Circulation and property transport changes diagnosed from ocean hydrographic observations: AMOC and ‘SOOC’

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7th Summer School on Theory, Mechanisms and Hierarchical Modelling of Climate Dynamics: ICTP Summer 2026
Estimating Ocean Transports: Single Sections, Box Models and Reanalysis Products

July 6, 2026

Methods: GO-SHIP, Argo, and moored arrays
Processes: Climate variability modes and anthropogenic change

Process: **Atlantic Meridional Overturning Circulation**
Result: Variations/trends in AMOC
Further work for AMOC and hydrography?

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Natural climate variability with interannual to millenial time scales

Interannual time scale (> 1 year, < 10 years)

ENSO

Decadal time scale (10 to multiple decades)

Pacific Decadal Oscillation (or Pacific-North America Pattern)

North Atlantic Oscillation (or Arctic Oscillation or NAM)

Southern Annular Mode

Centennial time scale (*can't detect with our hydrographic section record yet*)

Atlantic Overturning mode

What sets the time scales?

decadal to centennial suggests longer processes than just atmosphere

e.g. ocean circulation, ocean's planetary wave propagation, or changes in land surface

Modes of natural climate variability: role of ocean

Note that advection time scales are similar to these climate modes:

tropical ocean – years

ocean gyres - decades

ocean basins - centuries

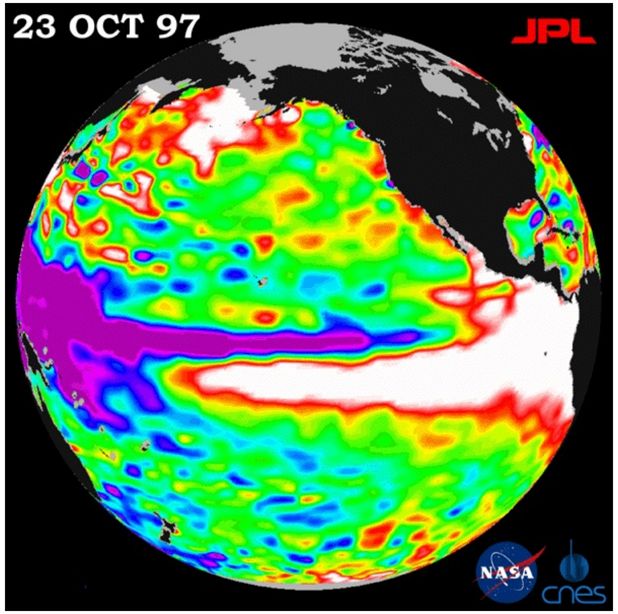
global ocean - ~1000 years

(1) Advection of heat and salinity anomalies: from surface forcing regions, subducted, and then returning to surface where they change the forcing for the atmosphere, or change the ice extent.

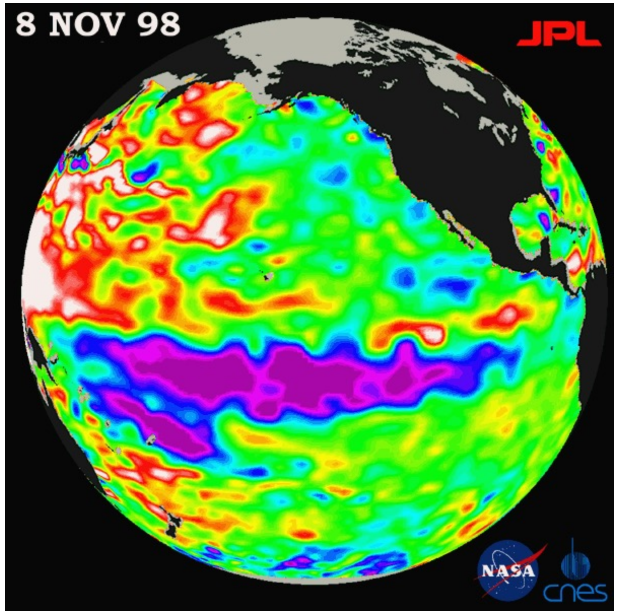
(2) Or similar advection that changes the upper ocean stratification, hence changing the mixed layer depths heated and cooled by the same air-sea fluxes, thus changing surface temperature

(3) Or propagation of anomalies via Rossby or Kelvin waves, which then reset the temperature in remote locations.

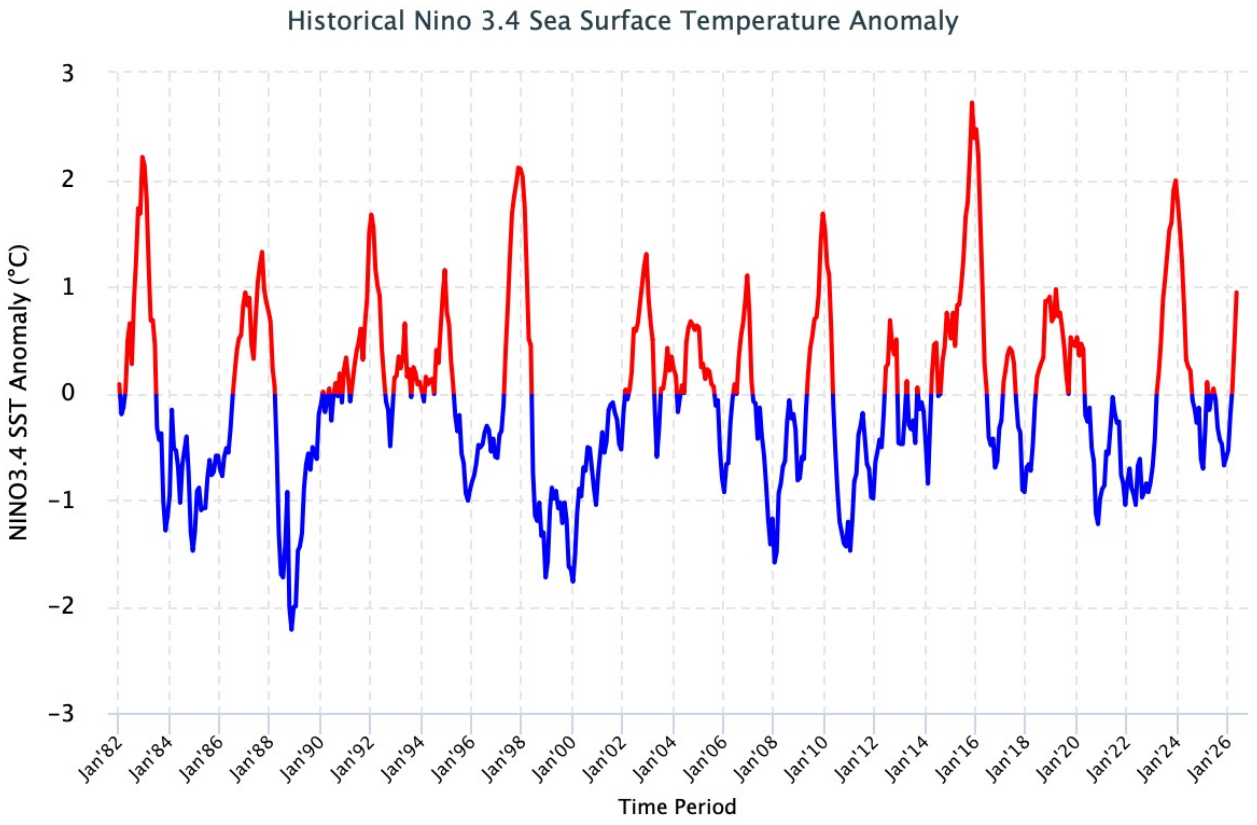
ENSO: interannual (5 to 7 years)



El Niño



La Niña



Nino 3.4 index for ENSO: surface temperature in central equatorial Pacific

Positive: El Nino

Negative: La Nina

A Super El Nino has already started this year

Ideas to do:

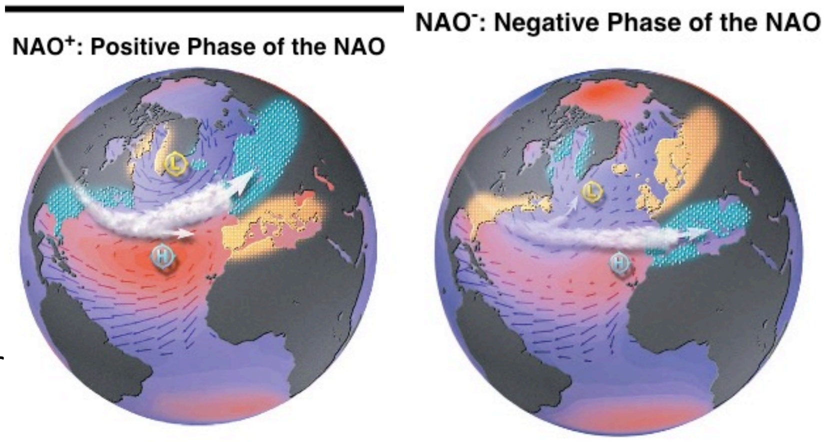
Begin inverse modeling of 10N P04E section as soon as ship docks (yesterday!)

Extend inverse modeling to Argo float data???

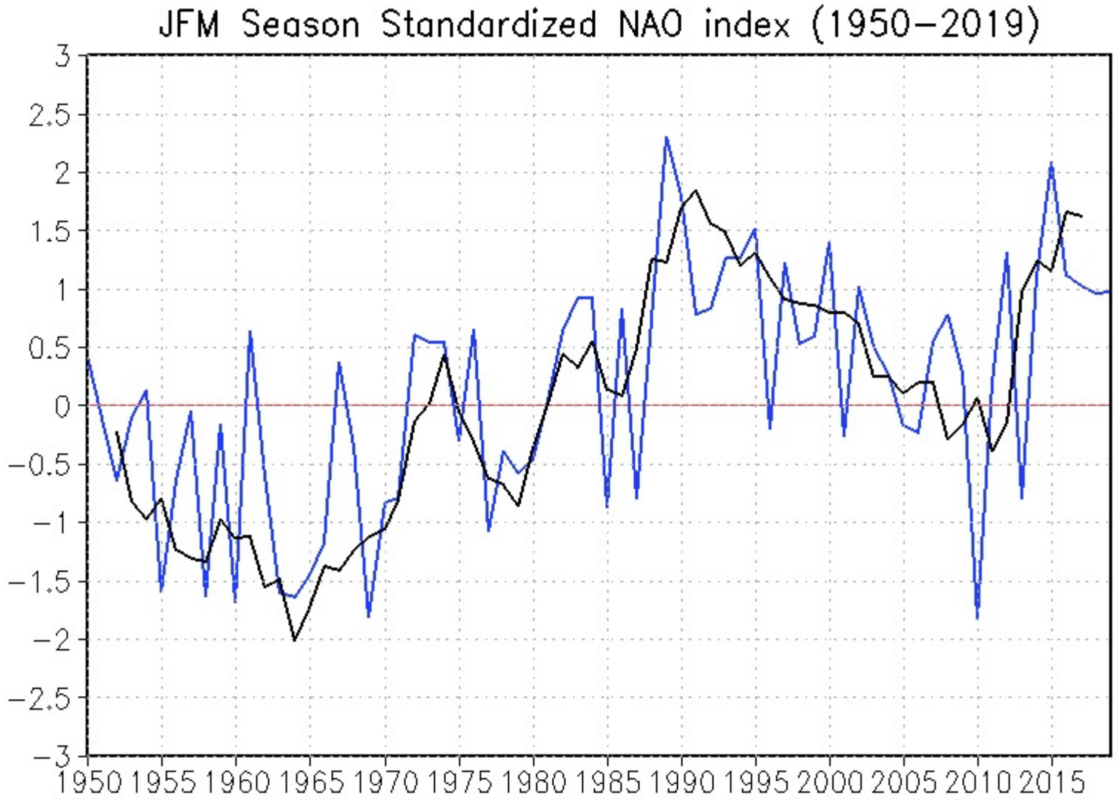
Analysis of the multiple state estimates (data assimilation model) for tropical Pacific

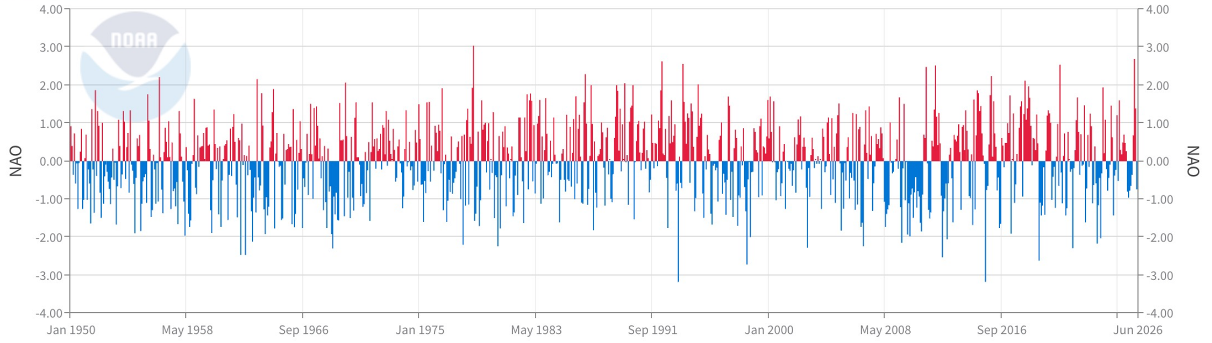
NAO index: Azores to Iceland atmospheric pressure difference

High: exceptionally cold Labrador Sea Water, warm/non-existent Eighteen Degree Water



The two extreme phases of the North Atlantic Oscillation (NAO) and some climatic impacts. Courtesy of Lamont Doherty Earth Lab./NOAA).





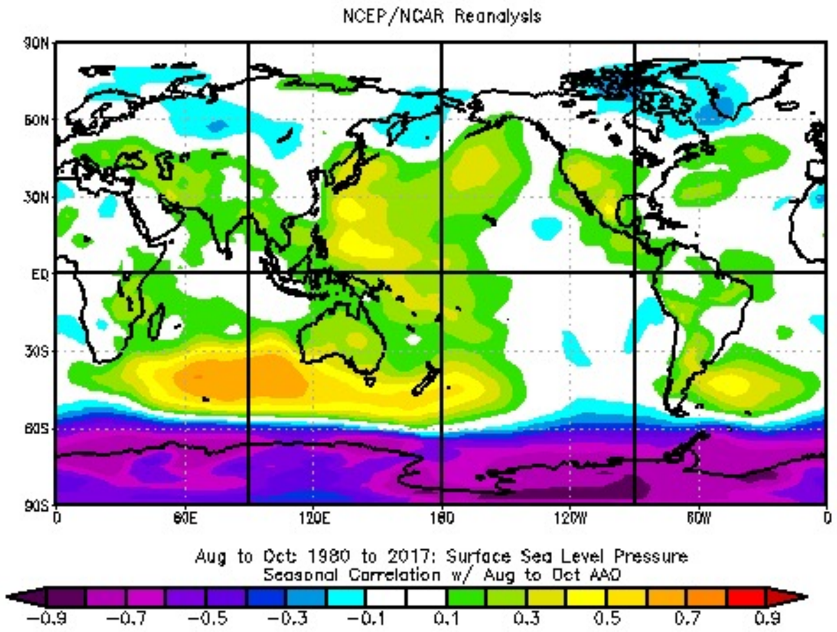
Source: https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/norm.nao.monthly.b5001.current.ascii.table

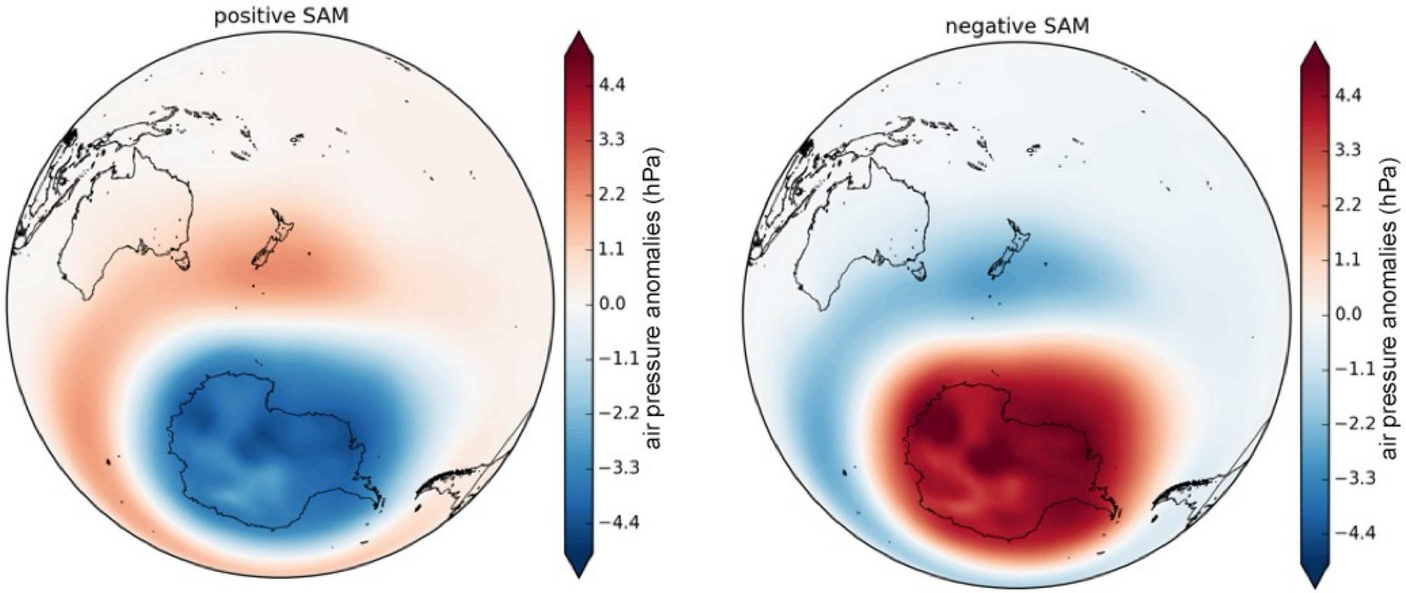
Powered by **ZingChart**

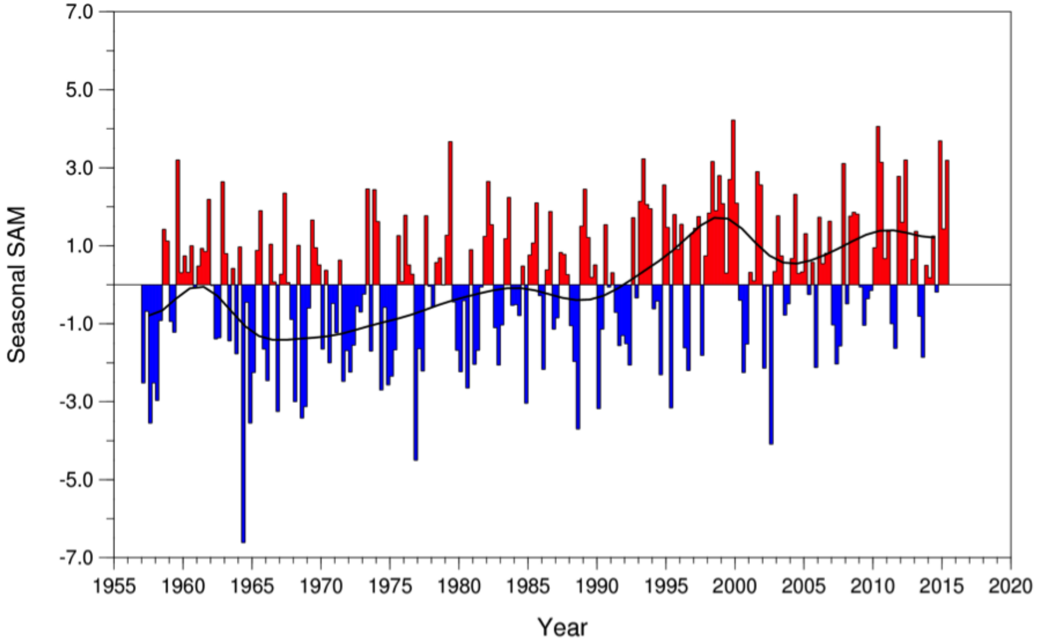
"A strongly positive AO and NAO were observed during early April and likely influenced the warmer-than-normal conditions observed over the majority of the U.S. during this period." https://www.ncei.noaa.gov/access/monitoring/monthly-report/synoptic/202604

Southern Annular Mode (SAM) (decadal)

Circumpolar mode; variation in surface pressure and hence in westerly wind strength



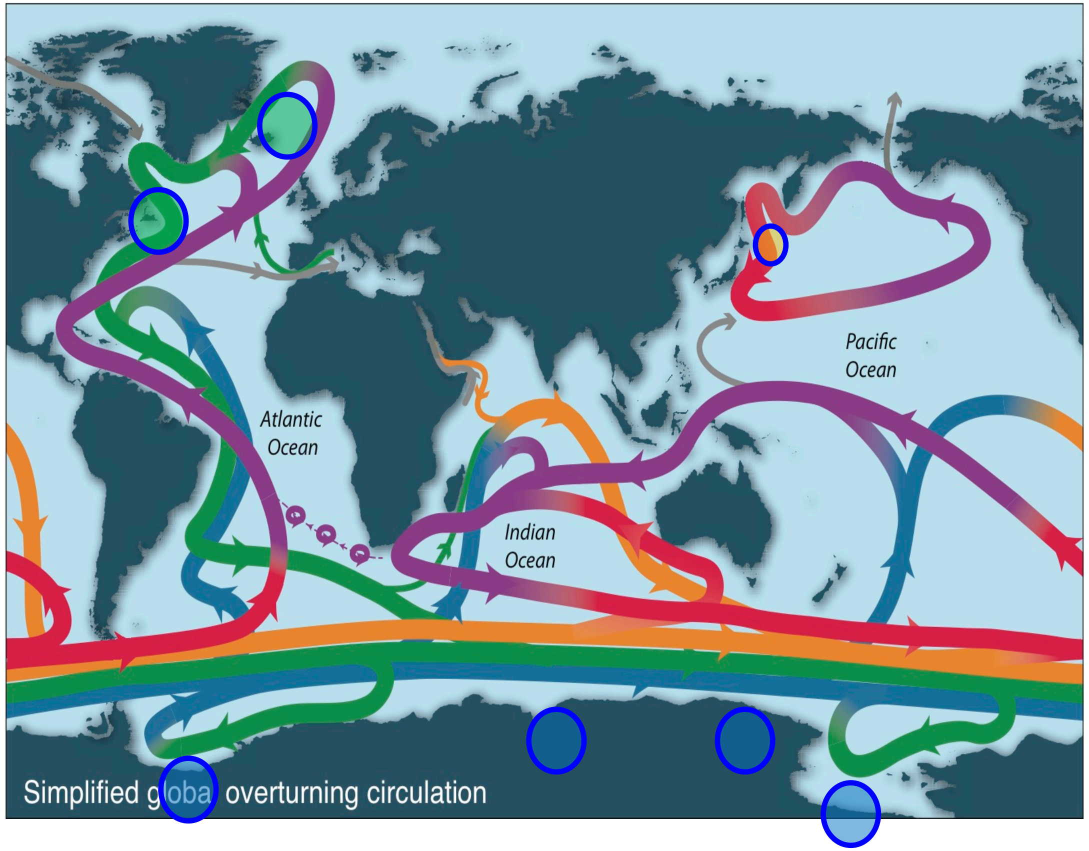




https://niwa.co.nz/climate-and-weather/southern-annular-mode

How might anthropogenic change affect the ocean's global overturning circulation?

Warming oceans: more temperature stratified, which would weaken GOC
Warming oceans: reduction in sea ice, affecting salinity stratification on short to long time scales
Wind changes: stronger westerlies, which would increase Antarctic overturning, strengthen NH circulation
Salinity changes: fresher high latitudes, which would weaken GOC
Salinity changes: higher Atlantic salinity, lower Pacific salinity, which would strengthen GOC
Etc!



How might salinity changes affect the ocean's global overturning circulation?

GOC strength is determined by salinity since there can be very cold water in all high latitude regions.
Salinity is a controlling factor in formation of all dense water masses.

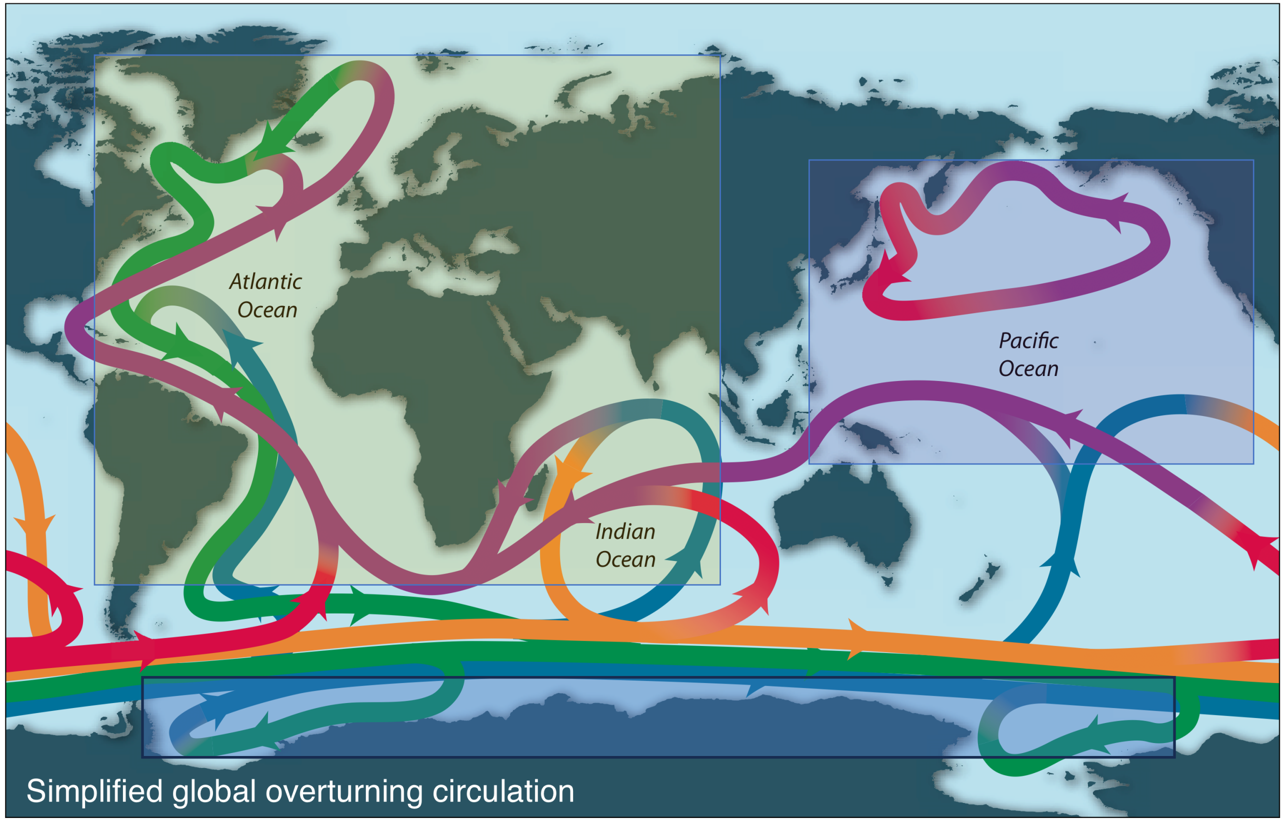
Salty Atlantic/Indian
Deep water sinking
(North Atlantic Deep Water)

Fresher Pacific
NO deep water sinking
(Very old deep water)

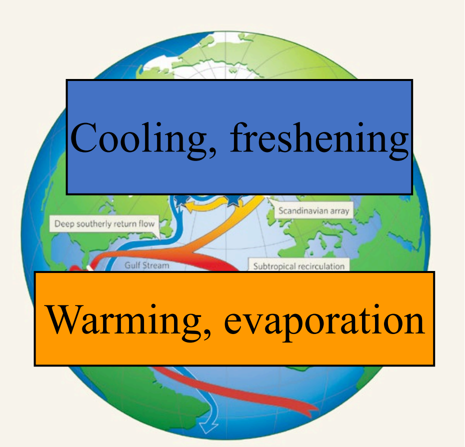
Atlantic gets saltier

Larger subtropical – subpolar contrast

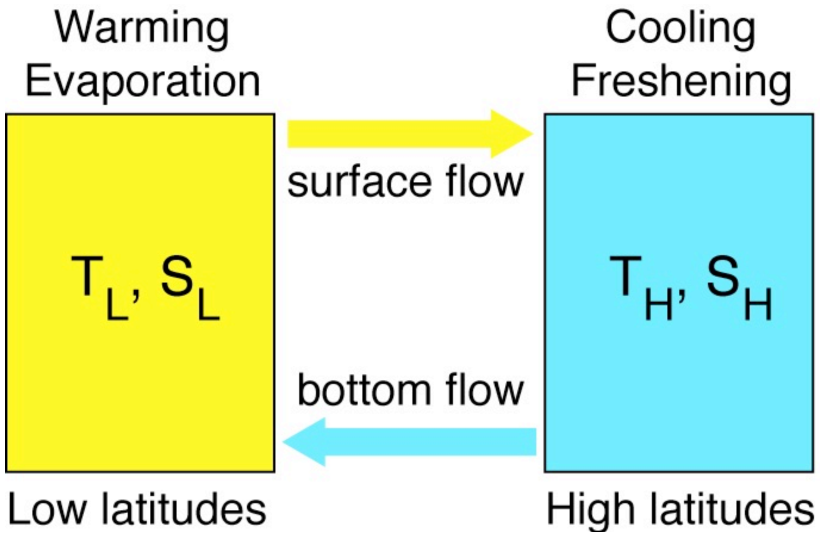
Subpolar fresher and warmer due to ice melt and warming -> reduction in AMOC



Sea ice brine rejection at Antarctic coast acting on salty upwelled CDW. Densest global watermass (AABW)



Salt oscillator (Stommel 1961): example of hysteresis



Model:

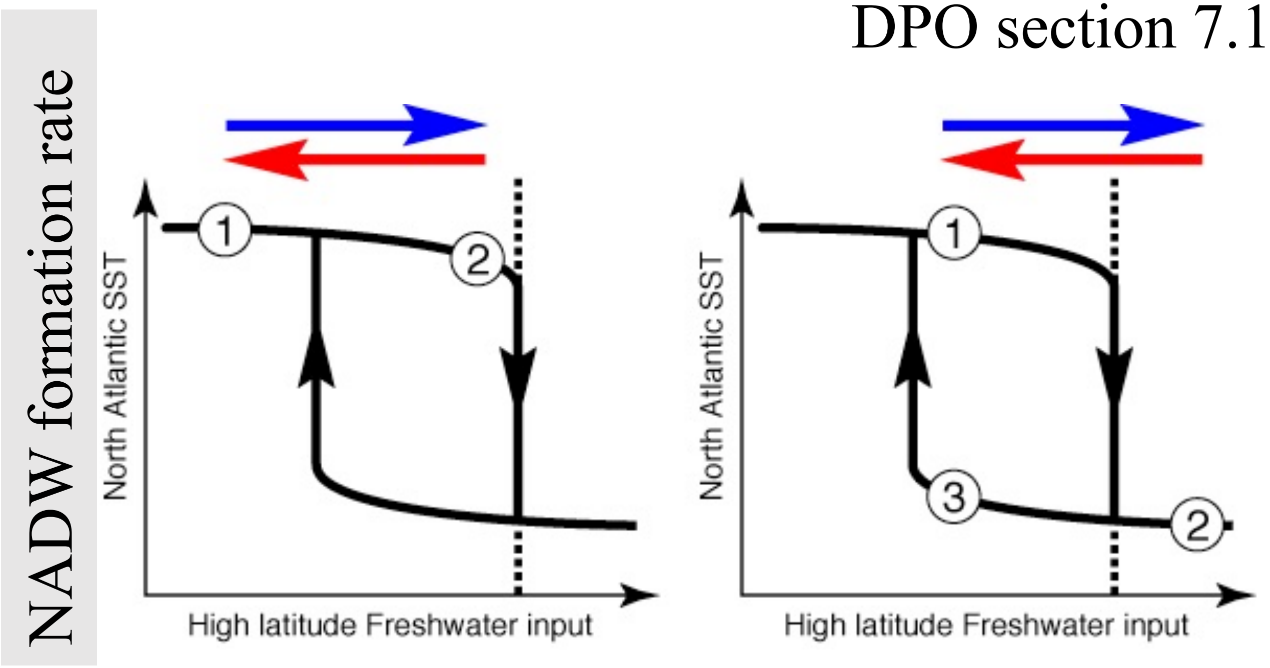
(1) increase freshwater at high latitudes.

Starts to reduce overturn and reduce high latitude SST slightly.

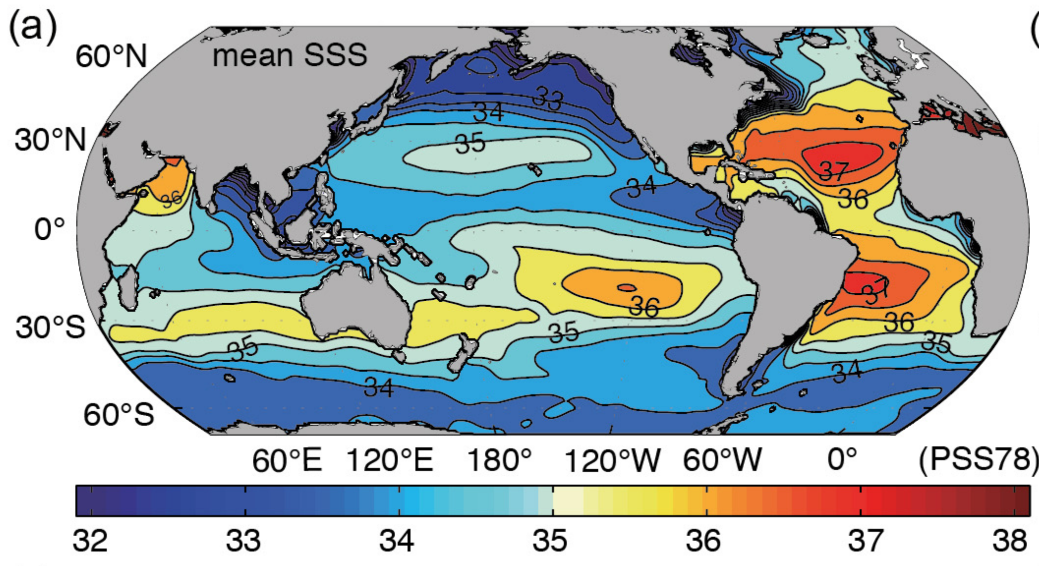
Then overturn shuts off, SST drops abruptly.

(2) Reduce freshwater at high latitudes. Takes a long time to restore (3) overturn (through circulation of high salinity into high latitude box - overshoot - hysteresis)

DPO section 7.10.4



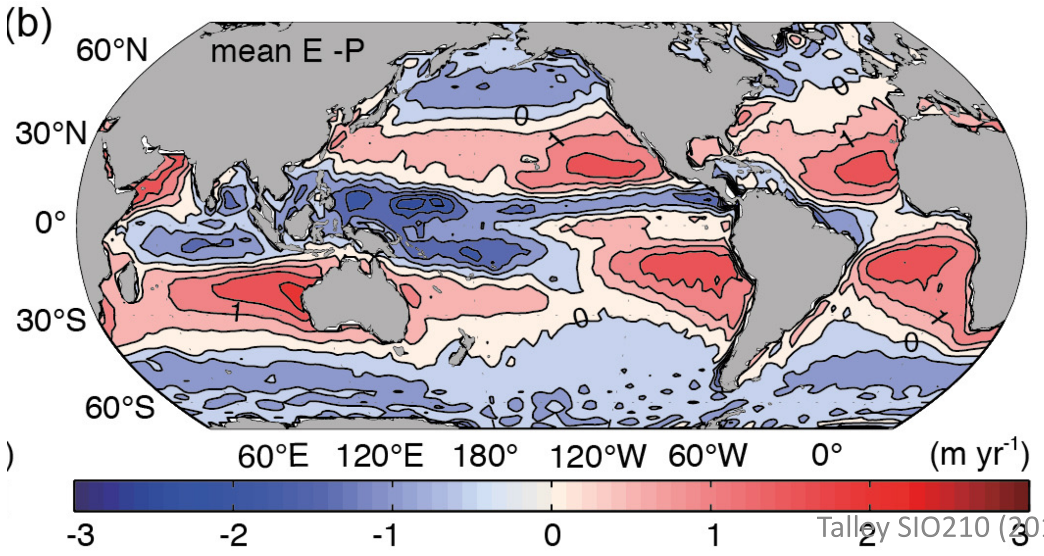
Ocean surface salinity acts as a rain gauge



Surface salinity

Orange is salty

Blue is fresh

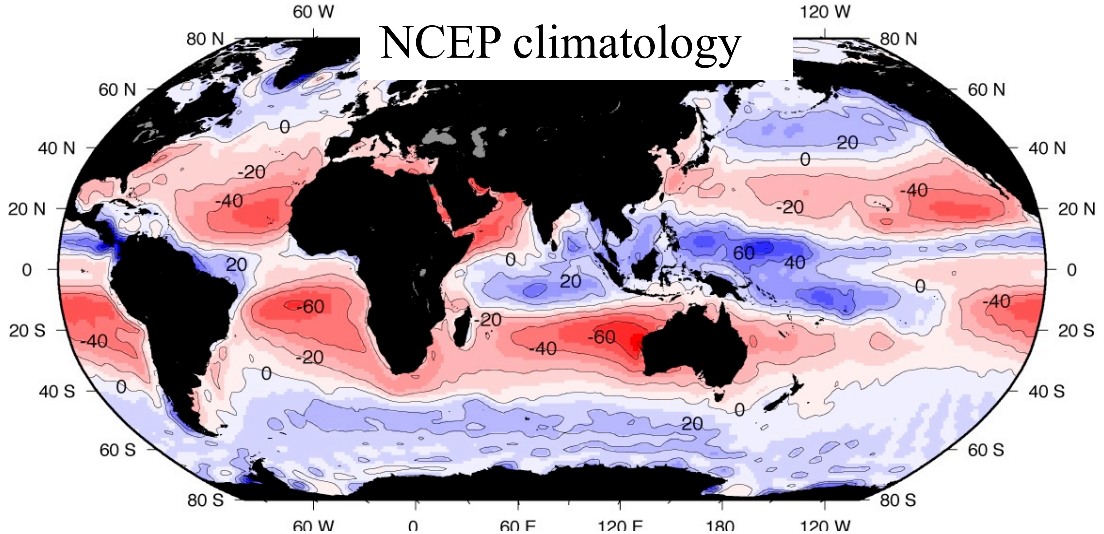


Evaporation minus Precipitation

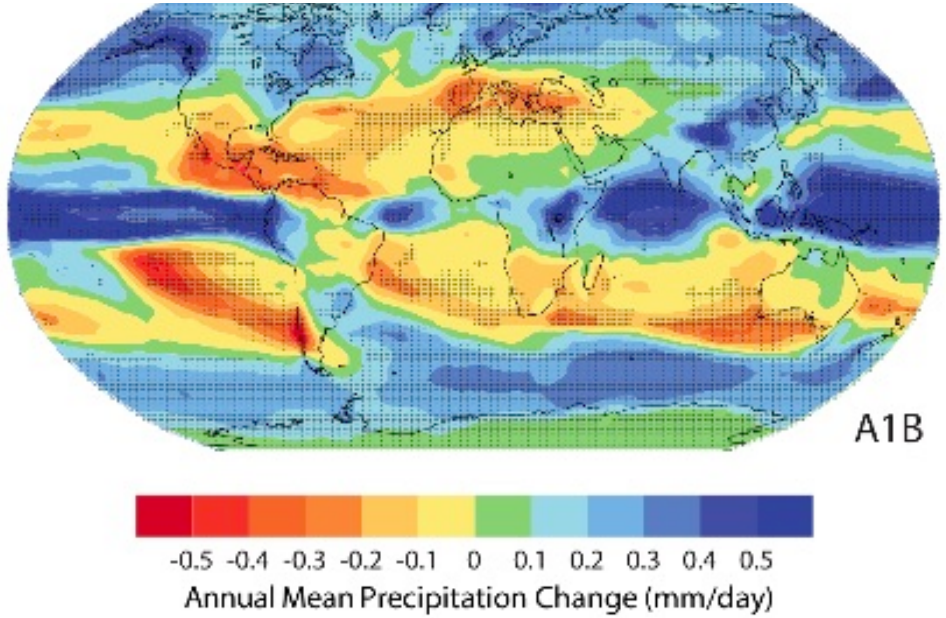
Red evaporates

Blue rains

Evaporation/precipitation and climate



Predicted precipitation change (IPCC, 2007)



- Ocean salinity integrates changes in E-P, runoff and ice melt
- Changes in salinity are more observable than changes in E-P etc.

A warmer world pumps more water vapor into the atmosphere (with the ocean an enormous holding tank for the water): increased hydrological cycle

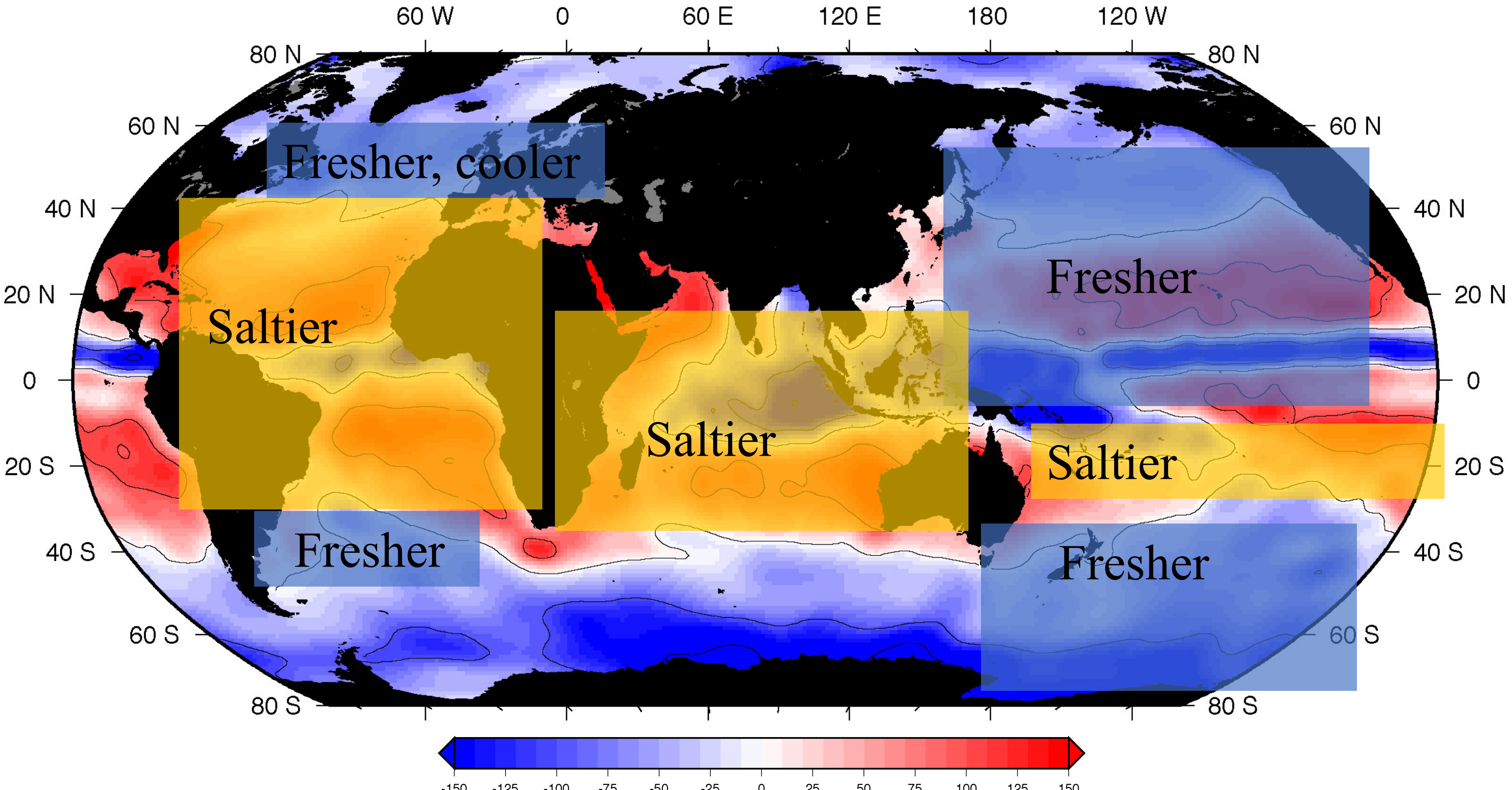
Impacts are recorded in ocean salinity, potential for (indirect) feedbacks on climate through changed ocean stratification

Dry areas become drier

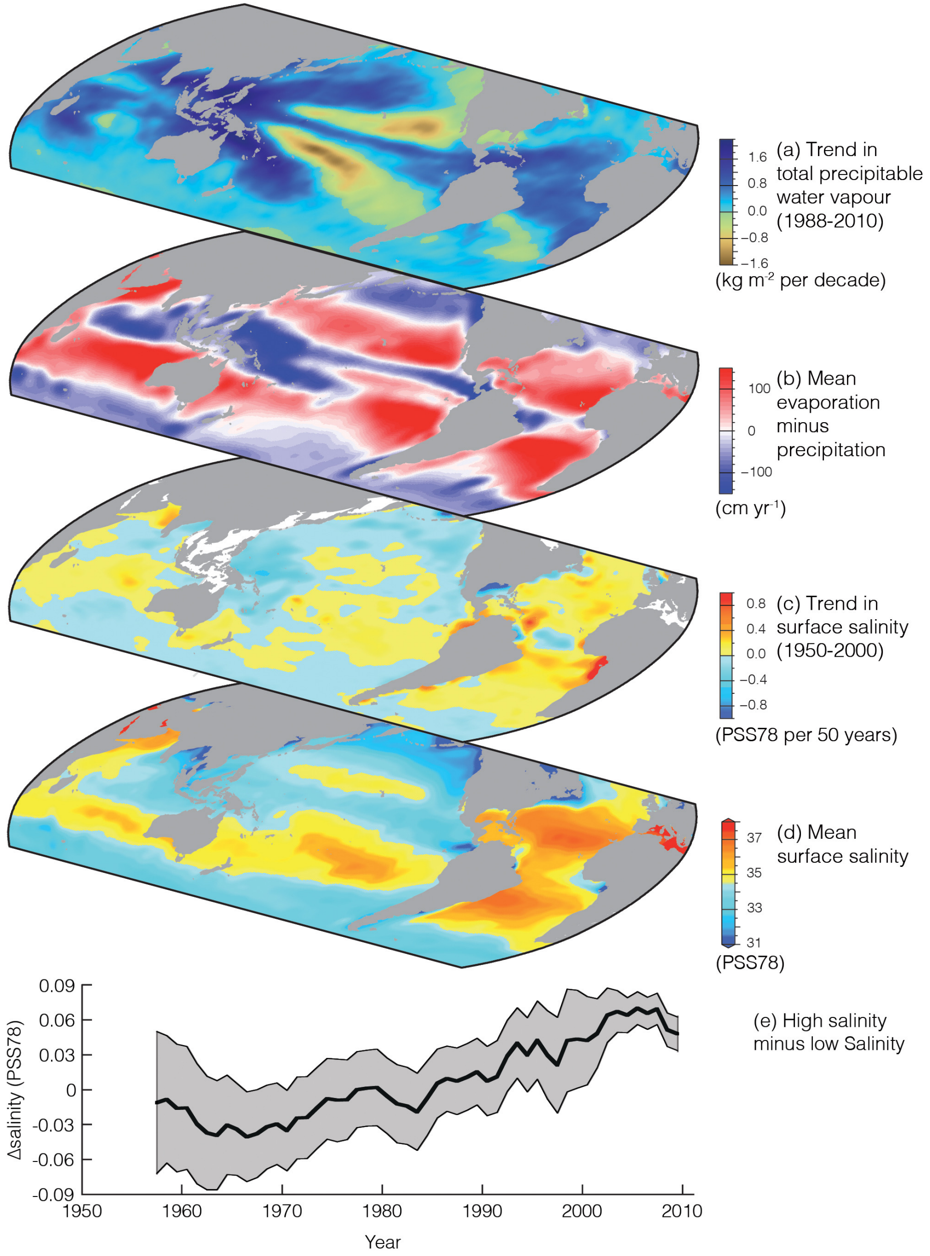
Wet areas become wetter

Large-scale salinity changes

- Fresh areas freshening and salty areas getting saltier (Boyer et al., 2005; IPCC, 2007).
- Suggests increase in atmospheric hydrological cycle, which is expected in a warmer world. (Observed changes in salinity scale approximately with change in water vapor content of atmosphere associated with mean temperature increase of atmosphere.)



Salty areas are getting saltier; fresh areas are getting fresher



Trend in water vapor in atmosphere: mostly wetter (because it's warmer)

Mean Evaporation - precipitation

Trend in surface salinity: Salty getting saltier, fresh getting fresher

Mean Salinity

IPCC AR5, 2013

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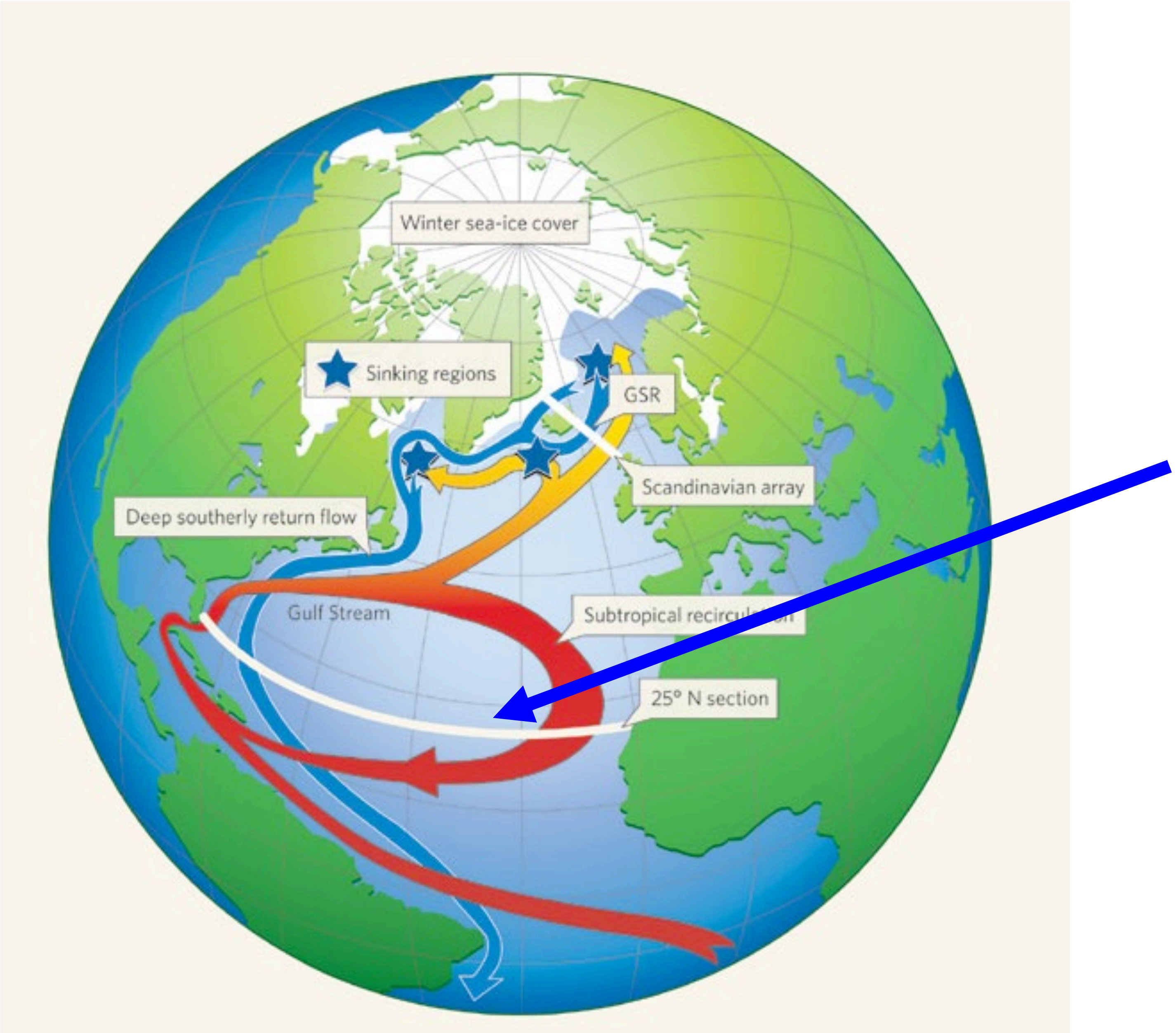
Is the AMOC changing, possibly in response?

https://usclivar.org/amoc/amoc-time-series



AMOC changes are largely due to NAO variability.

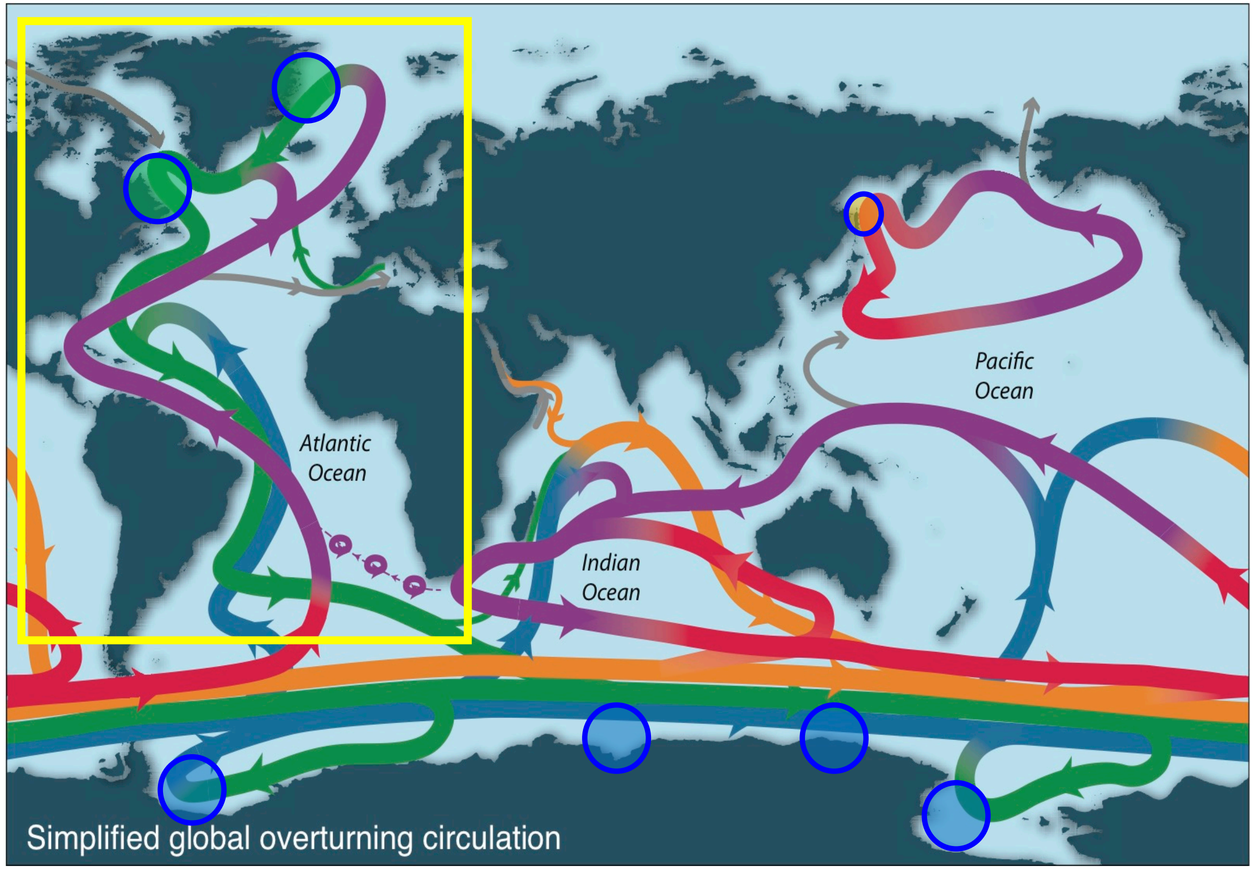
BUT, there continue to be reports of slowdown at 25° N

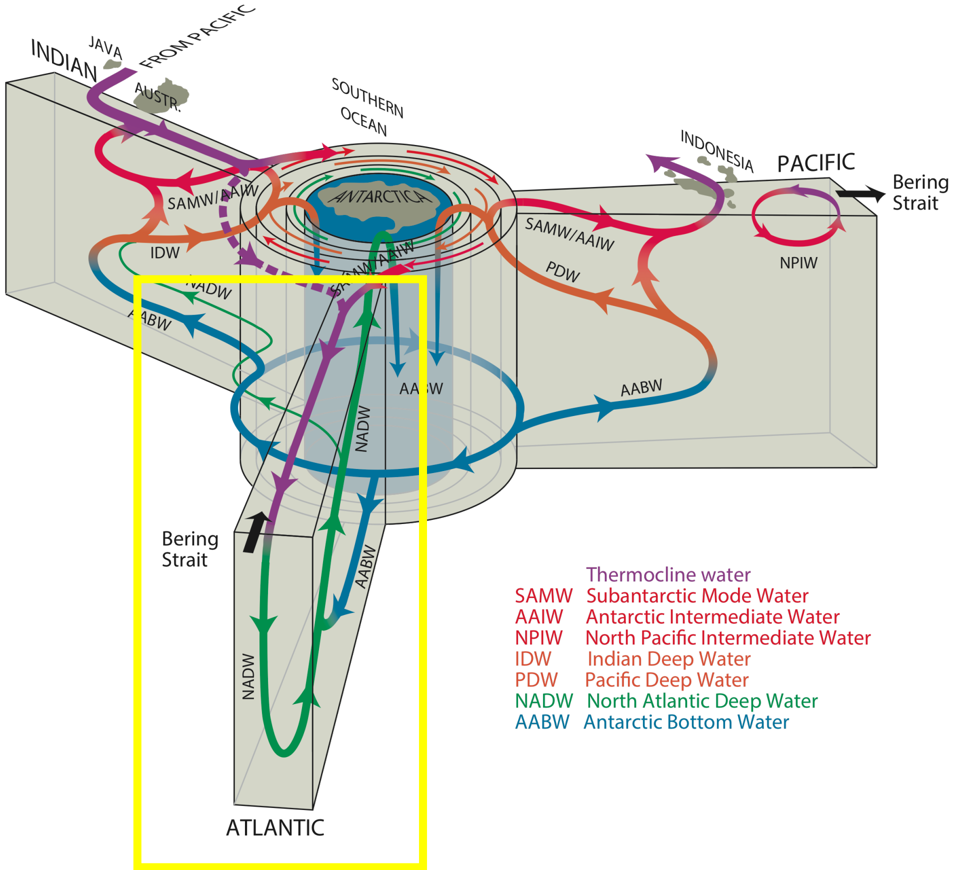
What do inverse models say?

(spoiler alert – changes are insignificant over 30 years – Cainzos et al. 2022)

Schematic from Quadfasel (Nature, 2005)

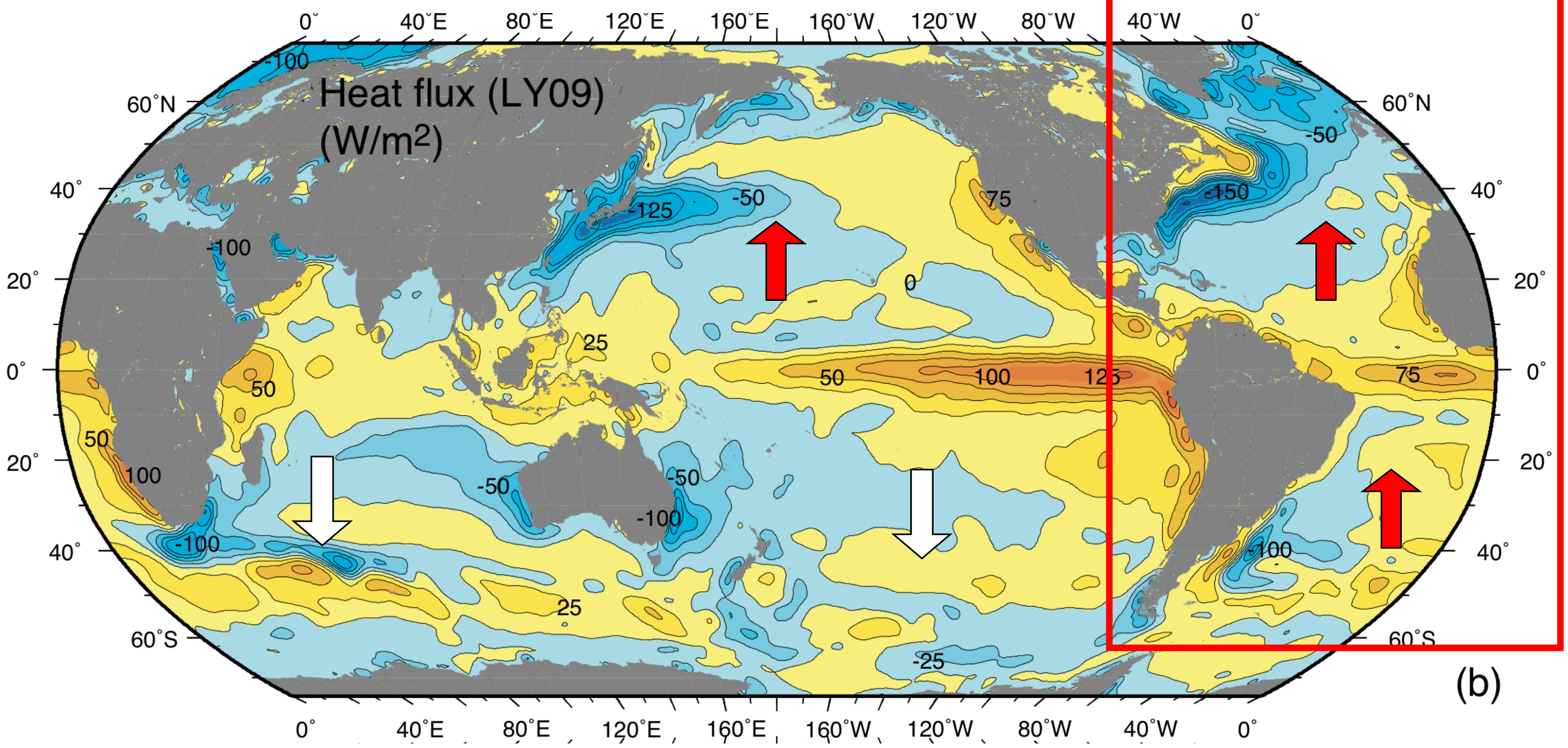
Atlantic Meridional Overturning Circulation (AMOC)





Talley (Oceanography, 2013)

Air-sea heat flux



DPO Fig. 5.15

Yellow/orange - ocean gains heat. Blue - ocean loses heat.

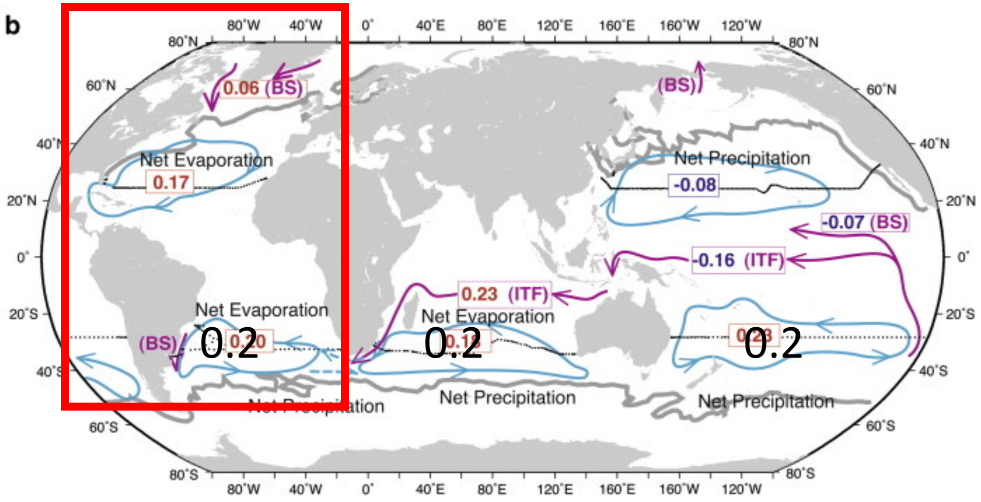
Heat transport: red is northward, white is southward.
Two components:
(1) poleward due to subtropical gyre circulation (warm western boundary current plus cooler subducted water).
(2) MOC in Atlantic (warm surface waters plus cold NADW)

Northern and southern hemisphere FW transport mechanism asymmetry

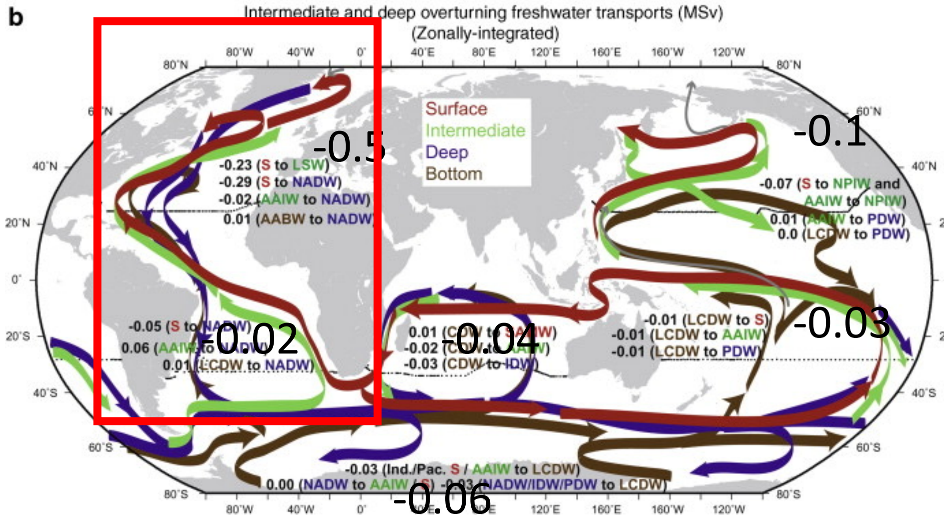
Talley (PiO 2008)

0.09 Sv

0.6 Sv



Upper ocean pathways



-0.6 Sv

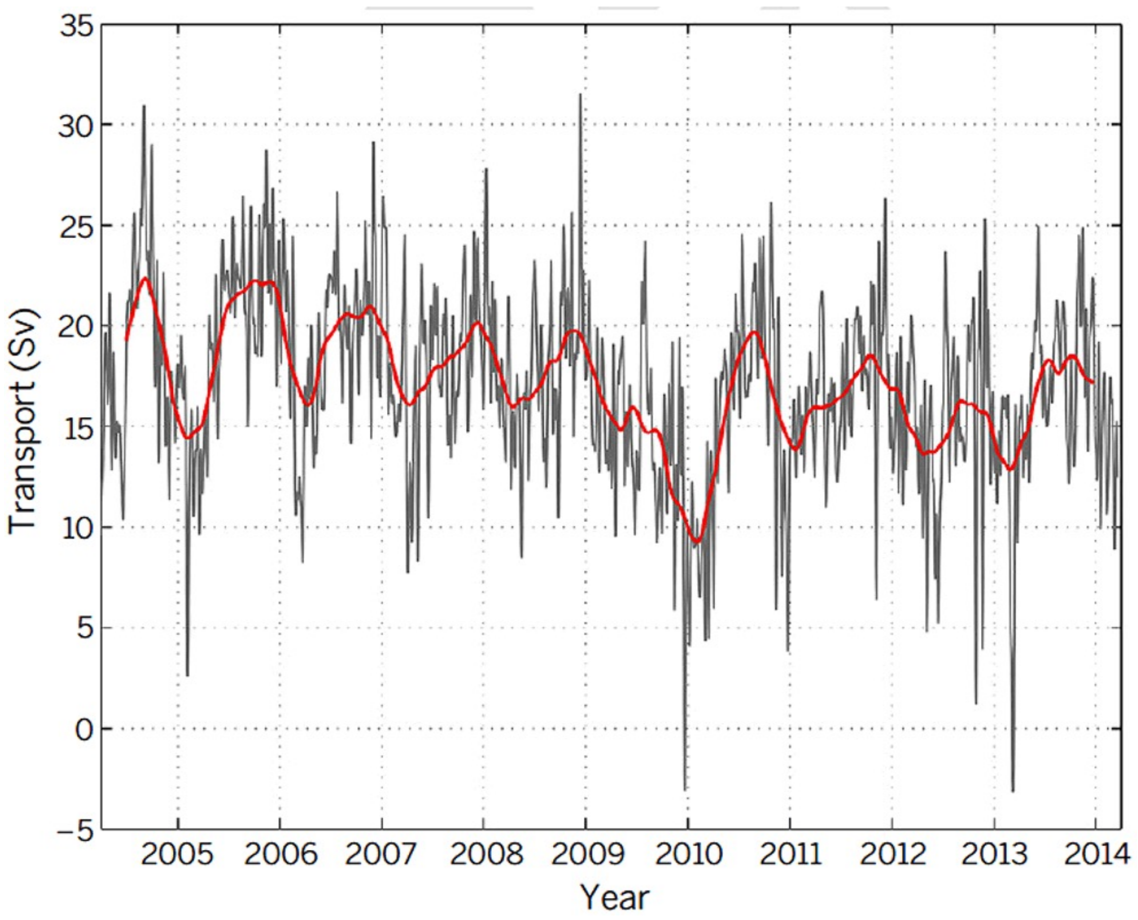
-0.09 Sv

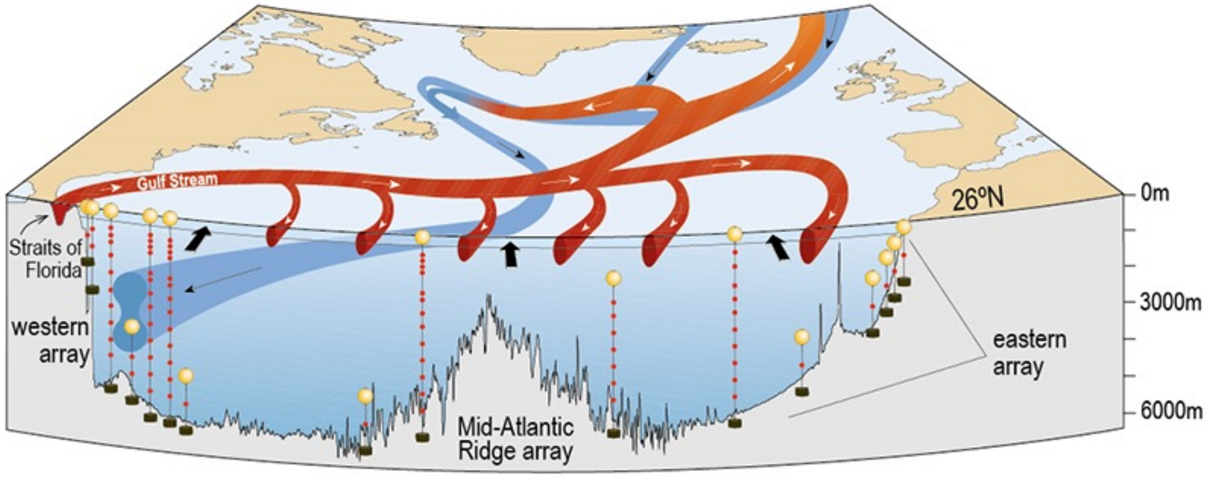
-0.06 Sv

Intermediate and deep pathways

- **Northern** hemisphere exports freshwater southward through **NADW and NPIW formation**
- **Southern** hemisphere exports freshwater northward through **upper ocean gyres**, (order of magnitude less through intermediate and deep water formation)
- Why: Salinity difference between inflow and outflow is larger if salty, warm subtropical surface water is transformed into fresh, cold deep/bottom water. Drake Passage inhibits transport of surface waters to Antarctica (Toggweiler and Samuels, 1995).
- Dumped freshwater on the Antarctic just floats in surface layer, can't become dense enough to sink since temperature difference between surface and deep water is small.

Is the Atlantic "AMOC" changing?





Consequence of AMOC slowdown:

Large heat uptake in northern North Atlantic

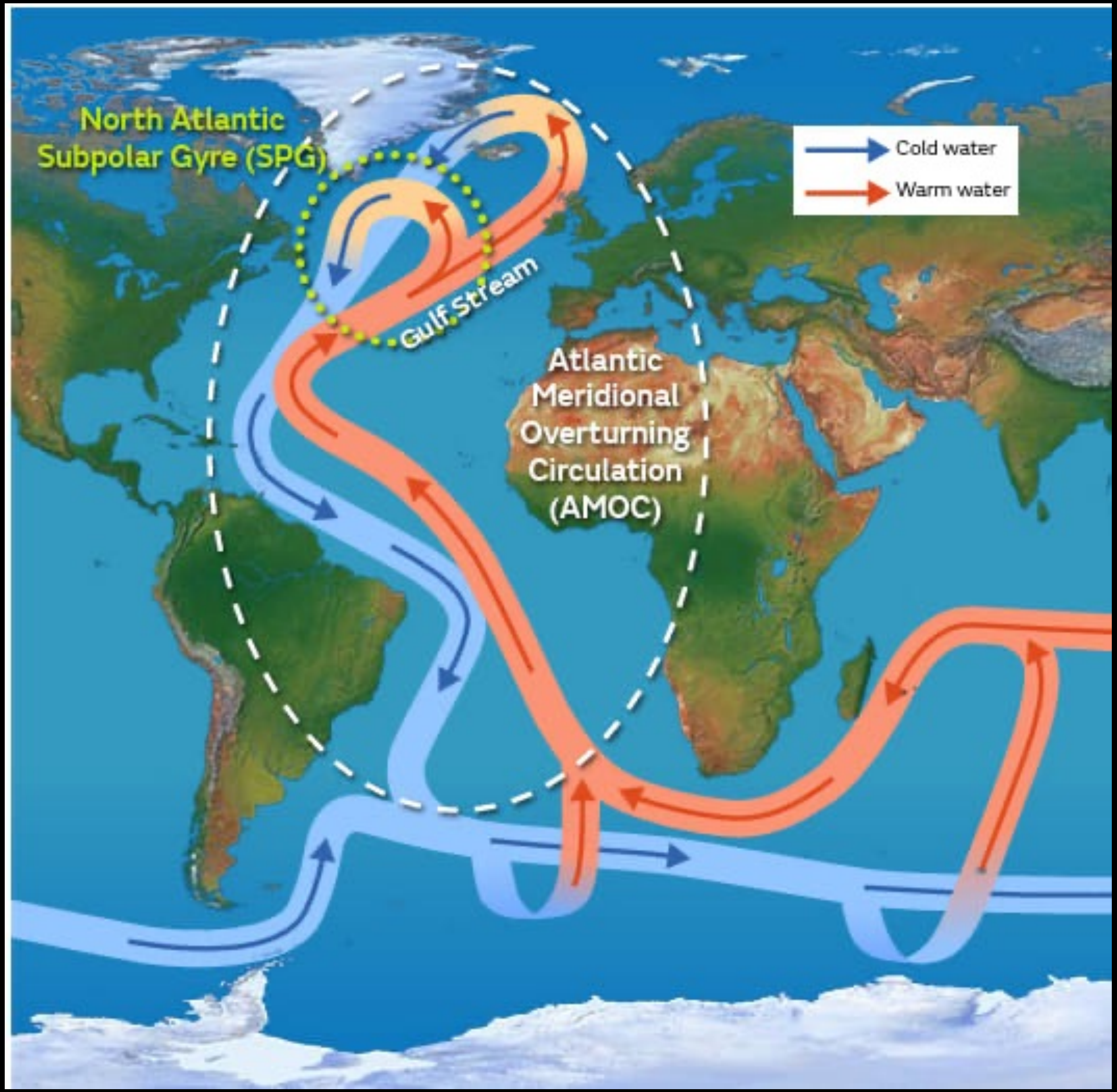
Paradoxically, SST cooling in the subpolar N. Atlantic (due to less Gulf Stream water)

From https://rapid.ac.uk/:
"Future projections of the MOC strength show that this large-scale circulation pattern is very likely to weaken over the 21st century; there is medium confidence that the MOC will not shutdown before 2100, though physically plausible, and the likelihood increases after 2100 under higher emissions scenarios (IPCC SROCC)."

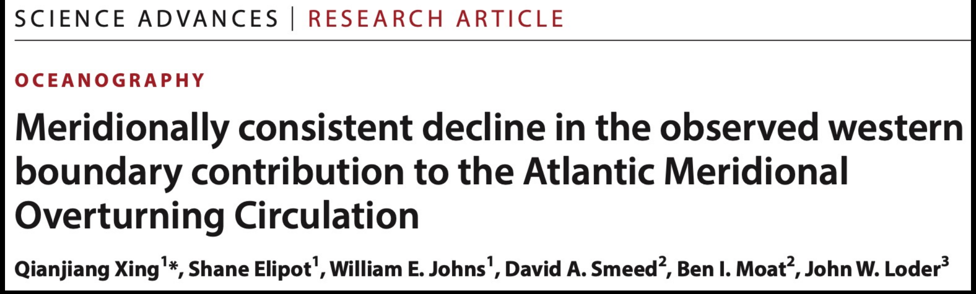
AMOC: Atlantic Meridional Overturning Circulation weakening

Will it collapse?
What happens when it weakens (or collapses)?

How do we observe the AMOC?
Interior ocean observations, including GO-SHIP and Argo profiling floats, and mooring lines.



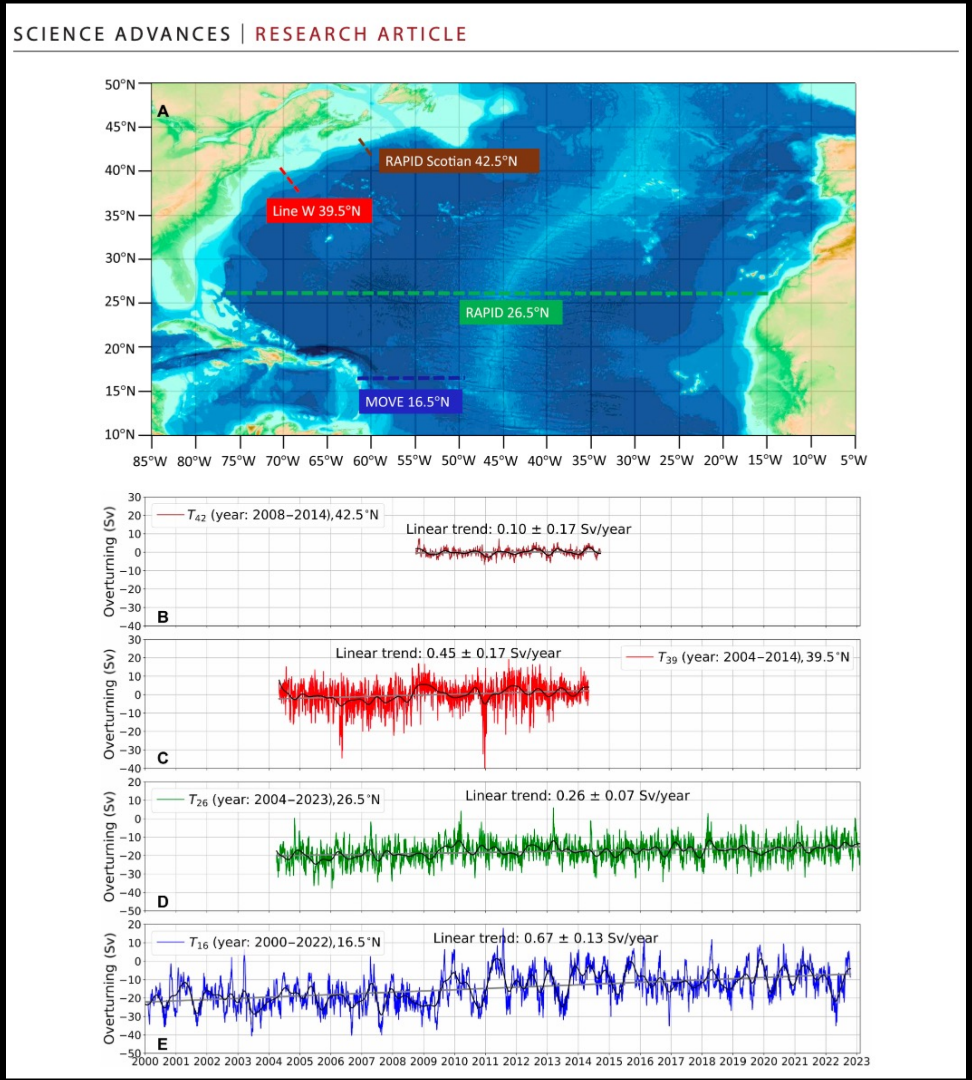
AMOC: Atlantic Meridional Overturning Circulation weakening


SCIENCE ADVANCES | RESEARCH ARTICLE

OCEANOGRAPHY

Meridionally consistent decline in the observed western boundary contribution to the Atlantic Meridional Overturning Circulation

Qianjiang Xing[1]*, Shane Elipot[1], William E. Johns[1], David A. Smeed[2], Ben I. Moat[2], John W. Loder[3]

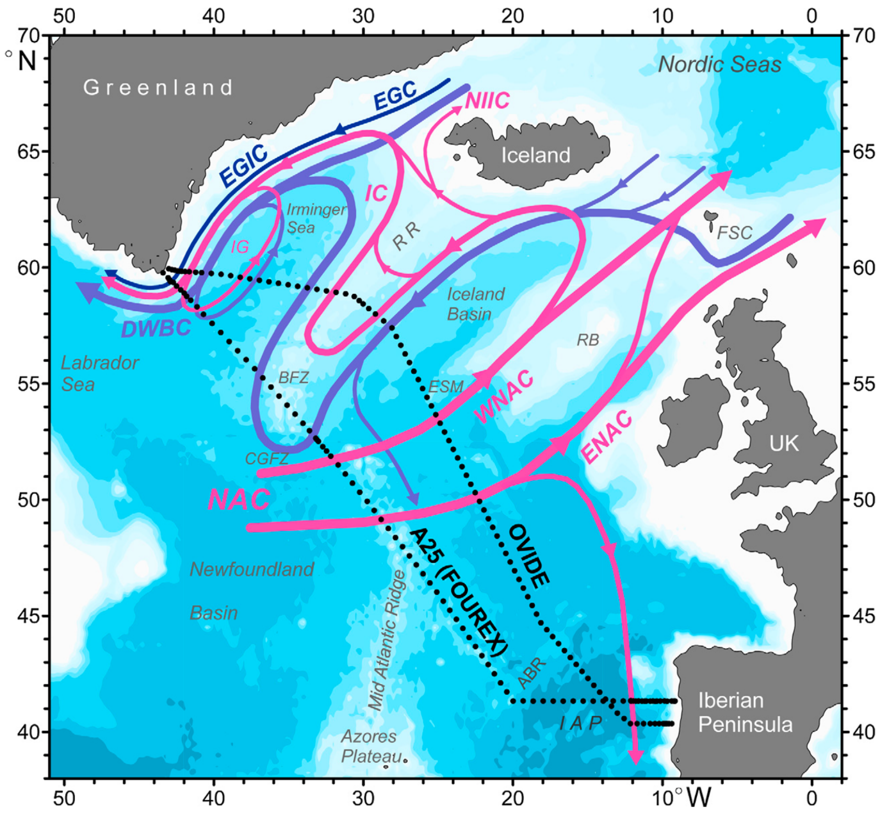


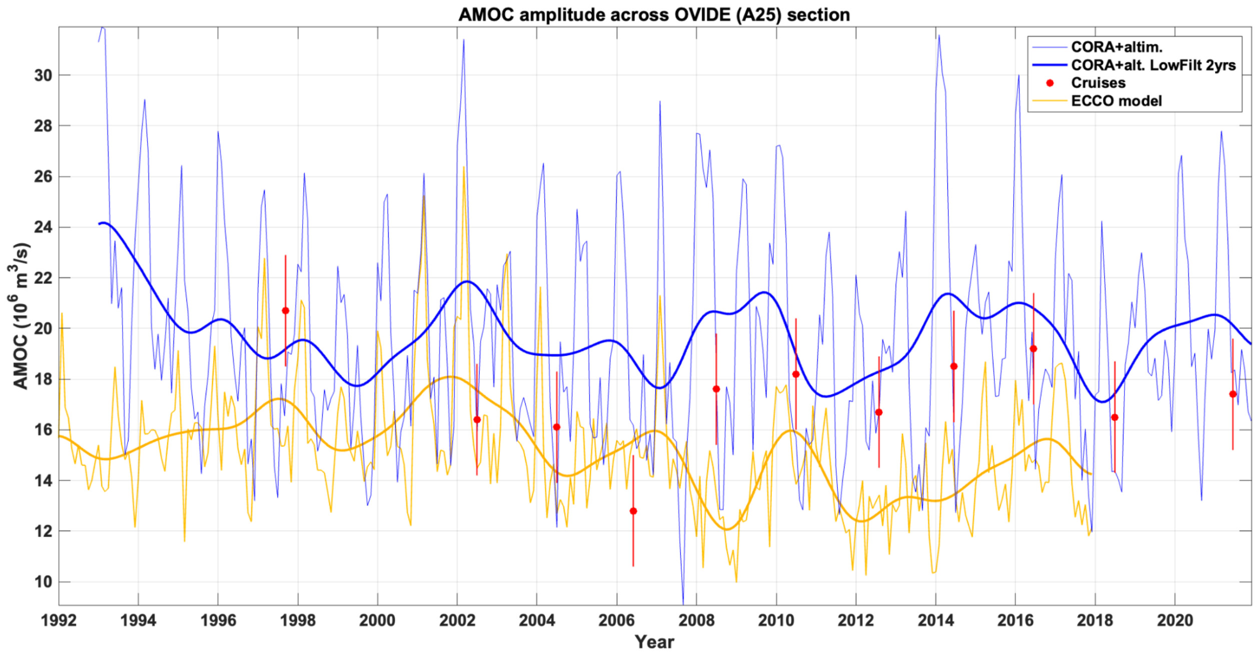
Observed weakening reported:
Xing et al. (April 6, 2026)

Modeled weakening projected:
Portmann et al. (April 15, 2026)

AMOC Circulation Change at 50°N: Hydrographic Sections and Argo

Mercier et al, 2015; 2024





AMOC upper limb across GO-SHIP/OVIDE line

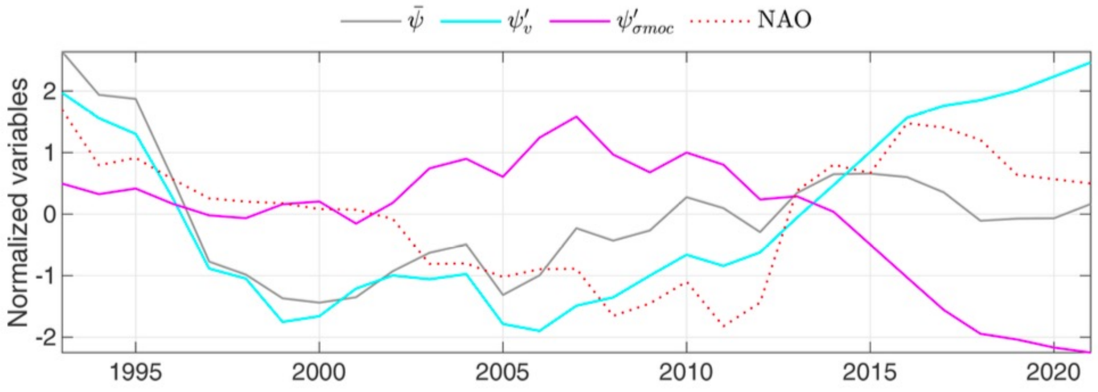
Compare with state estimate ECCO and other models

"Trends were calculated for the different time series over their entire duration but none were significant at the 95 % confidence level, and they are not described here"

Velocities computed from

- GO-SHIP data **inverse model** (red dots) (uses ADCP for ref velocity)
- Argo and satellite altimetry (blue 0-2000m) (CORA; uses altimetry surface velocities)
- ECCO ocean state estimation model (yellow)

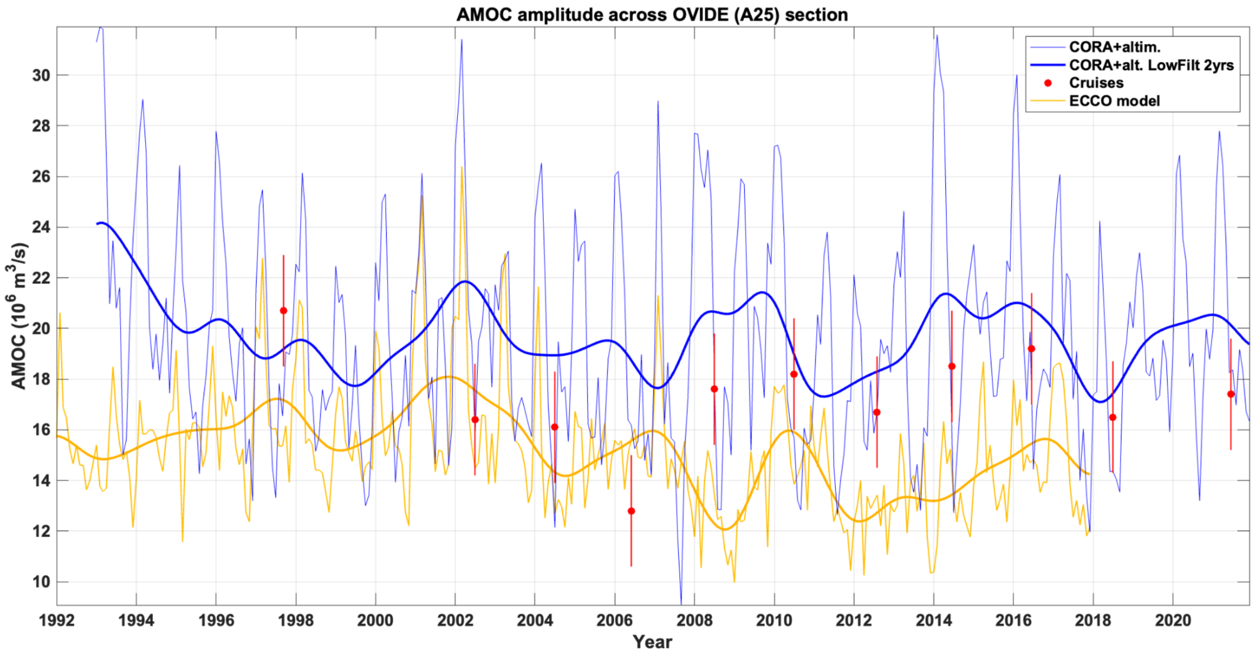
AMOC Circulation Change at 50°N: Hydrographic Sections and Argo



Total MOC
Velocity-driven component of MOC
Volume-driven component of MOC
North Atlantic Oscillation Index (dotted)

"The MOC strength ψ' is positively correlated with NAO (r=0.50; p=0.38), which is consistent with the fact that, on longer timescales, the variability of the MOC strength is mainly driven by ψ'v (velocity variations rather than thickness)"

Mercier et al 2024



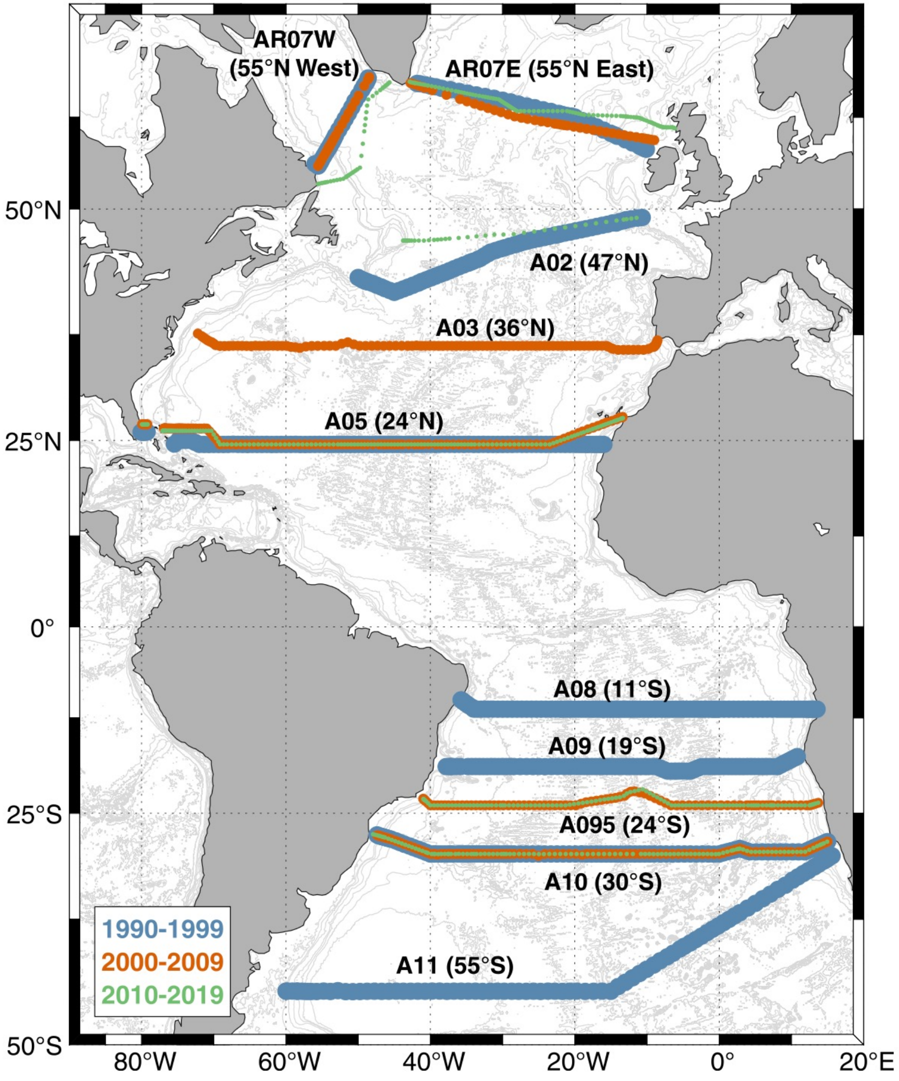
"Trends were calculated for the different time series over their entire duration but none were significant at the 95 % confidence level, and they are not described here"

Ideas to do:

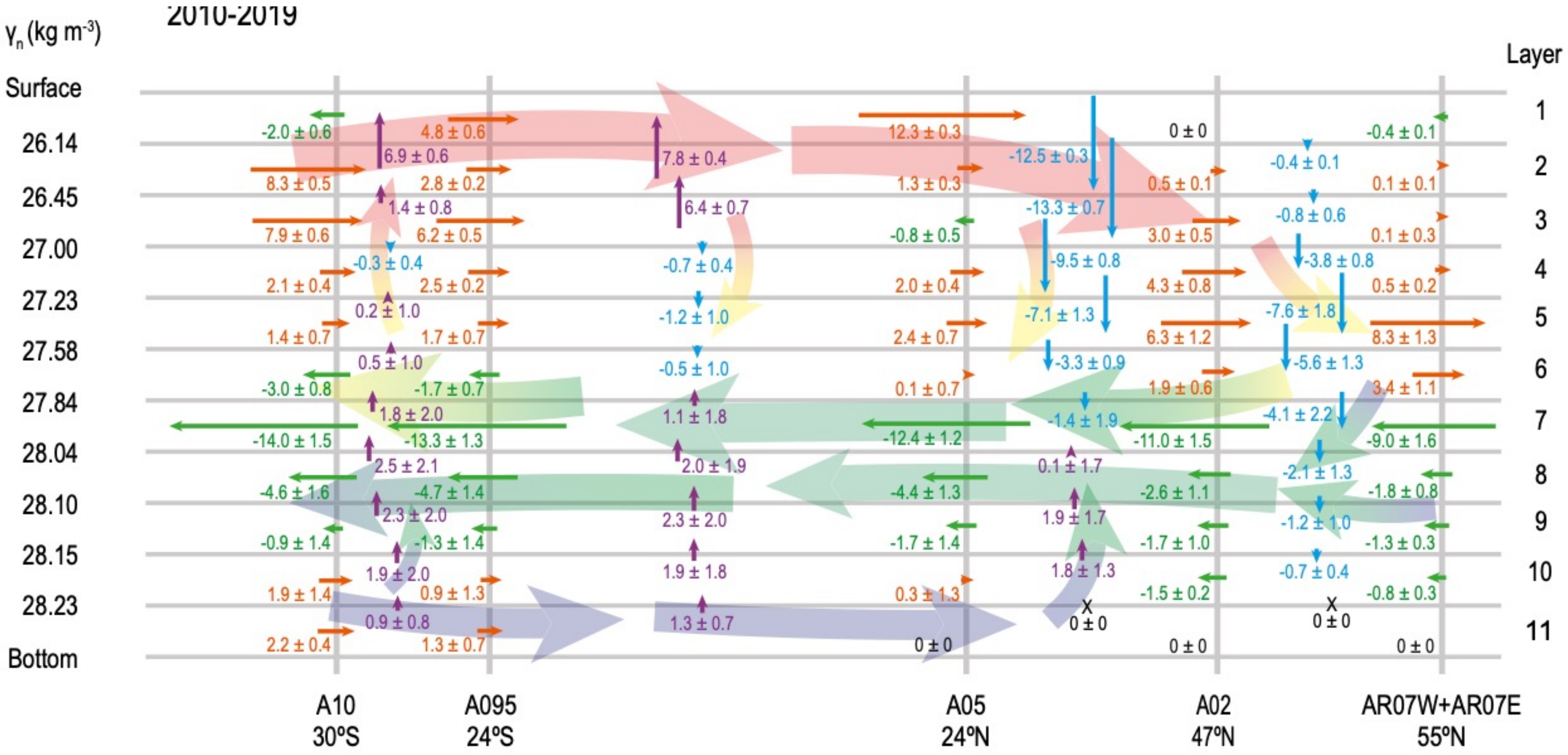
1. Much greater usage/comparison of hydrographic inverses with Argo-derived transport time series, providing monthly resolution

2. **Analyze this section for carbon, heat and freshwater**

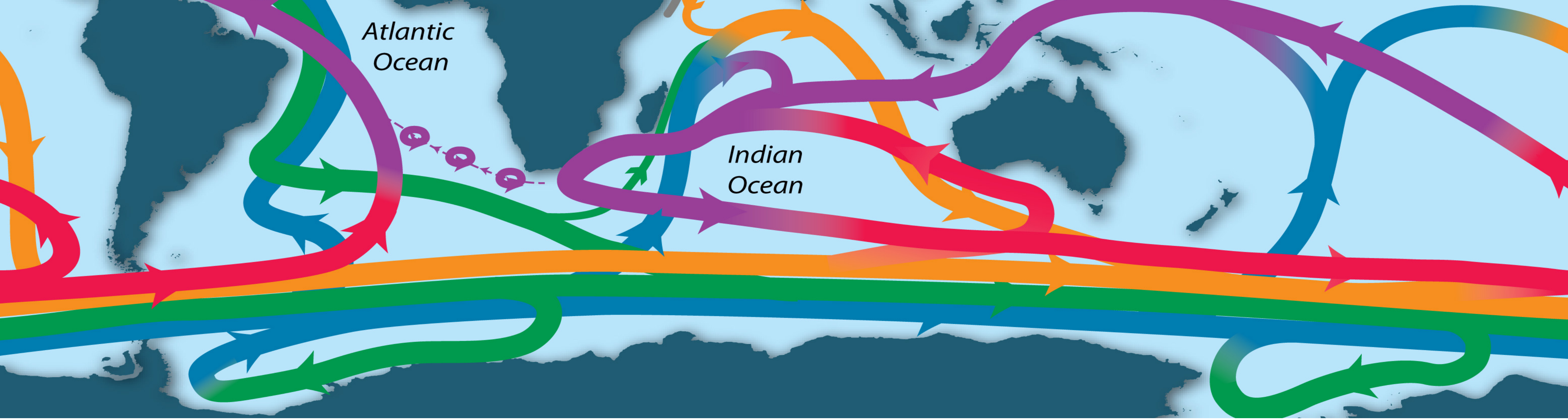
AMOC Change over 30 years from section data (see next talk!)



Cainzos et al. (GRL 2022)



"Our results show no changes in the AMOC for all sections analyzed over the whole Atlantic for the last 30 years. We also find an increased export of freshwater from the South Atlantic associated with an increase in upper salinity."



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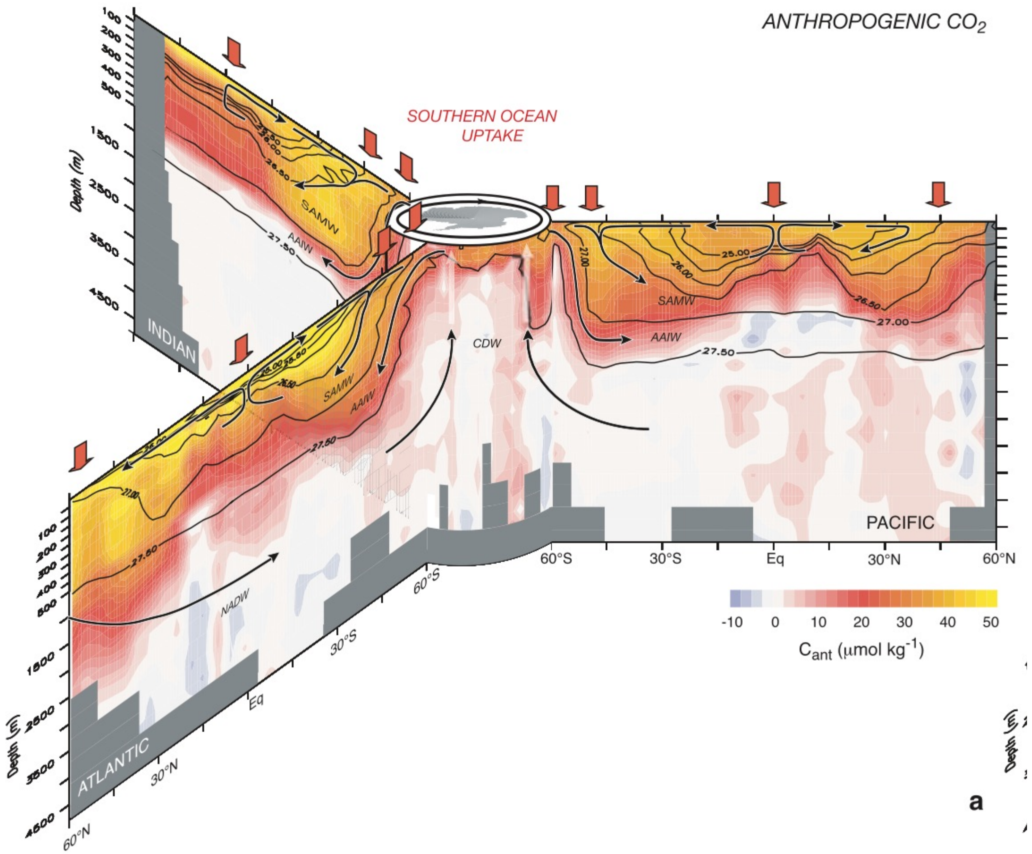
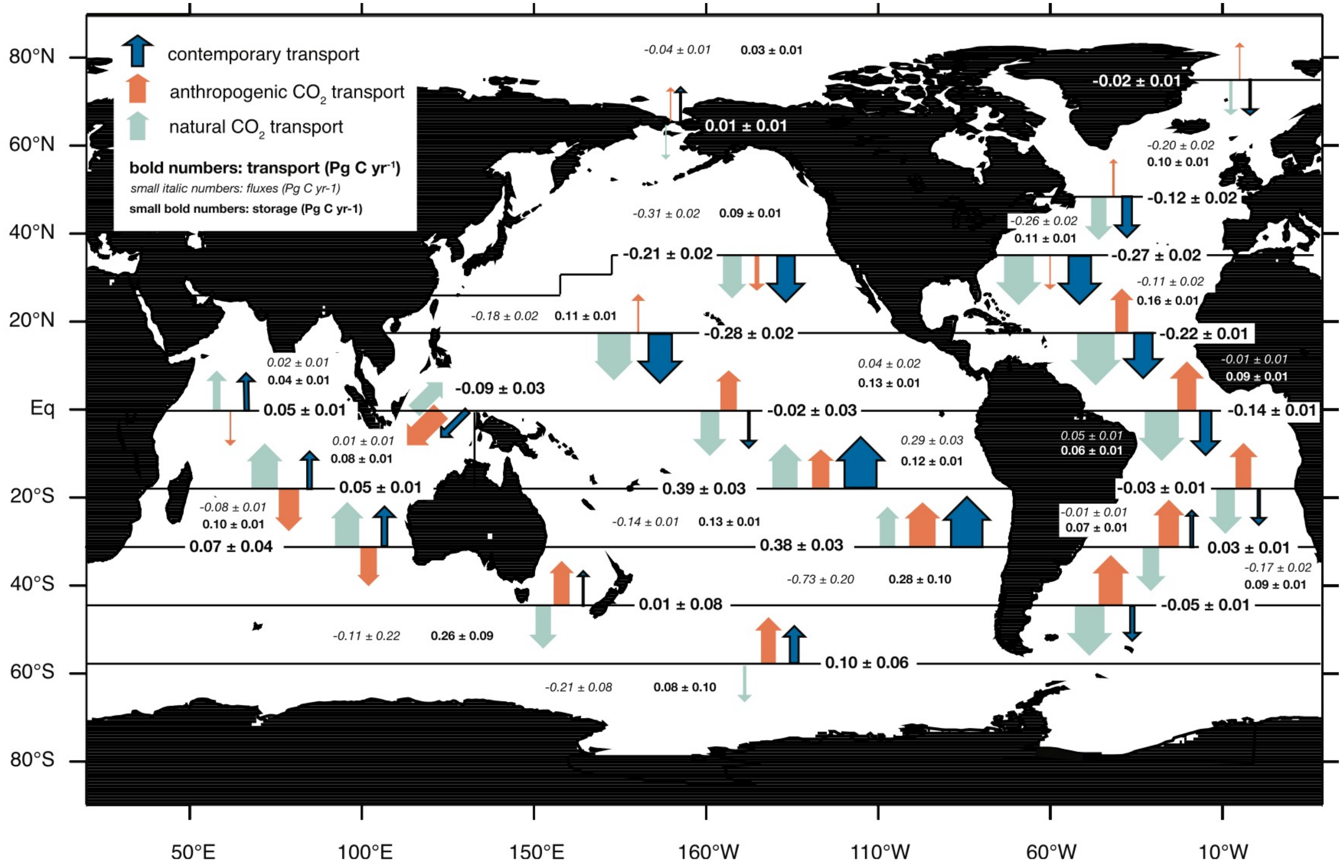
Anthropogenic carbon (trend)

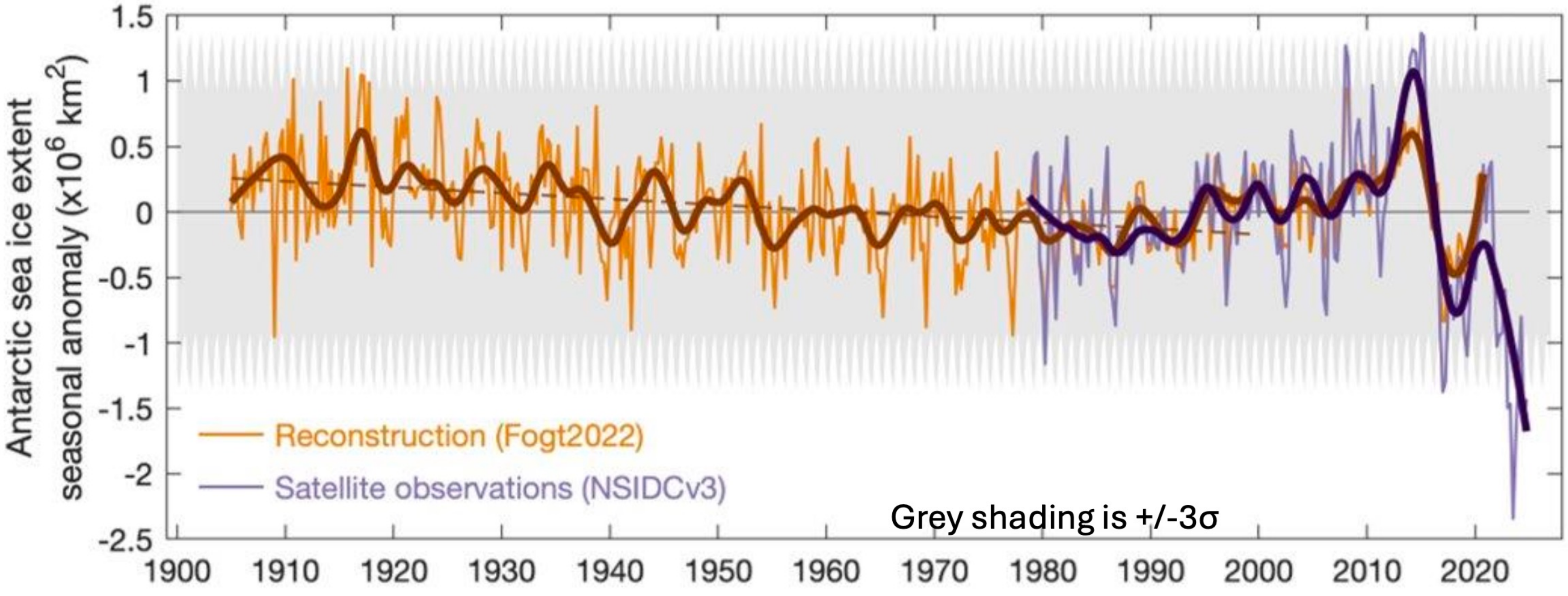




Gruber et al. (GBC 2009)

Southern Ocean: major changes in forcing and properties

Precipitous decline in Antarctic sea ice extent

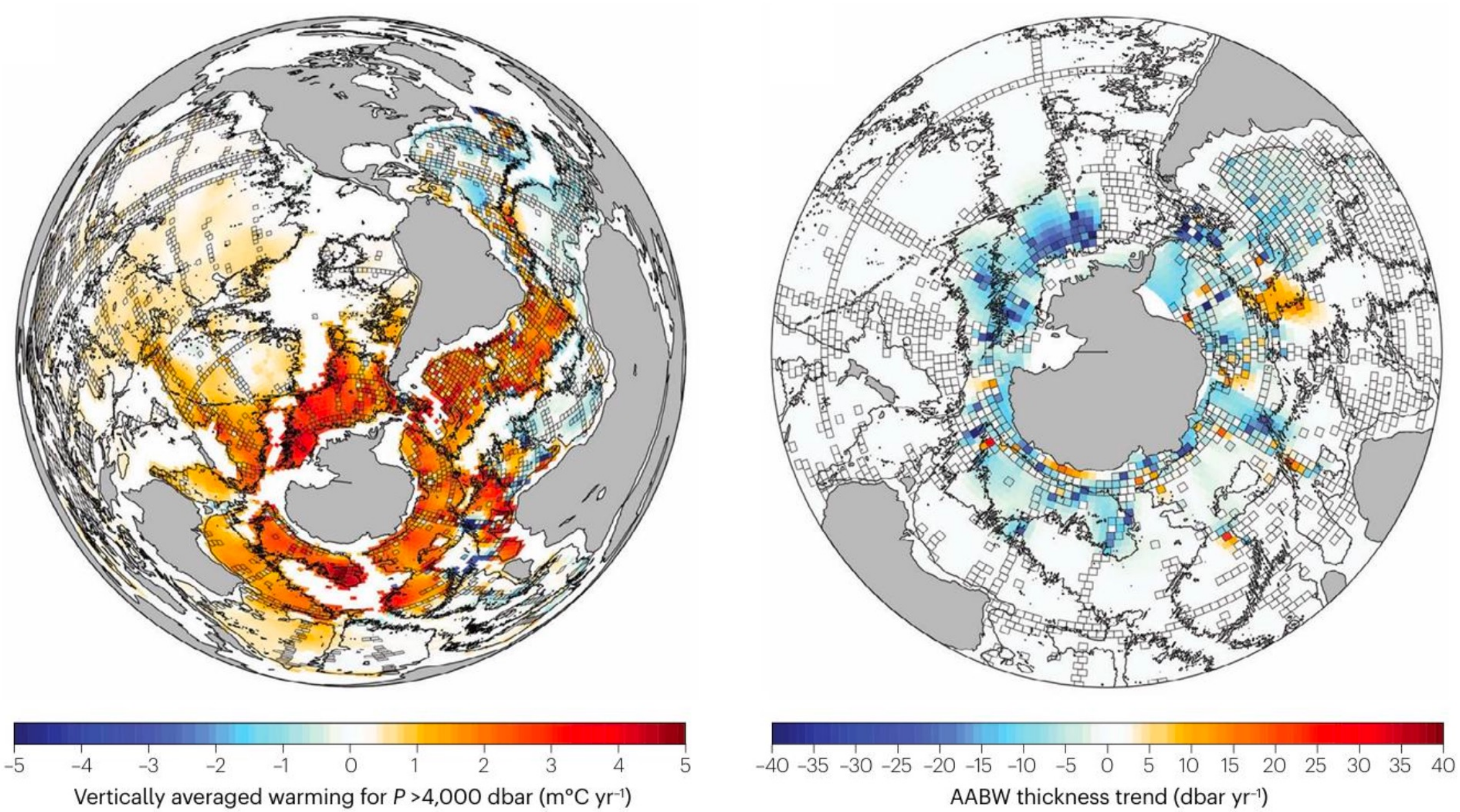


Slide from S. Rintoul (Polar Argo workshop, June 2026)

Abram et al. (2025); Purich and Doddridge (2023); Hobbs et al. (2024)

Southern Ocean: major changes in forcing and properties

Rapid warming of the deep ocean and contraction of AABW layer

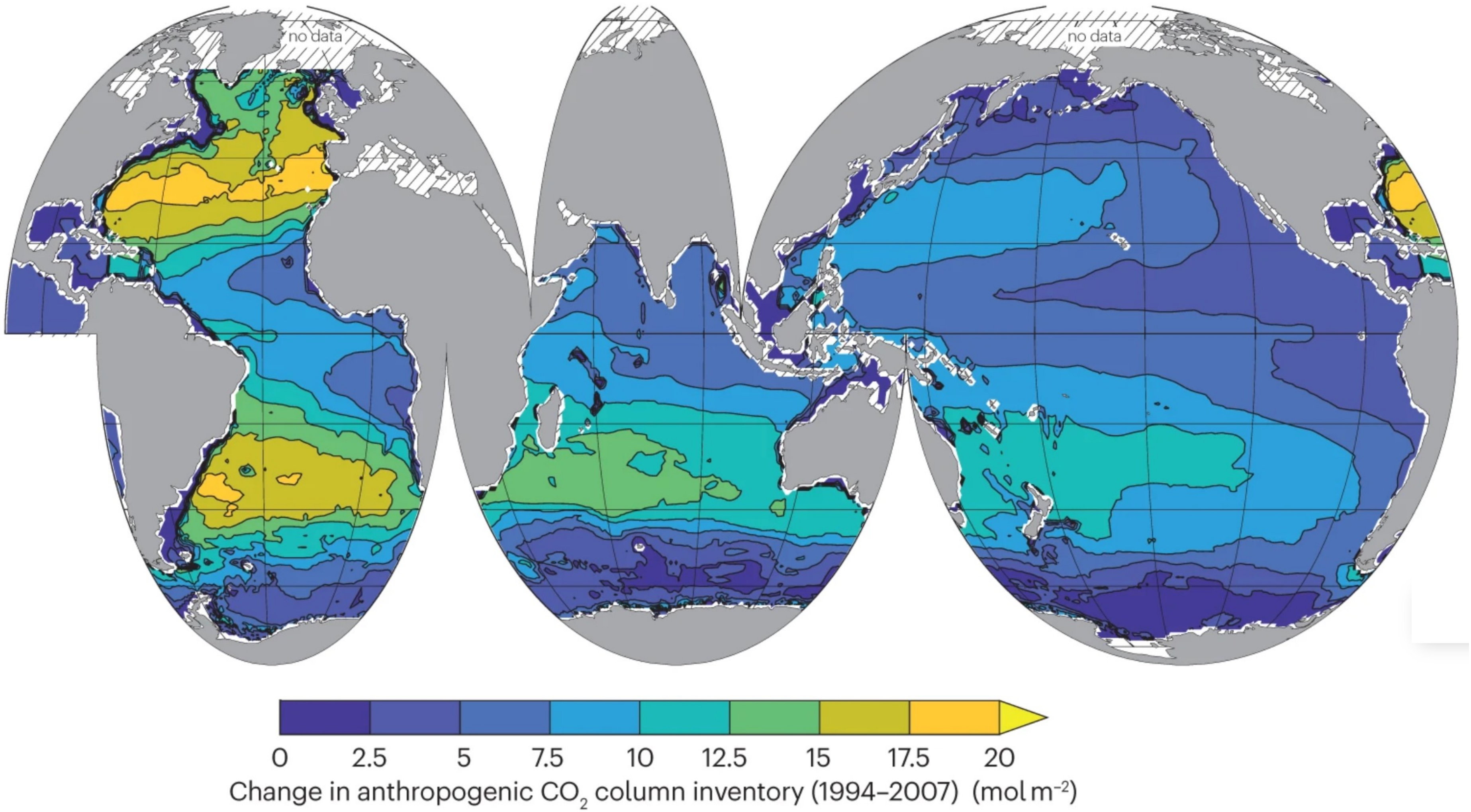


Slide from S. Rintoul (Polar Argo workshop, June 2026)

Rintoul et al., 2026; Johnson & Purkey, 2024

Anthropogenic carbon: GO-SHIP

25 to 30% of the extra CO_2 from human carbon emissions goes into the ocean

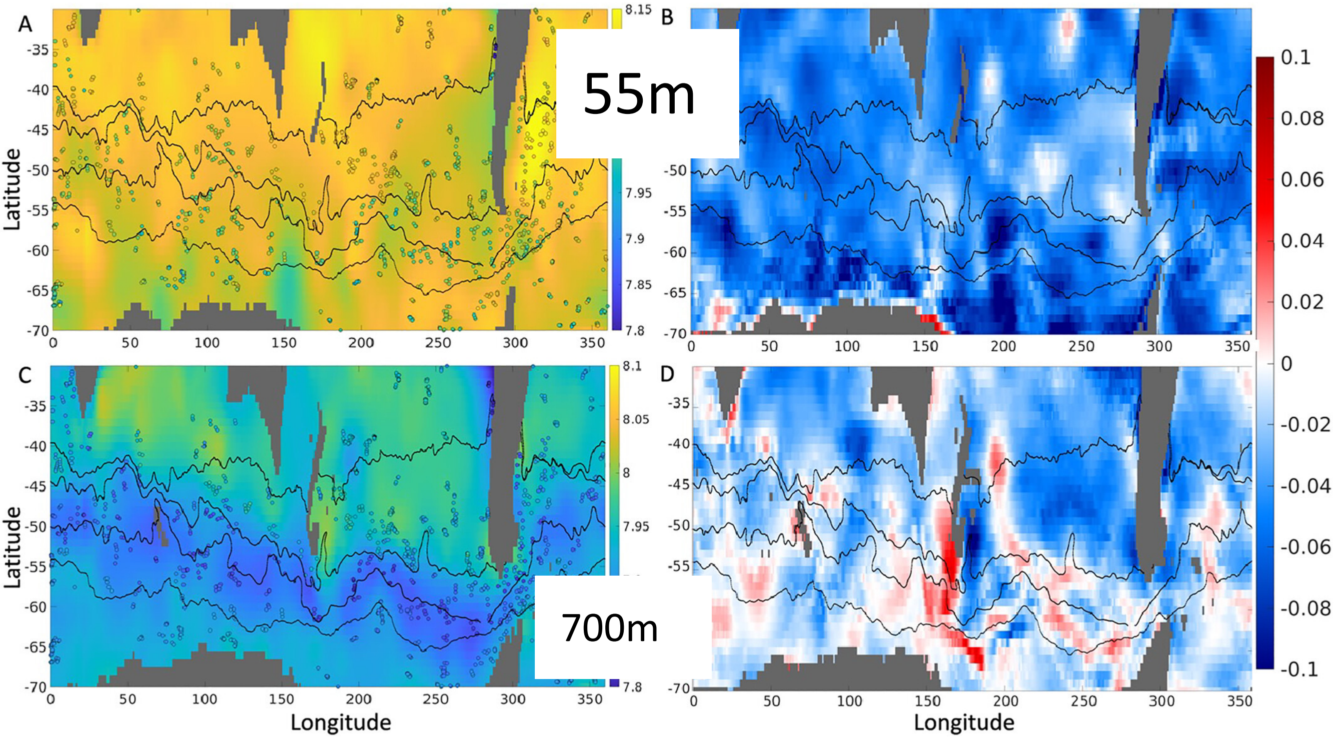


Gruber et al. (Nature, 2023)

Ocean acidification: GO-SHIP and OneArgo

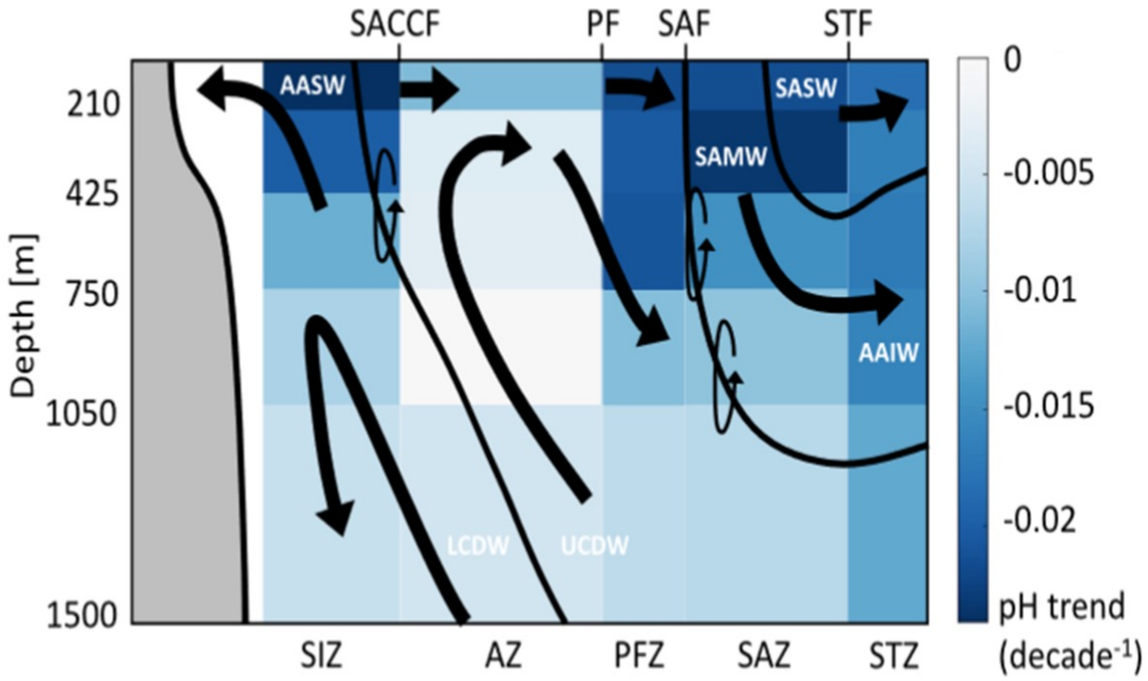
Idea to do:
Carbon transports and pH/aragonite saturation in Southern Ocean from WOCE/GO-SHIP: changes in calculated transports?

BGC Argo from SOCCOM (~2018) minus GLODAP using GO-SHIP (~2002)



BLUE = acidification

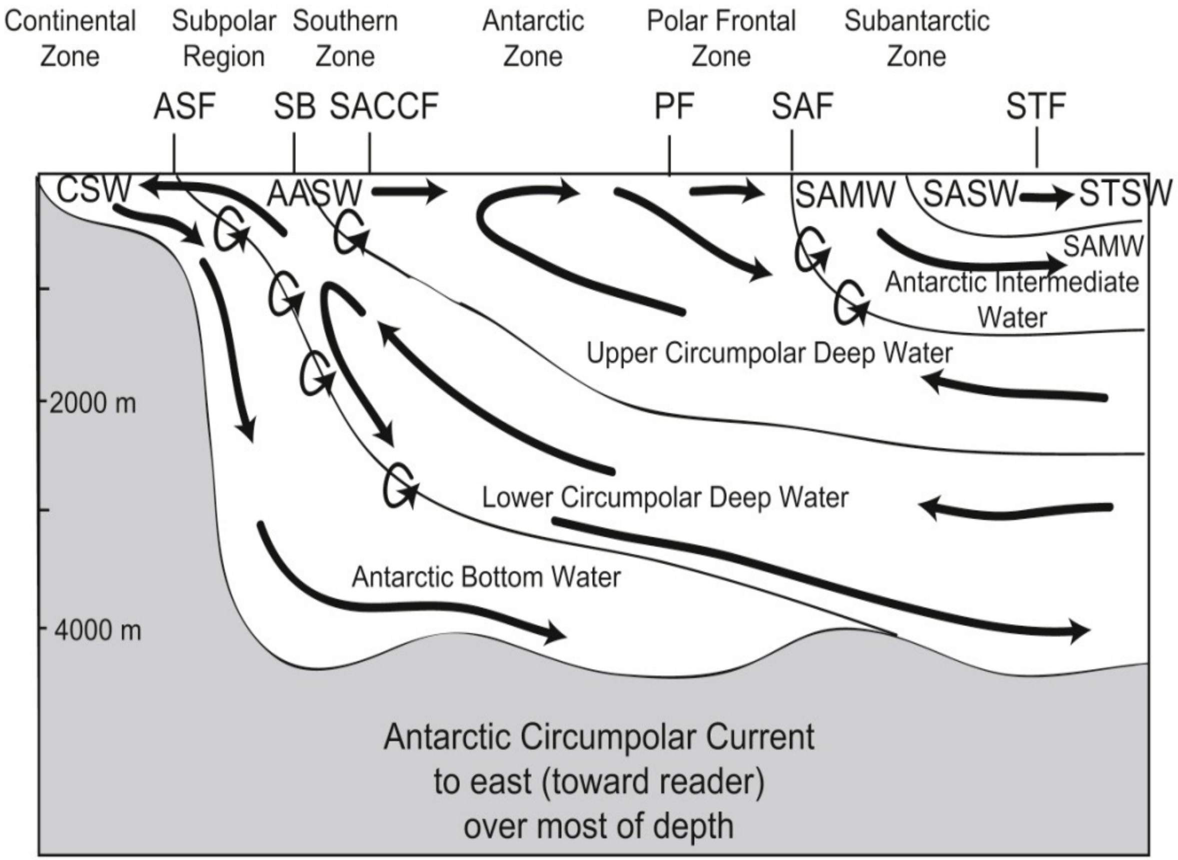
Zonally averaged rates of pH change (pH/decade) with overturning circulation overlaid.



Mapping uses B-SOSE (data assimilation) bias-corrected to floats

Mazloff et al. (JGR 2023)

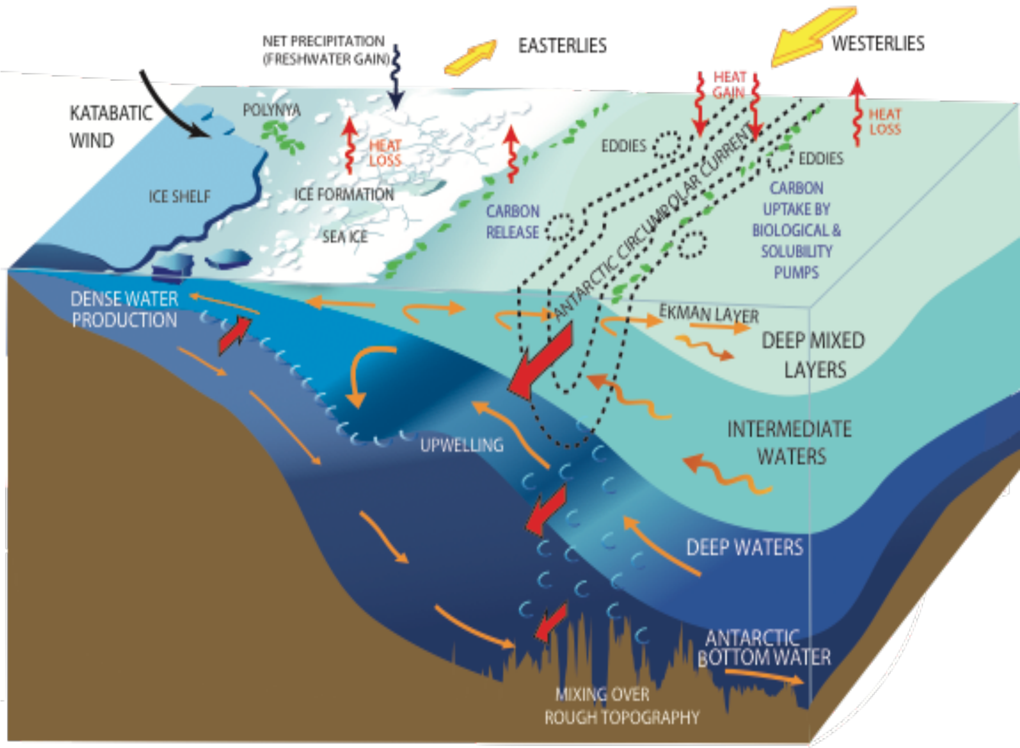
2-D (zonally-averaged) Southern Ocean overturn: 2 cells



Upper cell driven northward by Ekman

Deep Water upwells to surface

Form Bottom Water on shelves

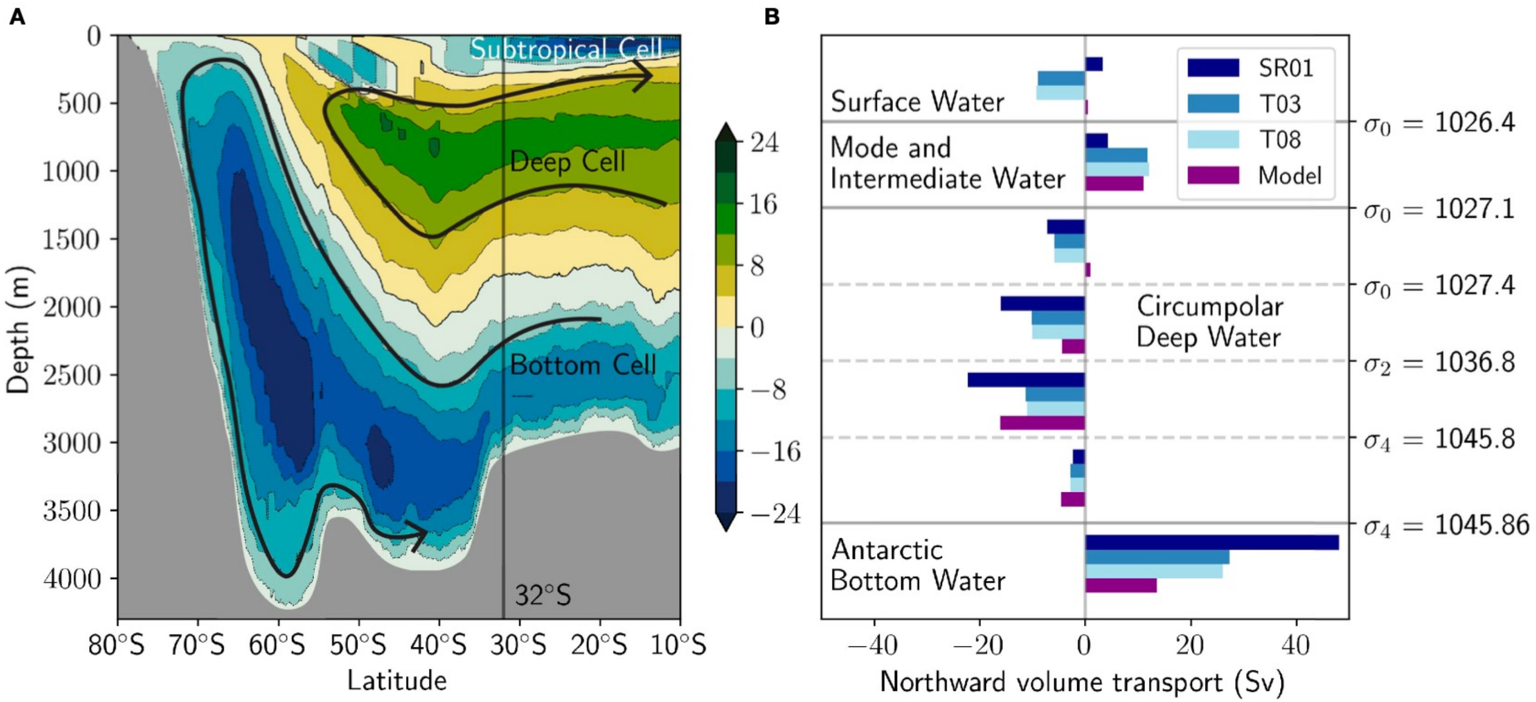


Talley et al. (DPO, 2011) based on Olbers, Speer

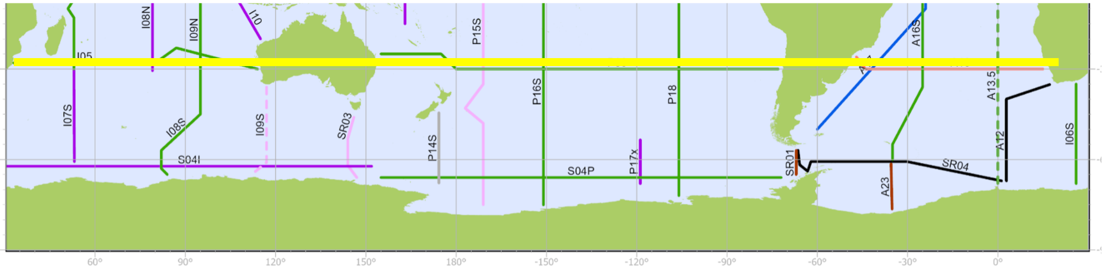
2-D Zonally-averaged overturning streamfunction (ACCESS-OM2-01 model)

Upper cell
'deep cell'

Lower cell
'bottom cell'



Inverse model transports at 32S
Compared with model



GO-SHIP GO-SHIP by nation (2014 - 2023) Status as of February 2026

Residual overturning circulation, so calculated on isopycnals and reprojected to depth

Yung et al. (FMARS, 2022)

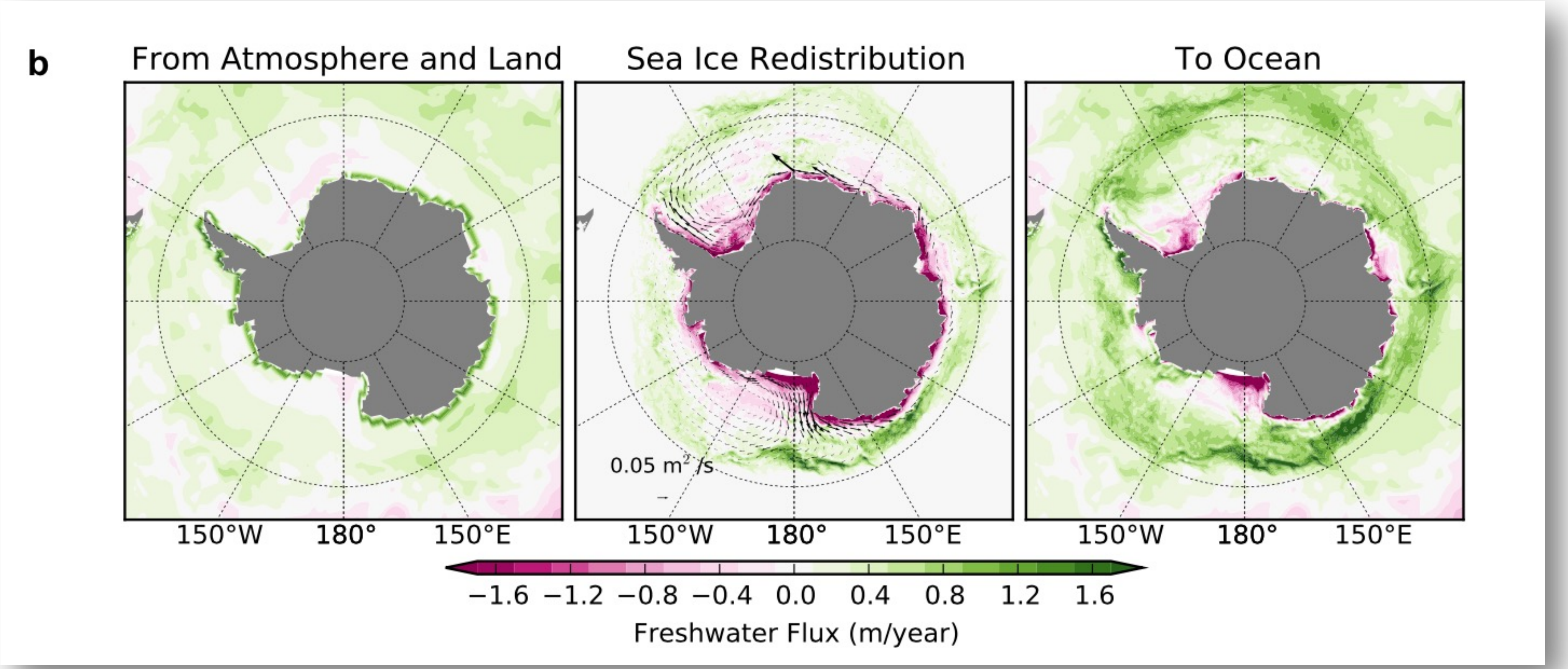
ACEAS
Australian Centre for Excellence in Antarctic Science

Southern Ocean overturning is controlled in part by salinity processes

Sea ice processes are important for both the lower and upper cells of the Southern Ocean overturning circulation

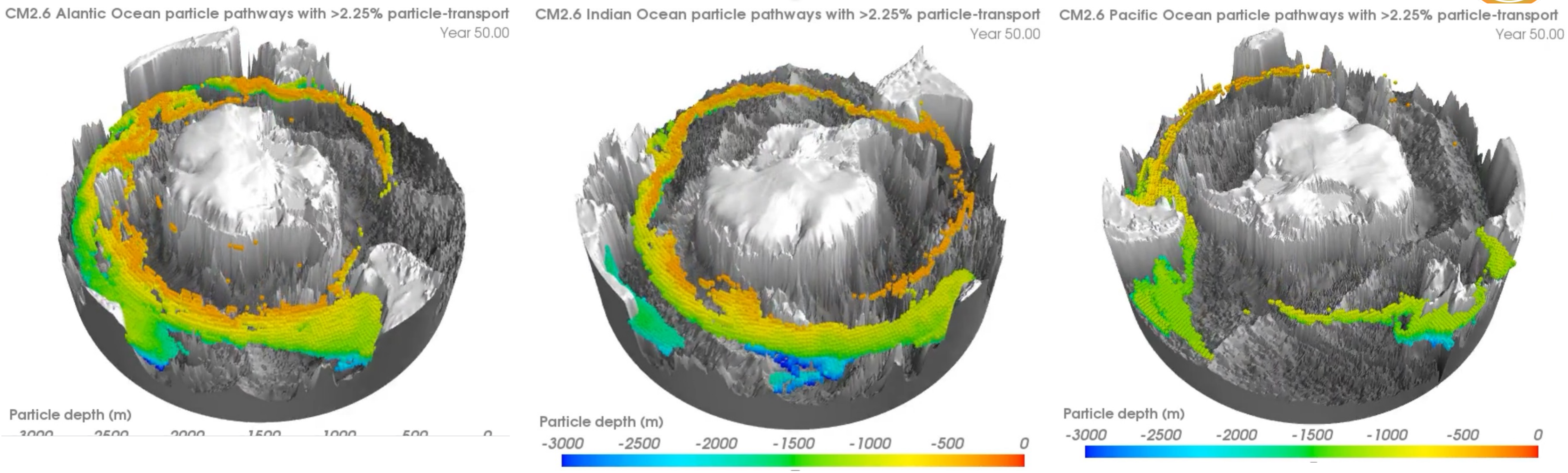
Brine rejection creates AABW (buoyancy loss)

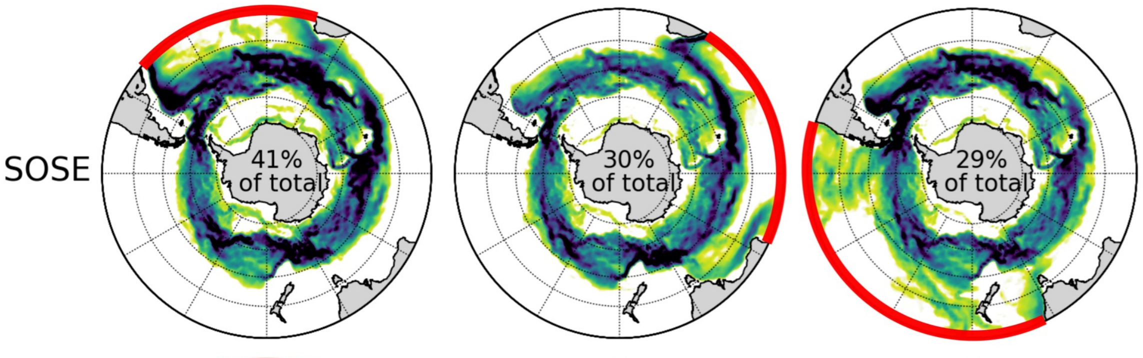
Sea ice blown north, melts and creates thermocline water (buoyancy gain)



Abernathey et al. 2016

3-D SOOC: Deep Waters spiralling upwards

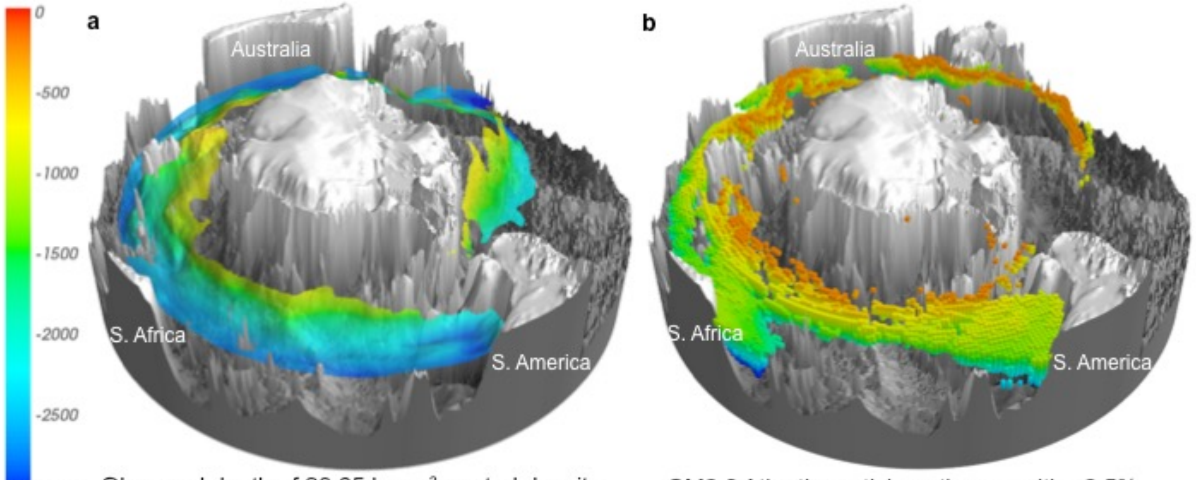




Deep Water particles released in each ocean

Tamsitt et al. (Nat. Comm. 2017, JGR 2018, JGR 2019)

3-D SOOC: Deep Waters spiralling upwards



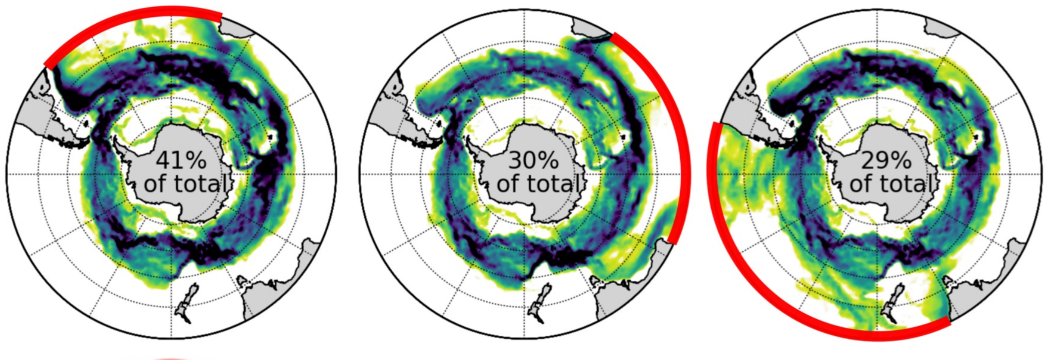
Observed depth of 28.05 kg m^{-3} neutral density surface with potential temperature >1.6C

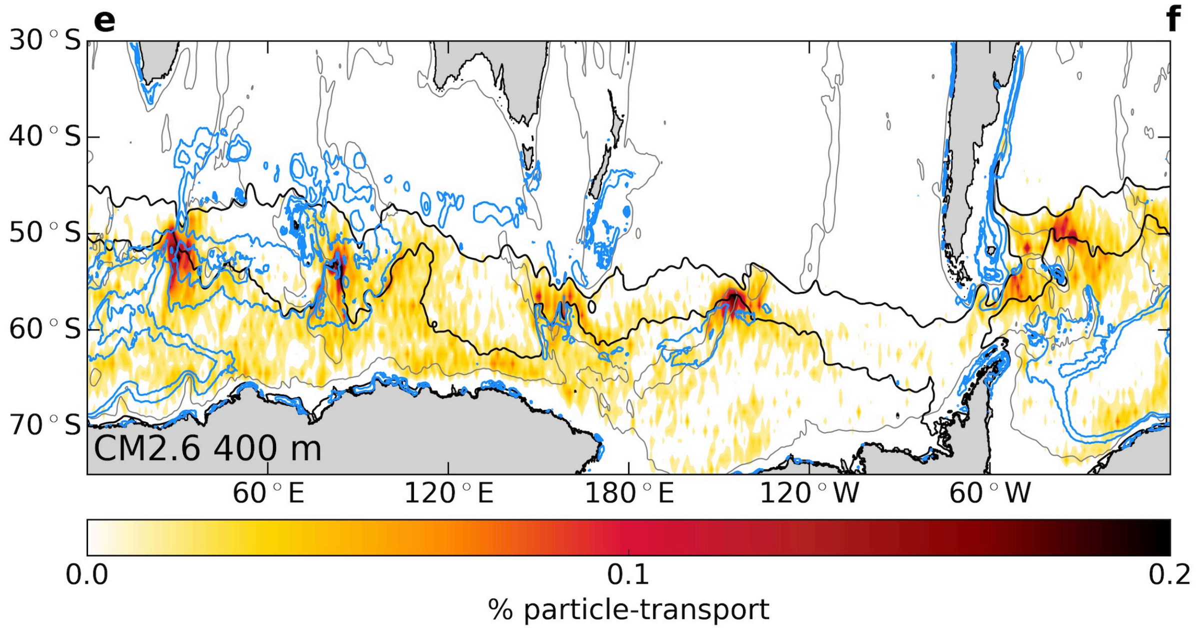
CM2.6 Atlantic particle pathways with >2.5% particle-transport

Upward spiraling pathway of Deep Waters to surface

Importance of topographic ‘hotspots’ for deep layer upwelling

Illuminate mean circulation pathways for deep waters: Deep Western and Eastern Boundary Currents



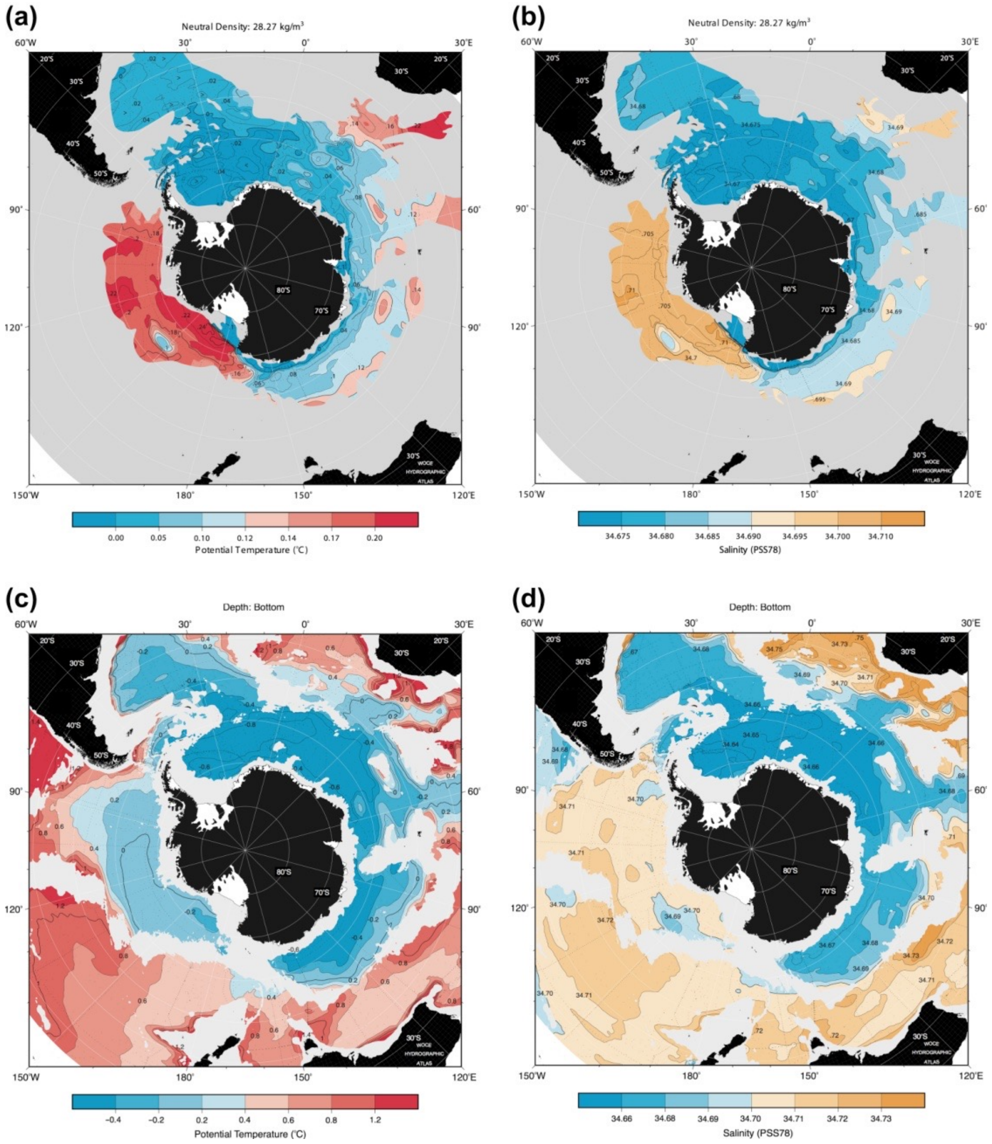


Particles upwelling across 400 m

Deep Water particles released in each ocean

Tamsitt et al. (Nat. Comm. 2017, JGR 2018, JGR 2019)

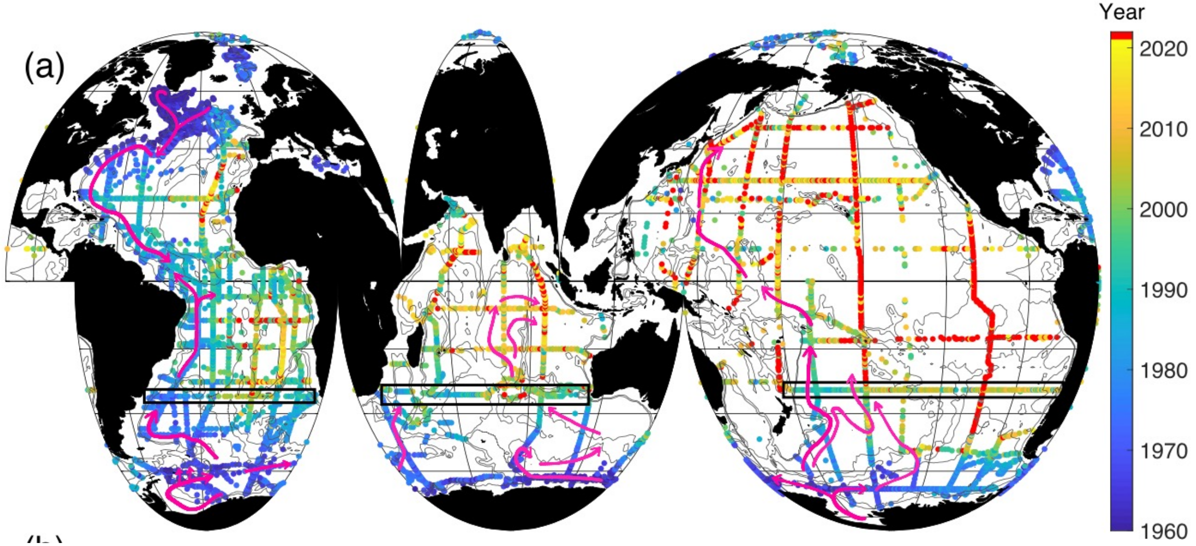
3-D SOOC: Antarctic Bottom Water is zonally asymmetric (multiple formation sites)



AABW T and S
28.27 gamma_n

AABW T and S
Bottom

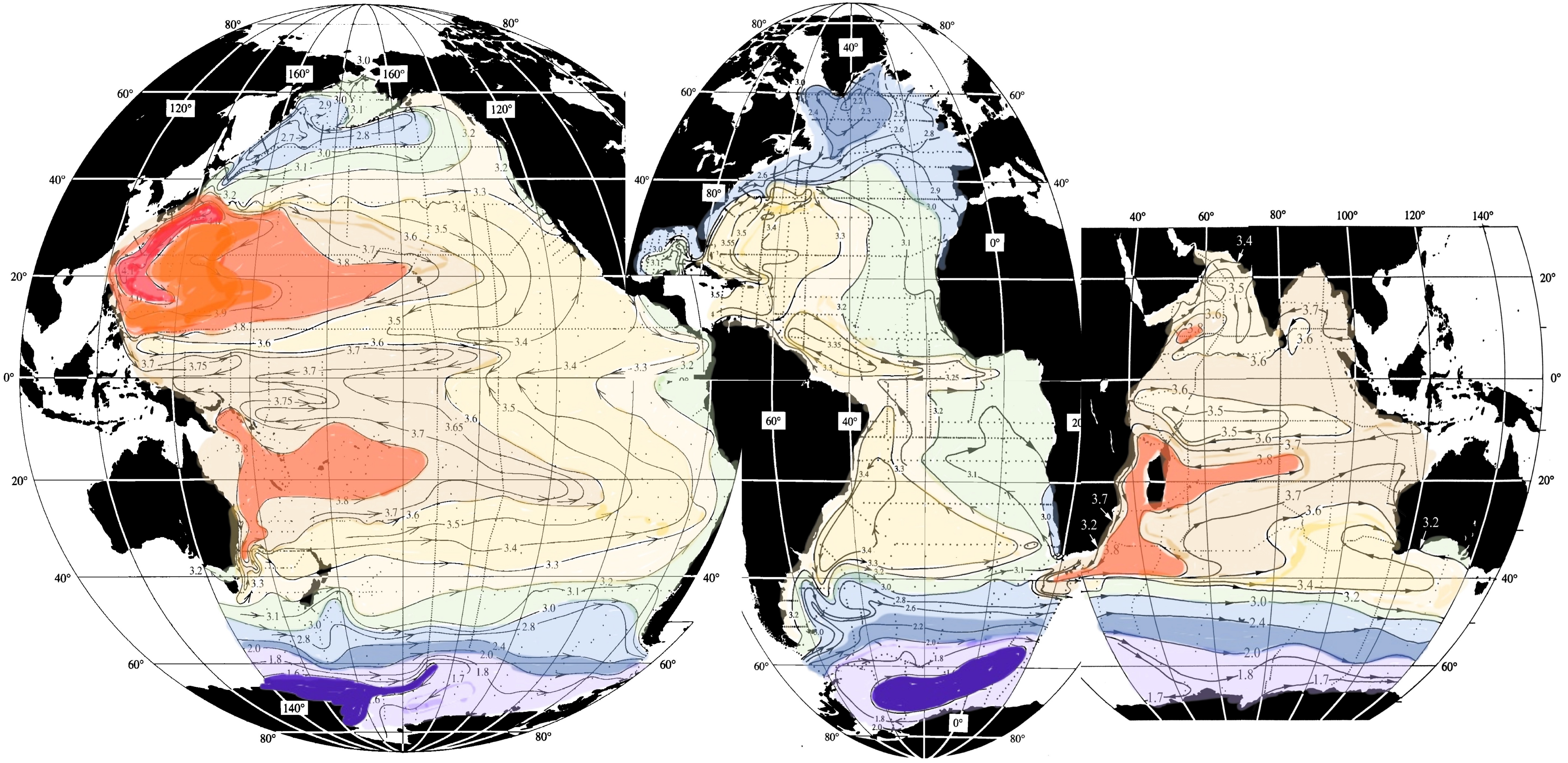
DPO FIGURE 13.16



Spread of bottom waters, based on age (WOCE/GO-SHIP tracers)

Cimoli et al. (JGR 2023)

3-D SOOC: Upper cell outflows are zonally asymmetric



DPO FIGURE 13.16

3-D SOOC: Upper cell outflows are zonally asymmetric

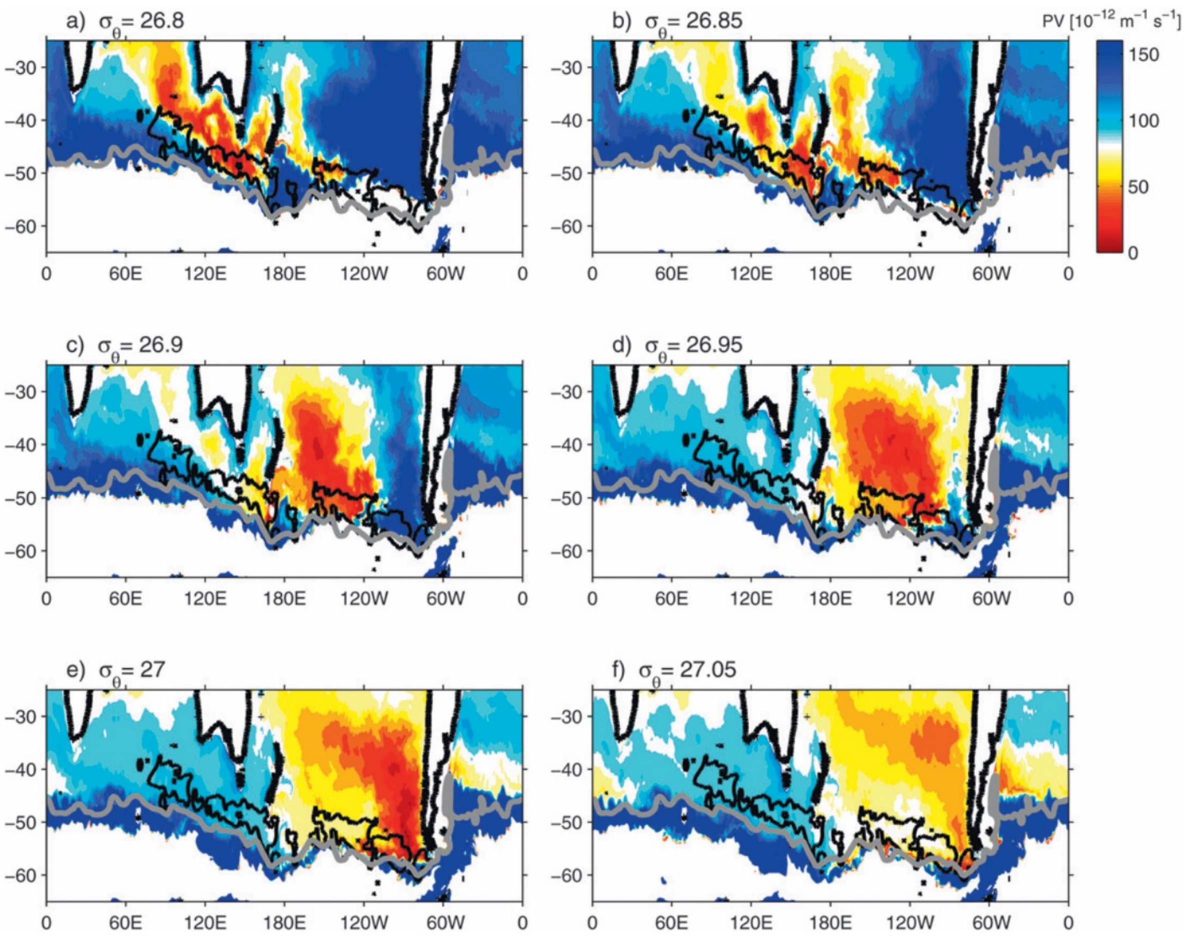
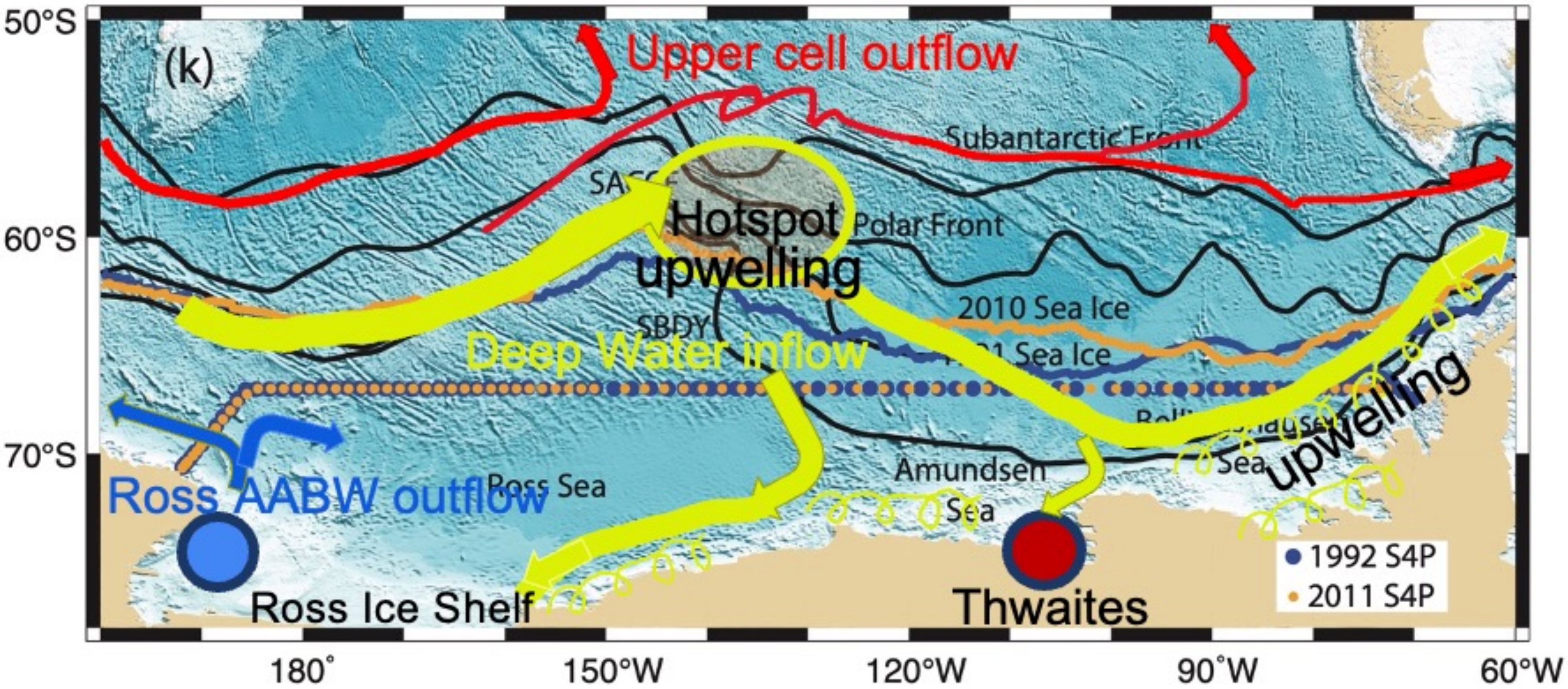


FIG. 4. As in Fig. 3, but showing σ_θ surfaces ranging from (a)–(f) 26.80 to 27.05.

Surface layer:
Subantarctic Mode Water potential vorticity (denser modes)
Cerovecki et al. (JPO, 2013)

3-D SOCCOM: Zonal asymmetry of Pacific Southern Ocean overturning (very rough!)

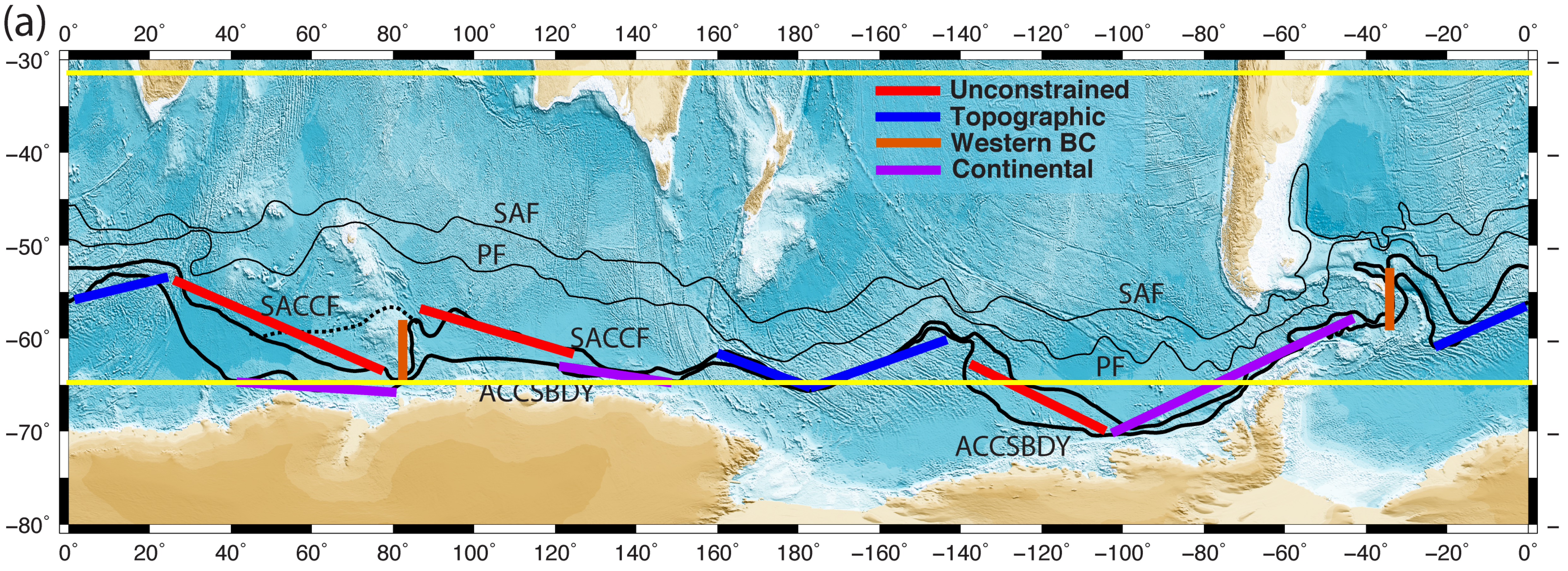
NSF Southern Ocean workshop (April 2024)
Unpublished concept – Talley/ Thompson



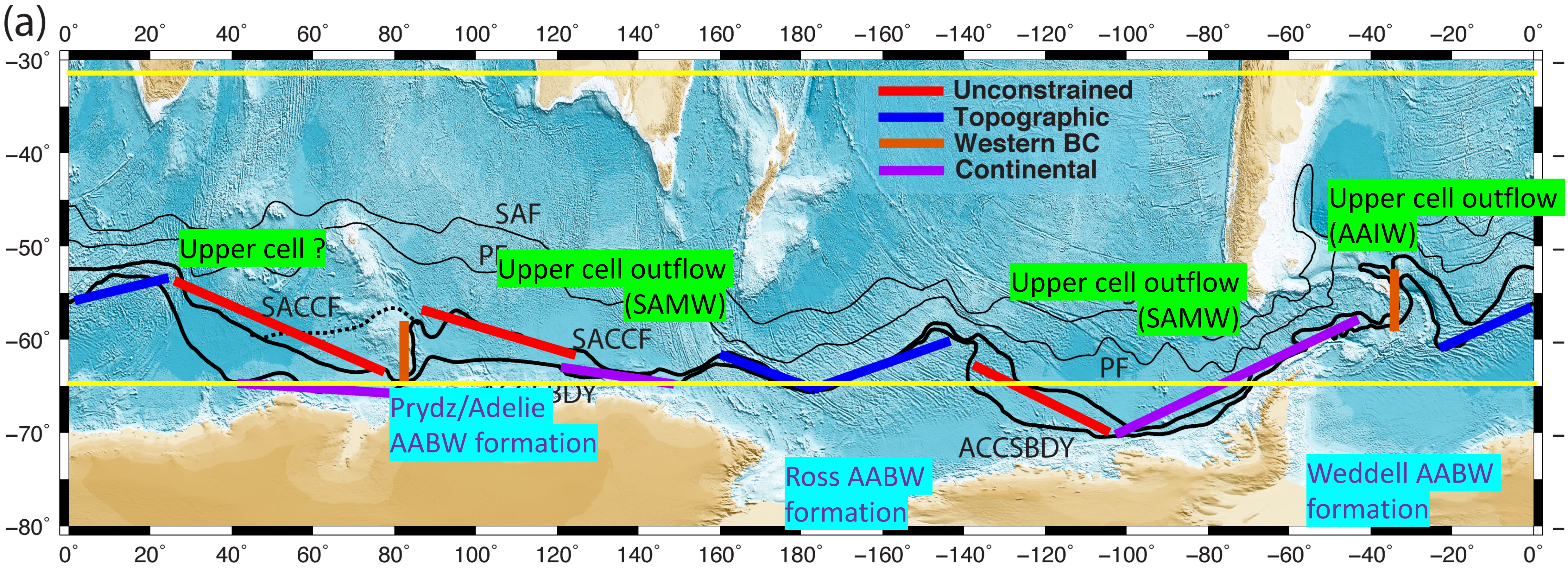
Lower cell dominates cold region:
AABW formation

Upper cell dominates warm region:
joining the thermocline

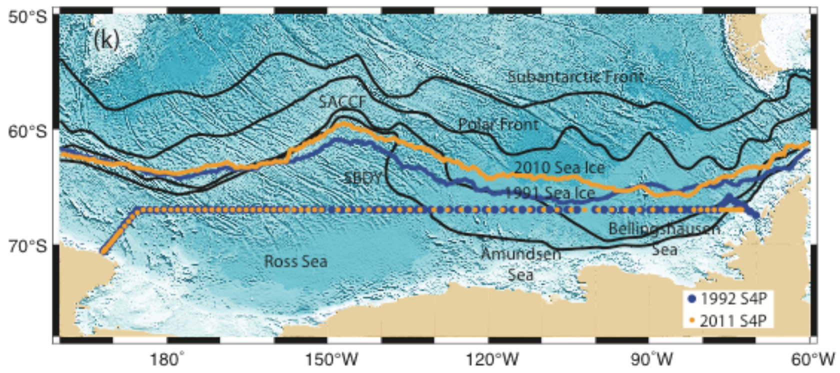
3-D SOCC: zonally-asymmetric locations of upper and lower cells

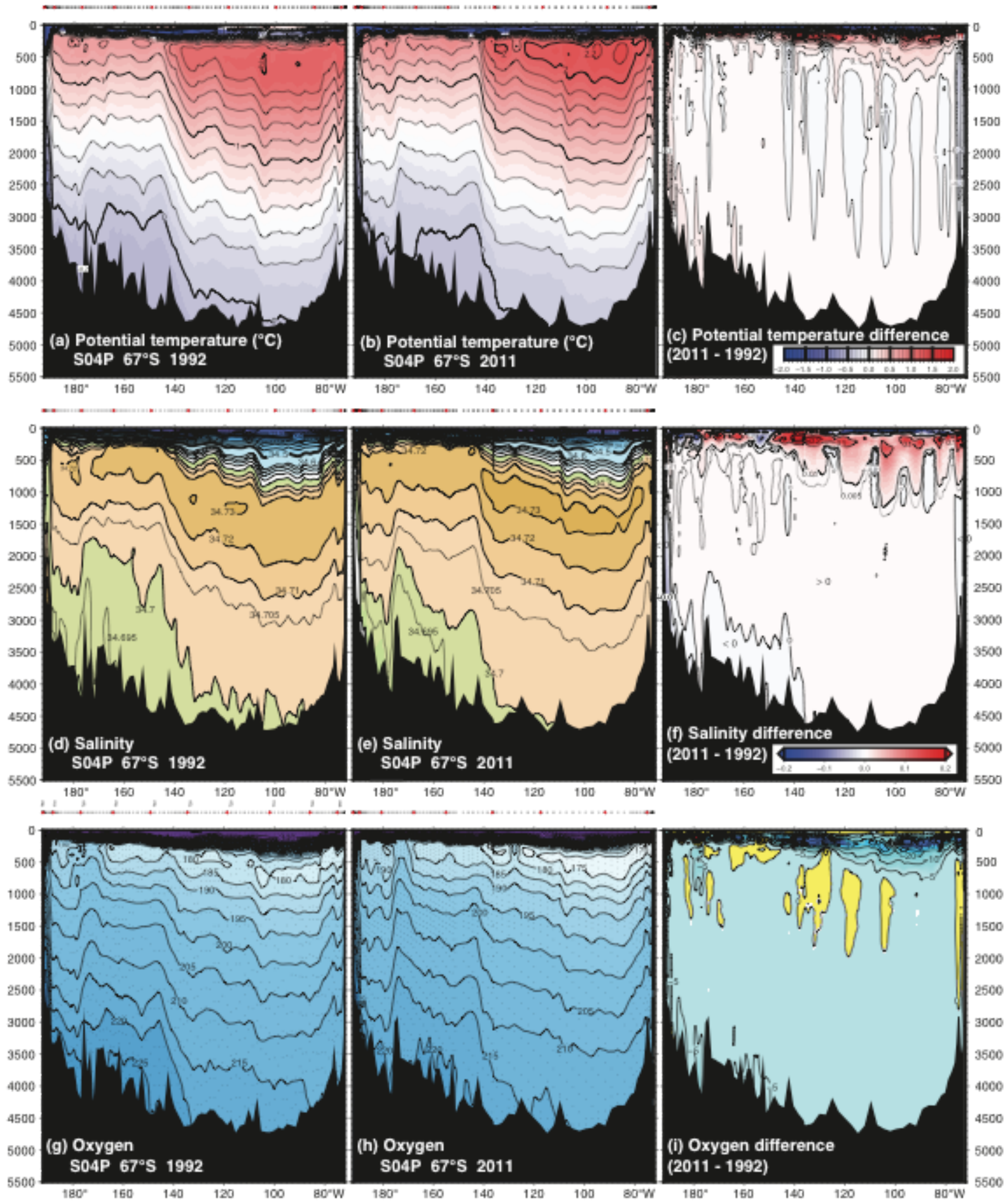


3-D SOCC: zonally-asymmetric locations of upper and lower cells



SOOC changes: 67°S (subpolar gyres and ACC upwelling regime)





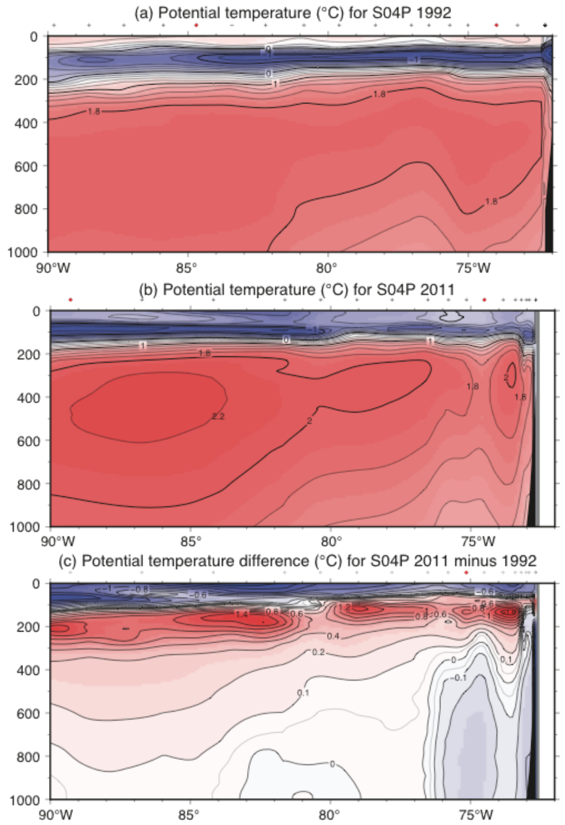
S04P 1992 and 2011

(no transport estimate yet)

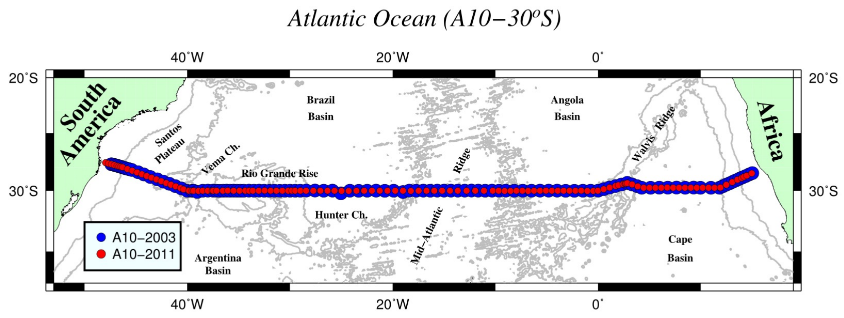
Property and front changes are consistent with stronger ACC, driving more northerly CDW faster towards the Antarctic Peninsula.

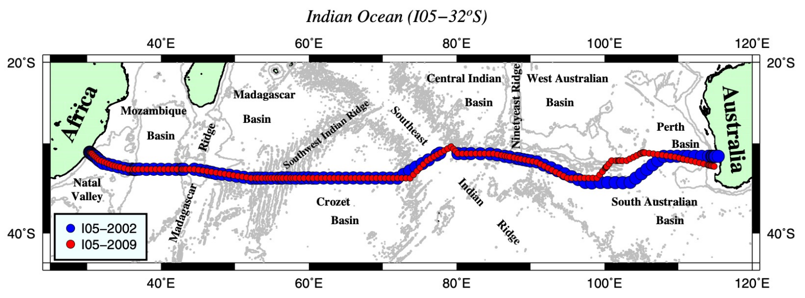
Consistent with stronger westerly wind.

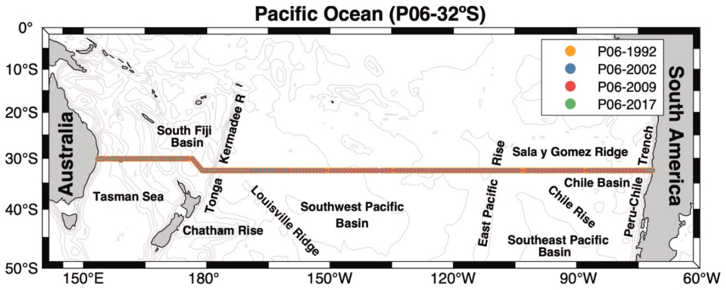
Talley (in prep, stalled out)

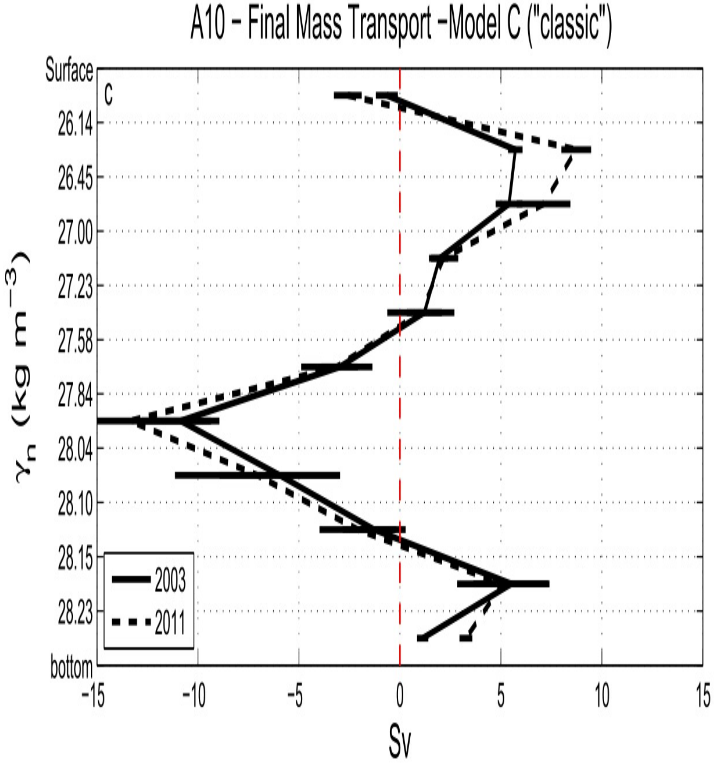


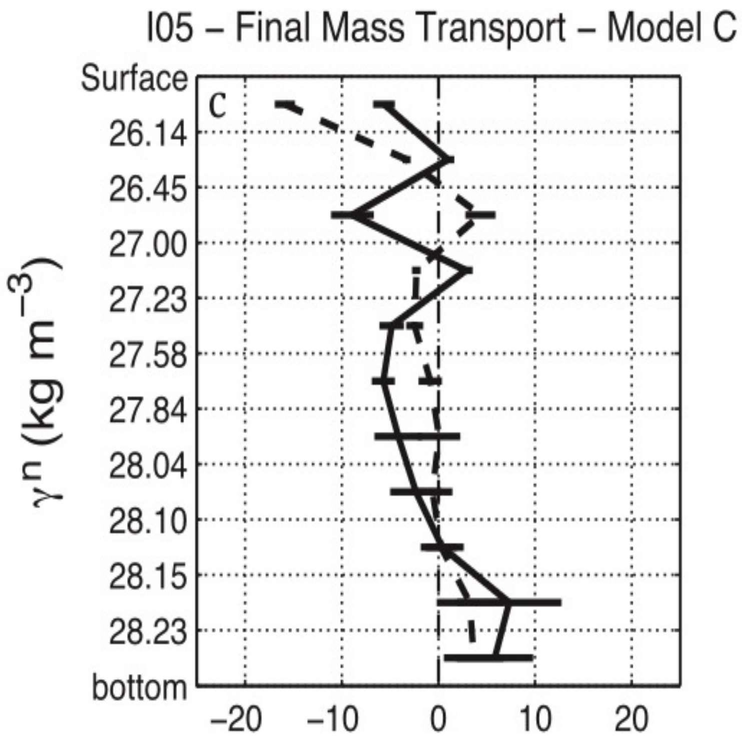
SOOC changes: 30°S (subtropical gyres; downwelling regime)

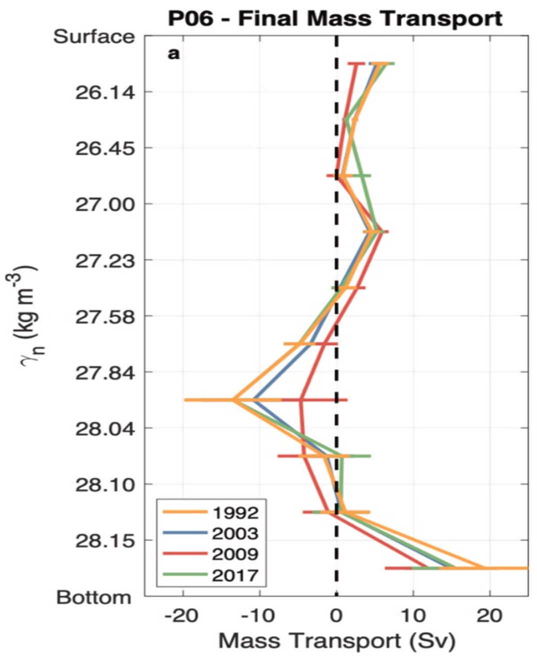












1992: 15.2 ± 10.3 Sv
2003: 13.2 ± 10.7 Sv
2009: 12.6 ± 10.0 Sv
2017: 15.3 ± 10.4 Sv

A10 (2003, 2011)
Hernandez-Guerra et al. (2019)

I05 (2002, 2009)
Hernandez-Guerra & Talley (2016)

P6 (1992, 2002, 2009, 2017)
Arumi-Planas et al. (2022)

SOOC changes: projects/ideas for inverse modeling

Ideas for inverse modeling focus:

Define a combined SOOC ocean transport index (or multiple indices)

67S (S04P and A23):
Contrast warm ACC and cold subpolar gyre transports and changes
Transports and property changes related to sea ice and wind changes

30S (A10, I05, P6): Carbon, heat, freshwater changes related to wind changes and northward exports from ACC

Choke points (I06S South Africa, I09S and SR3 Australia, SR4 Drake Passage) for changing inter-basin exchange

Methods?
Combine hydrographic and Argo float profiles for increased time resolution in top 2000 m (upper cell)
Can AI be used to streamline inverse modeling and potentially incorporation of multiple types of data (GO-SHIP and Argo?)