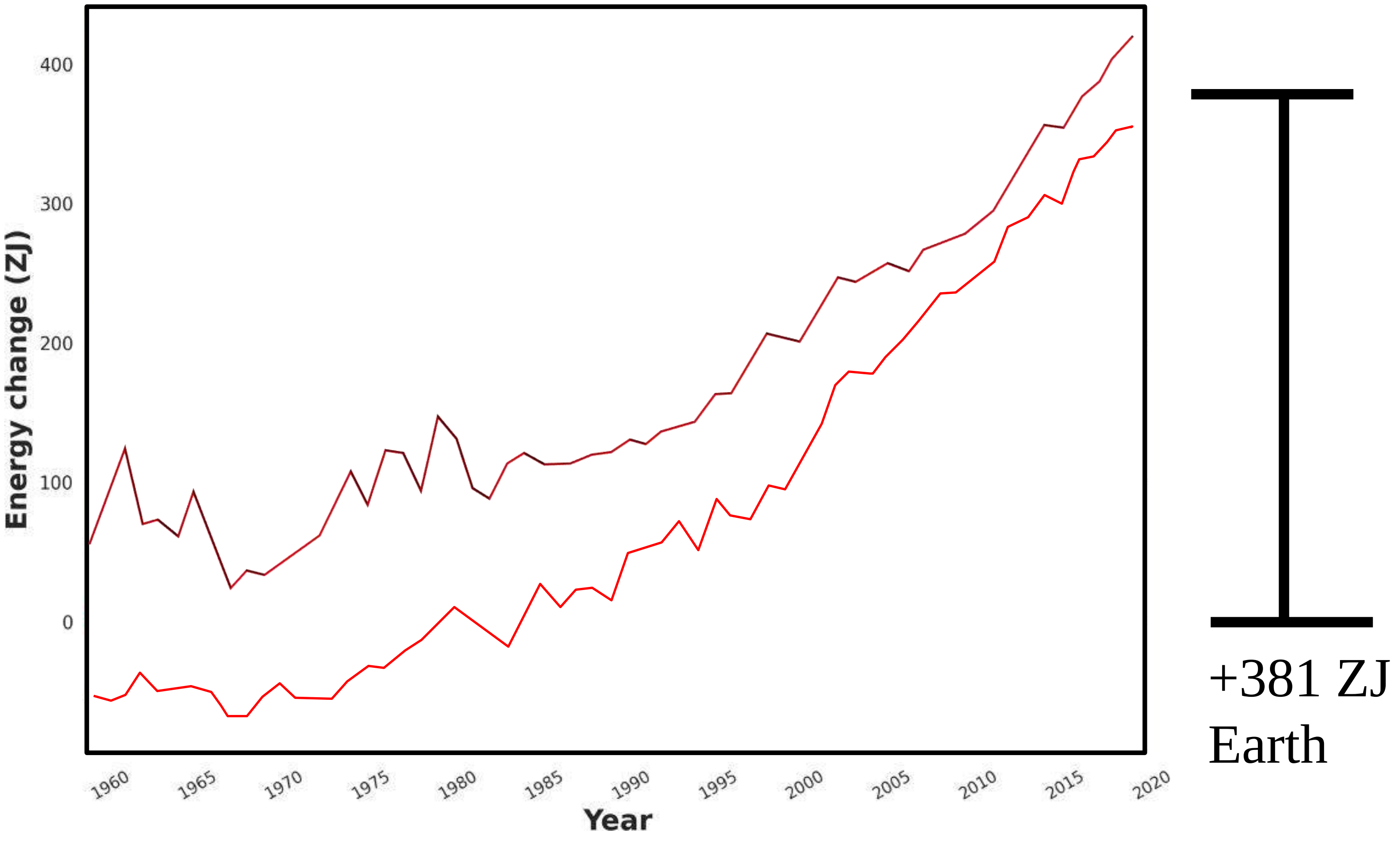
What Ocean Observations Tell Us About Ocean Warming: Surface to the Abyss

Sarah Purkey

May 21, 2025

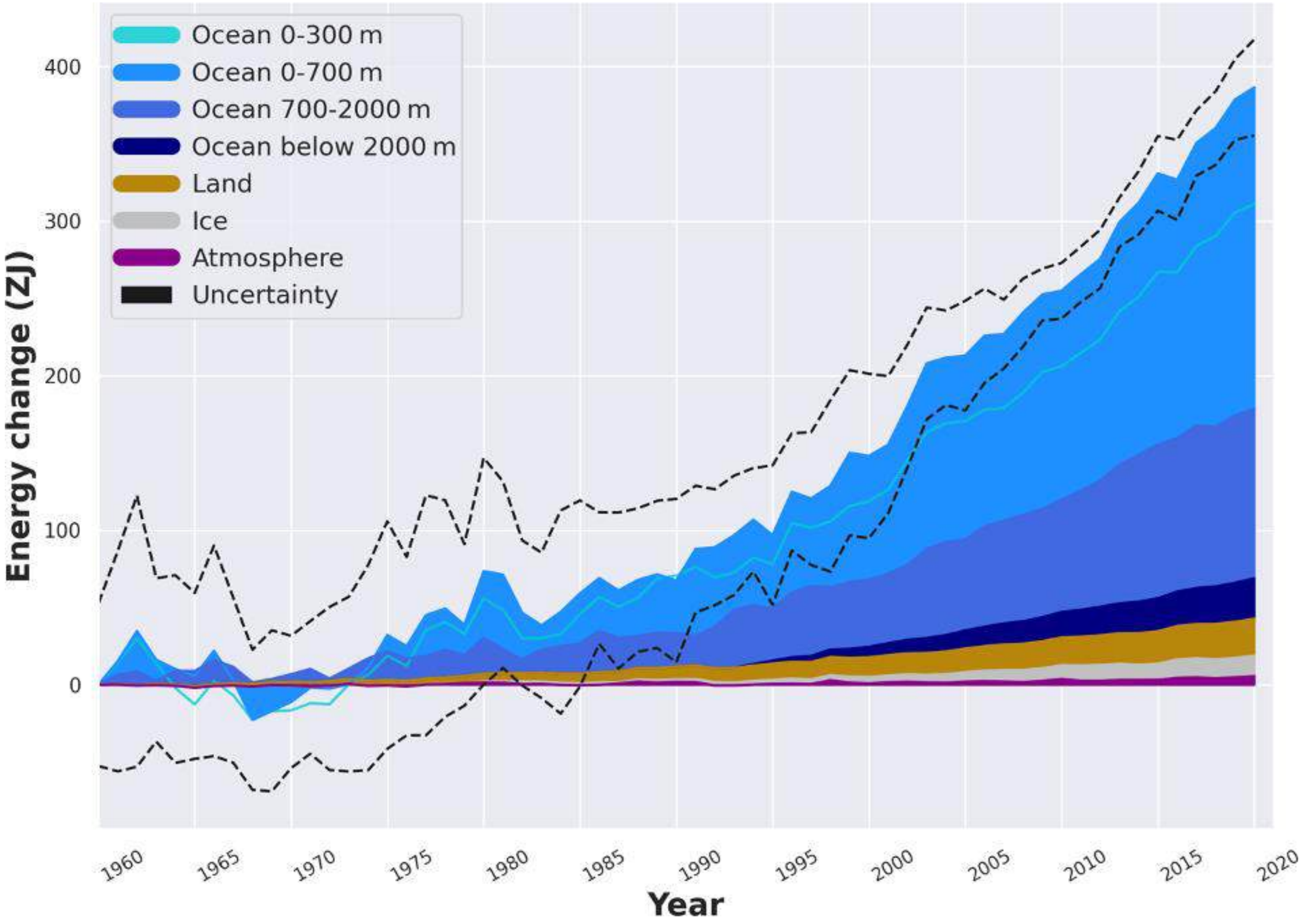
ECCO Summer School

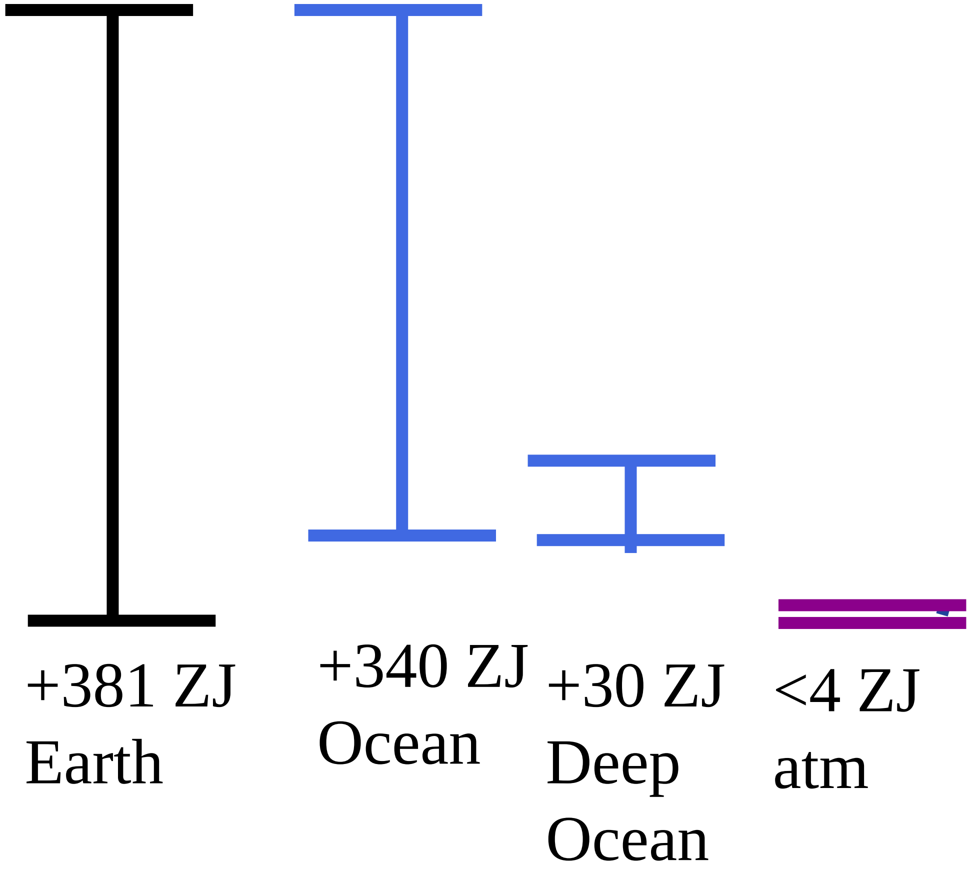
Global Warming



Von Schuckmann et al. 2023

Global Warming

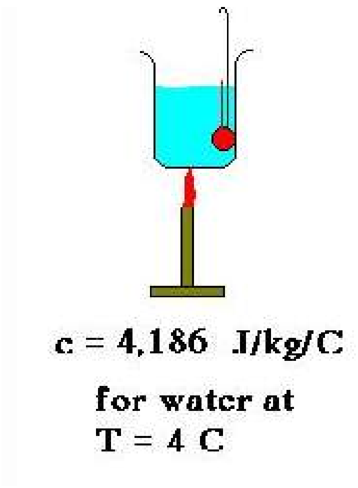




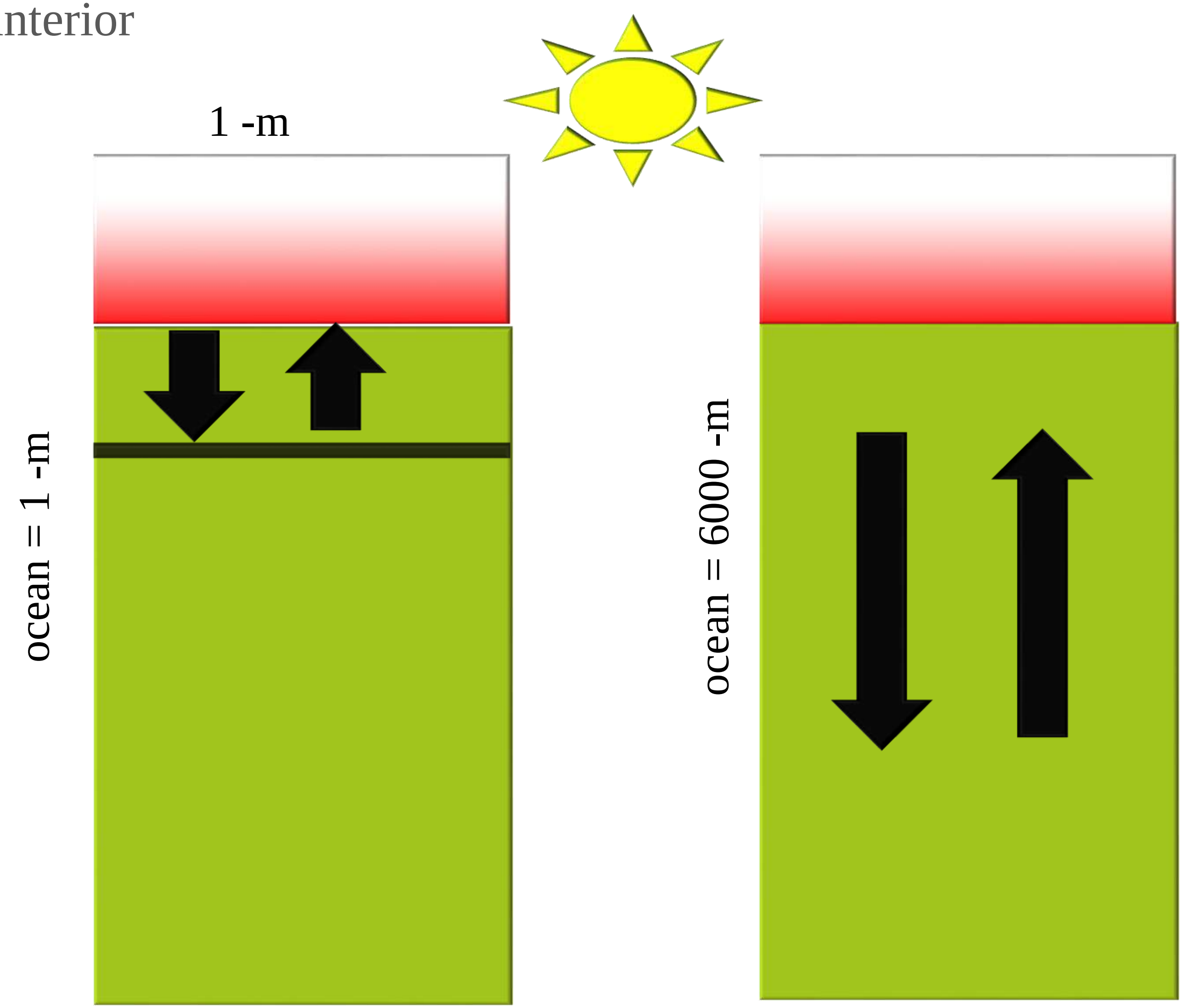
Von Schuckmann et al. 2023

Why is some much heat going into the ocean?

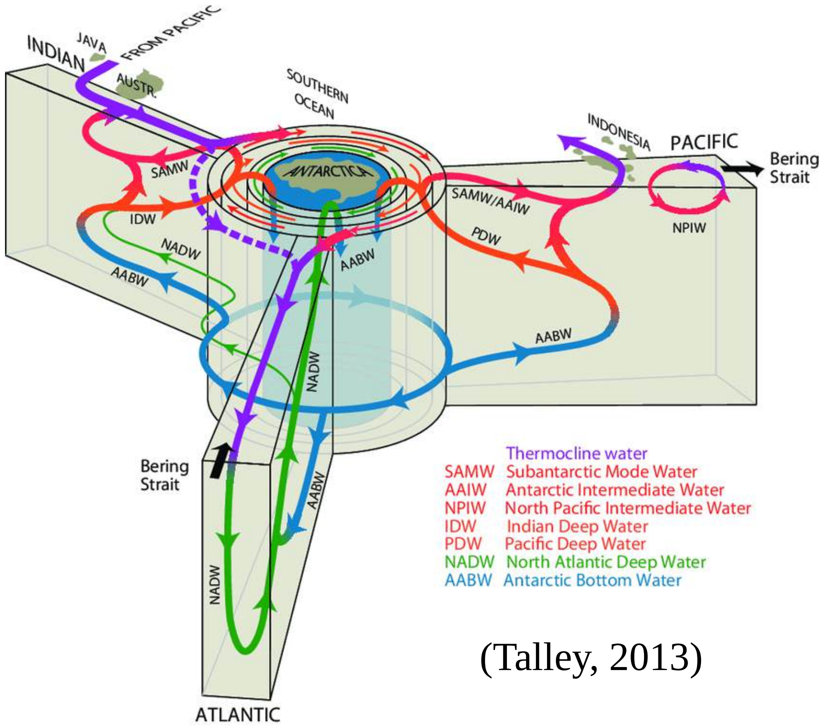
High heat capacity of water **AND** the ocean can transport heat from the surface to the interior



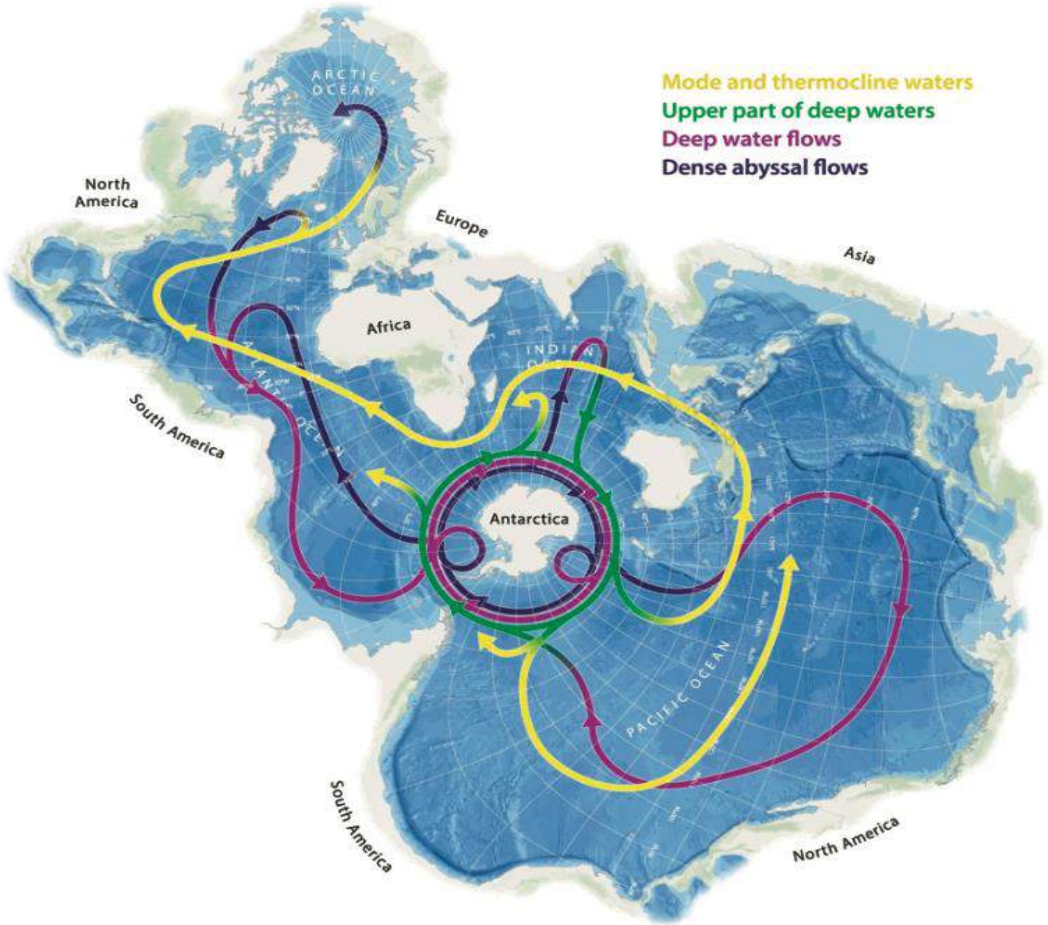
4186 J to raise 1 kg (m^3) of water by 1 deg C



Meridional Overturning Circulation (MOC)



(Talley, 2013)



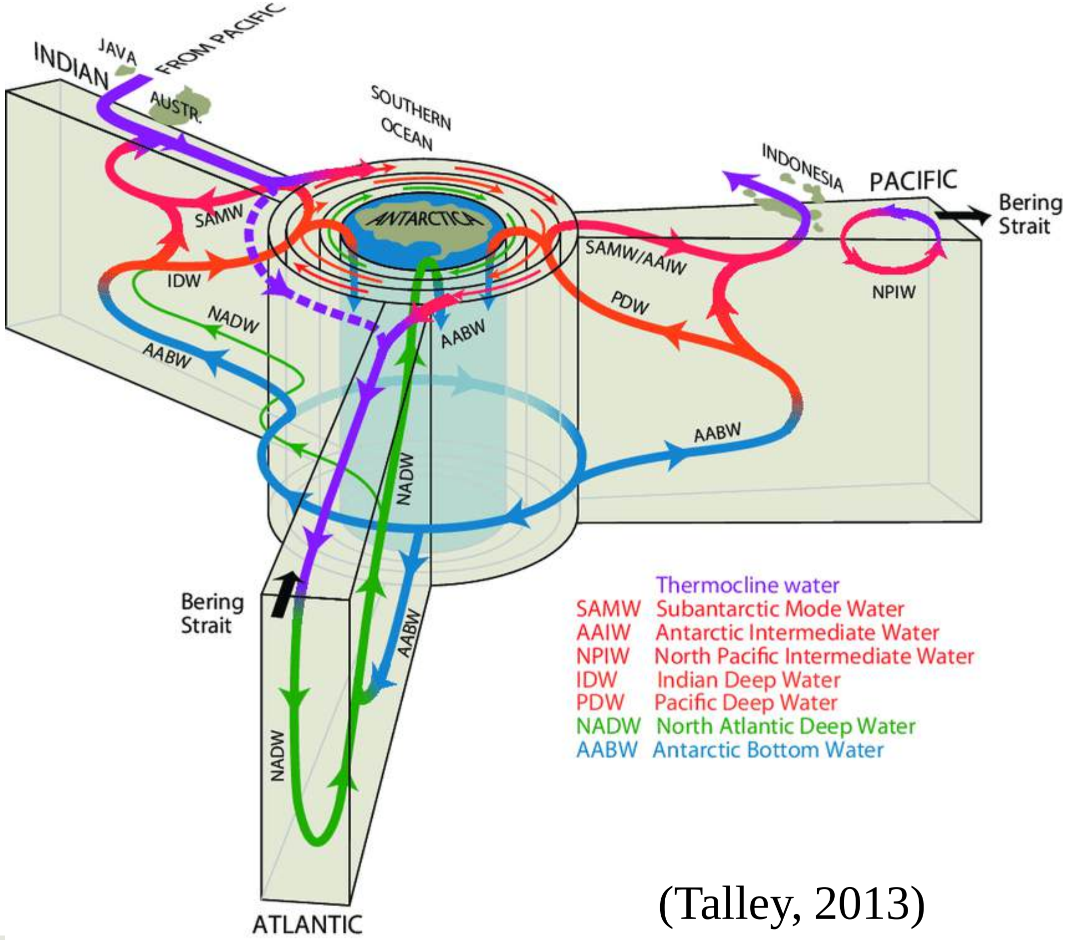
Meredith (Nat. Comm. 2022)

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

Outline

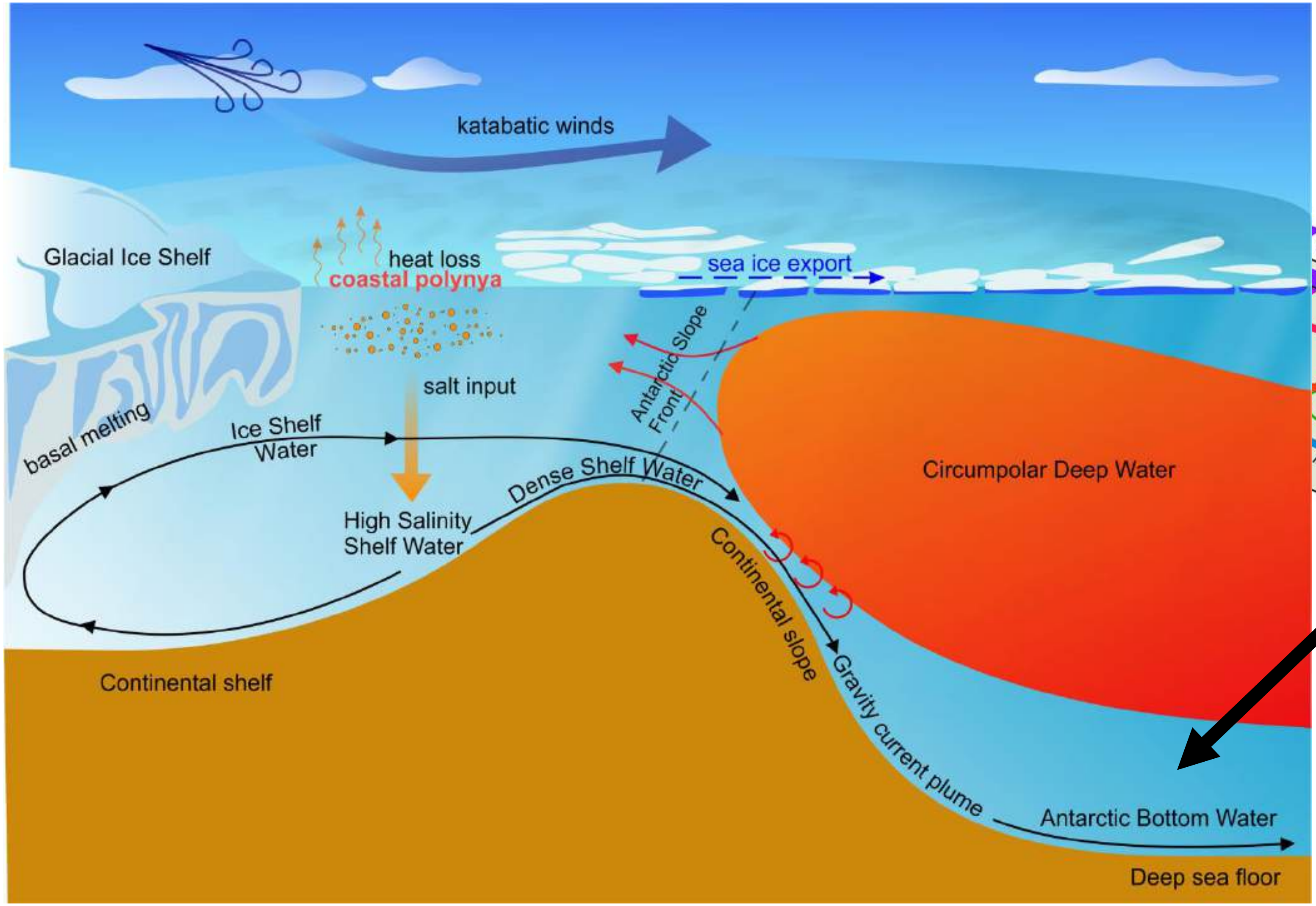
- Quick overview of Abyssal ocean circulation (deep MOC 101)
- Ocean observations (Argo and WOCE follow-ons)
- Ocean warming and changes in deep ocean circulation

Meridional Overturning Circulation (MOC)

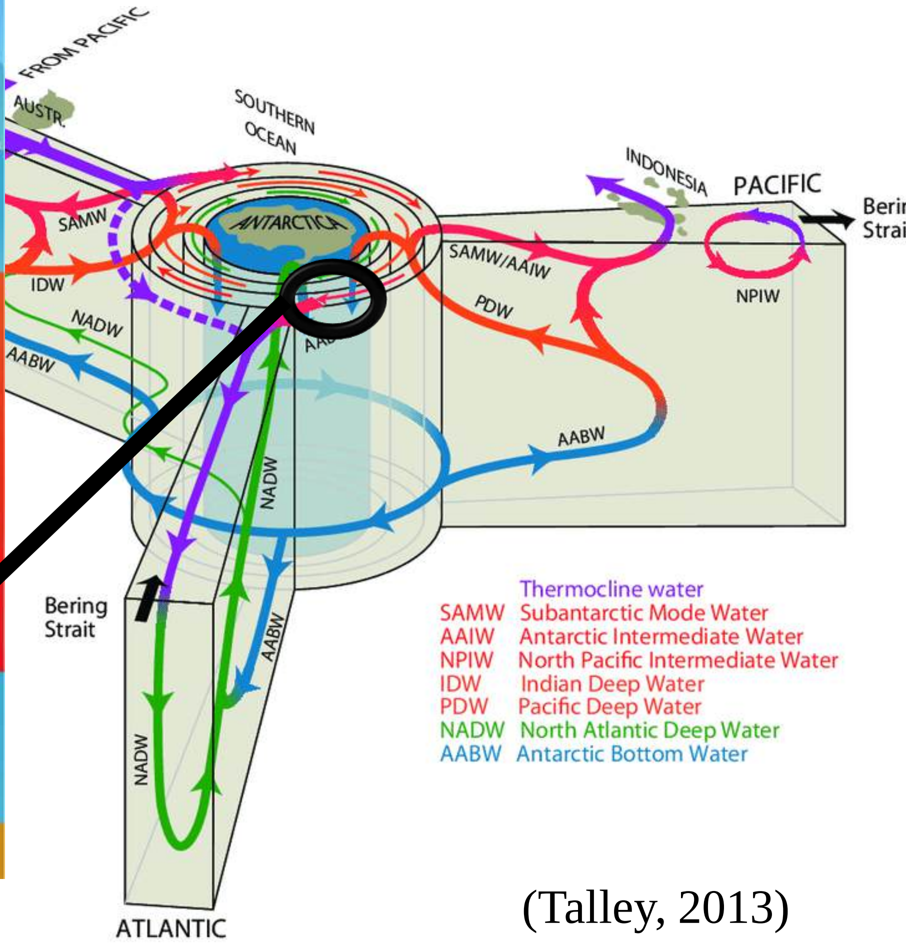


(Talley, 2013)

MOC: Antarctic Bottom Water (AABW)

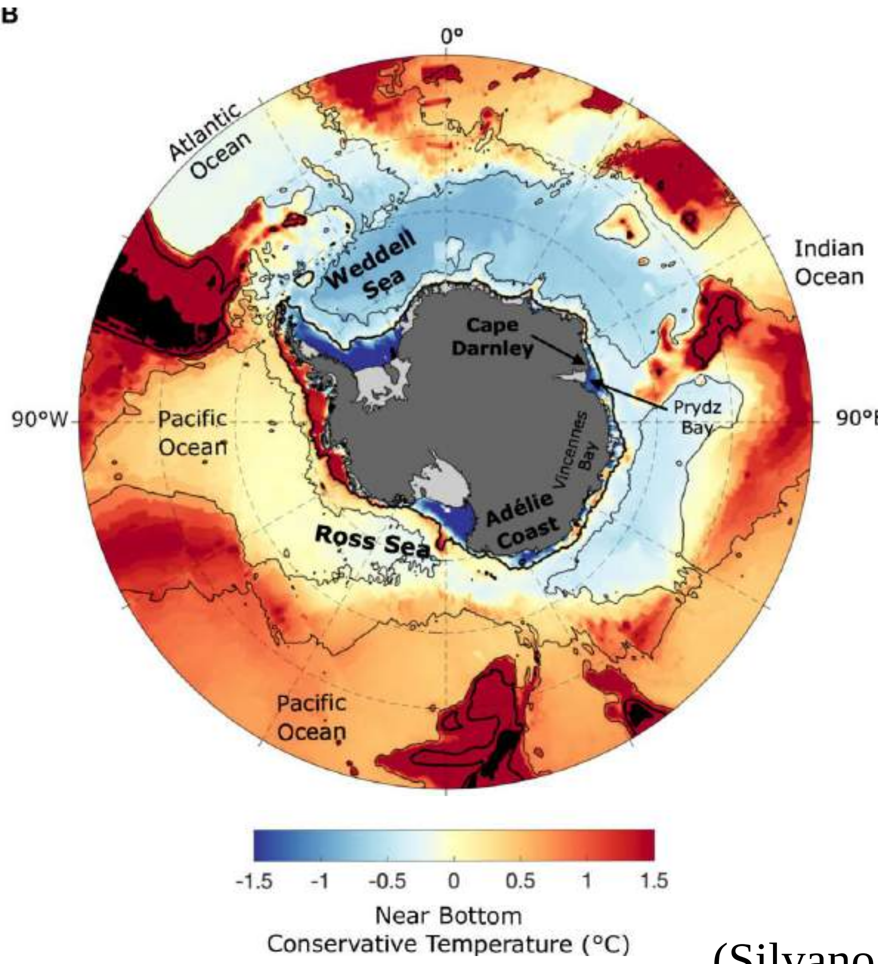


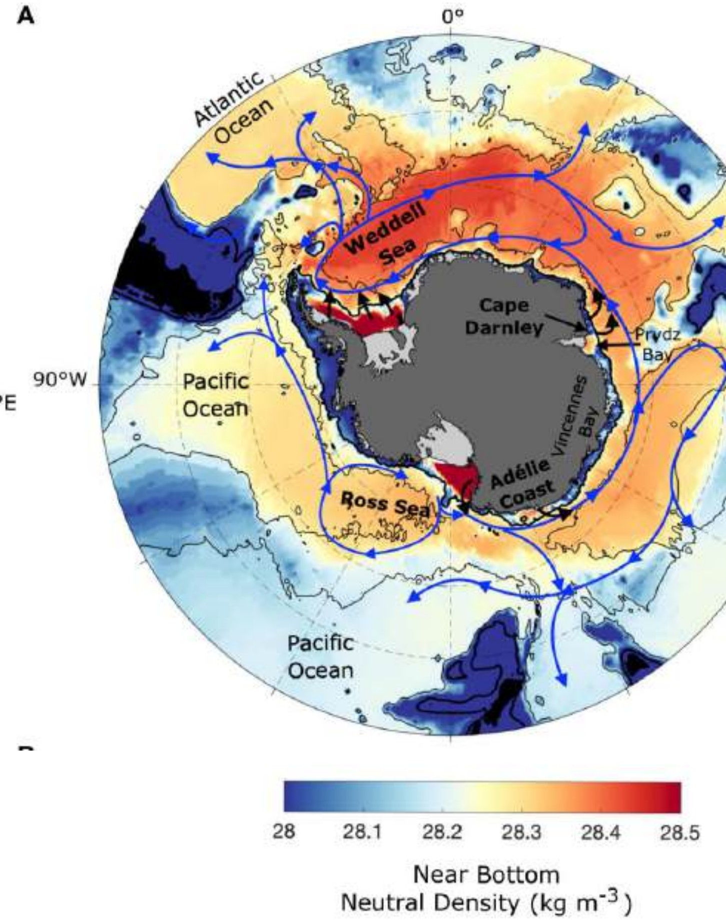
(Silvano et al. 2023)



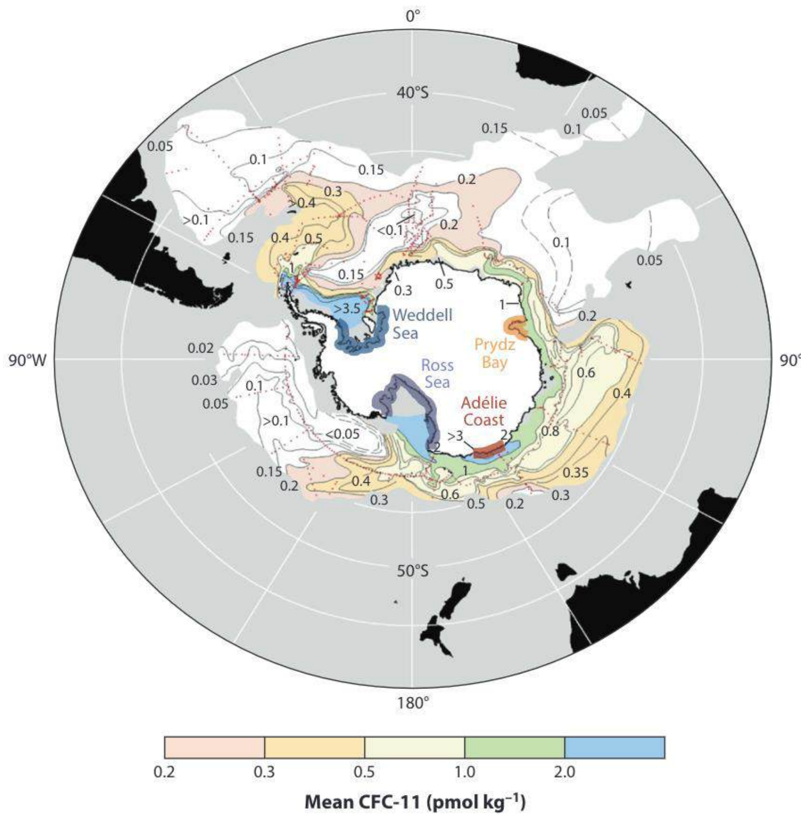
(Talley, 2013)

MOC: Antarctic Bottom Water (AABW)





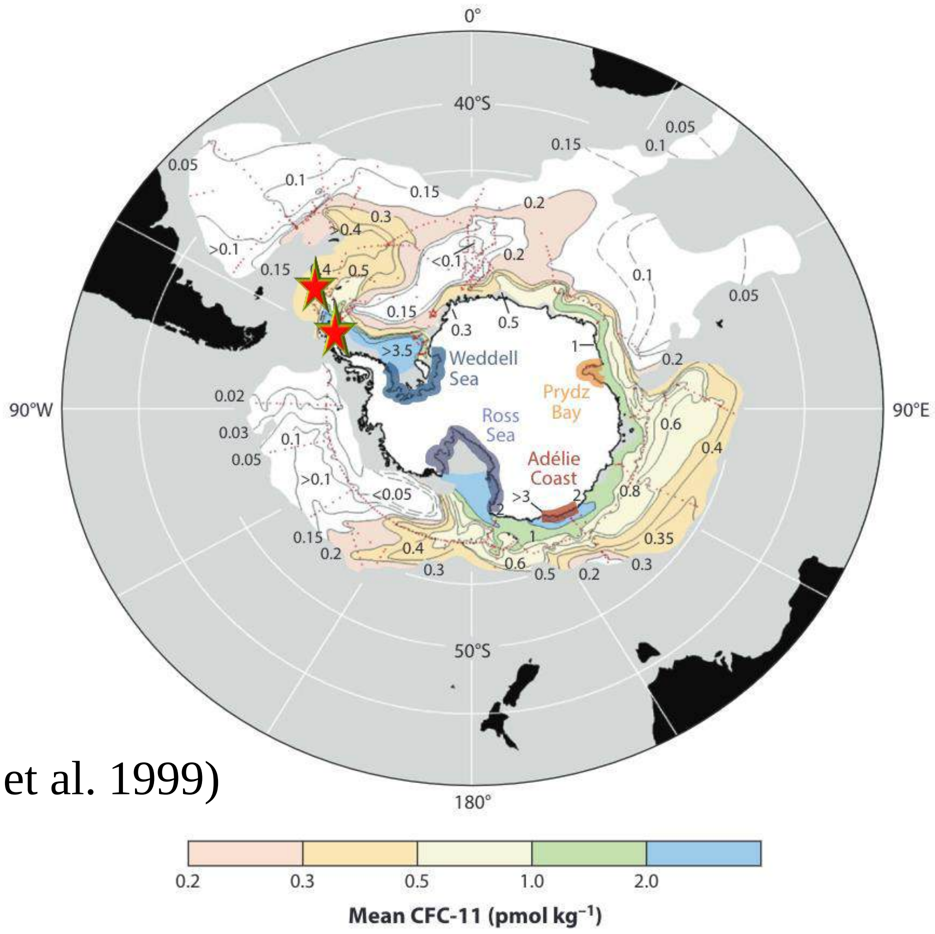
(Silvano et al. 2023)



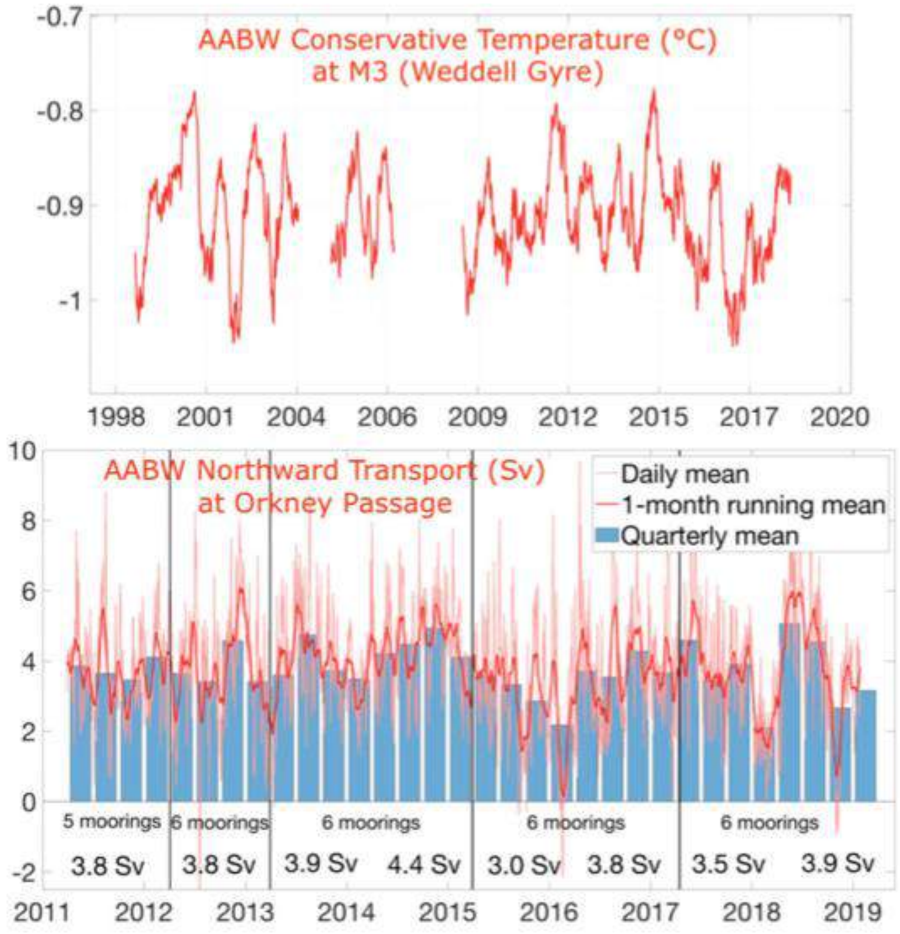
(Orsi et al. 1999)

- AABW is formed in 4 locations around the Antarctic coast

MOC: Antarctic Bottom Water (AABW)



(Orsi et al. 1999)

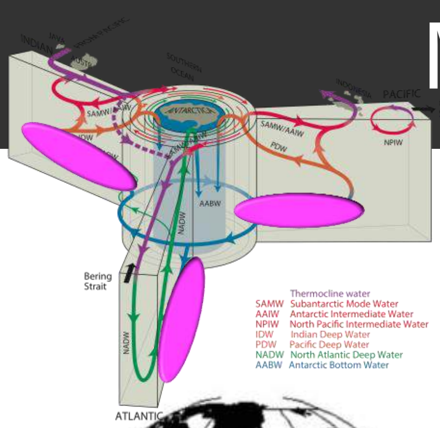


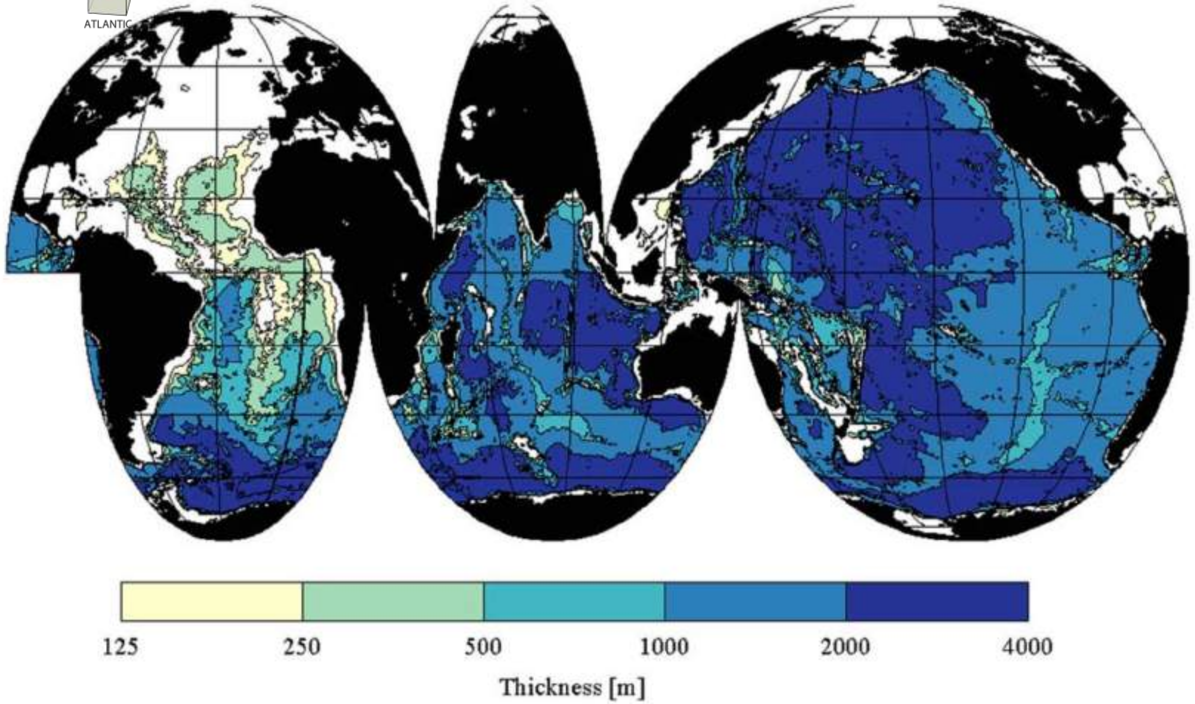
- AABW formation rates have been mostly estimated from ocean properties and tracers

- Limited direct observations of AABW formation show variability in properties and volume

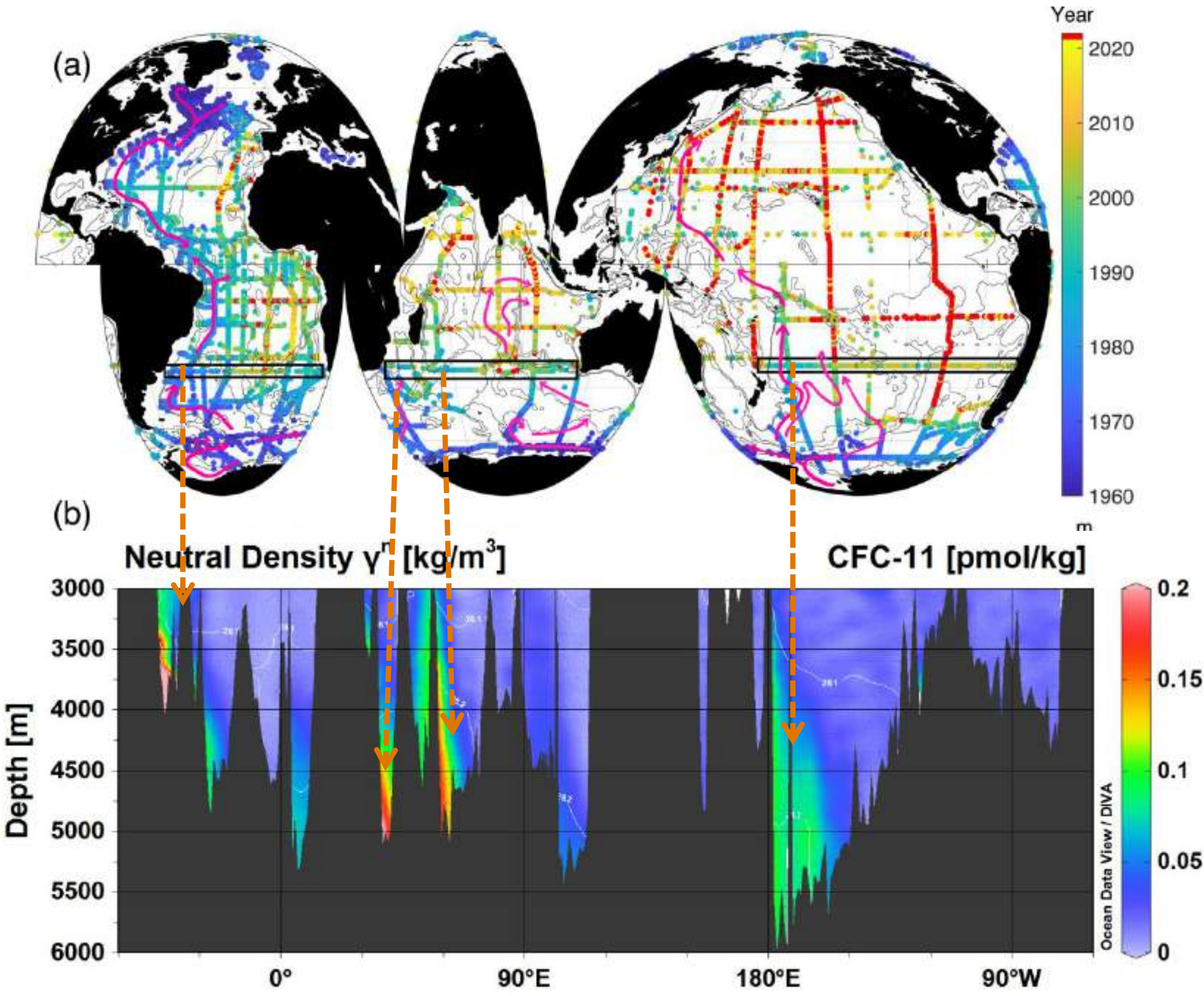
(Silvano et al. 2023)

MOC: Antarctic Bottom Water (AABW)





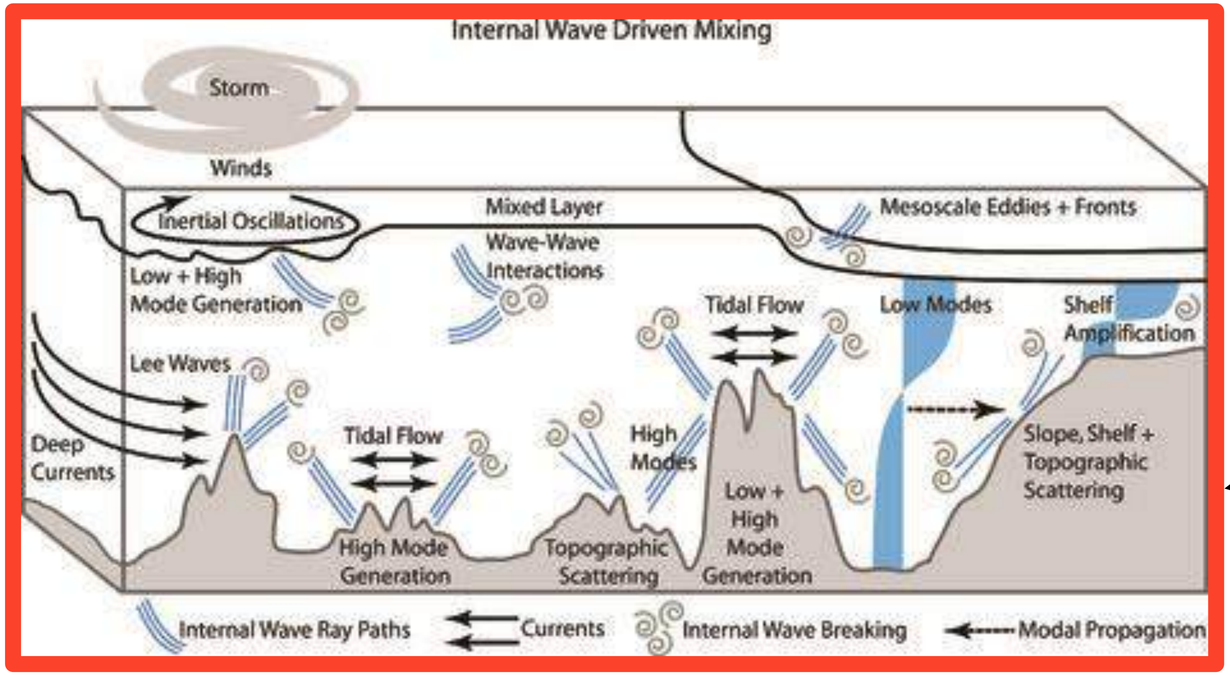
(Johnson 2008)



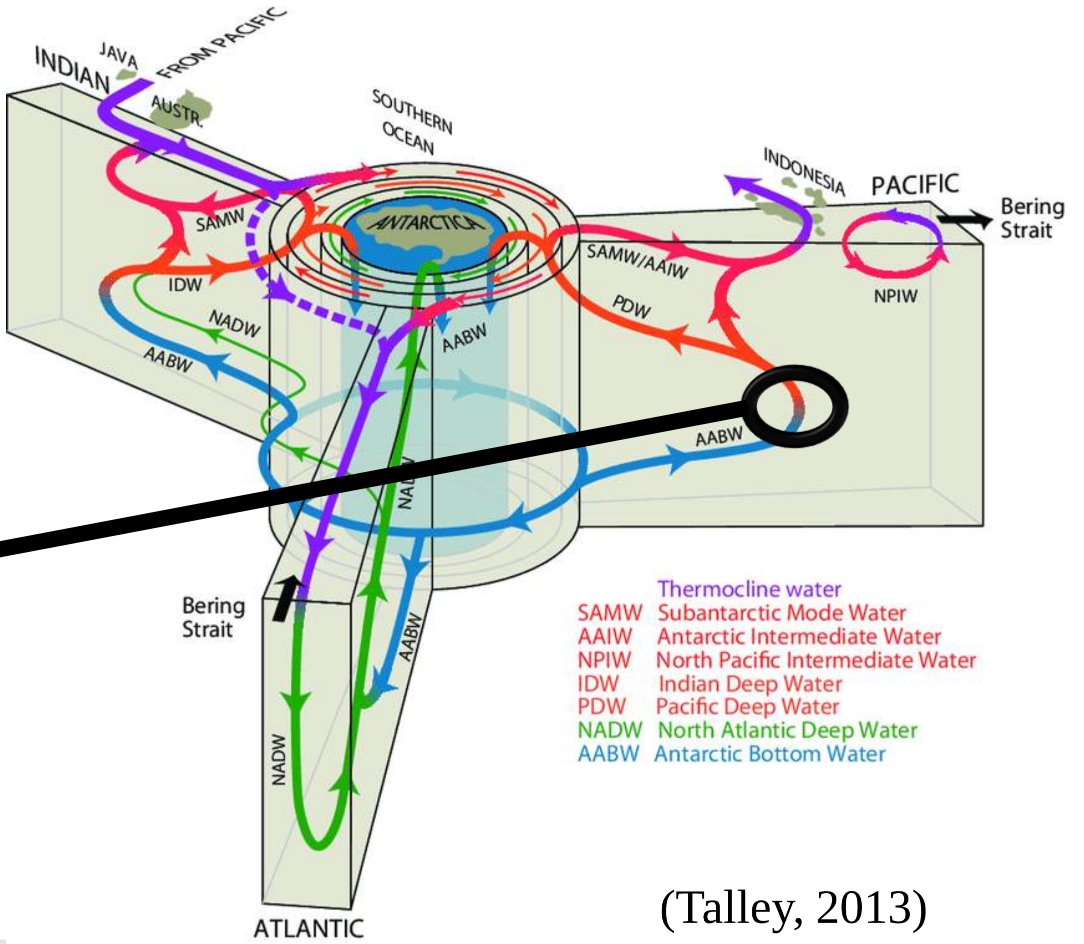
(Purkey et al., 2018)

(Cimoli et al., 2023)

MOC: Mixing



(MacKinnon et al. 2017)

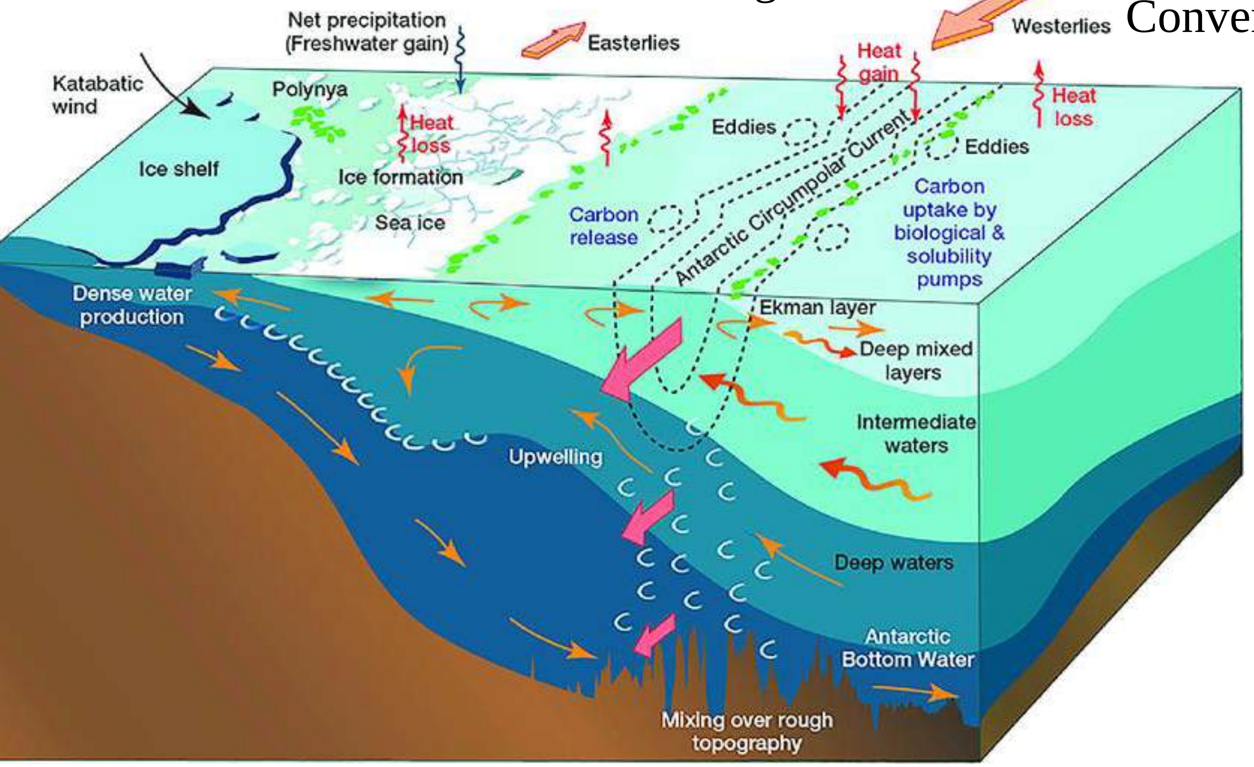


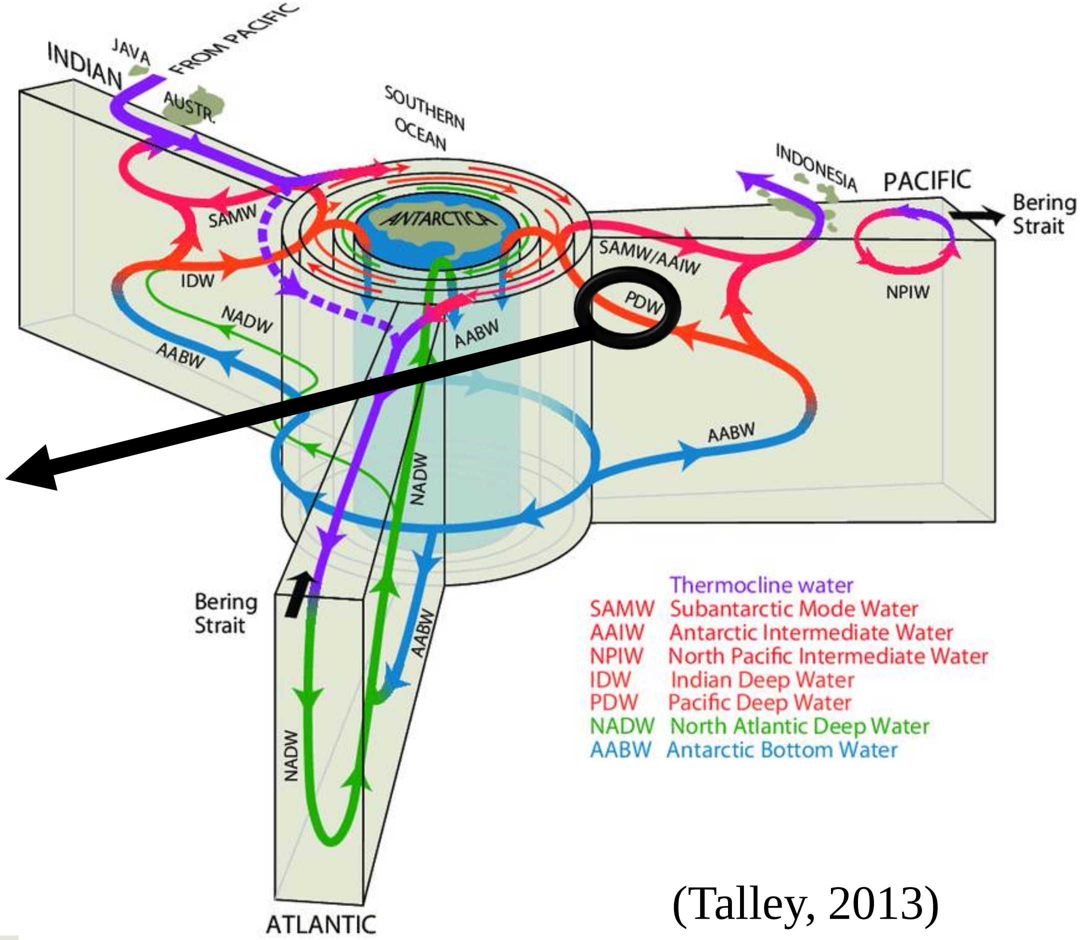
(Talley, 2013)

MOC: Upwelling

Ekman Divergence

Ekman Convergance





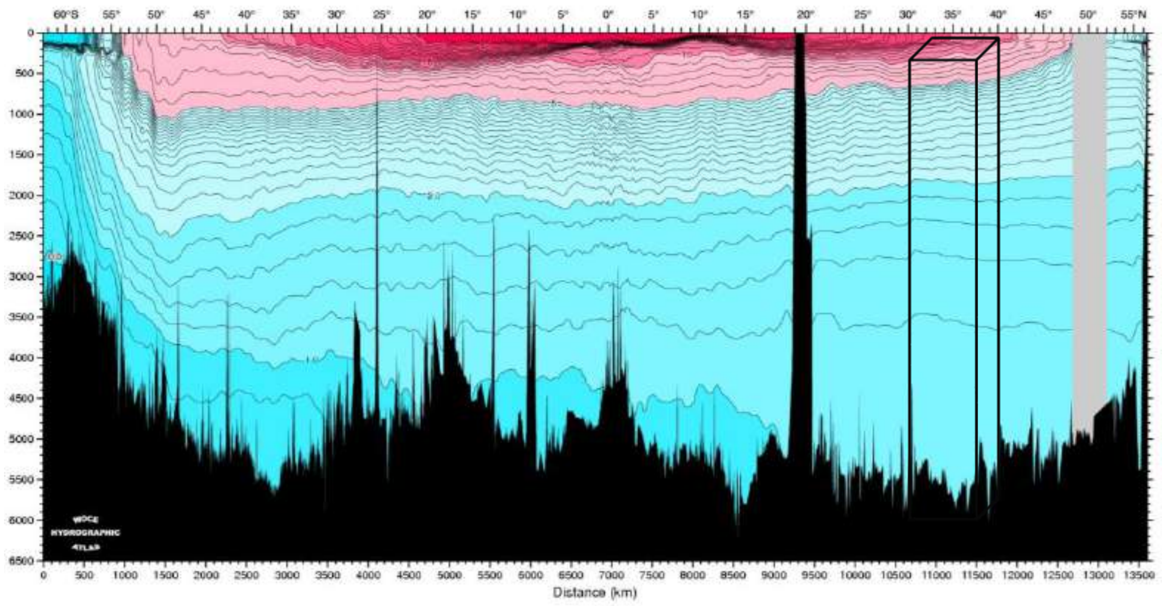
(Talley, 2013)

Bottom limb of the MOC

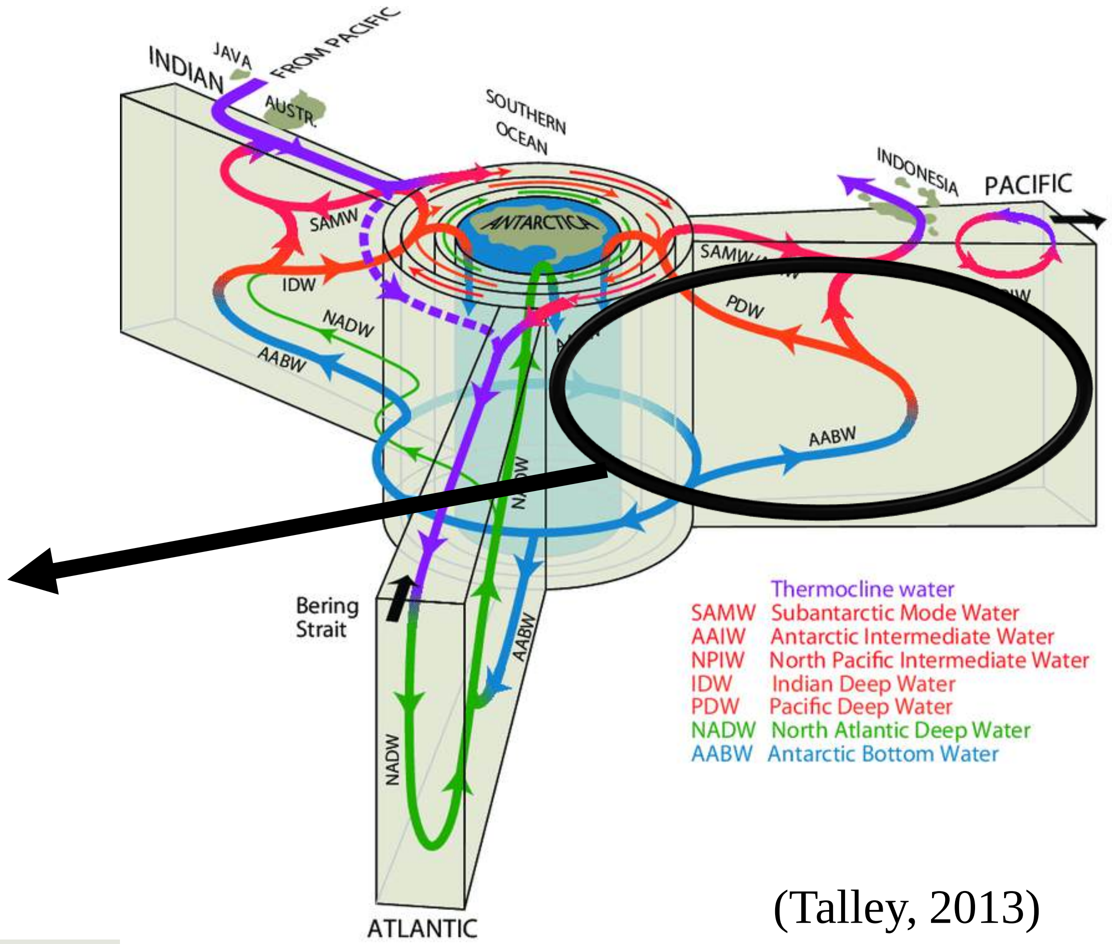
- Bottom water properties are set by the balance between the renewal of deepwater formed around Antarctica and the rate of mixing with overlying water

Pacific

Depth [m]



Latitude [°N]

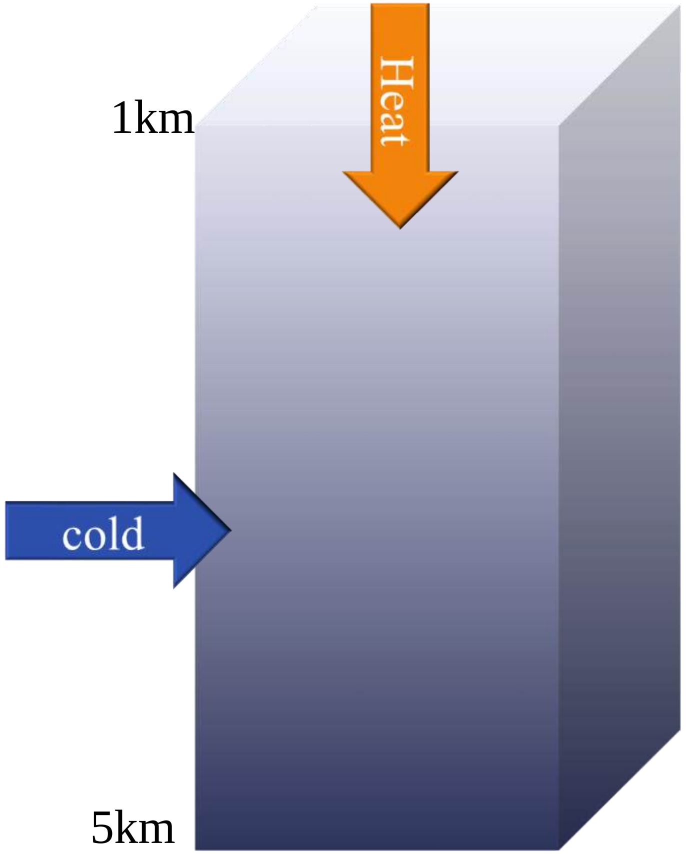


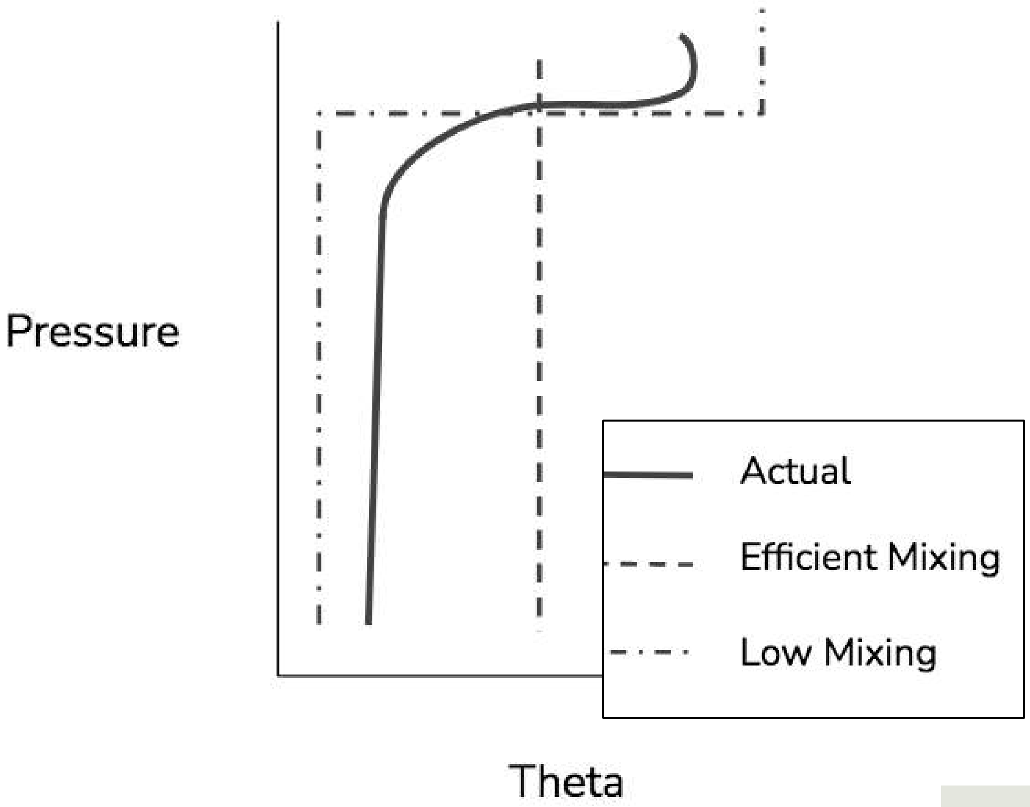
(Talley, 2013)

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

Advection + Mixing = 0

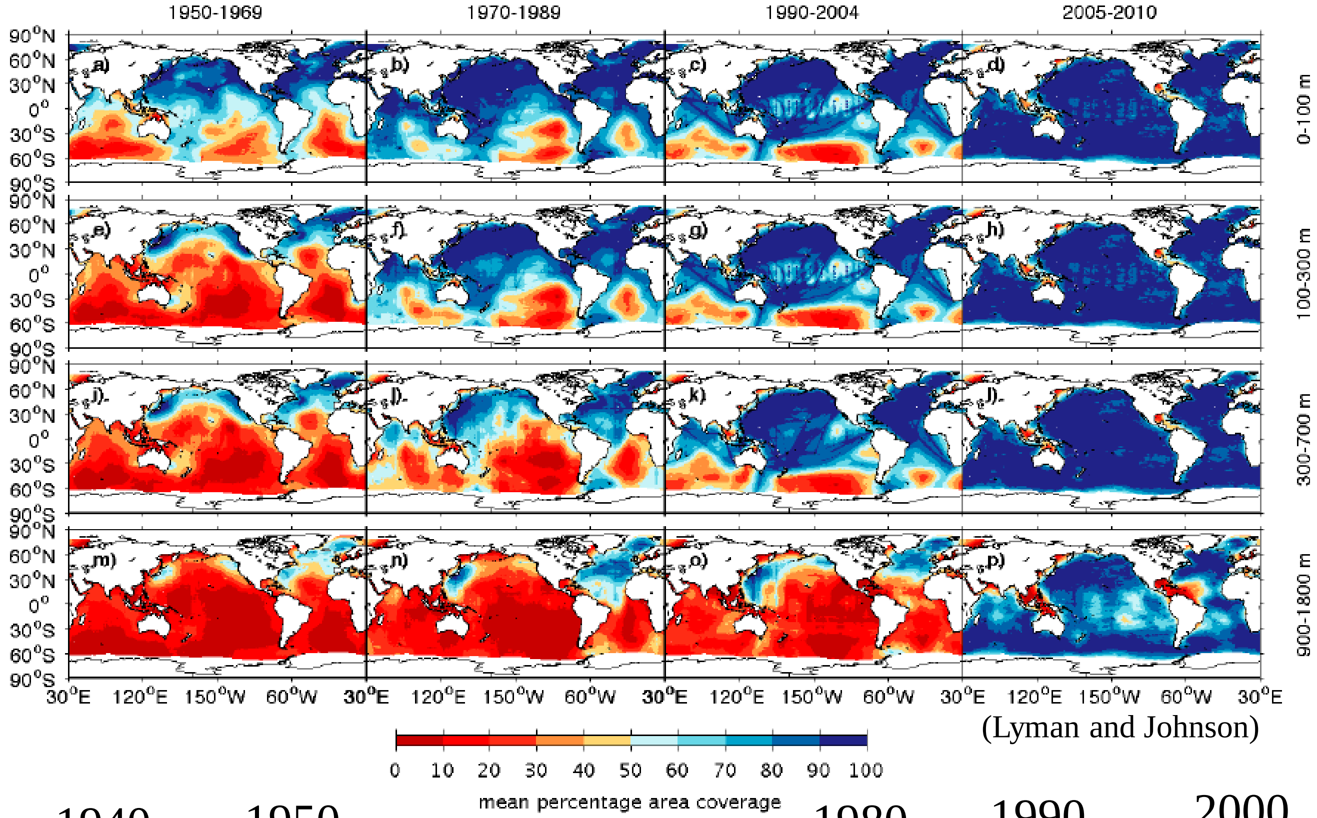




- In steady state, these two processes are equal and bottom temperature is constant in time

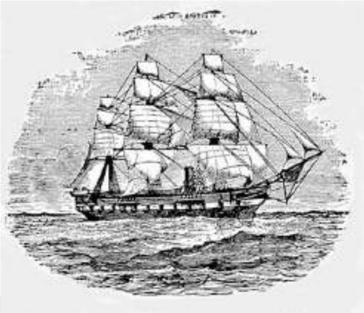
Ocean observation

Temperature is the oldest and best measured parameter !



(Lyman and Johnson)

1930 1940 1950 1960 1970 1980 1990 2000



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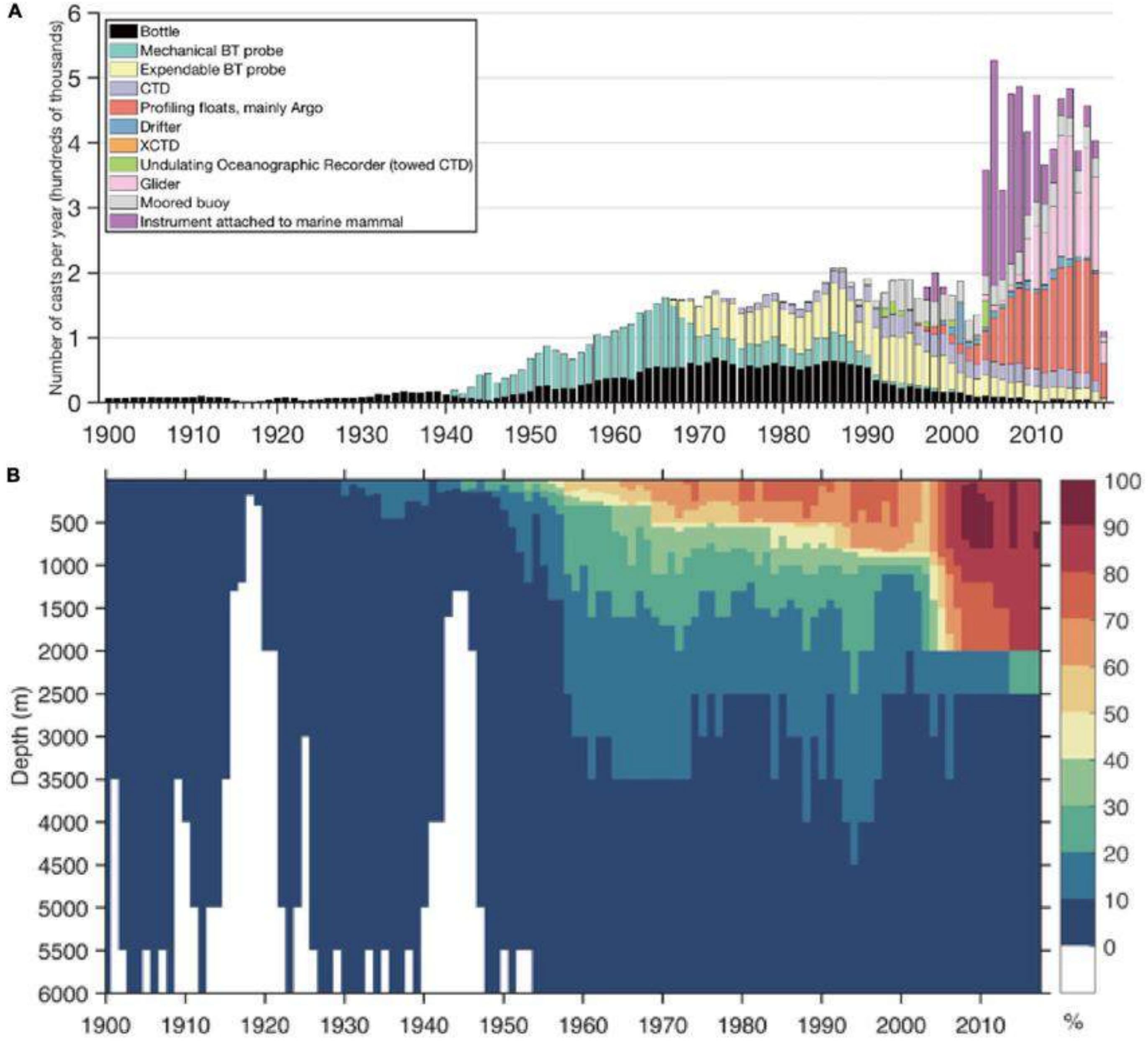
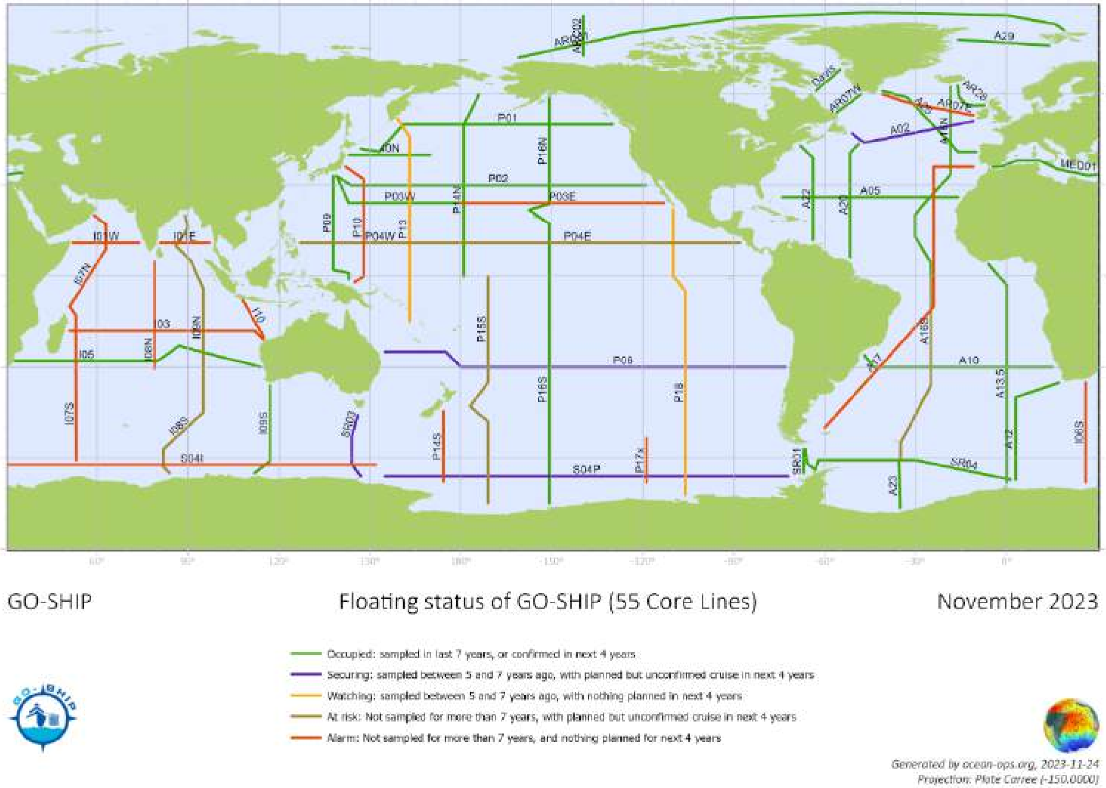
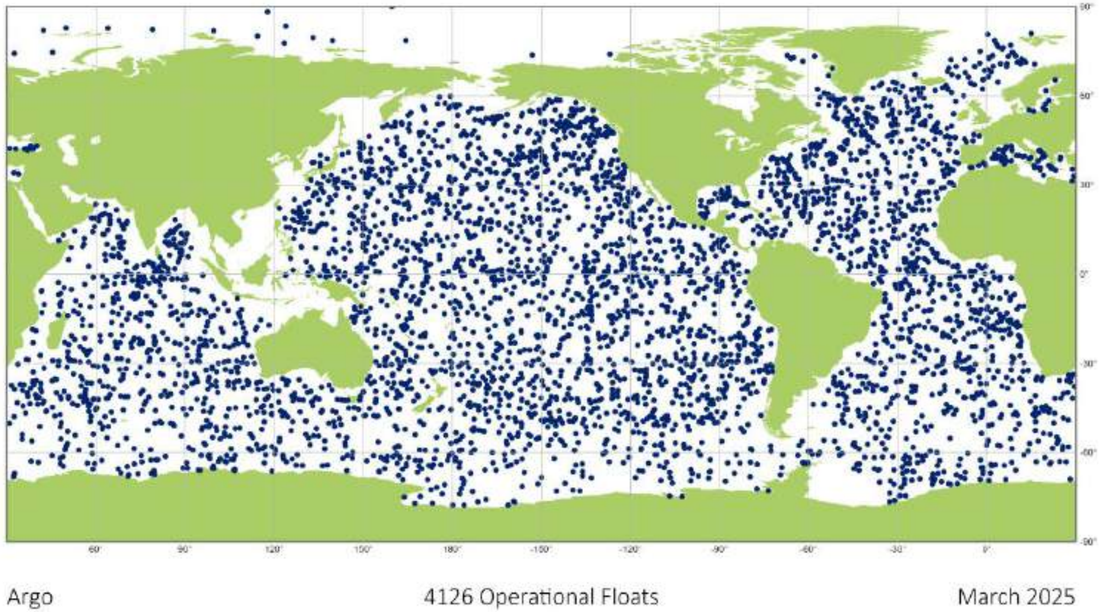


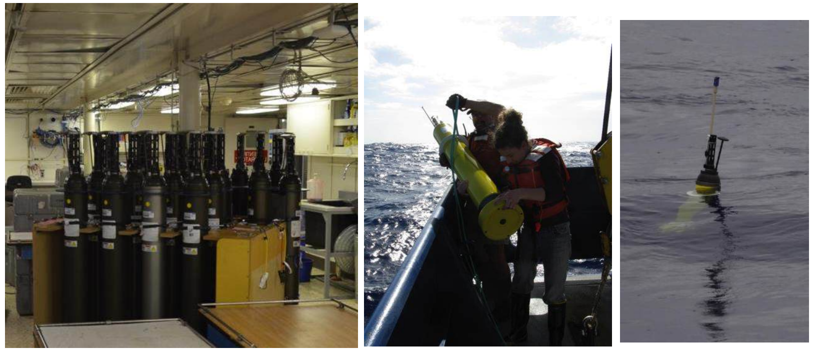
Observing the Interior Ocean

GO-SHIP



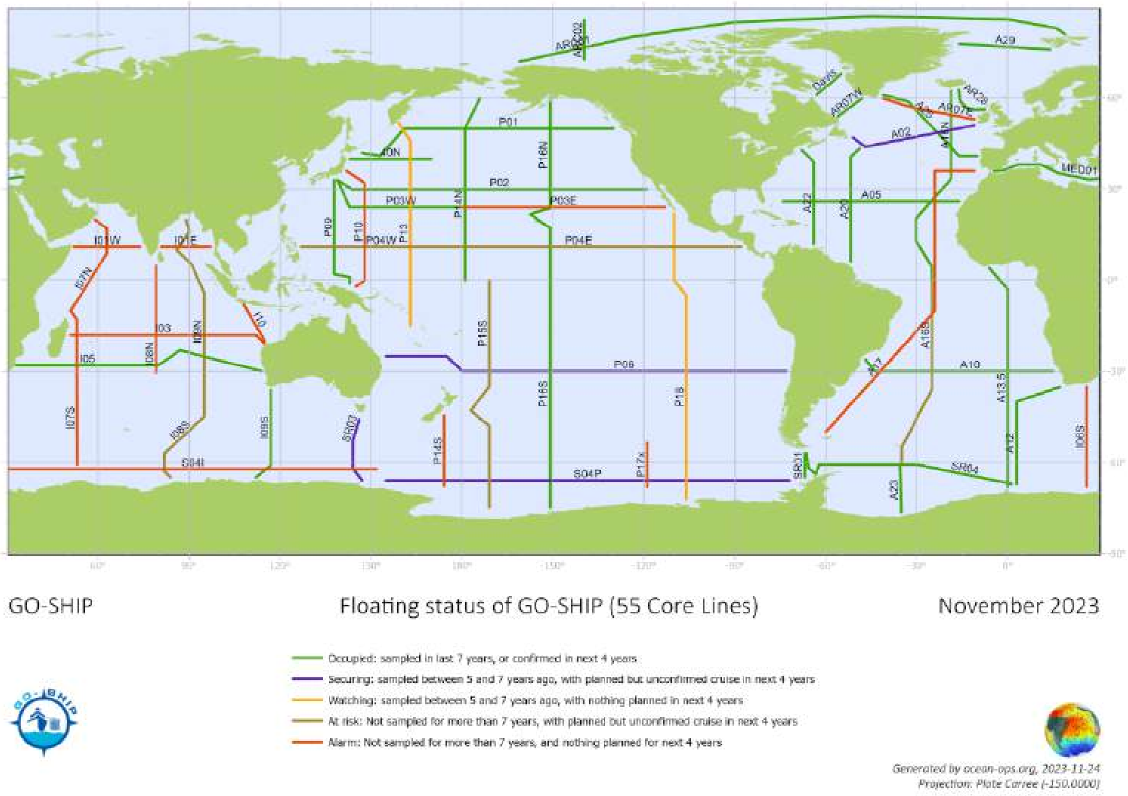
Argo

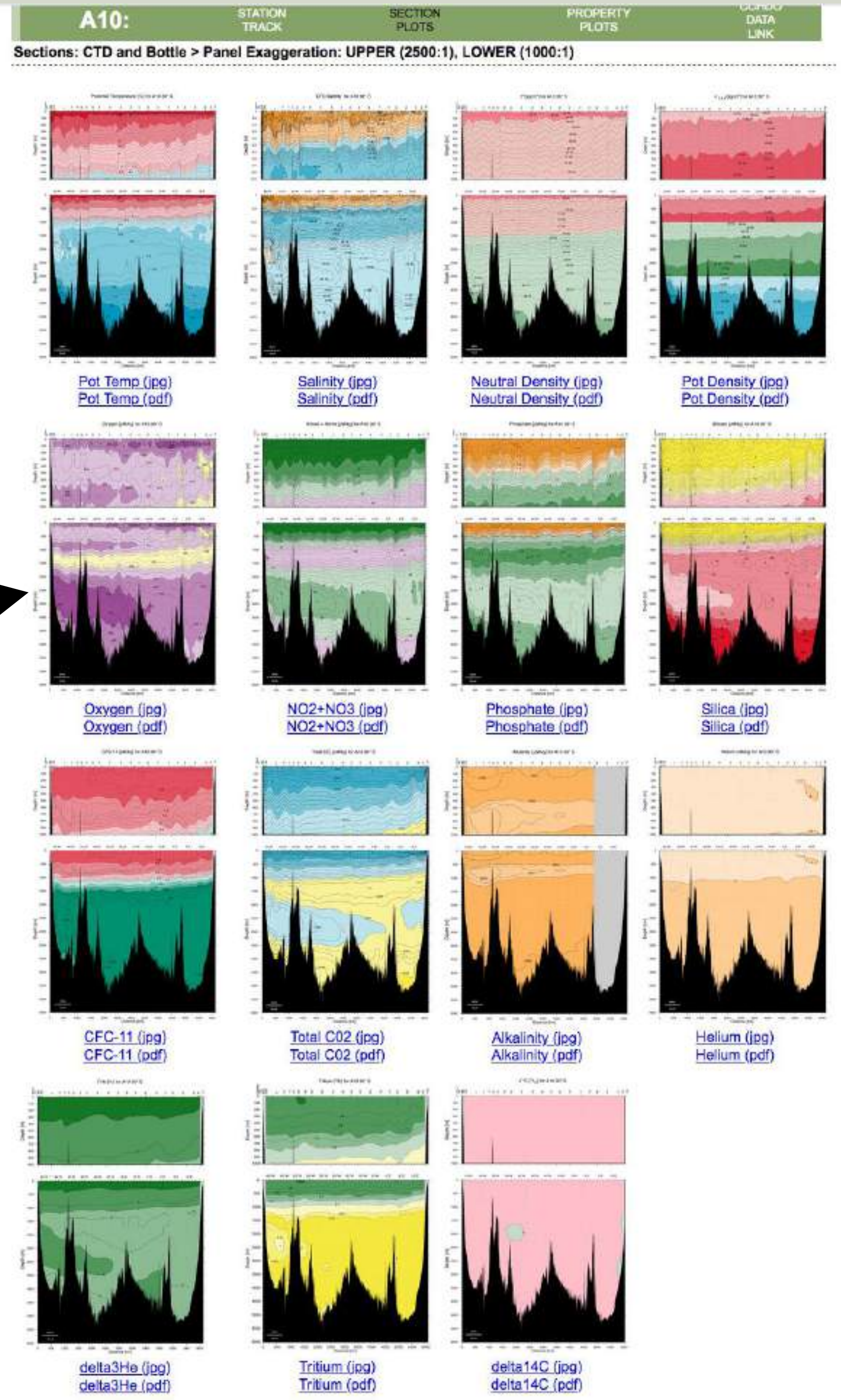




GO-SHIP Measurements

WOCE: World ocean circulations experiment



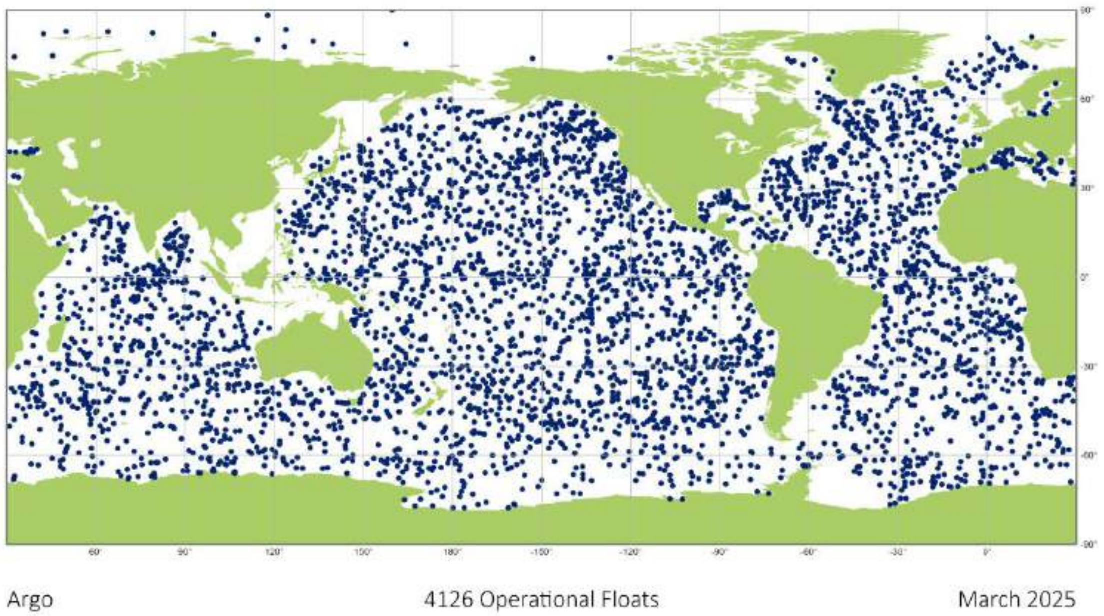


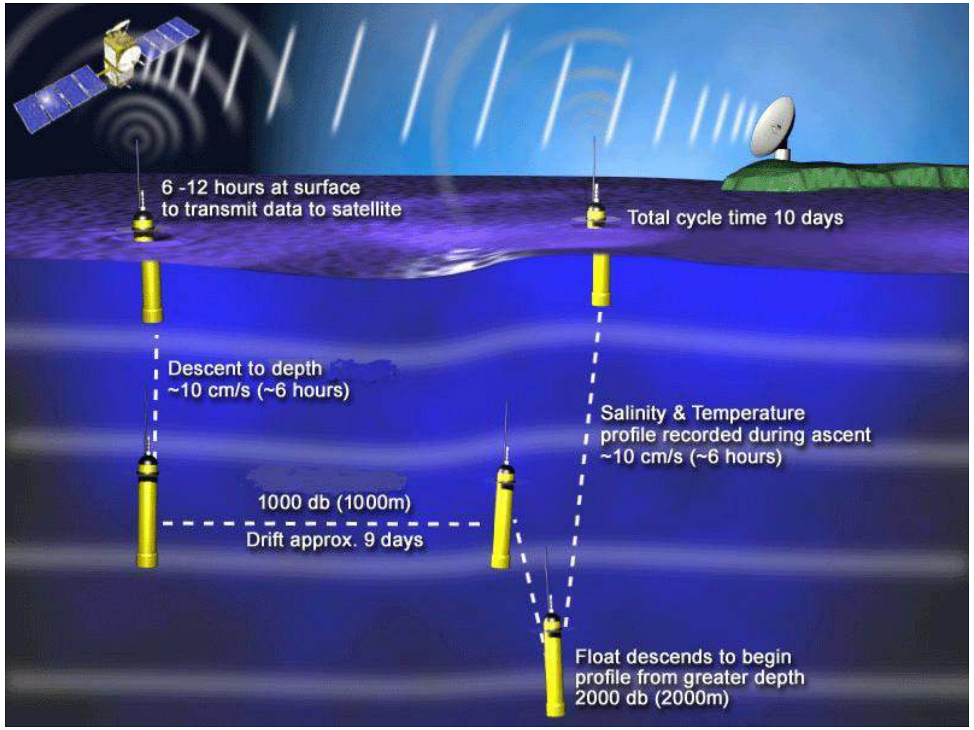
Full-depth, highest quality, multiparters ocean transects with decadal reoccupations for assessing variability

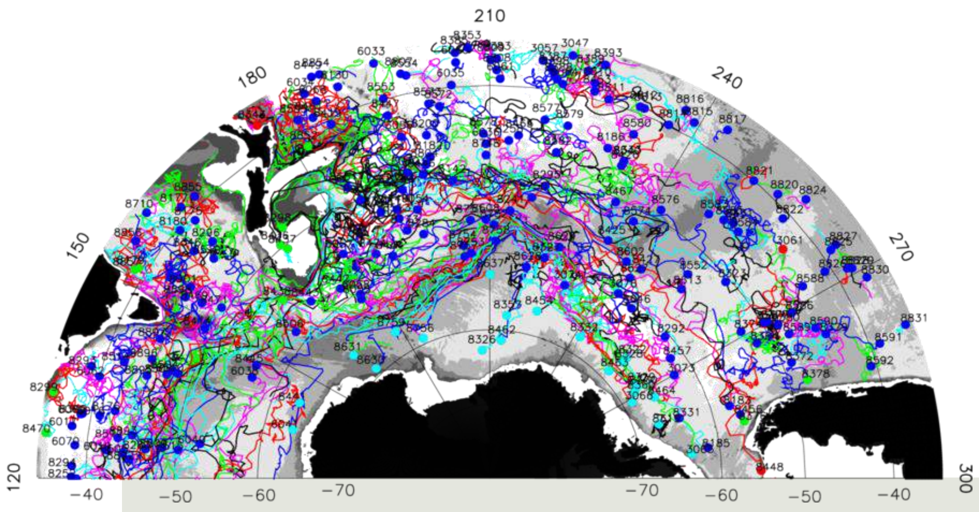
(https://www.go-ship.org/)

Repeat hydrography

Argo

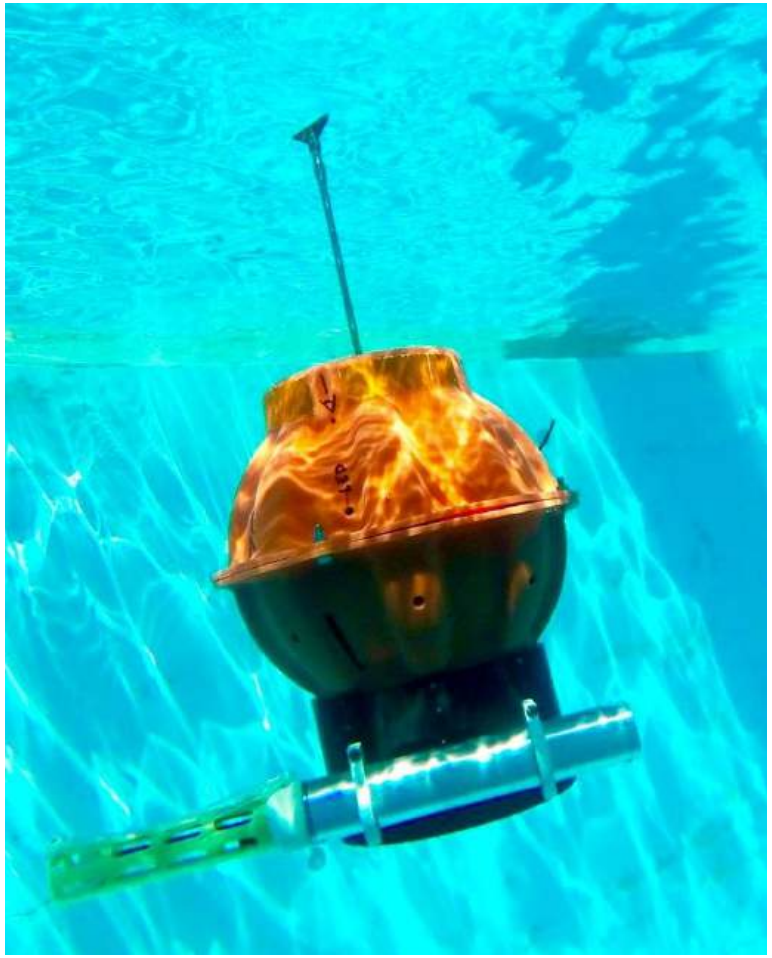


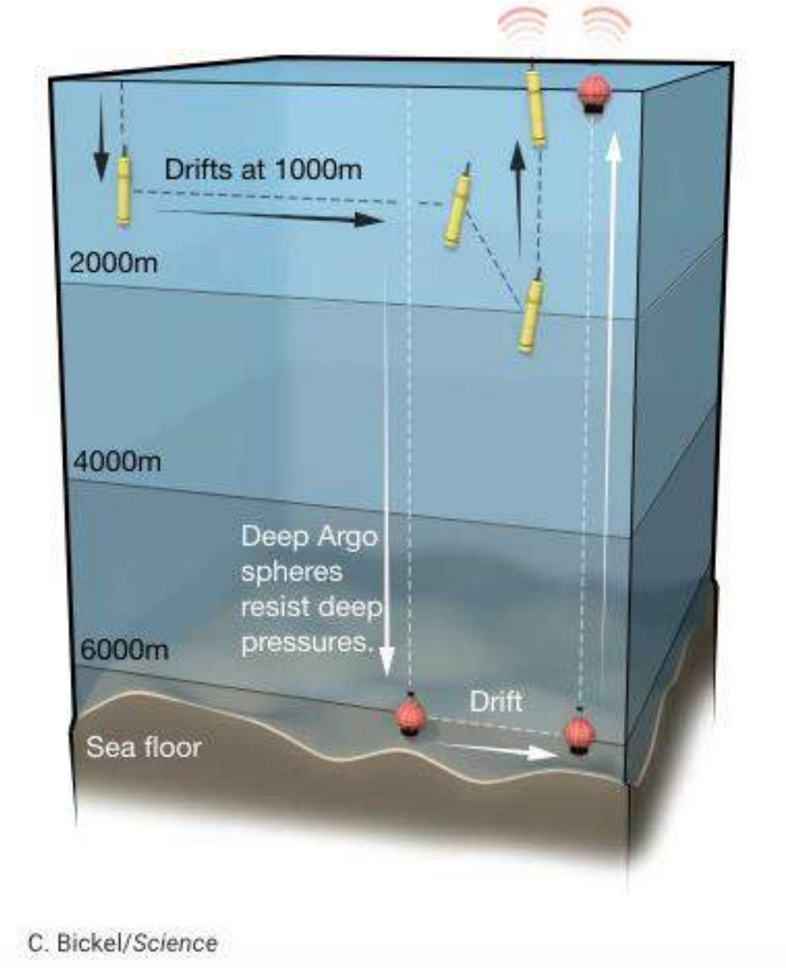




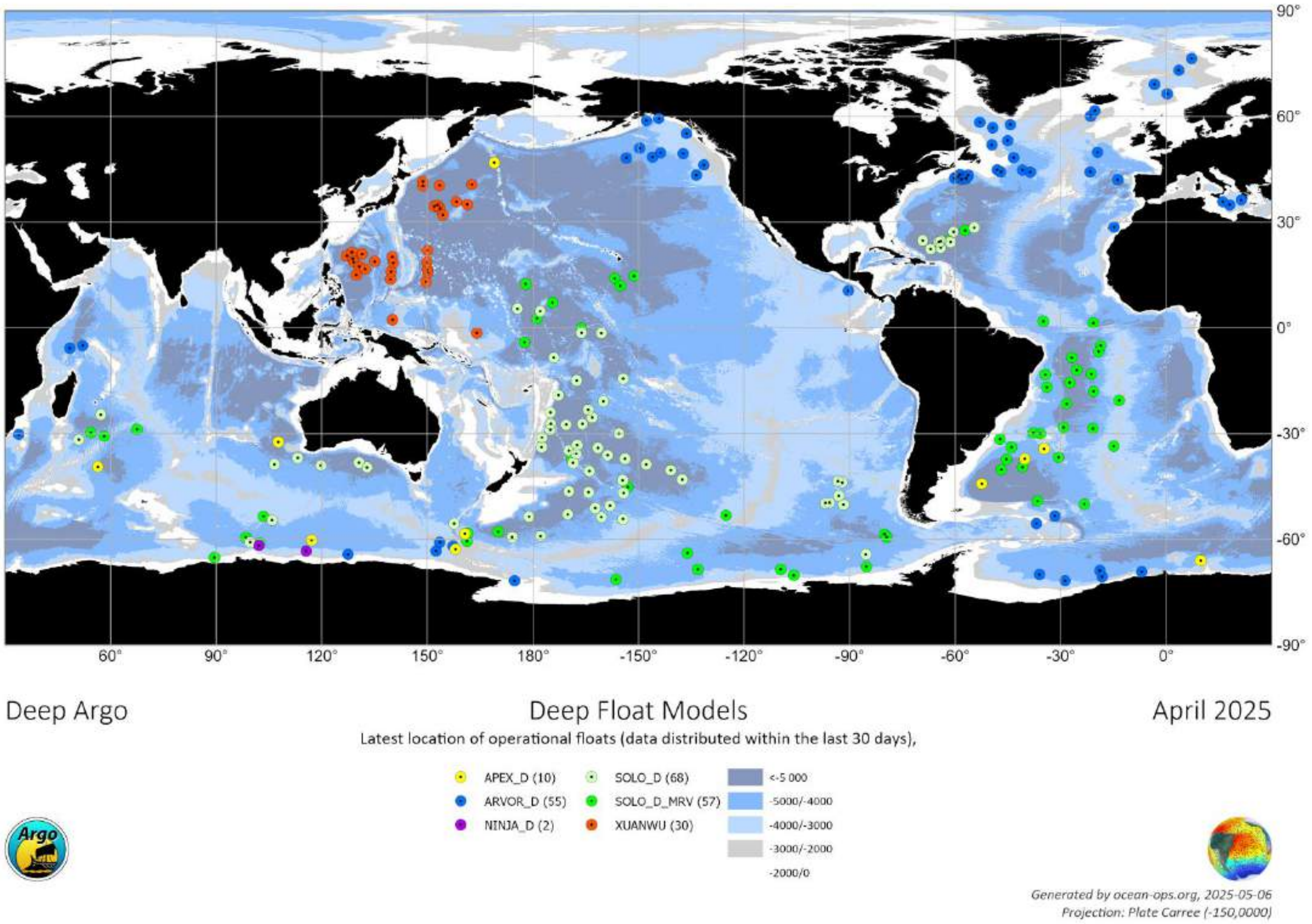
~12k profiles randomly distributed throughout the global ocean from 0-2000m, plus 1000m reference velocity

Deep Argo: 3 x deeper



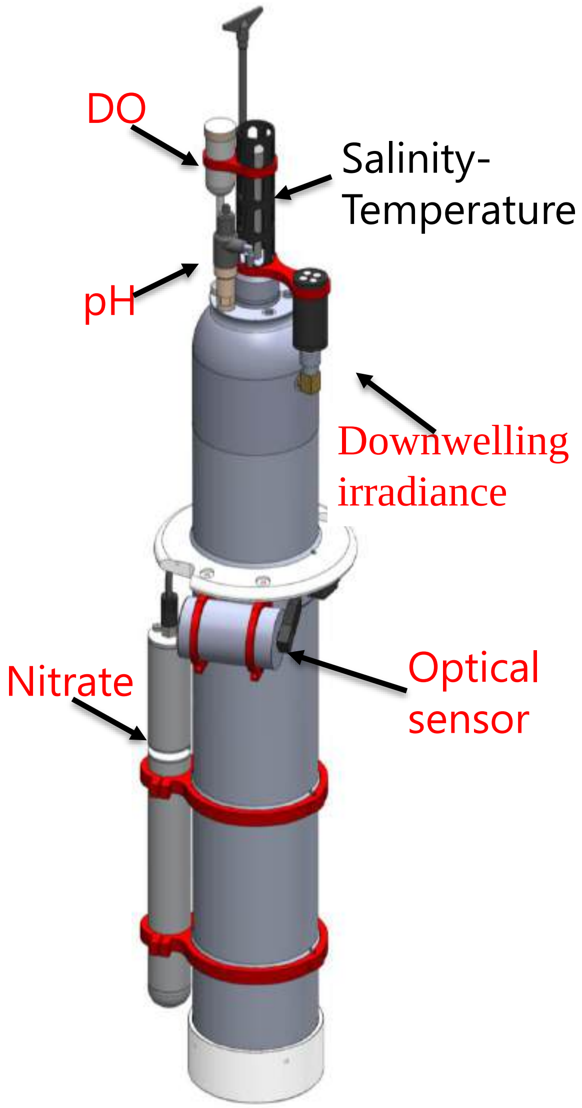


Deep Argo



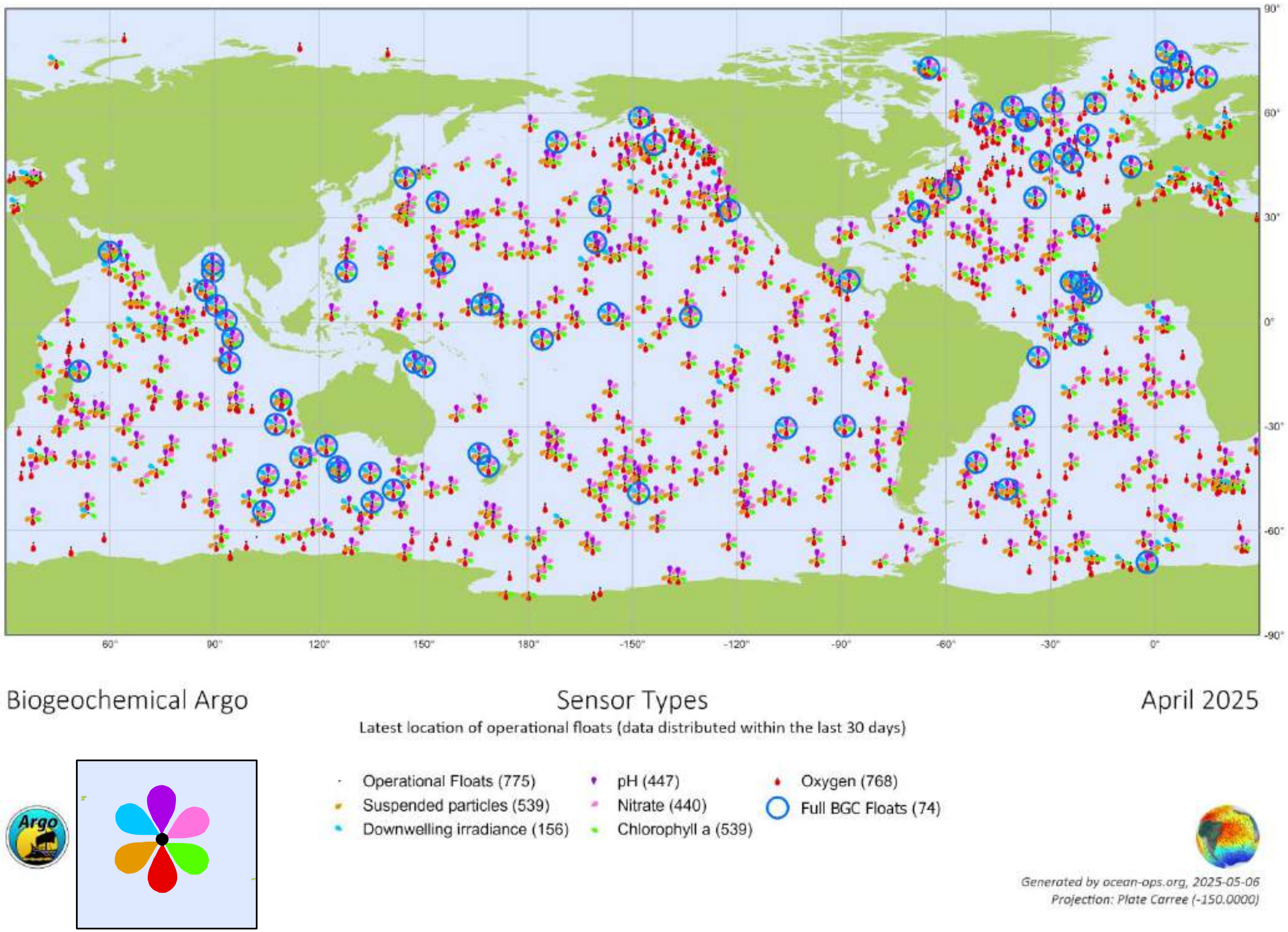
- 222 active Deep floats (some 4000 dbar max depth, some 6000 dbar max depth)

BGC Argo



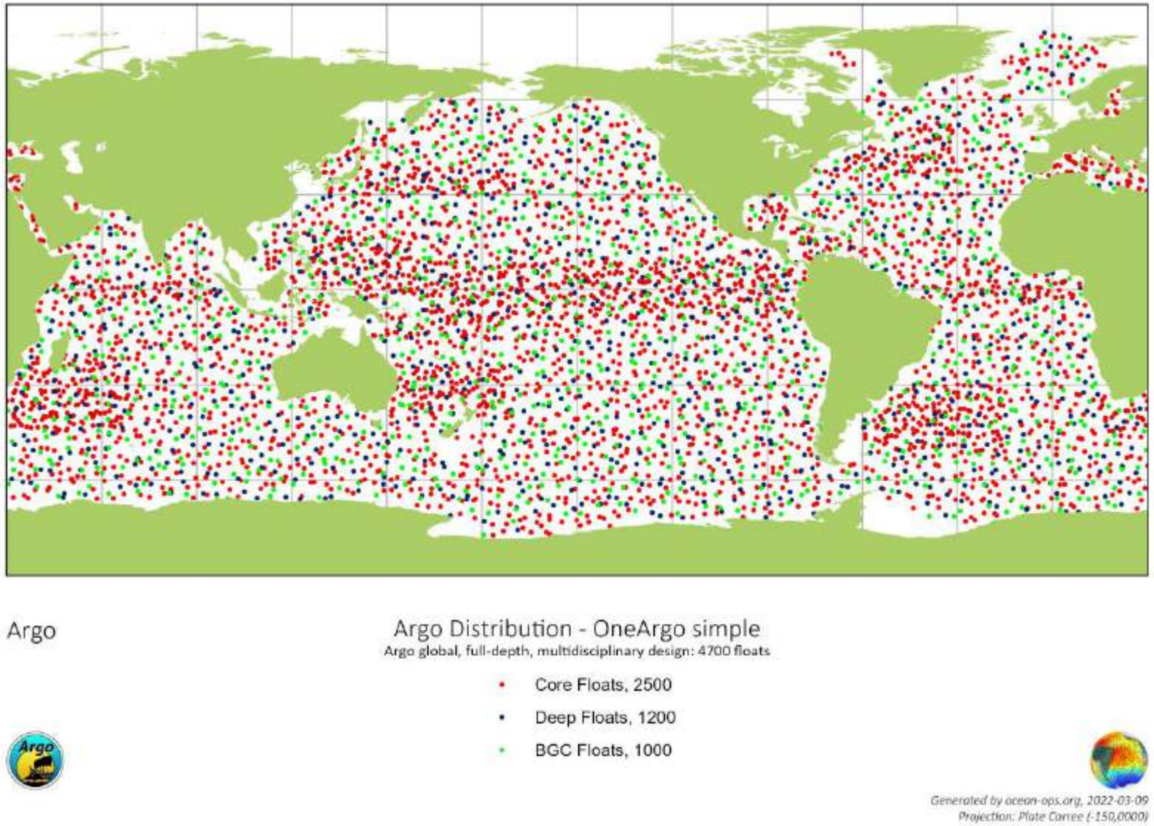
Salinity, temperature, depth	Ocean heat, freshwater, and circulation; Steric sea level rise
Oxygen	Deoxygenation; Ocean ventilation rates
pH	Ocean carbon uptake; Ocean acidification
Nitrate	Nutrient availability
Chlorophyll a	Phytoplankton abundance (fisheries); primary production
Backscatter	Suspended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

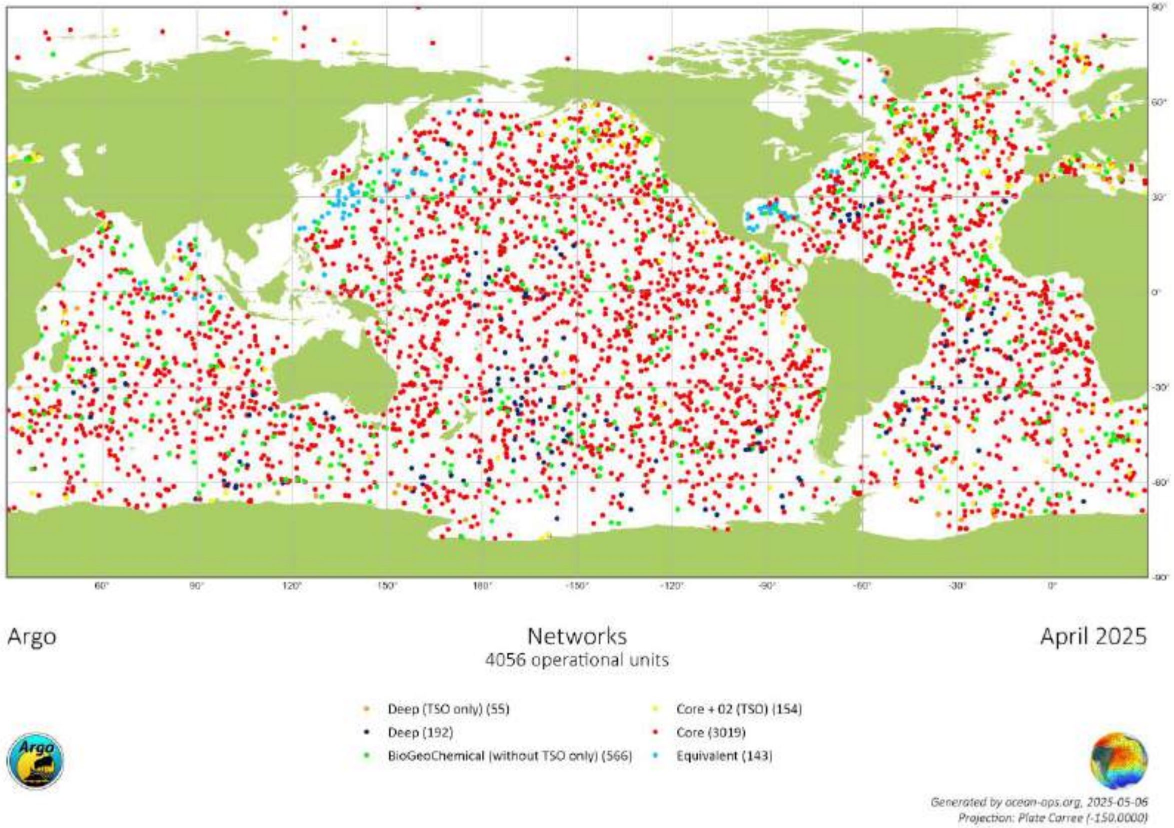
BGC Argo



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

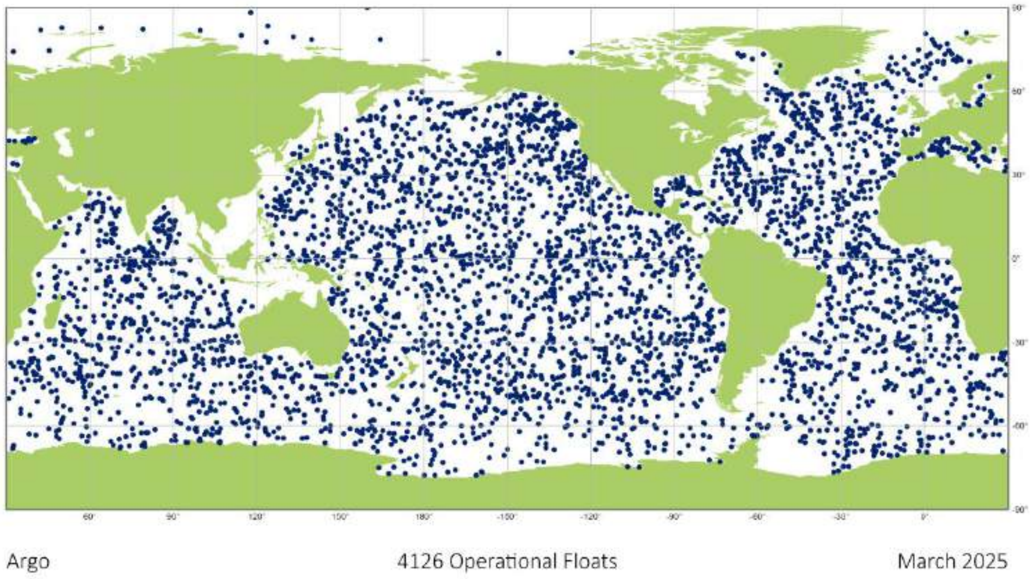
Progress towards One Argo

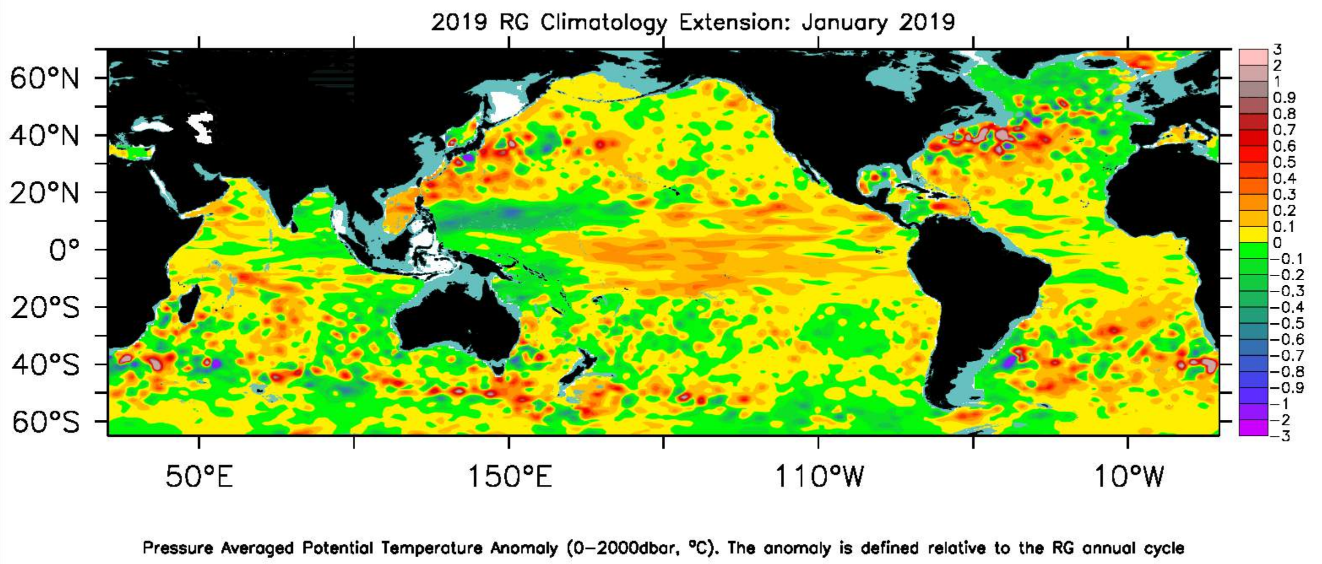


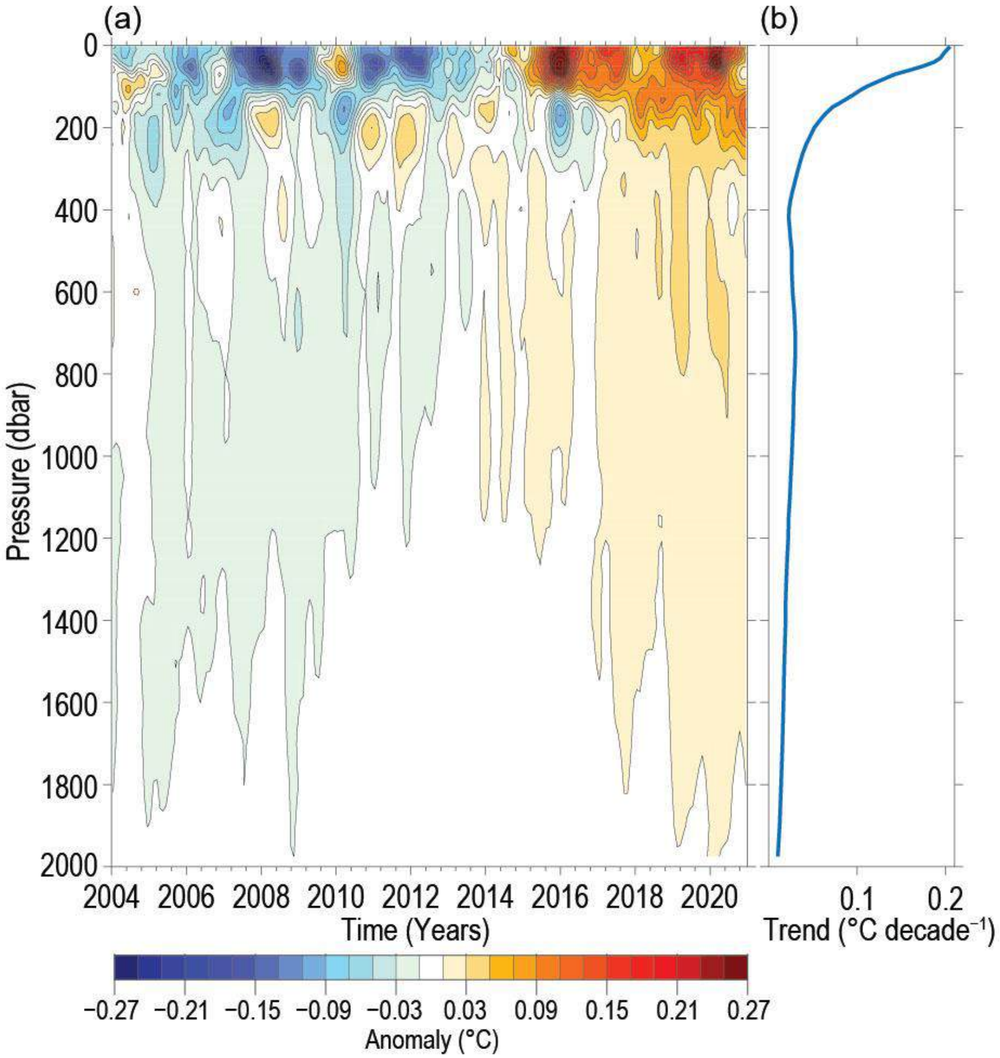


Ocean warming

Upper ocean heat content

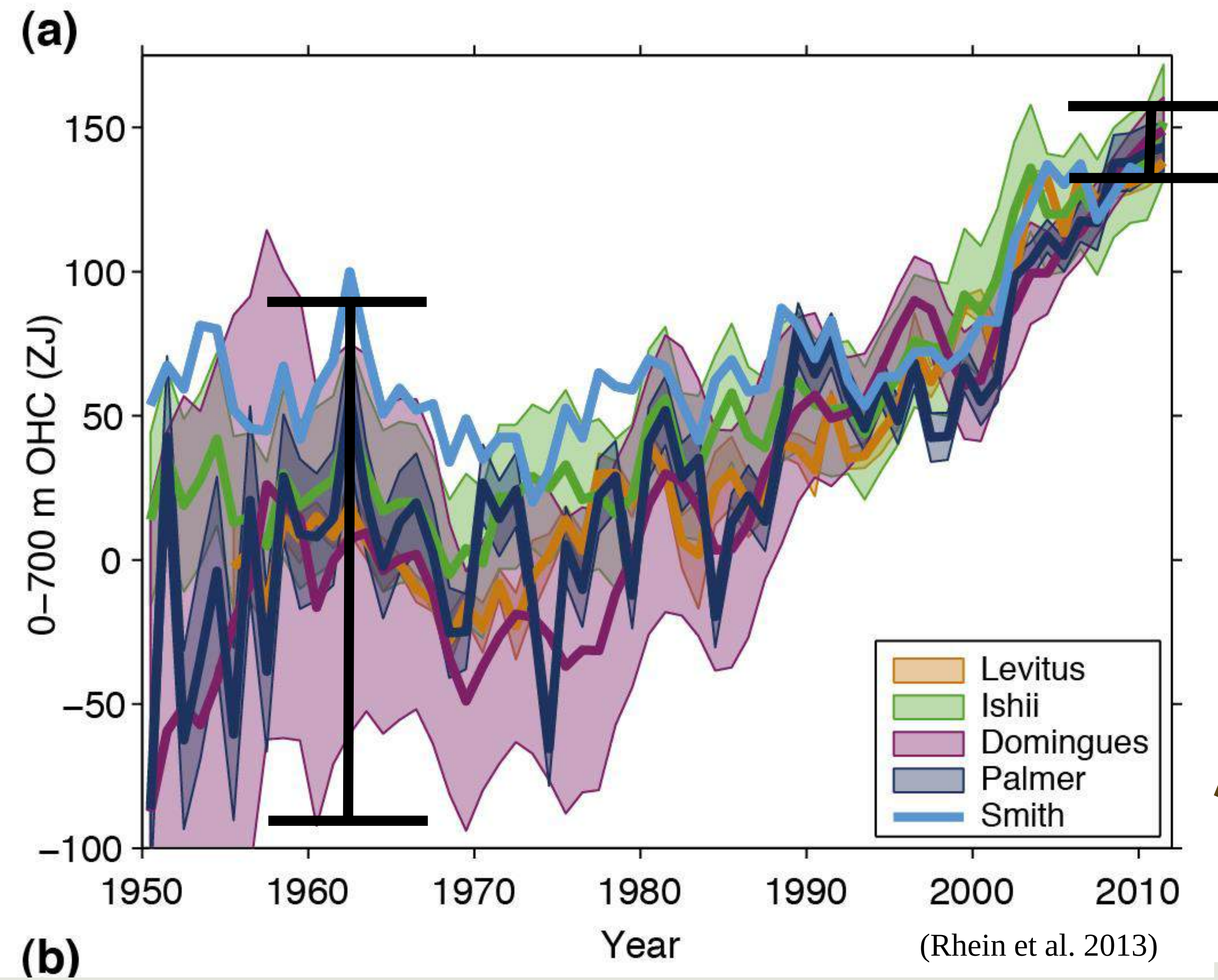






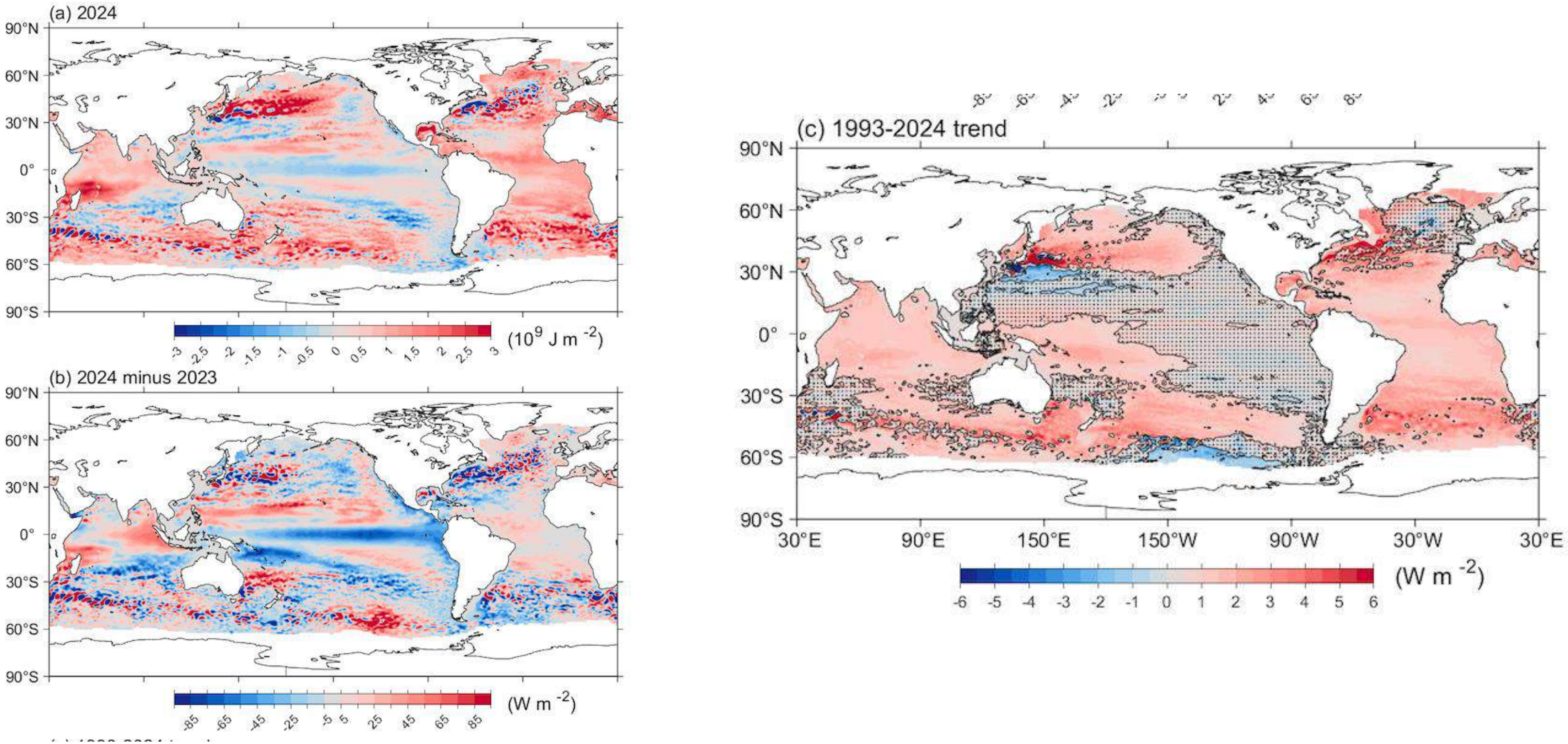
(Roemmich and Gilson)

Upper ocean heat content



(Rhein et al. 2013)

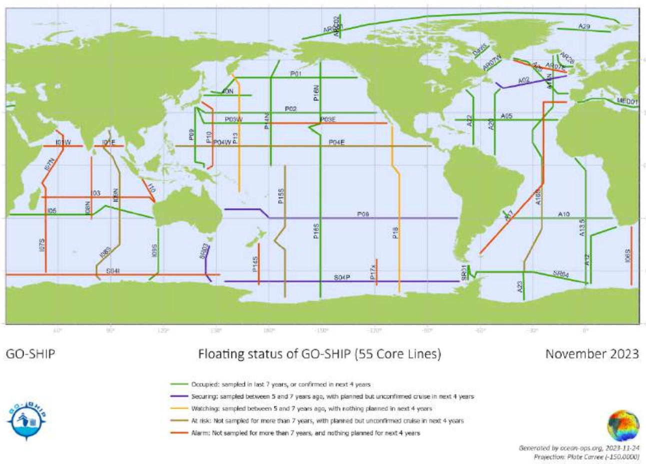
OHC: 0-2000m

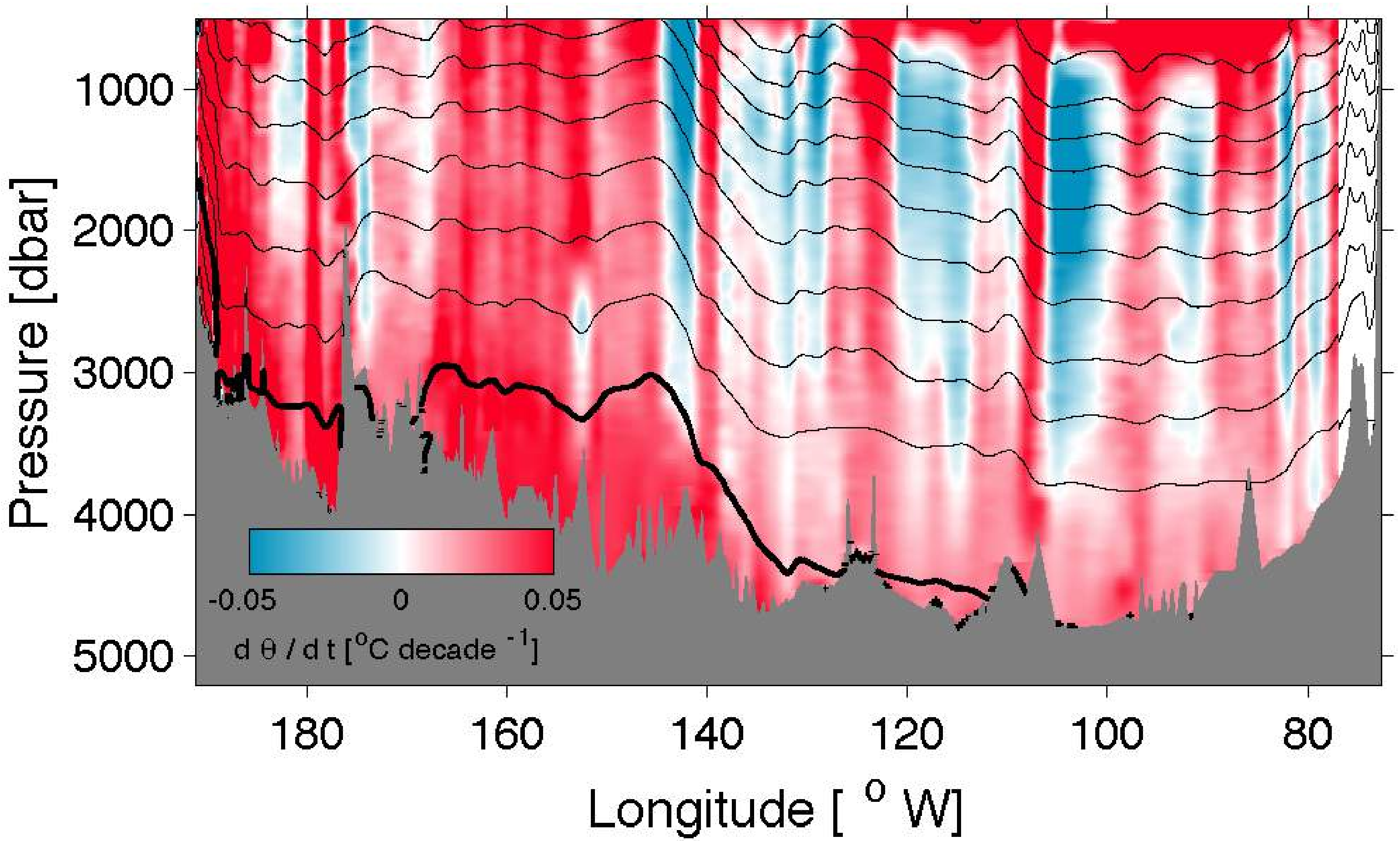


(2024 State of the climate, personal communication Greg Johnson)

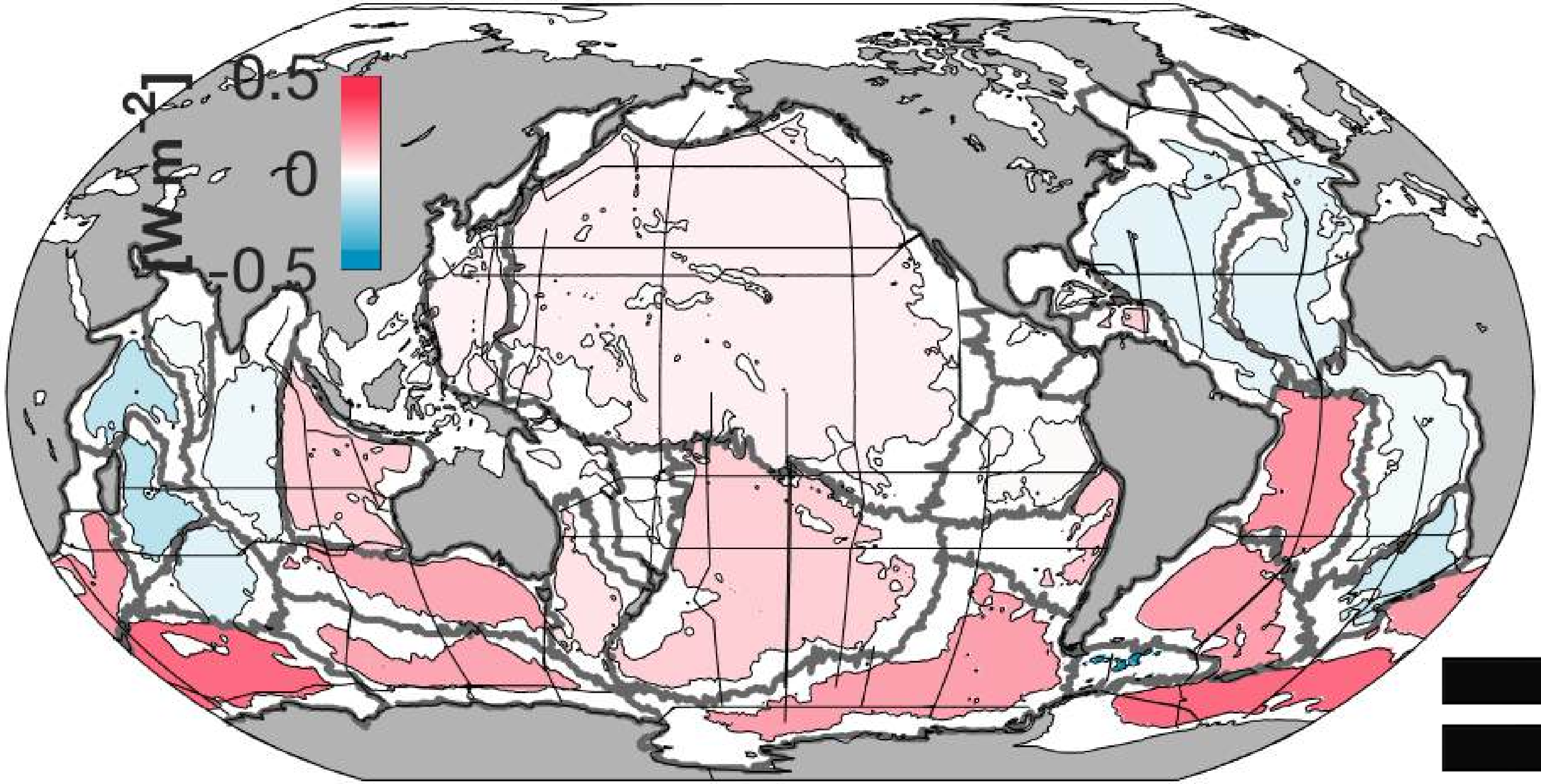
Below Argo?

Along WOCE Section





Accumulation of heat below 4000m



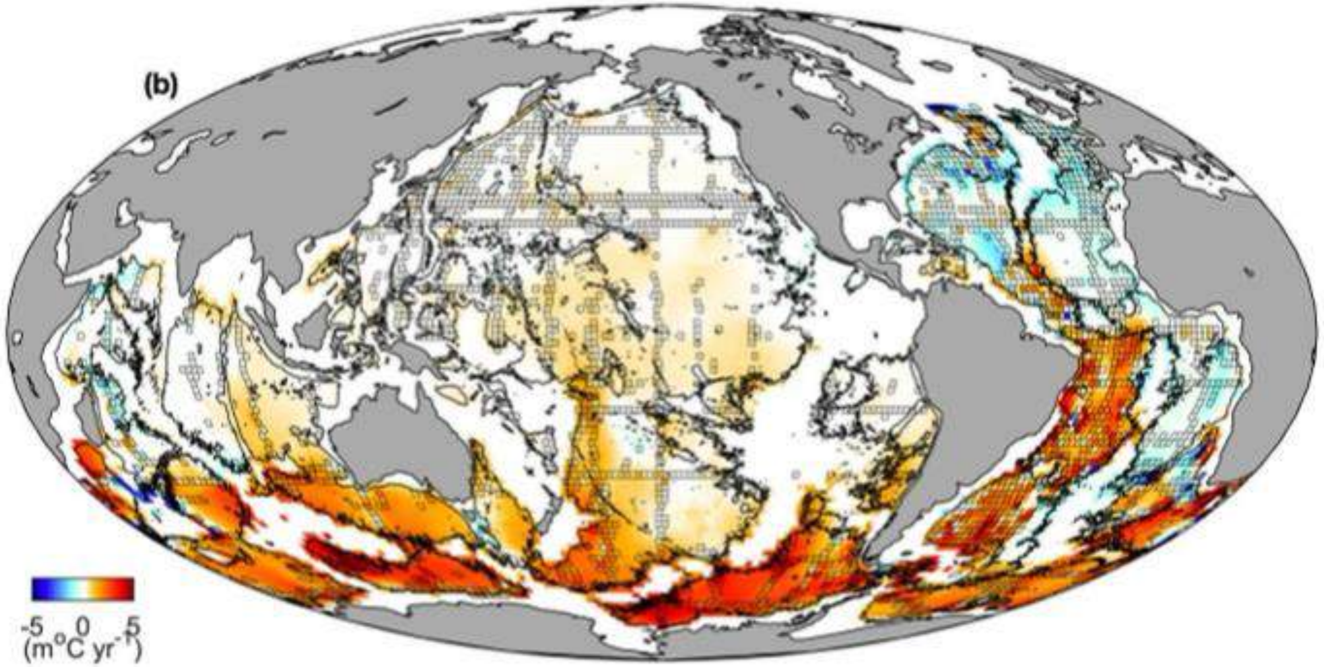
(Updated from Purkey and Johnson, 2010)

=

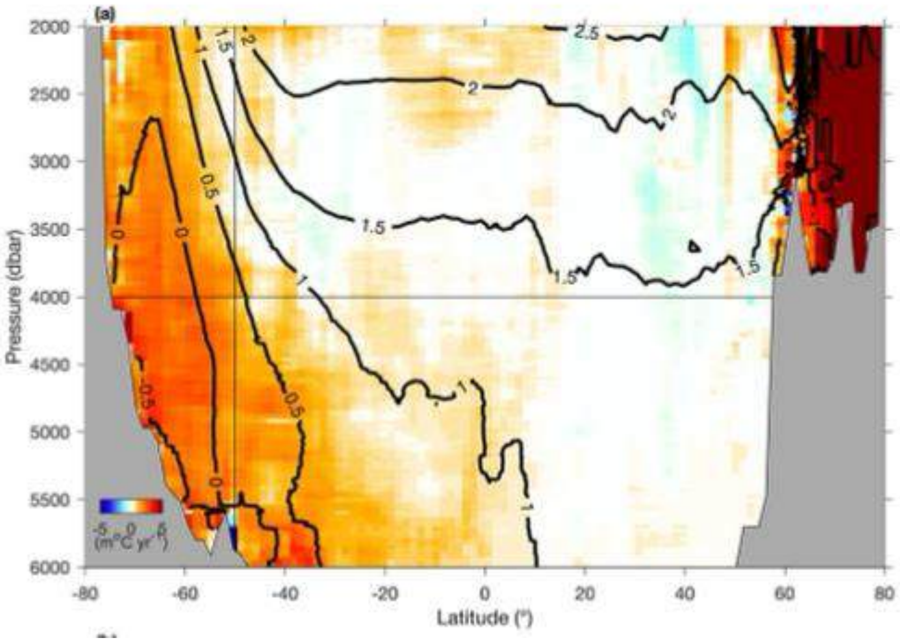
0.7 ZJ/yr

GO-SHIP + Deep Argo: Deep Ocean Warming

Deep Warming below 4000m

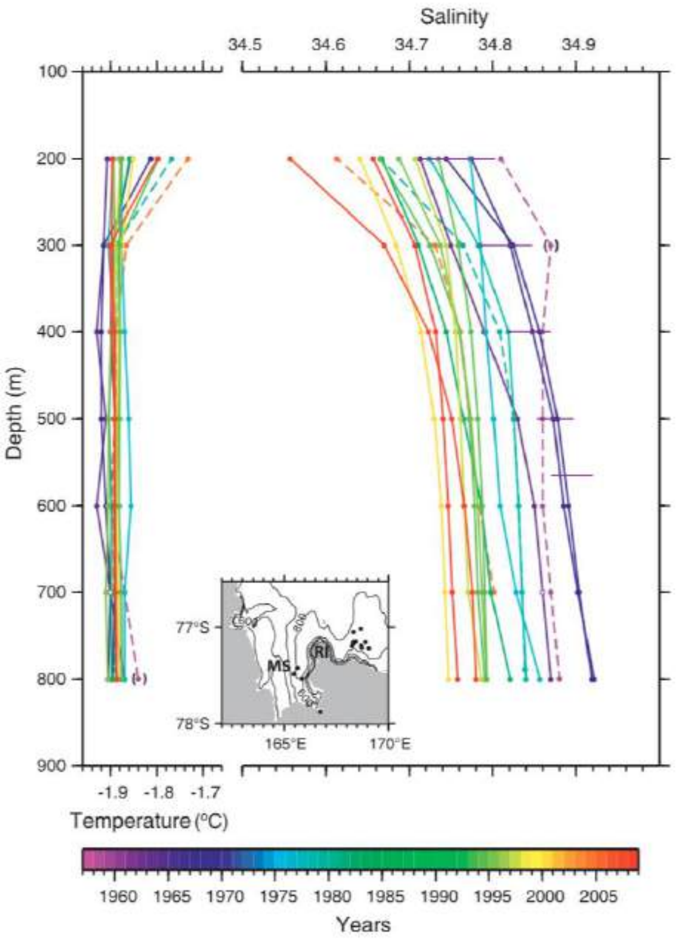


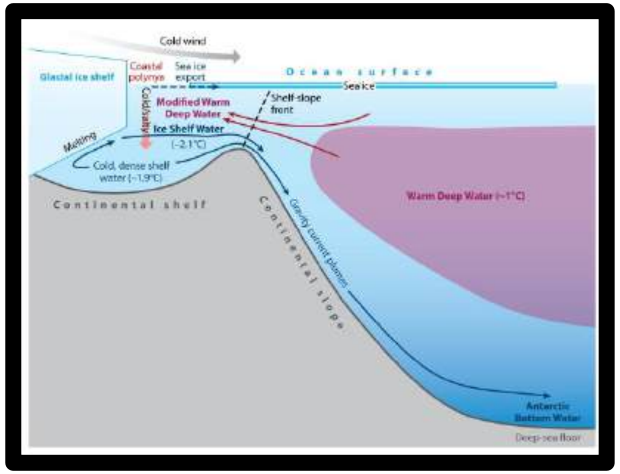
Zonal Mean Deep warming below 2000m

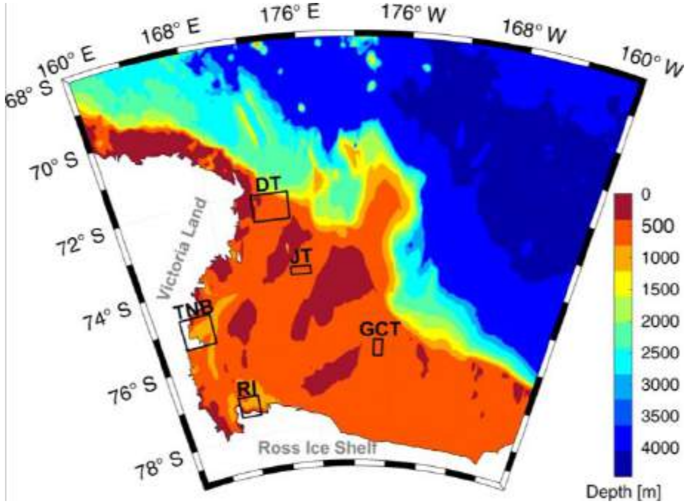


(Johnson and Purkey, 2024)

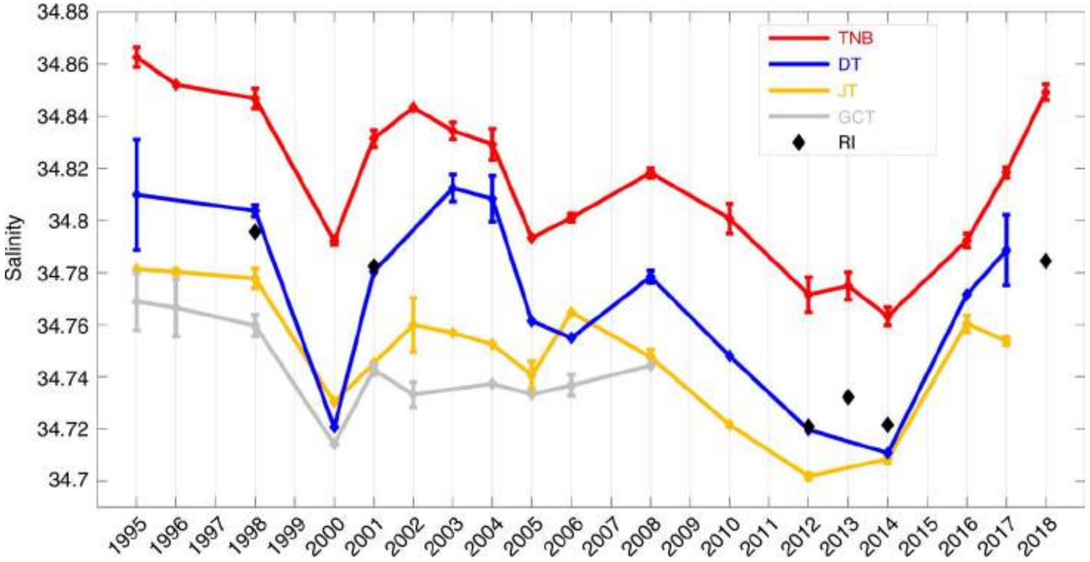
Ross Sea shelf water salinity variability





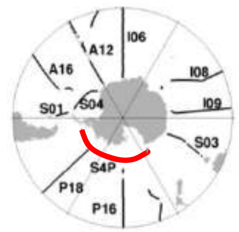


(Jacob and Giulivi, 2010)

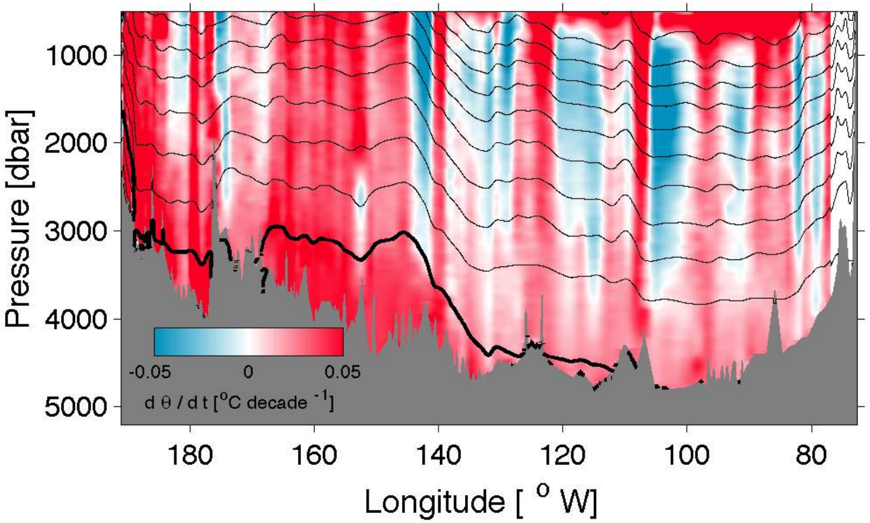


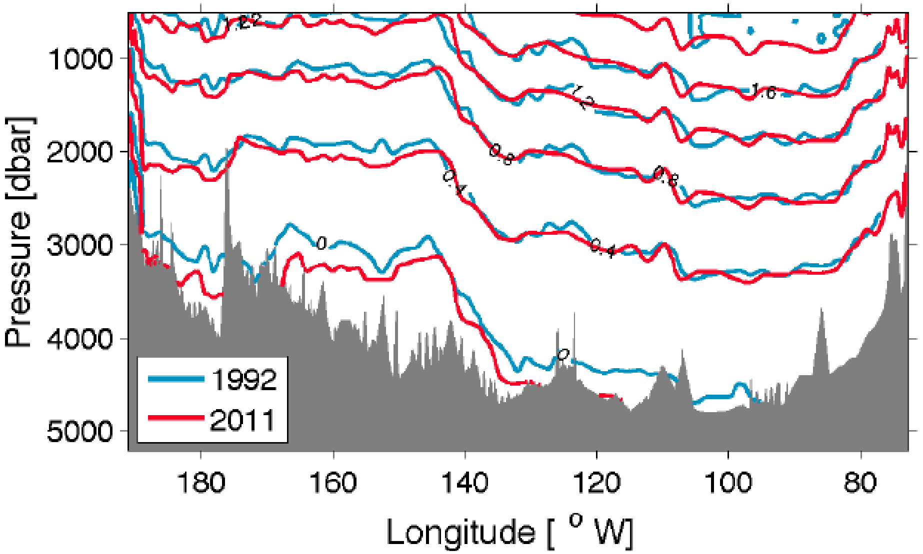
(Castagno et al. 2019)

Warming = Isotherm Heave



(Purkey & Johnson 2012)

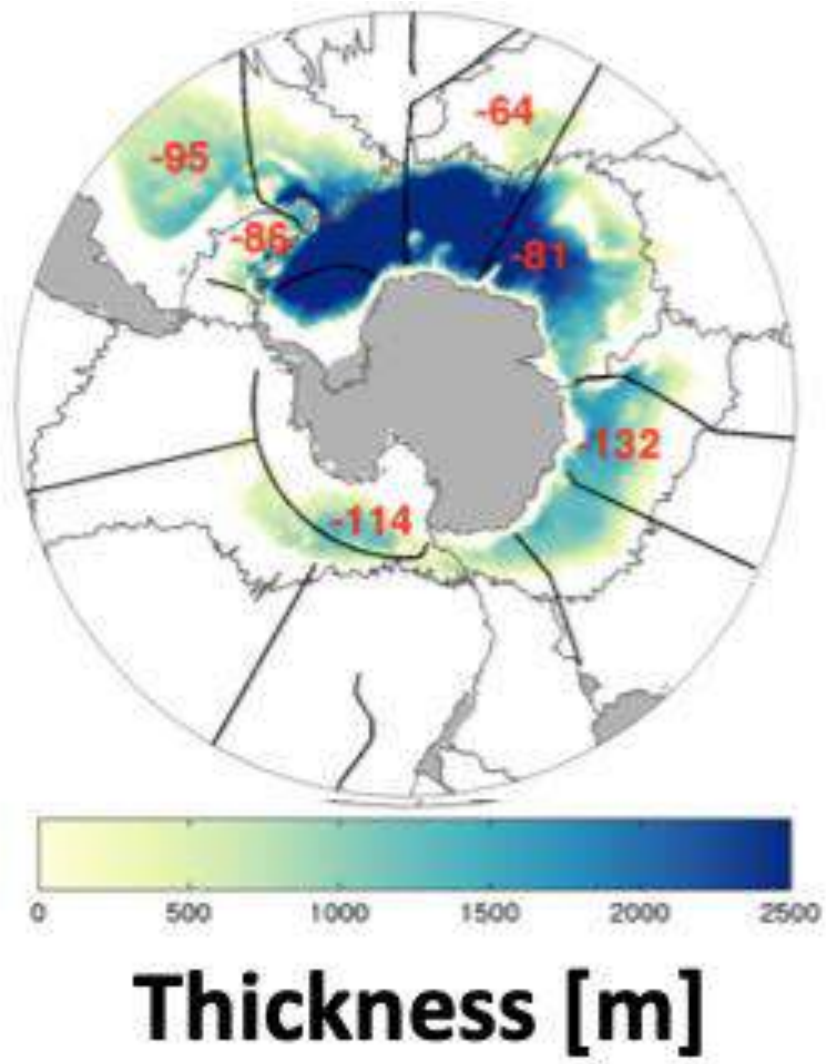




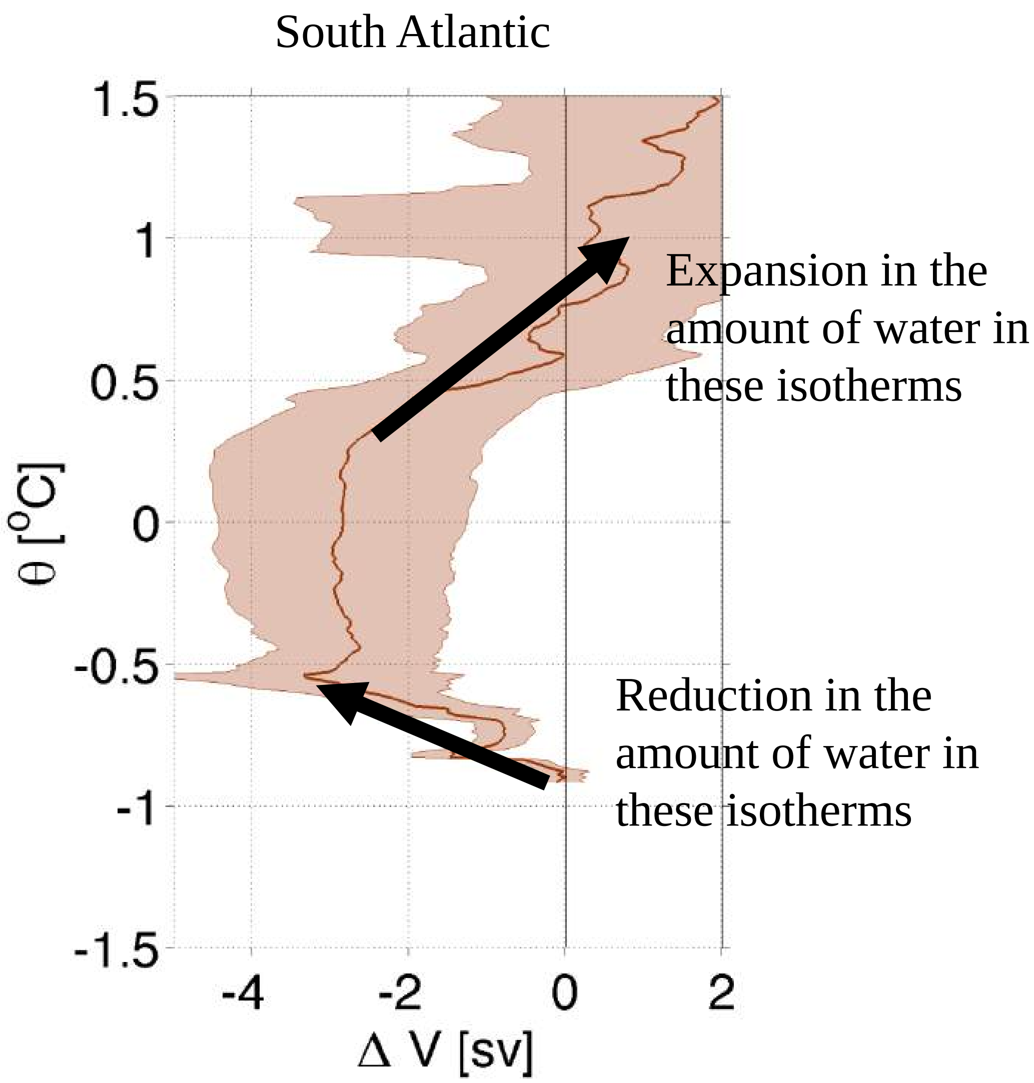
- Warming between 1992 and 2011 occupation of S4P

- Warming on isobars is equivalent to descending isotherms

Reduction in AABW compensated by an expansion of CDW?

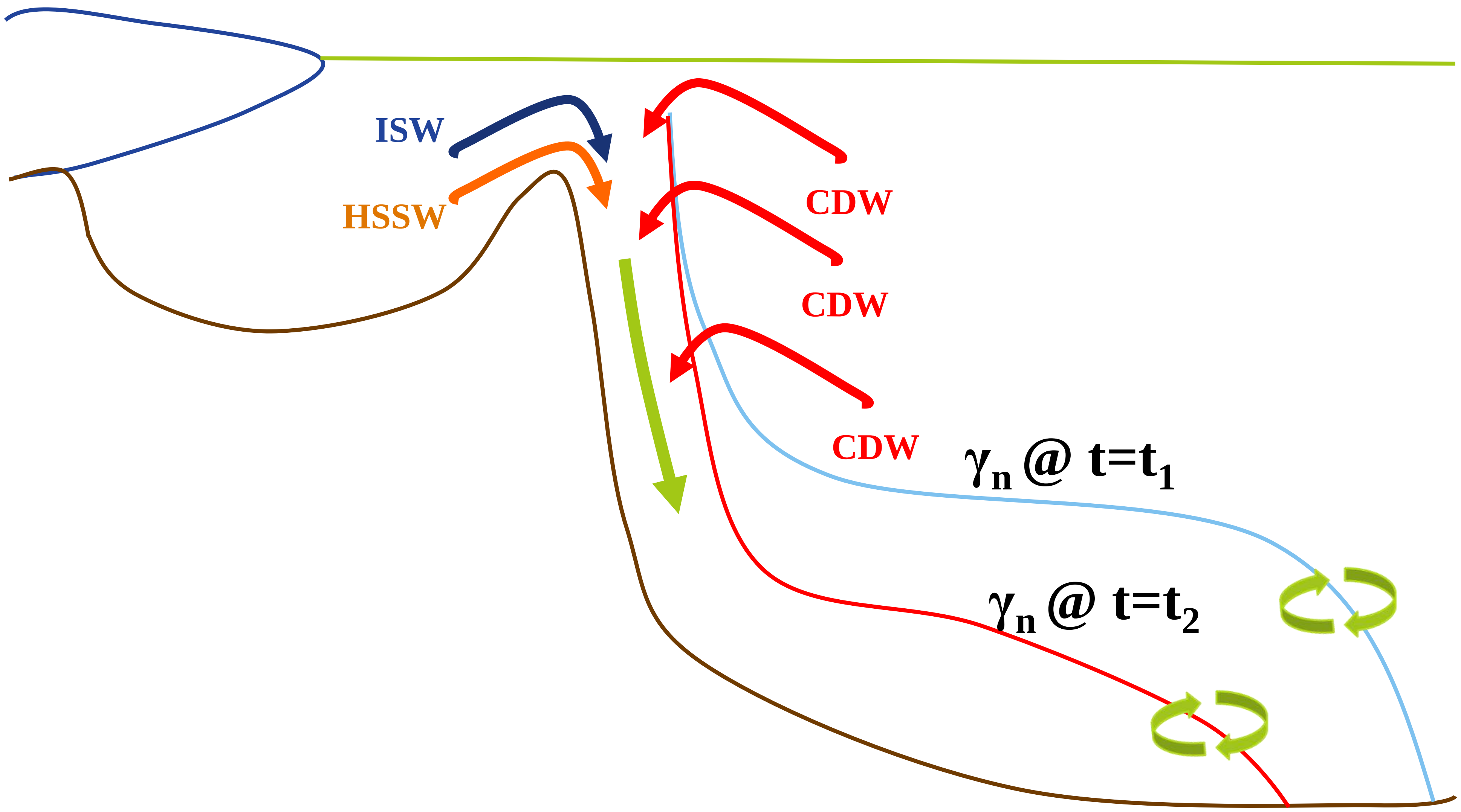


Red = change in thickness of AABW (m)



(Purkey and Johnson, 2012)

What is driving the loss of AABW?



A slow down in the deep MOC?

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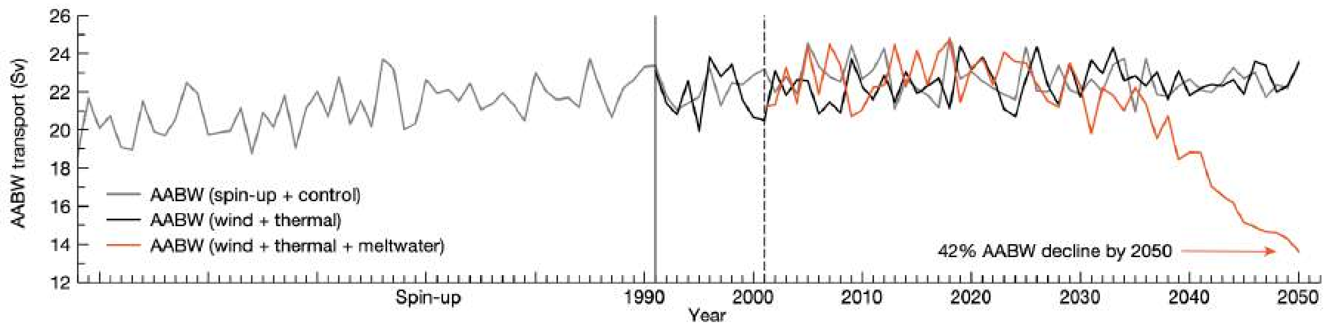
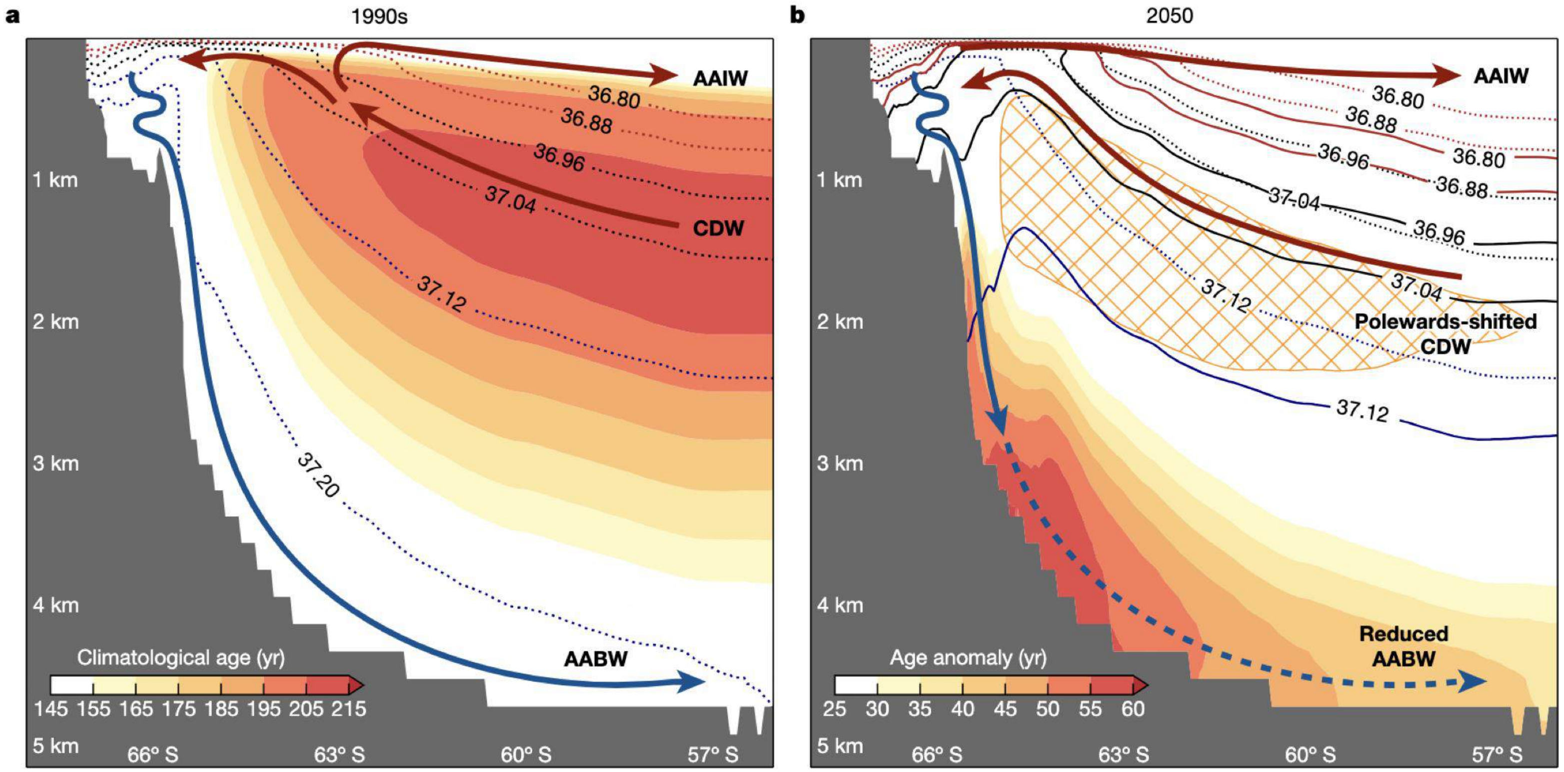
Qian Li, Matthew H. England, Andrew McC. Hogg, Stephen R. Rintoul & Adele K. Morrison

Nature **615**, 841–847 (2023) | Cite this article

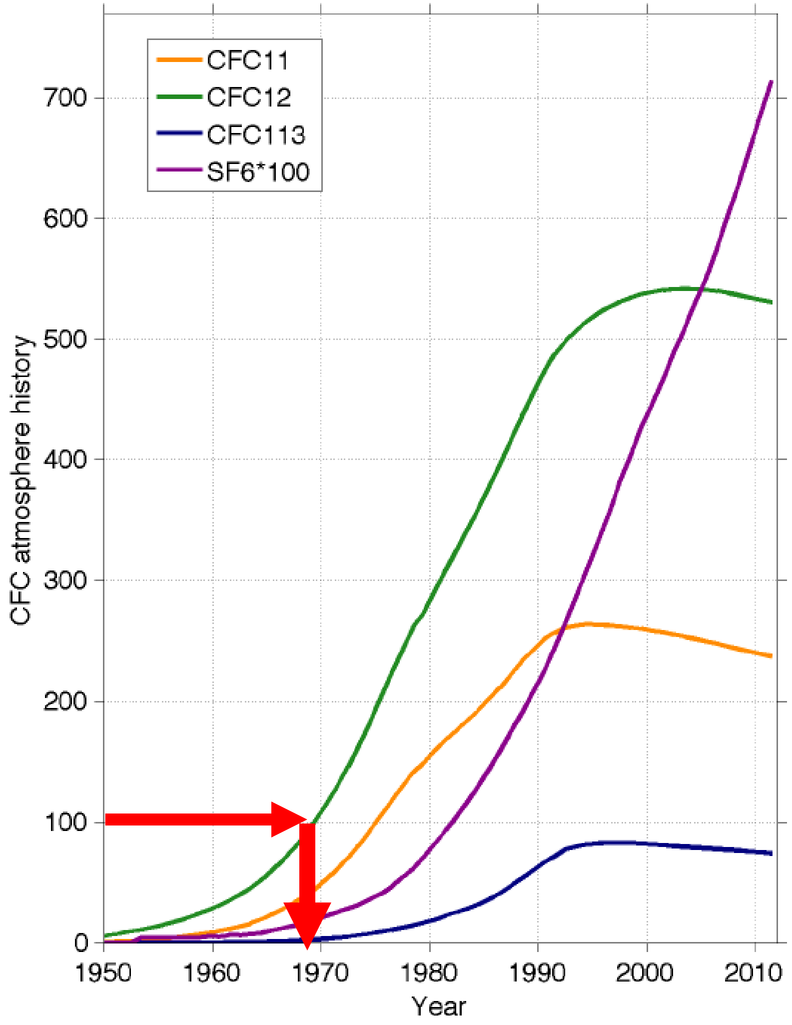
Abstract

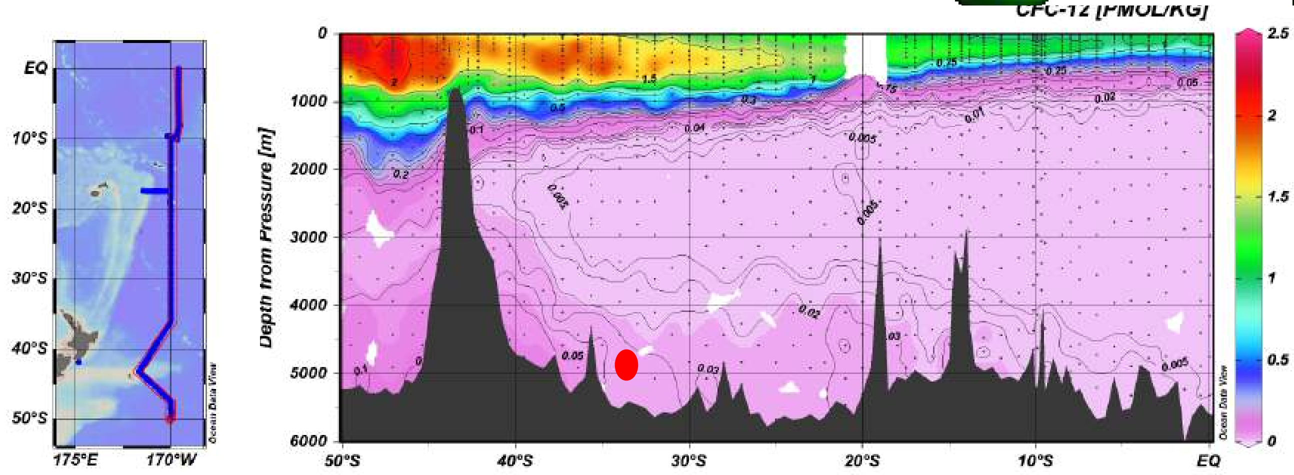


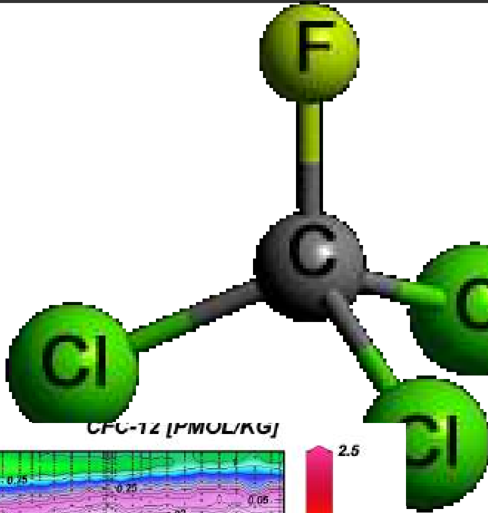


How can we observe this? Chlorofluorocarbons (CFCs)

CFCs' Atmospheric History

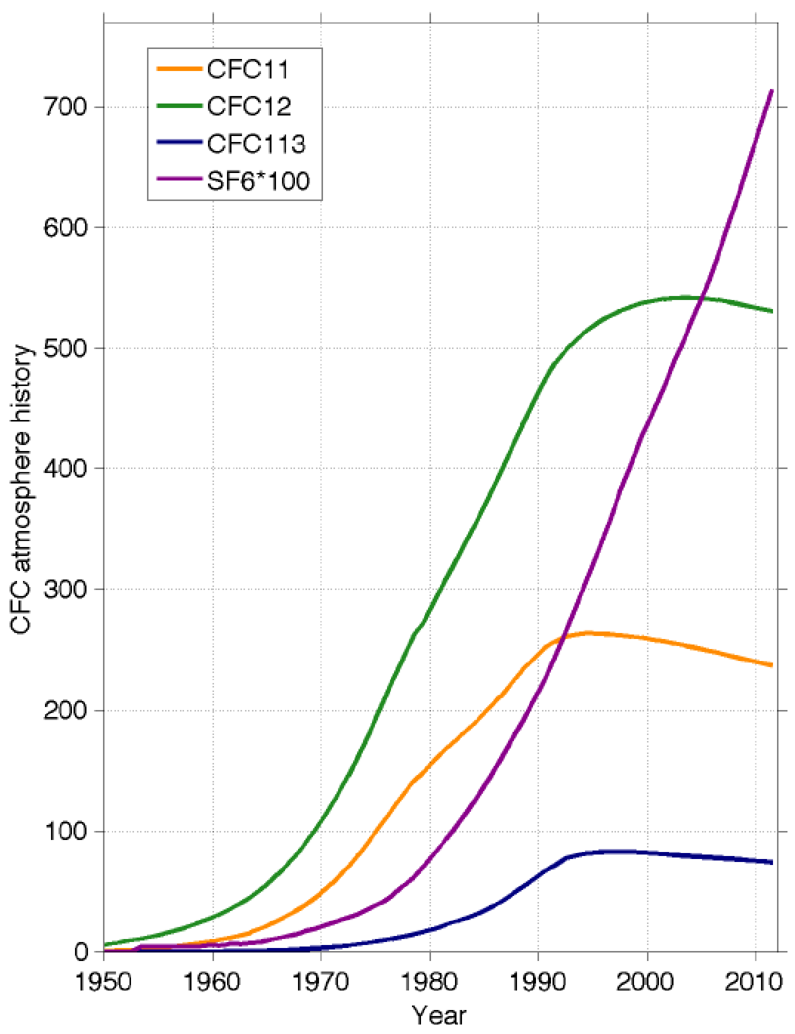


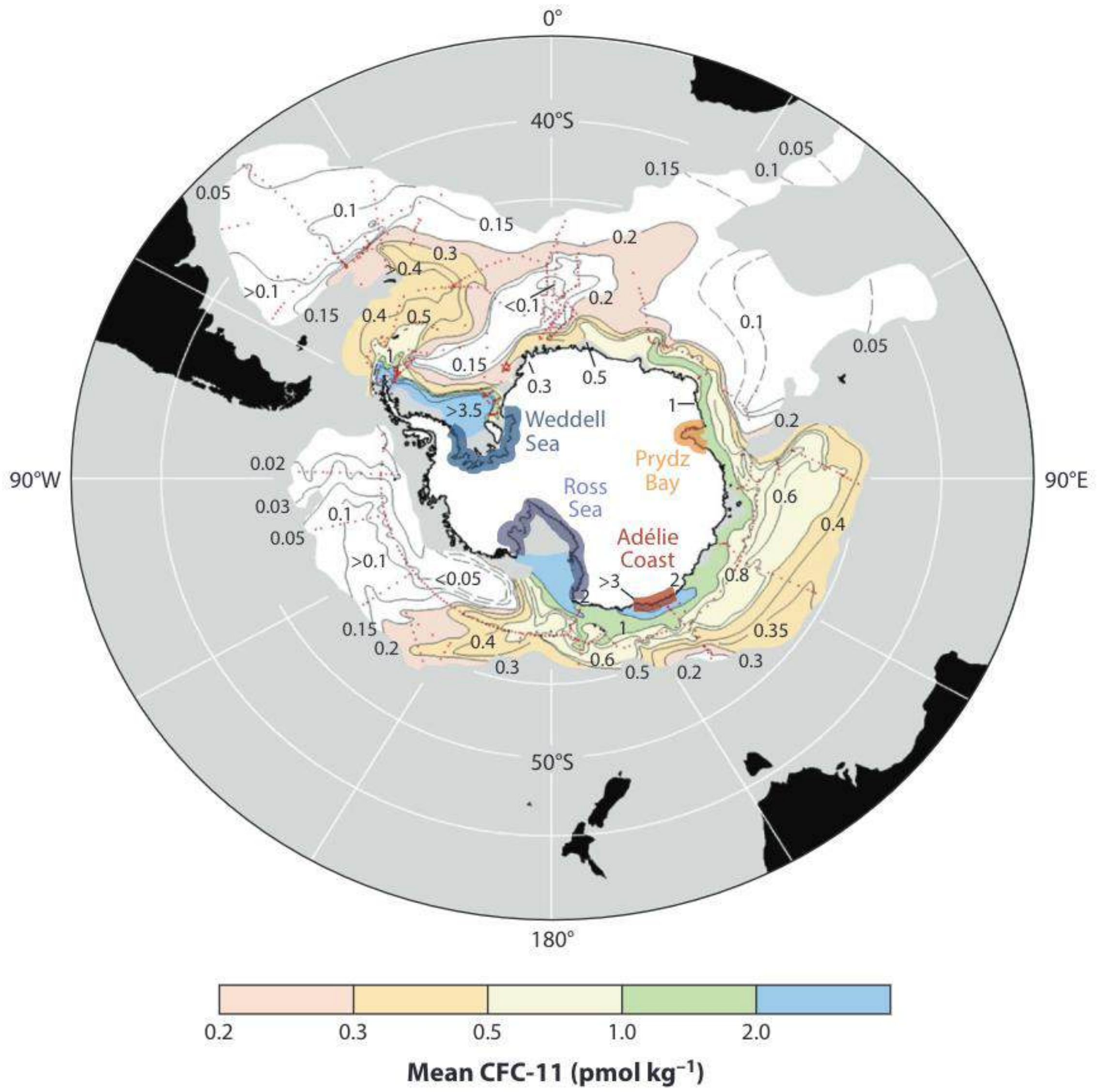




Transient tracers: Chlorofluorocarbons (CFCs)

CFCs' Atmospheric History



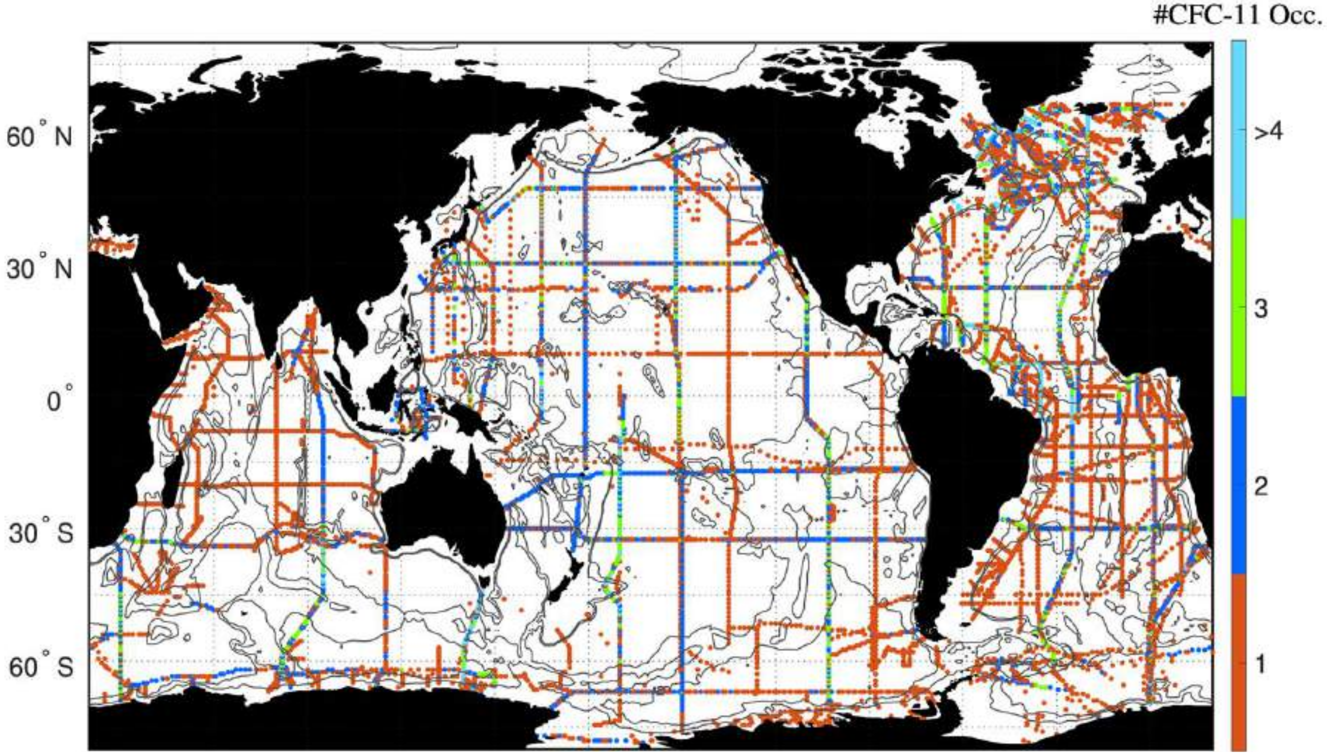


(Orsi et al. 1999)

Transient tracers: Chlorofluorocarbons (CFCs)

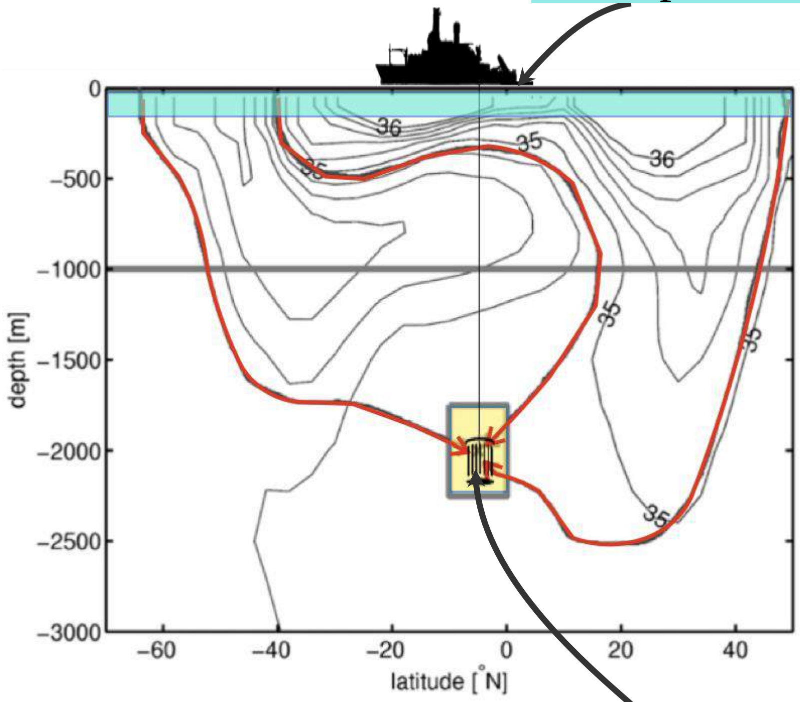
(Cimoli et al. 2023)

CFC 11 In-situ observations in 2023

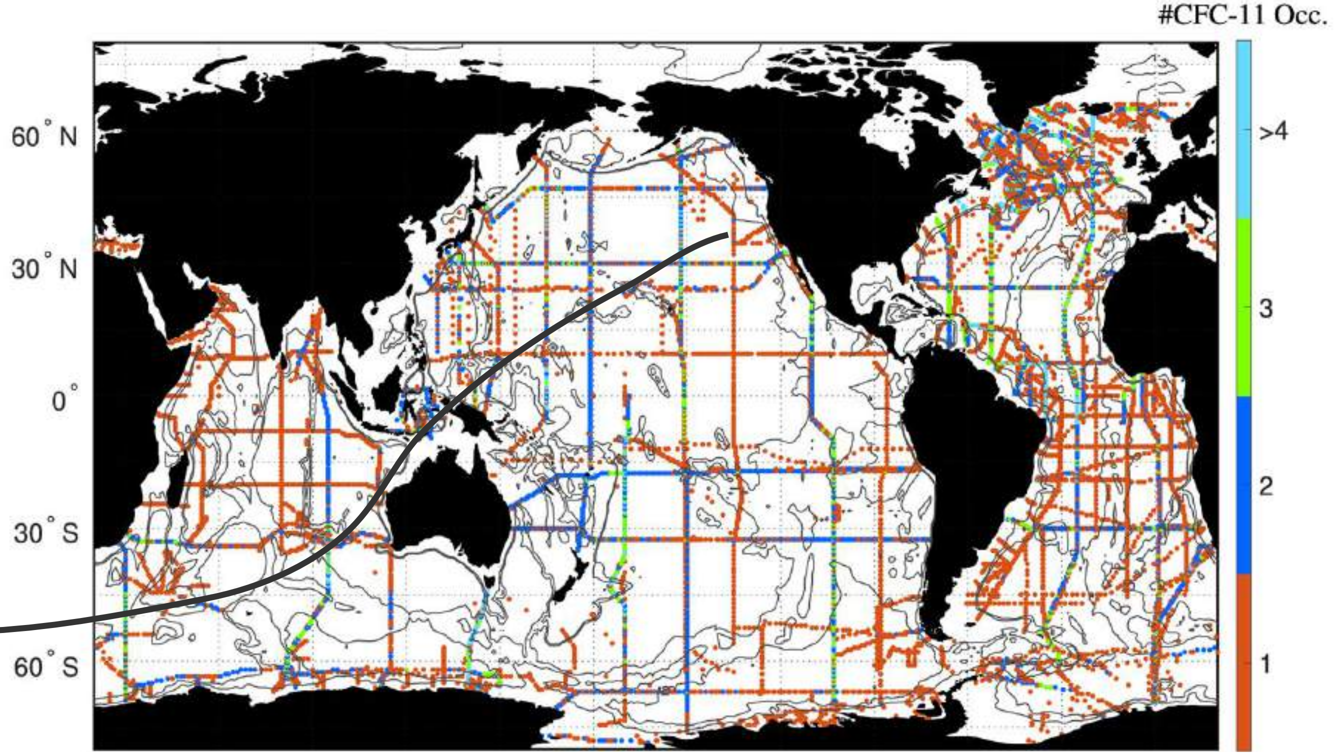


Method: CFC “time corrected” data set

Atmospheric CFCs and Sf6



CFC 11 In-situ observations in 2023



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

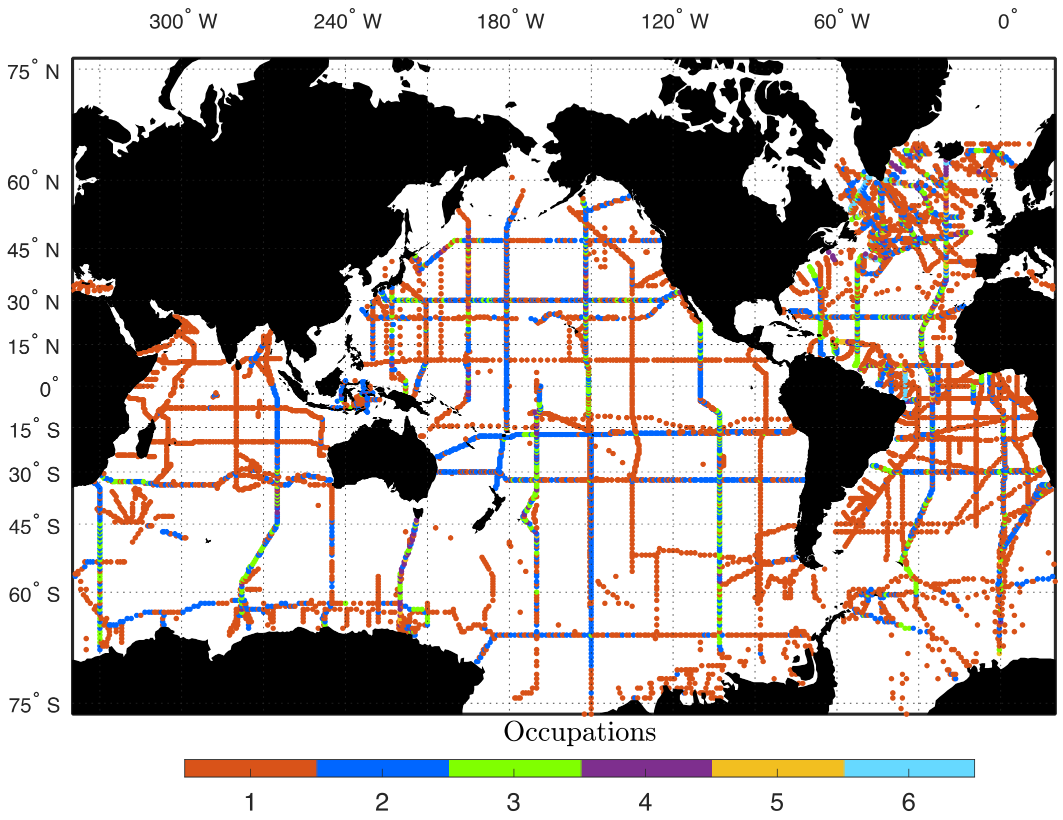
$$C(\mathbf{r},t) = \int_0^\infty C_{s,\gamma}(t-\tau)\, G(\mathbf{r},\tau)\, d\tau$$

glodap

GO-SHIP

Method: CFC “time corrected” data set

Data: ½ deg x ½ deg on 0.01 γ_n vertical grid



$$J = ||\mathbf{C} - C_s\mathcal{G}||_2^2 + ||\mathcal{G} - \mathcal{G}_0||_2^2 =$$
$$= (\mathbf{C} - C_s\mathcal{G})^T\mathbf{W}^{-1}(\mathbf{C} - C_s\mathcal{G}) + (\mathcal{G} - \mathcal{G}_0)^T\mathbf{S}^{-1}(\mathcal{G} - \mathcal{G}_0).$$

Discrepancy with observations ***C***

Discrepancy with first guess G_0

Cs= surface boundary conditions
G= greens function
Go=first guest
C=tracer concentration
Solving for G that minimizing the cost function J

(Cimoli et al. 2023)

Method: CFC "time corrected" data set

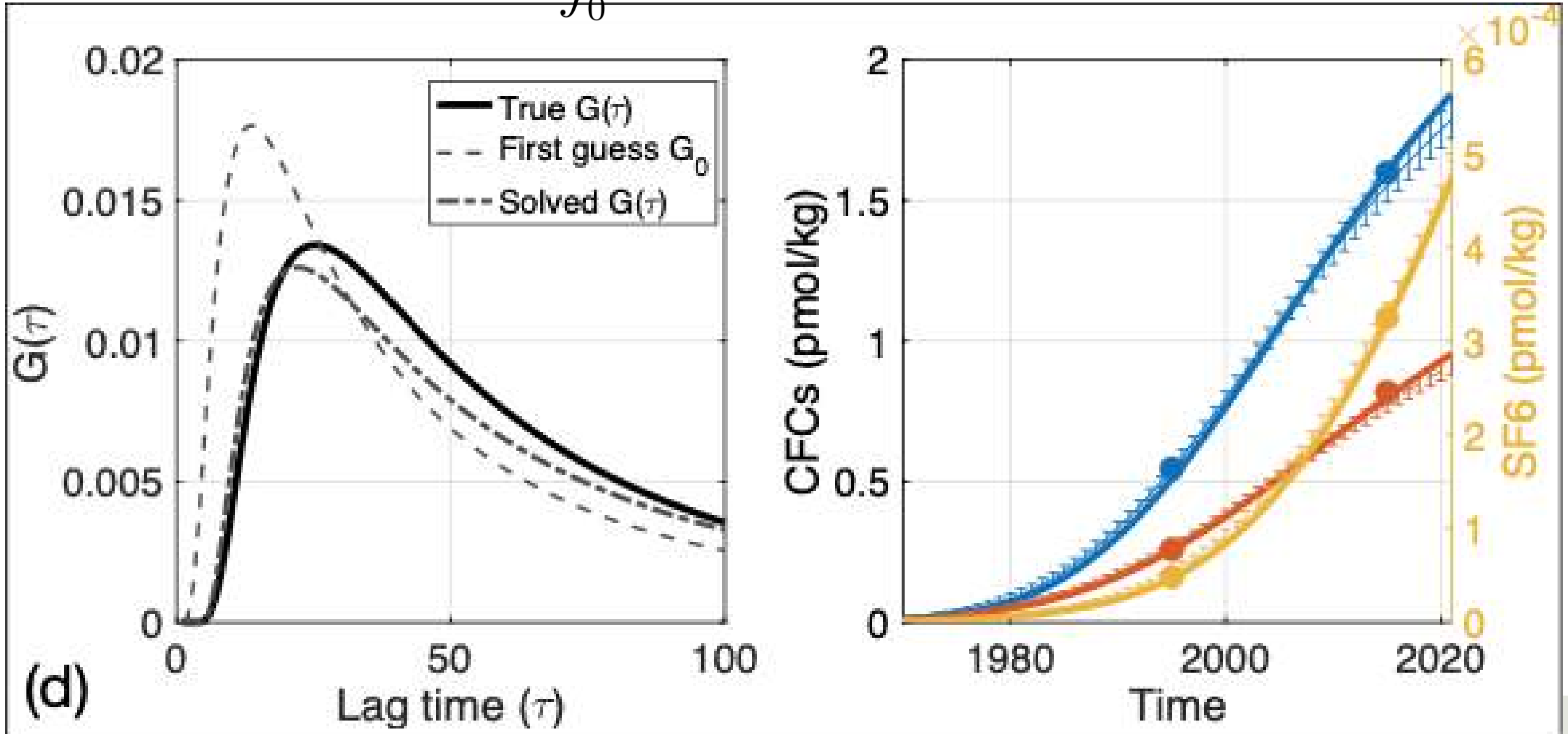
TIME CORRECTION METHOD: Example with synthetic data

- 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 (—+—)

$$J = ||\mathbf{C} - C_s\mathcal{G}||_2^2 + ||\mathcal{G} - \mathcal{G}_0||_2^2 =$$
$$= (\mathbf{C} - C_s\mathcal{G})^T\mathbf{W}^{-1}(\mathbf{C} - C_s\mathcal{G}) + (\mathcal{G} - \mathcal{G}_0)^T\mathbf{S}^{-1}(\mathcal{G} - \mathcal{G}_0).$$

Discrepancy with observations ***C*** Discrepancy with first guess G_0

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



OUTCOMES (Global, full water column):

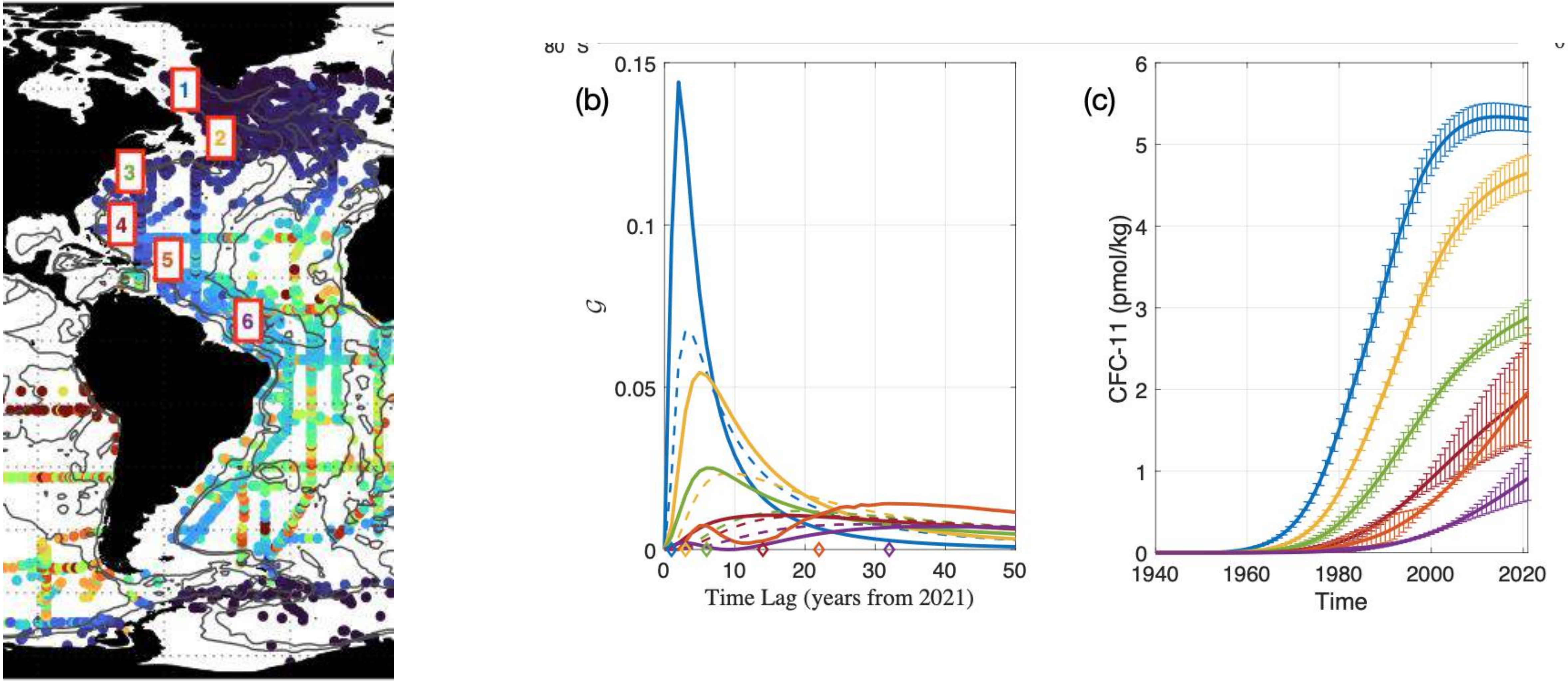
- TTD (Green's functions) at each location in the ocean interior (where tracer data is available)
- Annually-resolved CFCs and SF6 concentration

Used to investigate:

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

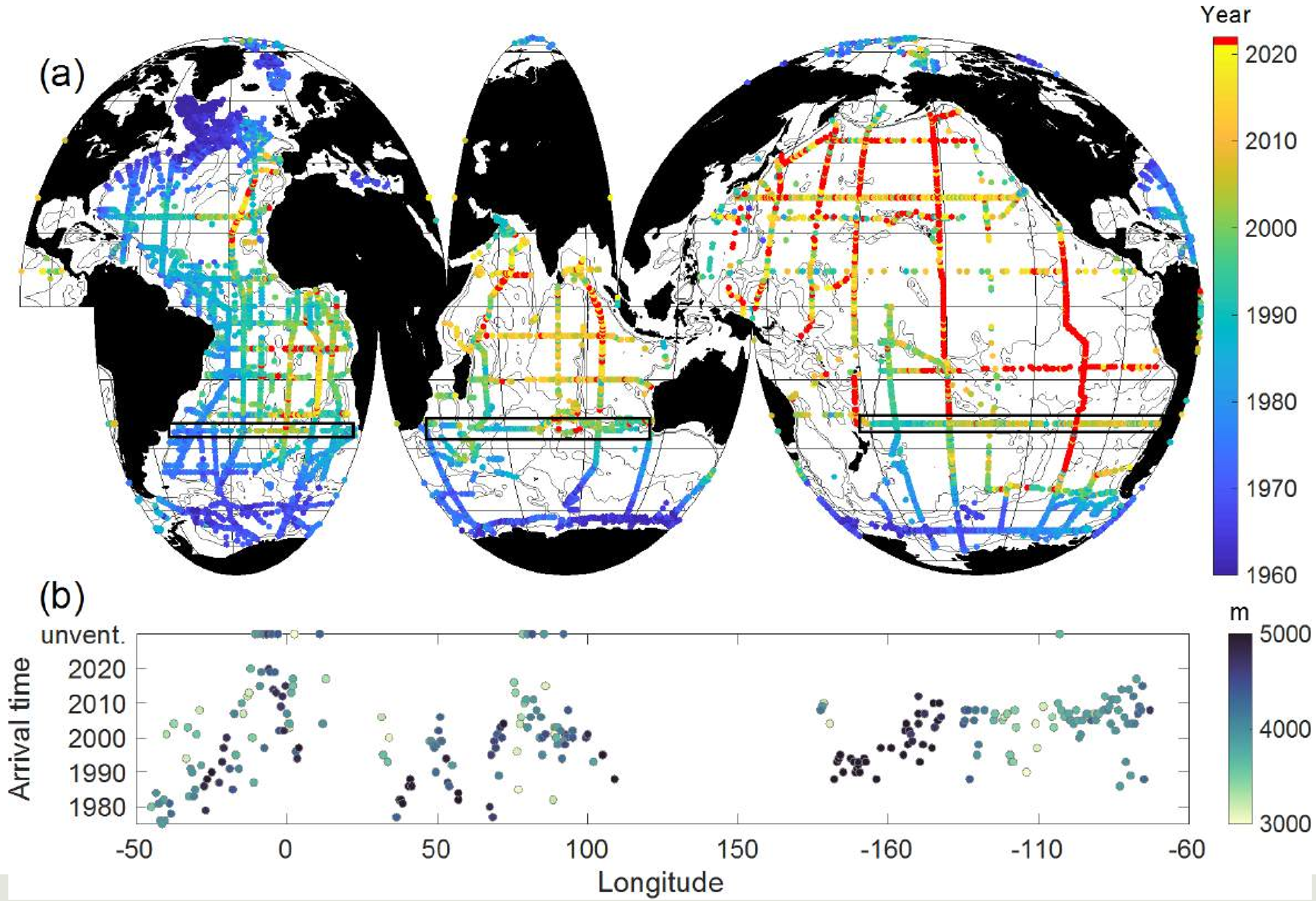
(Cimoli et al. 2023)

Example of Green’s function and CFC History



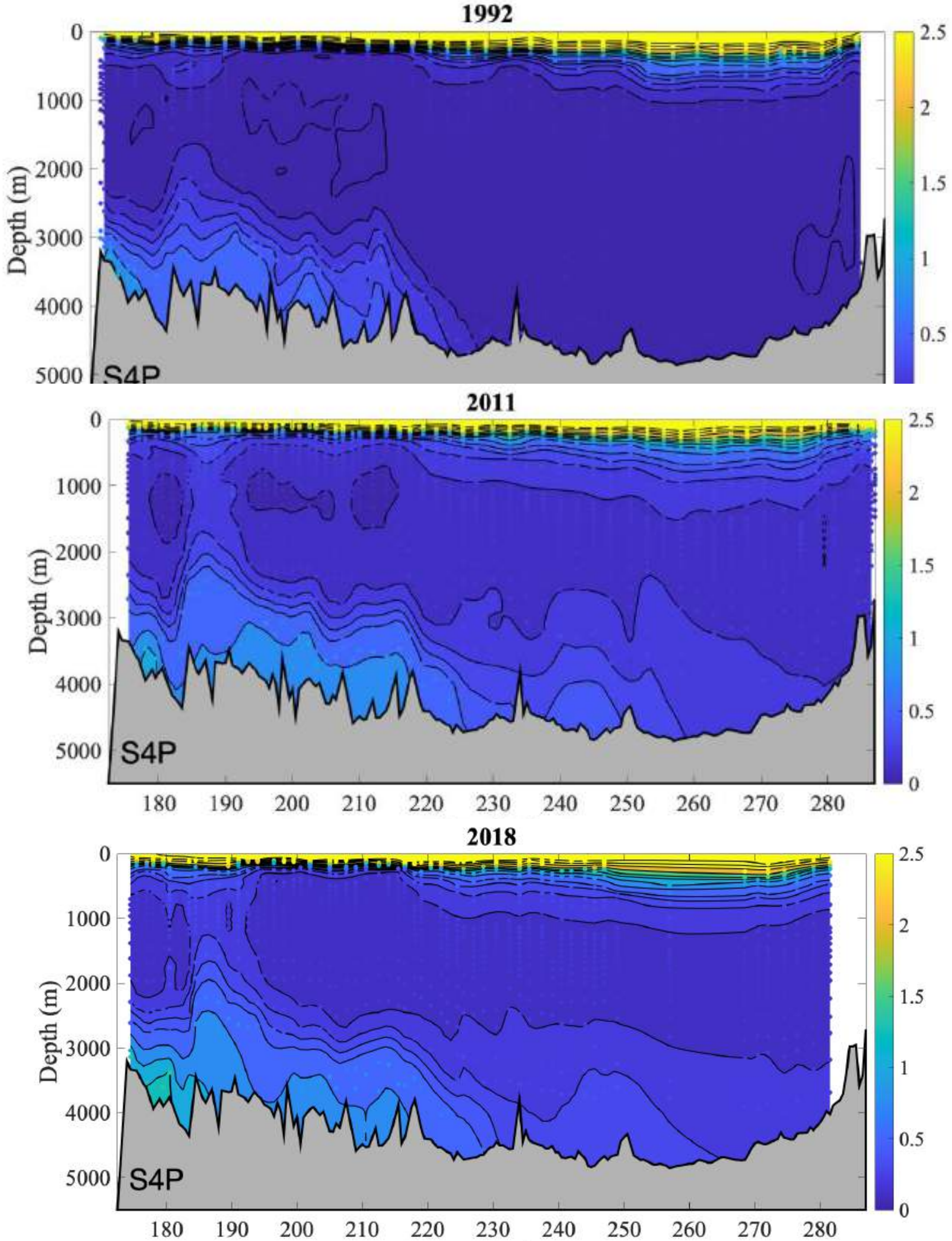
(Cimoli et al. 2023)

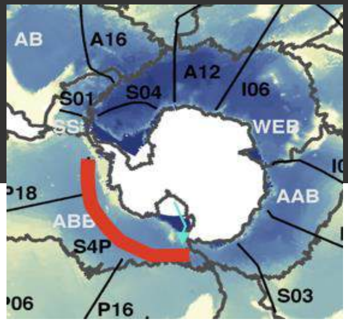
CFC Arrival time

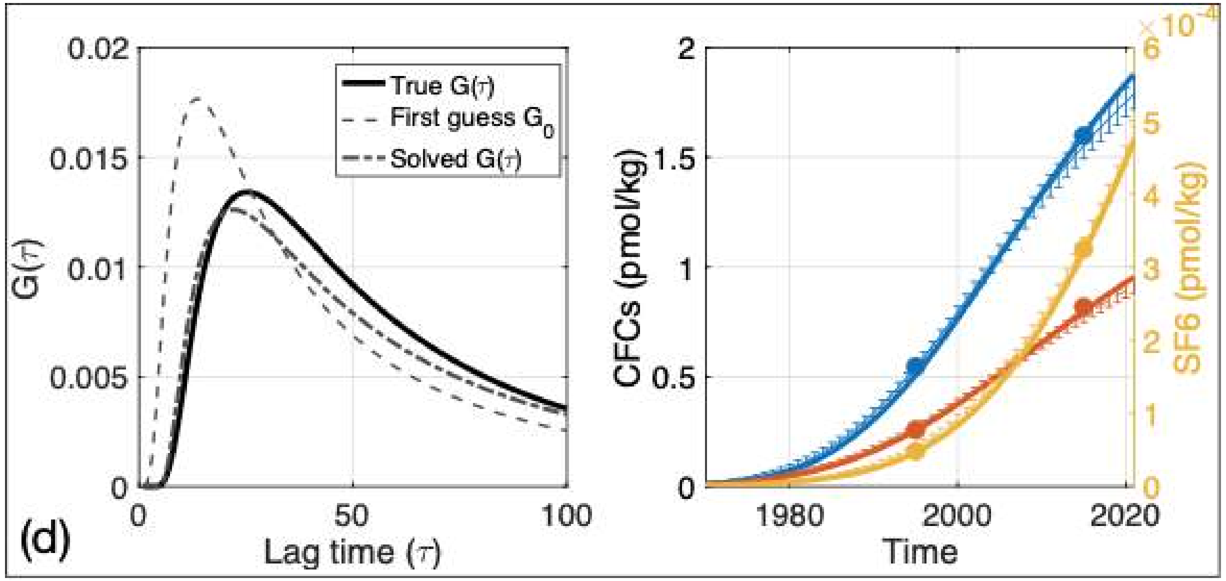


(Cimoli et al. 2023)

Ocean ventilation decadal variability

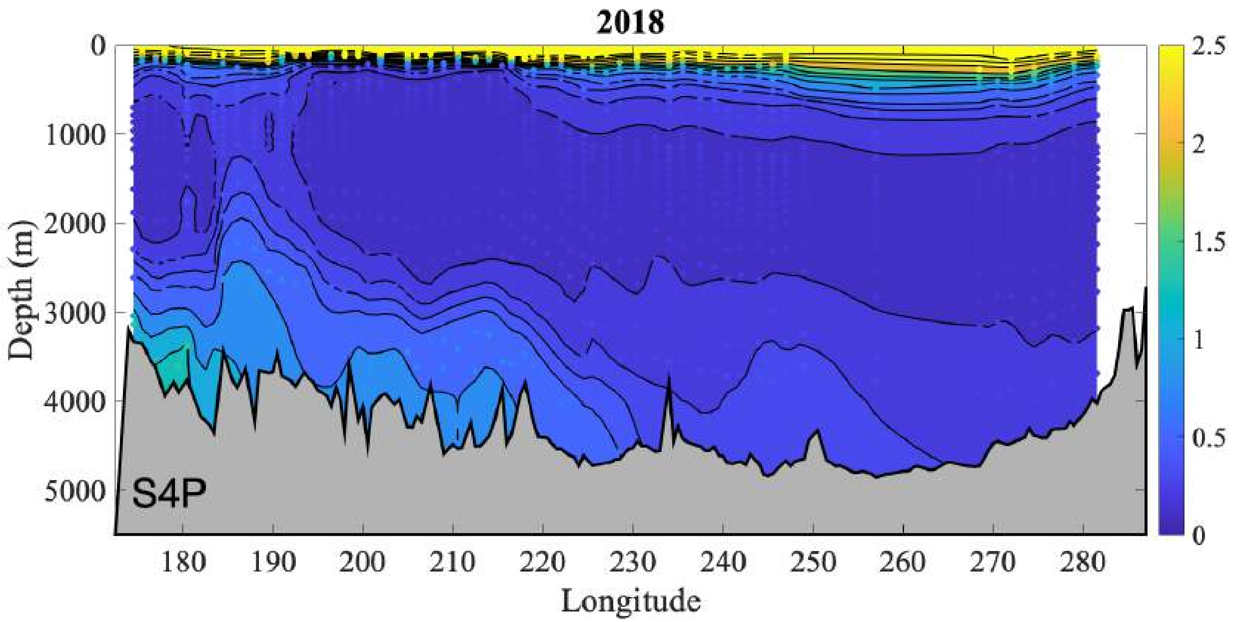




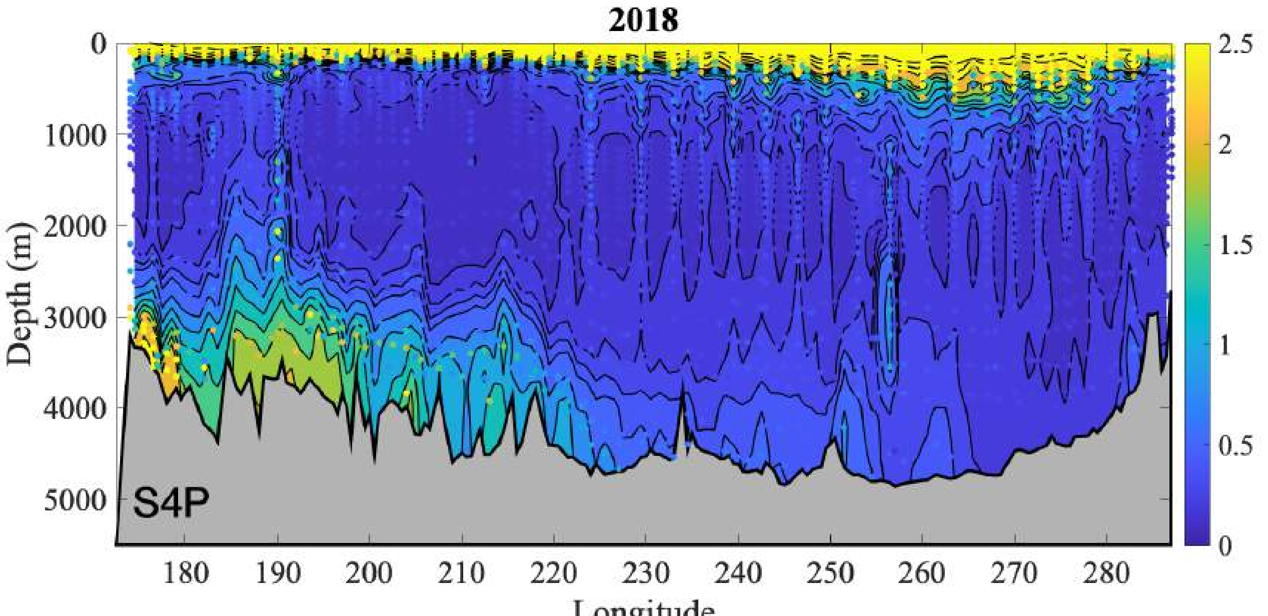


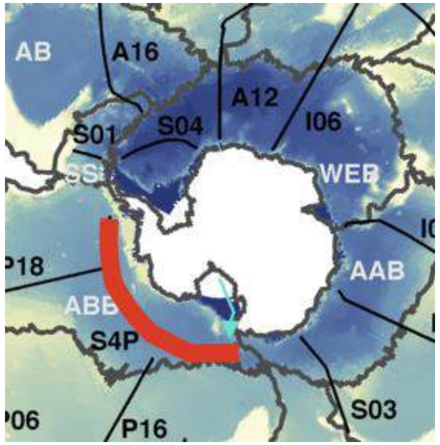
Ocean ventilation decadal variability

Observations

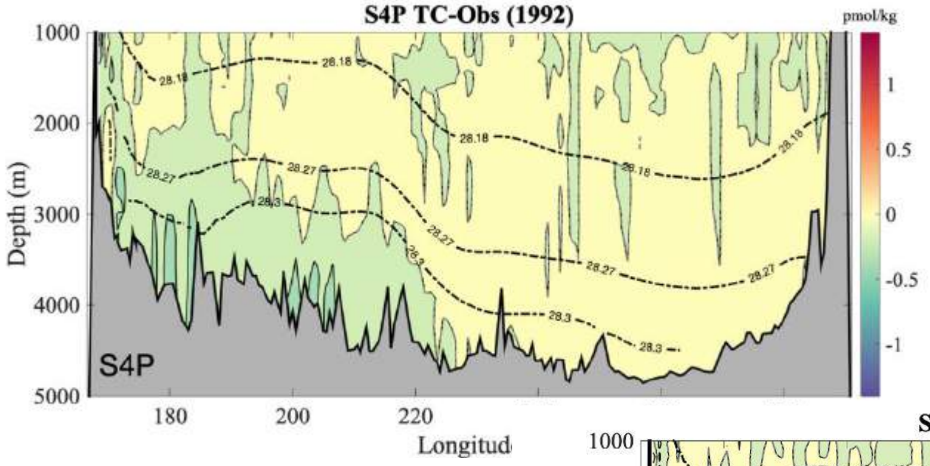


Predicted

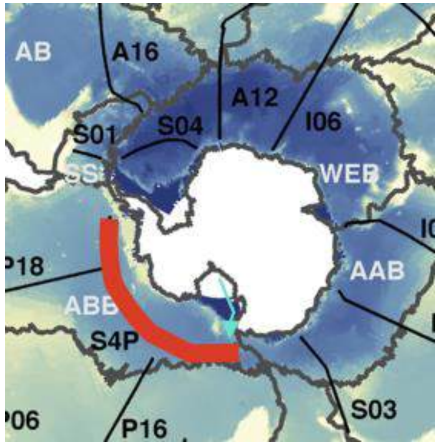


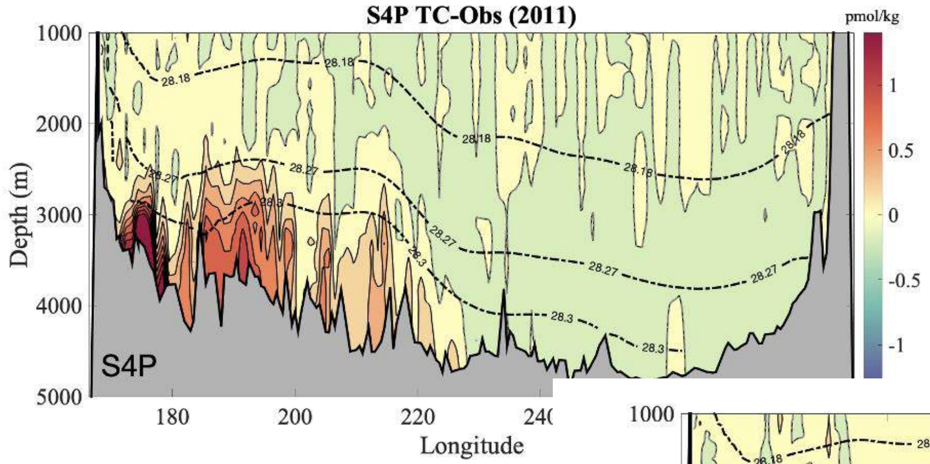


Ocean ventilation decadal variability

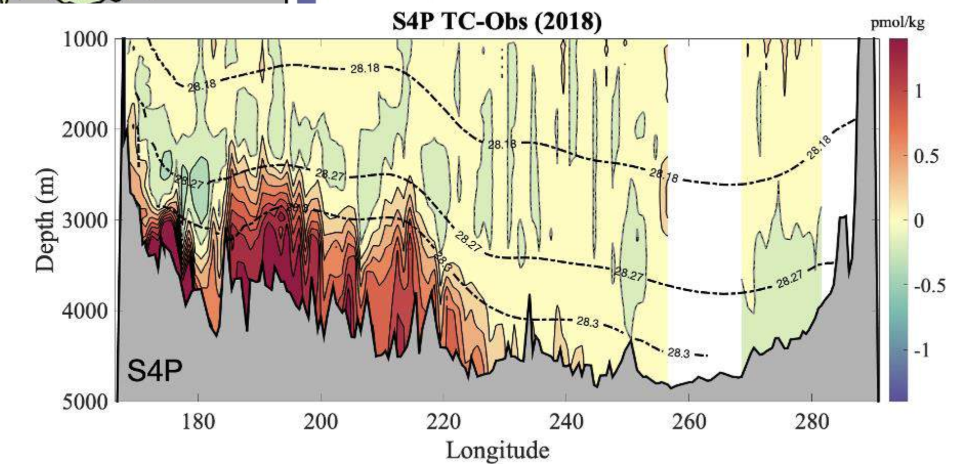


1992





2011



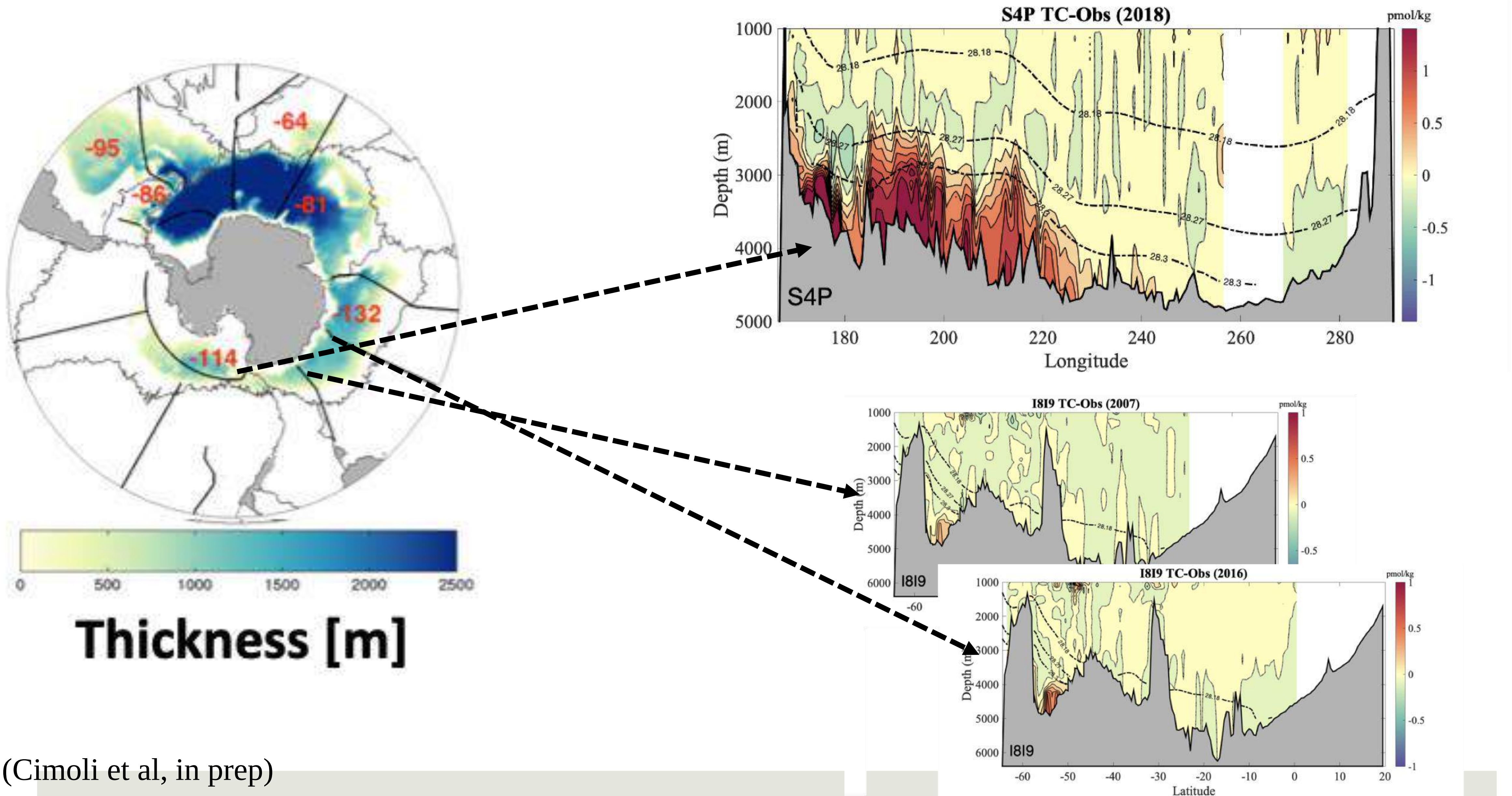
2018

Anomalies:
(Reconstructed - Observed) tracer concentrations

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

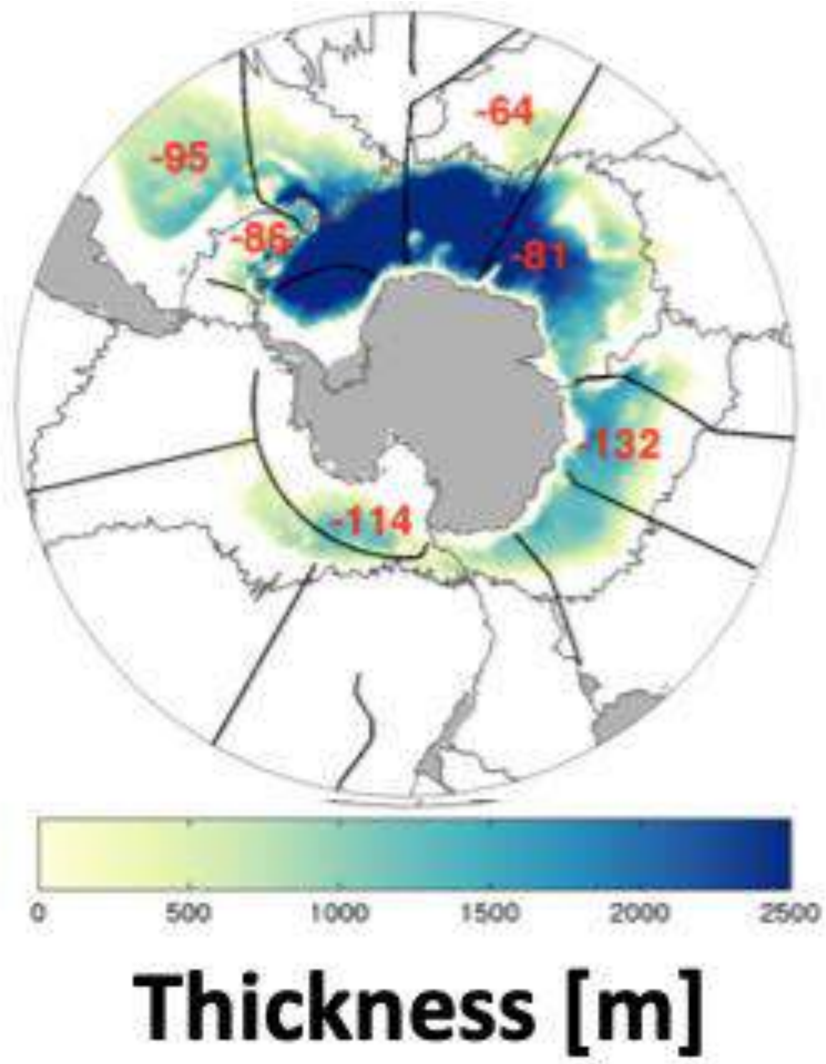
A slow down in the MOC?

Changes in expected CFC

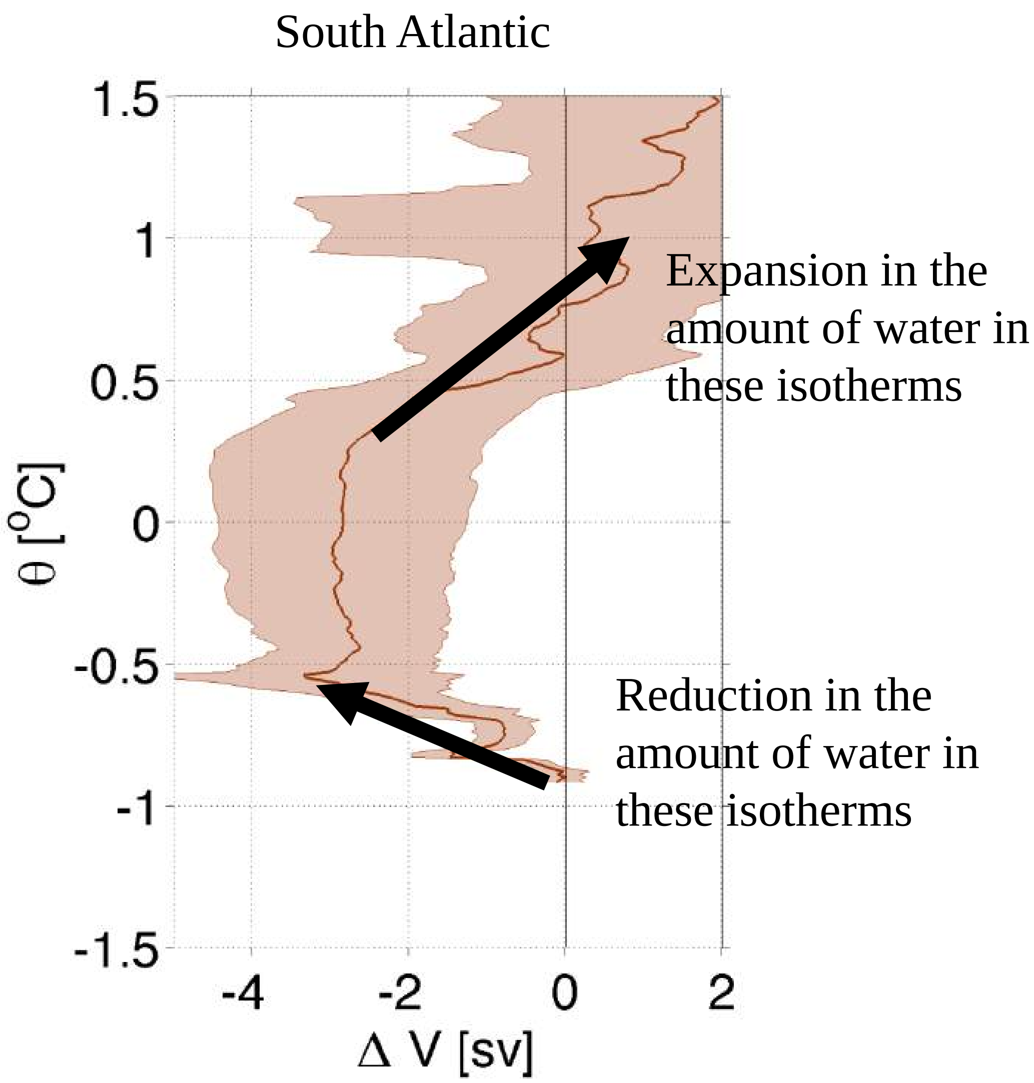


(Cimoli et al, in prep)

Reduction in AABW compensated by an expansion of CDW?

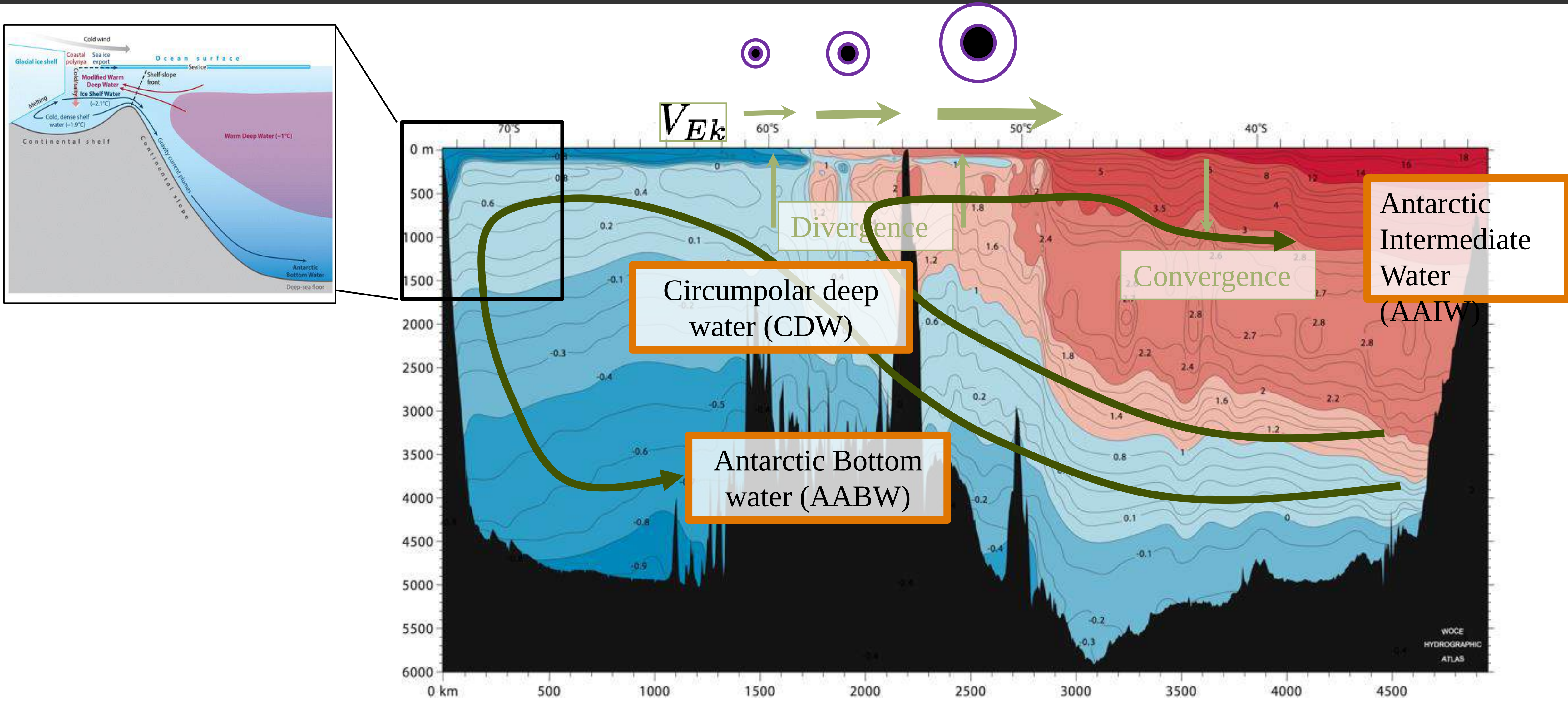


Red = change in thickness of AABW (m)



(Purkey and Johnson, 2012)

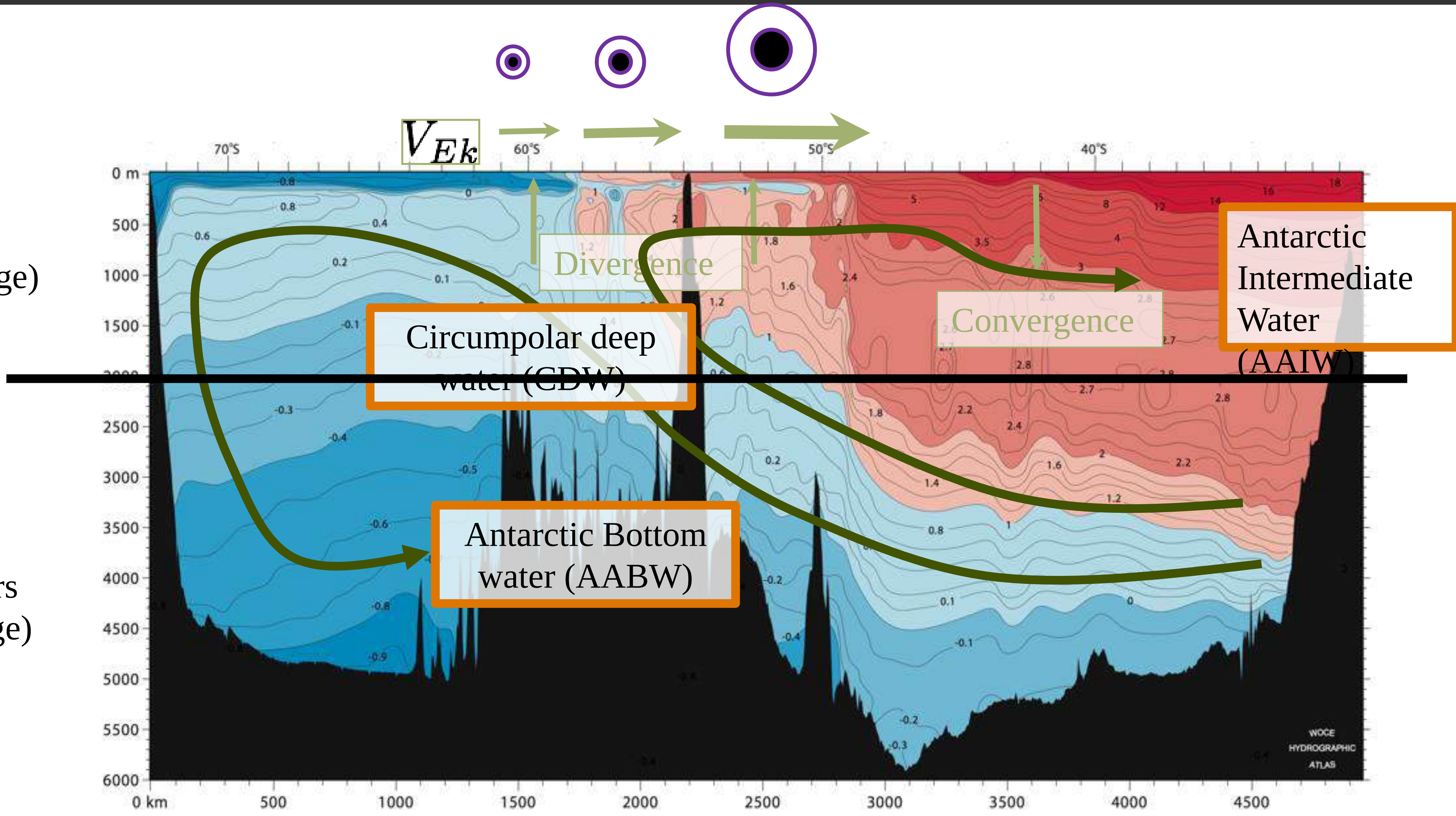
Southern Ocean Watermasses



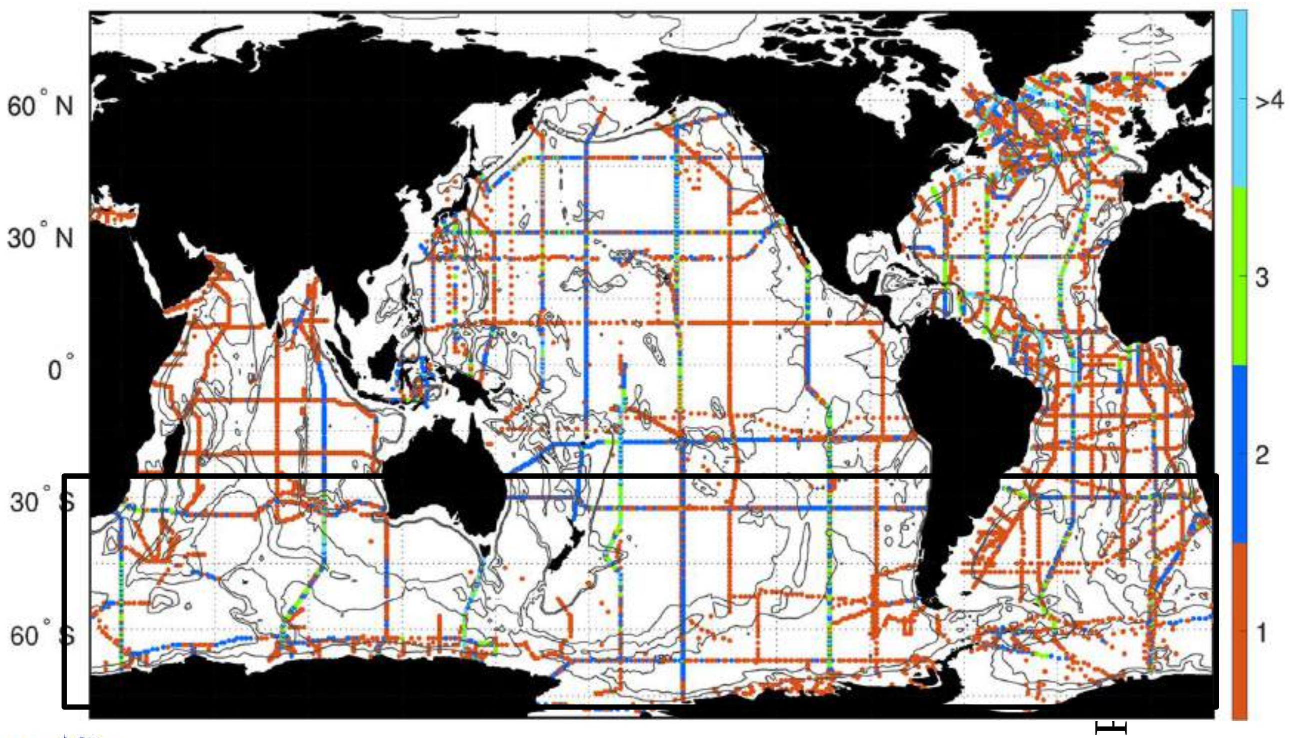
Southern Ocean Watermasses

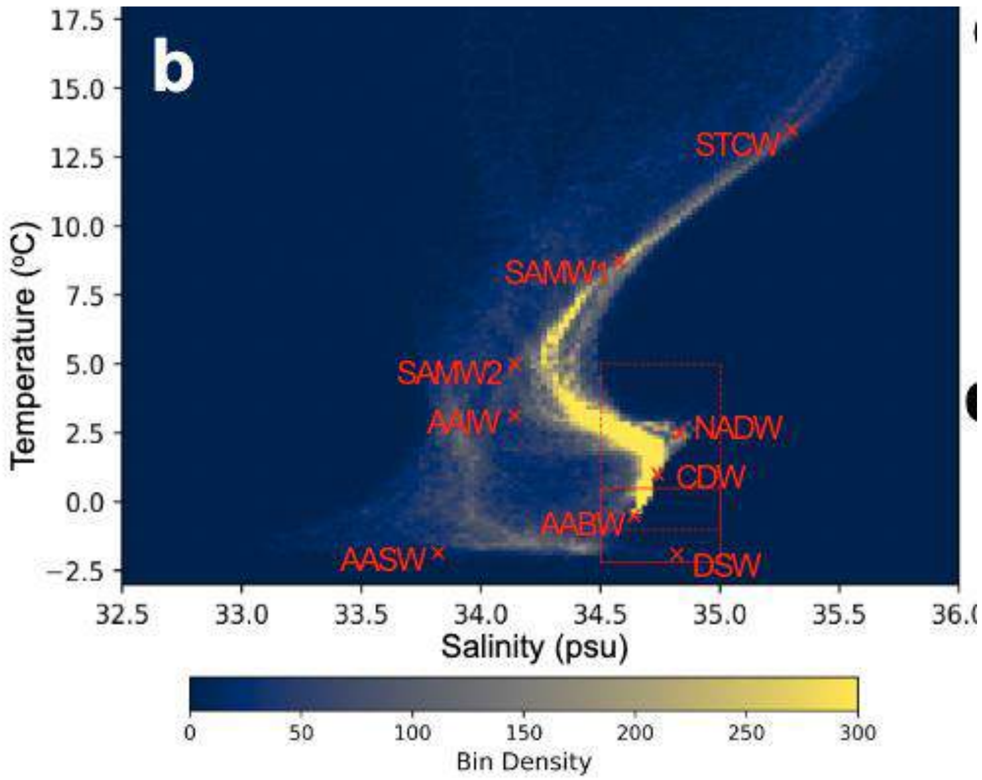
Argo
(Good Spatial
and temporal coverage)

GO-SHIP
(Multiple parameters
but Decadal coverage)



Southern Ocean Watermasses





glodap

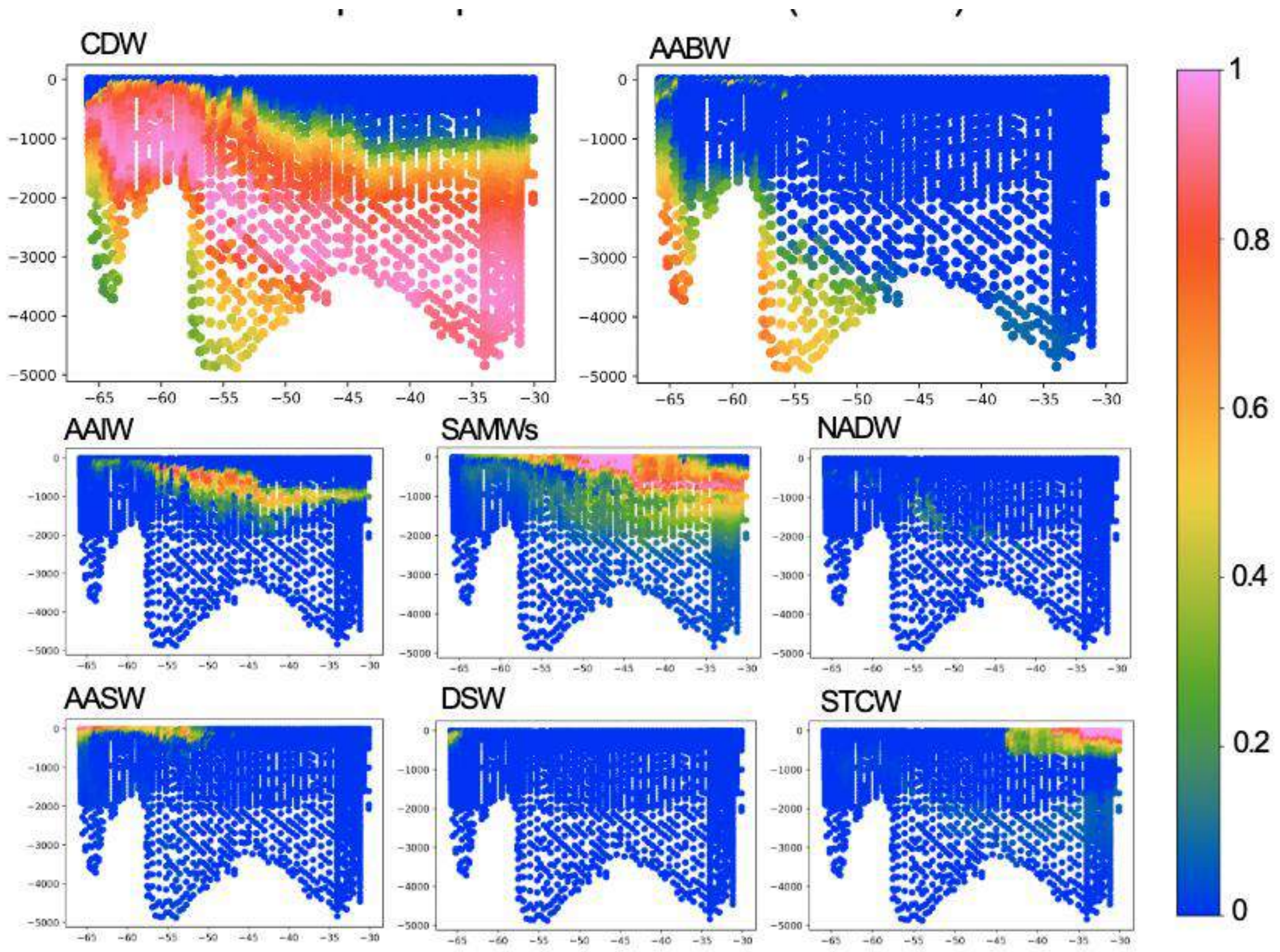
- GLODAP gridded and ship-based profile data in the Southern Ocean of include T, S, dissolved Oxygen, Nitrate, Phosphate, Alkalinity
- Calculate conservative tracers (NO, PO, Salinity, **θ**)
- Define 9 Southern ocean water masses

(Lanham et al, in prep

Method: OMP analysis

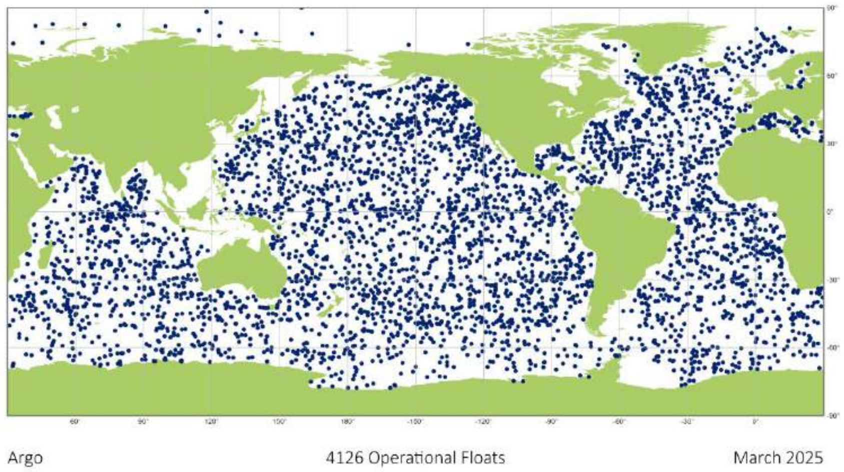
- Assume that all observed data can be explained as a linear mixture of each of these source waters
- Solve with non-negative Least-Squares machinery from Wunsch (2008) to give an optimal solution with minimal residuals

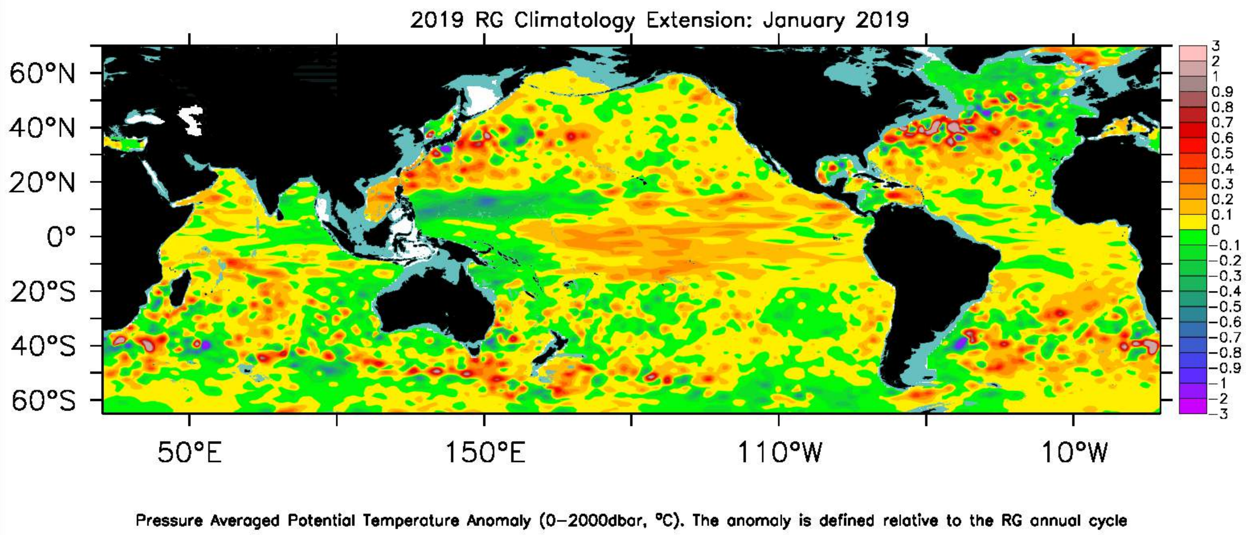
I08 S in 2007



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





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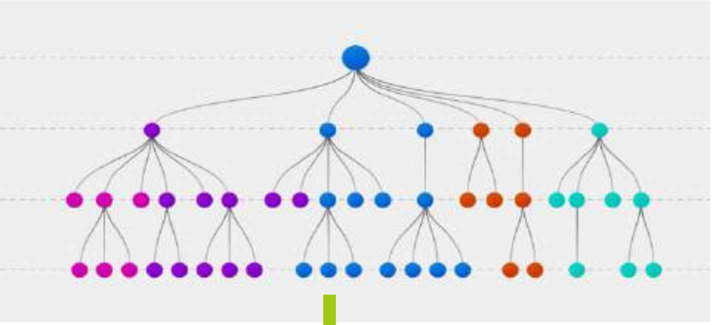
  - Apply to the 20 years of monthly gridded Argo gridded data
  - Look at the integrated ”thickness” of each watermass
  - Remove seasonal cycle

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-01

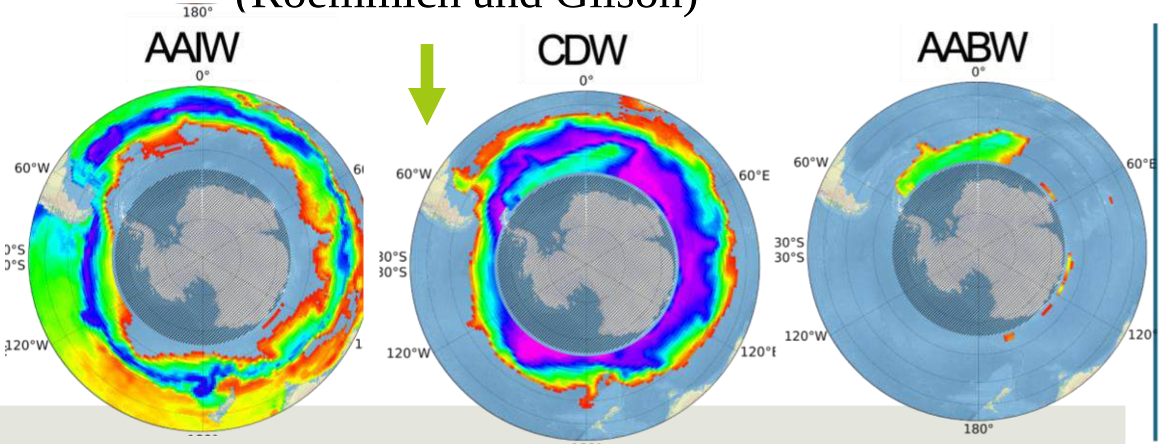
Temperature, Salinity, Lat, Lon, Depth

Random Forest Models

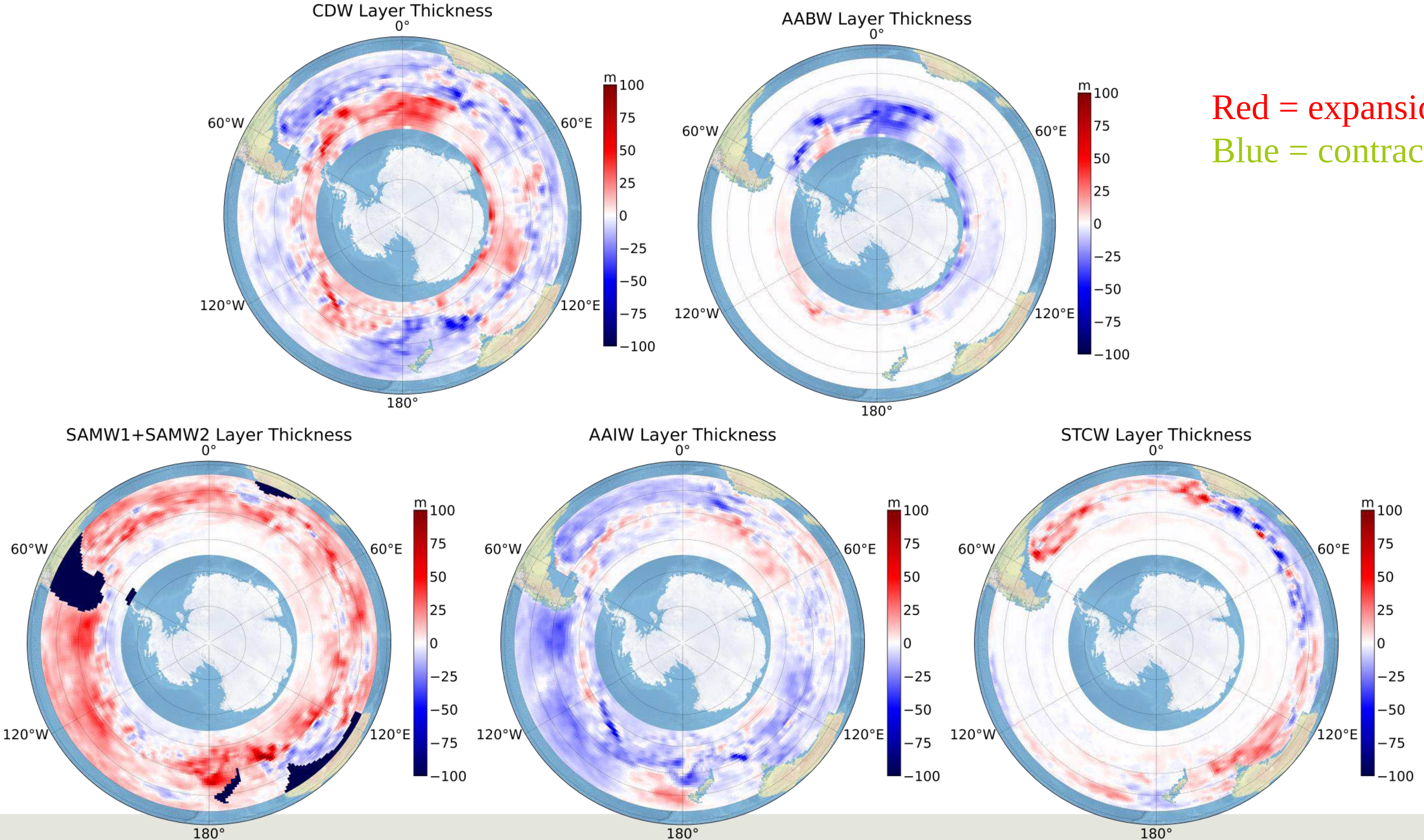


20 years of monthly gridded Argo Data (Roemmich and Gilson)

700m (July 2020)



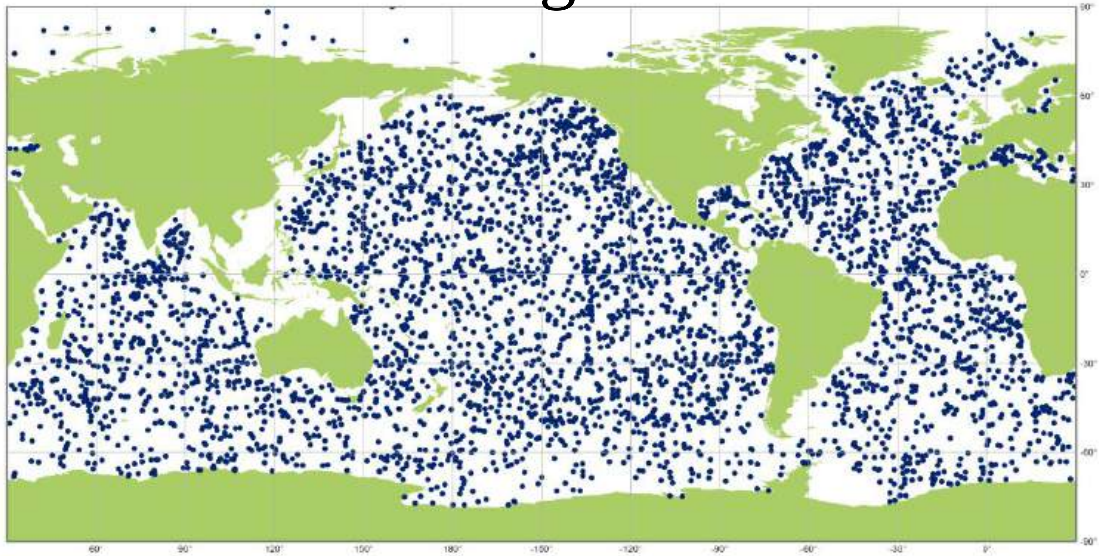
Change in Watermass thickness: avg(2019-2023) - avg(2004-2008)



Red = expansion
Blue = contraction

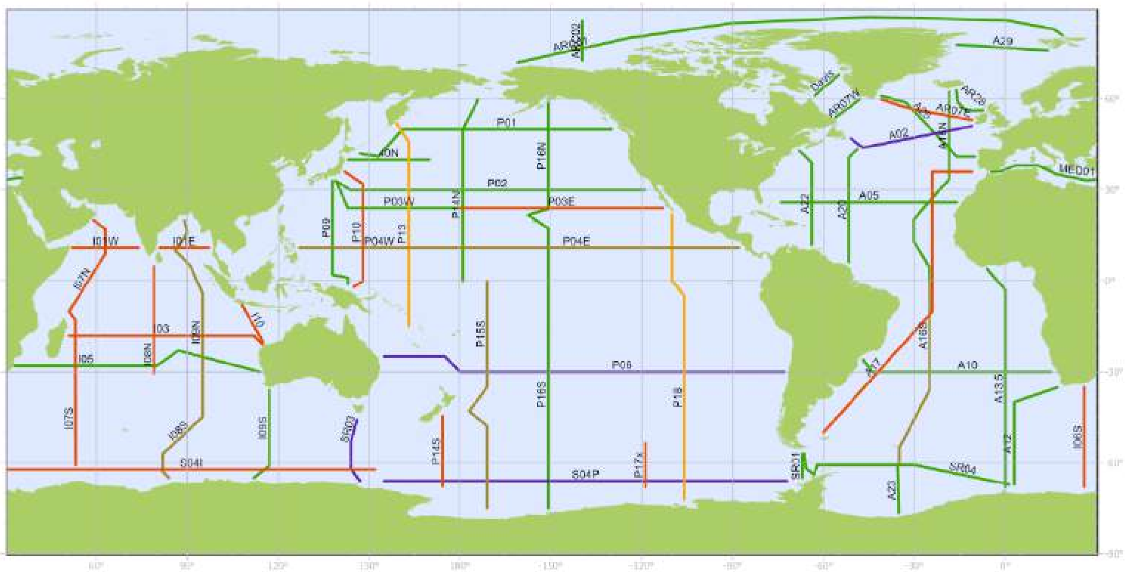
Future of Ocean Observing?

Argo



Argo 4126 Operational Floats March 2025

GO-SHIP



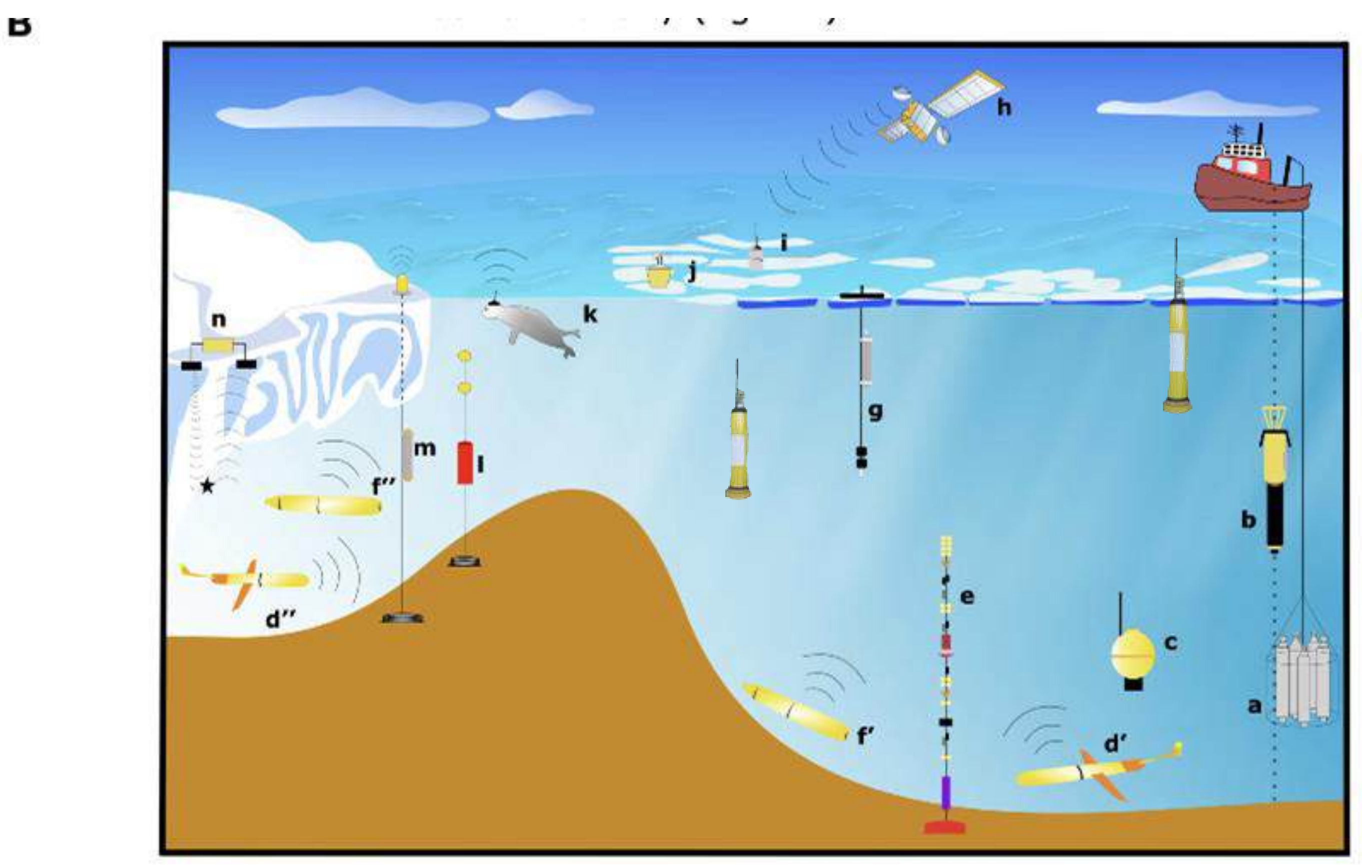
GO-SHIP Floating status of GO-SHIP (55 Core Lines) November 2023

- 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 challages

- 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.



(Silvano et al. 2023)

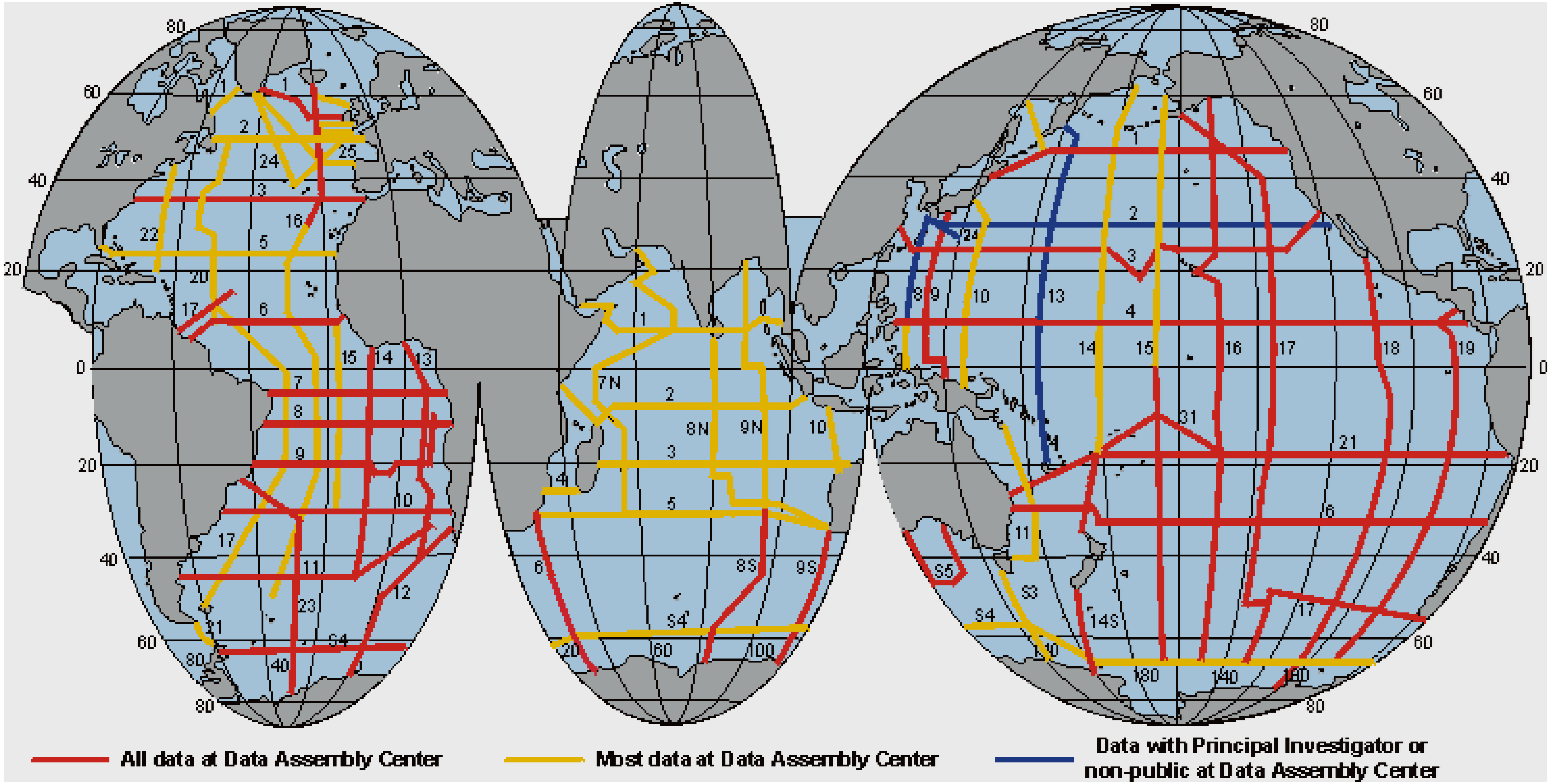
Thank you and questions

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

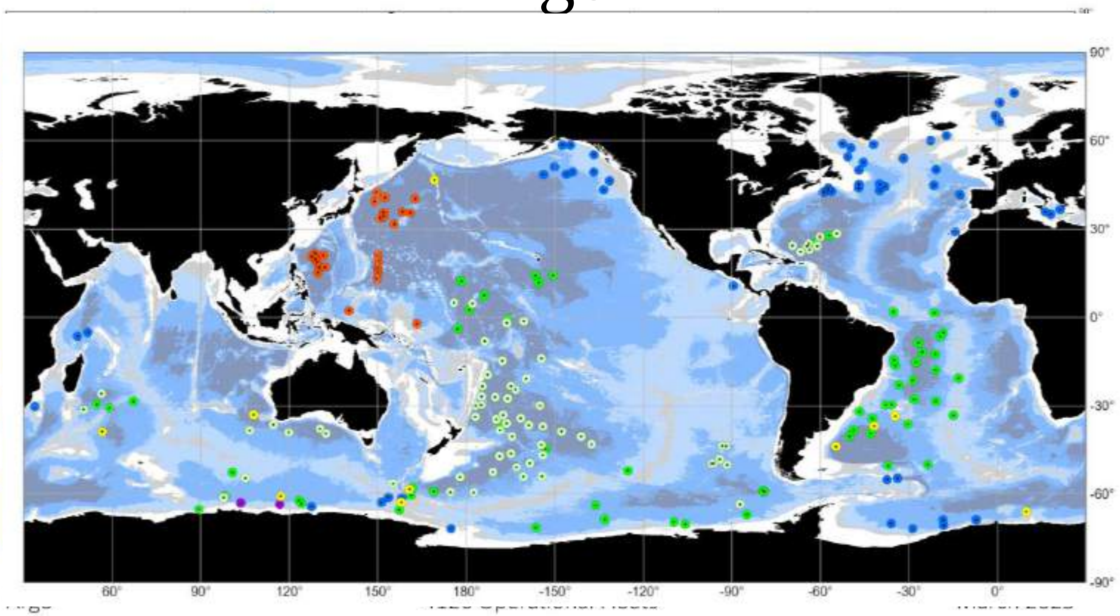
WOCE

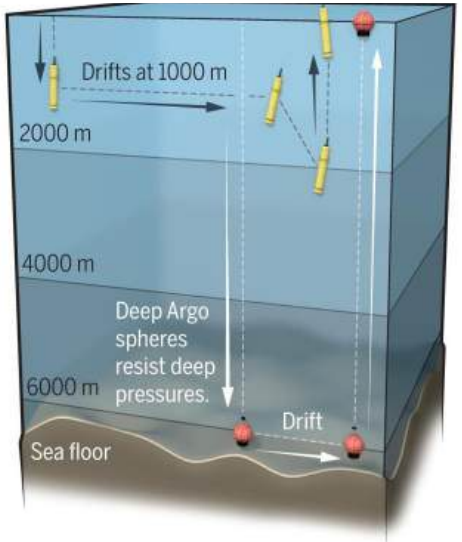
WOCE: World ocean circulations experiment



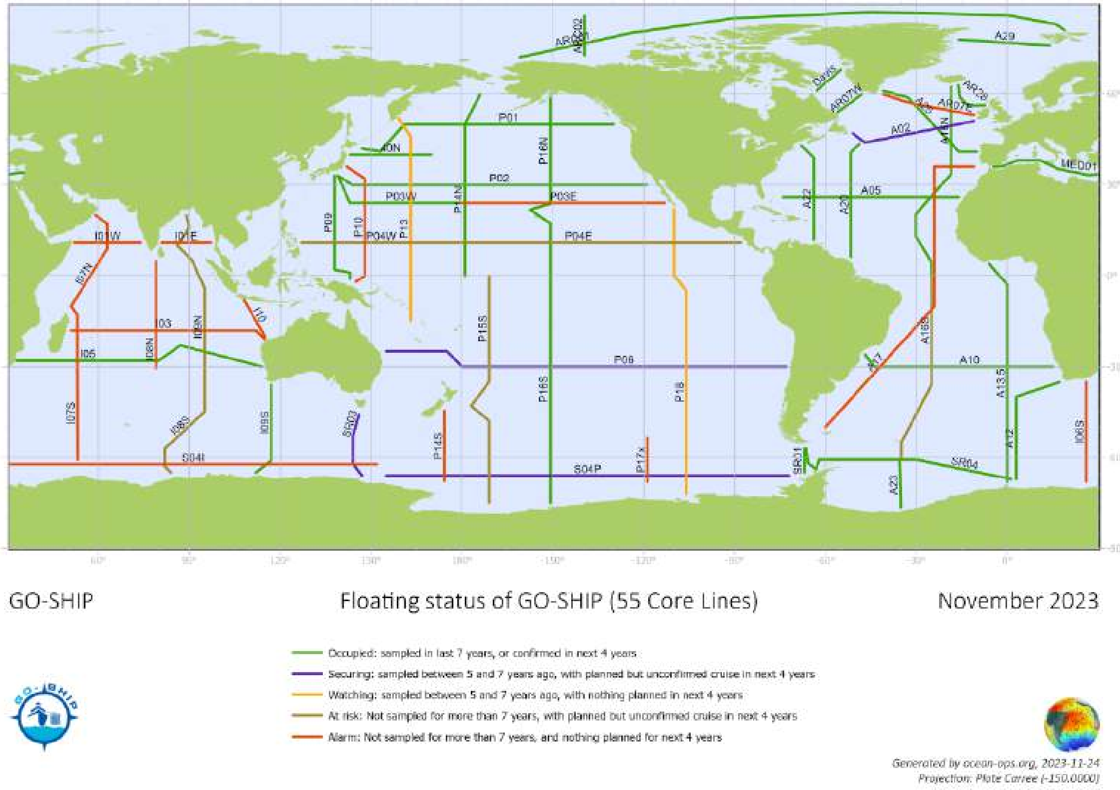
Observing the Interior Ocean

Argo



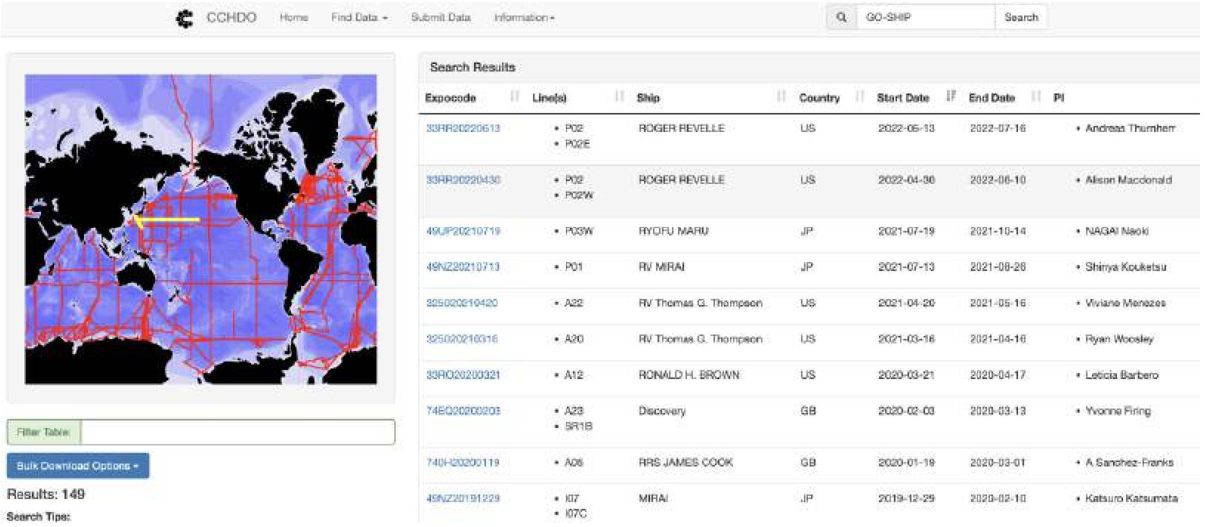


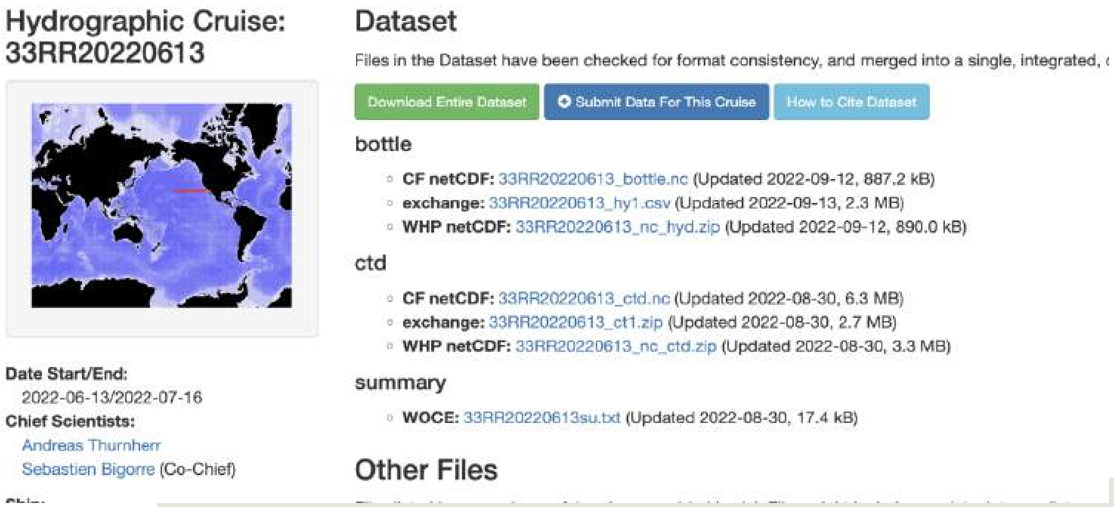
GO-SHIP



GO-SHIP data

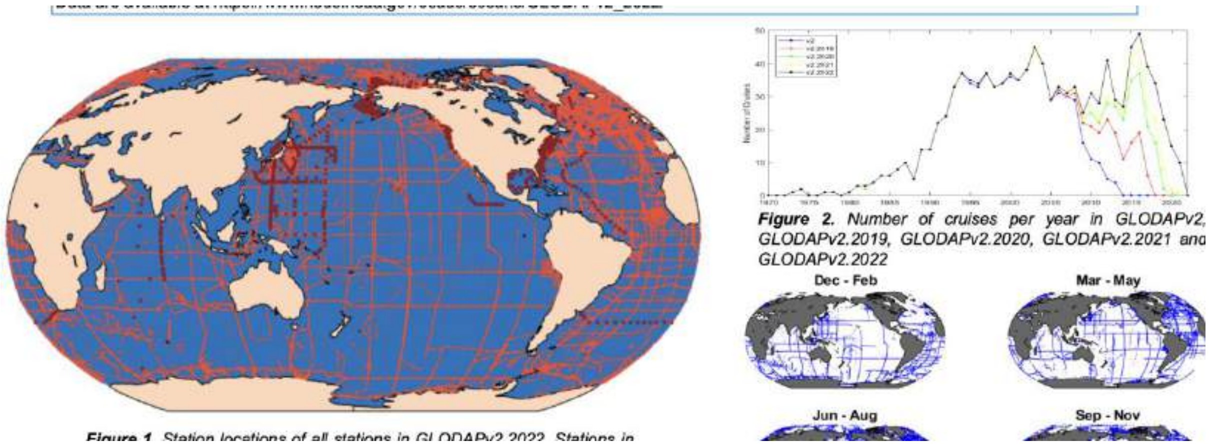
CCHDO: https://cchdo.ucsd.edu/





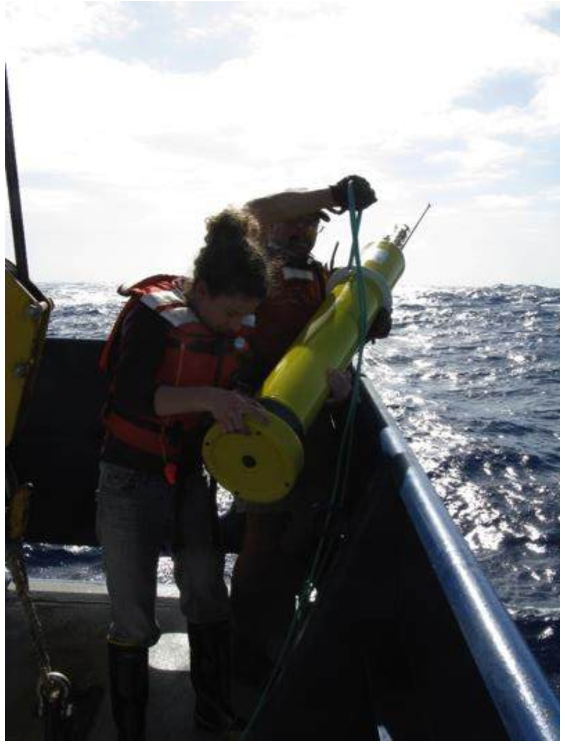
JOA : https://joa.ucsd.edu/

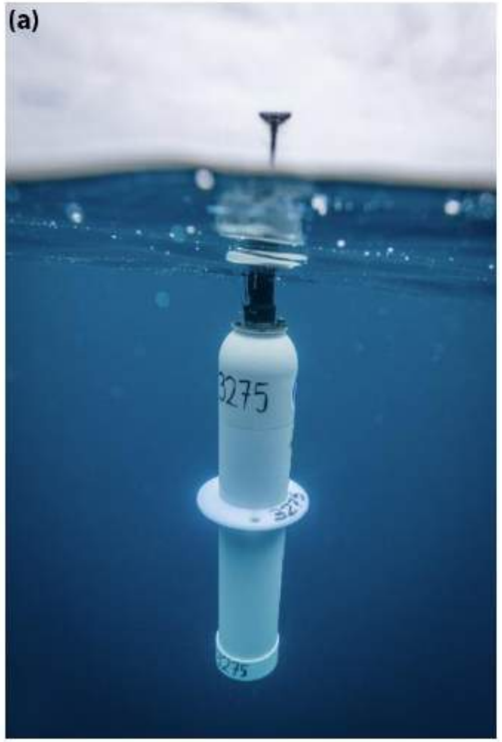
Glodap: https://www.glodap.info/



Argovis

Argo

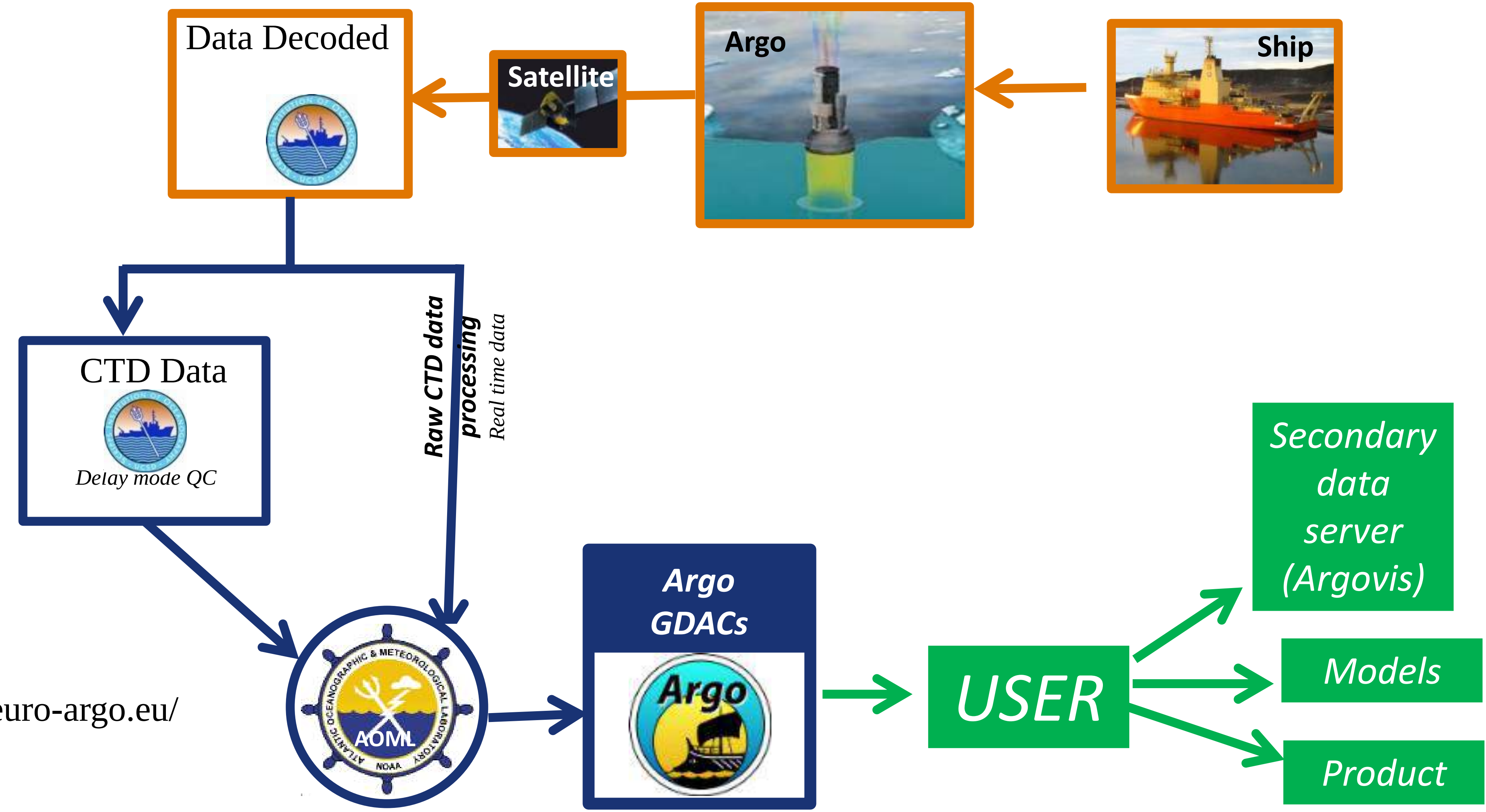





Argo Data

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

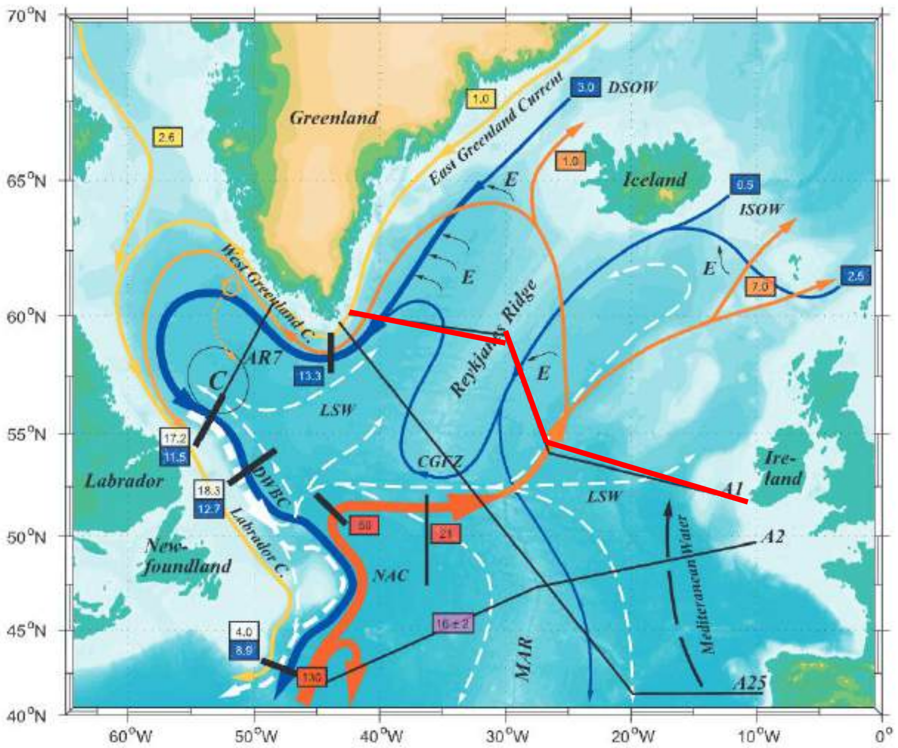
- data access
- list of gridded products
- “how to” manual

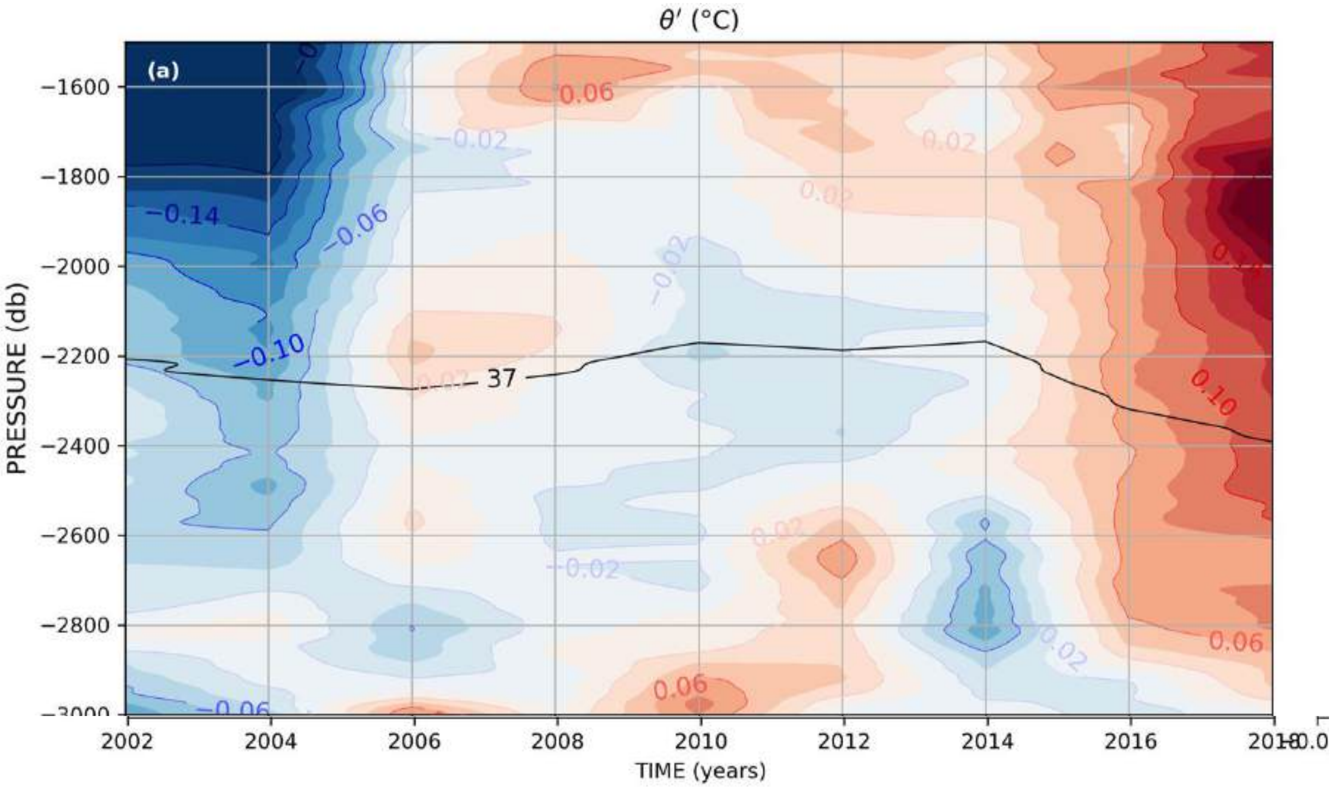


Add matlab packages

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

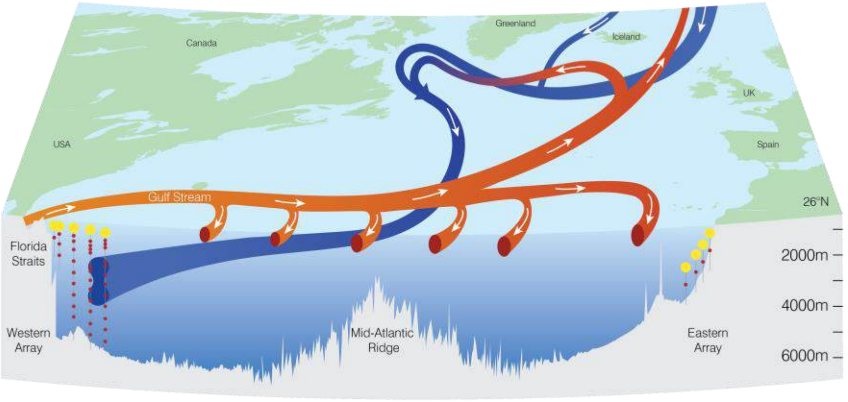
NADW Variability

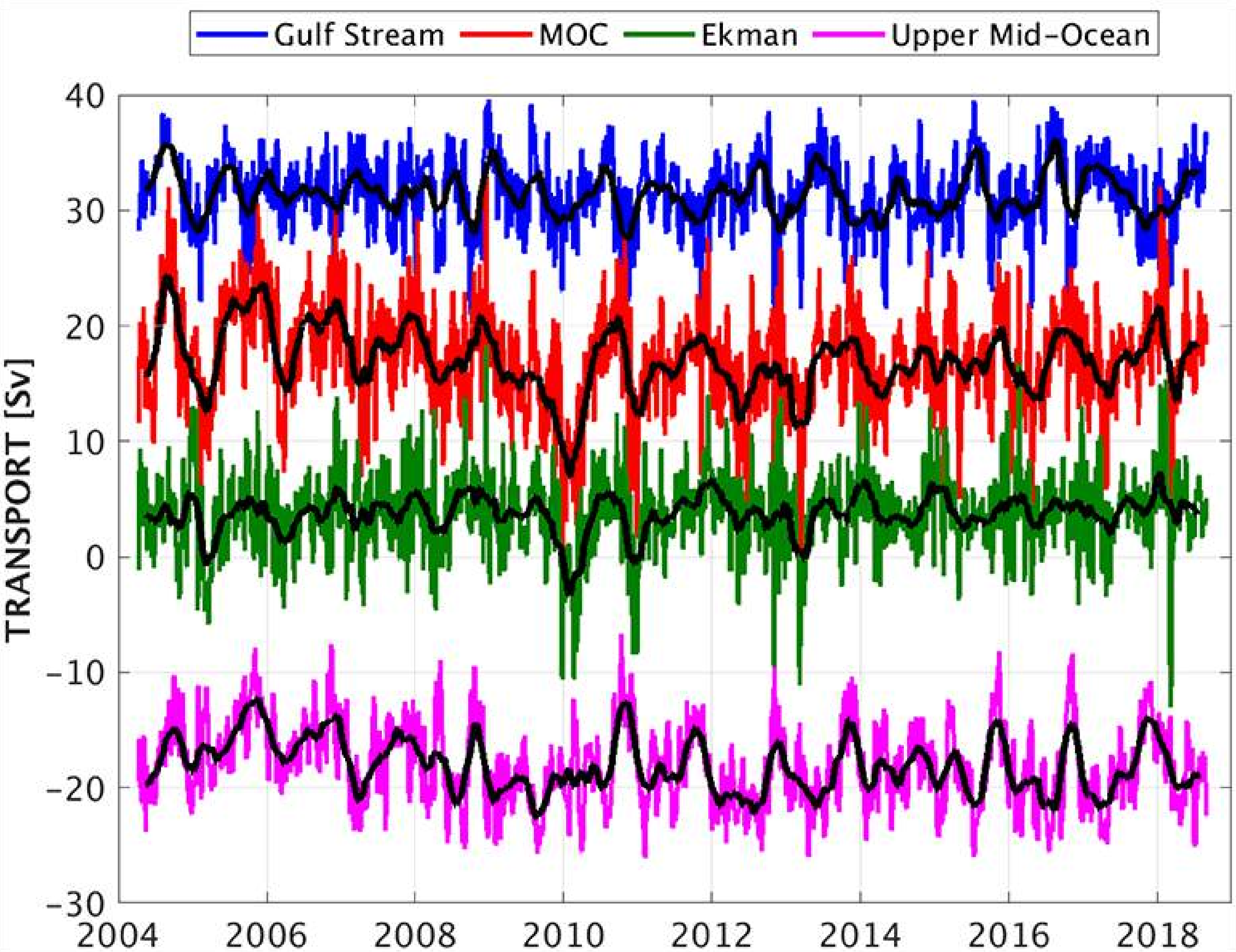




(Desbruyeres et al. 2022)

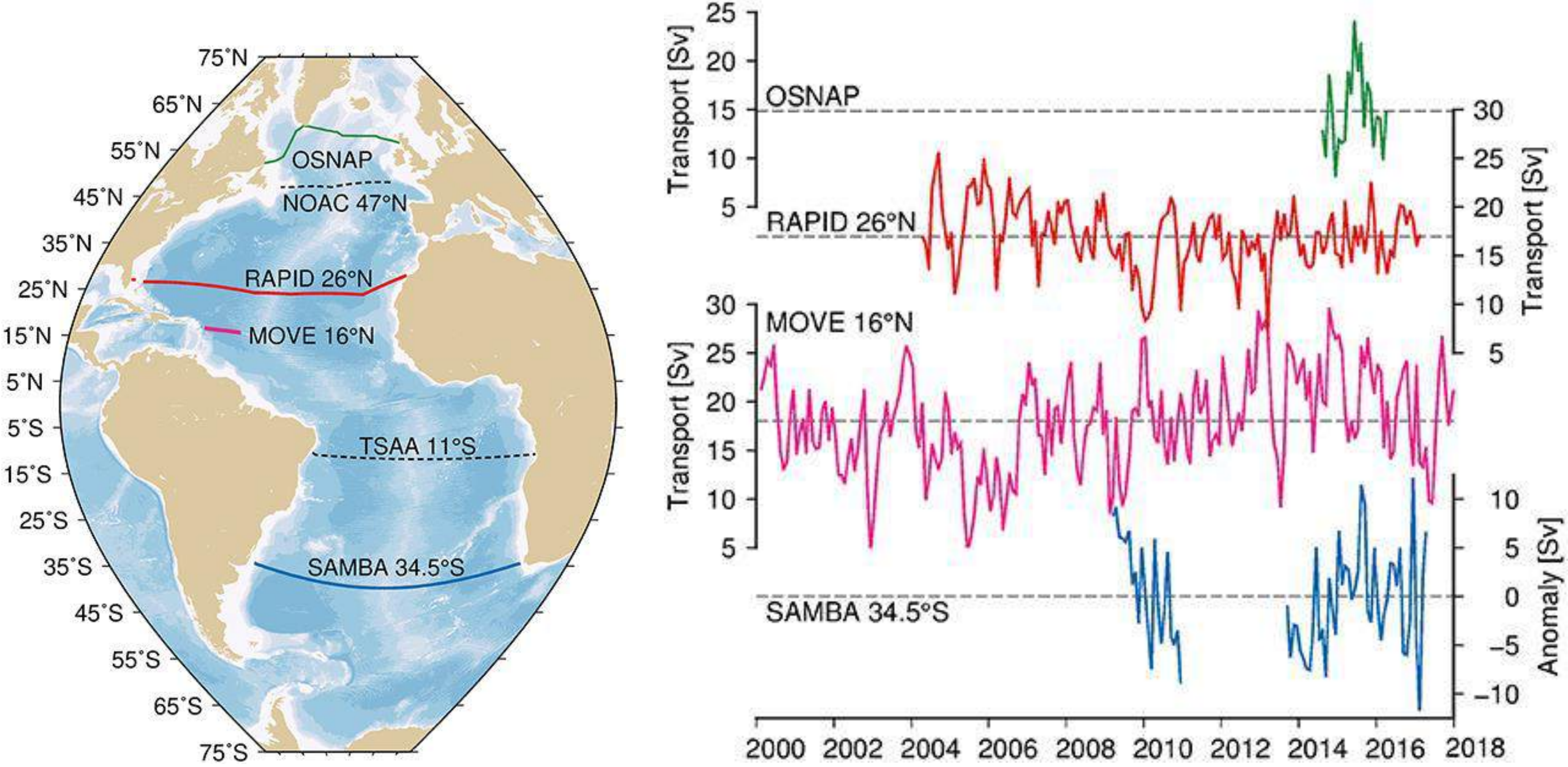
Long-term monitoring of the MOC





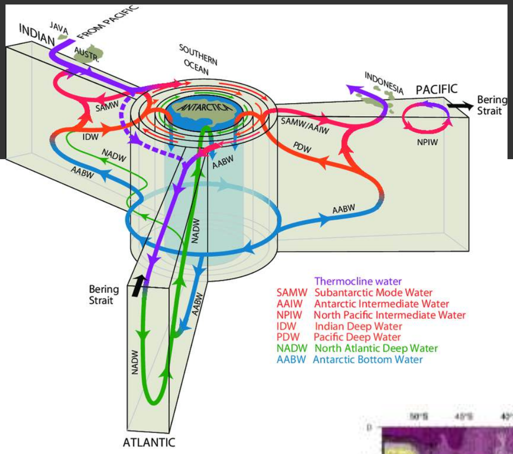
(RAPID: https://rapid.ac.uk/)

Long-term monitoring of the MOC



(Frajka-Williams et al. 2019)

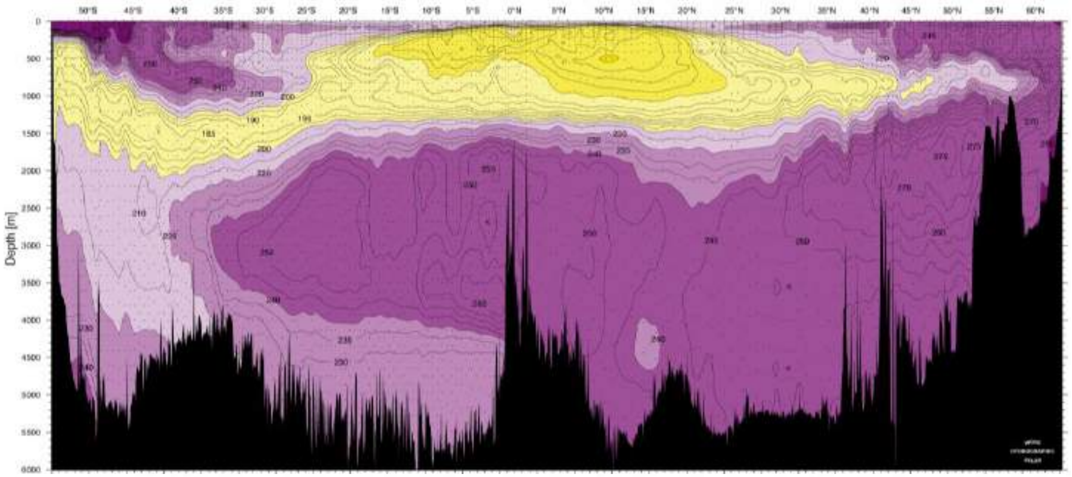
AABW and NADW in the MOC

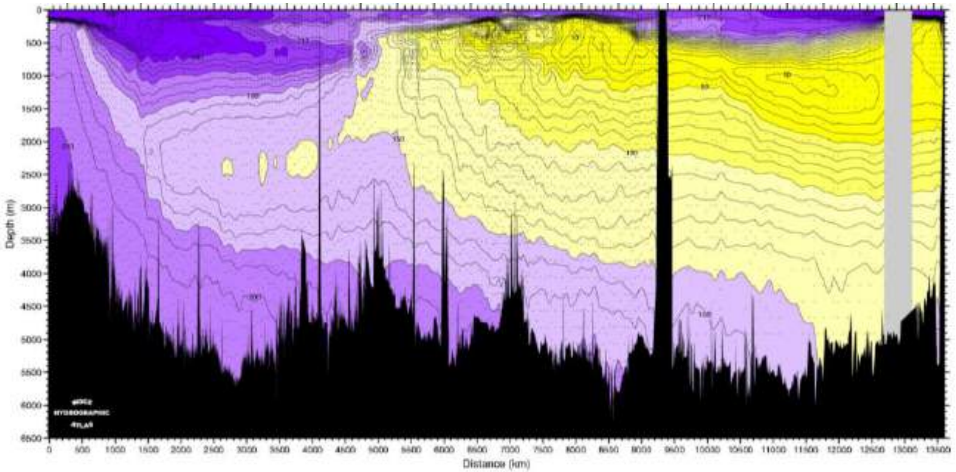


Atlantic

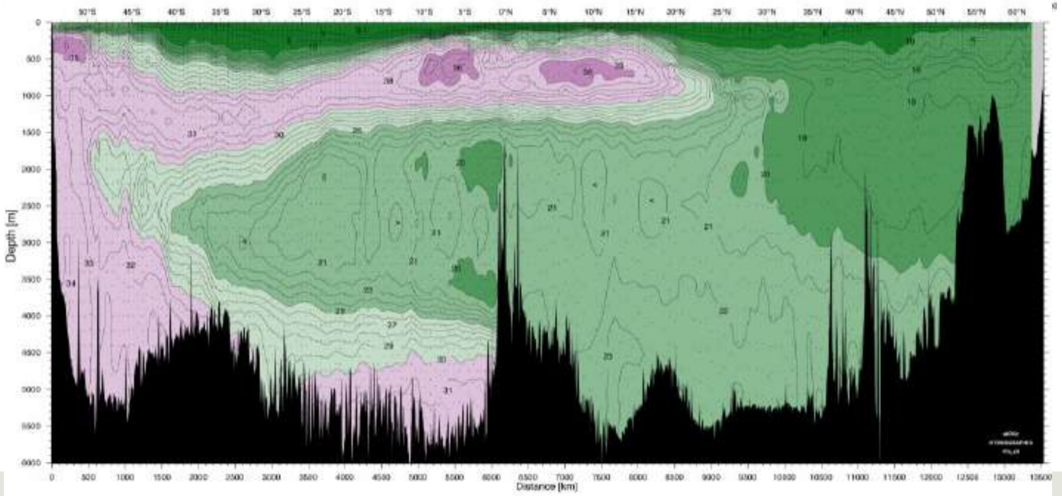
Pacific

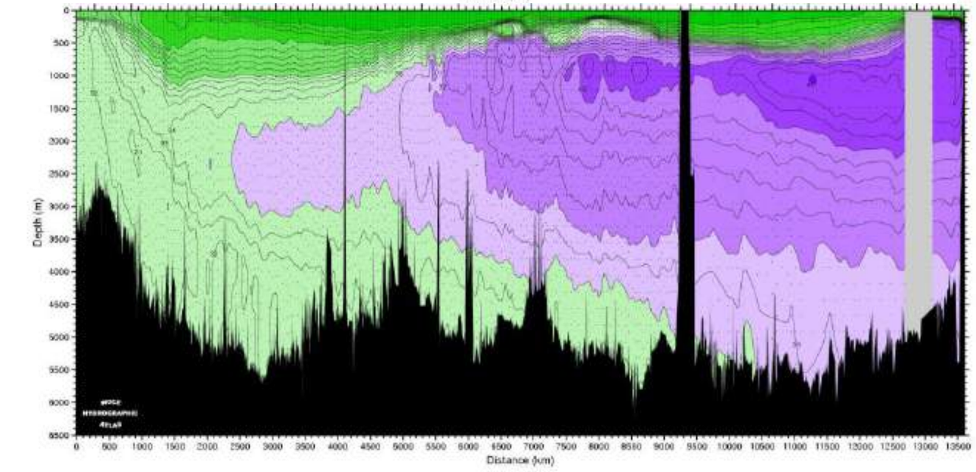
Oxygen



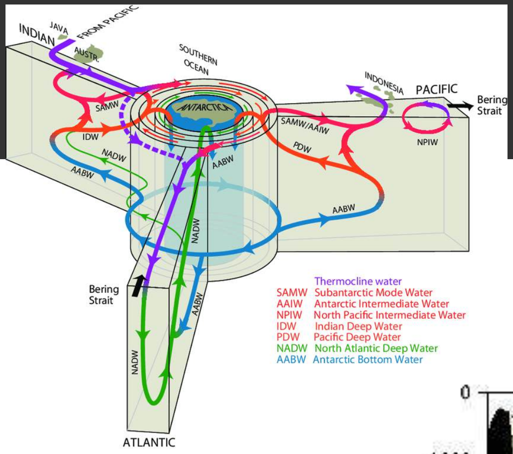


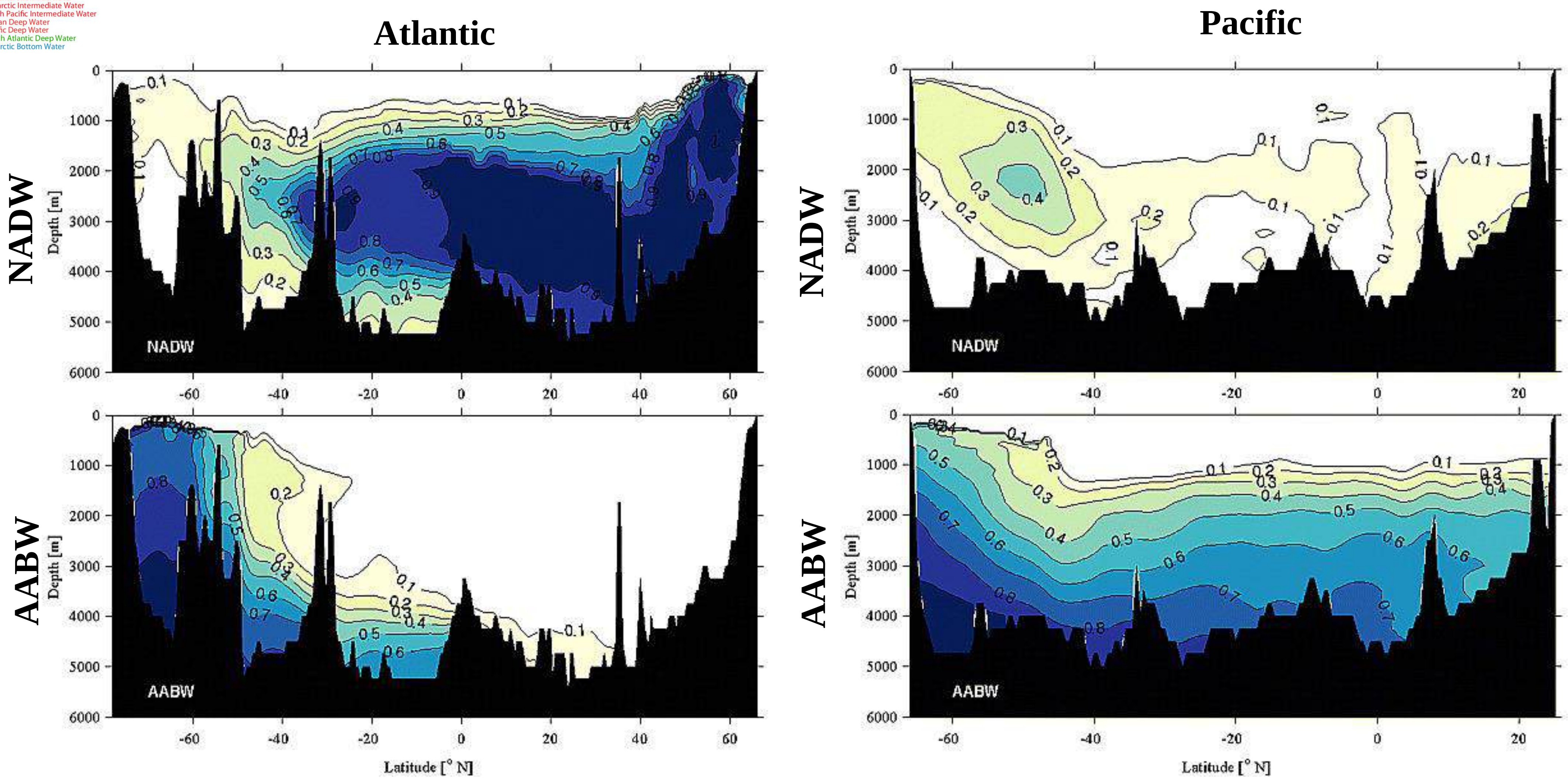
Nitrate





AABW and NADW in the MOC

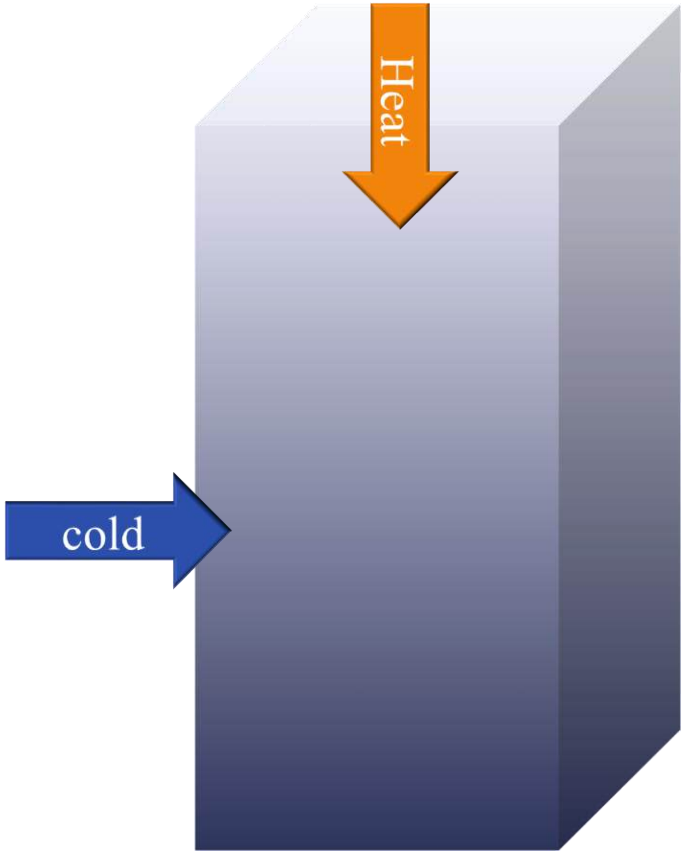


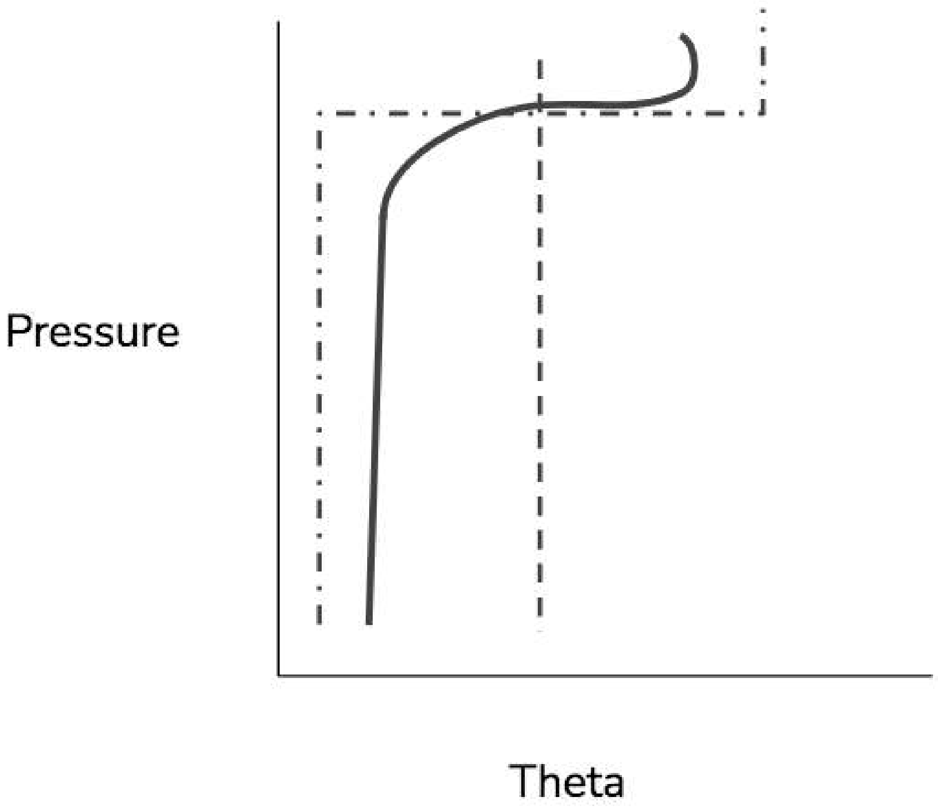


The Global Meridional Overturning Circulation (MOC)

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

Advection + Mixing = 0

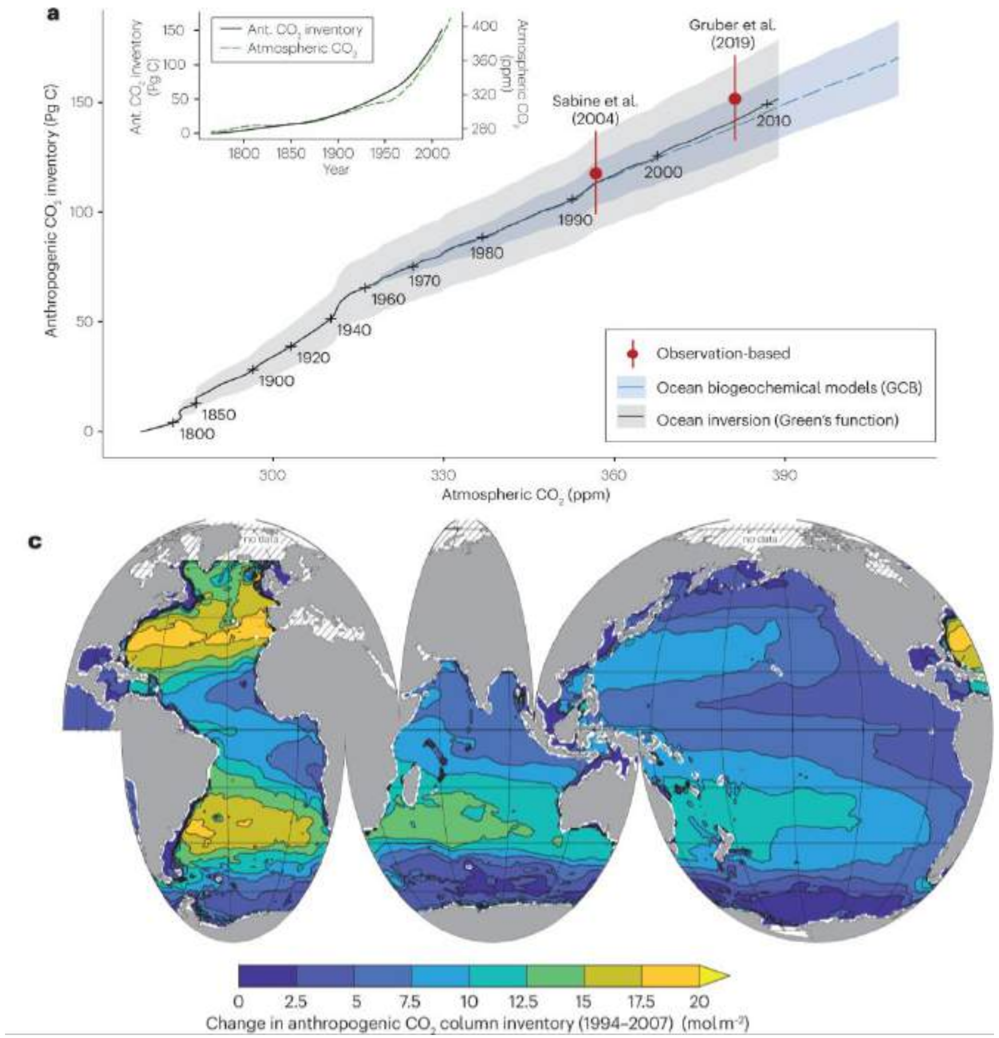




- In steady state, these two processes are equal and bottom temperature is constant in time

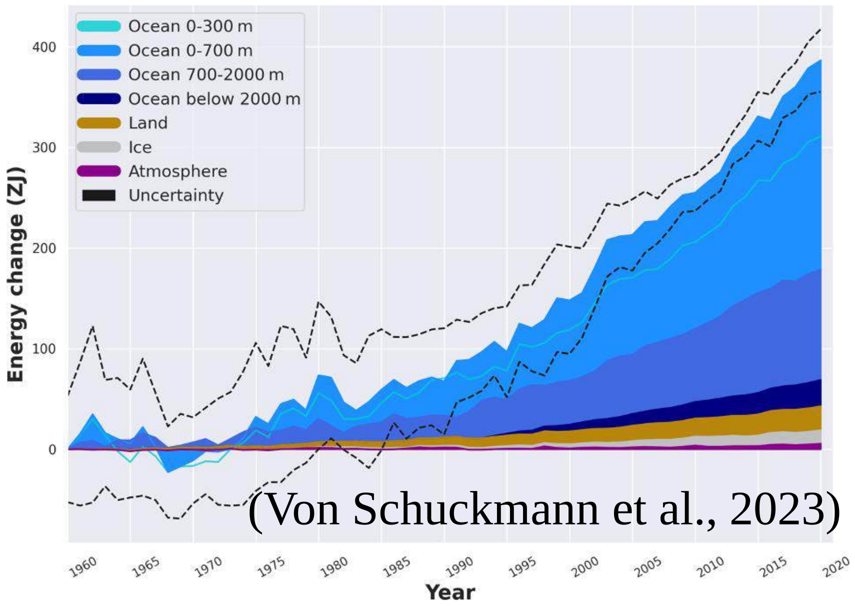
Ocean Ventilation Matters for Carbon and Heat Uptake

Anthropogenic Carbon

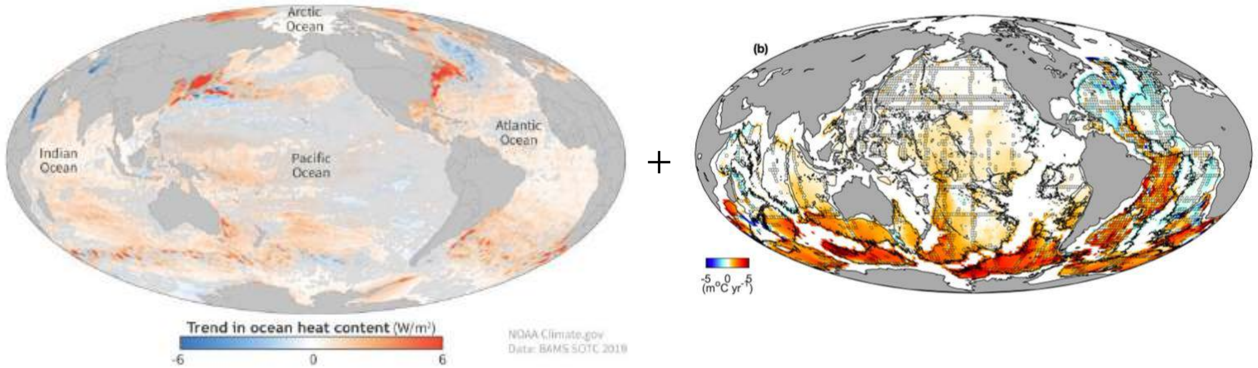


(Gruber et al., 2023)

Anthropogenic Heat



(Von Schuckmann et al., 2023)



(OHC state of the climate)