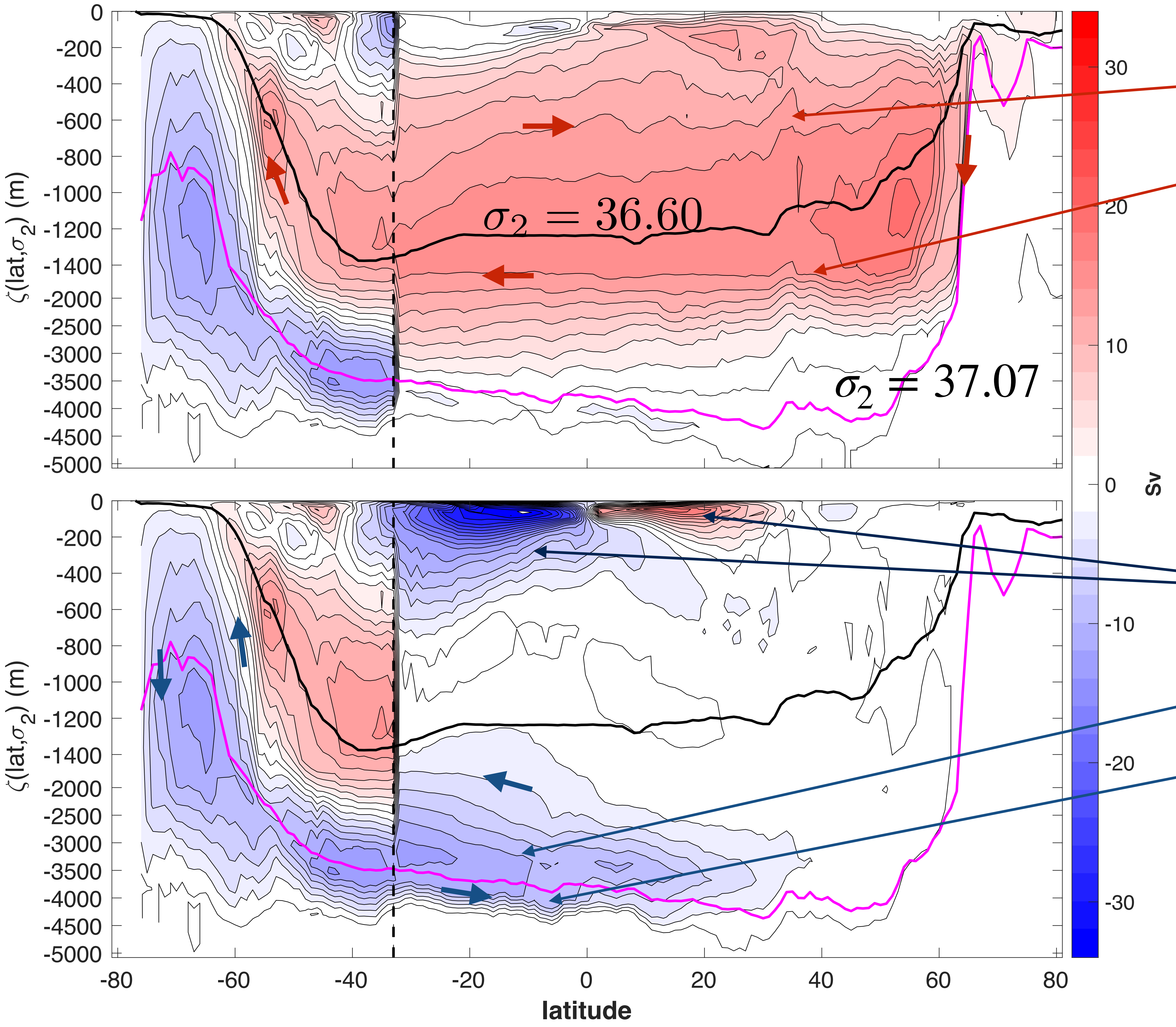
# Global routes of the mid-depth meridional overturning circulation: a Lagrangian analysis

**Louise Rousselet*, Paola Cessi and Gael Forget^**

Scripps Institution of Oceanography
University of California, San Diego
Department earth planetary sciences
^Massachusetts Institute of Technology, Cambridge
*now at Institut Méditerranéen d'Océanologie, Marseille

# 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

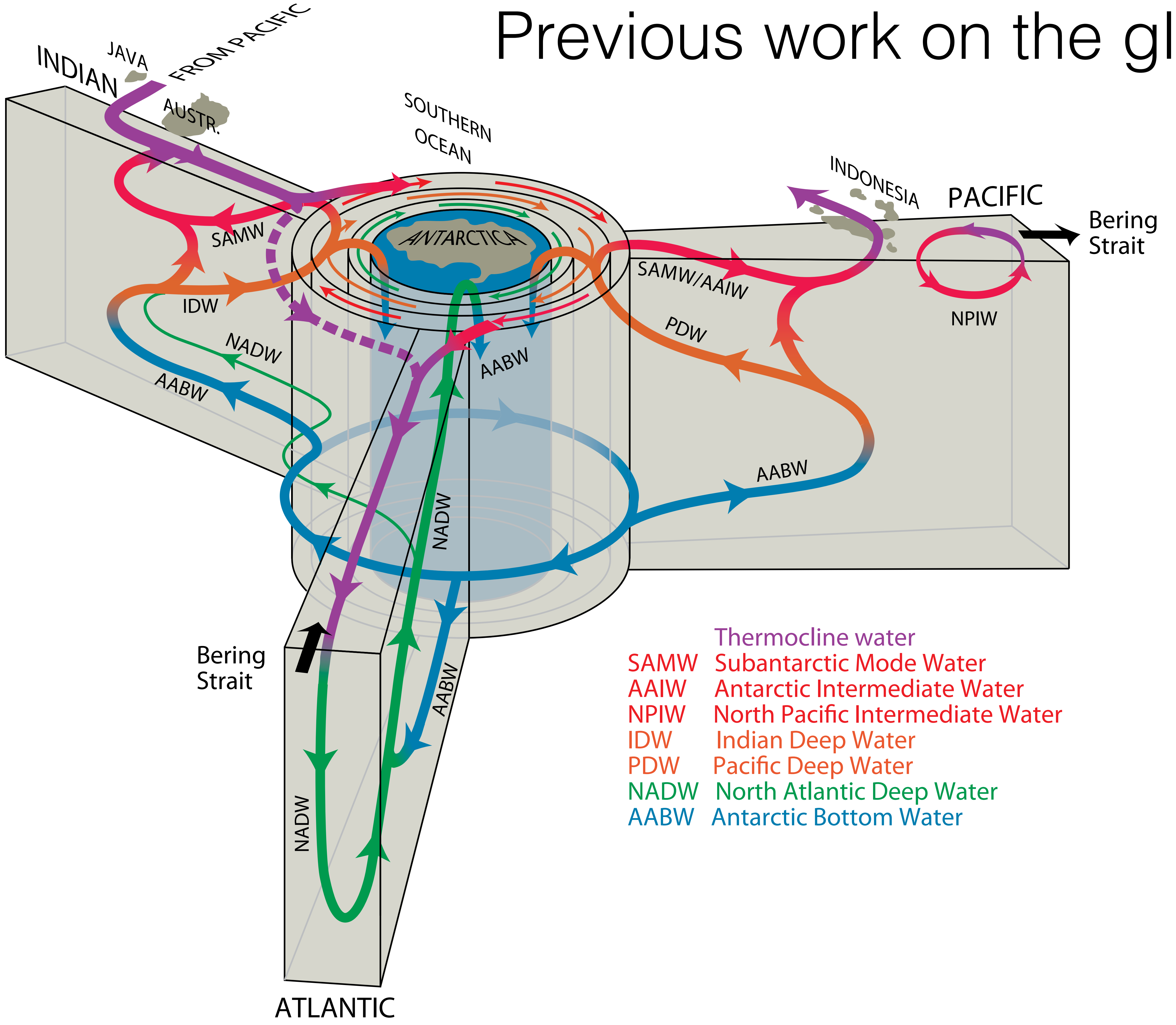
Abyssal cell flow **across** isopycnals

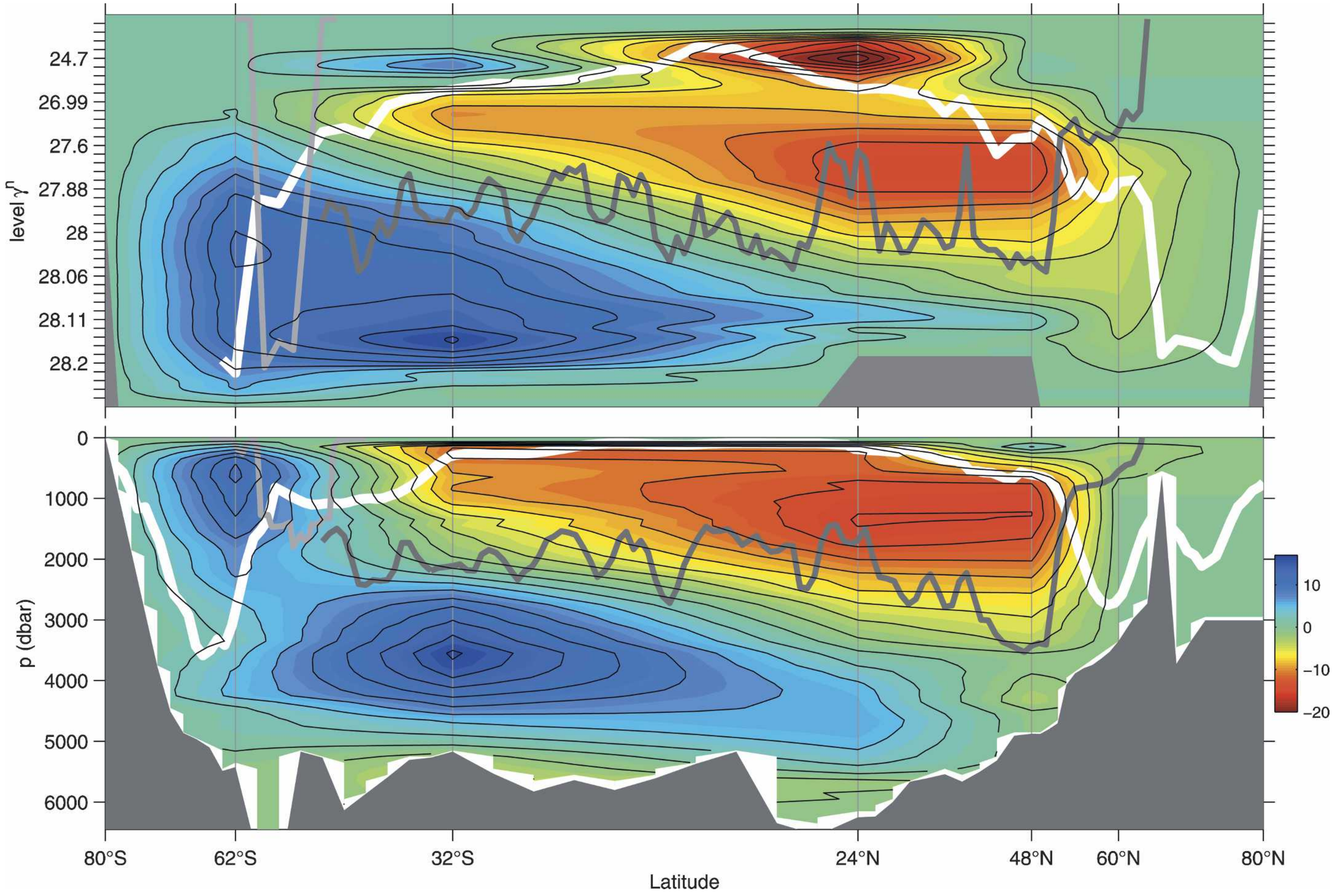
Cells are closed in Southern Ocean and are connected

Zonal integration obscures interbasin exchanges

Rousselet, L. et al, 202. *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 analysis of NADW routes according to ECCOv4

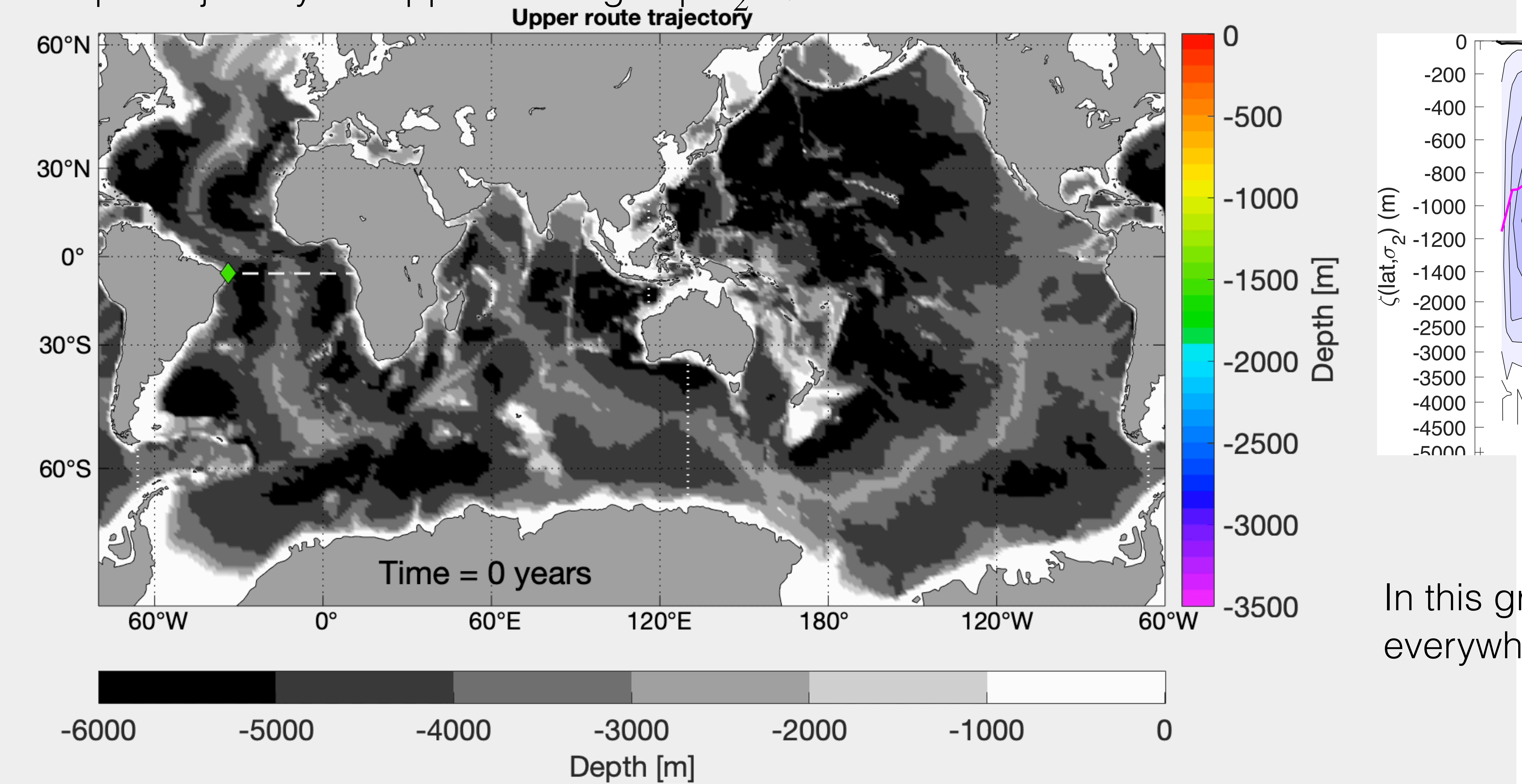
Advect~64000 particles with monthly climatology of ECCO velocity, 1-year periodic, repeated for 8100 years backward in time

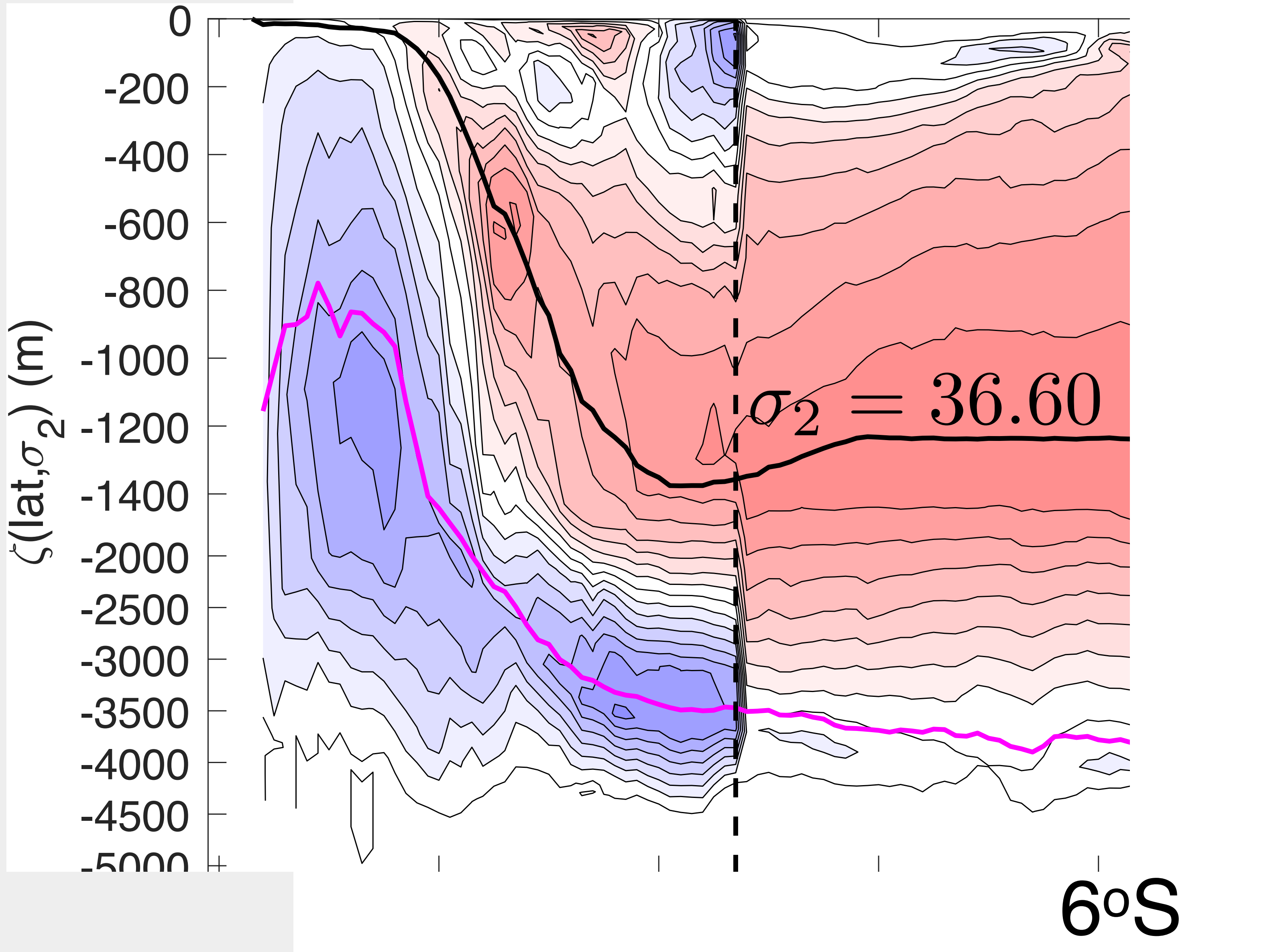
Exit section: **6°S for $\sigma_2 < 36.6$: 13.6 Sv:** upper branch

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

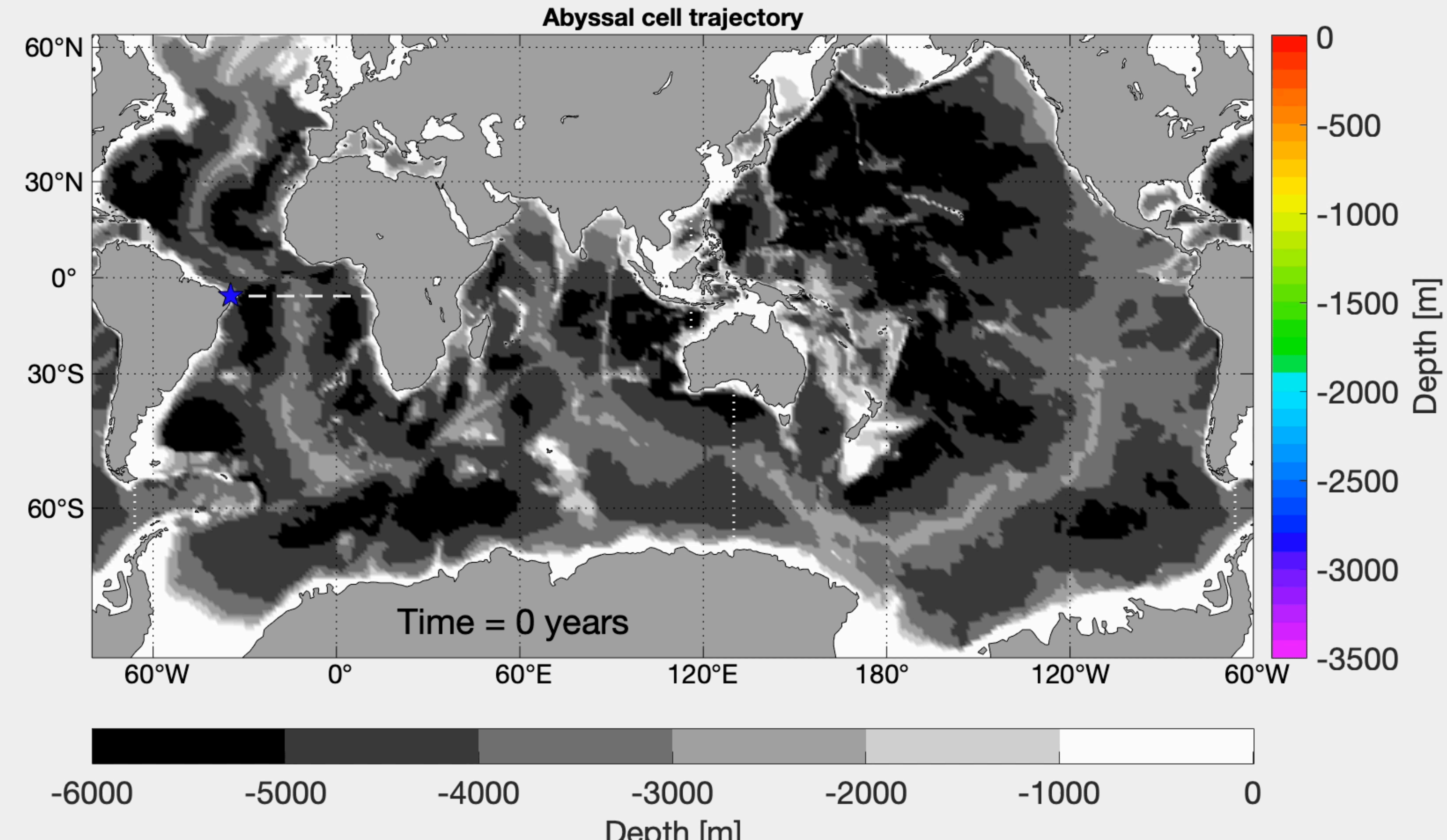
Advect~64000 particles backward in time with monthly climatology of ECCO velocity, 1-year periodic, repeated 8100 years

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

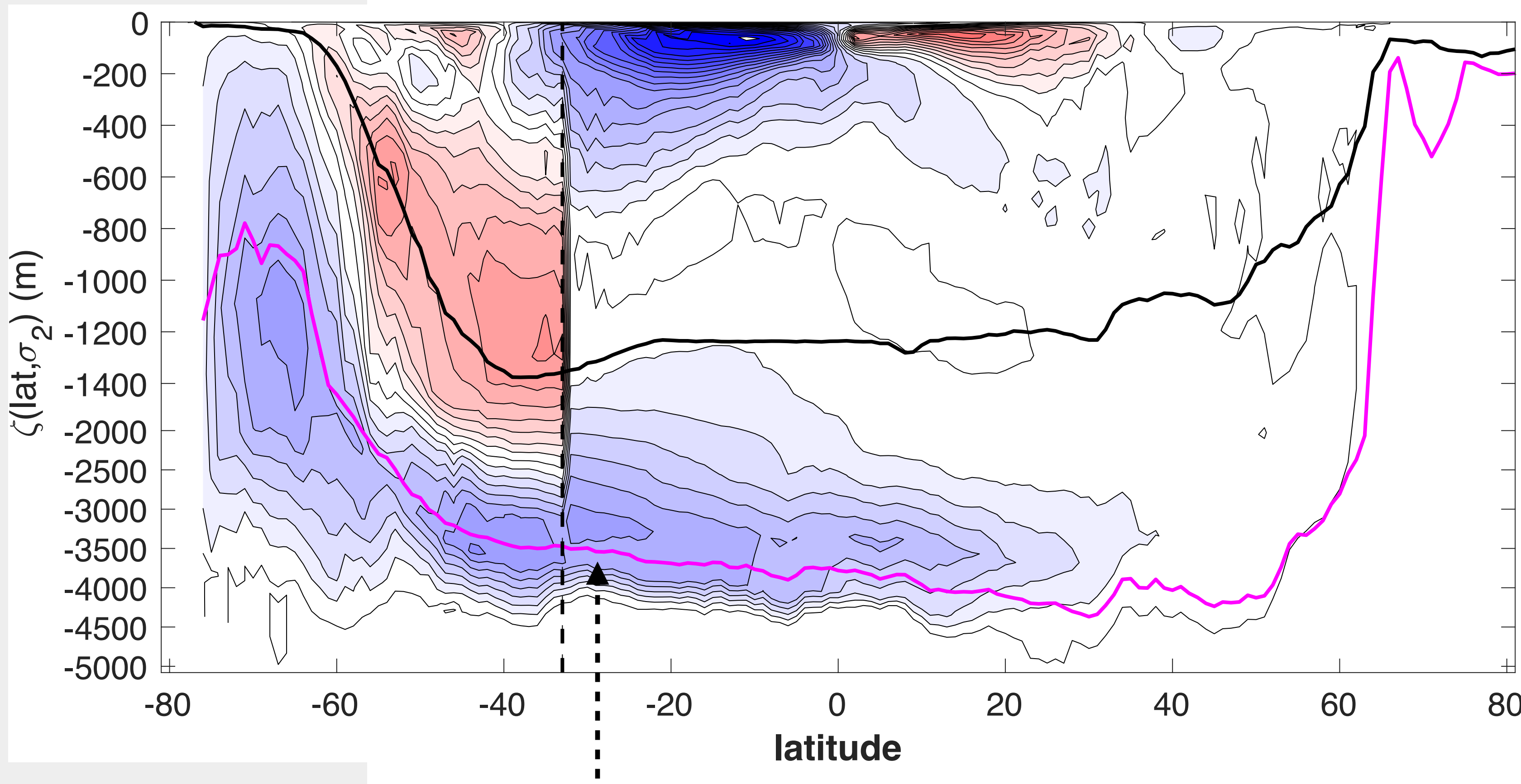
Entry section: **cross 6ºS** for $\sigma_2 \geq 36.6$ **or**
after going through Drake Passage **or**
after going through Tasman Leakage **or**
after going through Indonesian Throughflow

lower branch NADW

Sample trajectory for abyssal IndoPacific group: forward in




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




Abyssal Cell

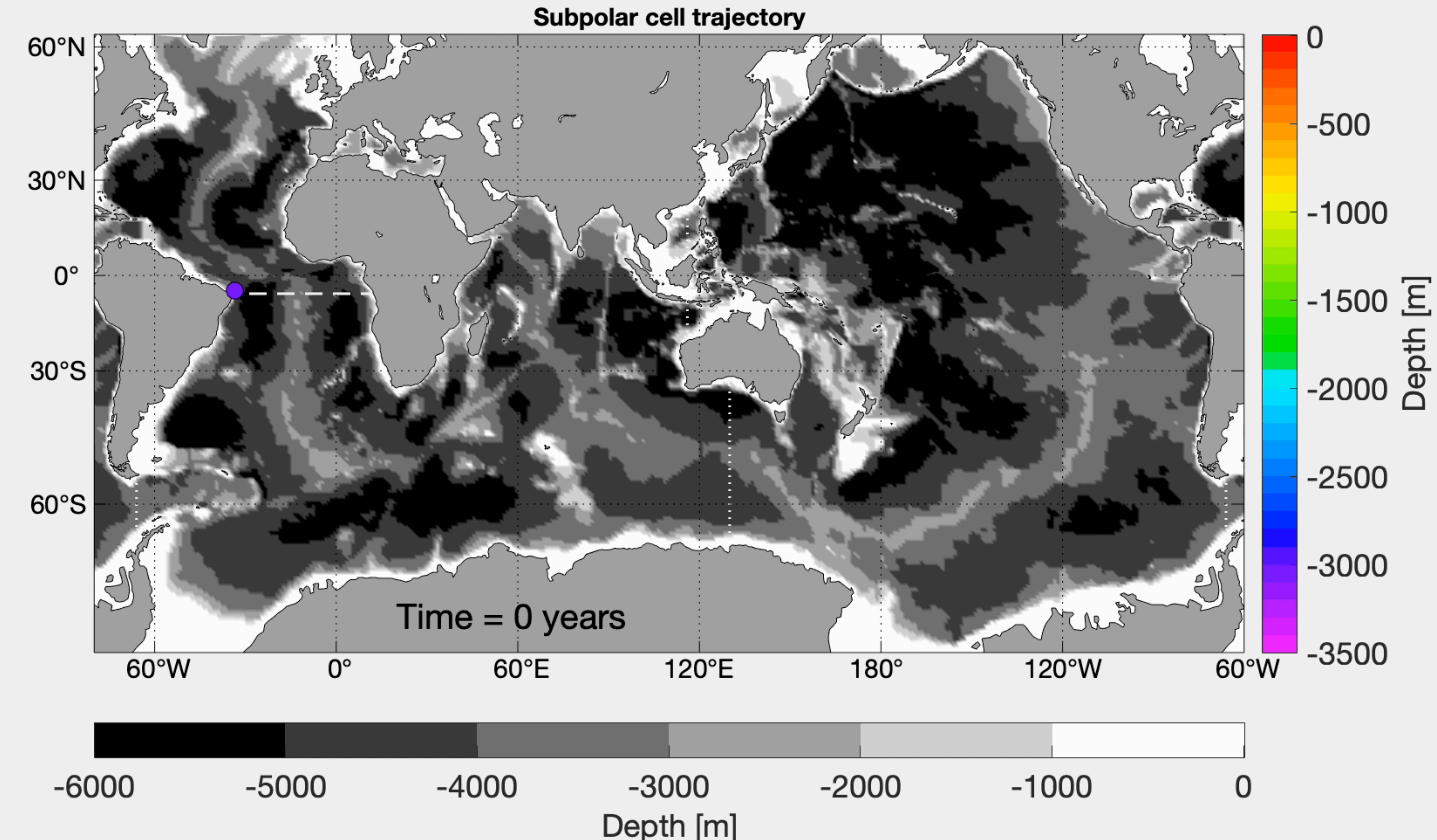
# Lagrangian analysis of NADW routes according to ECCOv4

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

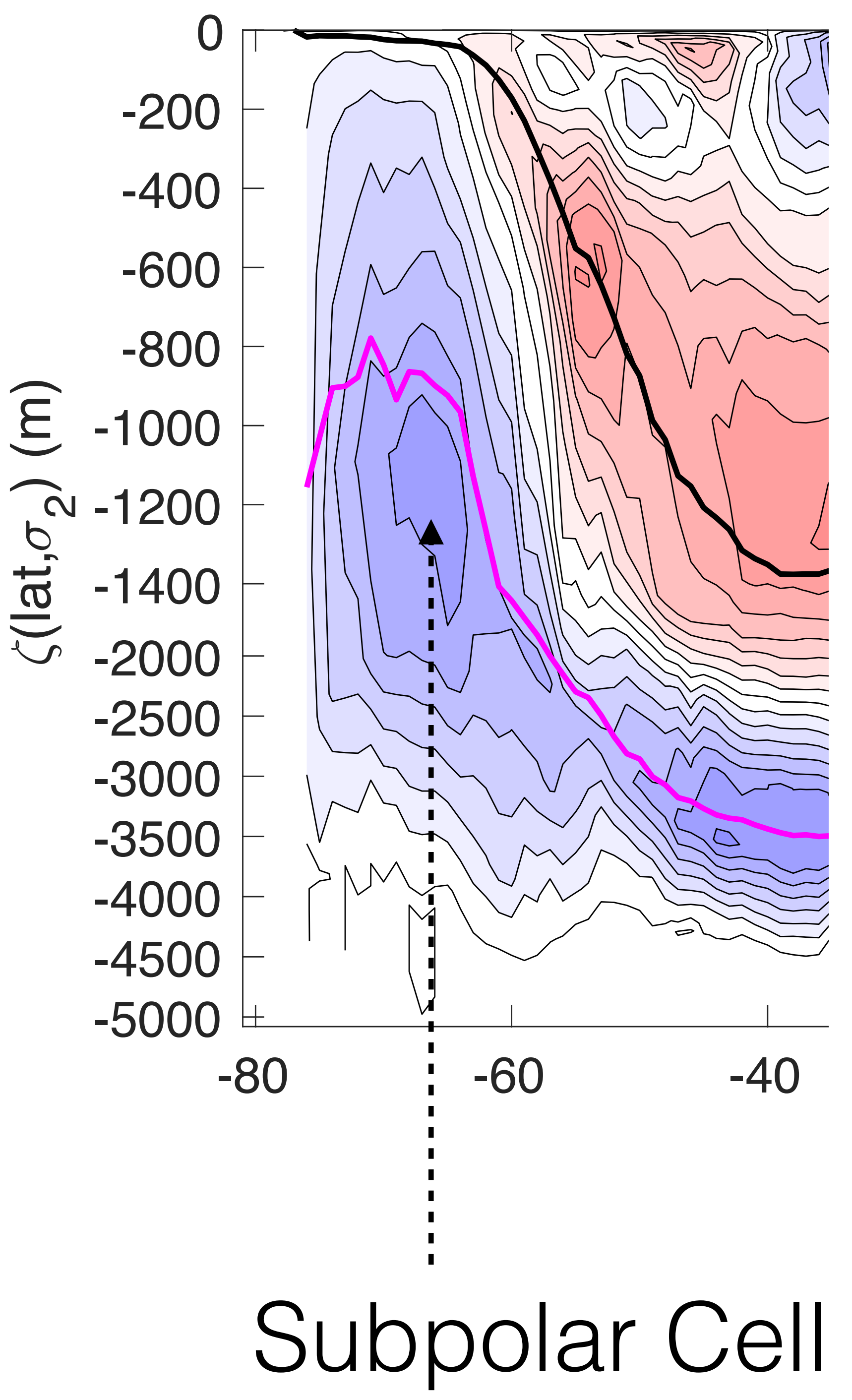
Exit section: **6°S for $\sigma_2 < 36.6$: 13.6 Sv:** upper branch

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

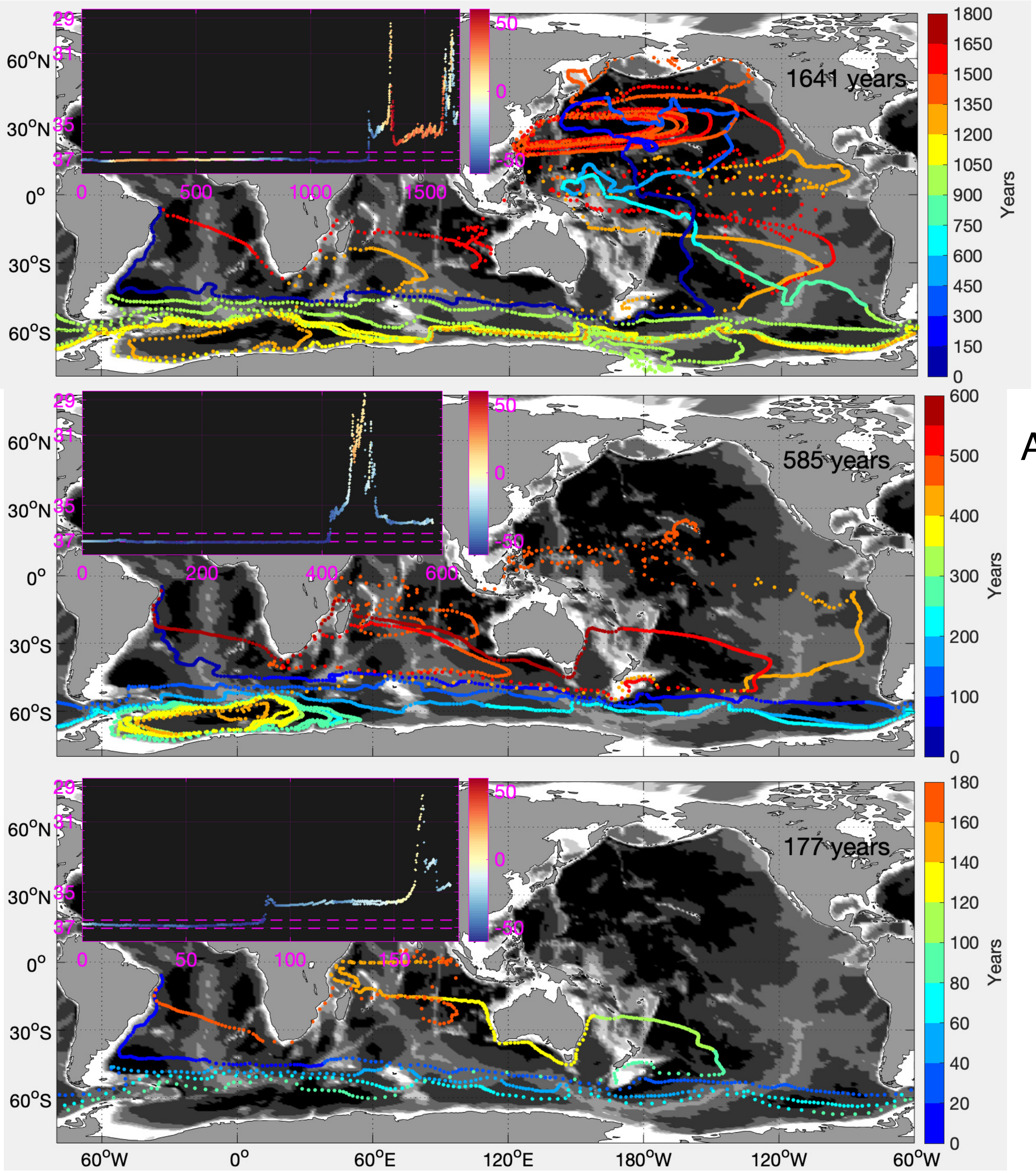
Sample trajectory for Subpolar Cell group: forward in time




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



# 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$^o$S
2. **Subpolar cell 2.7Sv:** cross $\sigma_2 = 37.07$ only south of 30$^o$S
3. **Upper route 4.4Sv:** never cross $\sigma_2 = 37.07$

Representative trajectories for each route (color is time)
$\sigma_2$ is plotted in inset

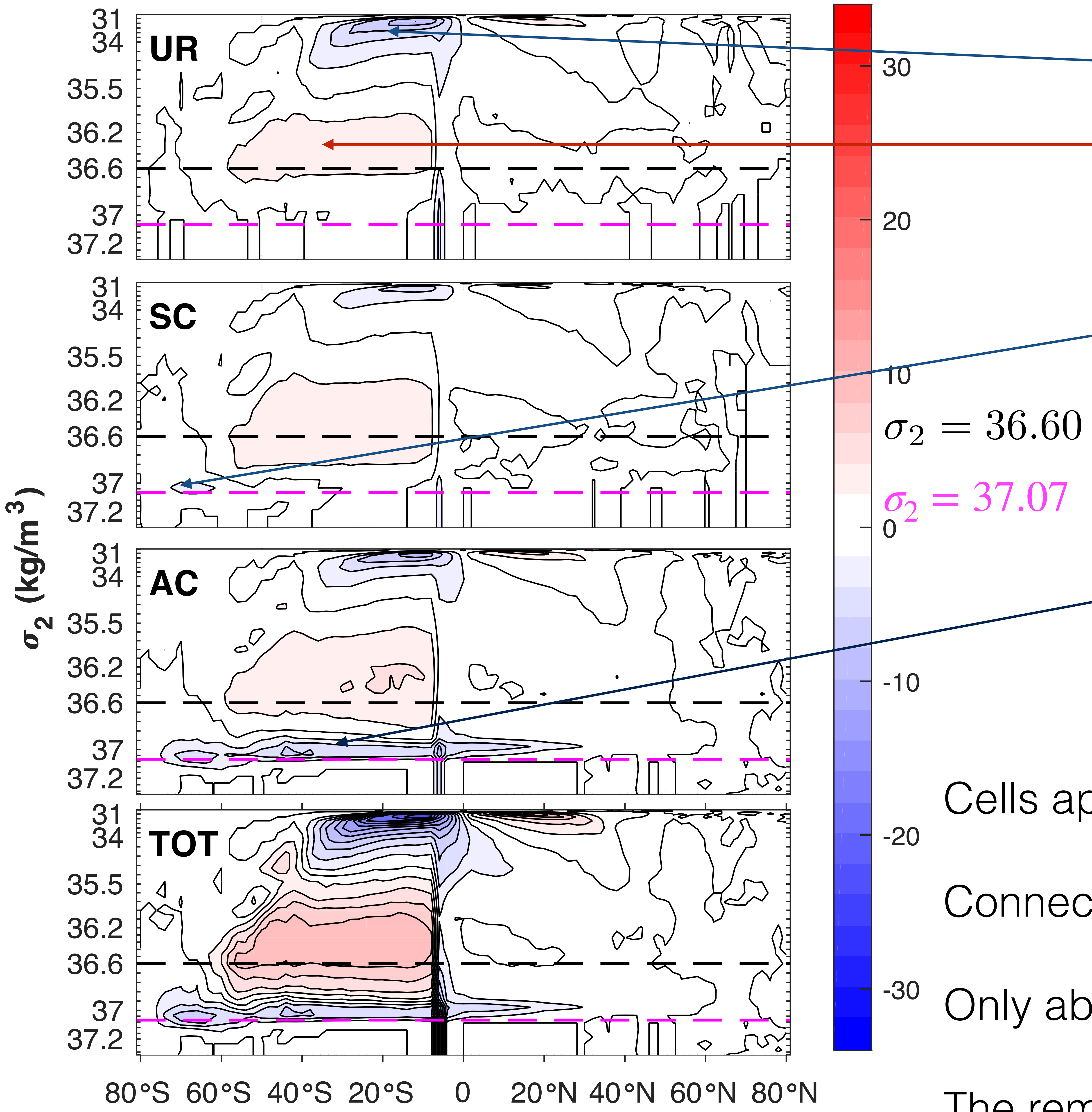
Abyssal cell - 6.5Sv: NADW downwells in northern ACC,
**first** enters abyssal Indo-Pacific as CDW,
then re-enters ACC where it upwells.
Does not sink as AABW

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*

# Zonally integrated and ensemble averaged residual overturning circulation ($\sigma_2$ coordinates)




Integrated over all longitudes

**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

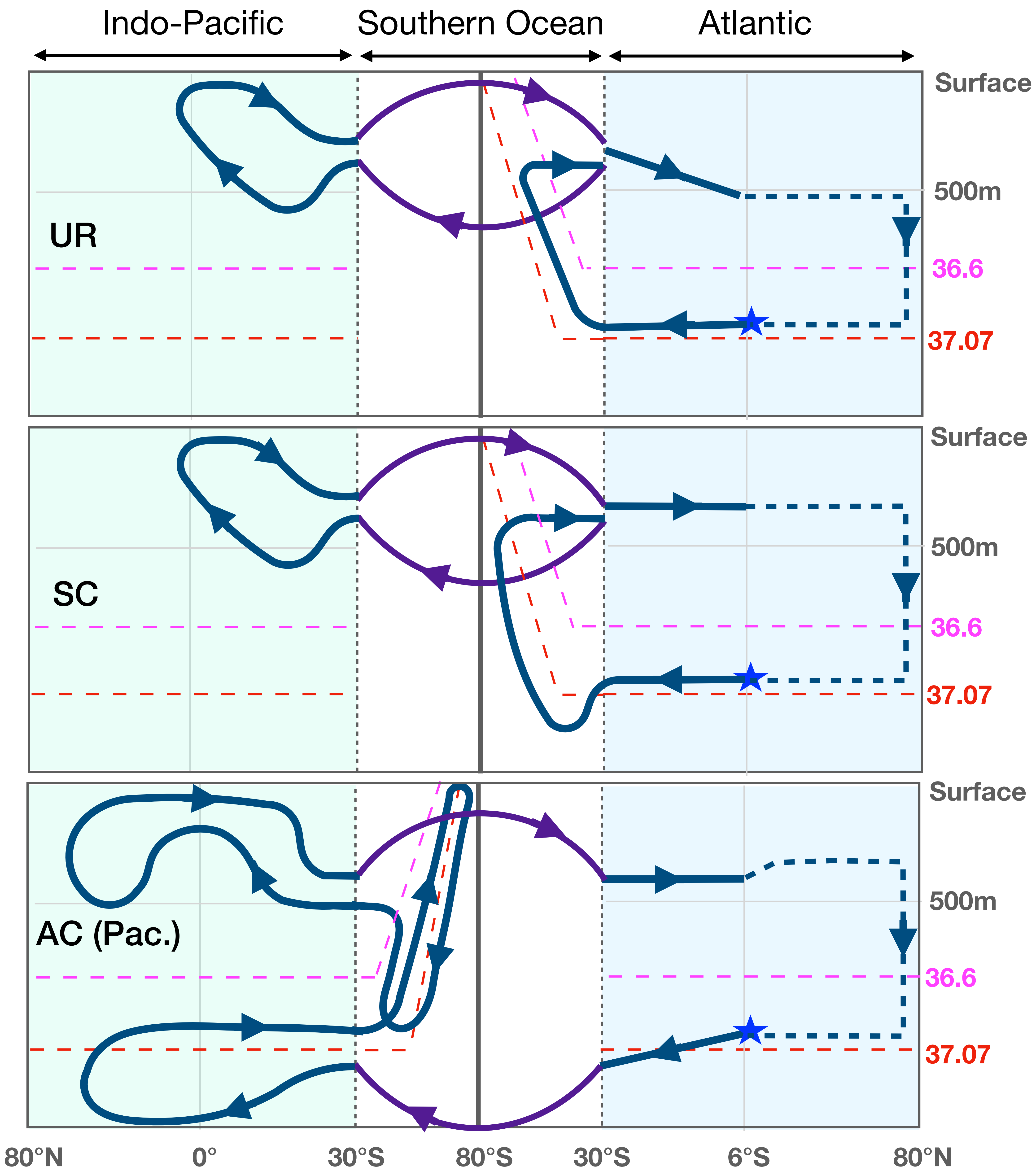
Cells appear separated in the zonal integration

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

# The routes of NADW according to ECCOv4 - schematic




**Upper route:** NADW upwells in ACC,flows around ACC, gyres, upwells again in tropical Indo-Pac., enters S.Atl. from Aghulas

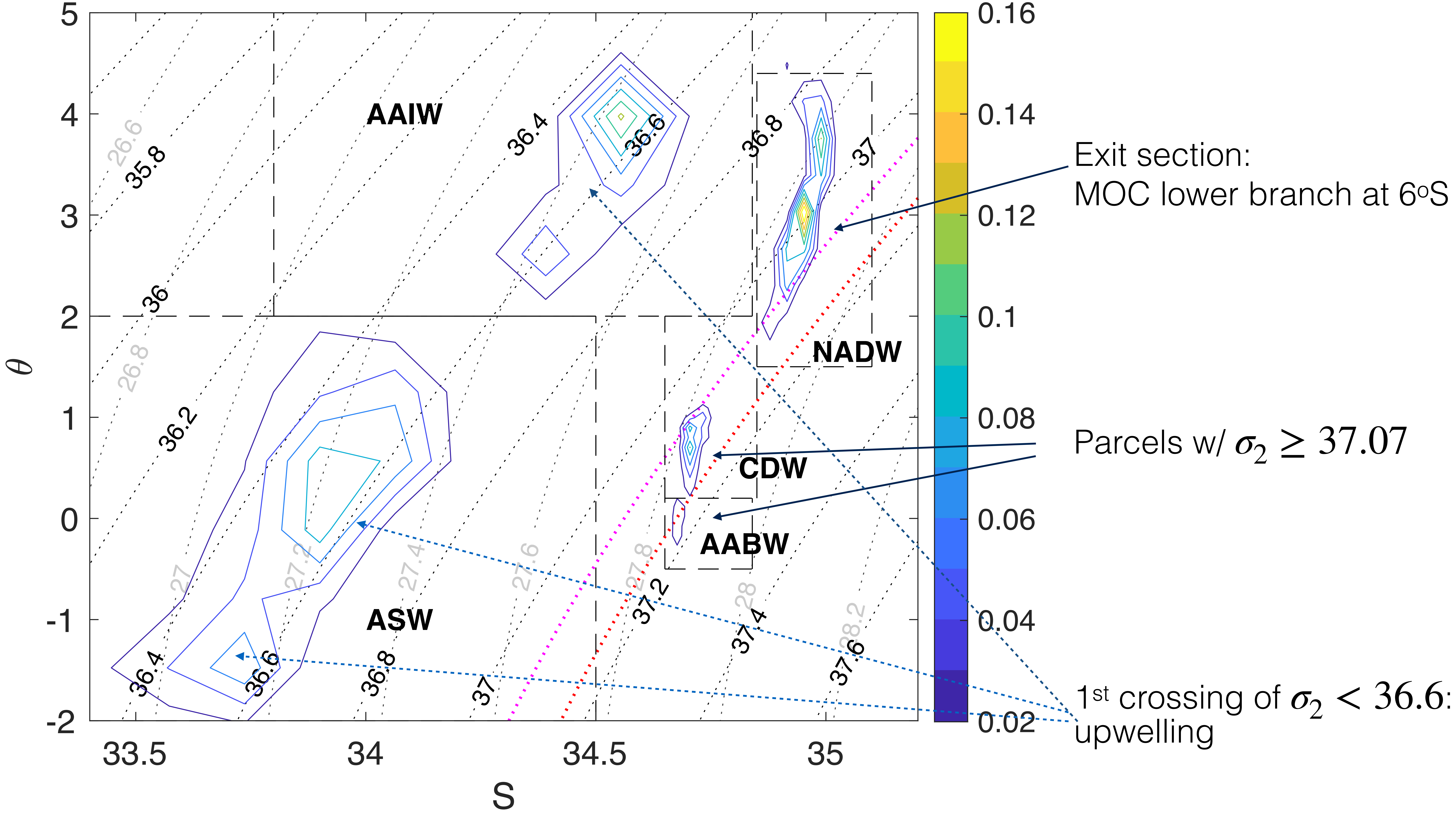
**Subpolar cell:** NADW downwells in ACC, flows around Weddell and Ross gyres, where it also upwells, following the upper route thereafter. Qualitatively similar to UR, except for an excursion in Weddell and Ross gyres

**Abyssal cell:** NADW downwells in ACC, enters **first** abyssal Indo-Pacific, re-enters ACC where it upwells, downwells, then follows upper route.

The abyssal Indo-Pacific is not visited by directly formed AABW

Rousselet, L. & Cessi, P., 2022. *J. Phys. Oceanogr.*

# Parcels conditional histograms in T-S space

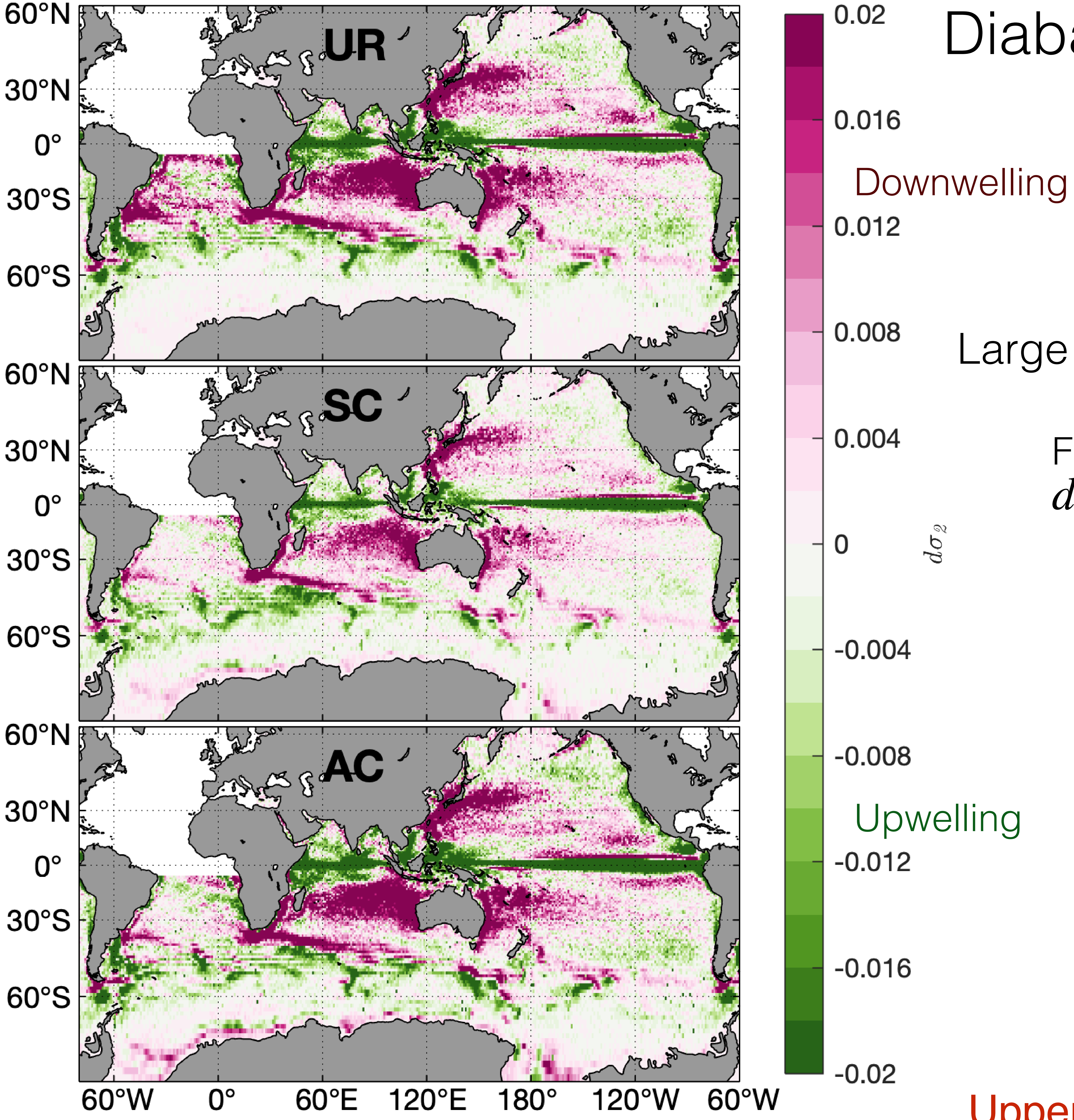



Majority of abyssal water is CDW not AABW: topography and ACC confine AABW

# Diabatic changes along trajectories

$$\frac{d\sigma_2}{dt} = \frac{\partial \sigma_2}{\partial \theta}\bigg|_S \dot{\theta} + \frac{\partial \sigma_2}{\partial S}\bigg|_\theta \dot{S}$$

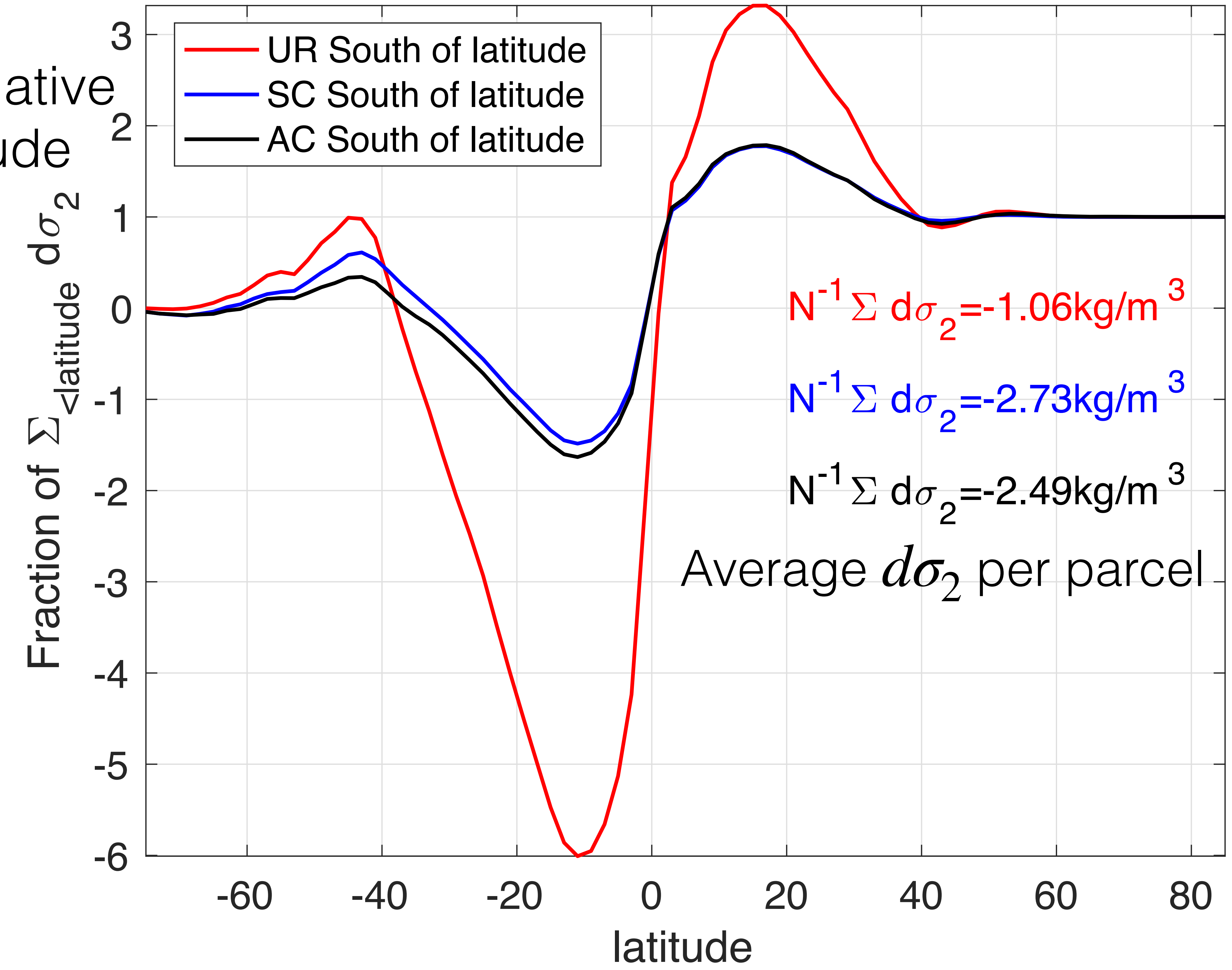
Sources/sinks for $\theta$ and $S$




Vertically averaged $d\sigma_2$ in lat-lon bins

Large diabatic changes in the basin regions: **upwelling** near equator

Fraction of cumulative $d\sigma_2$ south of latitude




Upper route is not so adiabatic outside of Atlantic basin!

All particles sample the surface in the wind-driven gyres

Rousselet, L. & Cessi, P., 2022. *J. Phys. Oceanogr.*

- 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: $\sigma_2$ along trajectories