Global routes of the meridional overturning circulation: a Lagrangian analysis

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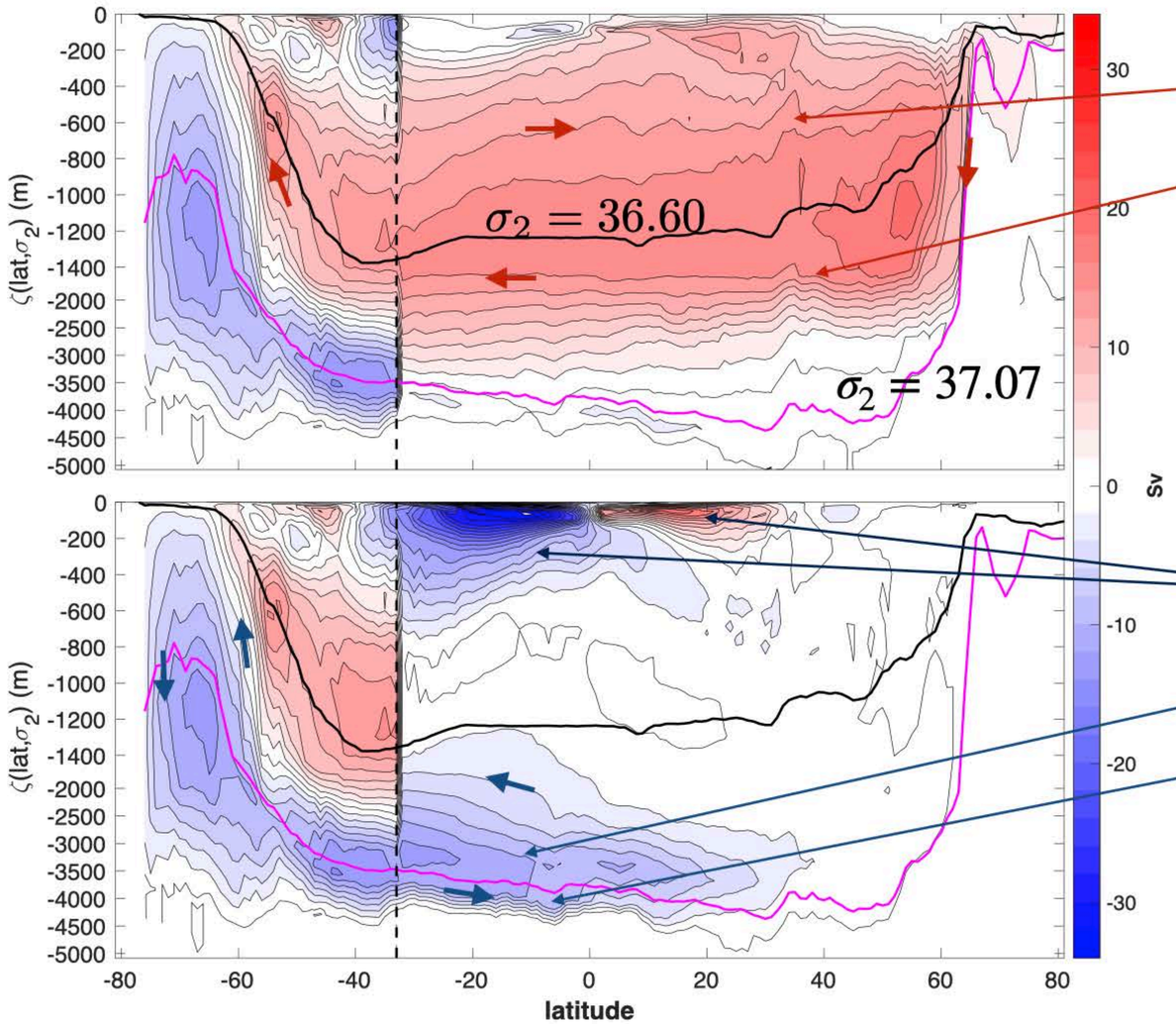
Zonally integrated residual overturning circulation (density coordinates)



All longitudes Atlantic (top), IndoPacific (bottom) sector

Atlantic sector

Upper branch of mid-depth cell - AMOC

Lower branch of mid-depth cell - AMOC

AMOC flows **along** isopycnals except at endpoints

Indo-Pacific sector

Subtropical cells: Ekman transport and its return

Upper branch of abyssal cell - mostly Indo-Pacific

Lower branch of abyssal cell - mostly Indo-Pacific

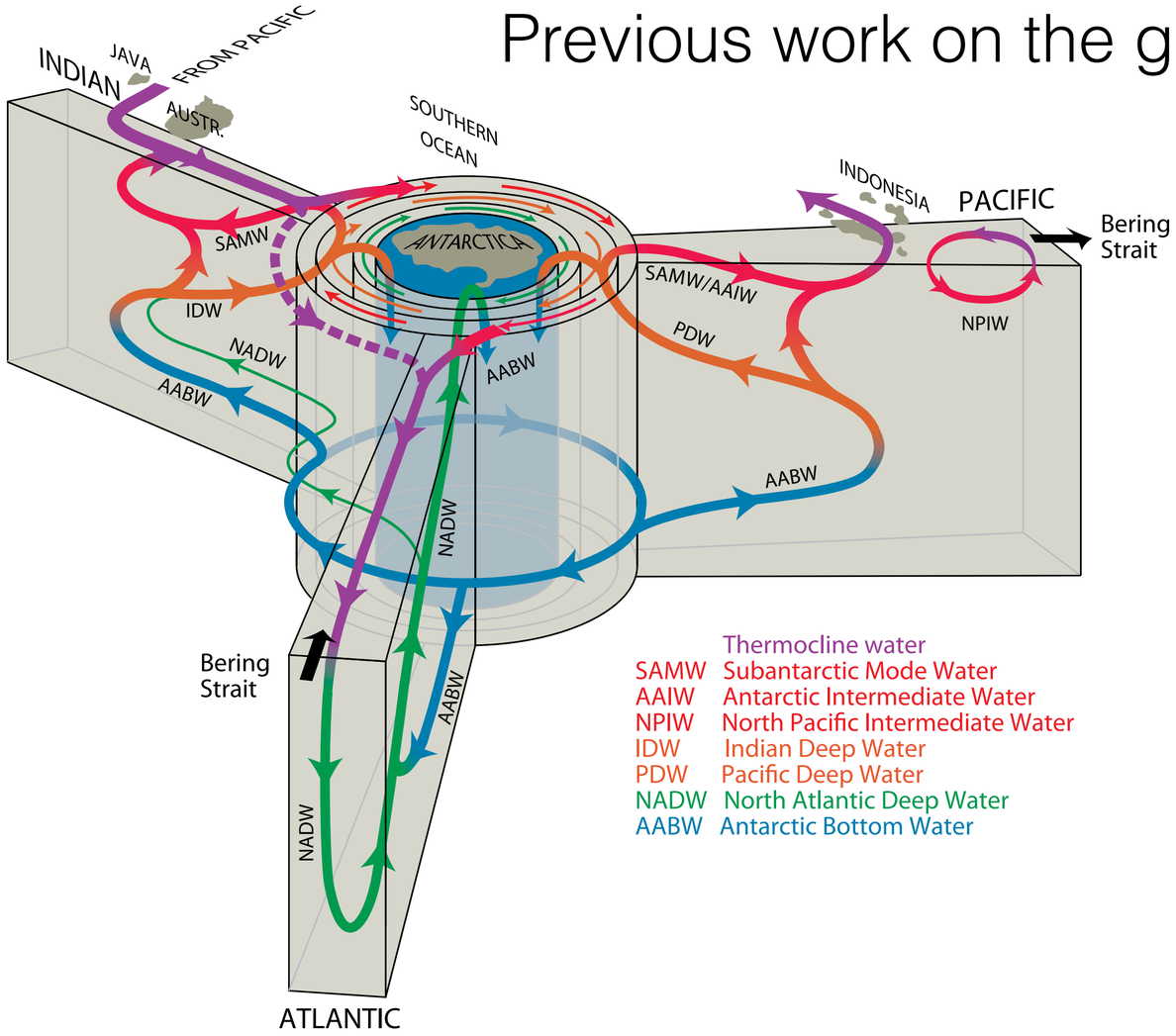
Abyssal cell flow **across** isopycnals

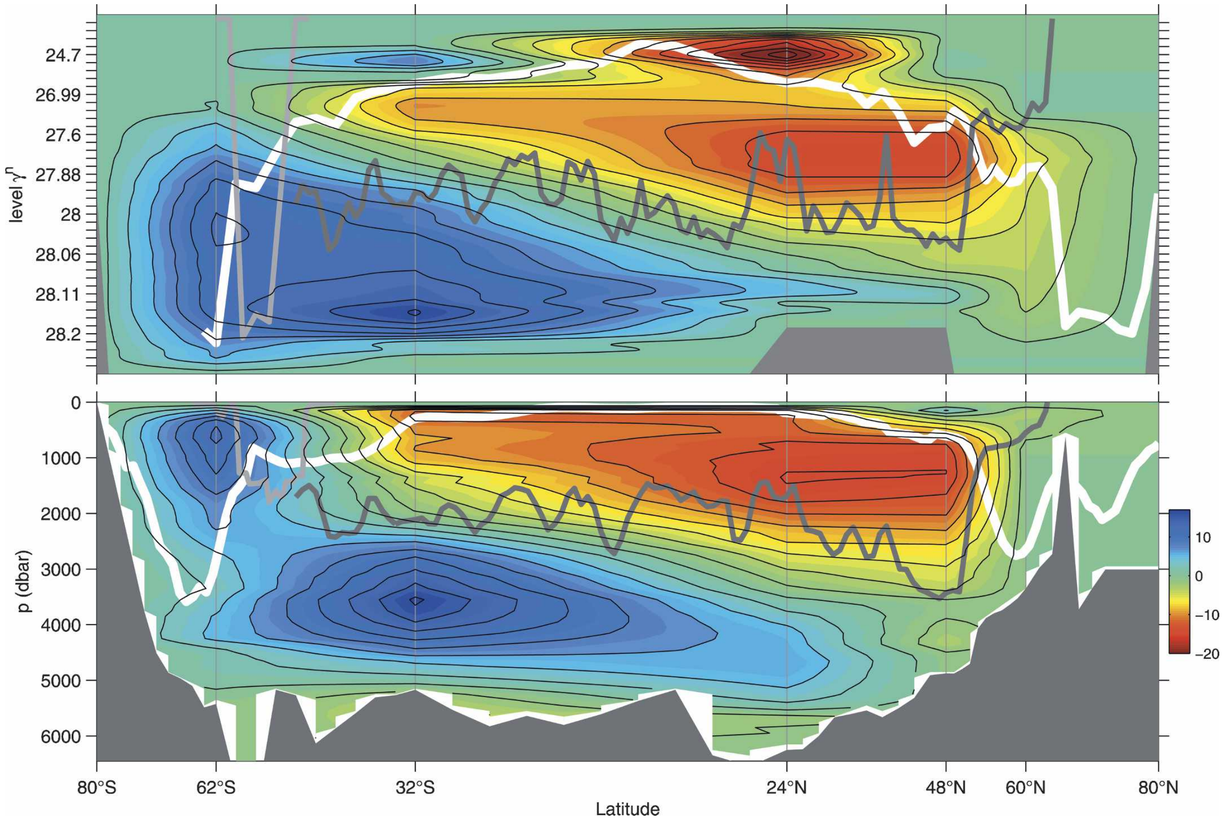
Cells are closed in Southern Ocean and are connected

Zonal integration obscures interbasin exchanges

Rousselet, L. et al, 2020. *Science Advances*

Previous work on the global reach of the Mid-depth overturning





Talley (2013): **100%** of NADW becomes AABW before returning to the upper AMOC

Lumpkin & Speer (2013): **75%** of NADW joins the abyssal cell before returning to the upper AMOC

In both cases hydrography is used, but neither Argo, nor remotely sensed data.

Use ECCO velocities to trace partcels around the world starting in the AMOC.

Lagrangian equations

$$\dot{x} = u(x, y, z, t)$$
$$\dot{y} = v(x, y, z, t)$$
$$\dot{z} = w(x, y, z, t)$$

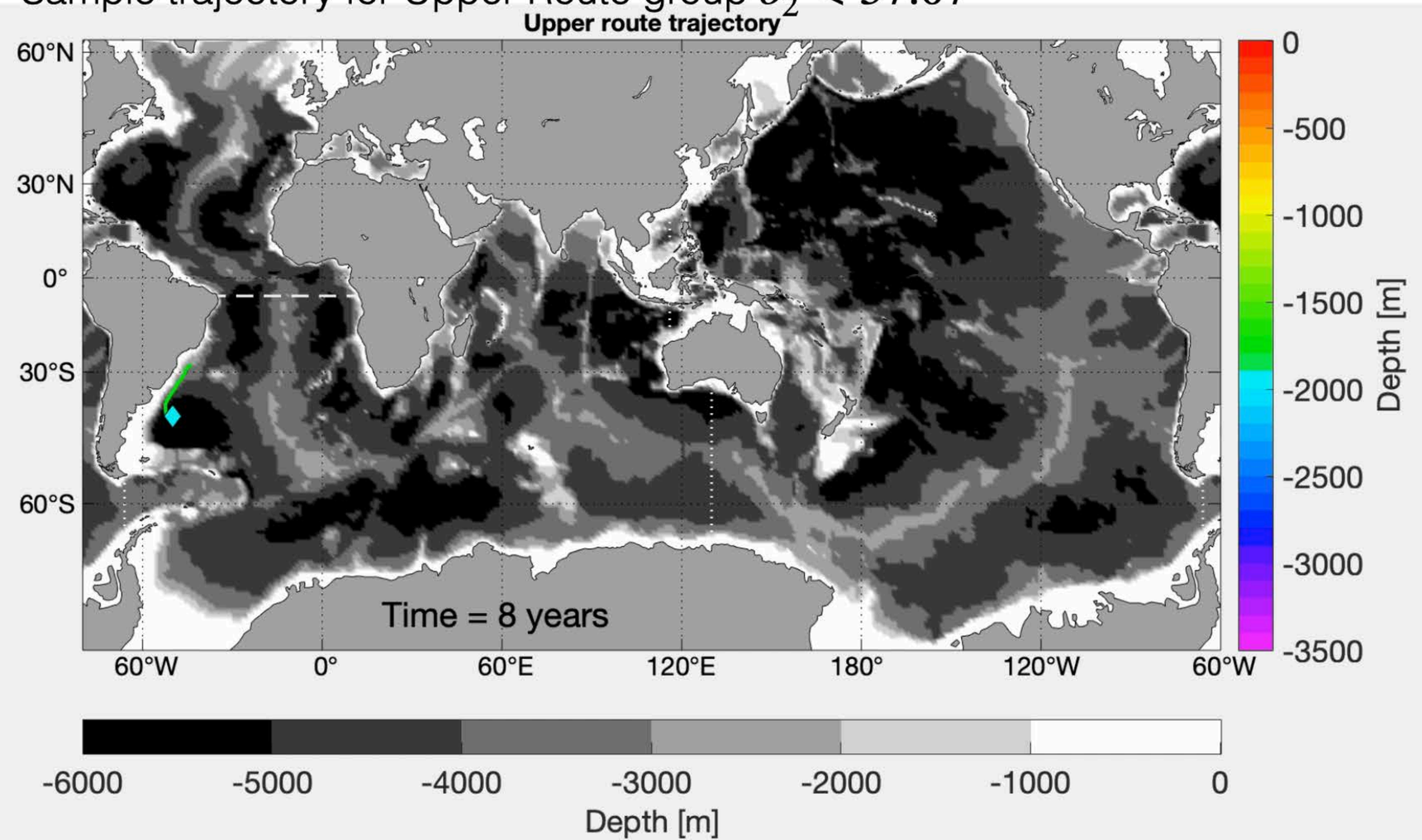
Lagrangian analysis of NADW routes according to ECCOv4

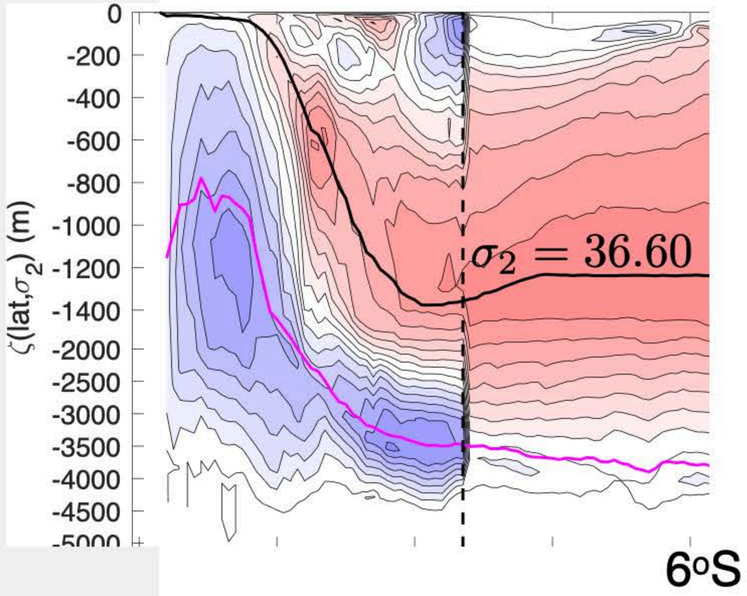
Advect~64000 particles with monthly climatology of ECCO velocity,1-year periodic, repeated for 8100 years backward in time

Exit section: **6°S for $\sigma_2 < 36.6$: 13.6 Sv:** upper branch

Entry section: **cross 6°S** for $\sigma_2 \geq 36.6$ **or**
after going through Drake Passage **or**
after going through Tasman Leakage **or**
after going through Indonesian Throughflow
} lower branch

Sample trajectory for Upper Route group $\sigma_2 < 37.07$





In this group $\sigma_2 < 37.07$ everywhere

Lagrangian analysis of NADW routes according to ECCOv4

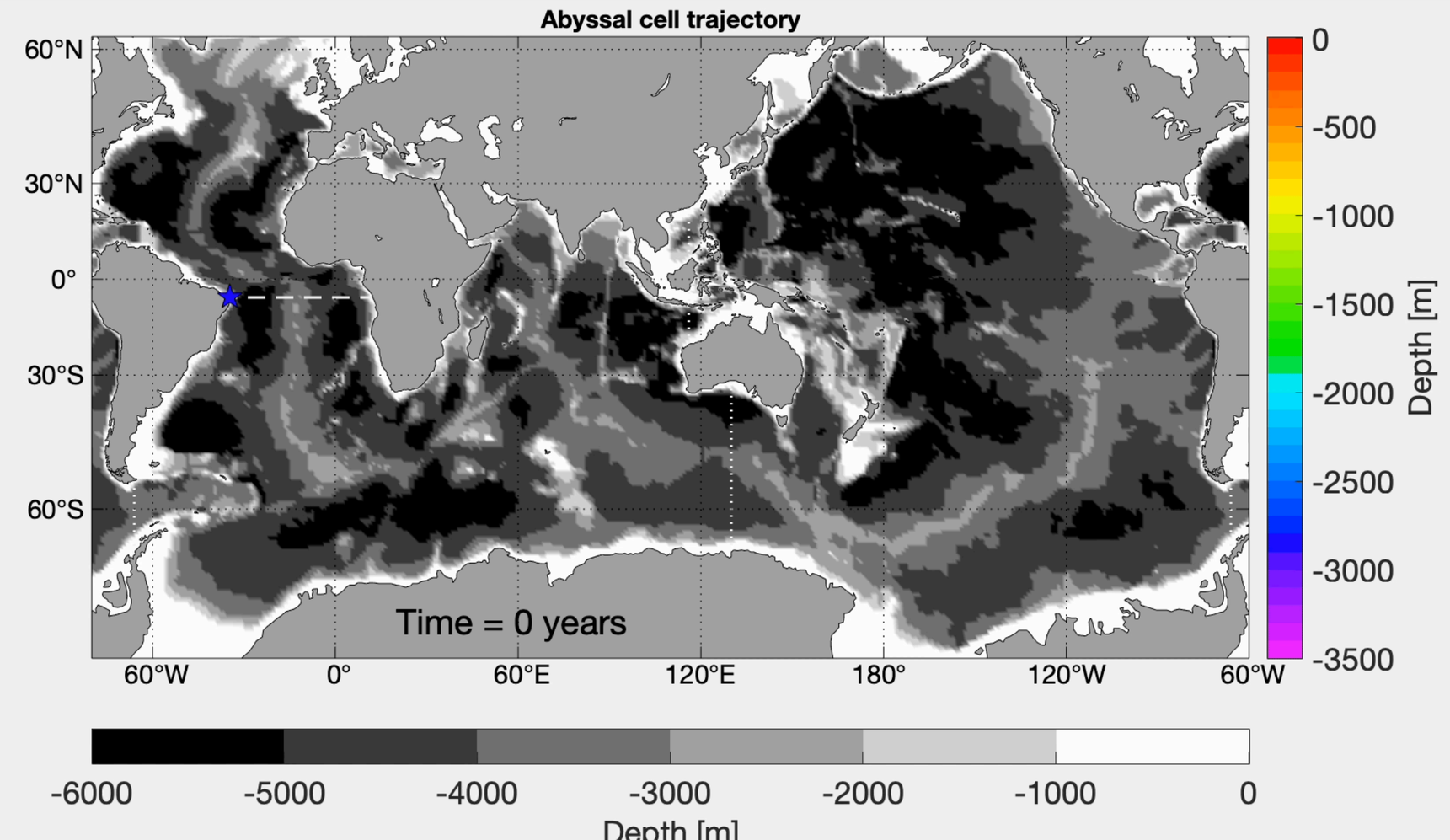
Advect~64000 particles backward in time
with monthly climatology of ECCO velocity,
1-year periodic, repeated 8100 years

Entry section: **cross 6°S** for $\sigma_2 \geq 36.6$ **or**
after going through Drake Passage **or**
after going through Tasman Leakage **or**
after going through Indonesian Throughflow

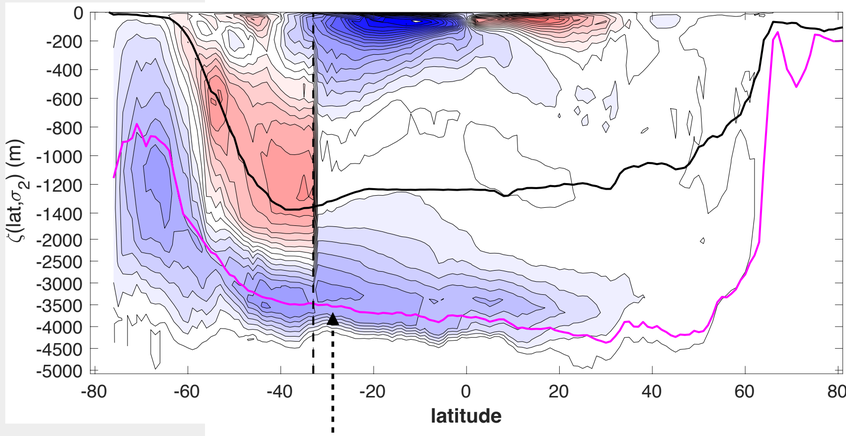
} lower branch NADW

Exit section: **6°S for** $\sigma_2 < 36.6$: **13.6 Sv:** upper branch

Sample trajectory for abyssal IndoPacific group: forward in



In this group $\sigma_2 > 37.07$
north and south of 30°S



Abyssal Cell

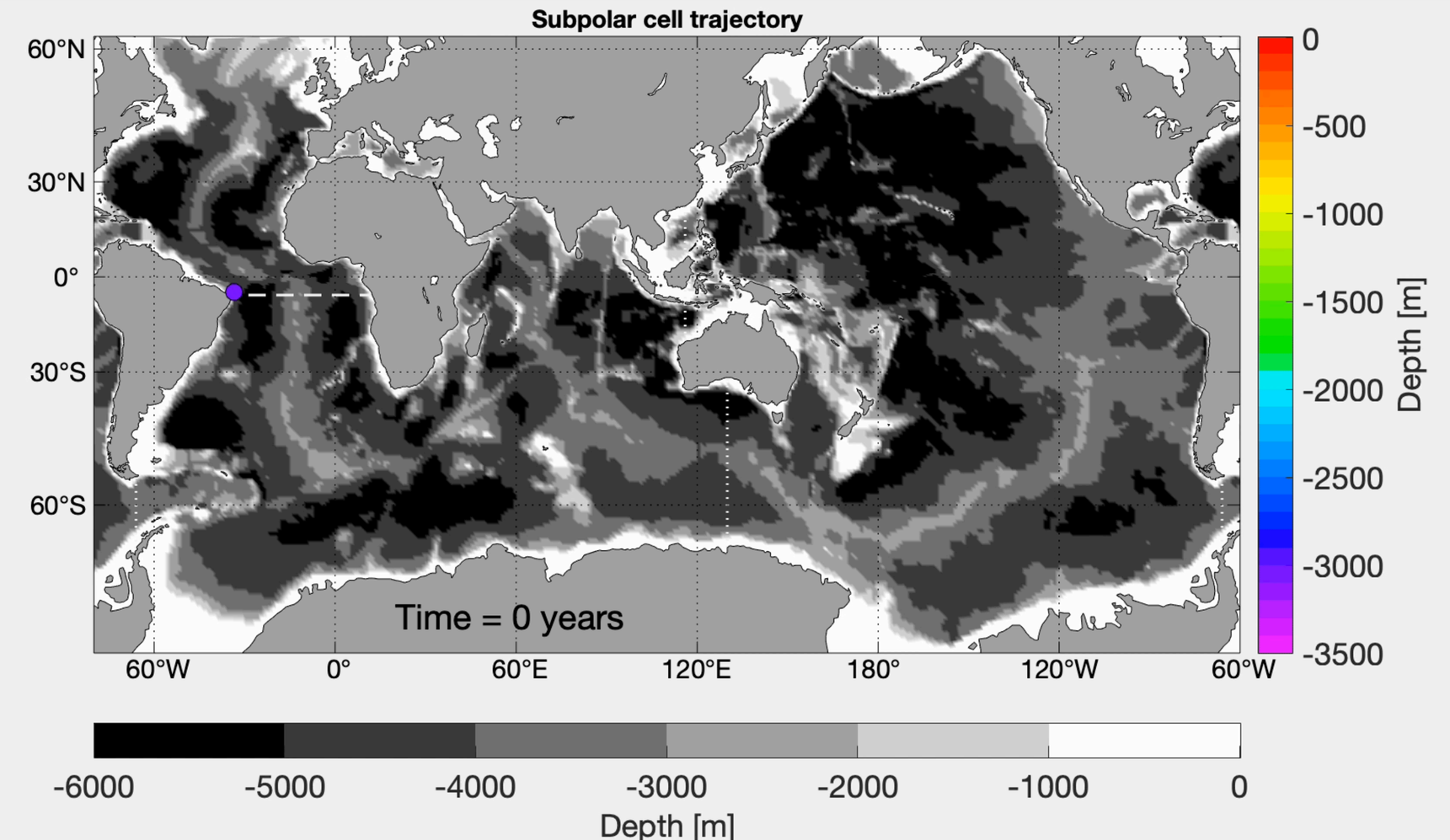
Lagrangian analysis of NADW routes according to ECCOv4

Advect~64000 particles with monthly climatology of ECCO velocity, 1-year periodic, repeated 8100 years backward in time

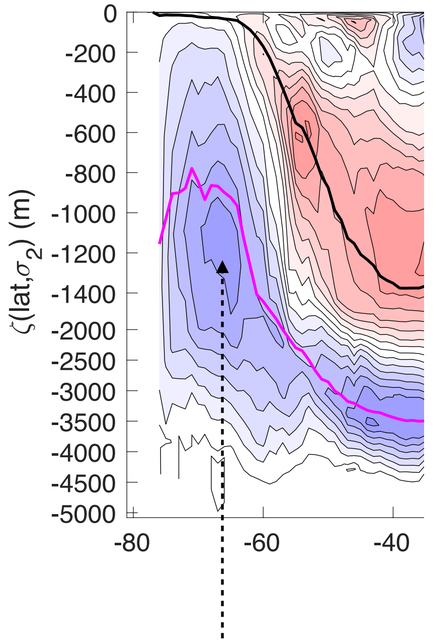
Exit section: **6°S** for $\sigma_2 < 36.6$: **13.6 Sv:** upper branch

Entry section: **cross 6°S** for $\sigma_2 \geq 36.6$ **or**
after going through Drake Passage **or**
after going through Tasman Leakage **or**
after going through Indonesian Throughflow
} lower branch

Sample trajectory for Subpolar Cell group: forward in time

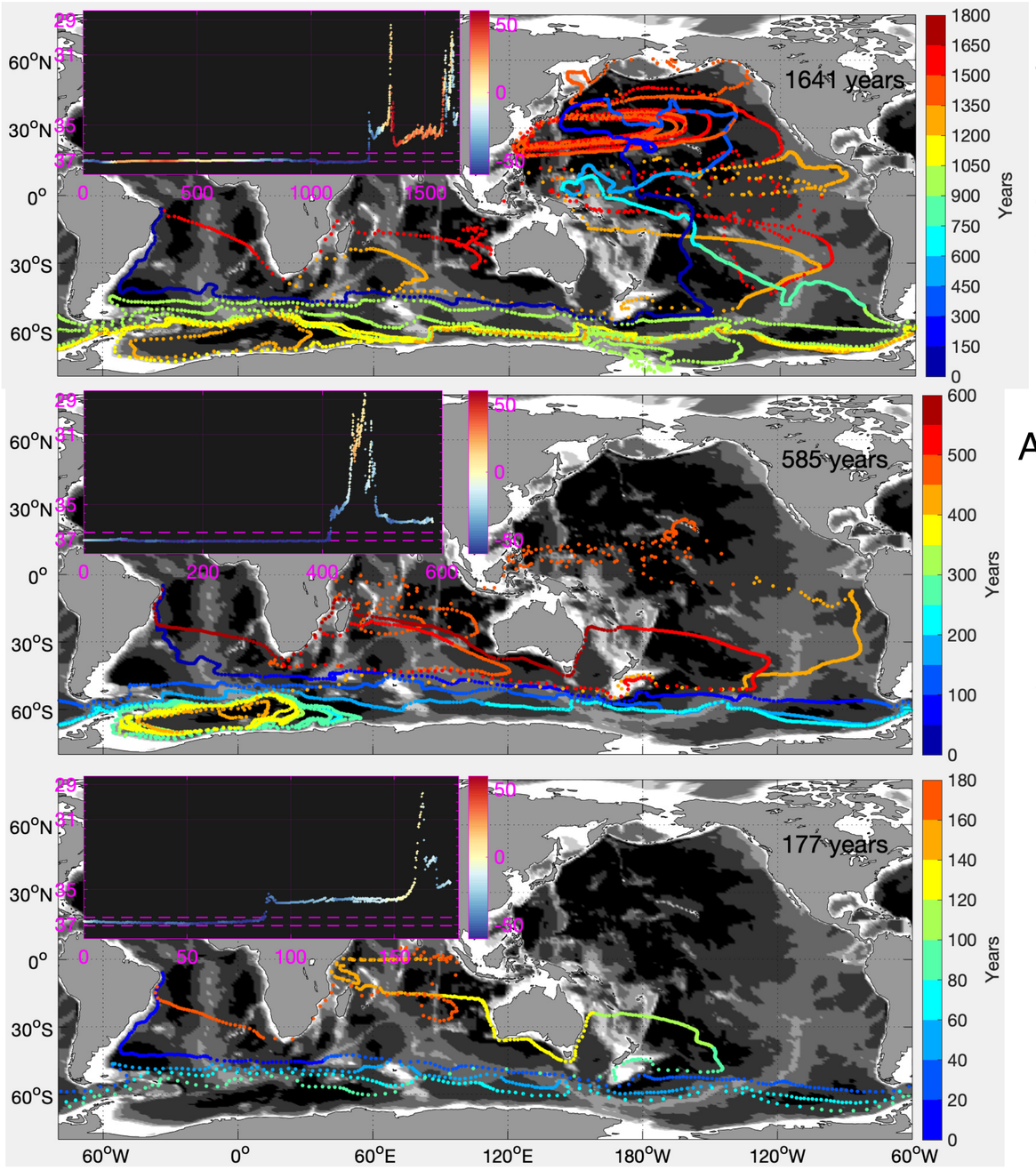


In this group $\sigma_2 > 37.07$
only south of 30°S



Subpolar Cell

The routes of NADW according to ECCOv4



Three qualitatively distinct groups of particles:

1. **Abyssal cell 6.5Sv:** cross $\sigma_2 = 37.07$ north&south of 30°S
2. **Subpolar cell 2.7Sv:** cross $\sigma_2 = 37.07$ only south of 30°S
3. **Upper route 4.4Sv:** never cross $\sigma_2 = 37.07$

Representative trajectories for each route (color is time)
σ_2 is plotted in inset

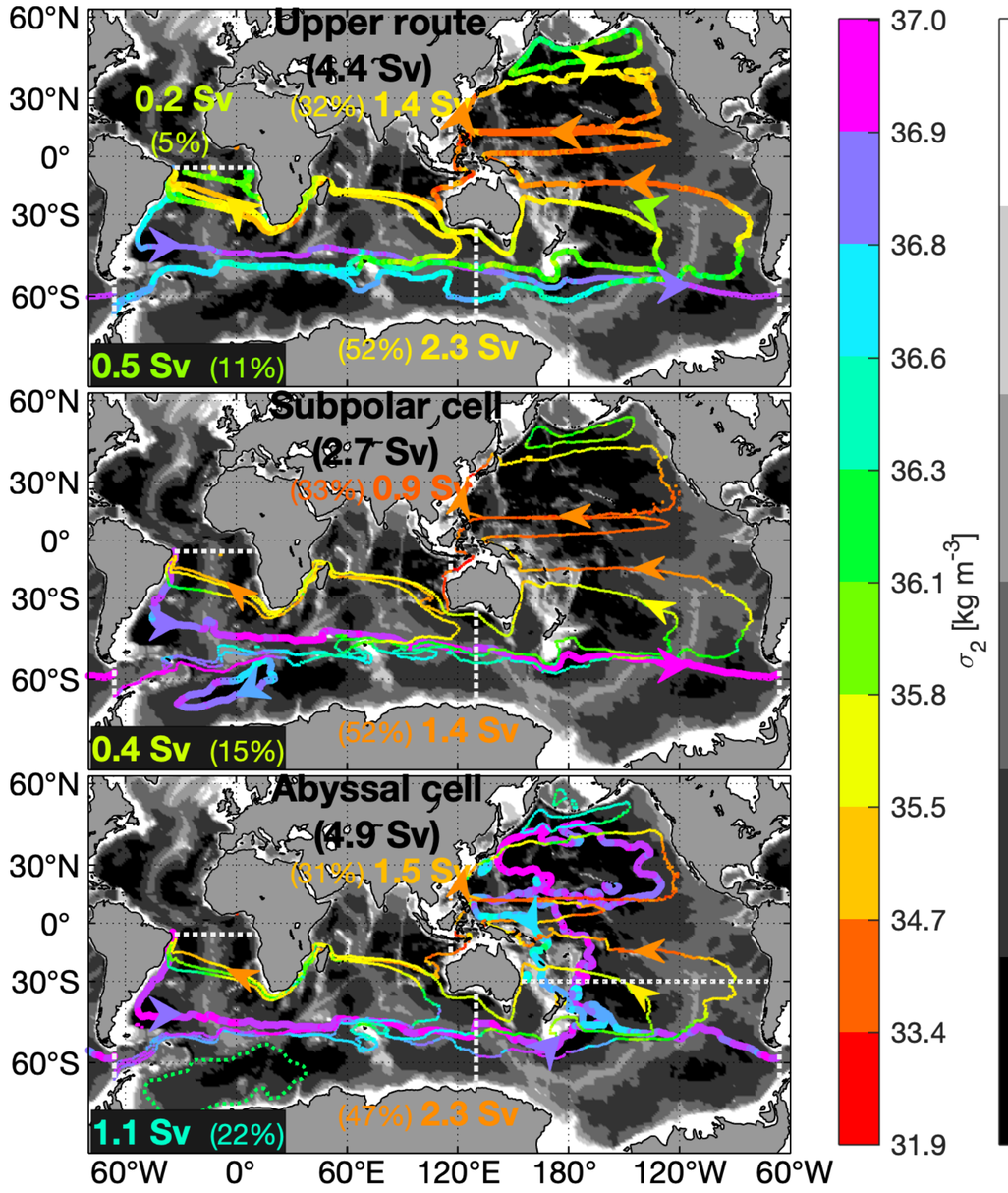
Abyssal cell - 6.5Sv: NADW downwells in northern ACC,
first enters abyssal Indo-Pacific as CDW,
then re-enters ACC where it upwells.
Does not sink as AABW

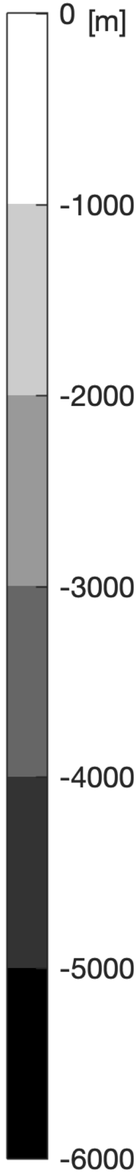
Subpolar cell - 2.7Sv: NADW downwells in ACC as CDW,
flows around Weddell and Ross gyres,
where it also upwells.

Upper route - 4.4Sv: NADW upwells in ACC,
flows around gyres,
and enters S.Atl. from warm route

Rousselet, L. et al, 202. *Science Advances*

Median paths between selected sections





NADW exits the S. Atl. to enter ACC

Exits from ACC into basins at Kerguelan Plateau

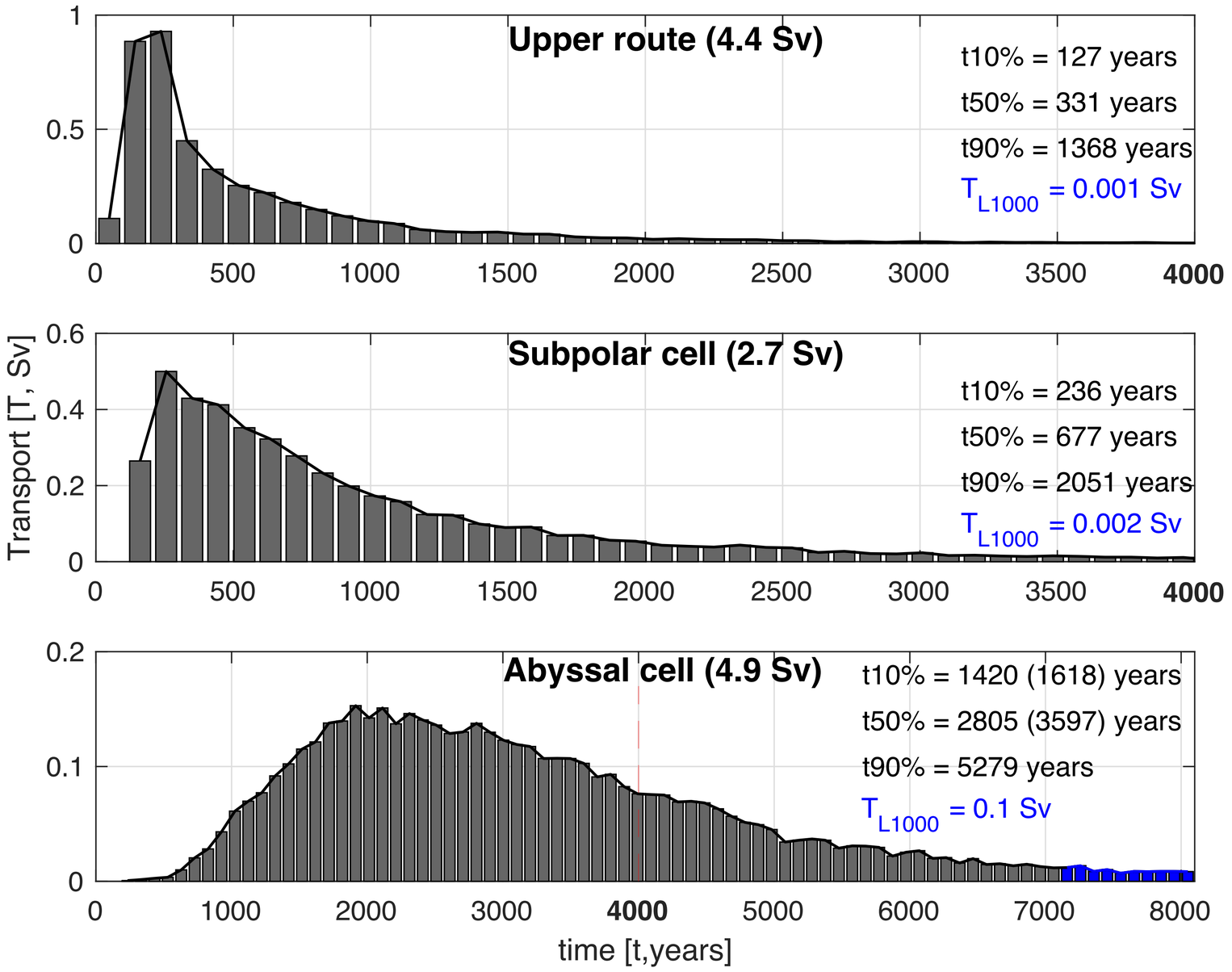
Enters the Supergyre of the Southern Ocean

Enter the South Atlantic from Indonesian Throughflow or Western Australian Coast, via South Africa (warm route)

NADW takes a detour in abyssal IndoPacific **before** entering ACC and Antarctic region

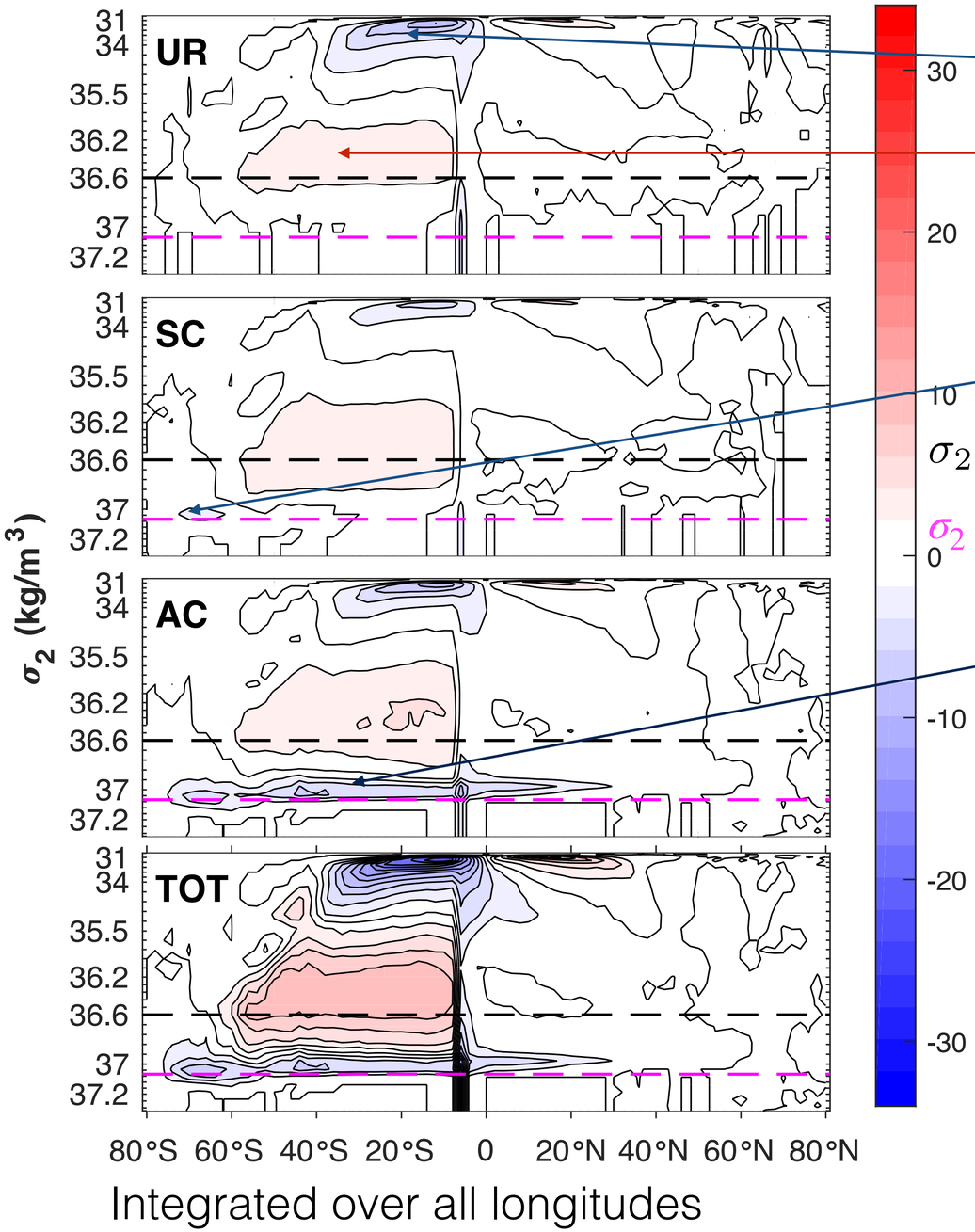
Rousselet, L., Cessi, P. and Forget, G., 2021. *Science Advances*,

Transit times from 6S (lower AMOC) to 6S (upper AMOC)



Only the Abyssal Cell (48%) has potential to sequester carbon and heat w/millenial transit times

Zonally integrated and ensemble averaged residual overturning circulation (σ_2 coordinates)



Parcels in the Upper Route (UR - 32%)

Ekman Cell - associated with Supergyre

Mid-depth cell - AMOC

Parcels in the Subpolar Cell (SC - 20%)

Subpolar Cell - isolated from IndoPacific abyssal circulation, connected with AMOC and Ekman cell

Parcels in the Abyssal Cell (AC - 48%)

Abyssal cell - connected to AMOC, Ekman cell and SC, but SC visited ***after*** IndoPacific abyssal circulation

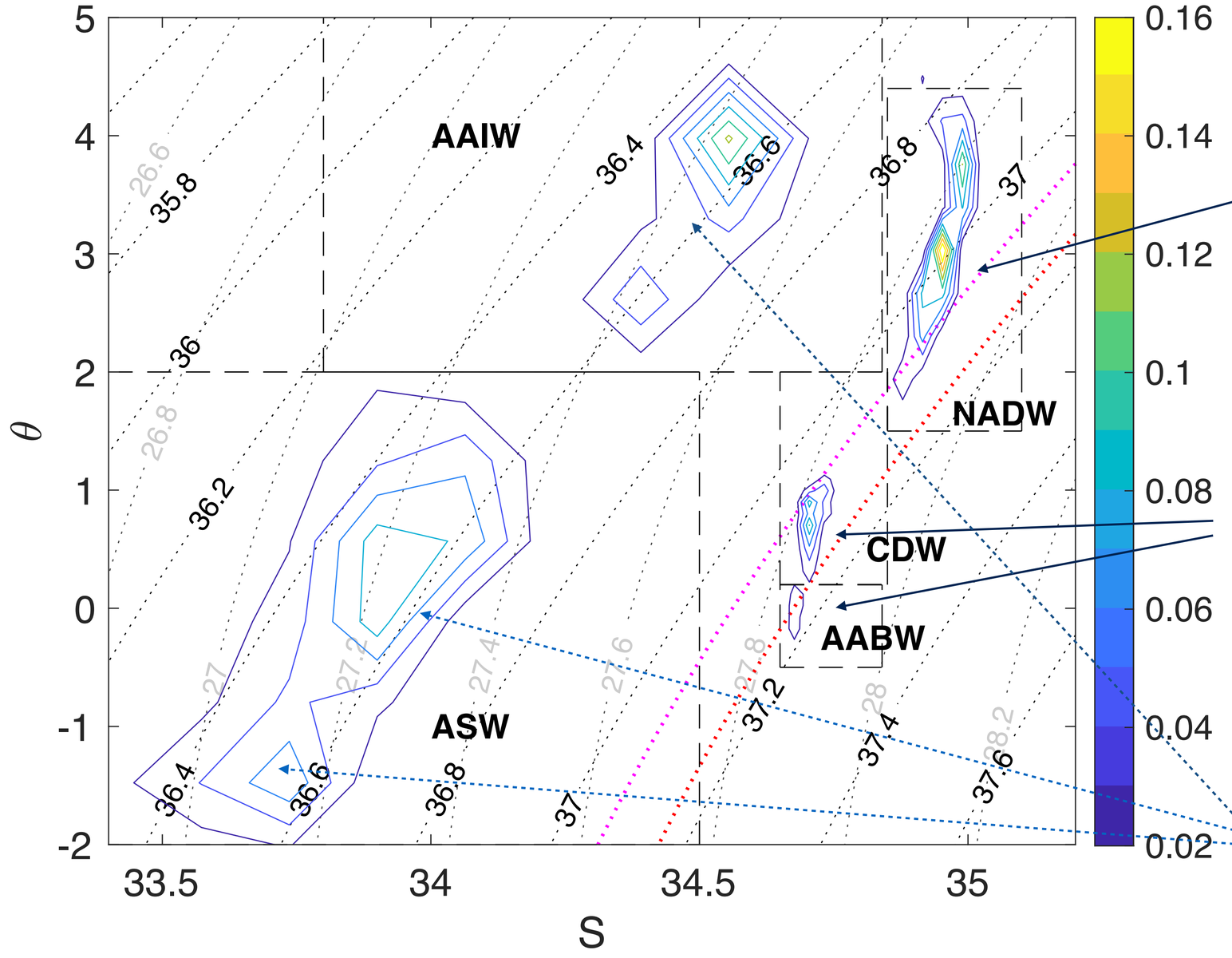
Cells appear separated in the zonal integration

Connected in 3D

Only abyssal circulation from AMOC is included (6.5Sv)

The remaining 7.5Sv in the abyssal cell do not originate from NADW

Parcels conditional histograms in T-S space



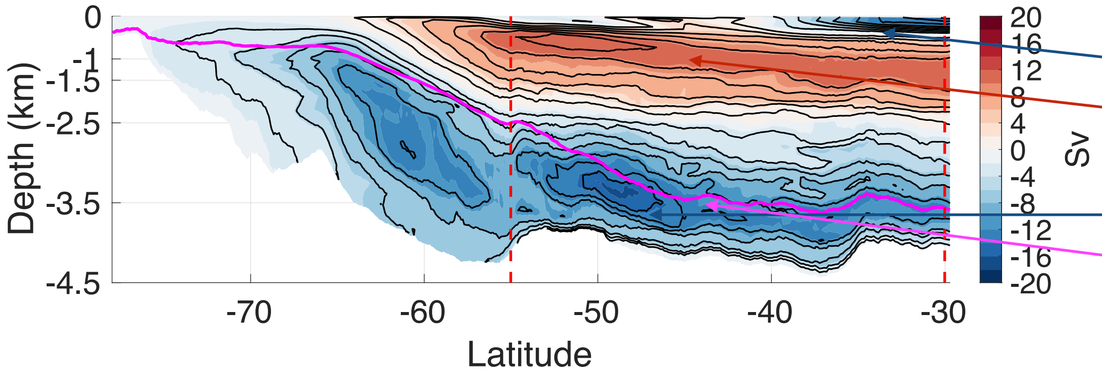
Exit section:
MOC lower branch at 6°S

Parcels w/ $\sigma_2 \geq 37.07$

1st crossing of $\sigma_2 < 36.6$:
upwelling

Majority of abyssal water is CDW not AABW: topography and ACC confine AABW

Recovering all the MOC: trace the lower branch of the abyssal cell in SOSE

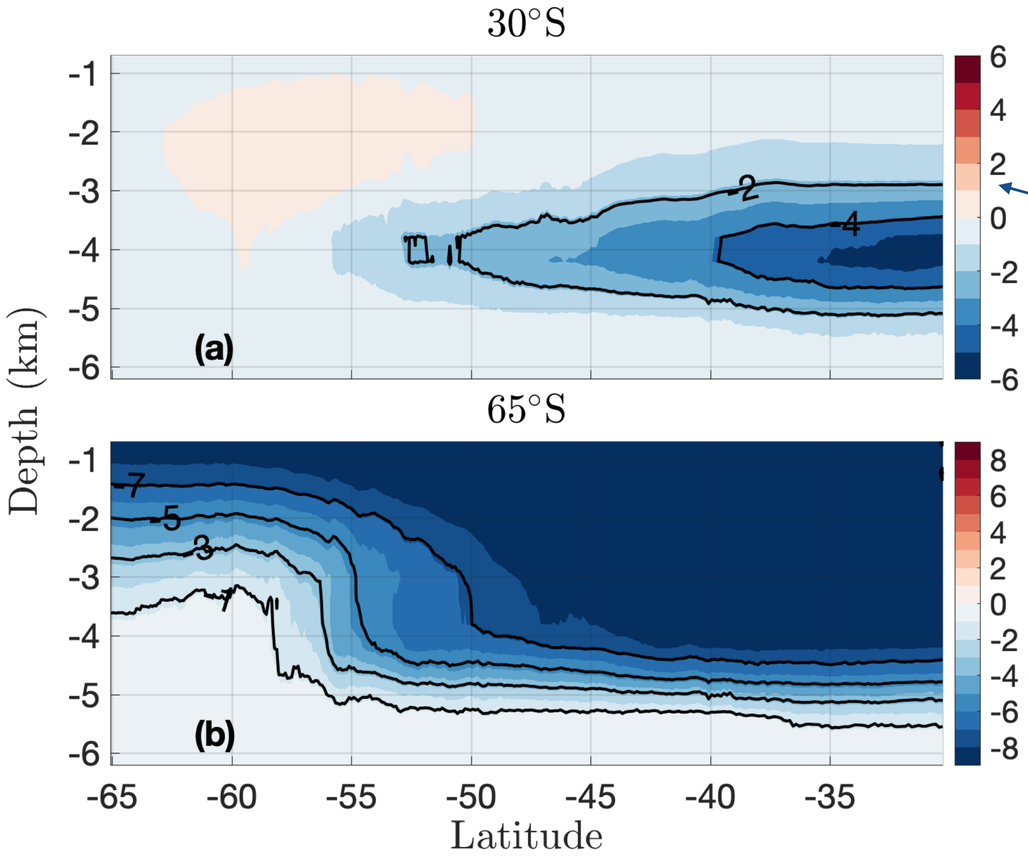


Ekman Cell - associated with Supergyre

Mid-depth cell - AMOC

Abyssal Cell - associated with Supergyre

$\sigma_2 = 37.07$

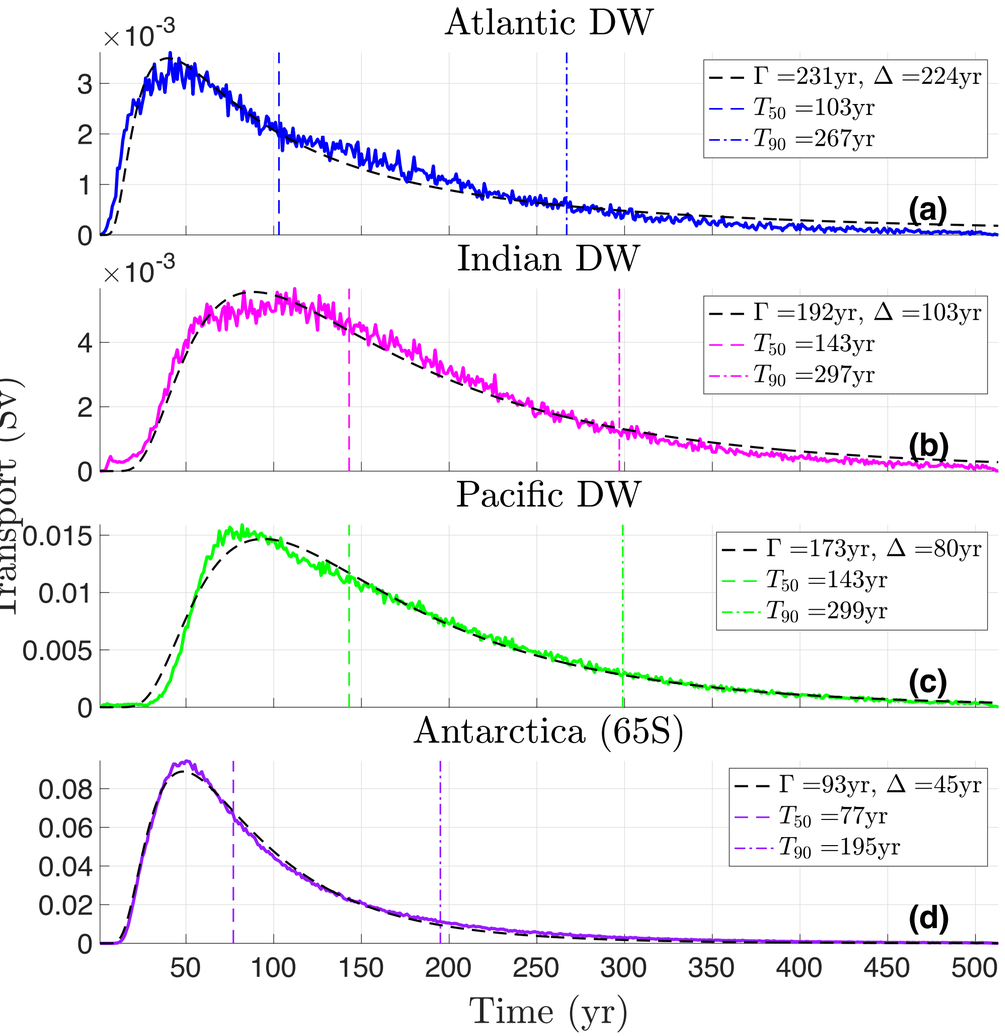


Seed parcels at 30°S below $\sigma_2 = 37.07$

Trace them back to 30°S above $\sigma_2 = 37.07$ (38%)

or to 65°S (62%)

Transit times to 30S: either from deep water at 30S or abyssal water at 65S



From the deep Atlantic sector to the abyssal flow

From the deep Indian sector to the abyssal flow

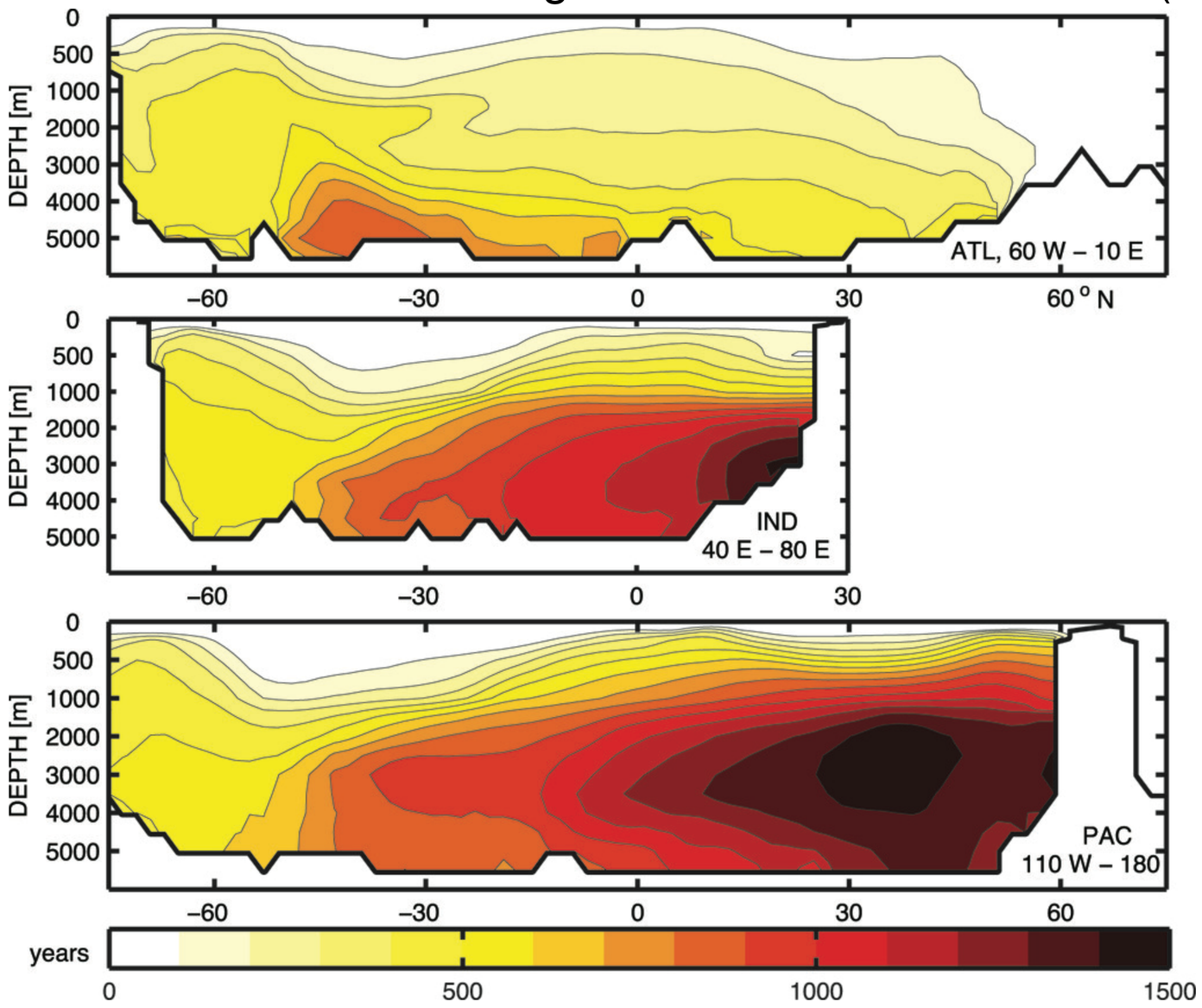
From the deep Pacific sector to the abyssal flow

From Antarctica to the abyssal flow

The time-scales are multi-decadal to centennial: ECCO gives times that are about twice as long (smaller v)

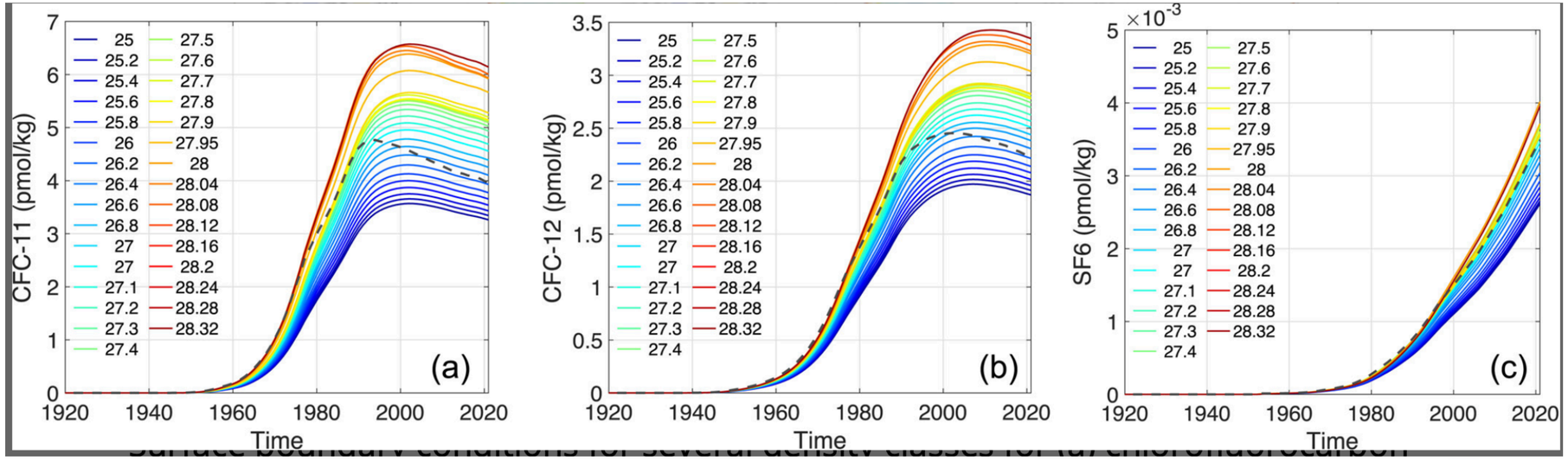
Transit times are 10 times faster than tracer age calculated from the surface (any source)

Mean age inferred from radiocarbon (Gebbie & Huybers, 2012 JPO)

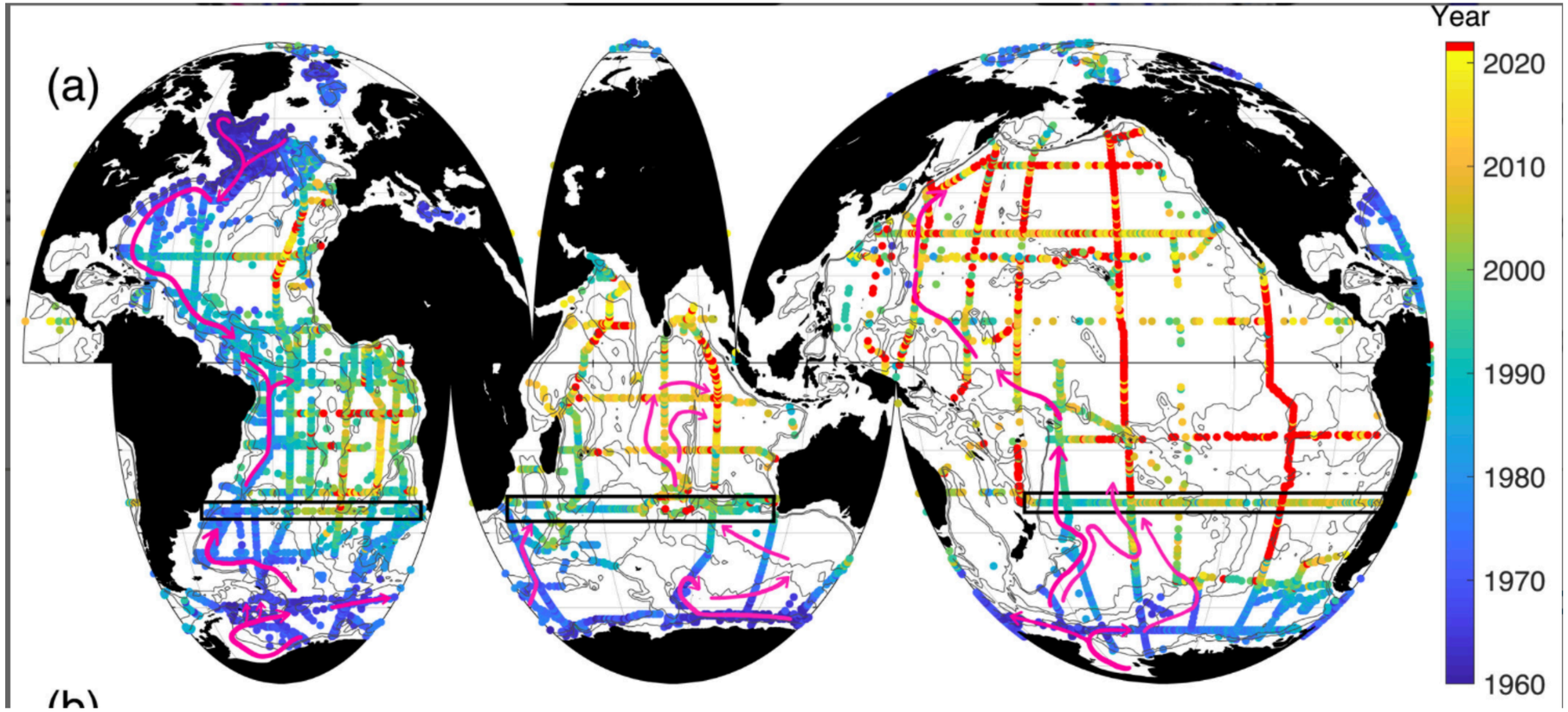


At 30S mean age is 800-900 years in all three sectors (from any surface source)

Mean age inferred from CFCs and SF6 (Cimoli, Gebbie, Purkey,)



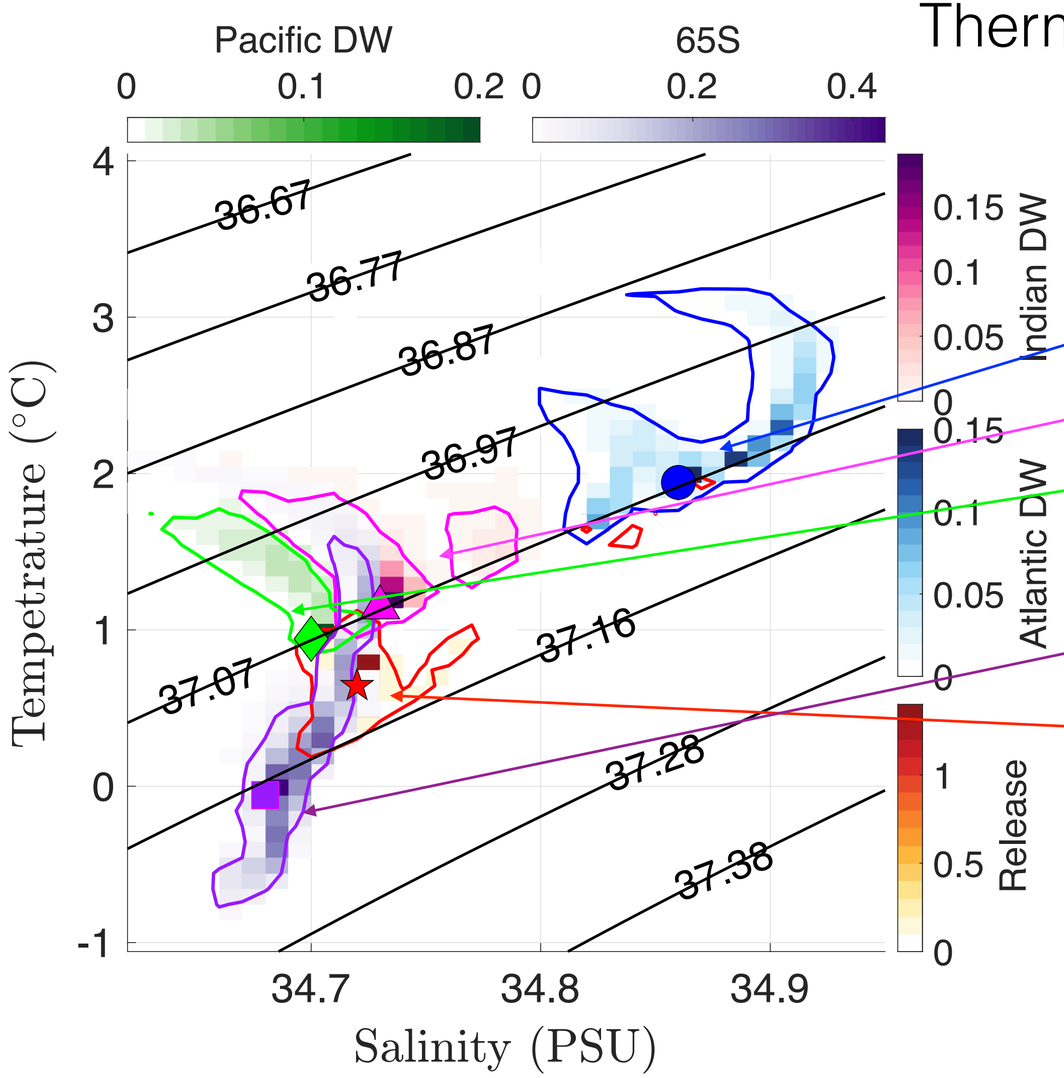
Surface forcing



Arrival time at bottom:

at 30S in Pacific 1990-2020

Thermohaline properties



North Atlantic Deep Water (NADW) originates from Atlantic sector

Indian Deep Water (IDW) originates from Indian sector

Pacific Deep Water (PDW) originates from Pacific sector

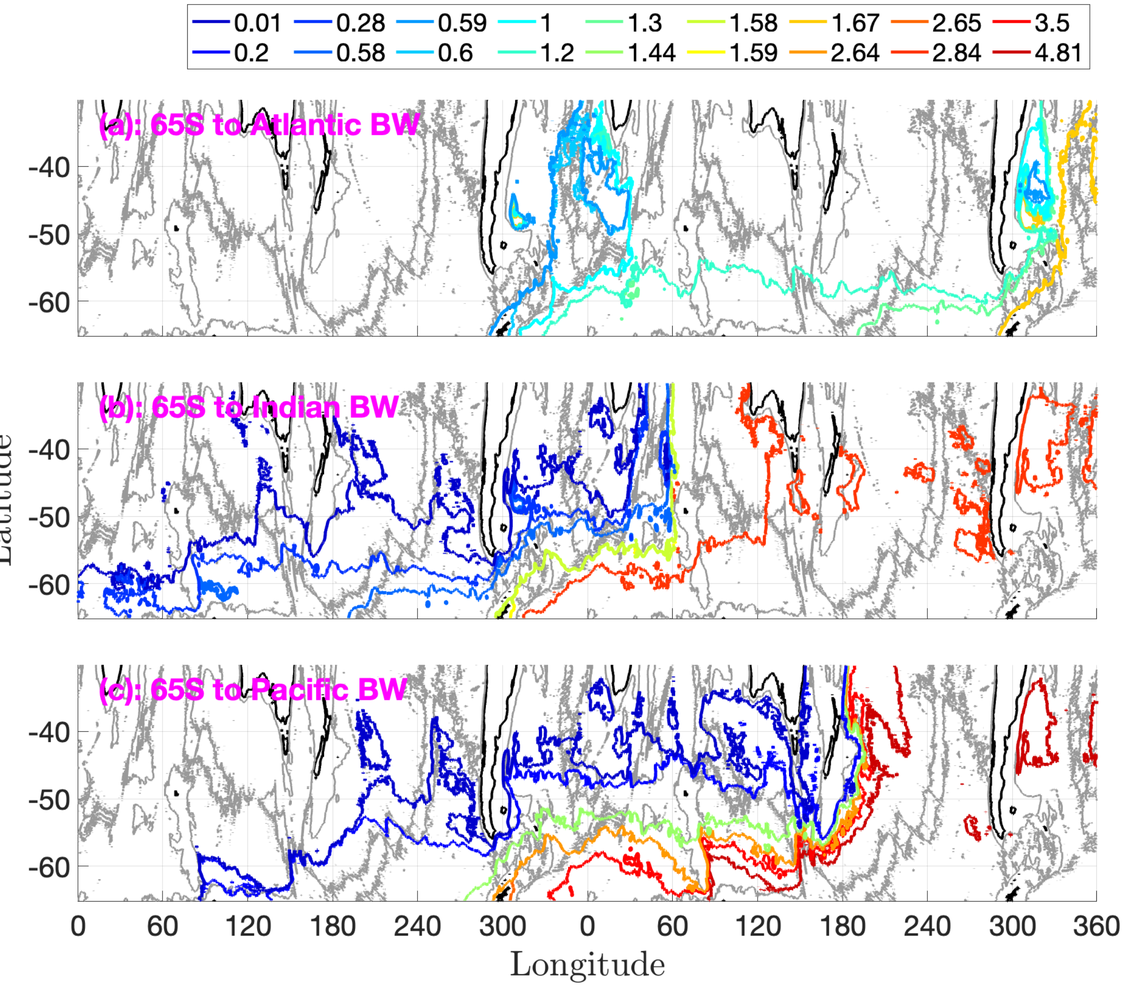
Antarctic Bottom Water (AABW) originates from 65S

Lower Circumpolar Water in the abyssal flow

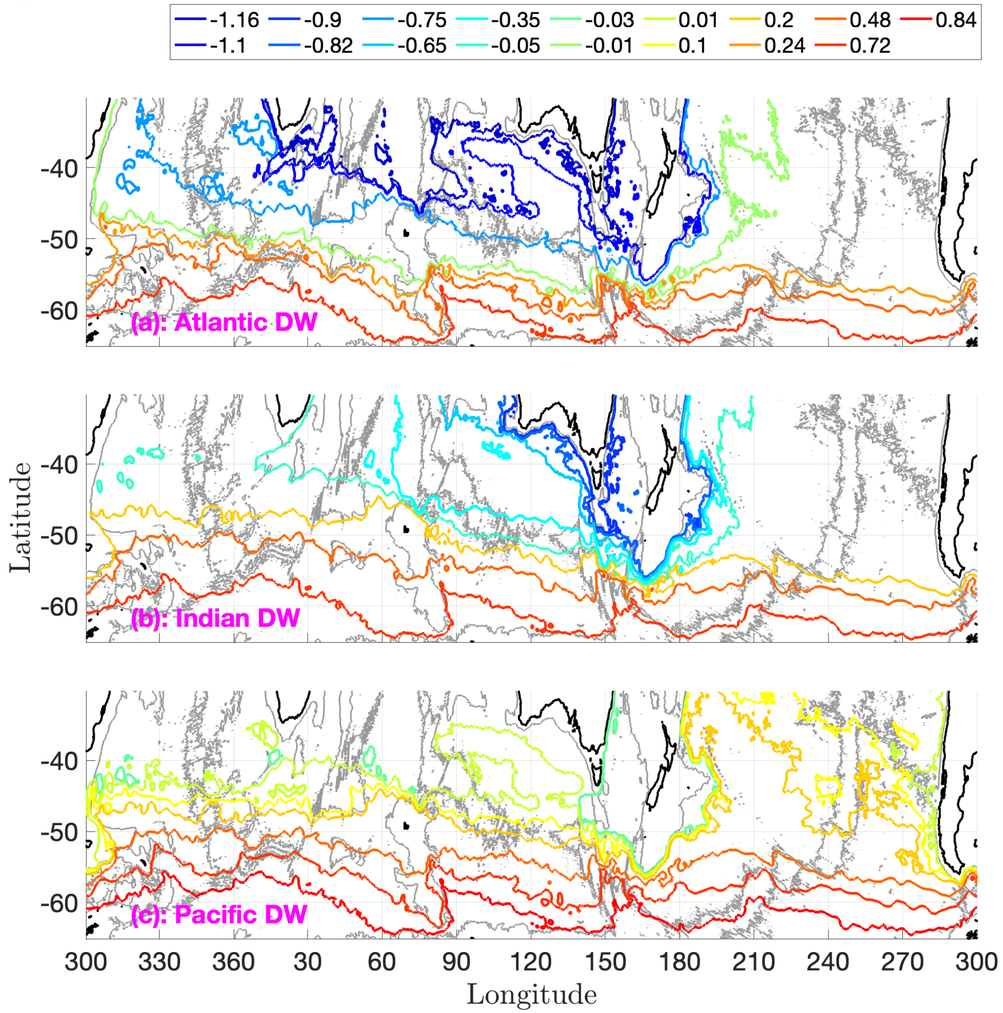
All the water masses get mixed in the bottom flow at 30S, to a mixture close to AABW, IDW and PDW.

NADW is difficult to recognize

The pathways



From 65S to the bottom water at 30S paths are direct



From deep waters at 30S to the bottom water at 30S paths have circumpolar loops
Deep waters are homogenized in a blend

- Lagrangian parcels trace origin of upper branch of meridional overturning circulation in the global ocean;
- In ECCO 48% samples the abyssal Indo-Pacific, with millennial residence times, before rejoining the AMOC;
- The abyssal IndoPacific is visited **before** AABW is formed, and is filled with CDW.
- An additional 20% samples the sub polar cell of the Southern Ocean, with centennial residence times;
- Initial buoyancy gain for all particles is in ACC, with large subsequent gain in Indo-Pacific tropics;
- Still need to account for 7.5Sv of abyssal circulation that do not originate from NADW (future work).

Inset: σ_2 along trajectories