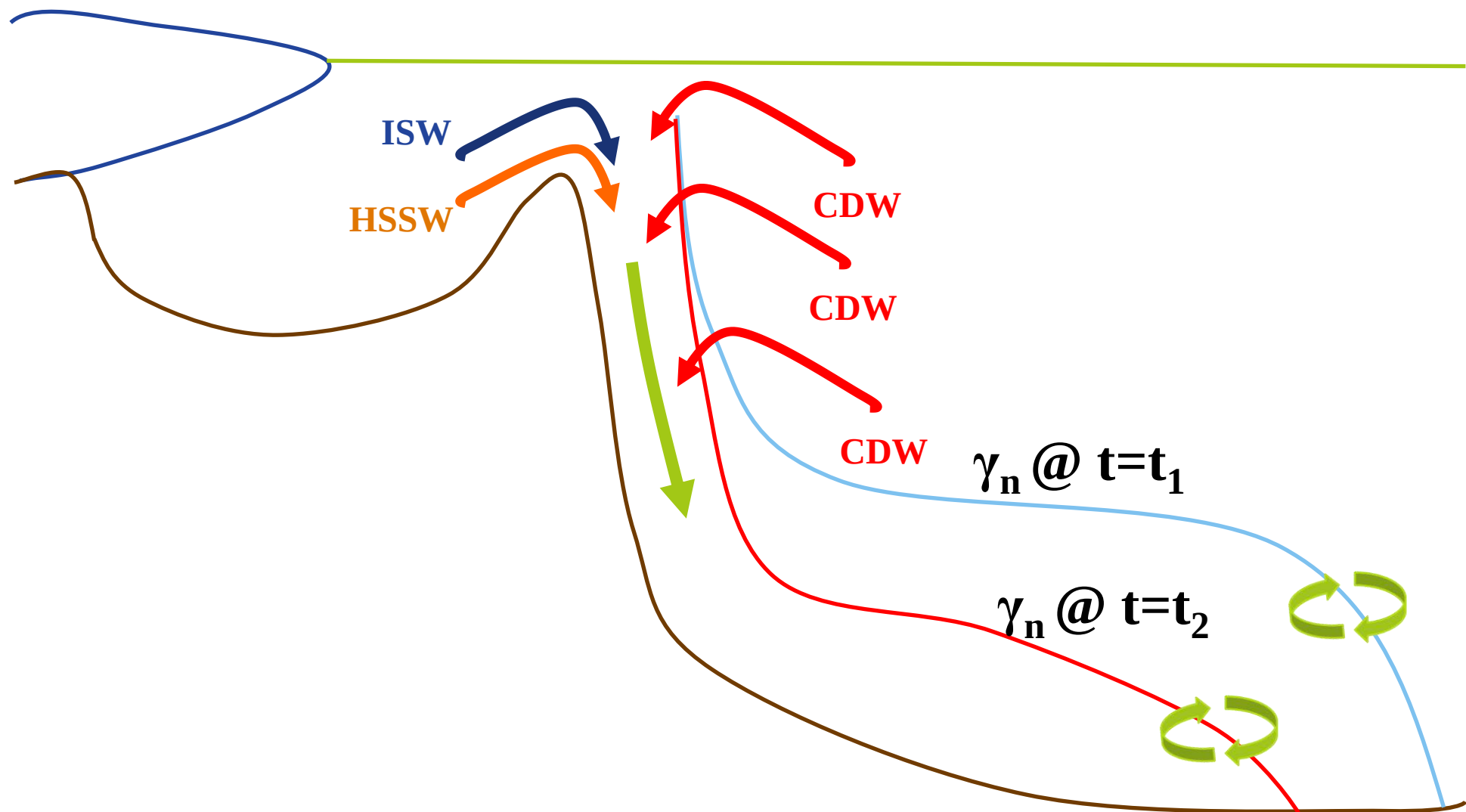


Red = change in thickness of AABW (m)



(Purkey and Johnson, 2012)

What is driving the loss of AABW?



A slow down in the deep MOC?

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Article | [Published: 29 March 2023](#)

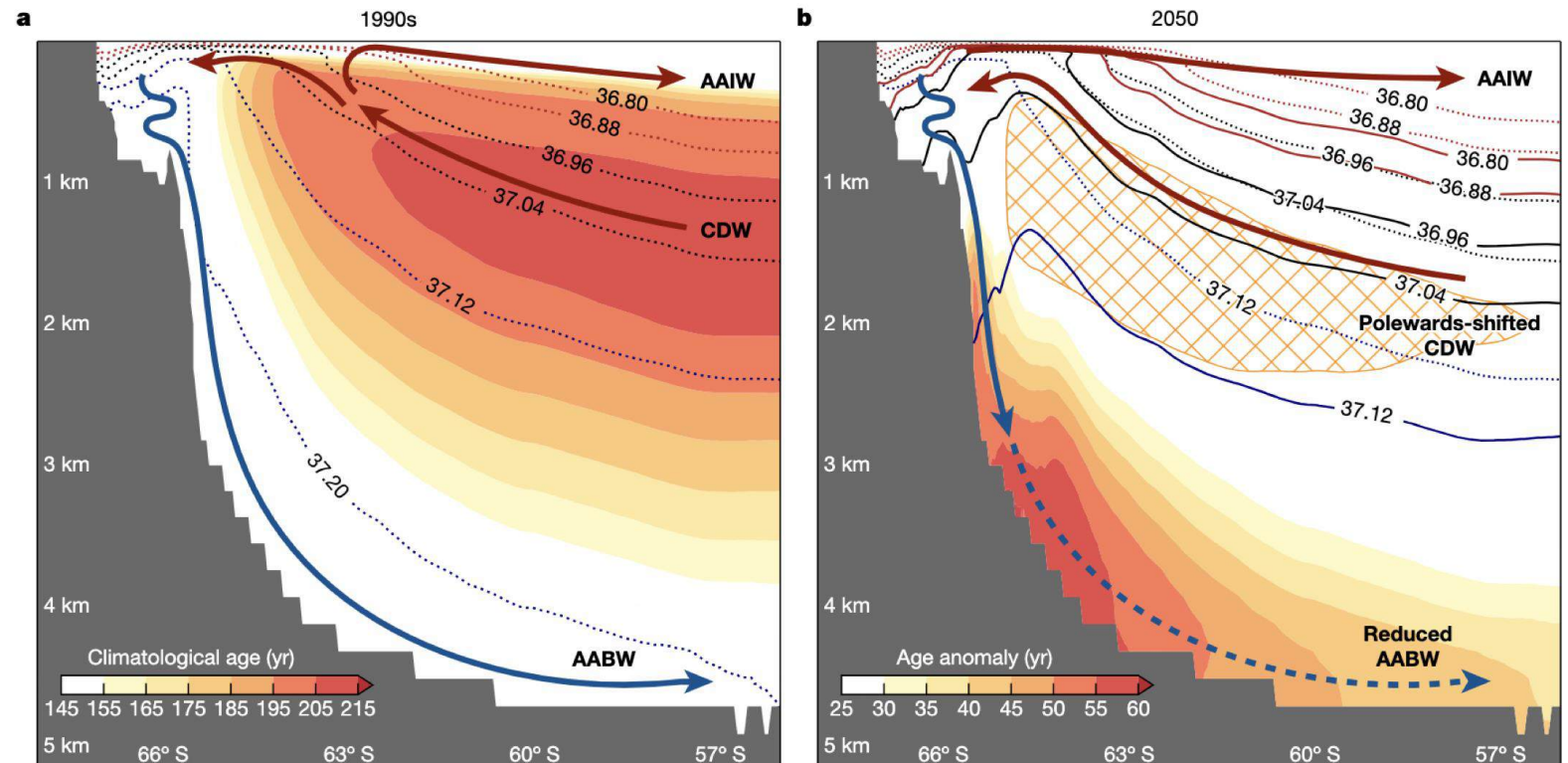
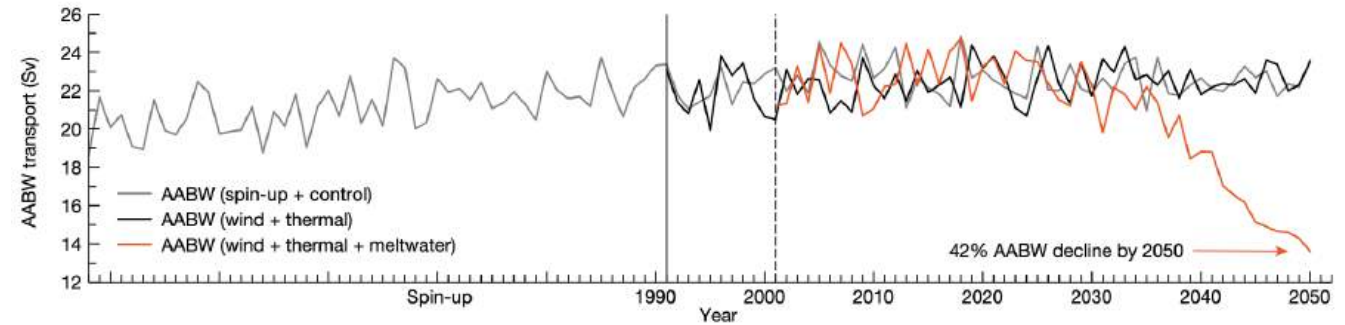
Abyssal ocean overturning slowdown and warming driven by Antarctic meltwater

[Qian Li](#), [Matthew H. England](#) , [Andrew McC. Hogg](#), [Stephen R. Rintoul](#) & [Adele K. Morrison](#)

[Nature](#) 615, 841–847 (2023) | [Cite this article](#)

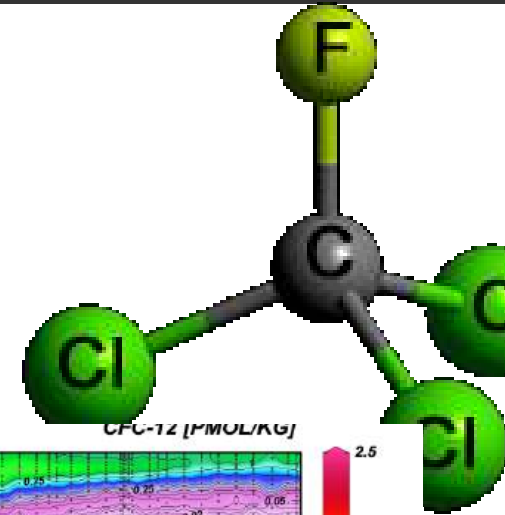
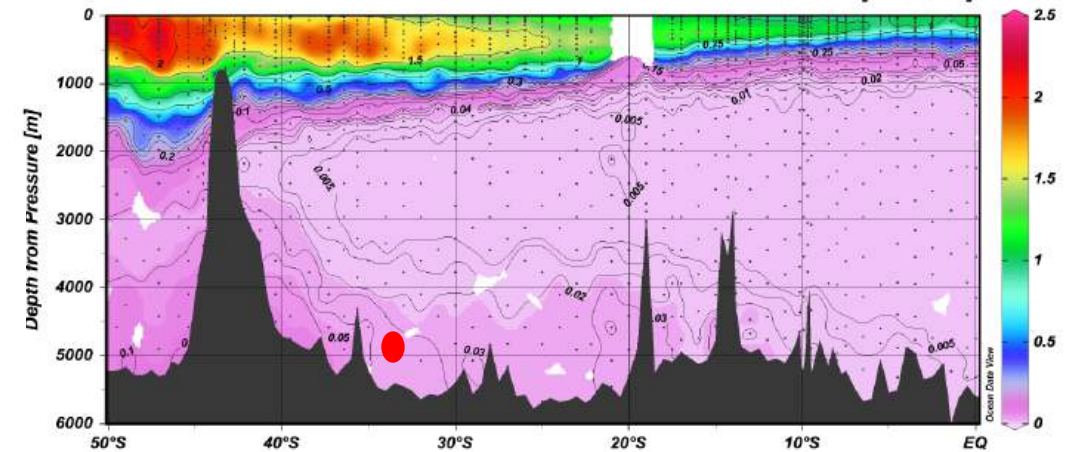
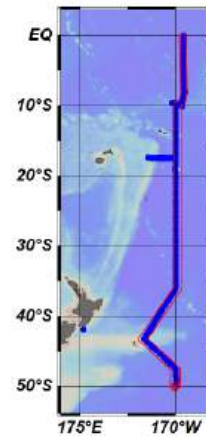
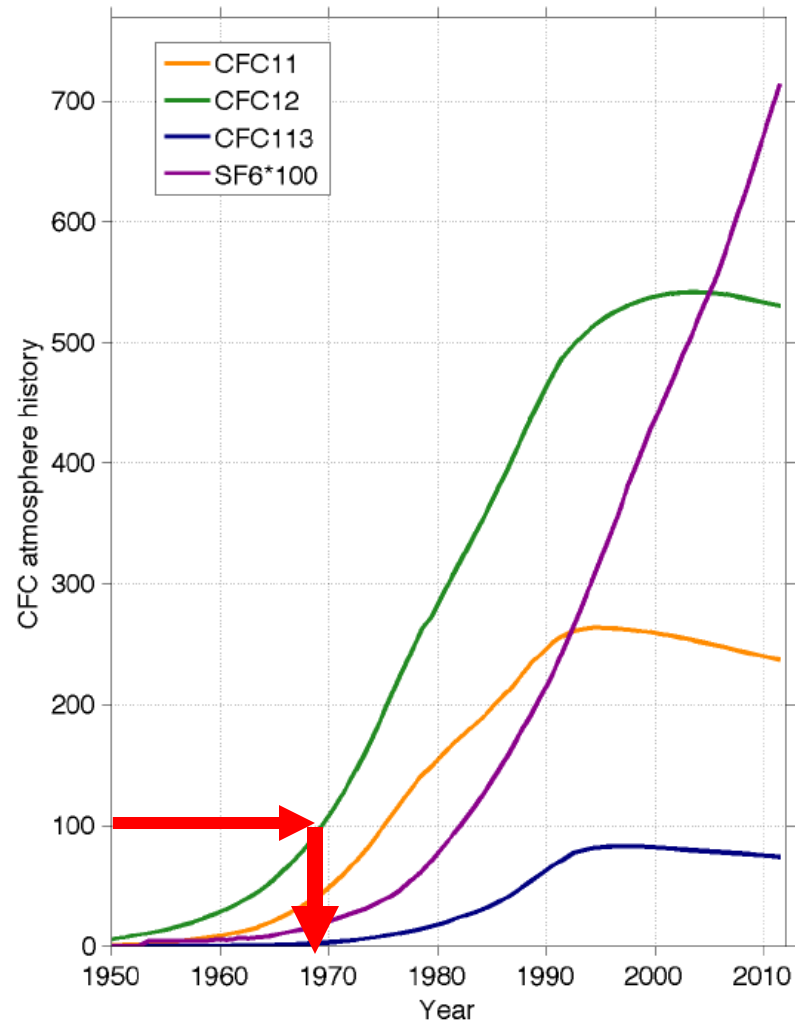
17k Accesses | 9 Citations | 2869 Altmetric | [Metrics](#)

Abstract



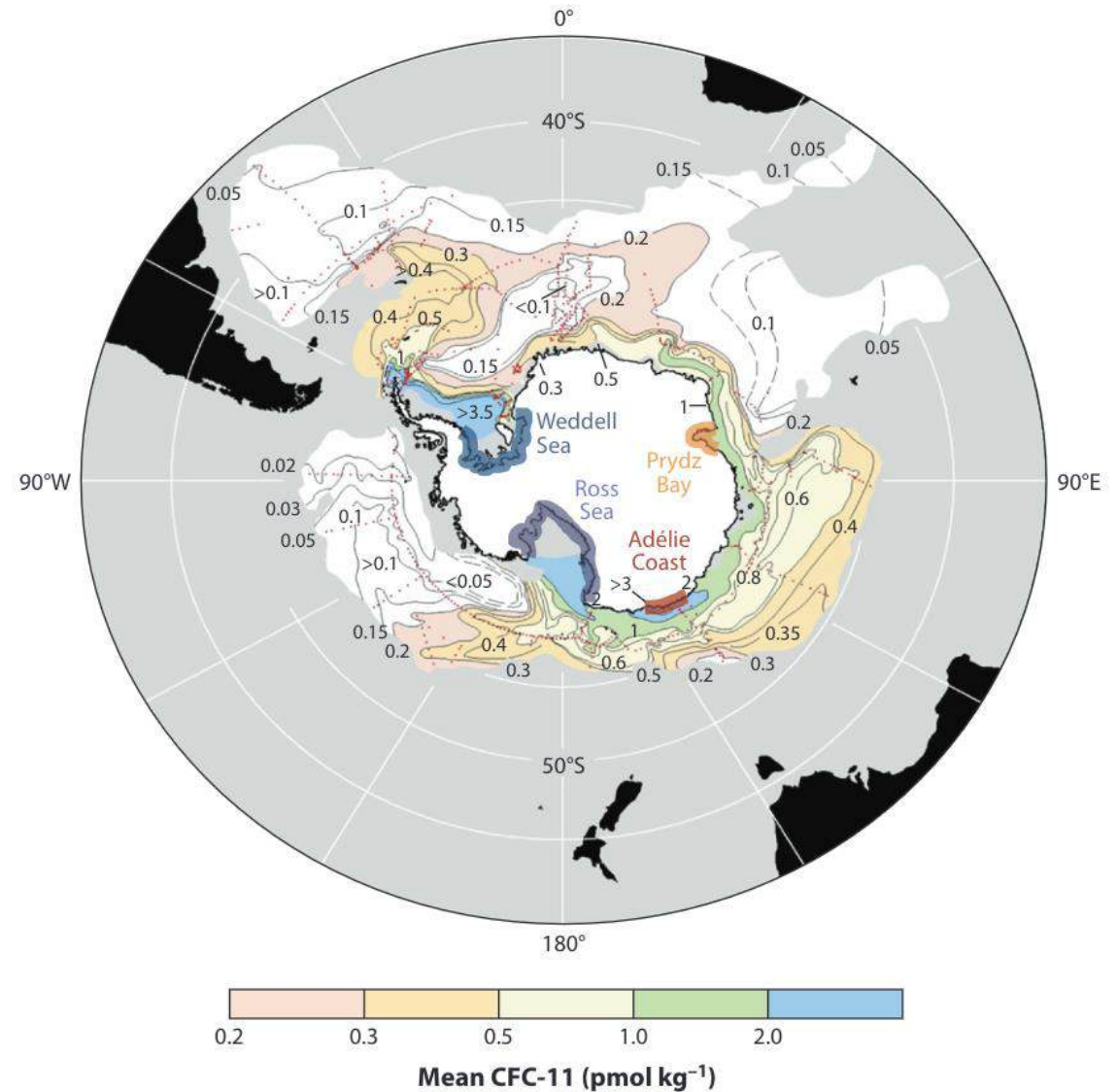
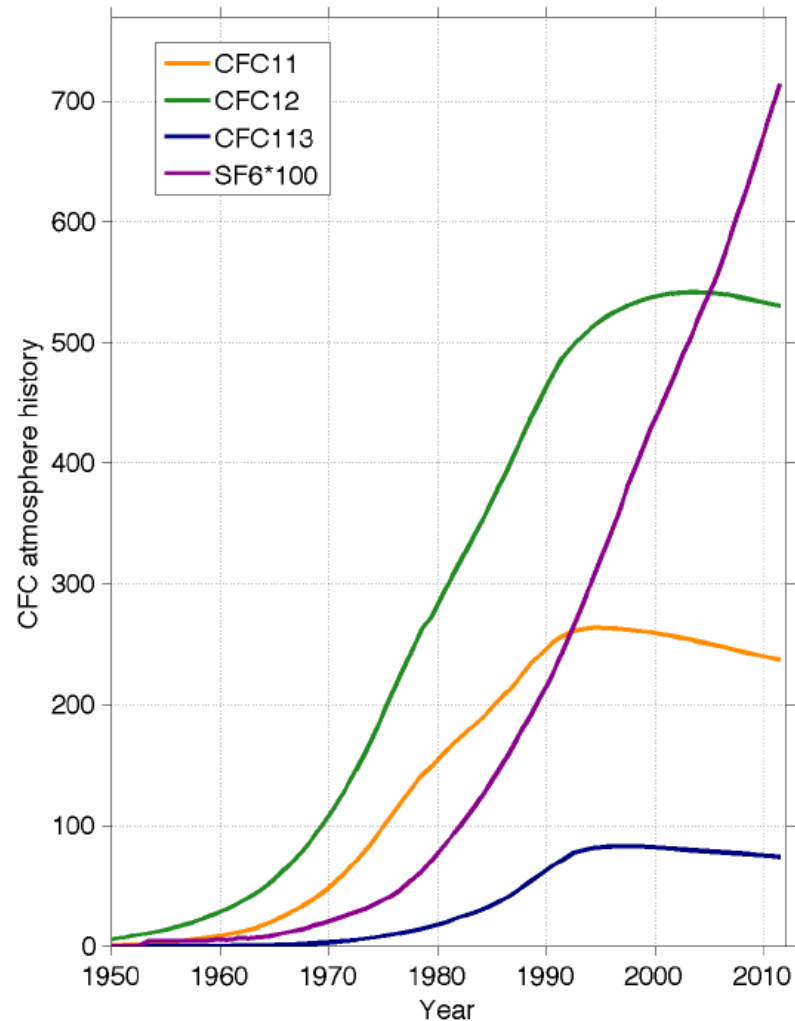
How can we observe this? Chlorofluorocarbons (CFCs)

CFCs' Atmospheric History



Transient tracers: Chlorofluorocarbons (CFCs)

CFCs' Atmospheric History



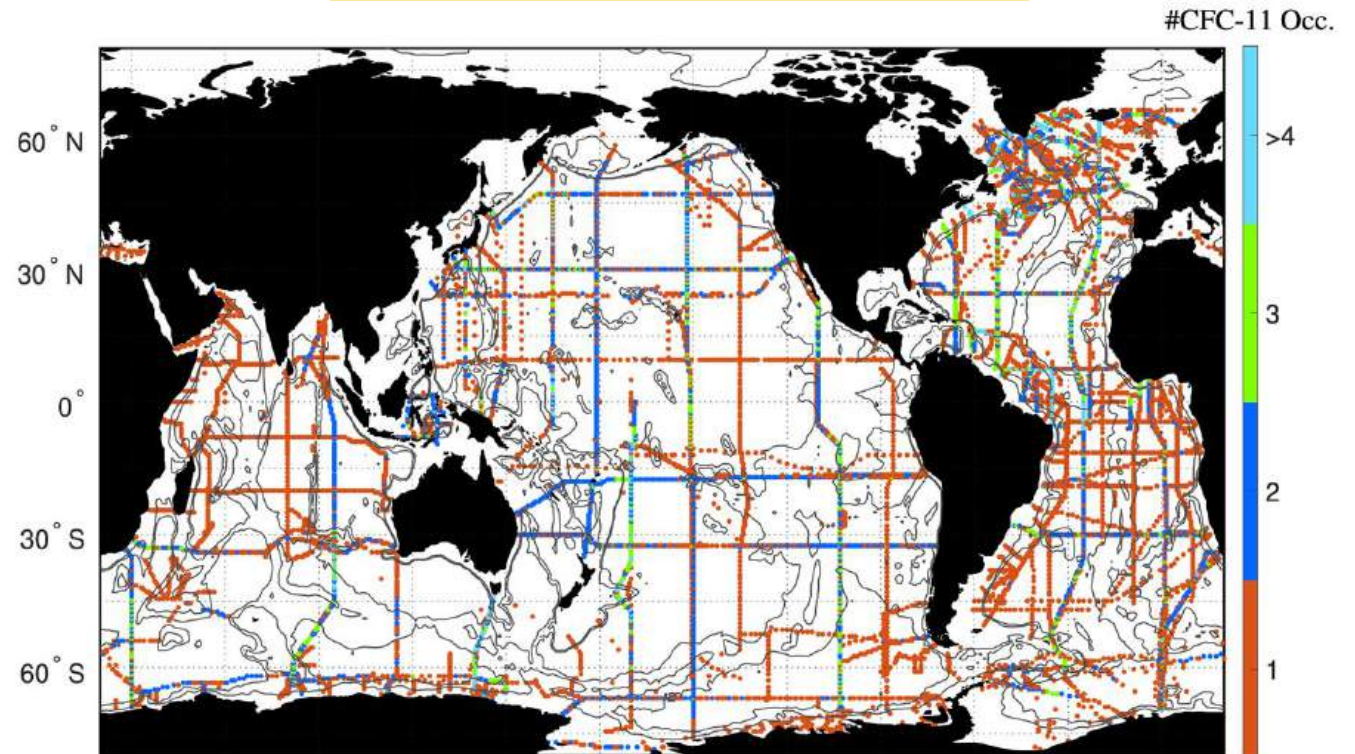
(Orsi et al. 1999)

Transient tracers: Chlorofluorocarbons (CFCs)



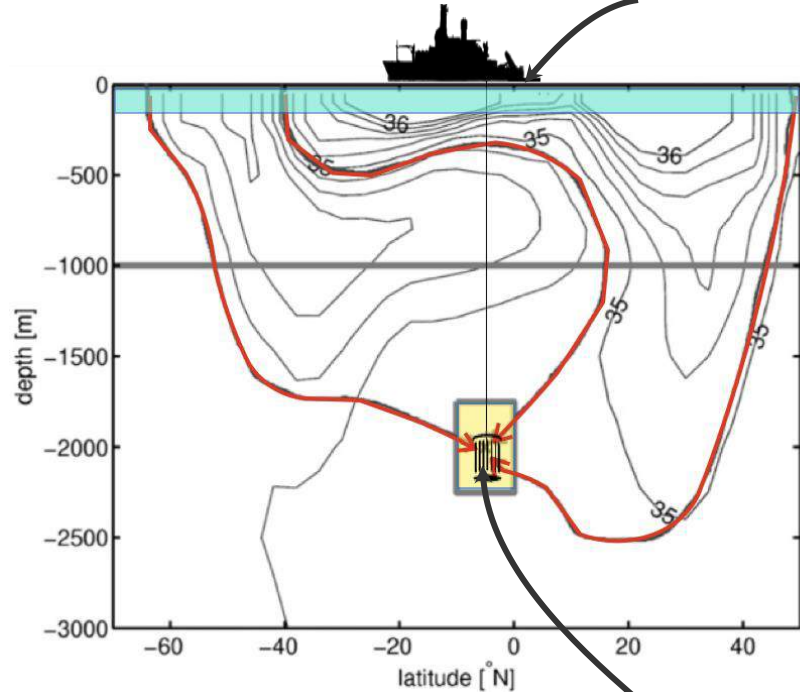
(Cimoli et al. 2023)

CFC 11 In-situ observations in 2023

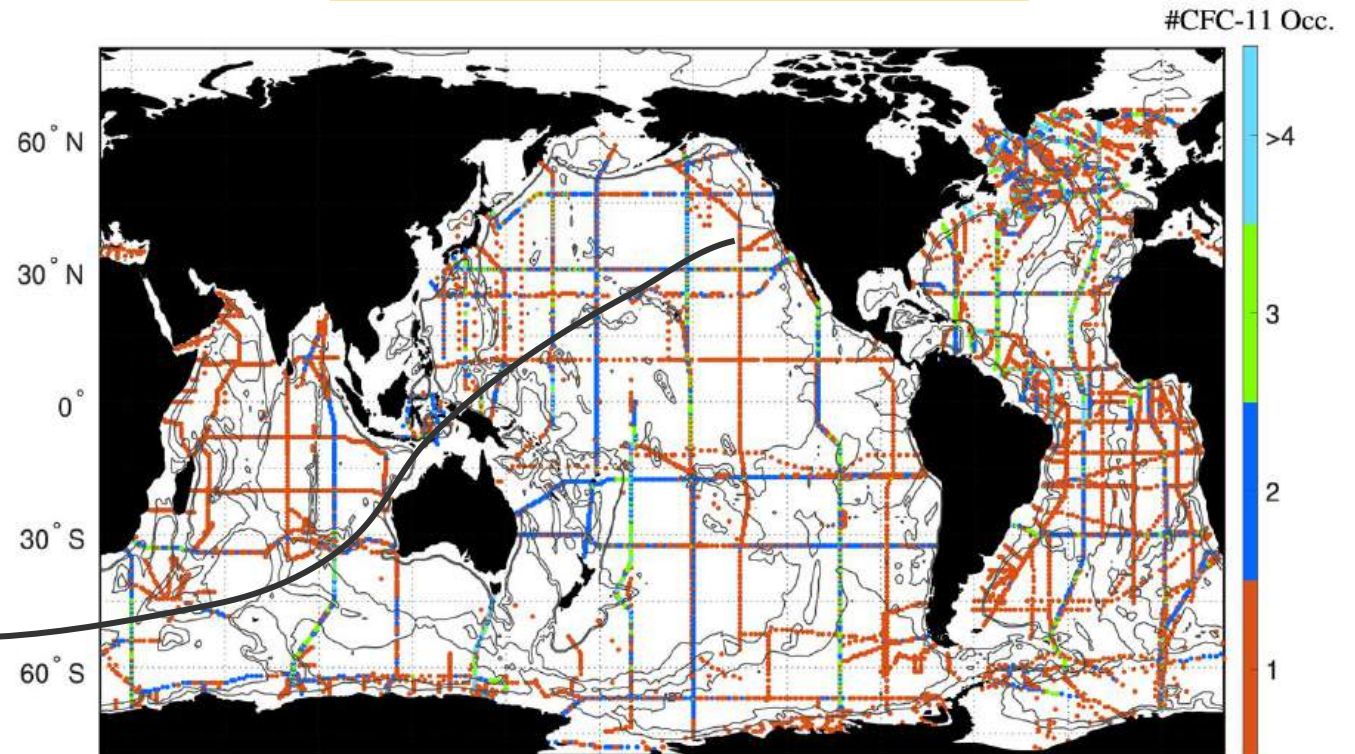


Method: CFC “time corrected” data set

Atmospheric CFCs and Sf6



CFC 11 In-situ observations in 2023

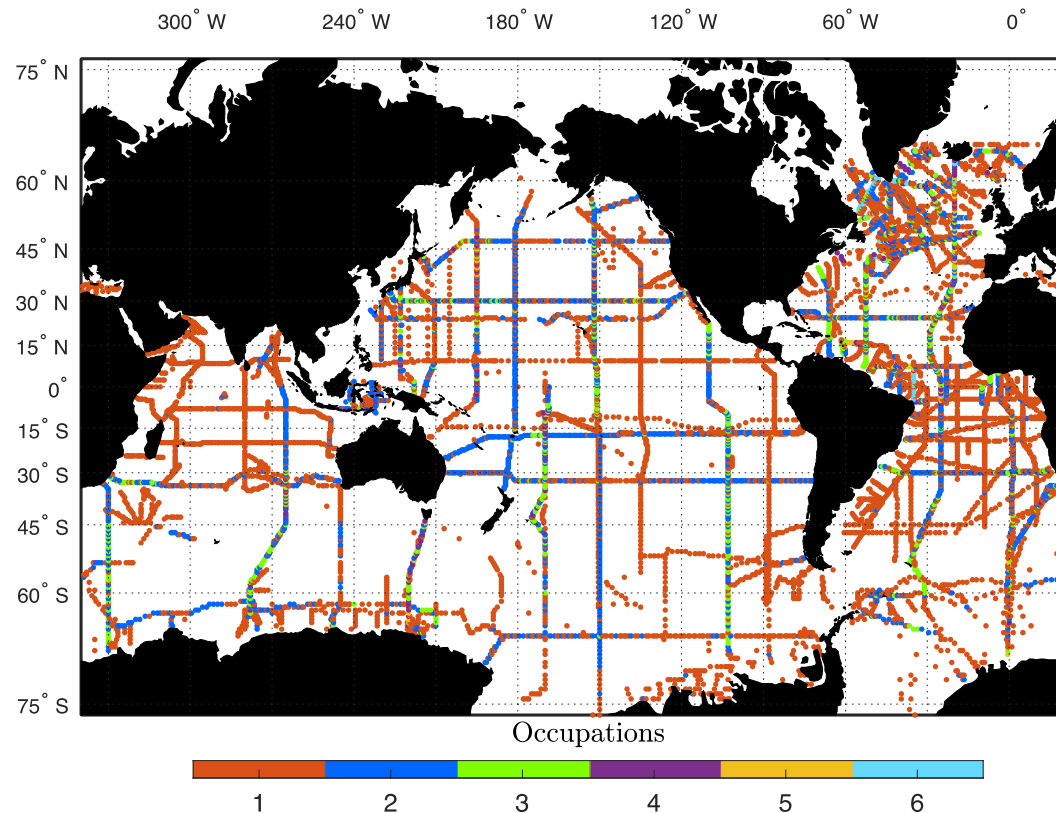


Find the Boundary Propagator (G)
that best fits the available data (C)

$$C(\mathbf{r}, t) = \int_0^\infty C_{s,\gamma}(t - \tau) G(\mathbf{r}, \tau) d\tau$$

Method: CFC “time corrected” data set

Data: $\frac{1}{2}$ deg x $\frac{1}{2}$ deg on 0.01 ν_n vertical grid



$$J = \|\mathbf{C} - C_s \mathcal{G}\|_2^2 + \|\mathcal{G} - \mathcal{G}_0\|_2^2 =$$
$$= \underbrace{(\mathbf{C} - C_s \mathcal{G})^T \mathbf{W}^{-1} (\mathbf{C} - C_s \mathcal{G})}_{\text{Discrepancy with observations } \mathbf{C}} + \underbrace{(\mathcal{G} - \mathcal{G}_0)^T \mathbf{S}^{-1} (\mathcal{G} - \mathcal{G}_0)}_{\text{Discrepancy with first guess } \mathcal{G}_0}.$$

Discrepancy with observations $\mathbf{C}$ Discrepancy with first guess $\mathcal{G}_0$

C_s = surface boundary conditions

$\mathcal{G}$ = greens function

$\mathcal{G}_0$ = first guest

$\mathbf{C}$ = tracer concentration

Solving for $\mathcal{G}$ that minimizing the cost function J

Method: CFC “time corrected” data set

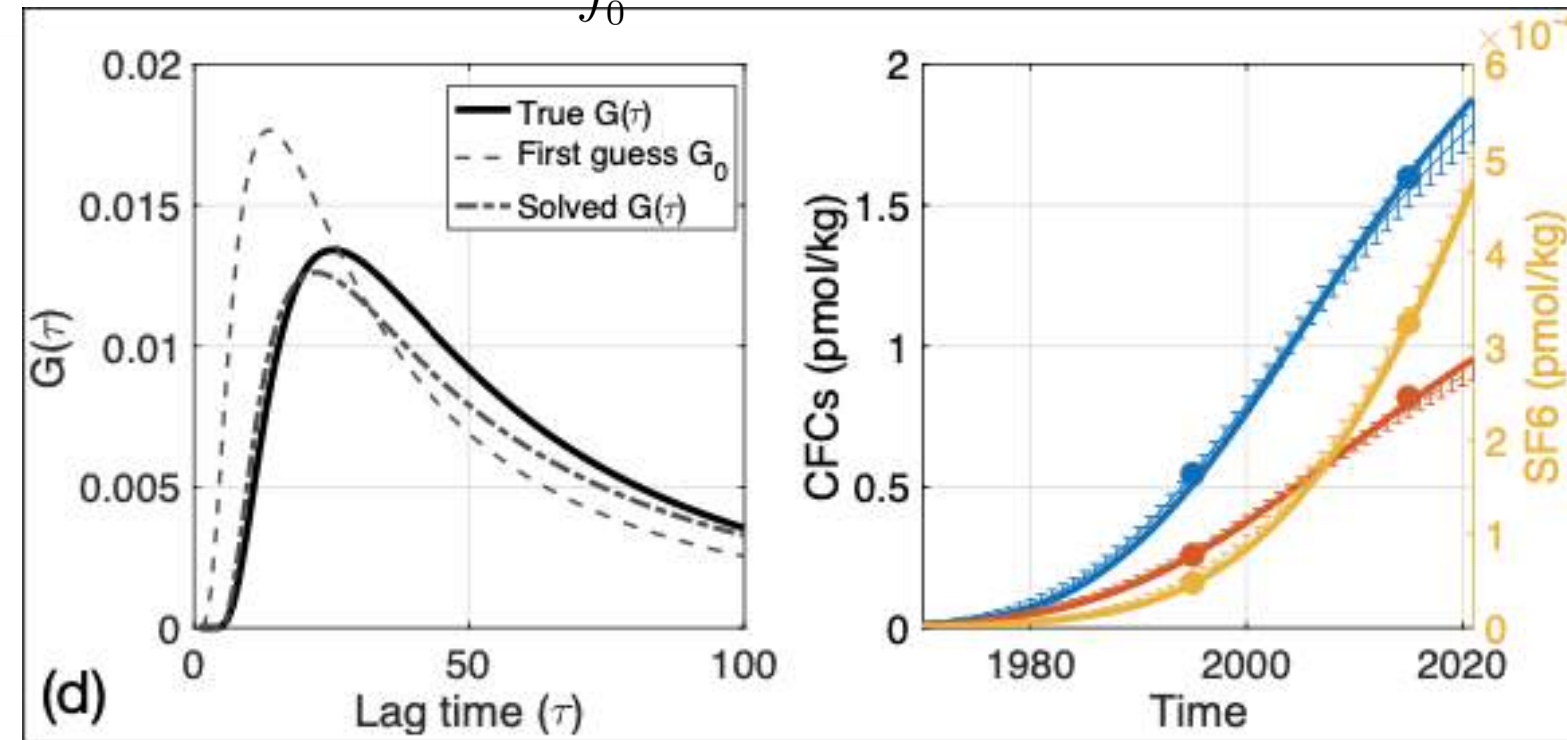
TIME CORRECTION METHOD: Example with synthetic data

- Assume we know the Green’s function (true $G(\tau)$ —)
 - predict the data concentration in the ocean interior (—, —, —)
 - subsample the synthetic tracer data generated (●, ●)
 - solved $G(\tau)$ (---)
 - predicted tracer concentration (—+—)

$$J = \underbrace{\|\mathbf{C} - C_s \mathcal{G}\|_2^2}_{\text{Discrepancy with observations } \mathbf{C}} + \underbrace{\|\mathcal{G} - \mathcal{G}_0\|_2^2}_{\text{Discrepancy with first guess } \mathcal{G}_0} = (\mathbf{C} - C_s \mathcal{G})^T \mathbf{W}^{-1} (\mathbf{C} - C_s \mathcal{G}) + (\mathcal{G} - \mathcal{G}_0)^T \mathbf{S}^{-1} (\mathcal{G} - \mathcal{G}_0).$$

Discrepancy with observations $\mathbf{C}$ Discrepancy with first guess $\mathcal{G}_0$

$$C(\mathbf{r}, t) = \int_0^\infty C_{s,\gamma}(t - \tau) G(\mathbf{r}, \tau) d\tau$$



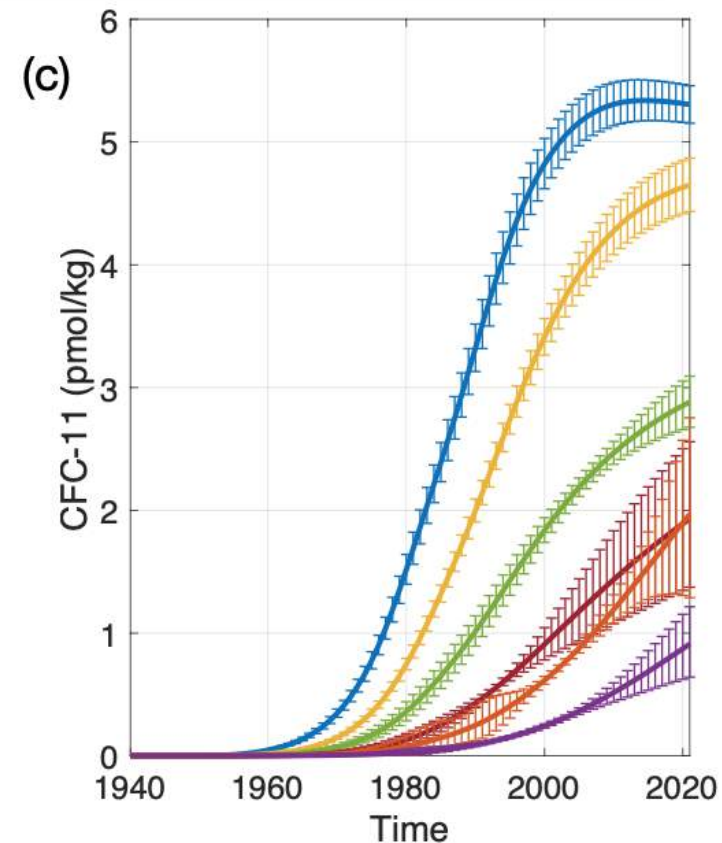
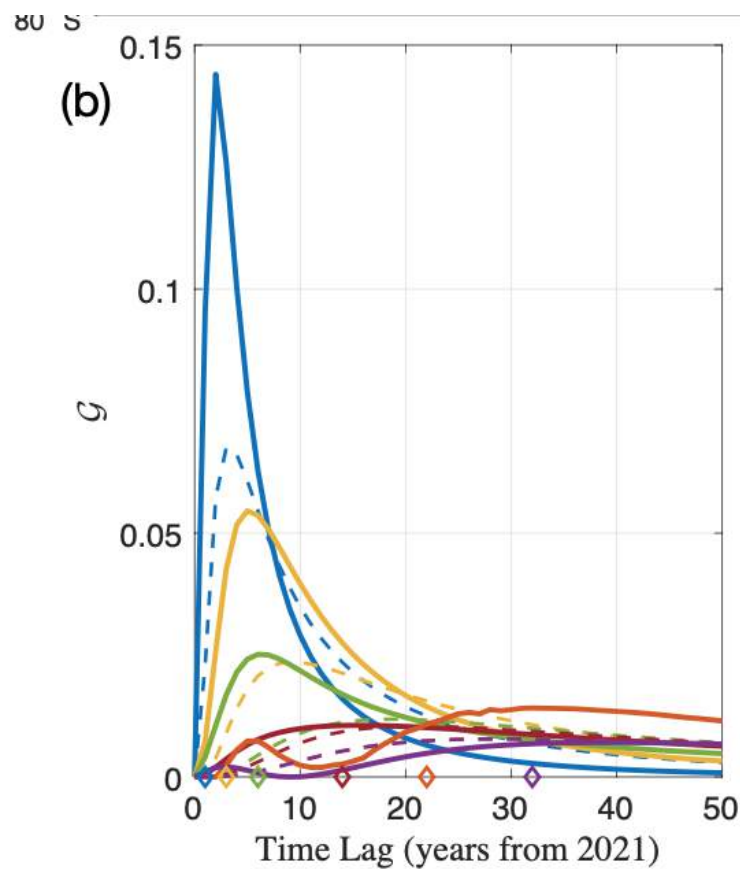
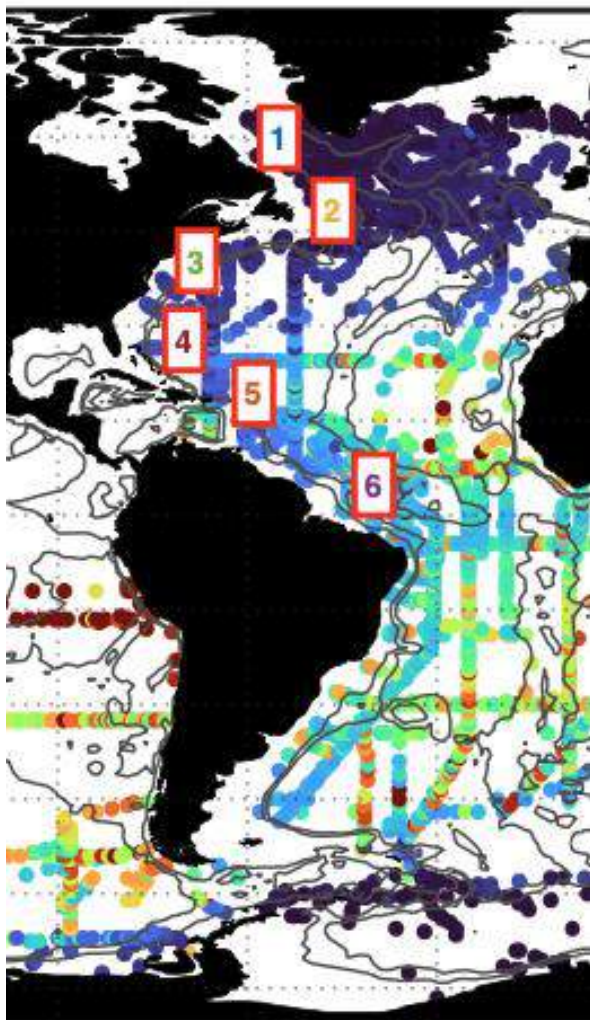
OUTCOMES^[L]_{SEP} (Global, full water column):

- TTD (Green’s functions) at each location in the ocean interior (where tracer data is available)
- Annually-resolved CFCs and SF6 concentration^[L]_{SEP}

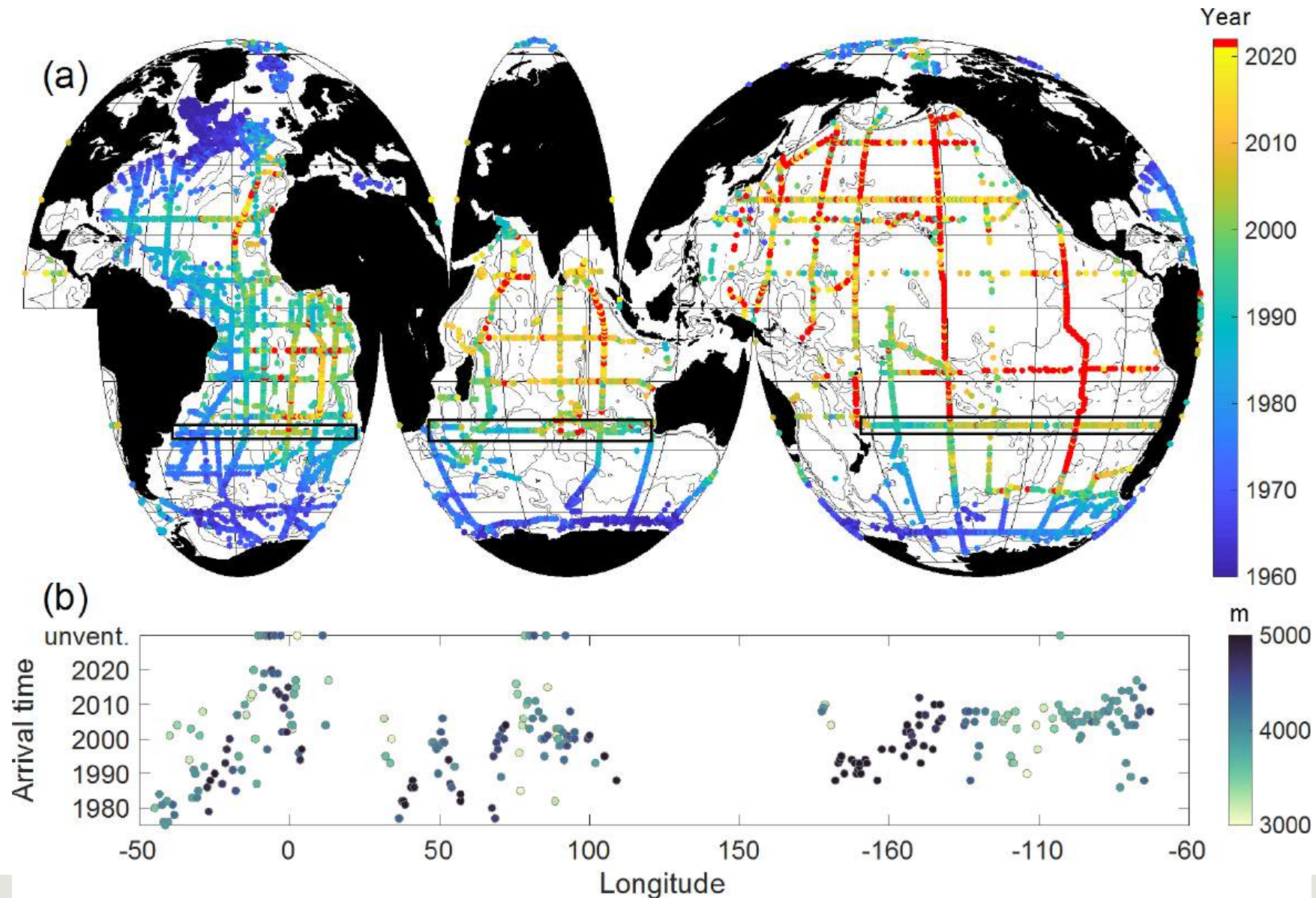
Used to investigate:

- Ventilation rates
- Pathways of water masses from the ocean surface to the ocean interior
- Decadal variability of ocean transport

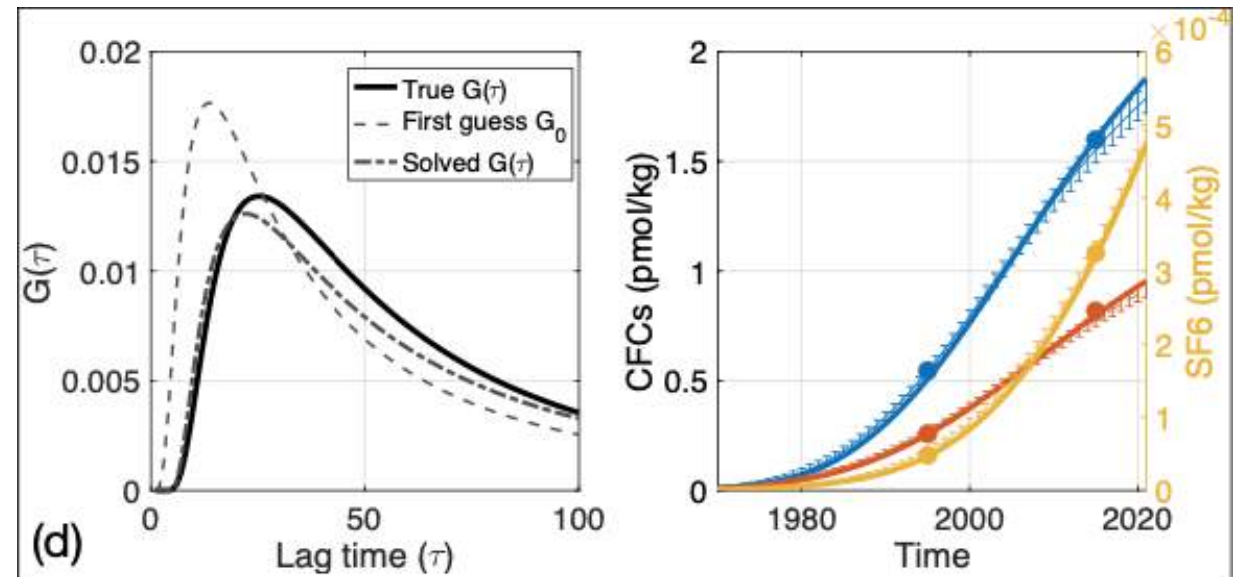
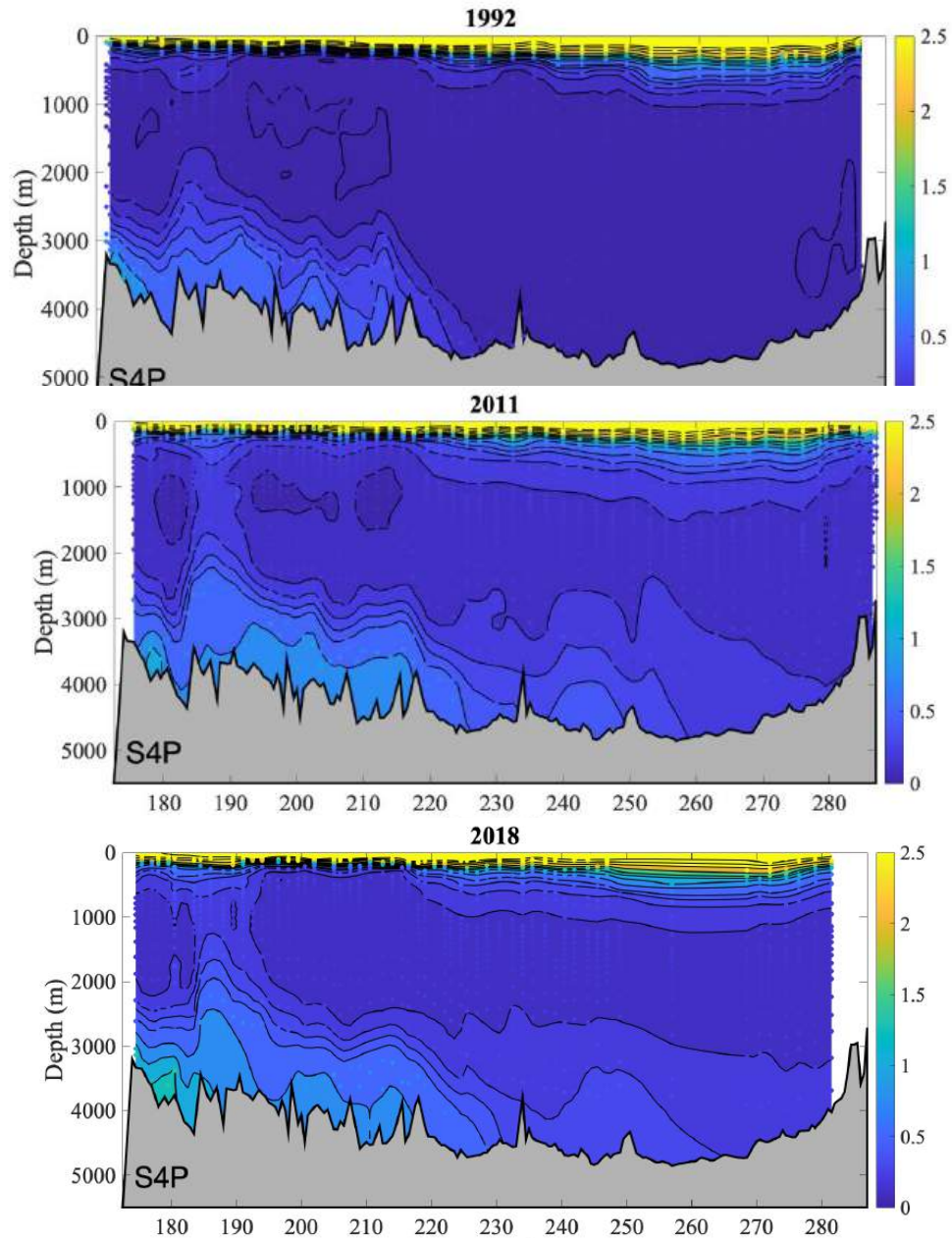
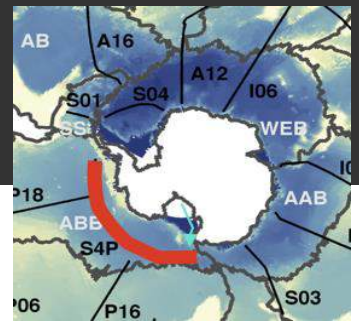
Example of Green's function and CFC History



CFC Arrival time

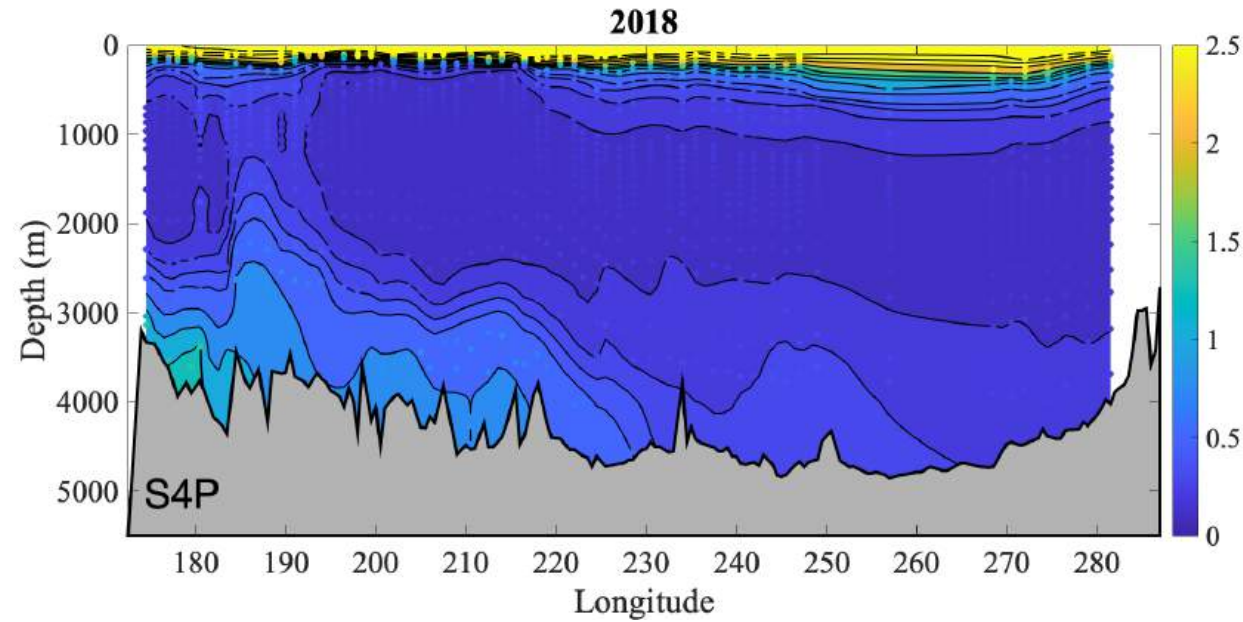


Ocean ventilation decadal variability

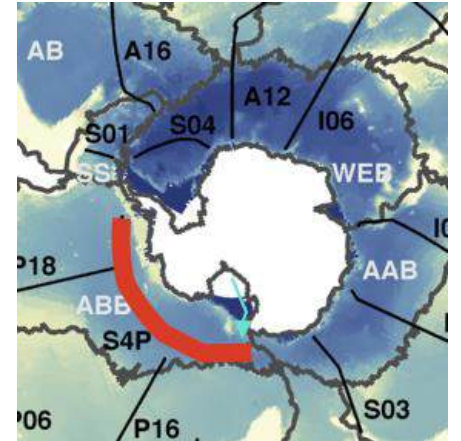
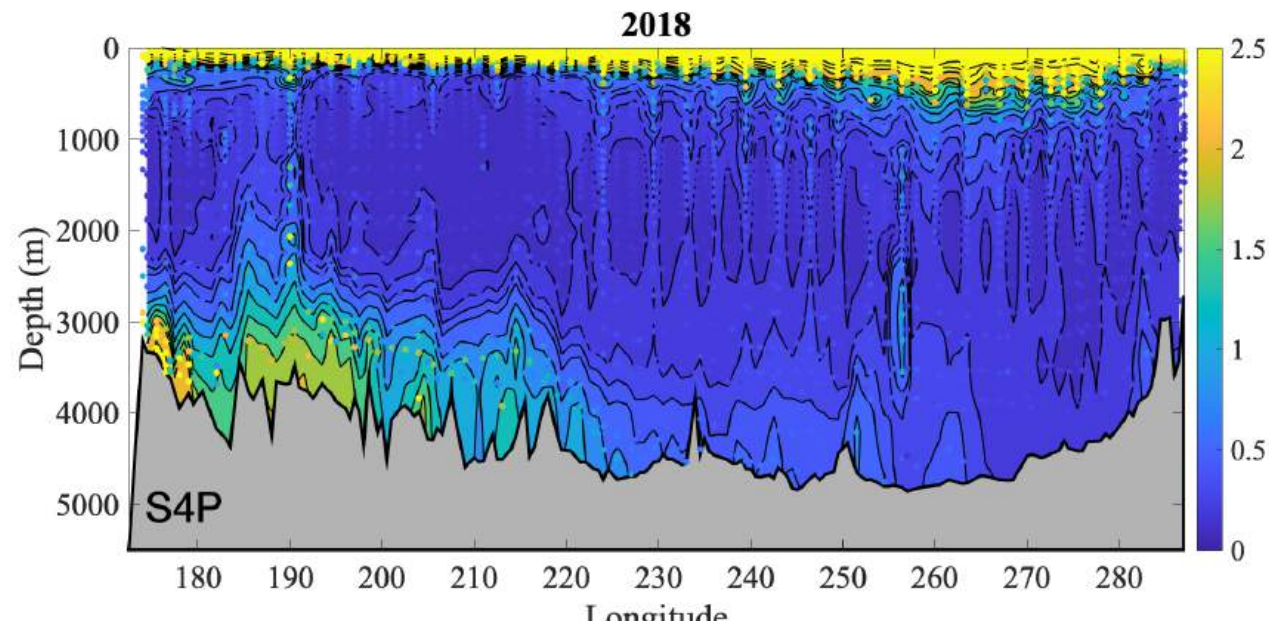


Ocean ventilation decadal variability

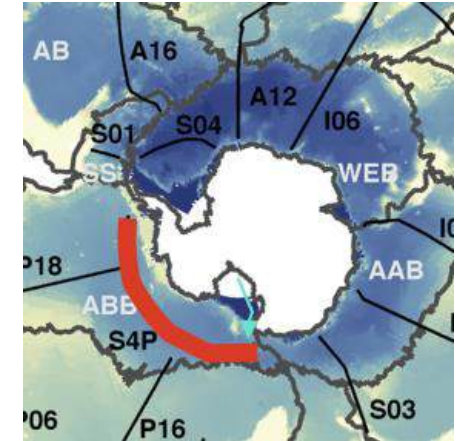
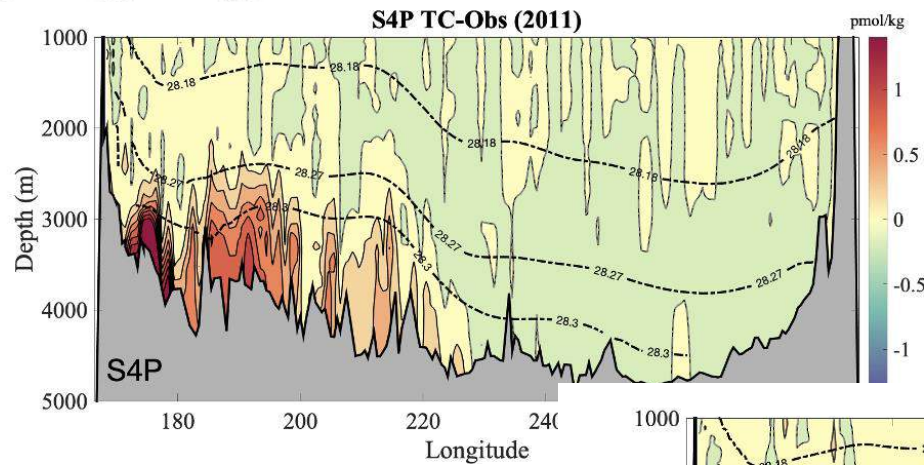
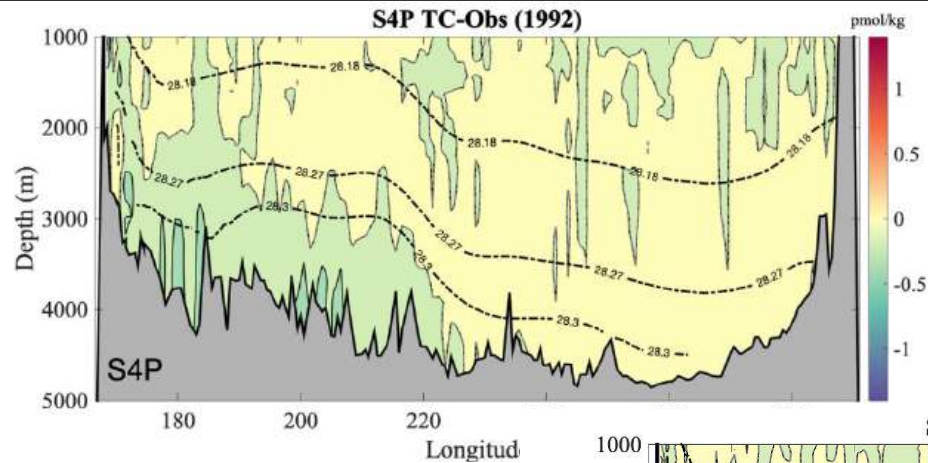
Observations



Predicted

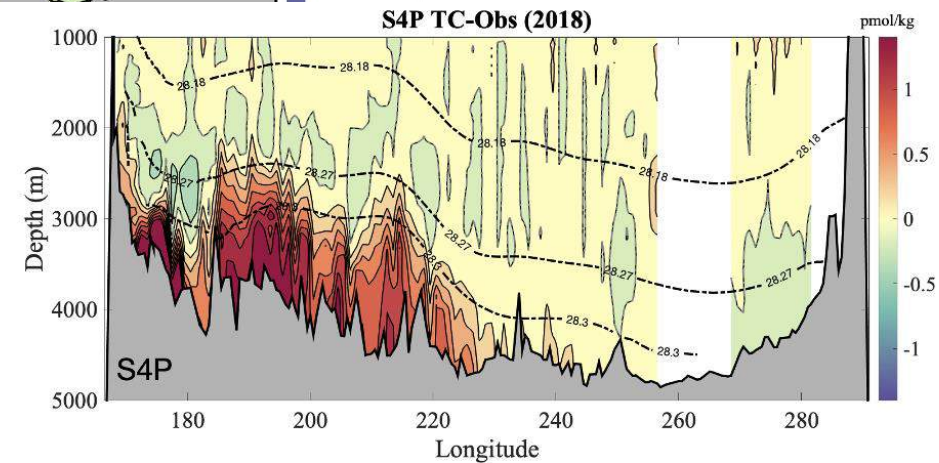


Ocean ventilation decadal variability



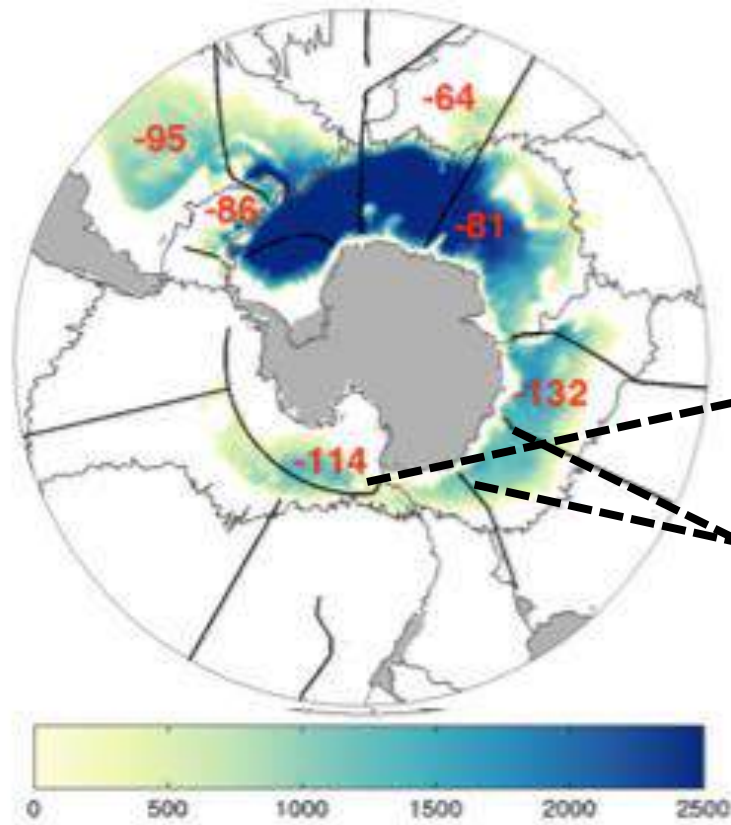
Anomalies:
(Reconstructed - Observed) tracer concentrations

+ (red): reconstructed time-mean circulation
slower than observed one

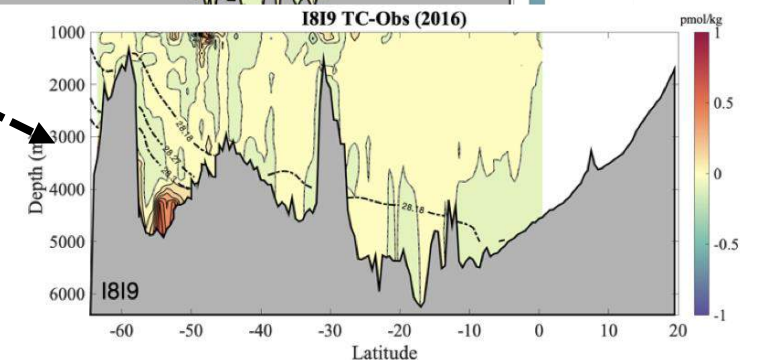
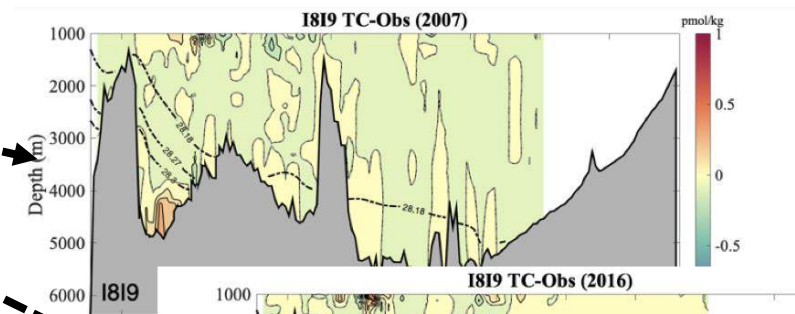
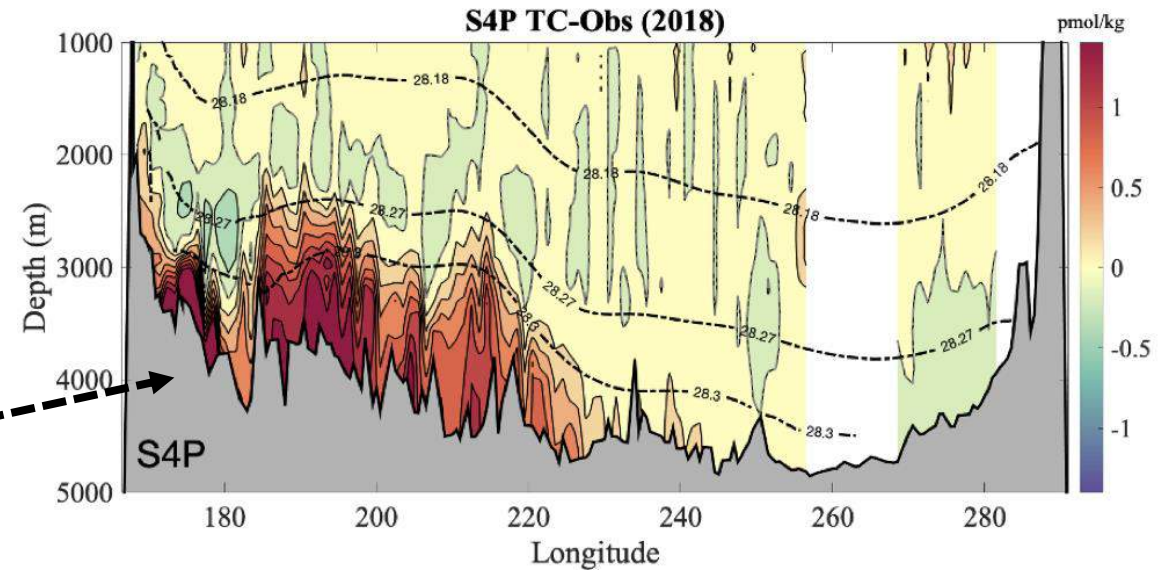


A slow down in the MOC?

Changes in expected CFC

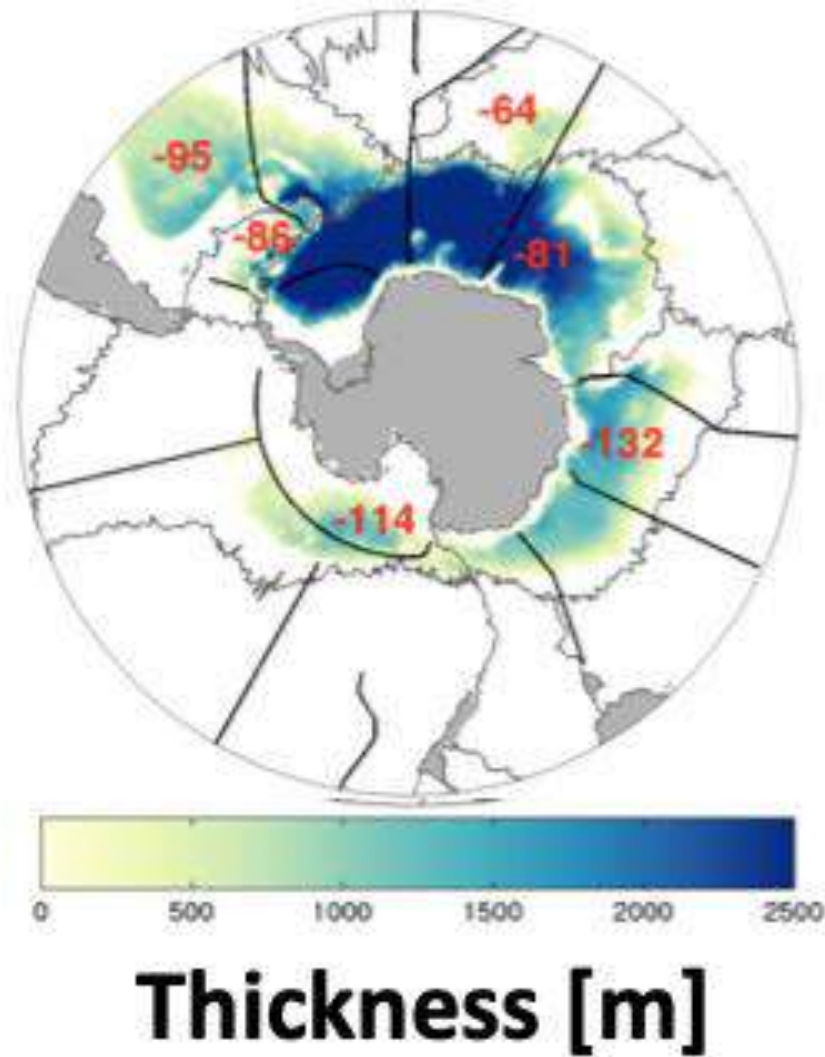


Thickness [m]

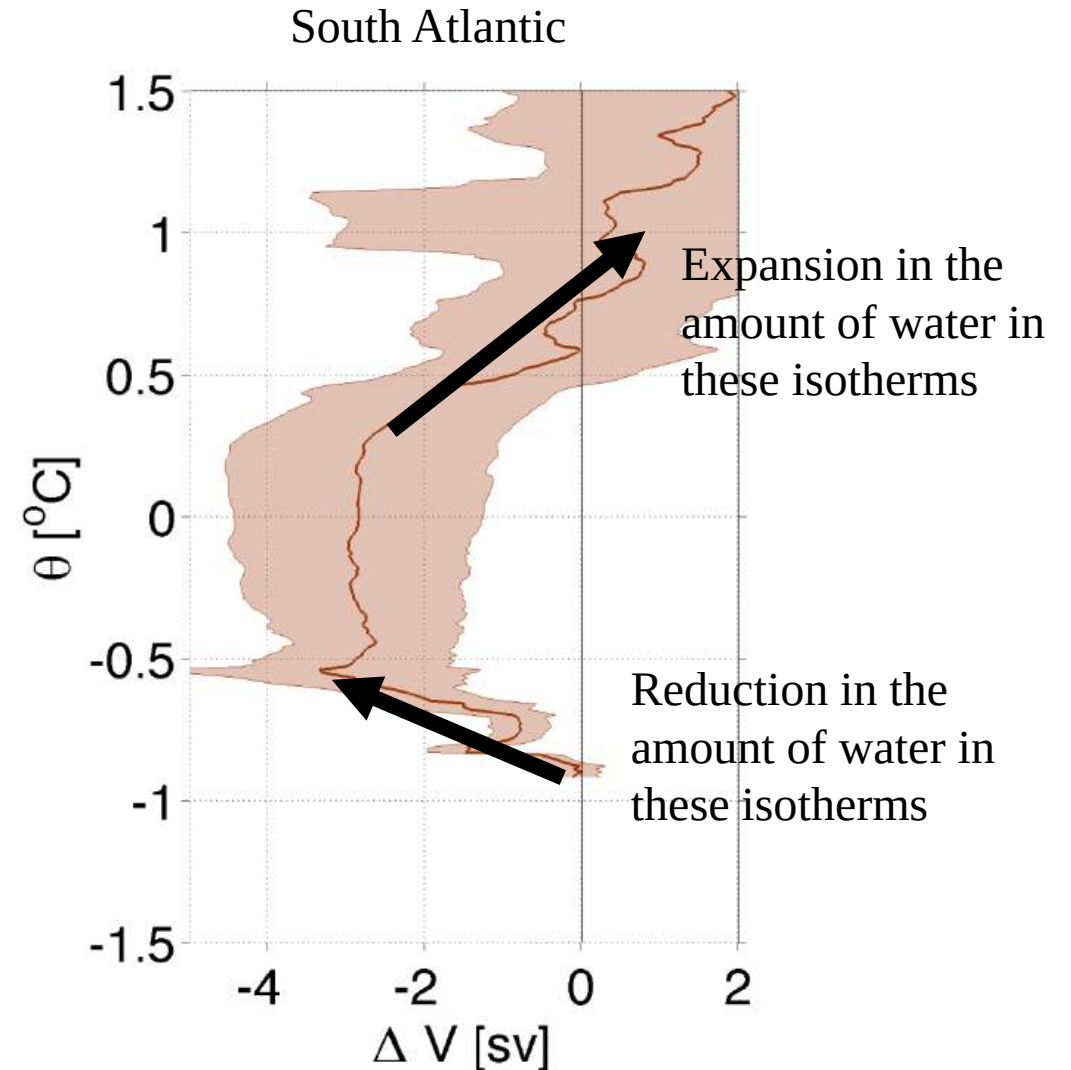


(Cimoli et al, in prep)

Reduction in AABW compensated by an expansion of CDW?

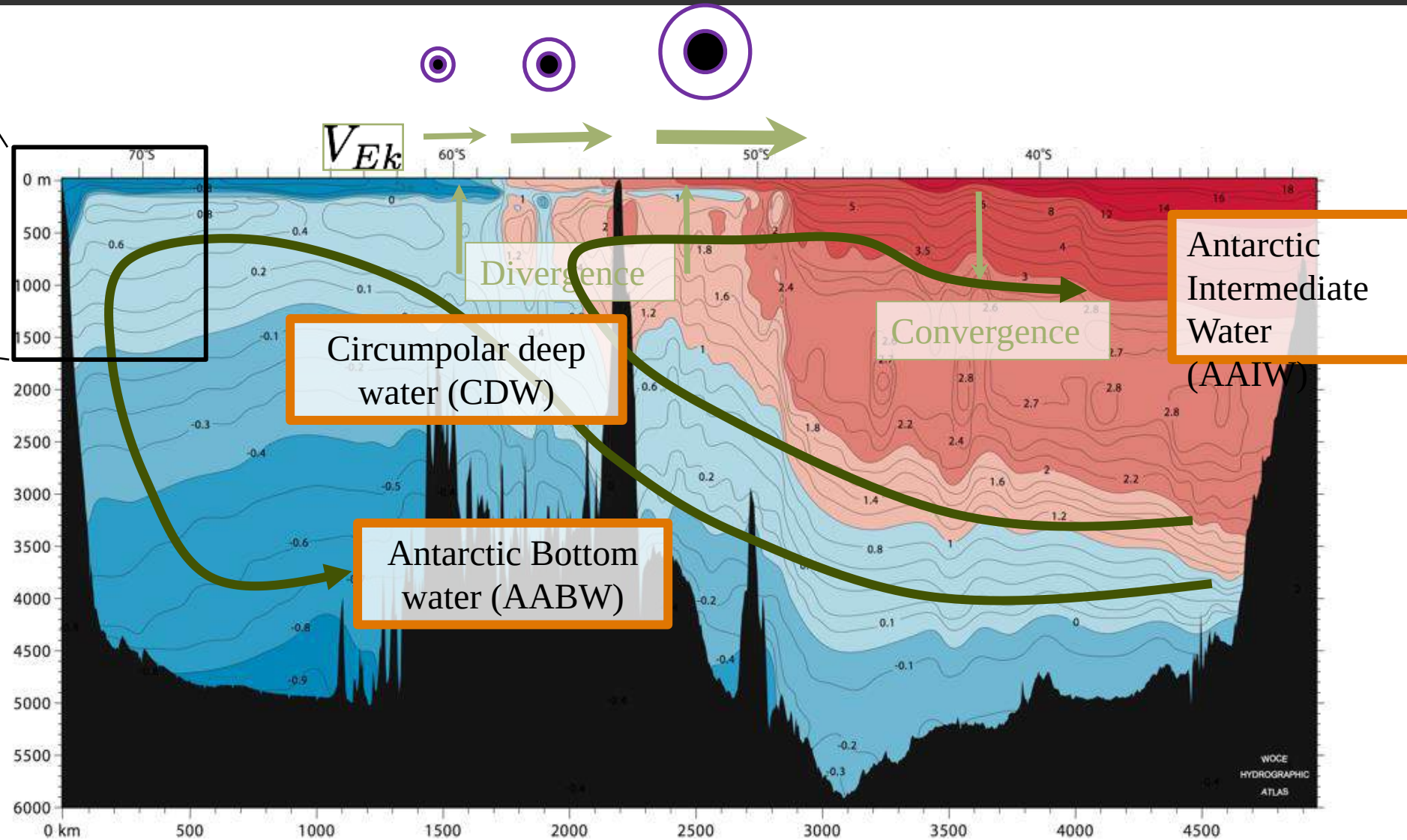
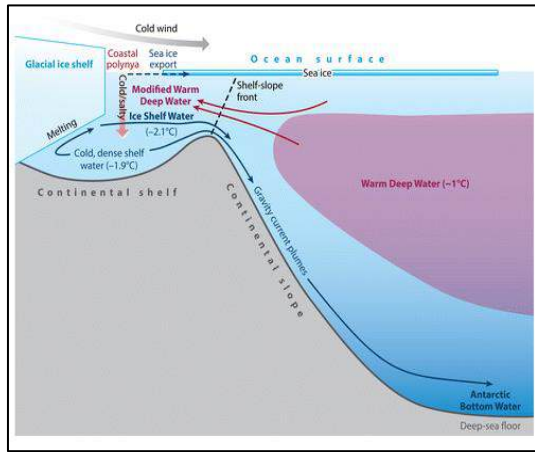


Red = change in thickness of AABW (m)



(Purkey and Johnson, 2012)

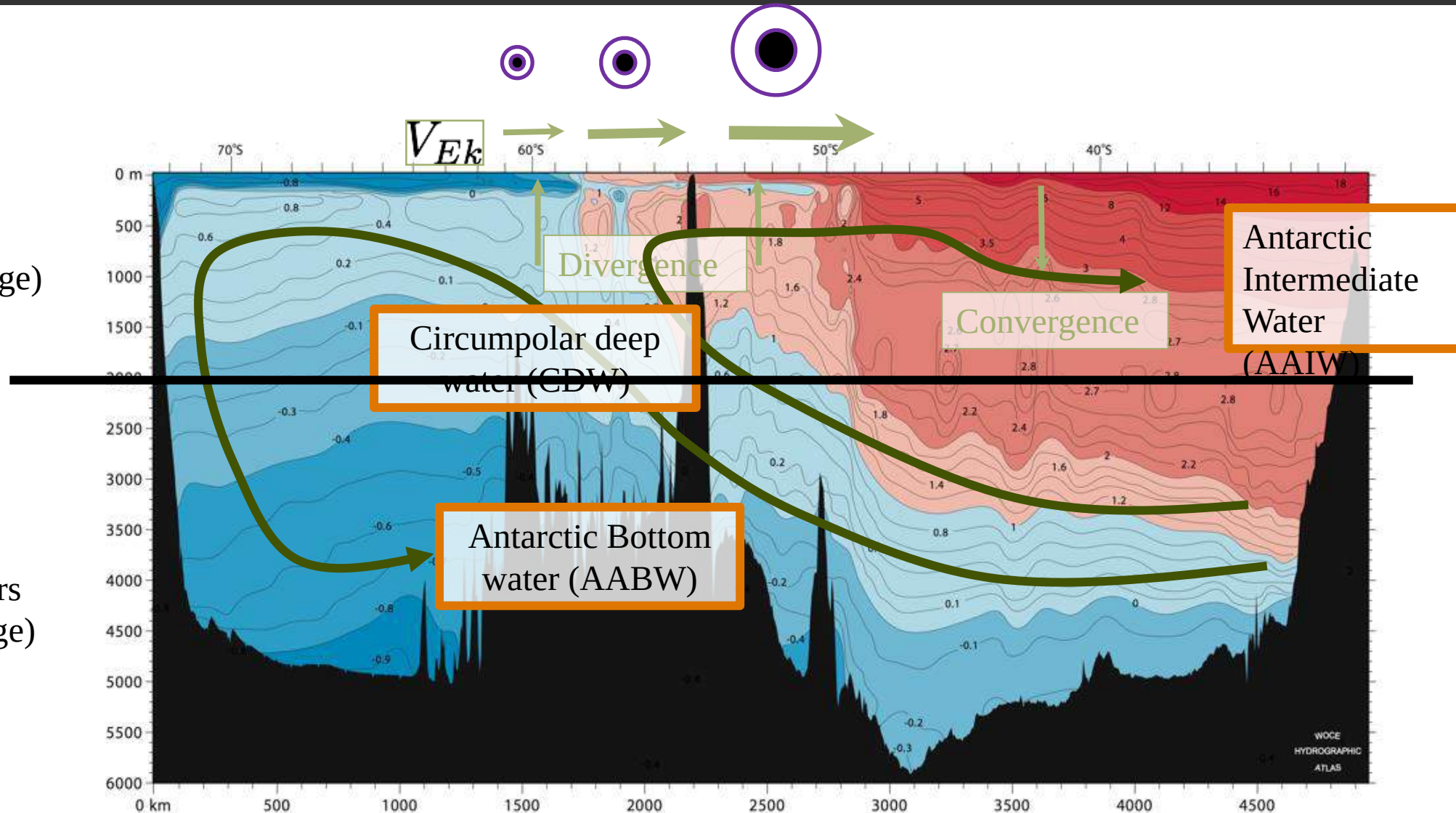
Southern Ocean Watermasses



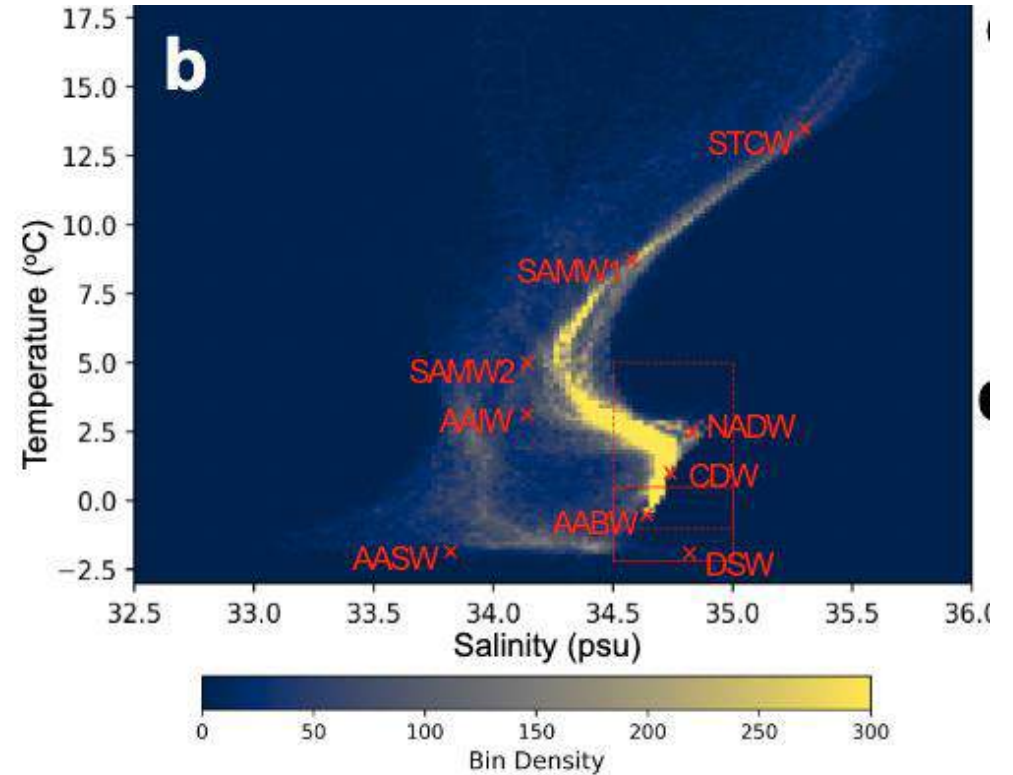
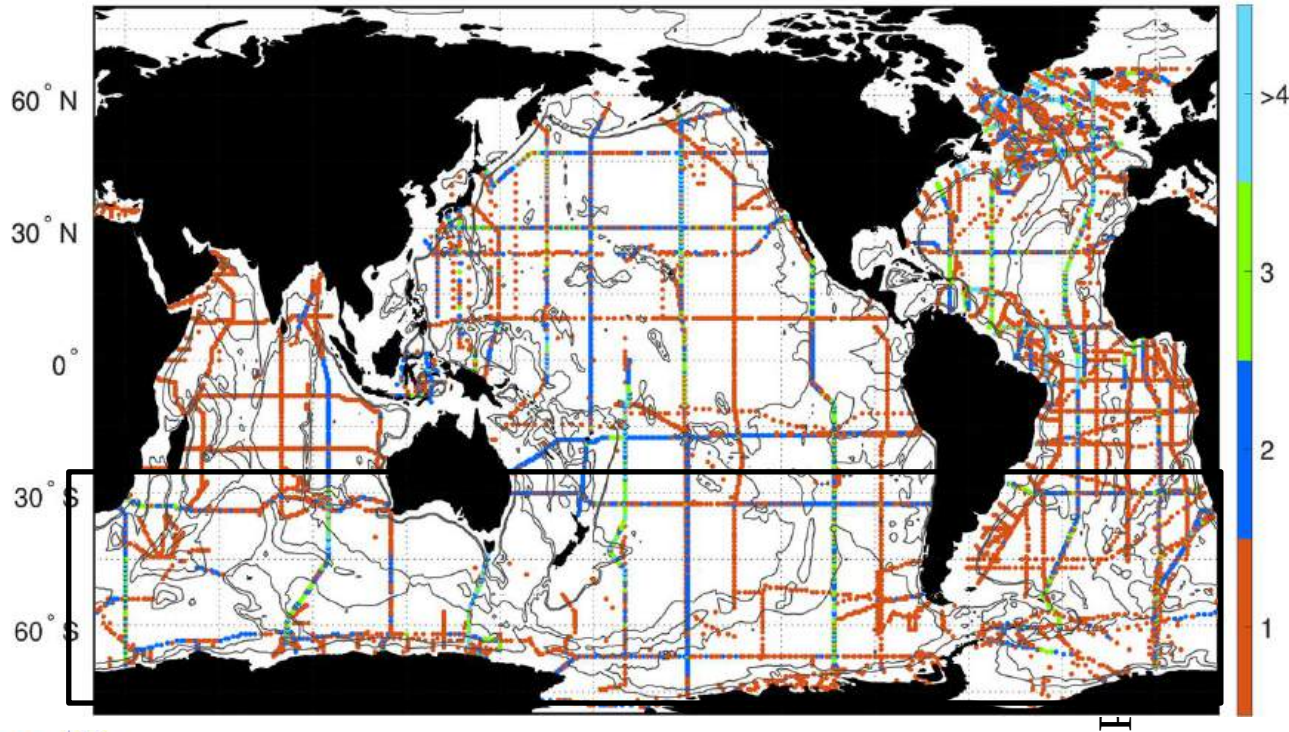
Southern Ocean Watermasses

Argo
(Good Spatial
and temporal coverage)

GO-SHIP
(Multiple parameters
but Decadal coverage)



Southern Ocean Watermasses

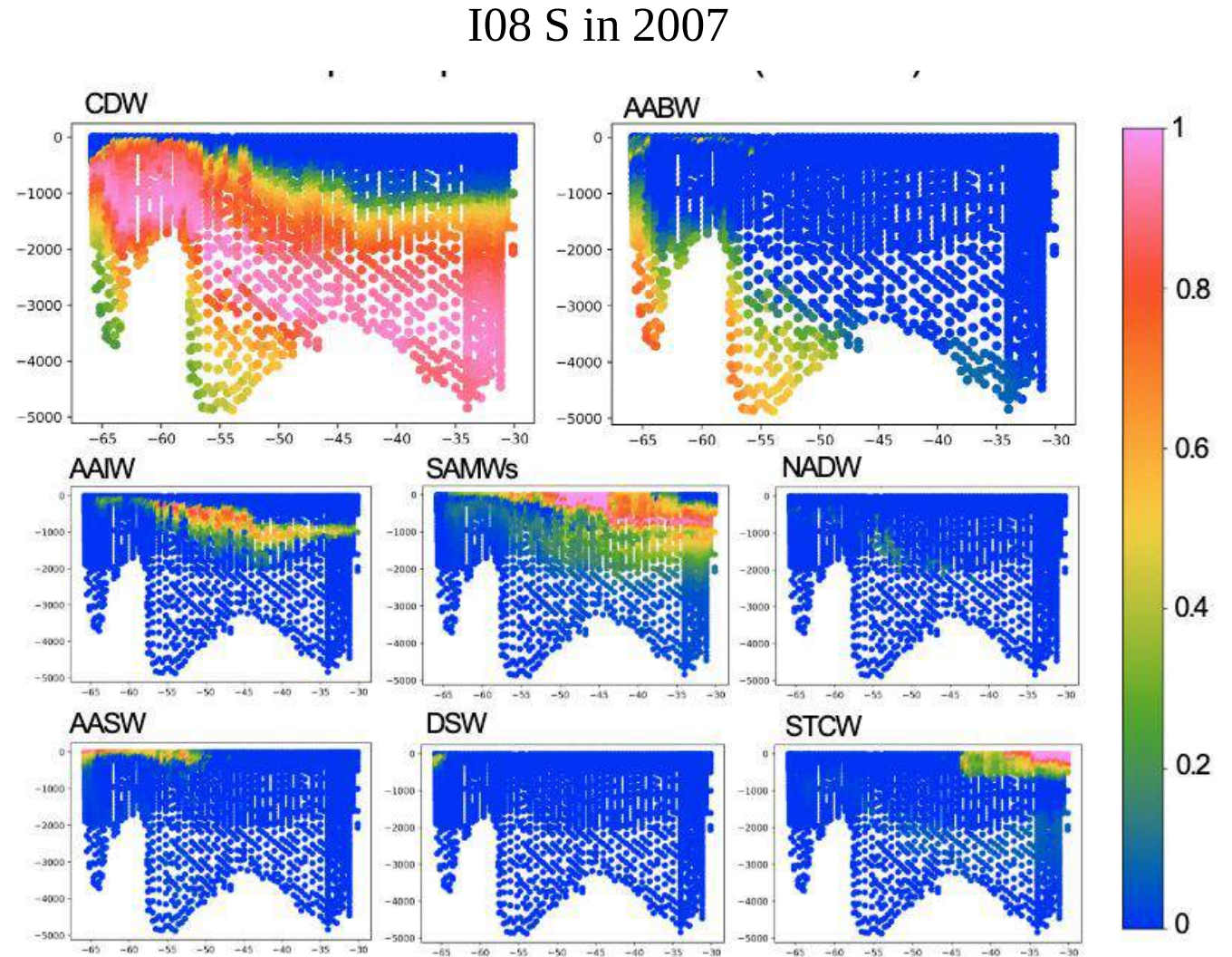


- GLODAP gridded and ship-based profile data in the Southern Ocean of include T, S, dissolved Oxygen, Nitrate, Phosphate, Alkalinity
- Calculate conservative tracers (NO, PO, Salinity, θ)
- Define 9 Southern ocean water masses

(Lanham et al, in prep)

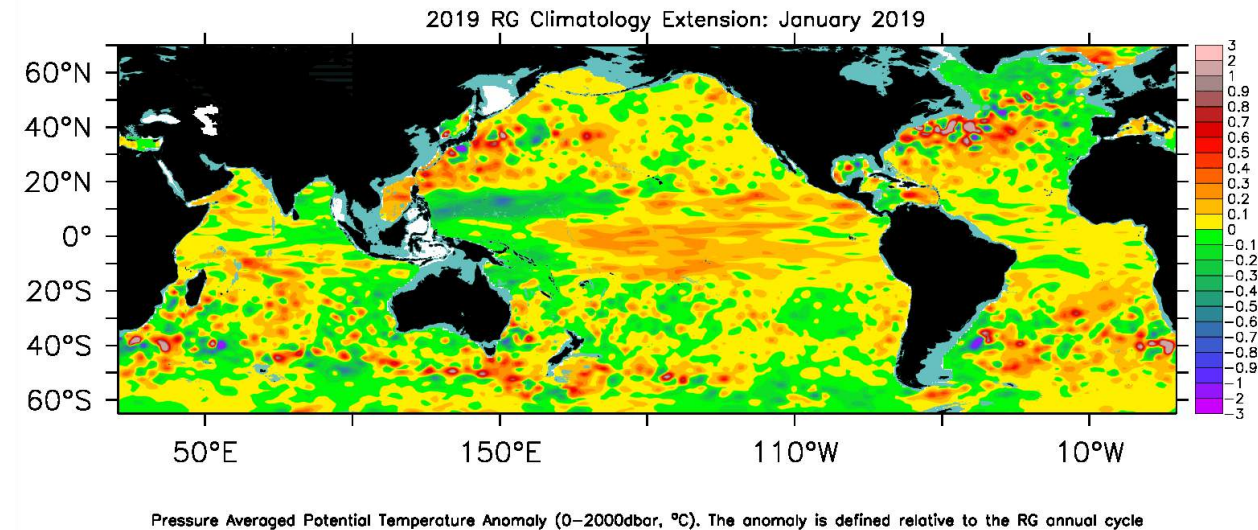
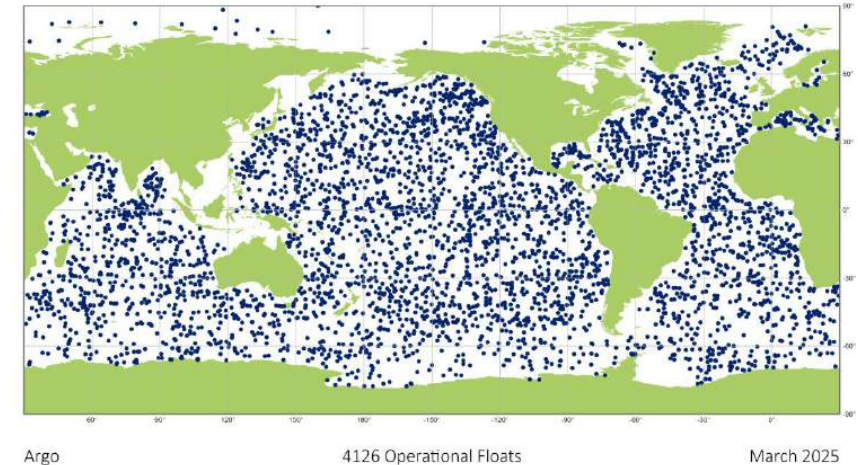
Method: OMP analysis

- Assume that all observed data can be explained as a linear mixture of each of these source waters
- Solve with non-negative Least-Squares machinery from Wunsch (2008) to give an optimal solution with minimal residuals



Method: Applying to Argo climatology using ML

- Used the found relationship to apply to the Roemmich-Gilson Argo Climatology
 - 1 deg x 1 deg, 0-2000m, monthly Argo objective map
 - Covers 2003-2025
- Use machine learning to estimate the Watermass fraction from Argo
 - Train Decision Tree/ random forest models on OMP output
 - we can achieve high levels of skill without tracers if we include lat, lon, depth in the training
 - Apply to the 20 years of monthly gridded Argo gridded data
 - Look at the integrated "thickness" of each watermass



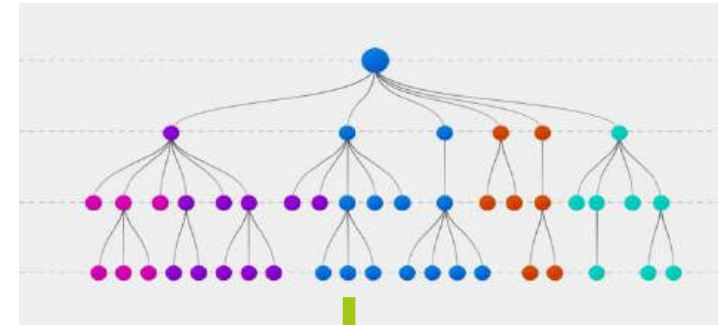
Method: Applying to Argo climatology using ML

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 - 1 deg x 1 deg, 0-2000m, monthly Argo objective map
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 - we can achieve high levels of skill without tracers if we include lat, lon, depth in the training
 - Apply to the 20 years of monthly gridded Argo gridded data
 - Look at the integrated "thickness" of each watermass
 - Remove seasonal cycle

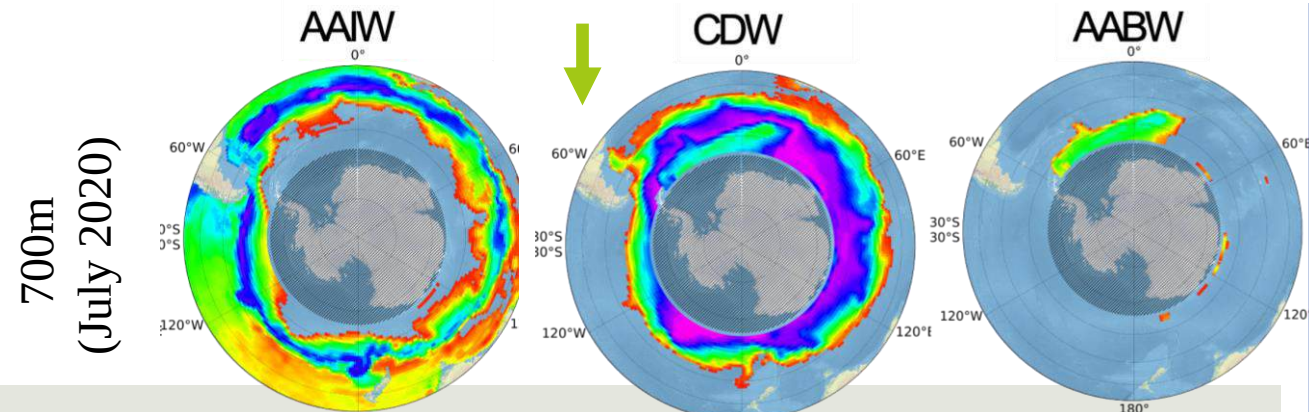
latitude	depth	longitude_sin	longitude_cos	STCW	SAMW1	SAMW2	HSSW	AASW	AAIW	NADW	CDW
-60.4630	20.0	-0.653513	0.756915	0.000000e+00	7.262207e-16	0.000000e+00	1.285253e-01	0.773907	0.000000e+00	6.977133e-16	9.358524e-16
-60.4630	100.8	-0.653513	0.756915	1.509557e-16	0.000000e+00	0.000000e+00	4.290318e-16	0.418883	0.000000e+00	0.000000e+00	3.398109e-16

Temperature, Salinity, Lat, Lon, Depth

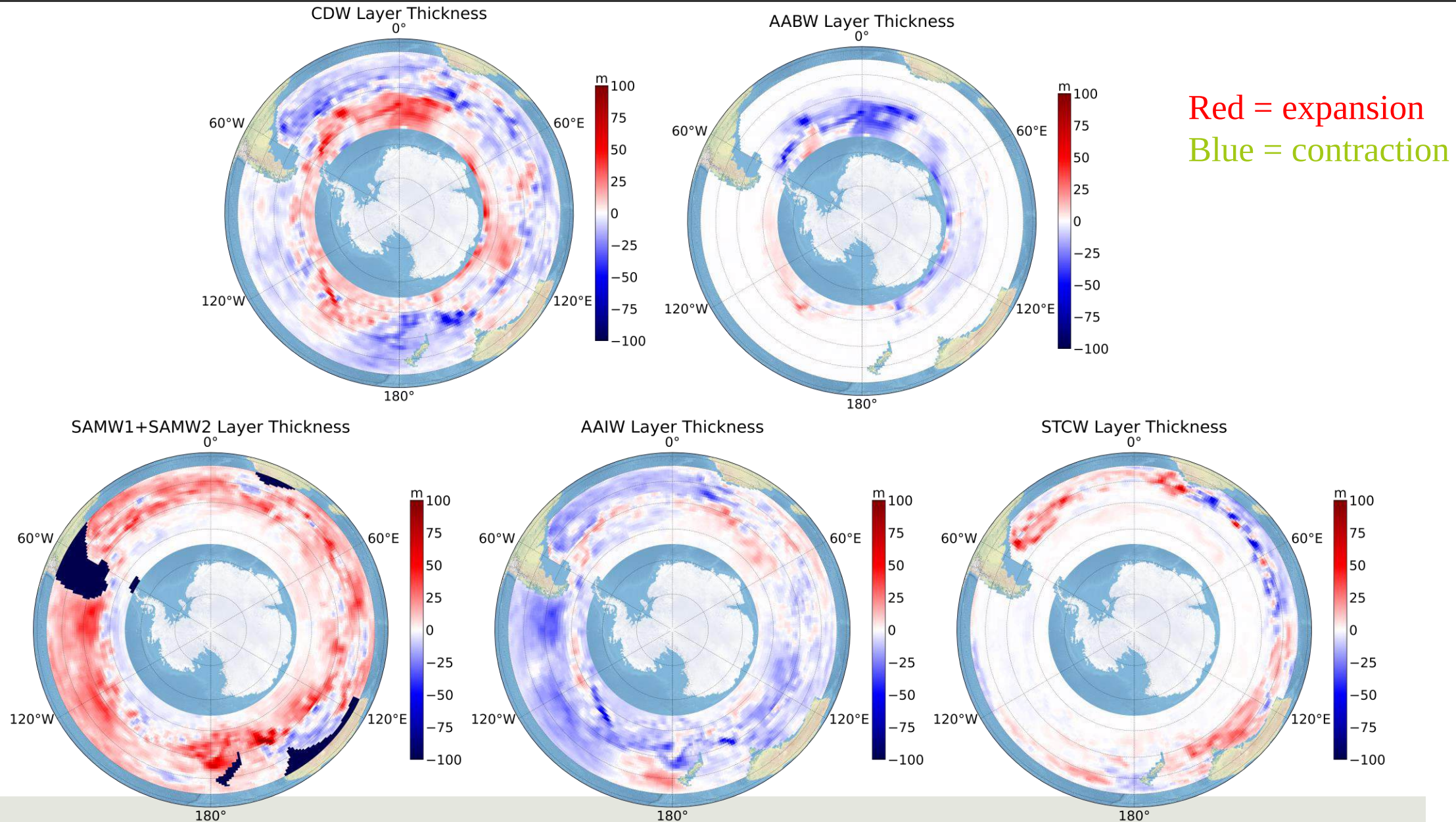
Random Forest Models



20 years of monthly gridded Argo Data (Roemmich and Gilson)

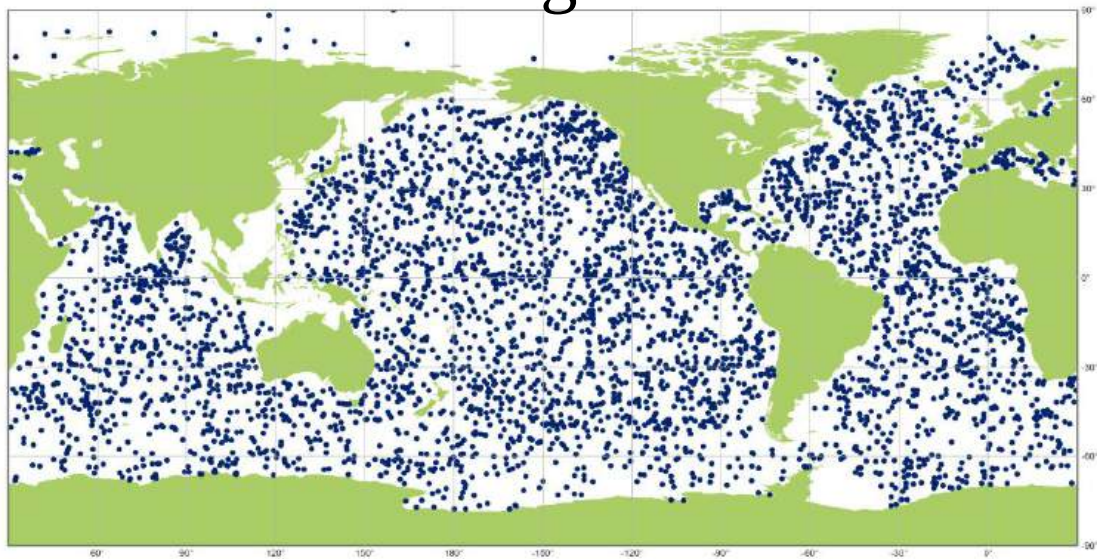


Change in Watermass thickness: avg(2019-2023) - avg(2004-2008)



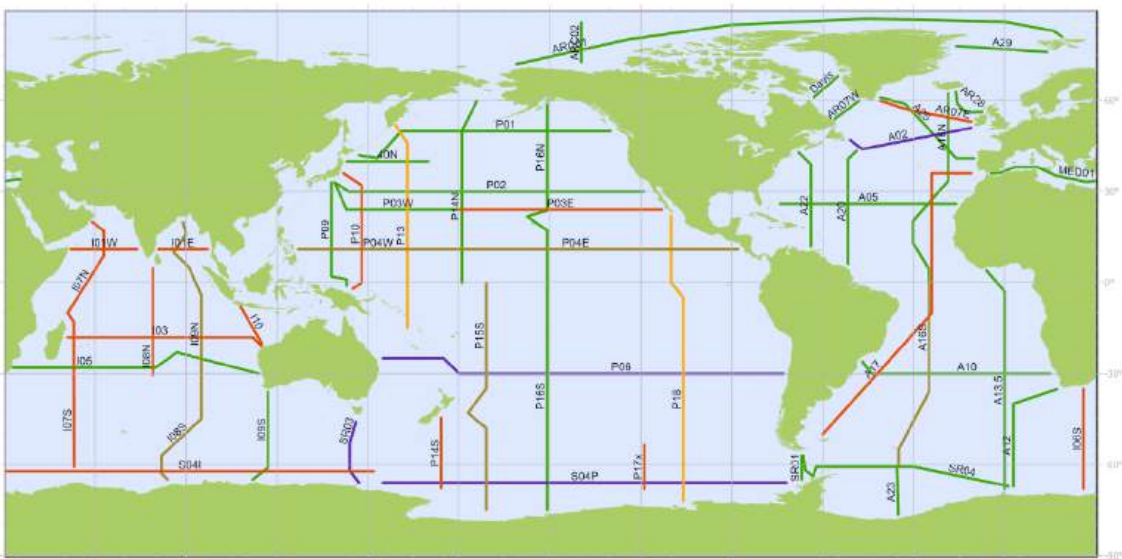
Future of Ocean Observing?

Argo



Argo 4126 Operational Floats March 2025

GO-SHIP



GO-SHIP Floating status of GO-SHIP (55 Core Lines) November 2023



- Occupied: sampled in last 7 years, or confirmed in next 4 years
- Securing: sampled between 5 and 7 years ago, with planned but unconfirmed cruise in next 4 years
- Watching: sampled between 5 and 7 years ago, with nothing planned in next 4 years
- At risk: Not sampled for more than 7 years, with planned but unconfirmed cruise in next 4 years
- Alarm: Not sampled for more than 7 years, and nothing planned for next 4 years



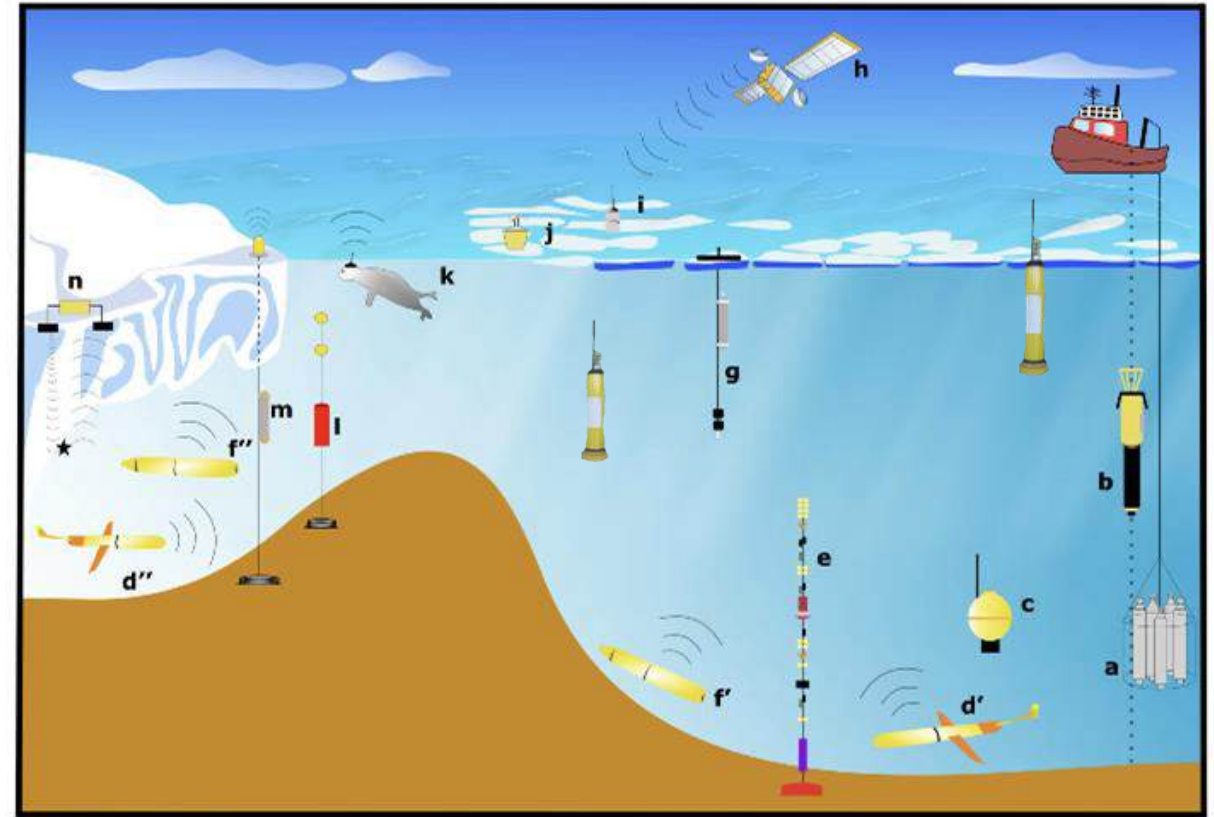
Generated by ocean-ops.org, 2023-11-24
Projection: Plate Carree (+150,0000)



Summary and challenges

- ❑ Antarctic Bottom Water (AABW) and North Atlantic Deep Water (NADW) fill the global deep and abyssal oceans
- ❑ Interior ocean properties are set by surface buoyancy forcings that are vulnerable to climate change, and hard to model!
- ❑ The abyssal ocean has warmed, likely due to a slowdown in AABW
- ❑ Monitoring the deep ocean in the coming decades will be critical to understanding climate.

B



(Silvano et al. 2023)

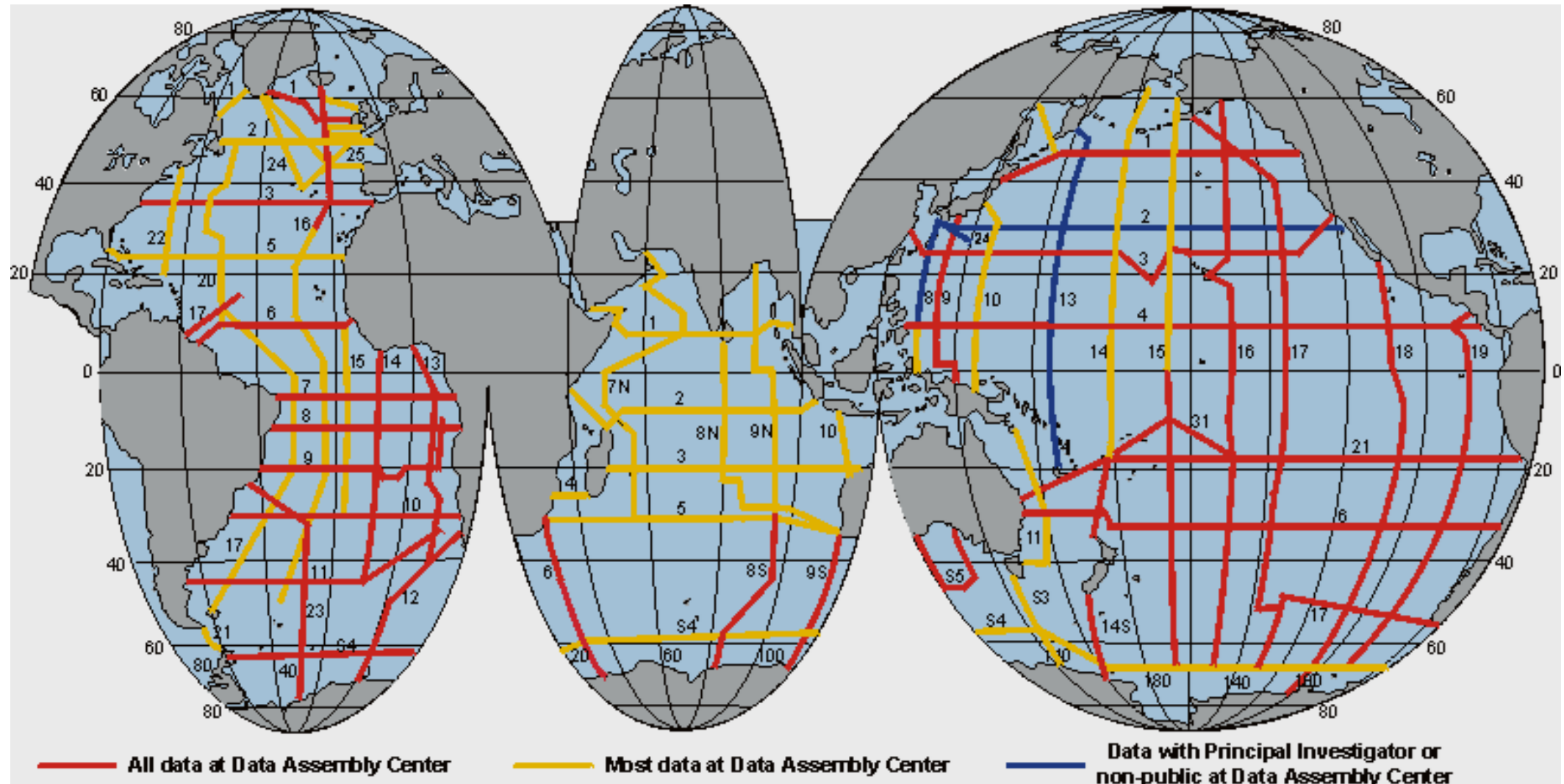
Thank you and questions

Laura Cimoli, Gebbie, G., Purkey, S. G., & Smethie, W. M. (2023). *Journal of Geophysical Research*: <https://doi.org/10.1029/2022JC019337>

Joshua Lanham, Purkey, Srinivasan, Mazloff, Cimoli, & Mashayek, (in prep), Observational evidence of poleward migration of warm Circumpolar Deep Water

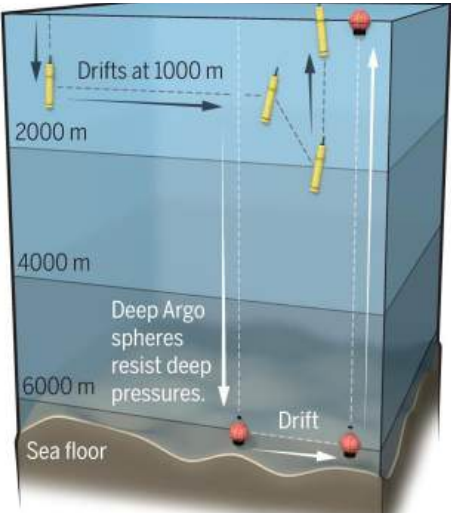
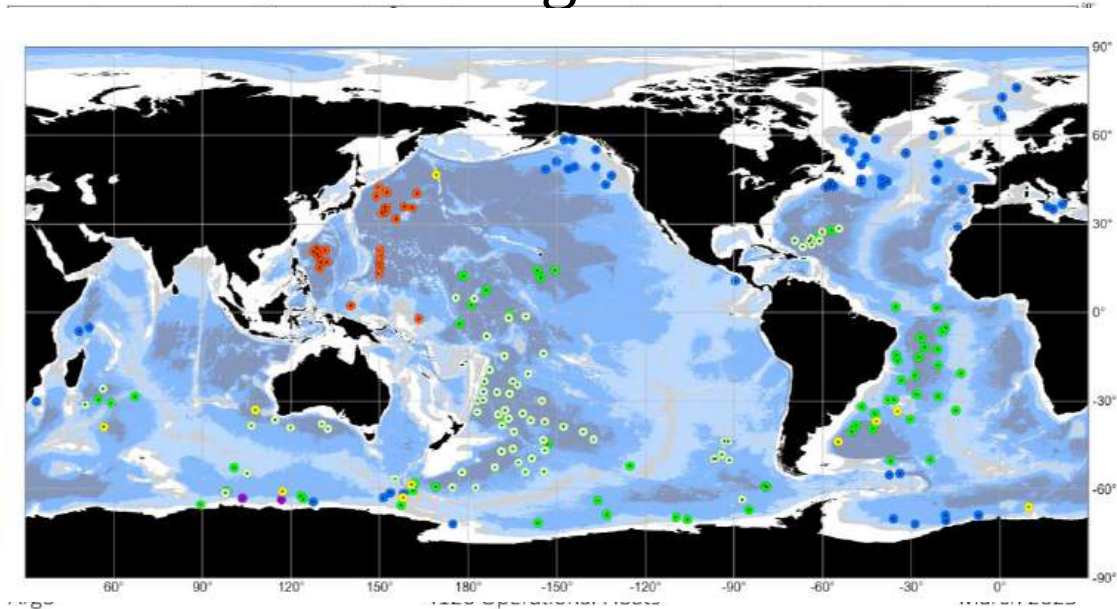
WOCE

WOCE: World ocean circulations experiment

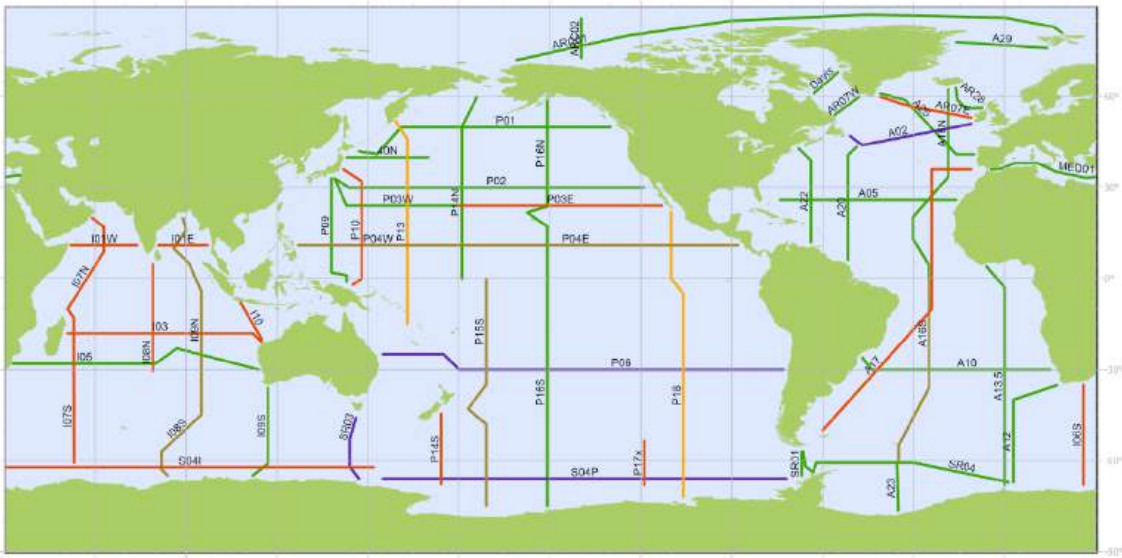


Observing the Interior Ocean

Argo



GO-SHIP



GO-SHIP data

CCHDO: <https://cchdo.ucsd.edu/>

CCHDO Home Find Data Submit Data Information

GO-SHIP Search

Search Results

Expcode	Line(s)	Ship	Country	Start Date	End Date	PI
33RR20220613	P02 P02E	ROGER REVELLE	US	2022-06-13	2022-07-16	Andreas Thurnherr
33RR20220430	P02 P02W	ROGER REVELLE	US	2022-04-30	2022-06-10	Aileen Macdonald
49UP20210719	P03W	RYOFU MARU	JP	2021-07-19	2021-10-14	NAGAI Naoki
49UZ20210713	P01	RV MIRAI	JP	2021-07-13	2021-08-26	Shinya Kouketsu
32S020210420	A22	RV Thomas G. Thompson	US	2021-04-20	2021-05-16	Viviane Meneses
32S020210316	A20	RV Thomas G. Thompson	US	2021-03-16	2021-04-16	Ryan Woolley
33RO20200321	A12	RONALD H. BROWN	US	2020-03-21	2020-04-17	Leticia Barbero
74EQ20200203	A23 SR1B	Discovery	GB	2020-02-03	2020-03-13	Yvonne Firing
740-02030119	A06	RPS JAMES COOK	GB	2020-01-19	2020-03-01	A. Sanchez-Franks
49UZ20191229	I07 I07C	MIRAI	JP	2019-12-29	2020-02-10	Katsuro Katsumata

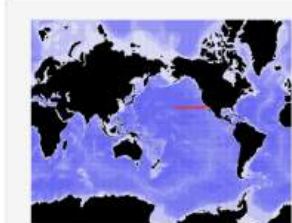
Filter Table

Bulk Download Options

Results: 149

Search Tips

Hydrographic Cruise: 33RR20220613



Date Start/End:
2022-06-13/2022-07-16

Chief Scientists:
Andreas Thurnherr
Sebastian Bigorre (Co-Chief)

Dataset

Files in the Dataset have been checked for format consistency, and merged into a single, integrated, dataset.

Download Entire Dataset Submit Data For This Cruise How to Cite Dataset

bottle

- CF netCDF: 33RR20220613_bottle.nc (Updated 2022-09-12, 887.2 kB)
- exchange: 33RR20220613_hy1.csv (Updated 2022-09-13, 2.3 MB)
- WHP netCDF: 33RR20220613_nc_hyd.zip (Updated 2022-09-12, 890.0 kB)

ctd

- CF netCDF: 33RR20220613_ctd.nc (Updated 2022-08-30, 6.3 MB)
- exchange: 33RR20220613_ct1.zip (Updated 2022-08-30, 2.7 MB)
- WHP netCDF: 33RR20220613_nc_ctd.zip (Updated 2022-08-30, 3.3 MB)

summary

- WOCE: 33RR20220613su.txt (Updated 2022-08-30, 17.4 kB)

Other Files

JOA : <https://joa.ucsd.edu/>

Java OceanAtlas Data

Explore cleaned, vetted World Ocean Bottle and CTD Profile Data

BEST VERTICAL SECTION DATA WORLD OCEAN ATLAS DATA LEGACY/HISTORICAL DATA

Glodap: <https://www.glodap.info/>

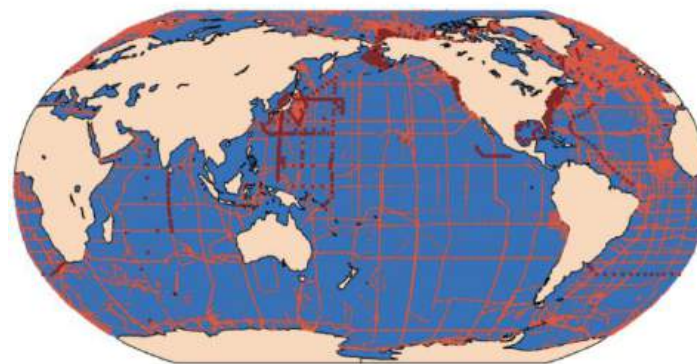


Figure 1 Station locations of all stations in GLODAPv2 2022. Stations in

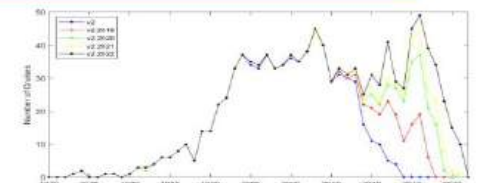
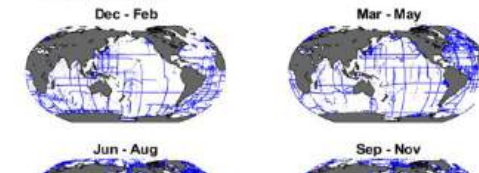


Figure 2. Number of cruises per year in GLODAPv2, GLODAPv2.2019, GLODAPv2.2020, GLODAPv2.2021 and GLODAPv2.2022



Argovis

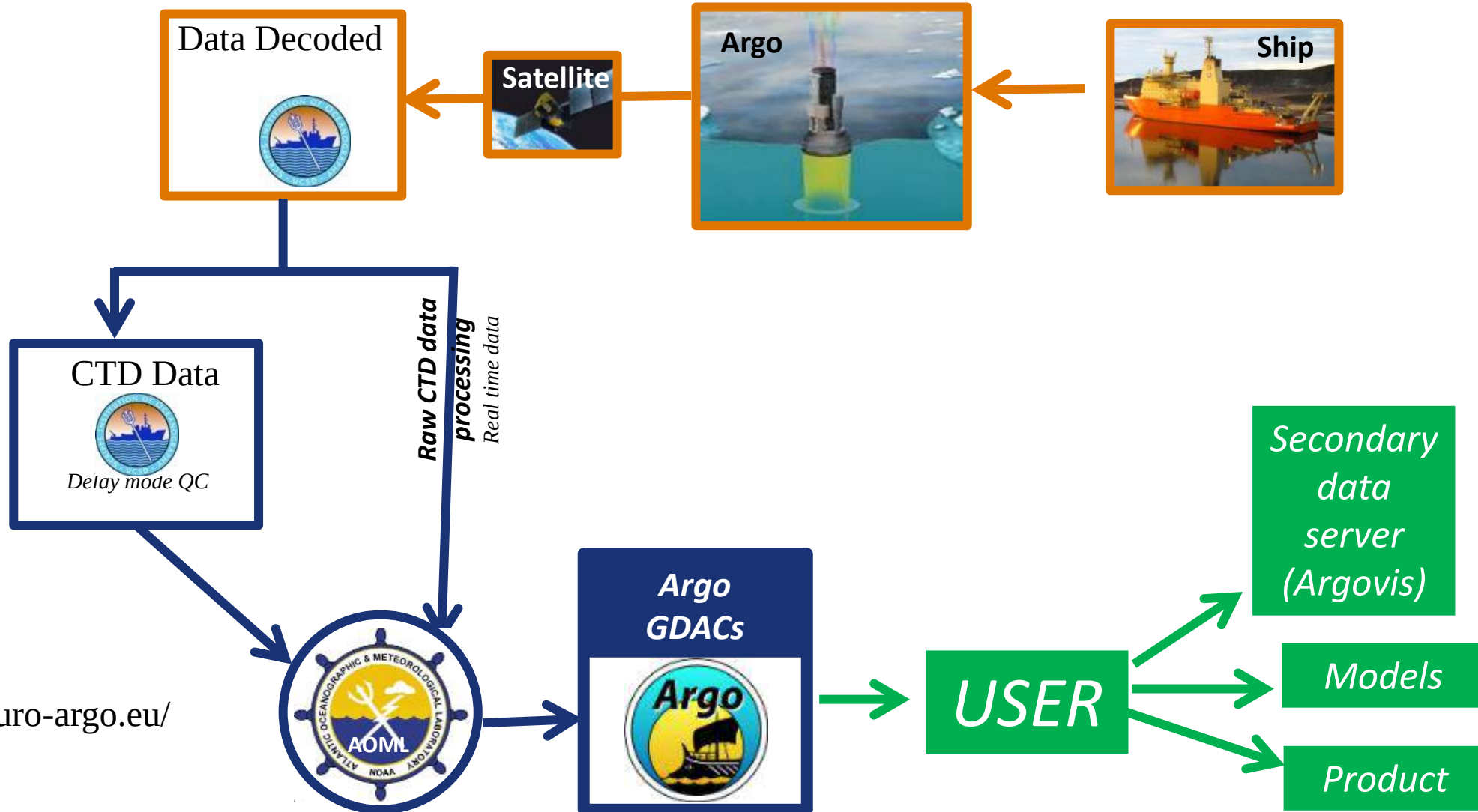
Argo



Argo Data

Argo Home page: <https://argo.ucsd.edu/>

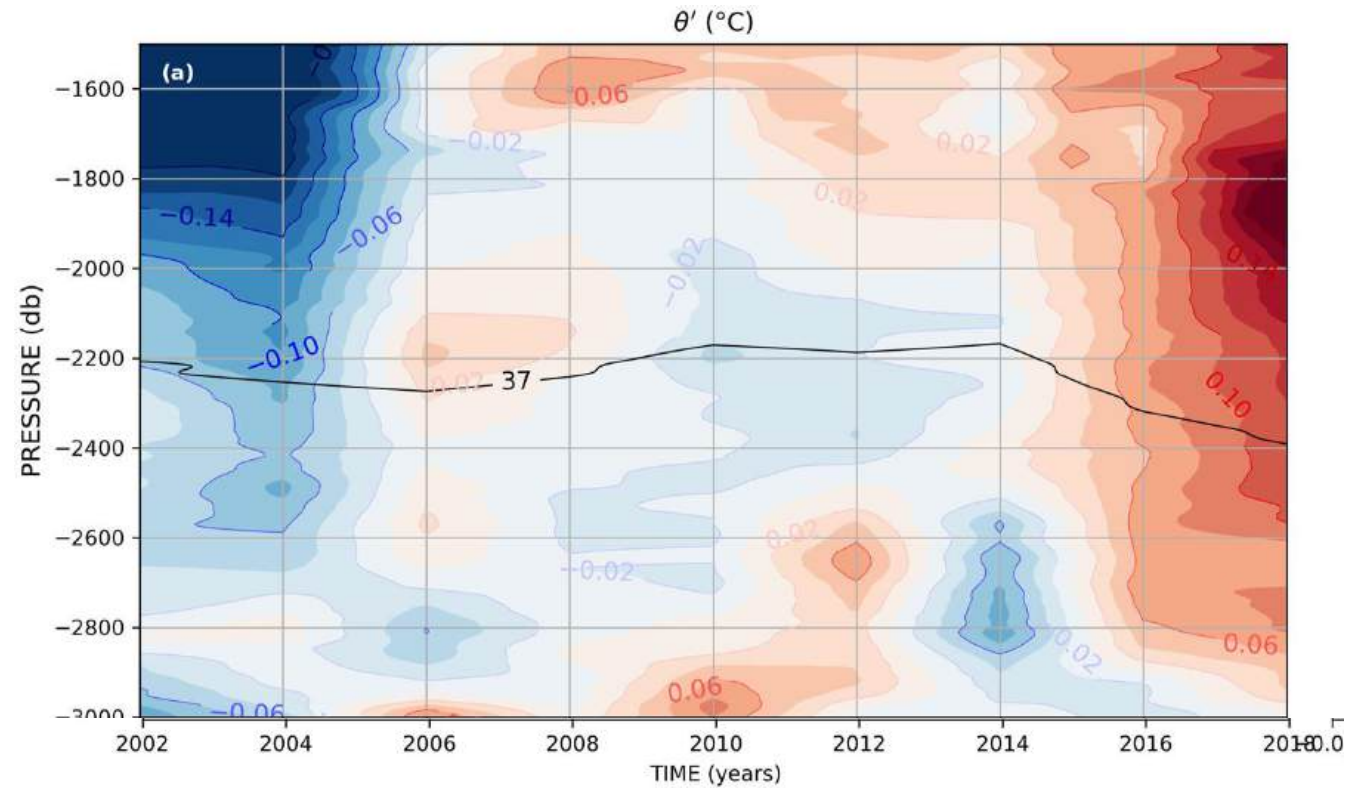
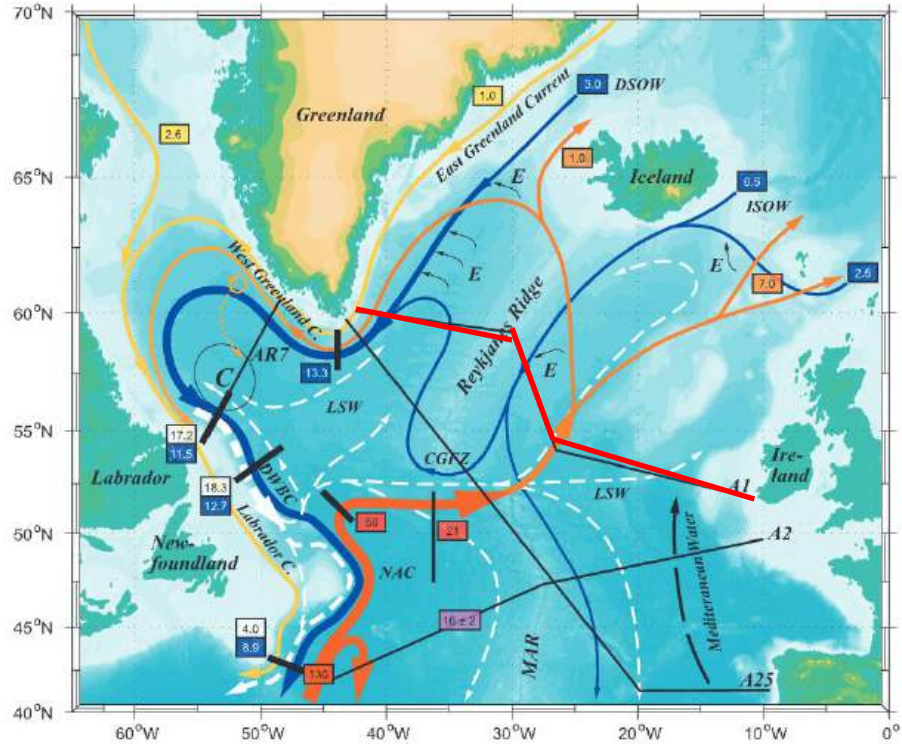
- data access
- list of gridded products
- “how to” manual



Add matlab packages

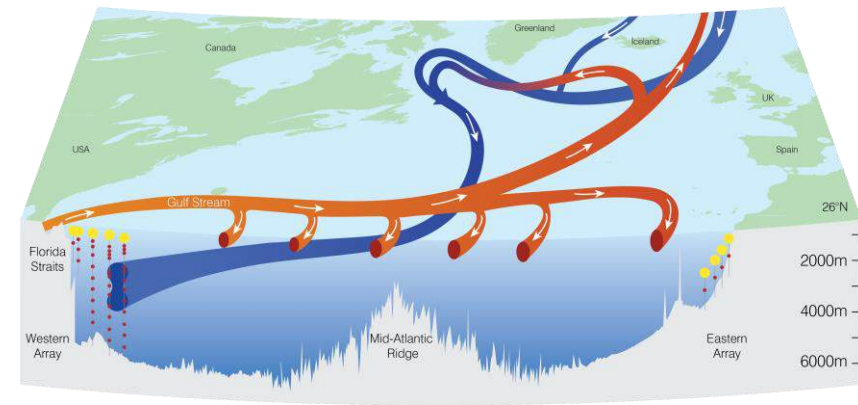
<https://fleetmonitoring.euro-argo.eu/>

NADW Variability

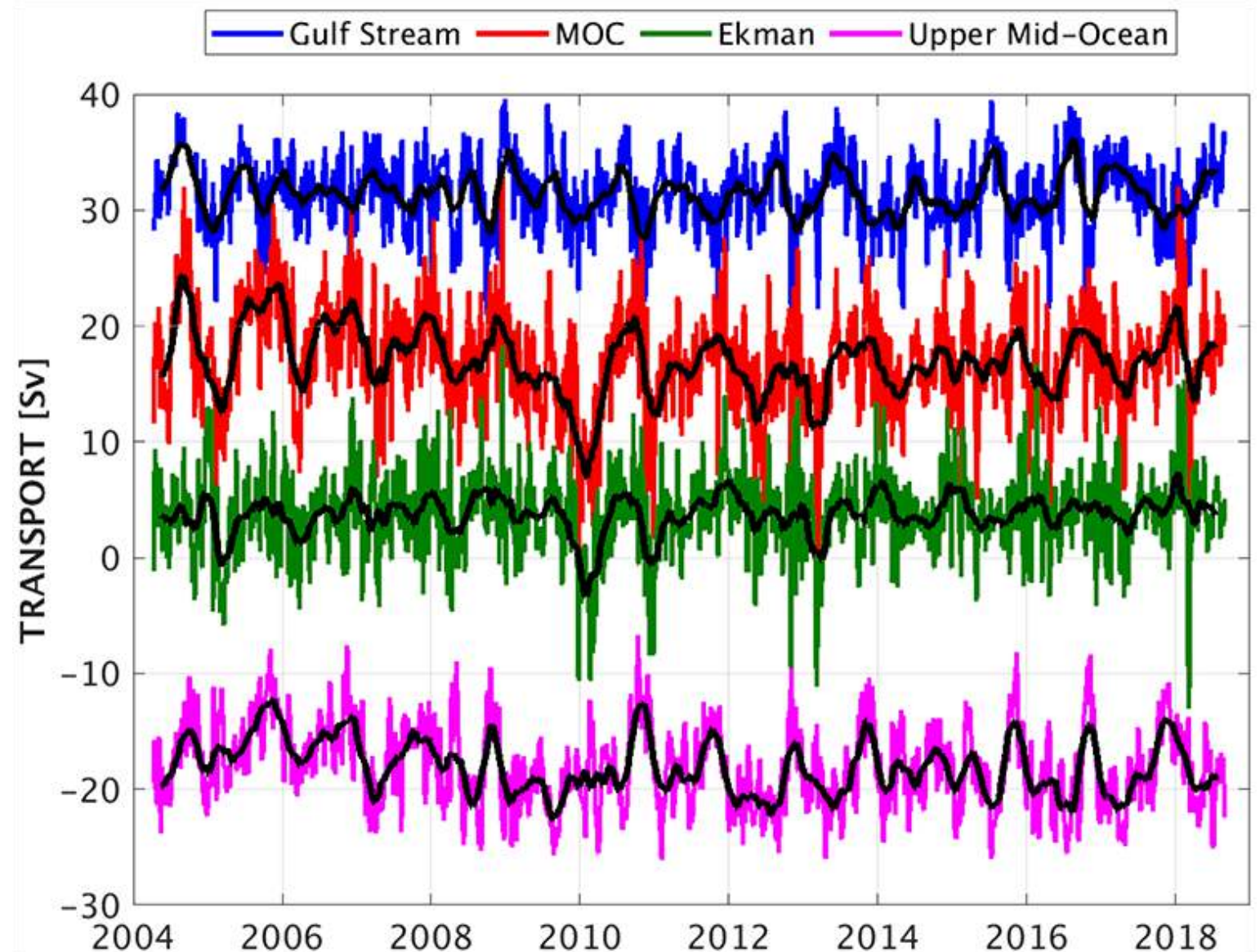


(Desbruyeres et al. 2022)

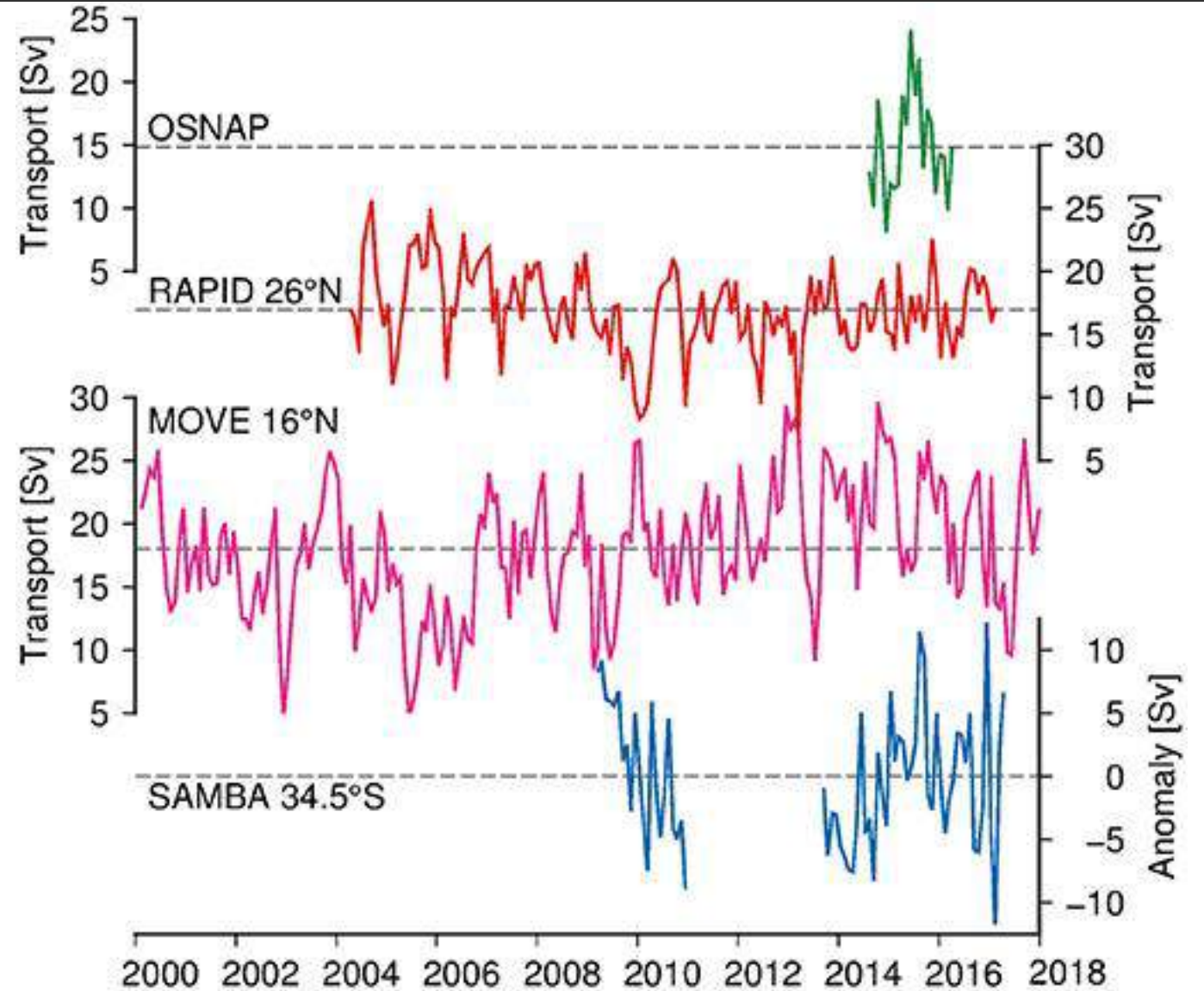
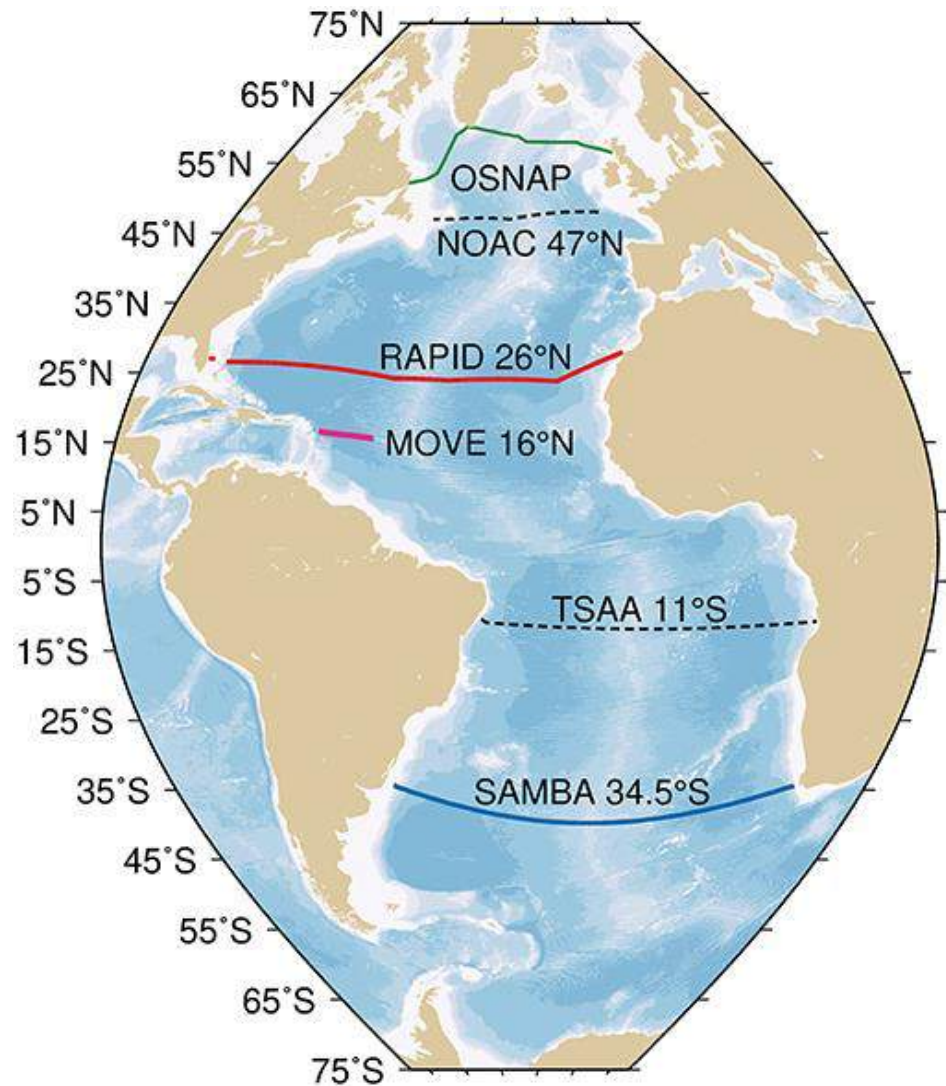
Long-term monitoring of the MOC



(RAPID: <https://rapid.ac.uk/>)

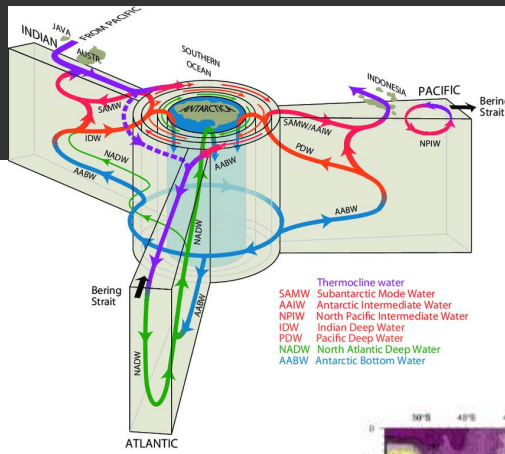


Long-term monitoring of the MOC



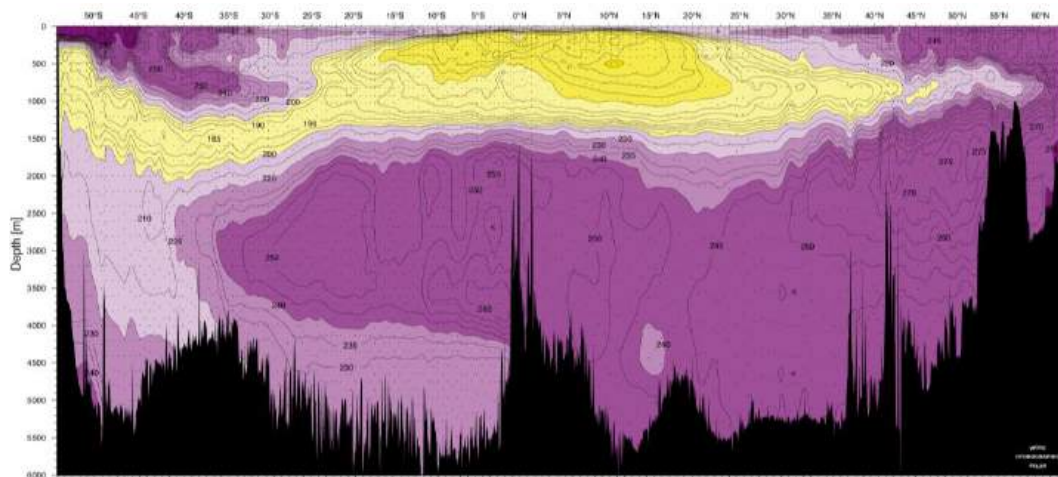
(Frajka-Williams et al. 2019)

AABW and NADW in the MOC

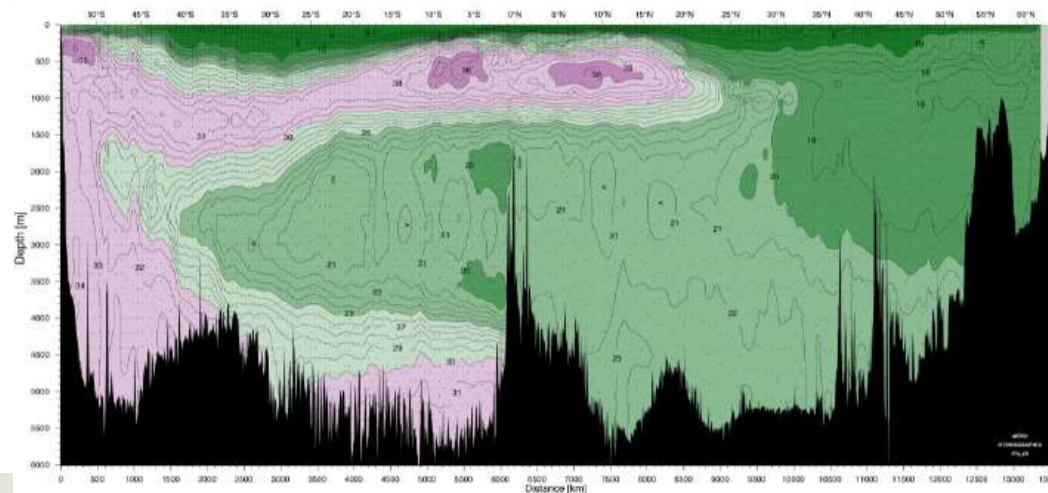


Atlantic

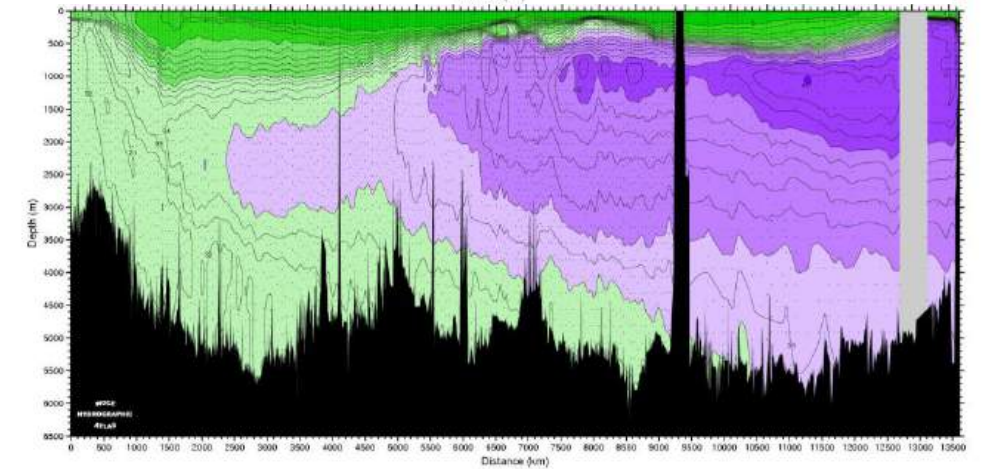
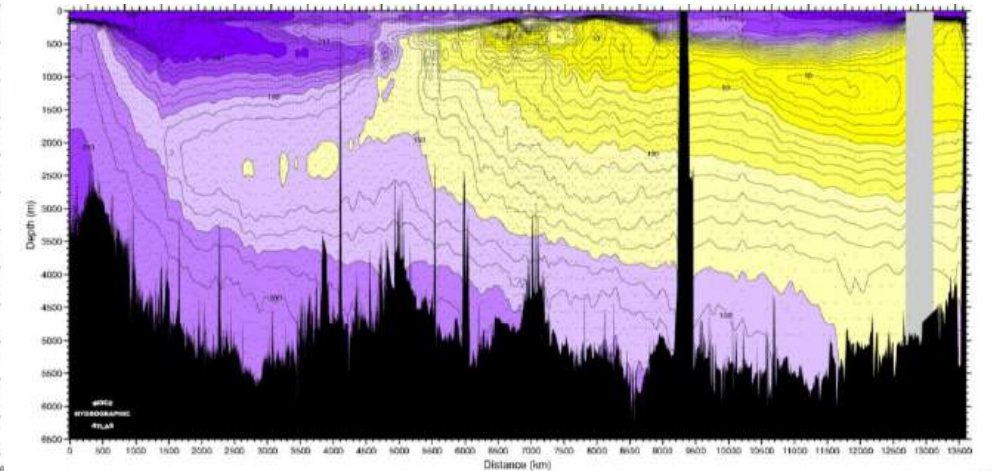
Oxygen



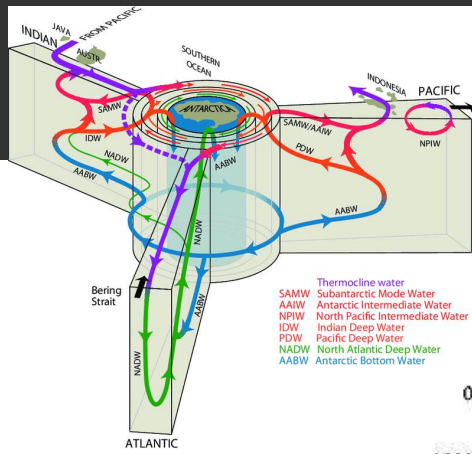
Nitrate



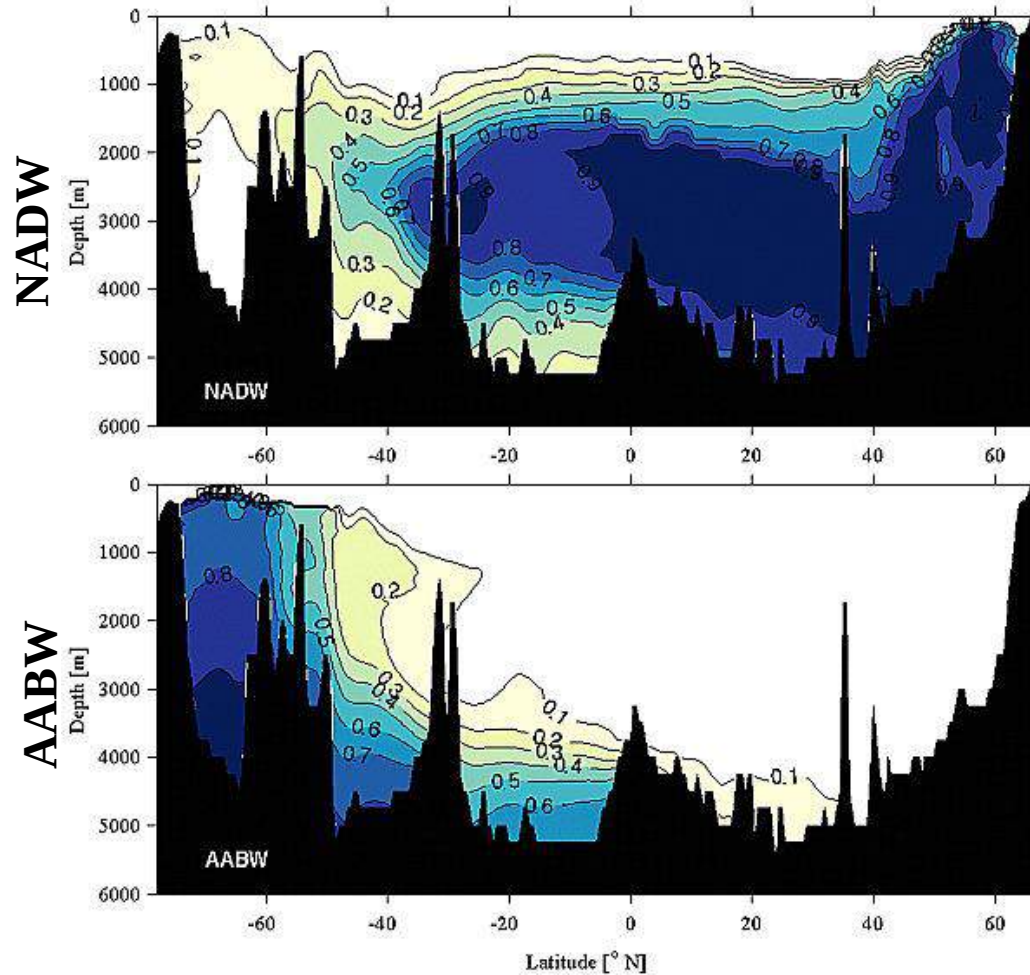
Pacific



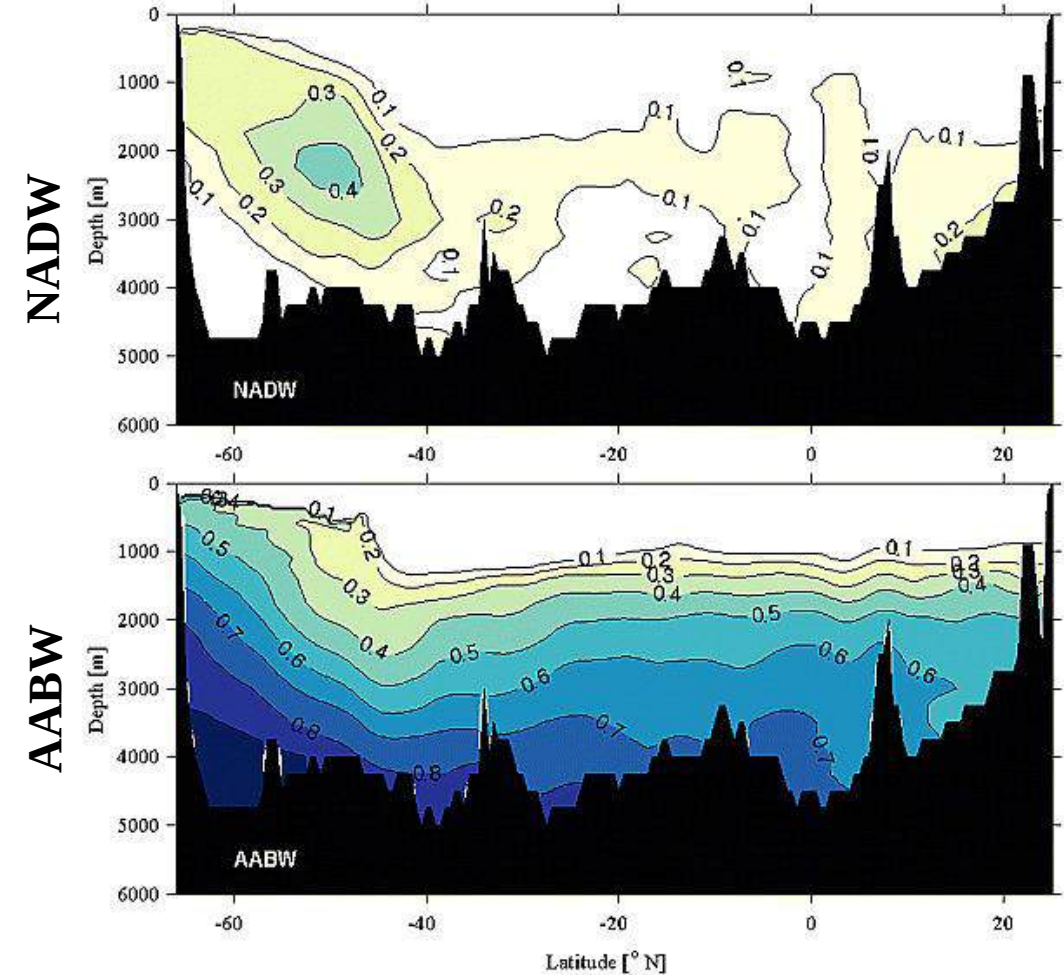
AABW and NADW in the MOC



Atlantic

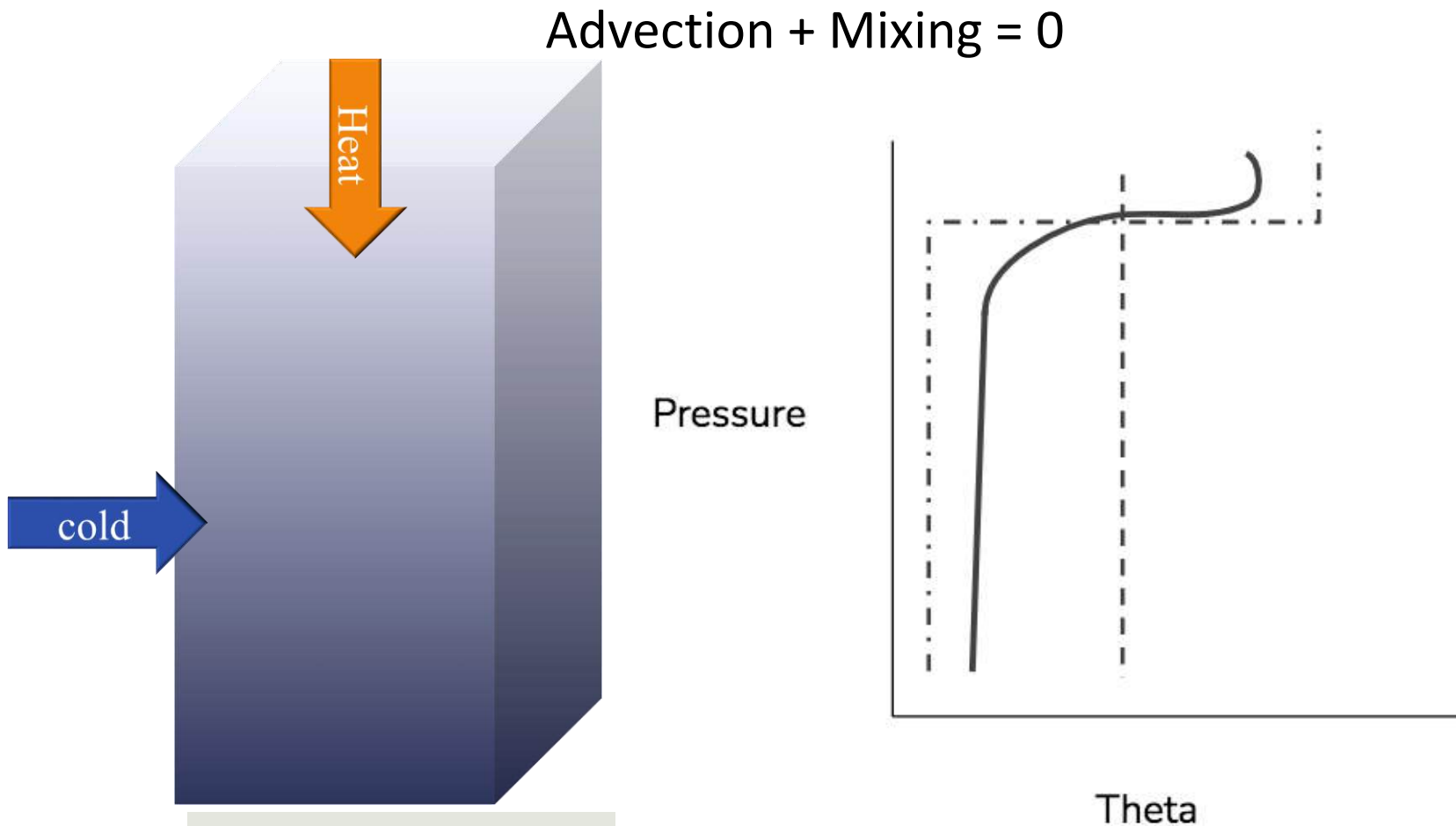


Pacific



The Global Meridional Overturning Circulation (MOC)

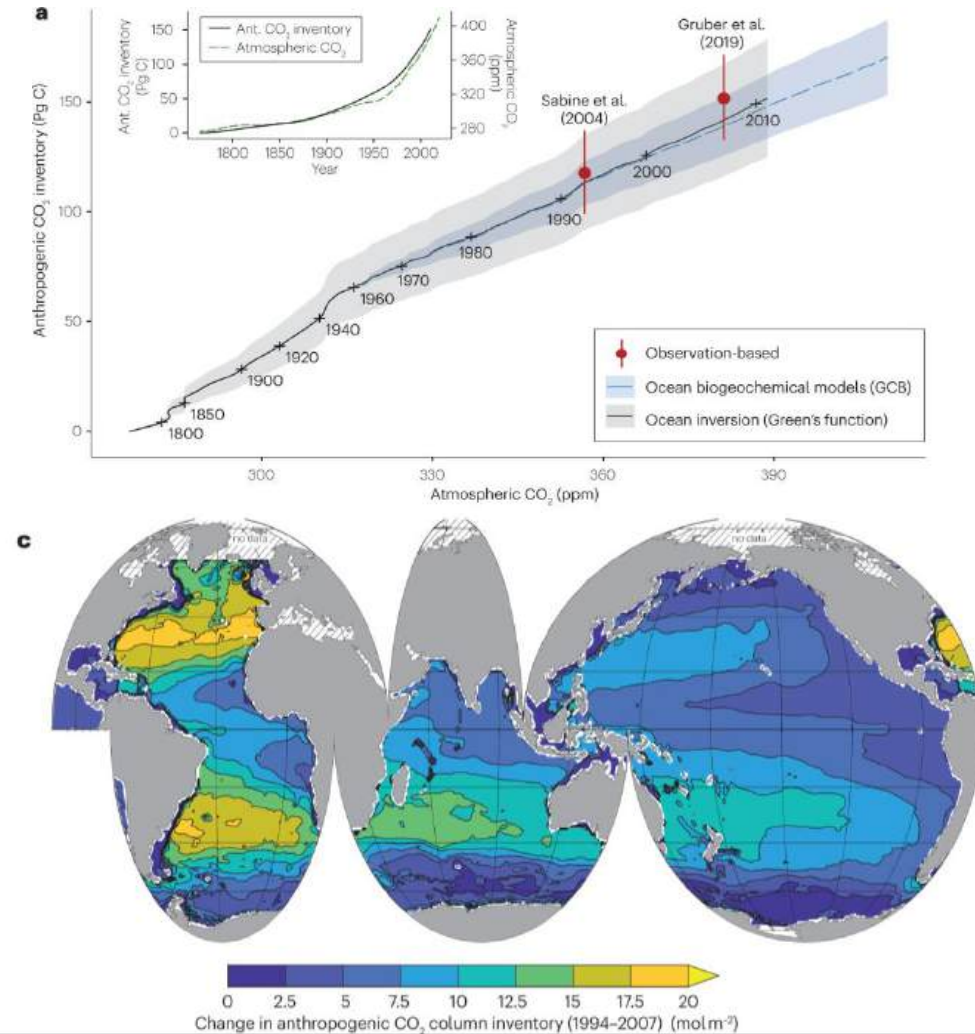
Bottom water properties are set by the balance between the renewal of deepwater formed around Antarctica and the rate of mixing with overlying water



- In steady state, these two processes are equal and bottom temperature is constant in time

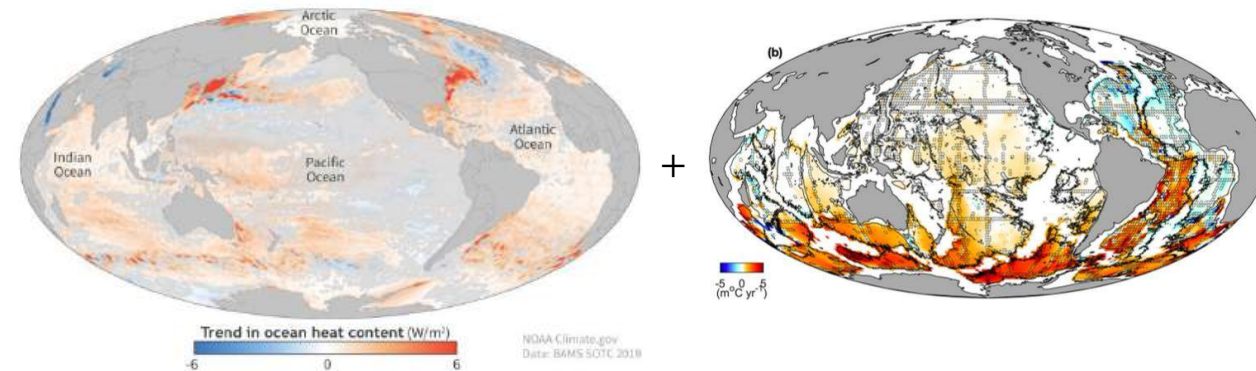
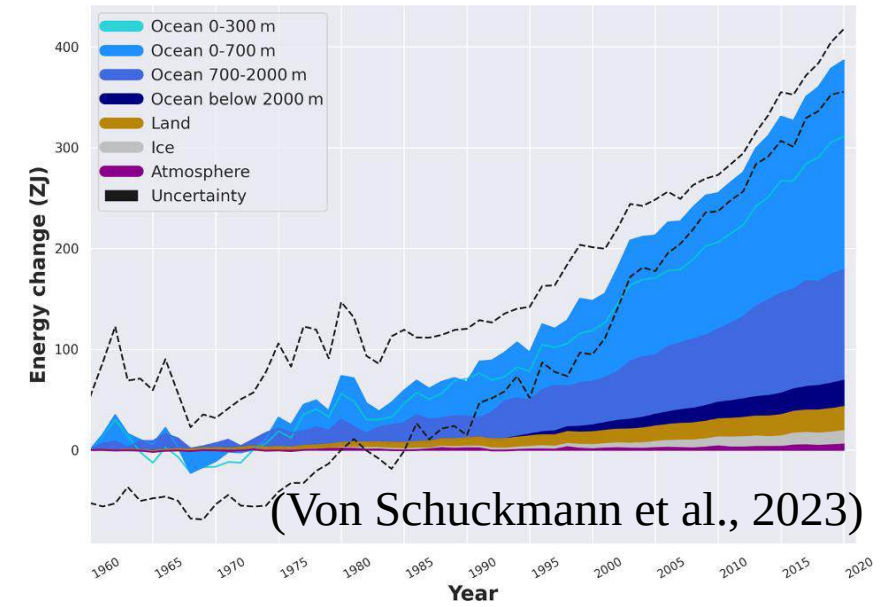
Ocean Ventilation Matters for Carbon and Heat Uptake

Anthropogenic Carbon



(Gruber et al., 2023)

Anthropogenic Heat



(OHC state of the climate)