# Eddies role in Lagrangian pathways in the Southern Ocean

Manuel Othón Gutiérrez Villanueva

Theory Seminar

Spring Quarter 2019

June 7, 2019

# Outline

1. 3D upwelling pathways of deep water masses in the SO (Tamsitt et al. 2017, Nature communications).
   - Role of bottom topography and eddies.

2. Does the eddy field strength affect the upwelling timescales of deep waters? (Drake et al. 2018).
   - Lagrangian (upwelling and spiraling) timescales in a hierarchy of model resolution.

3. Transformation of Deep Water Masses along Lagrangian upwelling pathways in the SO (Tamsitt et al. 2018, JGR-Oceans).
   - How deep water transforms along the SO.
   - Where diapycnal mixing is important along the Lagrangian pathways.

4. Discussion

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3. Transformation of Deep Water Masses along Lagrangian upwelling pathways in the SO (Tamsitt et al. 2018, JGR-Oceans).
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4. Discussion

# 1. 3D upwelling pathways of deep water masses in the SO (Tamsitt et al. 2017, Nature communications).

nature COMMUNICATIONS

ARTICLE

DOI: 10.1038/s41467-017-00197-0 OPEN

## Spiraling pathways of global deep waters to the surface of the Southern Ocean

Veronica Tamsitt[1], Henri F. Drake[2,6], Adele K. Morrison[2,7], Lynne D. Talley[1], Carolina O. Dufour[2], Alison R. Gray[2], Stephen M. Griffies[3], Matthew R. Mazloff[1], Jorge L. Sarmiento[2], Jinbo Wang[4] & Wilbert Weijer[5]

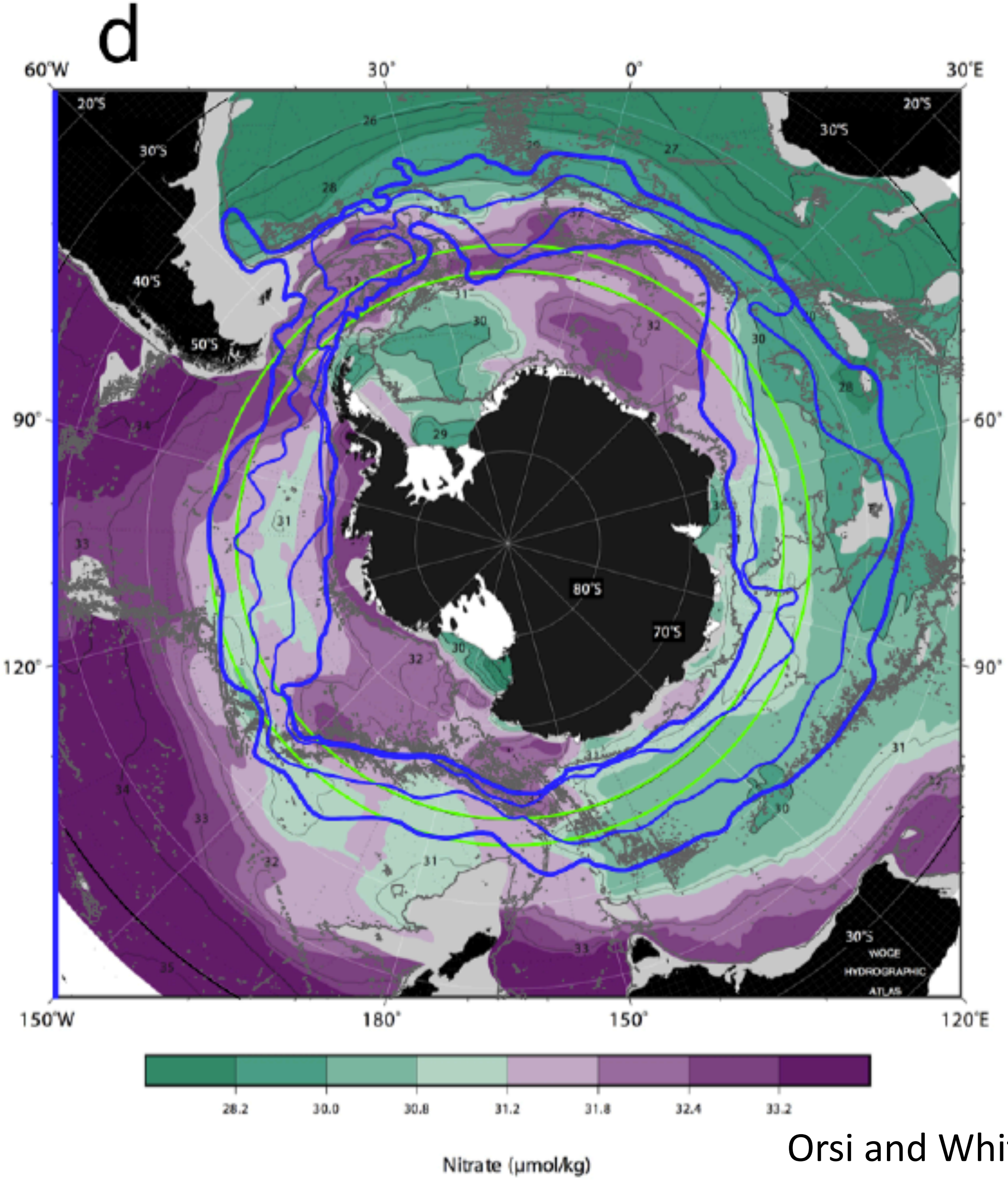
# Motivation

The specific geographic locations where deep waters return back to the surface in the Southern Ocean and the mechanisms related to this deep water return are poorly known.

The southeastward spiraling pathways of deep waters around Antarctica from its northernmost latitude to the continental margin has not been widely explored.

The paper tackles the following:

- Where does enhanced upwelling occurs?
- What are the upwelling time scales?
- How much does each major basin (Pacific, Atlantic and Indian) contribute to upwelled waters in the Southern Ocean?




Orsi and Whitworth (2005)

# Methods

## a) Models and state estimate

| | CM2.6 GCM | CESM GCM | SOSE (state estimate) |
|---|---|---|---|
| | High-resolution version of GFDL's CM2-0 coupled model | High-resolution coupled GCM | Data-assimilating, ocean general circulation model. Based on MITgcm. |
| **Resolution** | Global 1/10º ocean and sea ice models.<br>50 km for atmosphere and land models | Nominal 1/10º ocean (POP2) and sea-ice (CICE; Los Alamos NL).<br>1/4º atmosphere and land. | 1/6º from 24.7º S to 78º S with open northern boundary and sea-ice model. |
| **Parameterizations** | No eddy parameterization | No eddy parameterization | No eddy parameterization |
| **Output length (time)** | 12 years | 20 years | 6 years (2005-2010) |
| **Temporal resolution** | 5-day averaged velocity fields | Monthly averaged velocity fields | Daily averaged velocity fields |

# Methods

## b) Lagrangian methods (CESM and CM2.6)

| Code name | Connectivity Modeling System (Paris et al., 2013) |
|---|---|
| OGCMs supported | HYCOM, OFES, NEMO, SOSE, MOM, MITgcm |
| Language | Fortran |
| Advection method | Runge-Kutta 4 in time; tricubic in space |
| Diffusion method | Brownian motion for background diffusion, random displacement within the mixed layer. |
| Primary usage | Dispersion, connectivity, fate of pollutants. |
| Shortcomings | No support for non-orthogonal grids. |

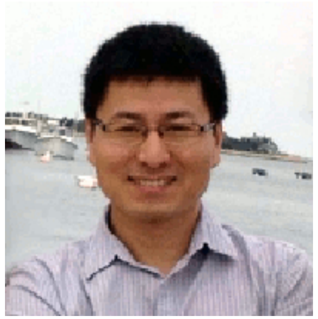
*Claire Beatrix Paris*

# Methods

## b) Lagrangian methods (SOSE)

| Code name | Octopus |
|---|---|
| OGCMs supported | MITgcm; any C-grid |
| Language | Fortran |
| Advection method | Runge-Kutta 4 in time; trilinear in space |
| Diffusion method | Brownian motion for background diffusion with random displacement or randomly added velocities. |
| Primary usage | 3D water mass pathway, particle/tracer dispersion, cross-frontal transport, Argo float simulation. |
| Shortcomings | Not very efficient in reading large model output.<br>Not very user friendly (no manual, just the code “as it is”). |

*orianapoindexter.com*



*Jinbo Wang*

# Methods

**b) Lagrangian methods**

- >2.5 x $10^6$ particles released at 30º S from 1000 – 3500 m.

- Re-released at same location every month for the duration of the model output.

- Time step for particle advection: 1 hr (12 hrs) for CM2.5 and CESM (SOSE).

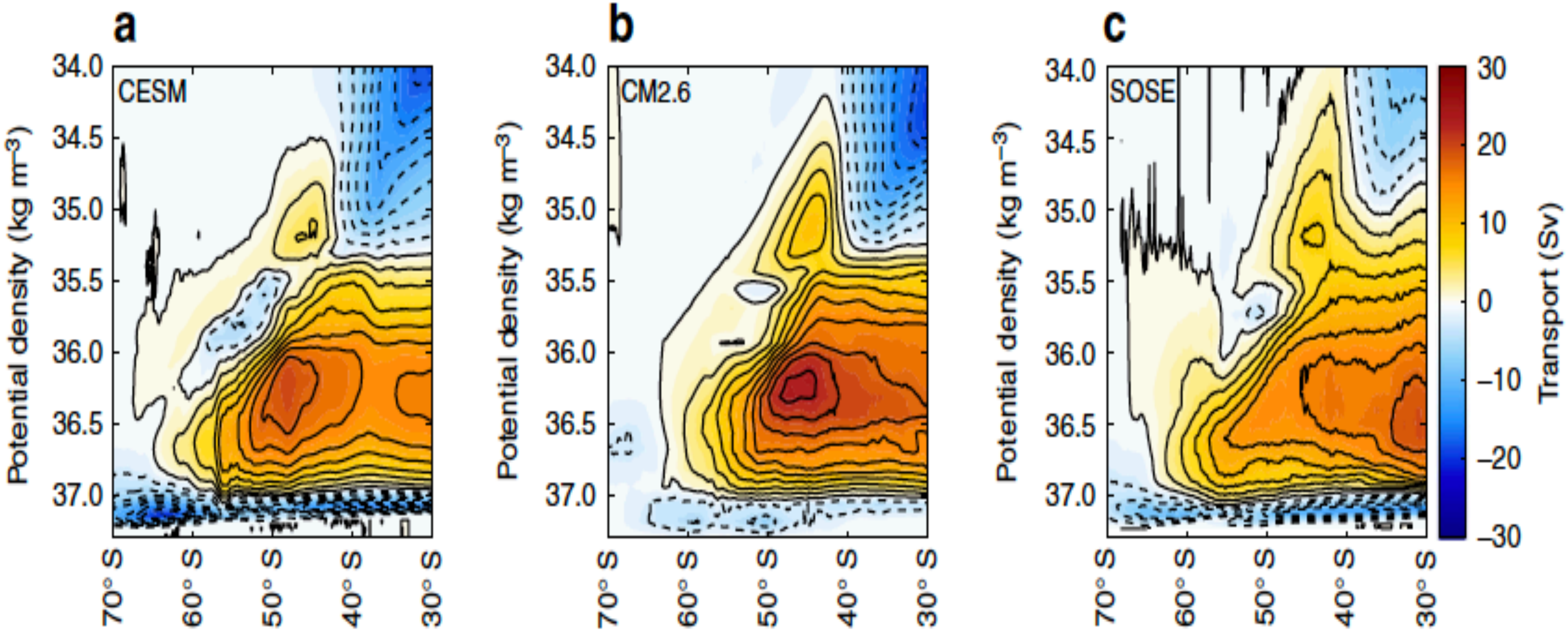
- Trajectories integrated for 200 years, looping through the model.
  - Particles were retained if they reach the mixed layer and remain south of 30º S.

- Each particle is assigned with the meridional volume transport when released.

# Results

## Model comparisons

Southern Ocean zonally averaged circulation (MOC)

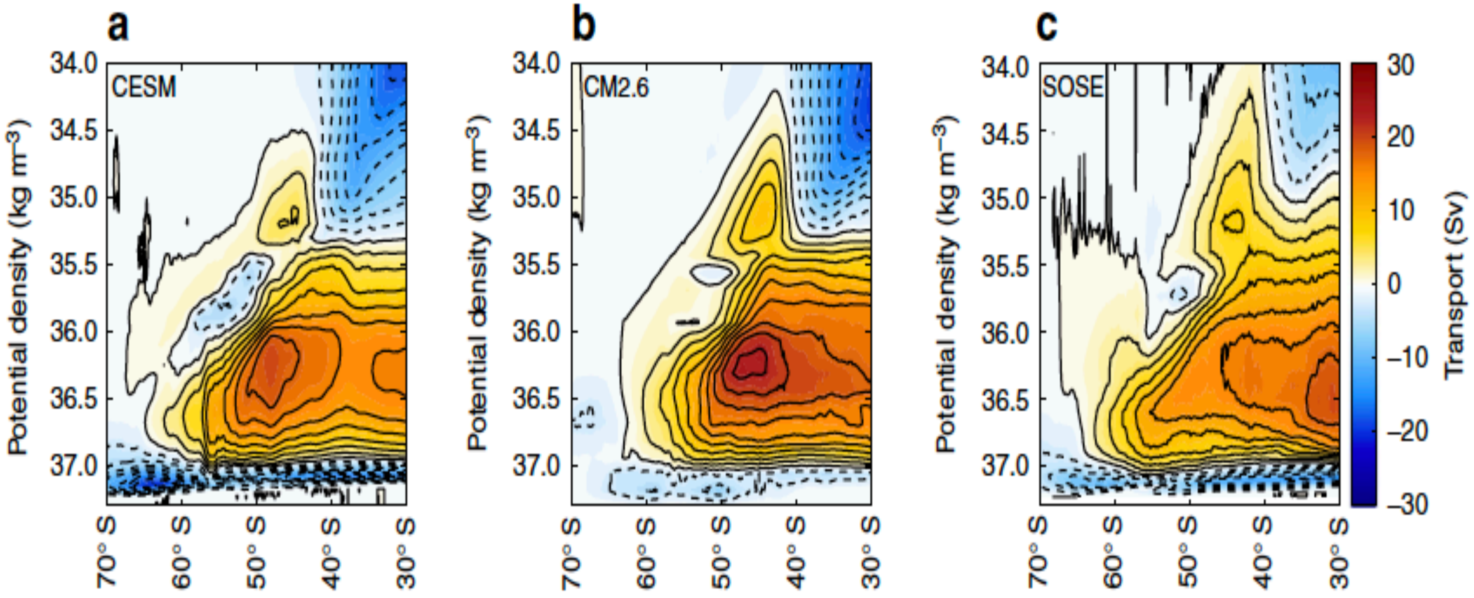



MOC structure is similar in the 3 models.
CESM shows the strongest abyssal cell, whereas CM2.6 has the strongest upper cell.

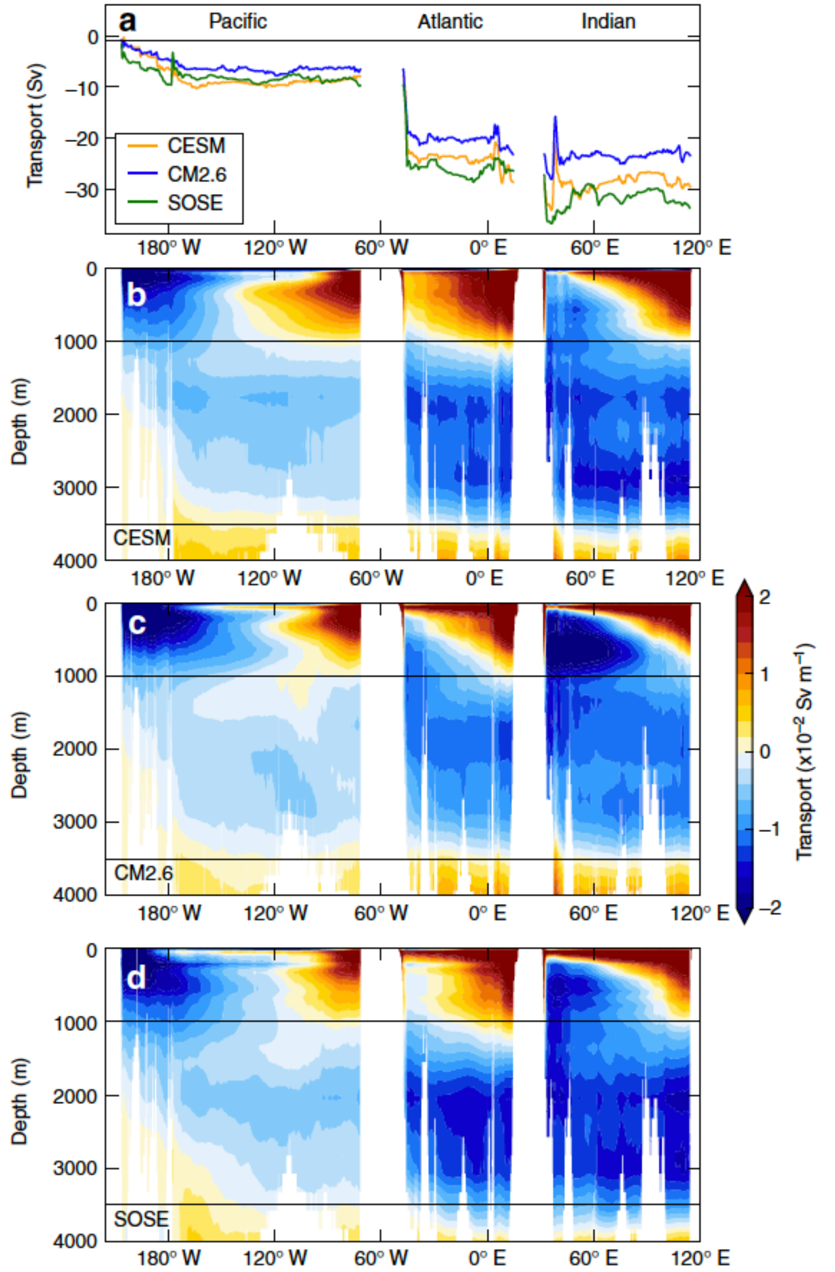
# Results

## Model comparisons

Southern Ocean zonally averaged circulation (MOC)




Time-mean meridional volume transport at 30º S

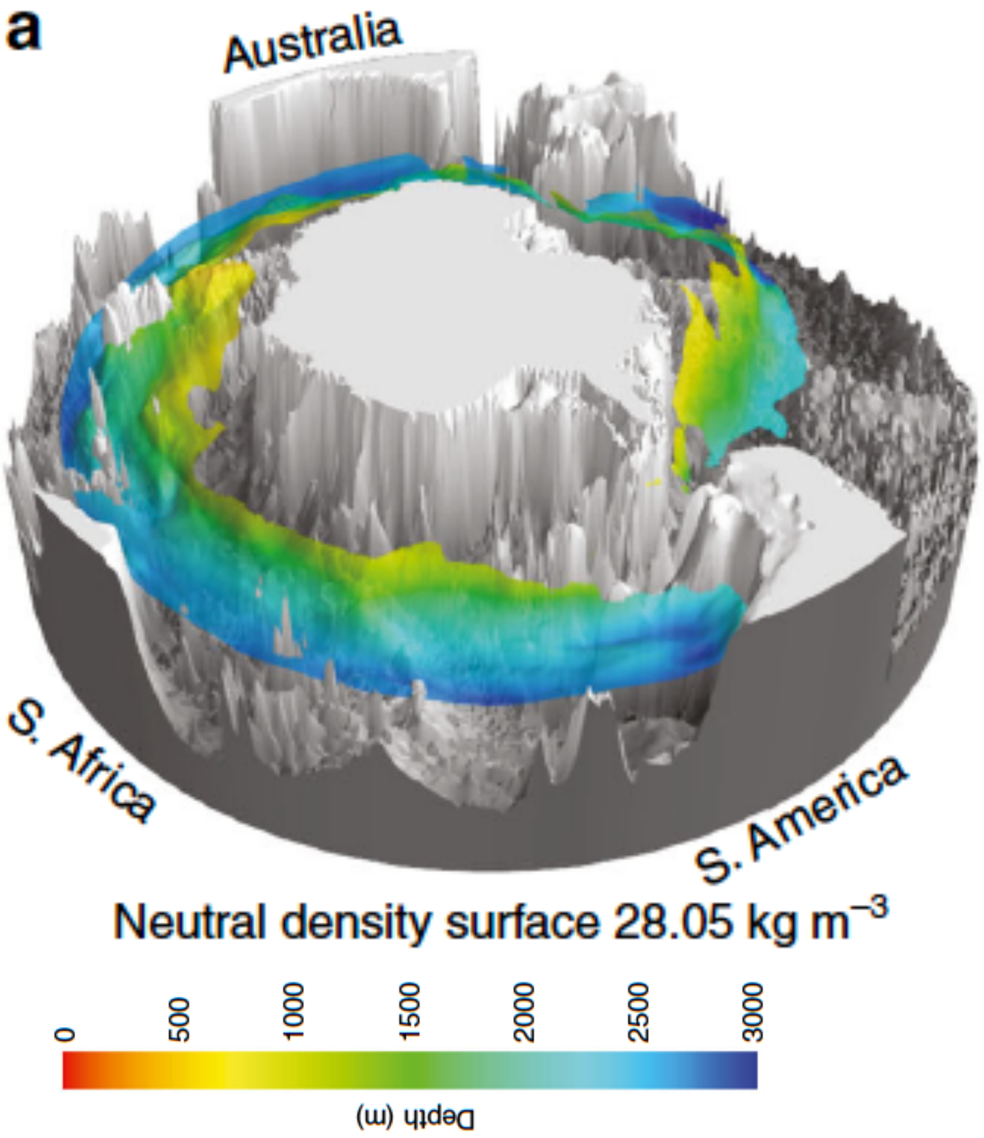


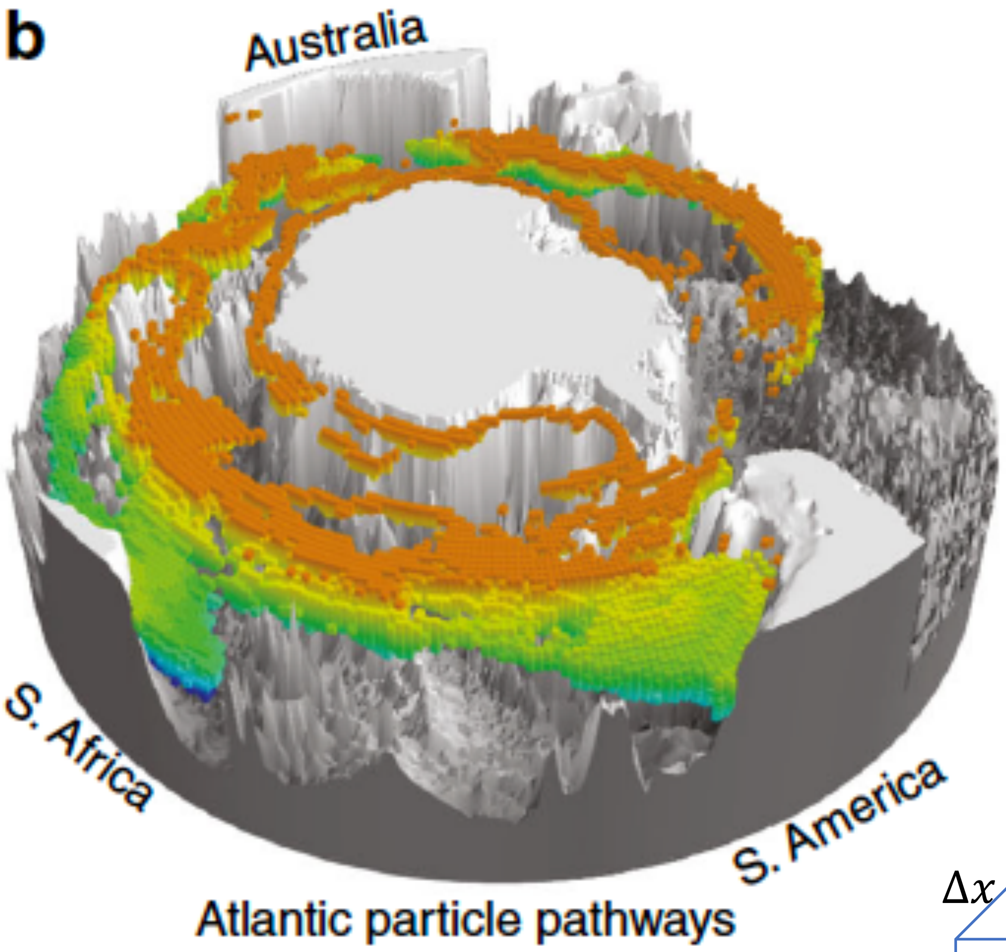

Similar zonal structure of the meridional volume transport at 30º S (integrated from 1000– 3500 m).

SOSE shows the largest volume transport in the Atlantic and Indian Ocean.

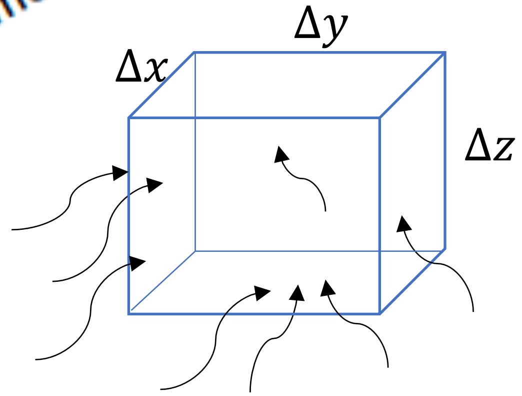
# Results

## Spiraling pathways



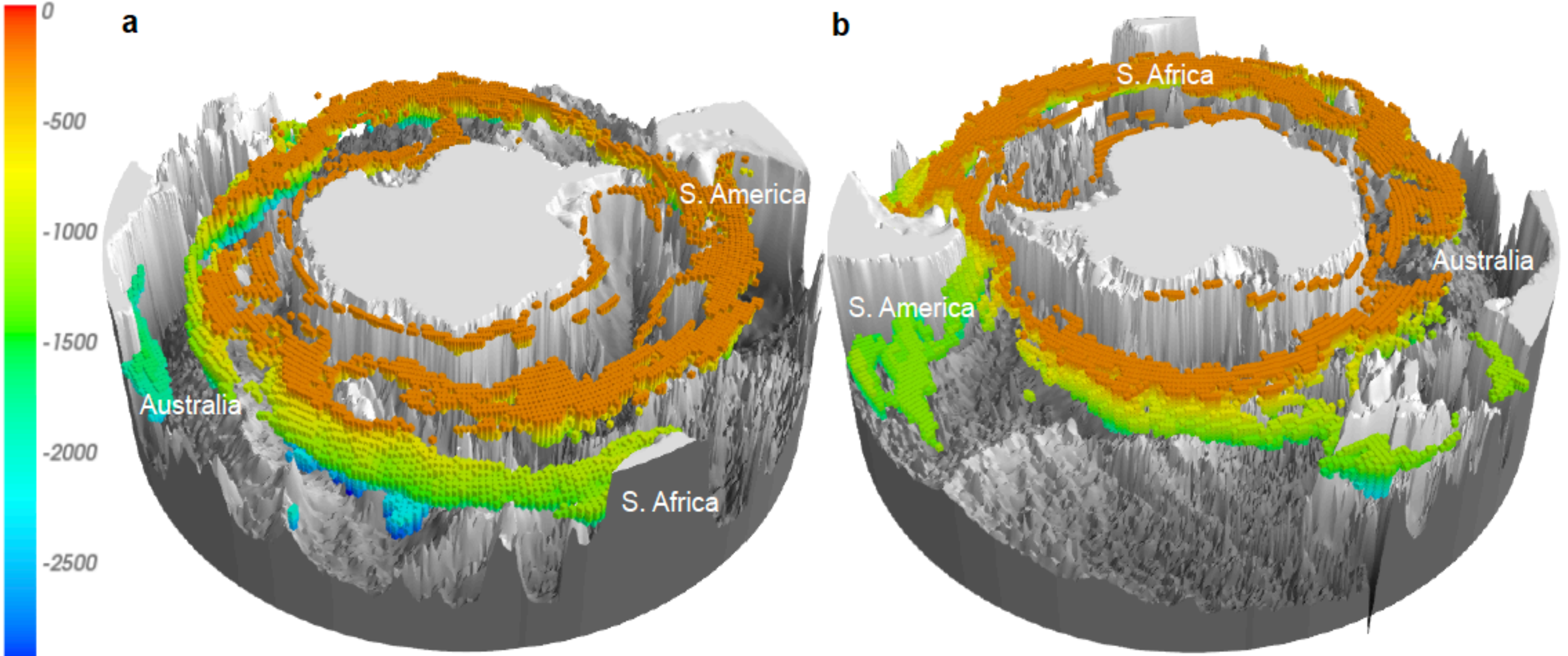




**b**. 1º lon x 1º lat x 100 m depth grid boxes visited by >3.5% of the total upwelling particle-transport.



# Results

## Spiraling pathways

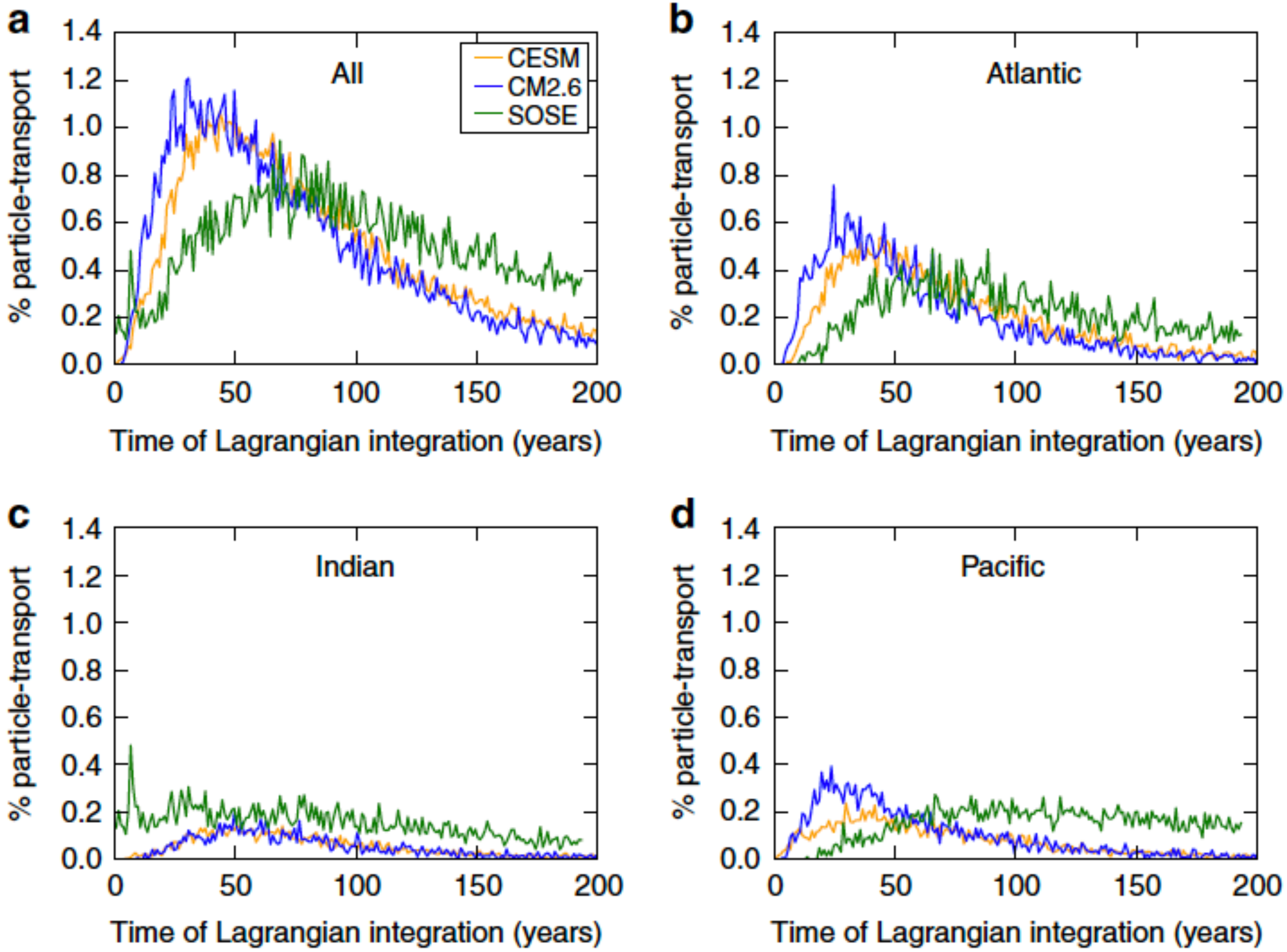



CM2.6 Indian particle pathways with >3.5% particle-transport

CM2.6 Pacific particle pathways with >3.5% particle-transport

# Results

## Upwelling Timescales



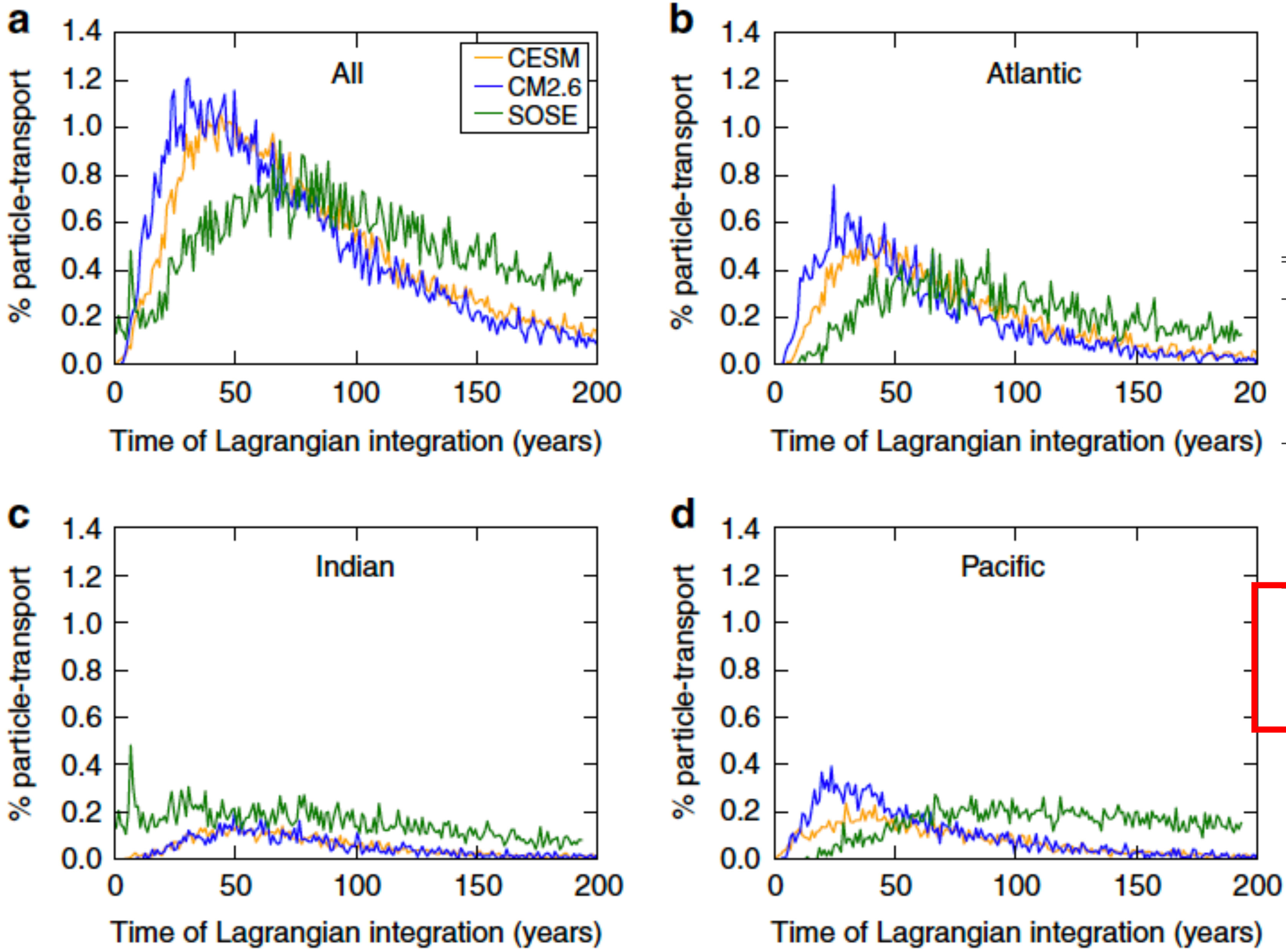

Upwelling timescales: From the initial position to when the particle reaches the base of the mixed layer.

**Particle transport weighting:** "Particles assigned with more transport initially have a larger contribution to the pathway distributions".

**Particle transport:** Particle trajectories weighted by their initial transport at 30º S.

# Results

## Upwelling Timescales




Upwelling timescales: From the initial position to when the particle reaches the base of the mixed layer.

| Model | | Median | Mean | Mode |
|---|---|---|---|---|
| CESM | Total | 70 | 79 | 41 |
| | Atlantic | 61 | 72 | 48 |
| | Indian | 68 | 78 | 50 |
| | Pacific | 58 | 68 | 41 |
| CM2.6 | Total | 62 | 72 | 28 |
| | Atlantic | 49 | 61 | 28 |
| | Indian | 68 | 78 | 48 |
| | Pacific | 47 | 60 | 22 |
| SOSE | Total | 92 | 96 | 81 |
| | Atlantic | 89 | 96 | 82 |
| | Indian | 76 | 82 | 29 |
| | Pacific | 109 | 111 | 93 |

# Results

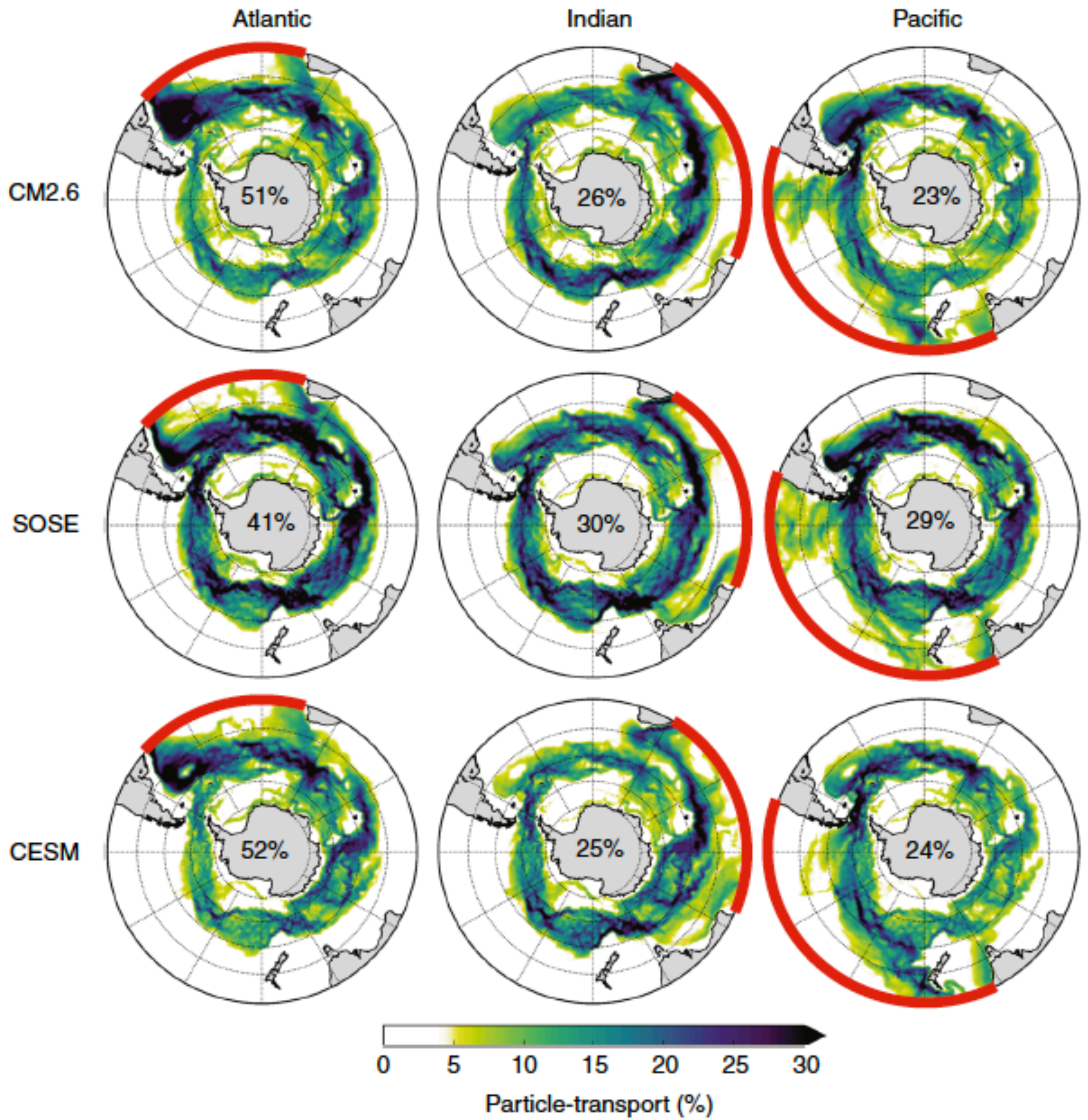
## Particle pathways to the mixed layer

Preferred particle pathways to the ACC:

- Via DWBCs along continents or topographic ridges.
- “Eddy-driven” eastern pathways (e.g. Aguhlas current and below the East Australian Current).

Upwelling enhanced within the ACC at major topographic ridges.

Particle-transport varies depending of the model.



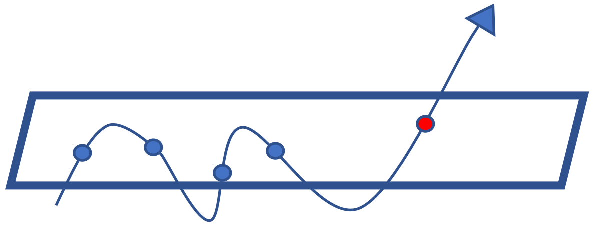
# Results

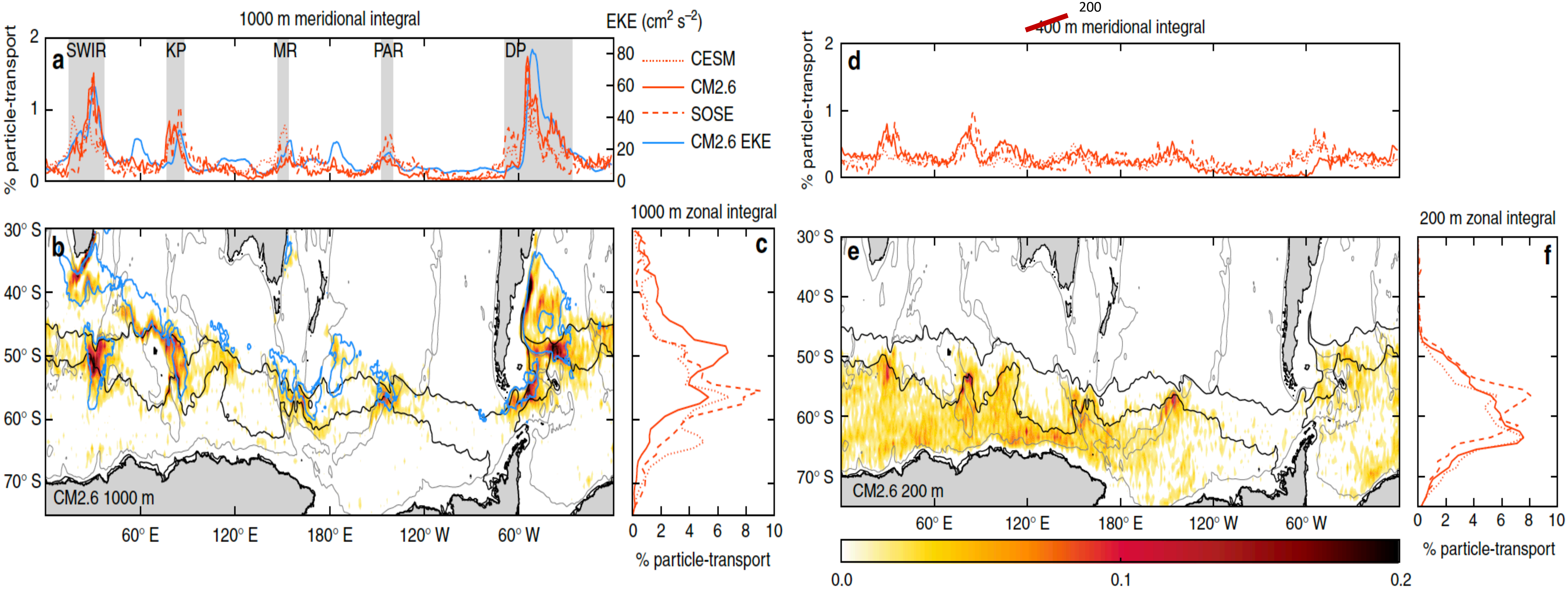
## Role of topography and eddies

**a,d:** Percent of total upwelling particle transport crossing 1000 (200) m, integrated in latitude.

**b,e:** Percent of particle transport crossing 1000 (200) m in each 1º x 1º grid box.

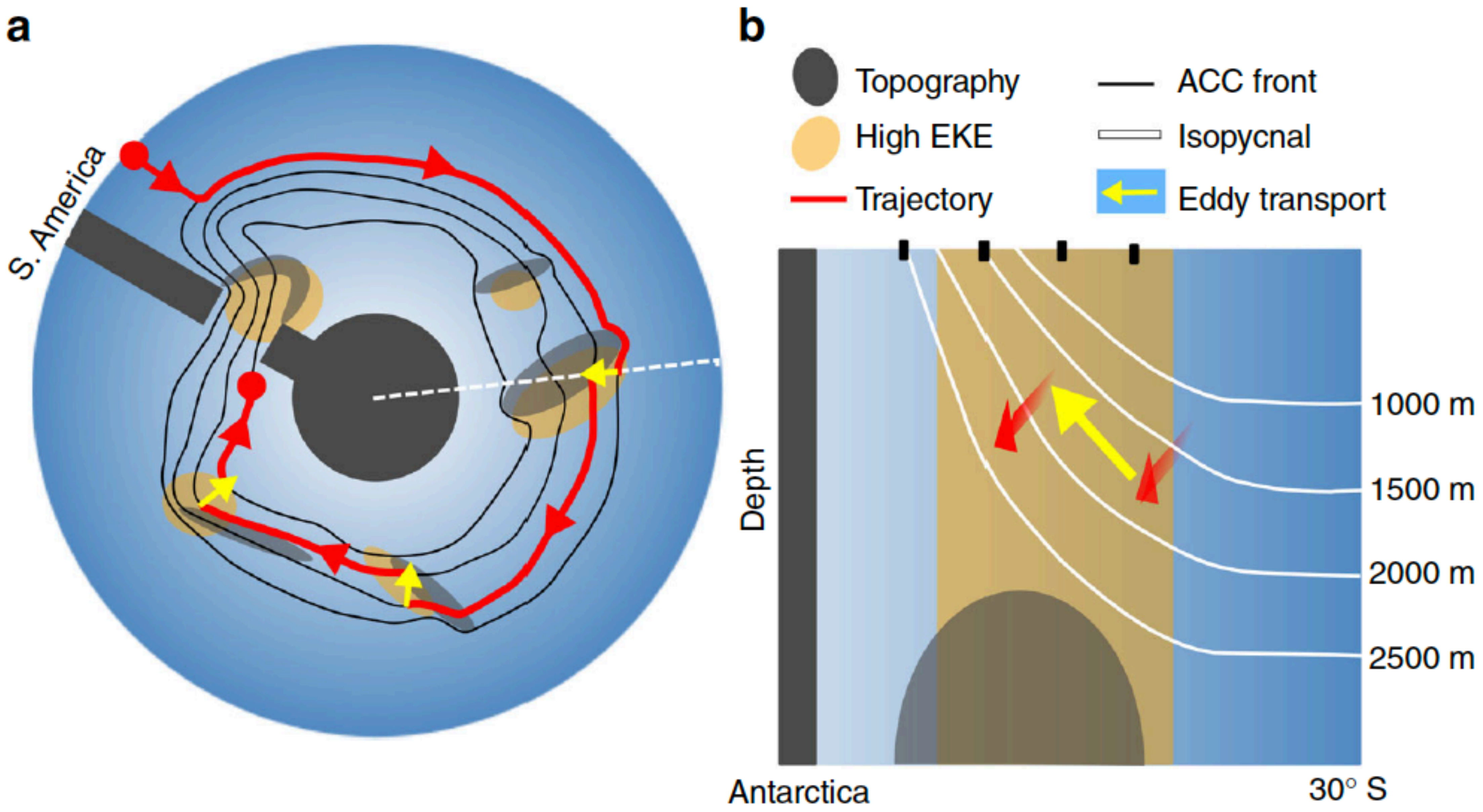
**c,f:** Percent of particle transport crossing 1000, integrated in longitude.





# Summary

## A conceptual view of deep water masses pathways



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   - Lagrangian (upwelling and spiraling) timescales in a hierarchy of model resolution.

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4. Discussion

# 3. Does the eddy field strength affect the upwelling timescales of deep waters? (Drake et al. 2018).

**Geophysical Research Letters**

**RESEARCH LETTER**

10.1002/2017GL076045

## Lagrangian Timescales of Southern Ocean Upwelling in a Hierarchy of Model Resolutions

**Henri F. Drake[1,2], Adele K. Morrison[1,3], Stephen M. Griffies[1,4], Jorge L. Sarmiento[1], Wilbert Weijer[5], and Alison R. Gray[1,6]**

[1]Department of Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ, USA, [2]Now at Massachusetts Institute of Technology and Woods Hole Oceanographic Institution Joint Program in Oceanography, Cambridge, MA, USA, [3]Now at Research School of Earth Sciences, Australian National University, Canberra, ACT, Australia, [4]NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA, [5]Los Alamos National Laboratory, Los Alamos, NM, USA, [6]Now at School of Oceanography, University of Washington, Seattle, WA, USA

**Key Points:**
- The timescales and 3-D structure of Circumpolar Deep Water (CDW) upwelling are missing from the zonally integrated overturning framework
- Lagrangian transit times of upwelling CDW are longer with coarser grid spacing or longer temporal averaging of the sampled velocity field
- As horizontal model resolution increases, particles complete fewer circumpolar loops thereby limiting interbasin merging of CDW

**Supporting Information:**
- Supporting Information S1
- Movie S1

**Correspondence to:**
H. F. Drake,
hdrake@mit.edu

**Abstract** In this paper we study upwelling pathways and timescales of Circumpolar Deep Water (CDW) in a hierarchy of models using a Lagrangian particle tracking method. Lagrangian timescales of CDW upwelling decrease from 87 years to 31 years to 17 years as the ocean resolution is refined from 1° to 0.25° to 0.1°. We attribute some of the differences in timescale to the strength of the eddy fields, as demonstrated by temporally degrading high-resolution model velocity fields. Consistent with the timescale dependence, we find that an average Lagrangian particle completes 3.2 circumpolar loops in the 1° model in comparison to 0.9 loops in the 0.1° model. These differences suggest that advective timescales and thus interbasin merging of upwelling CDW may be overestimated by coarse-resolution models, potentially affecting the skill of centennial scale climate change projections.

# Motivation

"Model estimates of upwelling timescale have been limited to volume transport analysis in noneddying or time-averaged eddying models".

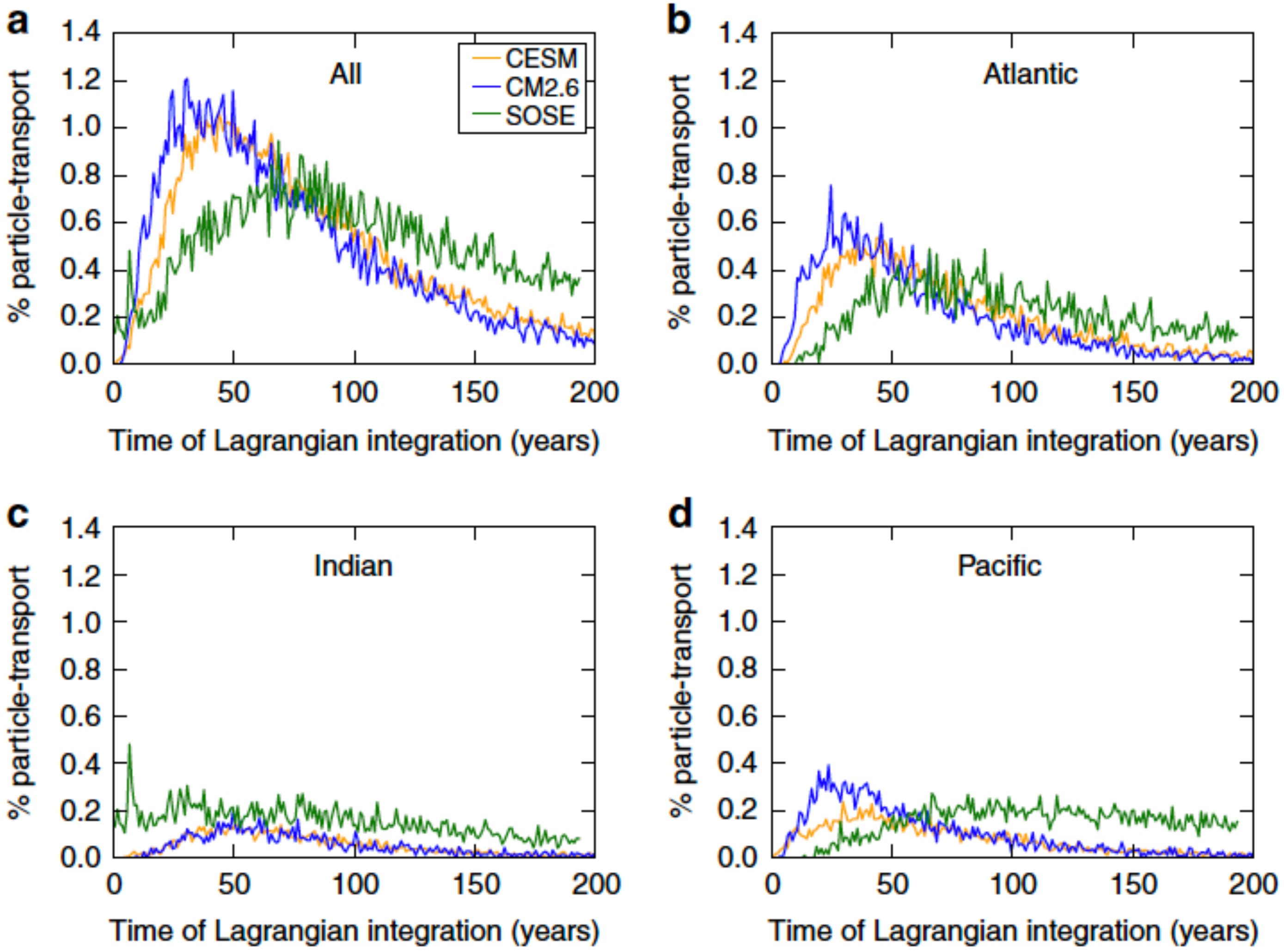
Doos (1995): 240 years

Iudicone et al. (2008): 140 years

Tamsitt et al. (2017): 28 – 81 years

The paper tackles the following:

- Does the strength of the eddy field cause differences in the upwelling timescales?




Tamsitt et al. (2017)

# Methods

## a) Models and state estimate

| | CM2-1 GCM | CM2.5 GCM | CM2.6 GCM |
|---|---|---|---|
| | High-resolution version of GFDL's CM2-0 coupled model | | |
| **Resolution** | Nominal ocean resolution of 1º | Nominal ocean resolution of 1/4º | Nominal ocean resolution of 1/10º |
| **Parameterizations** | Enhanced isopycnal diffusion and advection component (Ferrari et al., 2010) | No eddy parameterization | No eddy parameterization |
| **Output length (time)** | 11 years | | |
| **Temporal resolution** | 5-day averaged velocity fields | | |

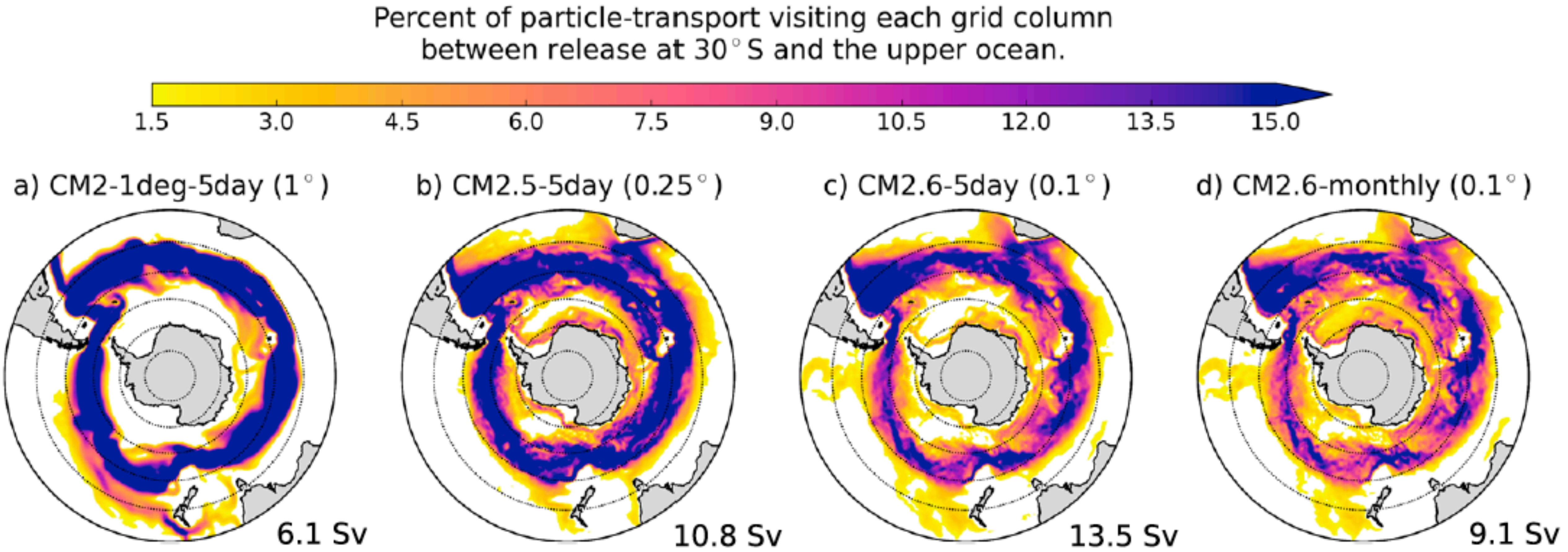
# Methods

## b) Lagrangian methods (CMS)

- 3.0 x $10^6$ particles released at 30° S from 1000 – 4000 m.
- Re-released at same location every 15th of each month for the duration of the model output:
  - CM2.6 -> 200 years; CM2.5 -> 300 years; CM2-1 -> 500 years.
- Time step for particle advection: 1 hr.
- Trajectories integrated for as long as needed, looping through the model.
  - Particles were retained if they reach the mixed layer (300 m) and remain south of 30° S.
- Each particle is assigned with the meridional volume transport when released.

# Results

## Model comparisons (percent of particle-transport)




d) CM2.6-monthly (0.1º): Fields were averaged every month for isolating the impact of eddy variability.

# Results

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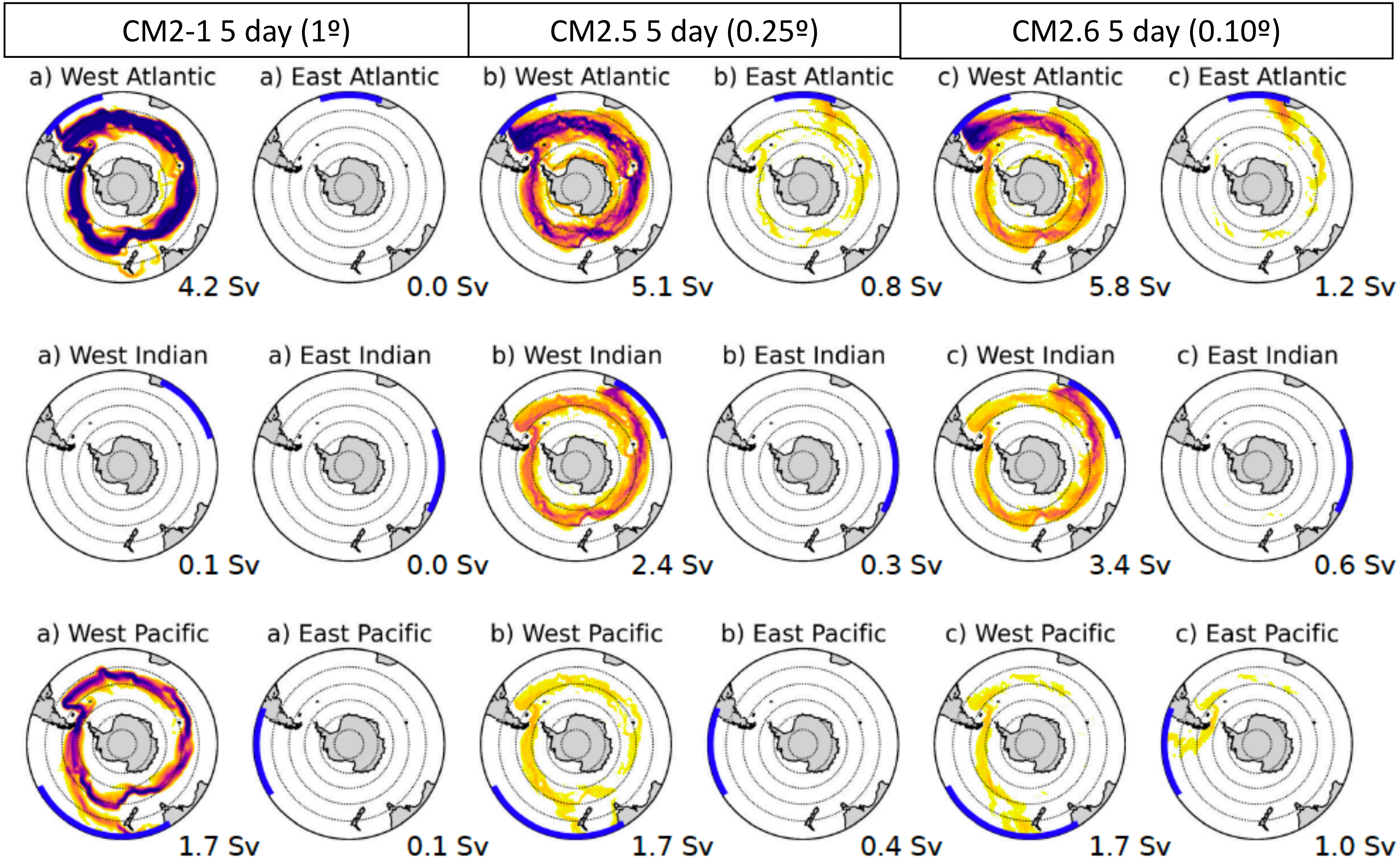
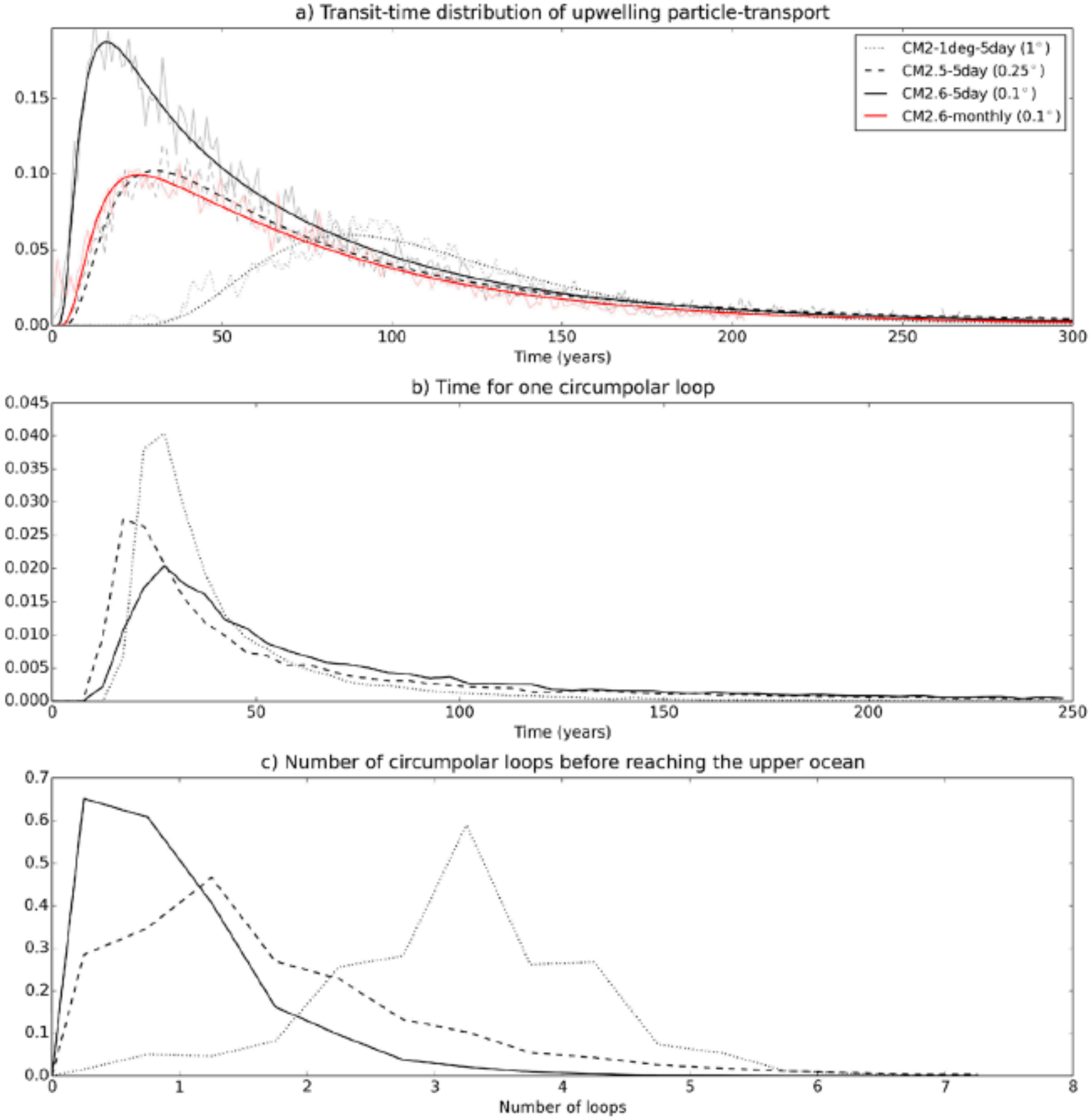


# Results

## Transport-scaled Transit time distributions for particles



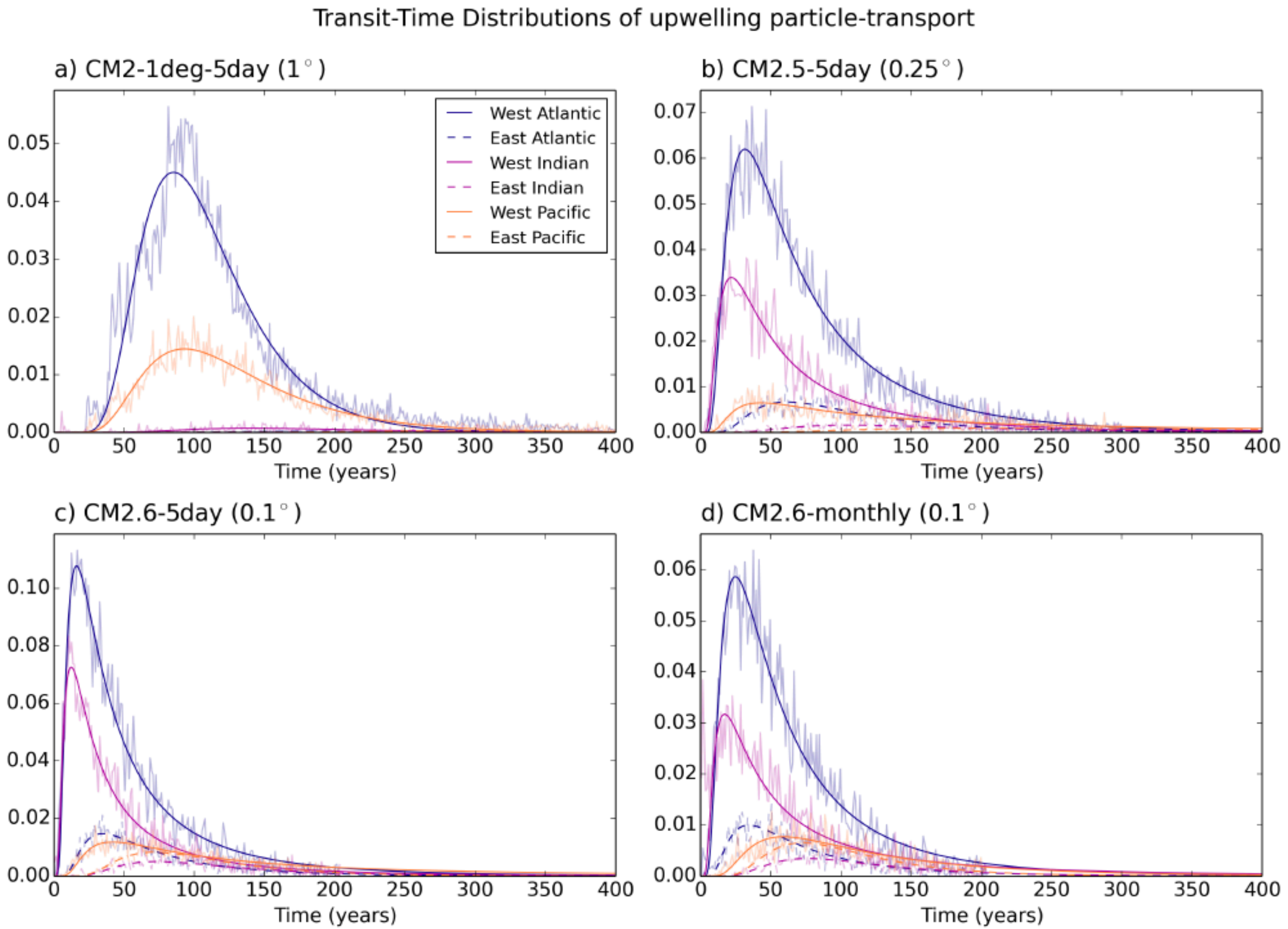

An increase of the model resolution shifts the transit times from 80 to 30-15 years.

Particles complete one circumpolar loop in ~30 years, regardless of the model resolution.

Particles in the non-eddying models make more loops around Antarctica before upwelling to the mixed layer.

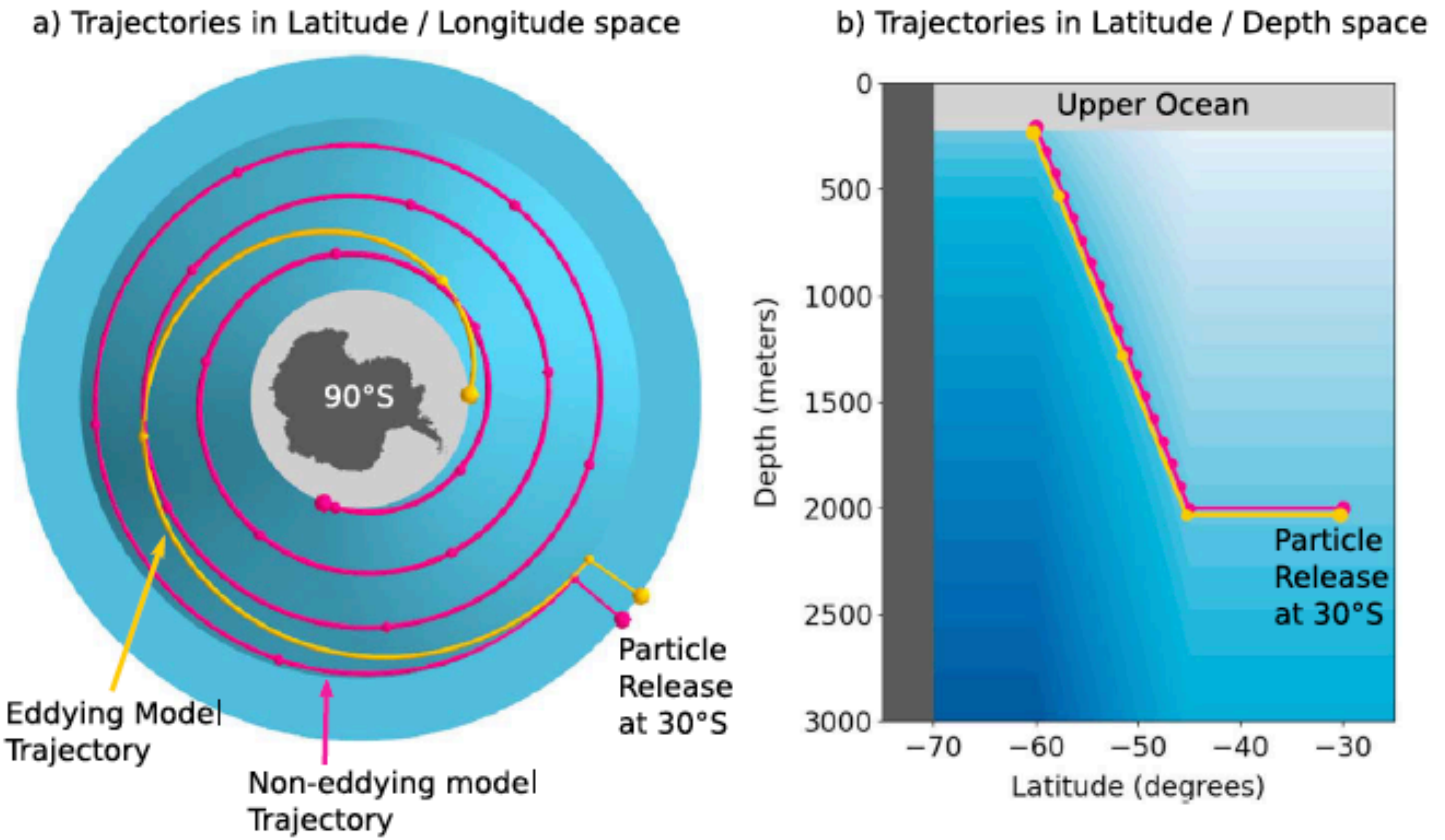
# Results

## Transit times distributions



# Summary

**A 3D schematic of CDW upwelling**



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1. 3D upwelling pathways of deep water masses in the SO (Tamsitt et al. 2017, Nature communications).
   - Role of bottom topography and eddies.

2. Does the eddy field strength affect the upwelling timescales of deep waters? (Drake et al. 2018).
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4. Discussion

# 4. Transformation of Deep Water Masses along Lagrangian upwelling pathways in the SO (Tamsitt et al. 2018, JGR-Oceans).

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Oceans

**RESEARCH ARTICLE**

10.1002/2017JC013409

**Special Section:**
The Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) Project: Technologies, Methods, and Early Results

## Transformation of Deep Water Masses Along Lagrangian Upwelling Pathways in the Southern Ocean

**V. Tamsitt[1], R. P. Abernathey[2], M. R. Mazloff[1], J. Wang[3], and L. D. Talley[1]**

[1]Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA, [2]Lamont Doherty Earth Observatory, Columbia University, Palisades, NY, USA, [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

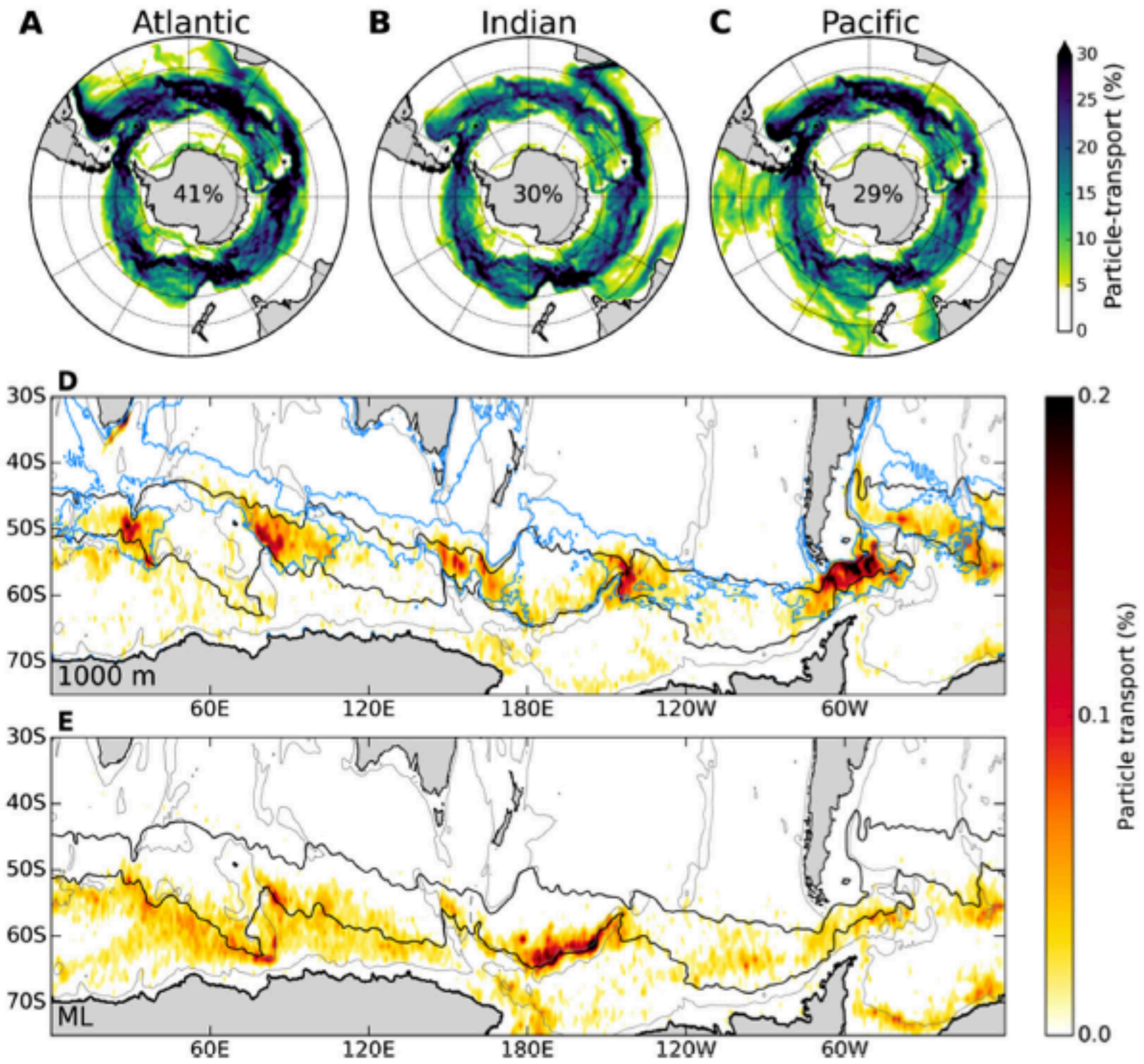
# Motivation

Upwelling at depth (1000 m) is enhanced at major topographic ridges in the ACC.

While upwelling in these hot spots is isopycnal, the role of diapycnal mixing in the large-scale ocean circulation and where it is important are not well known.

The paper tackles the following:

- Where does diapycnal mixing is important along the upwelling pathways of deep water?



# Methods

## b) Lagrangian experiment (SOSE/Octopus)

- Same as in Tamsitt et al. (2017).
- Random reshuffle of the vertical position of the particle within the ML is included to represent ML turbulent that is not resolved.
- At the looping time step, vertical position of particles is adjusted so it conserves $\gamma_n$.

## c) Analysis

- Mixed layer $ML(x, y, t)$ is defined using $\frac{\partial^2 \rho}{\partial z^2}$ to find the inflection point at which $\frac{\partial \rho}{\partial z}$ changes sign.
- Temperature and salinity recorded following each individual trajectory.

# Methods

## c) Analysis

**B. Surface diabatic layer:** Densest $\sigma_2(x,y)$ that outcrops at least once during the 6 year SOSE iteration.

Separates ventilated (exposed to surface fluxes) isopycnal layers from those that are not.

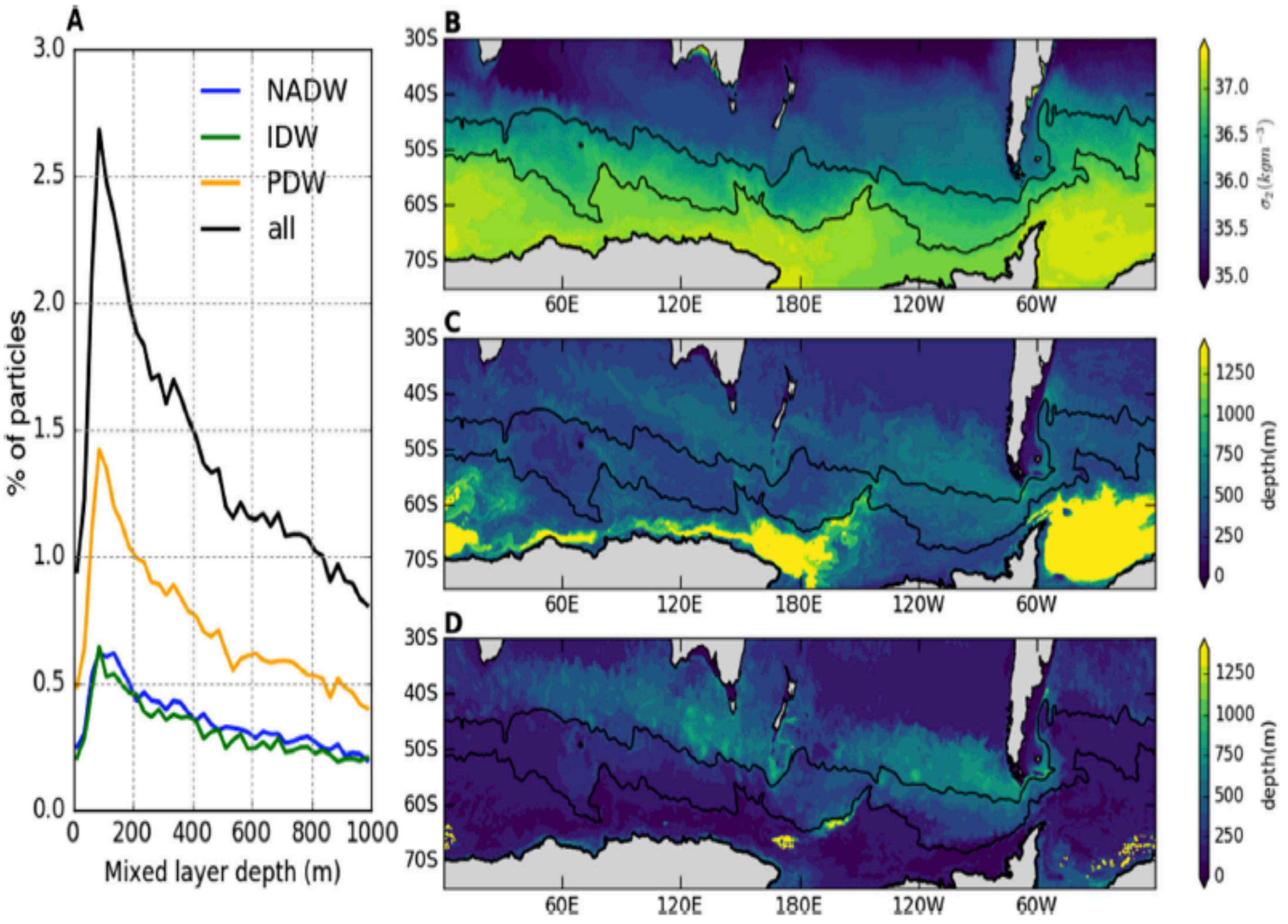
**D. Mixed layer bowl:** $\max(MLD(x,y))$.

**A. and other figures:** PDF

$$P(\chi)=\frac{1}{N}\sum_{i=1}^{N}\xi_i,$$

$$\xi_i=\begin{cases}1, & \text{if } \chi-\delta/2<\chi^i\leq\chi+\delta/2\\ 0, & \text{else}\end{cases},$$

$\chi$-> $\sigma_2, \gamma_n, \theta, S$, EKE



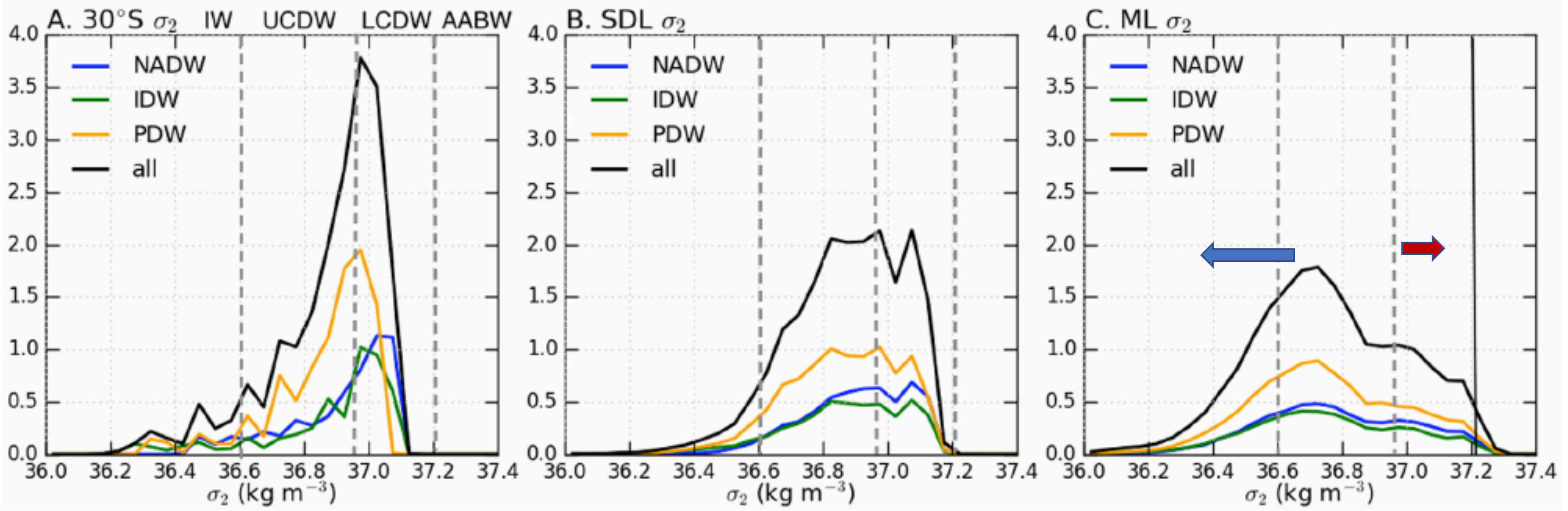
# Results

**Lagrangian water mass transformation**

- 30° S: Skewed towards lighter water masses.
- No-net density change when first crossing the SDL(?).
- Particles experience the largest density changes between SDL and ML.

Becoming denser

Becoming lighter



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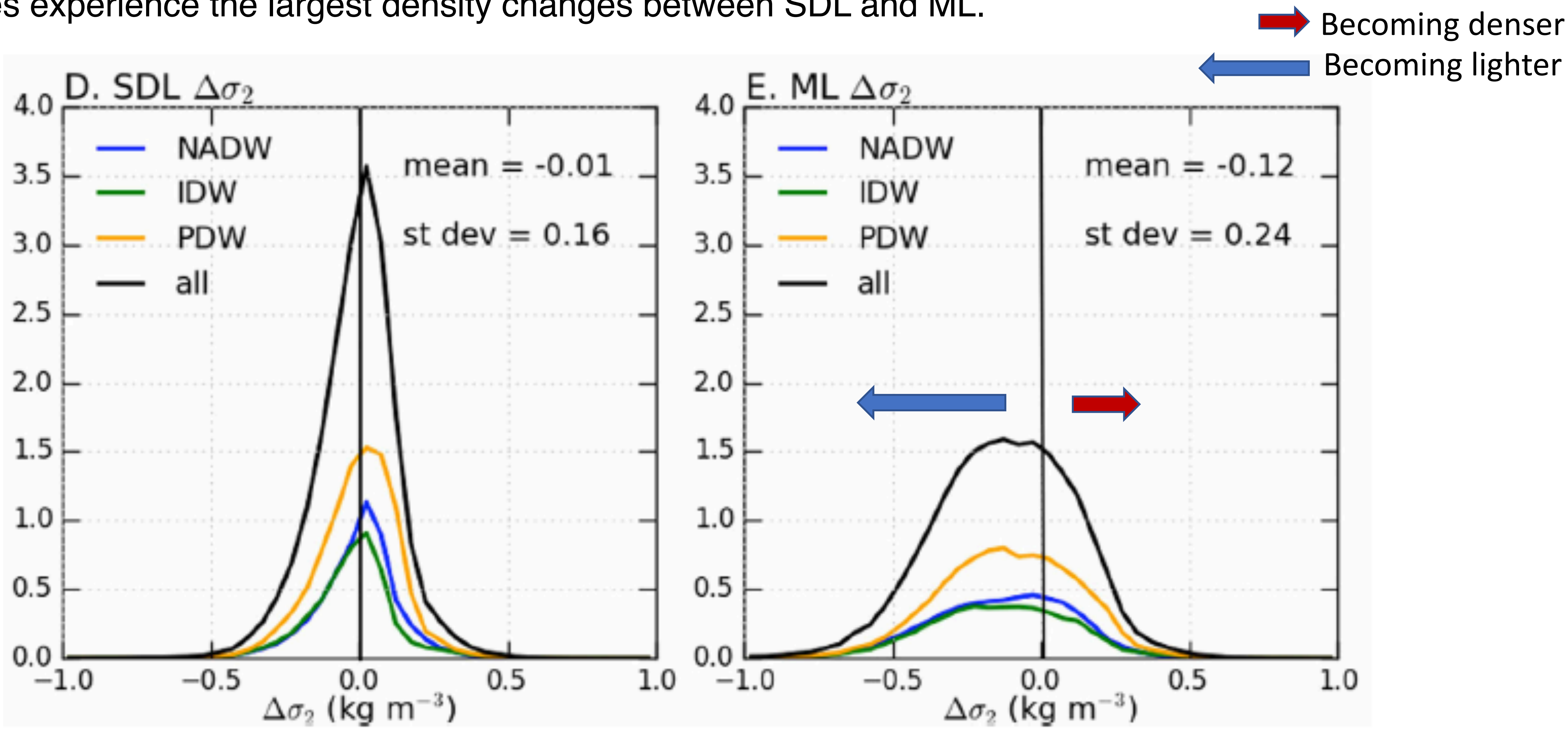

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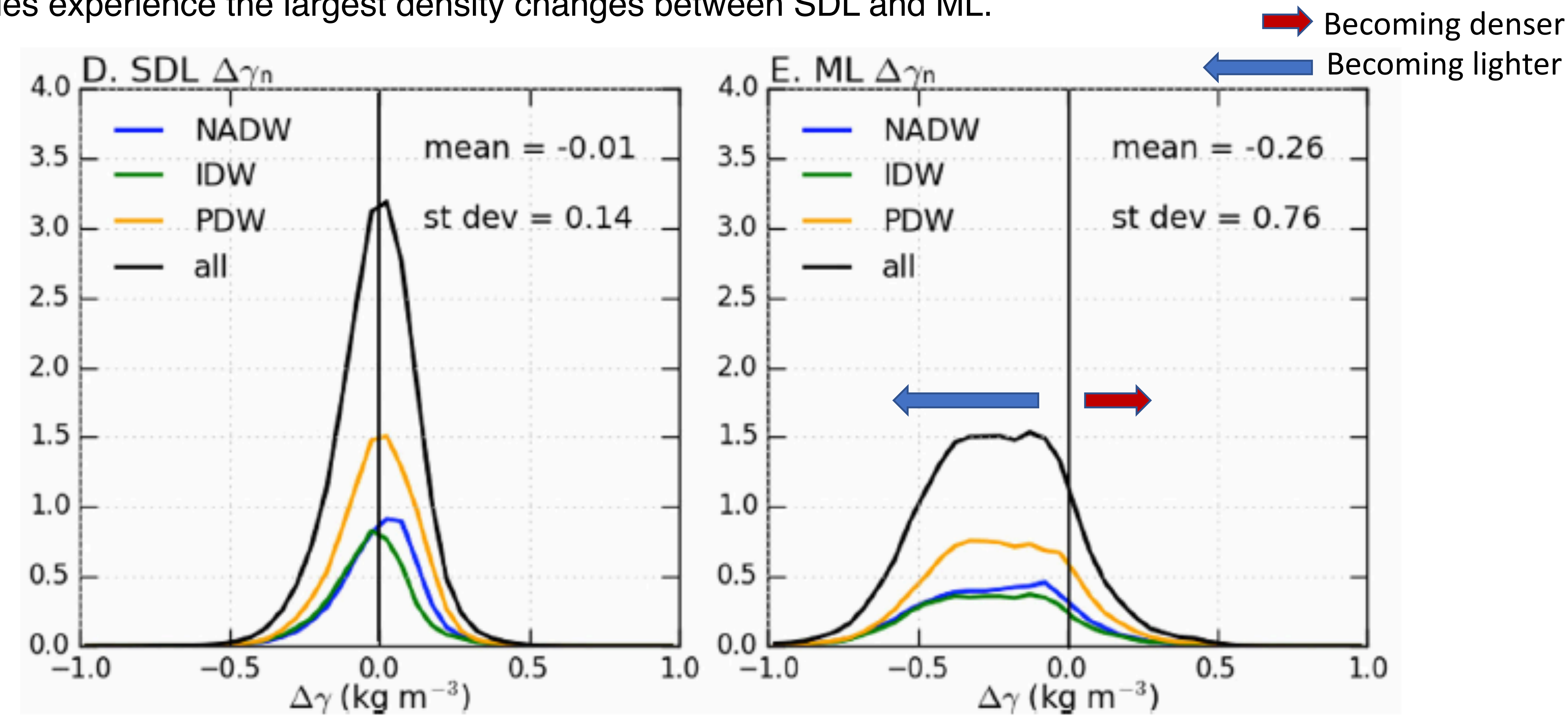


# Results

## Lagrangian water mass transformation

JOINT PDF

$$F_{xy}(r,s)\,dr\,ds = \text{Probability that } r < x \le r+dr,\ s < y \le s+ds$$

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} F_{xy}(r,s)\,dr\,ds = 1$$

A,C

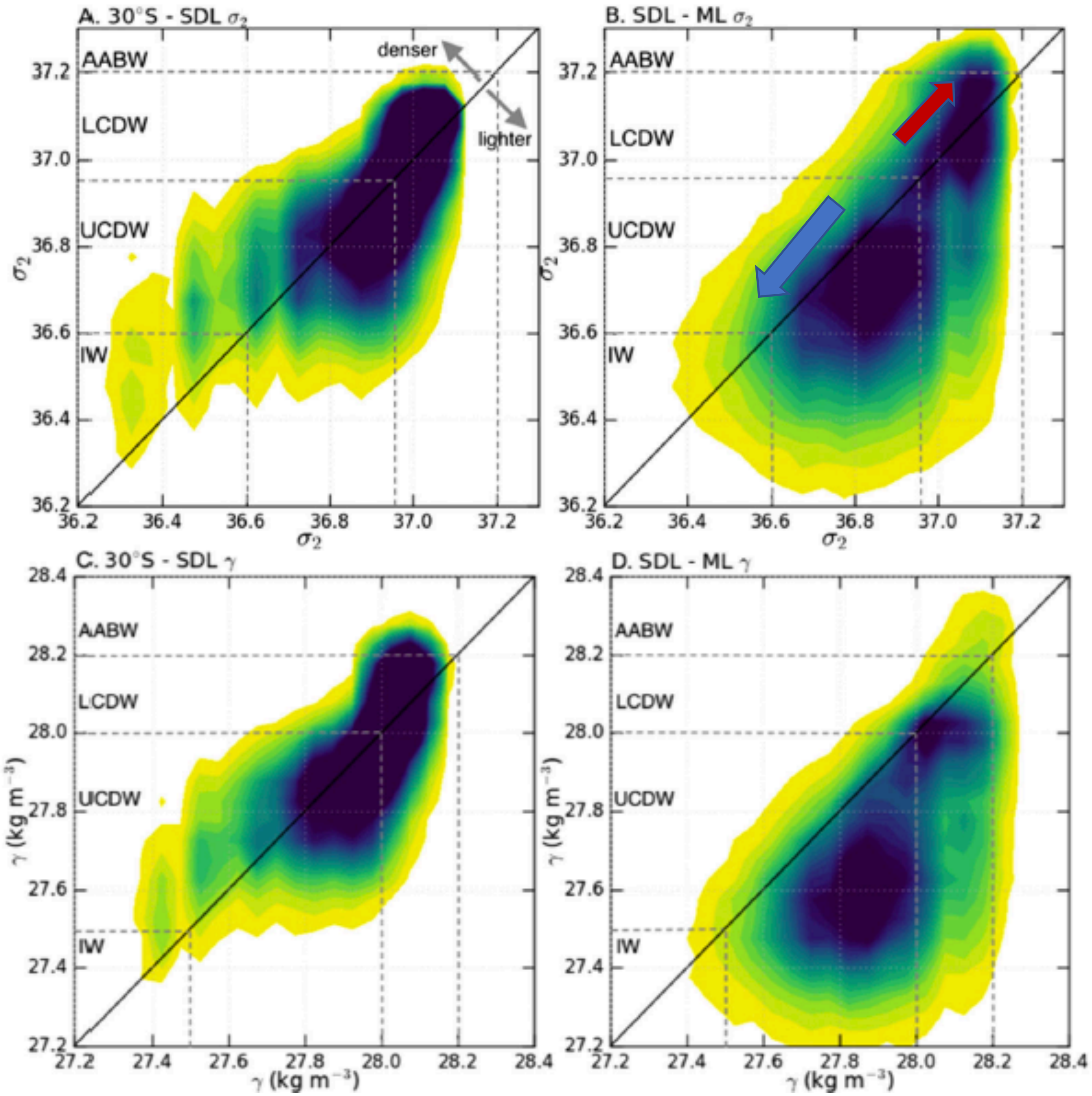
$x \rightarrow \sigma_2$ or $\gamma_n$ at 30° S

$y \rightarrow \sigma_2$ or $\gamma_n$ at $z = z_{SDL}$

B,D

$x \rightarrow \sigma_2$ or $\gamma_n$ at $z = z_{SDL}$

$y \rightarrow \sigma_2$ or $\gamma_n$ at $z = z_{MLD}$

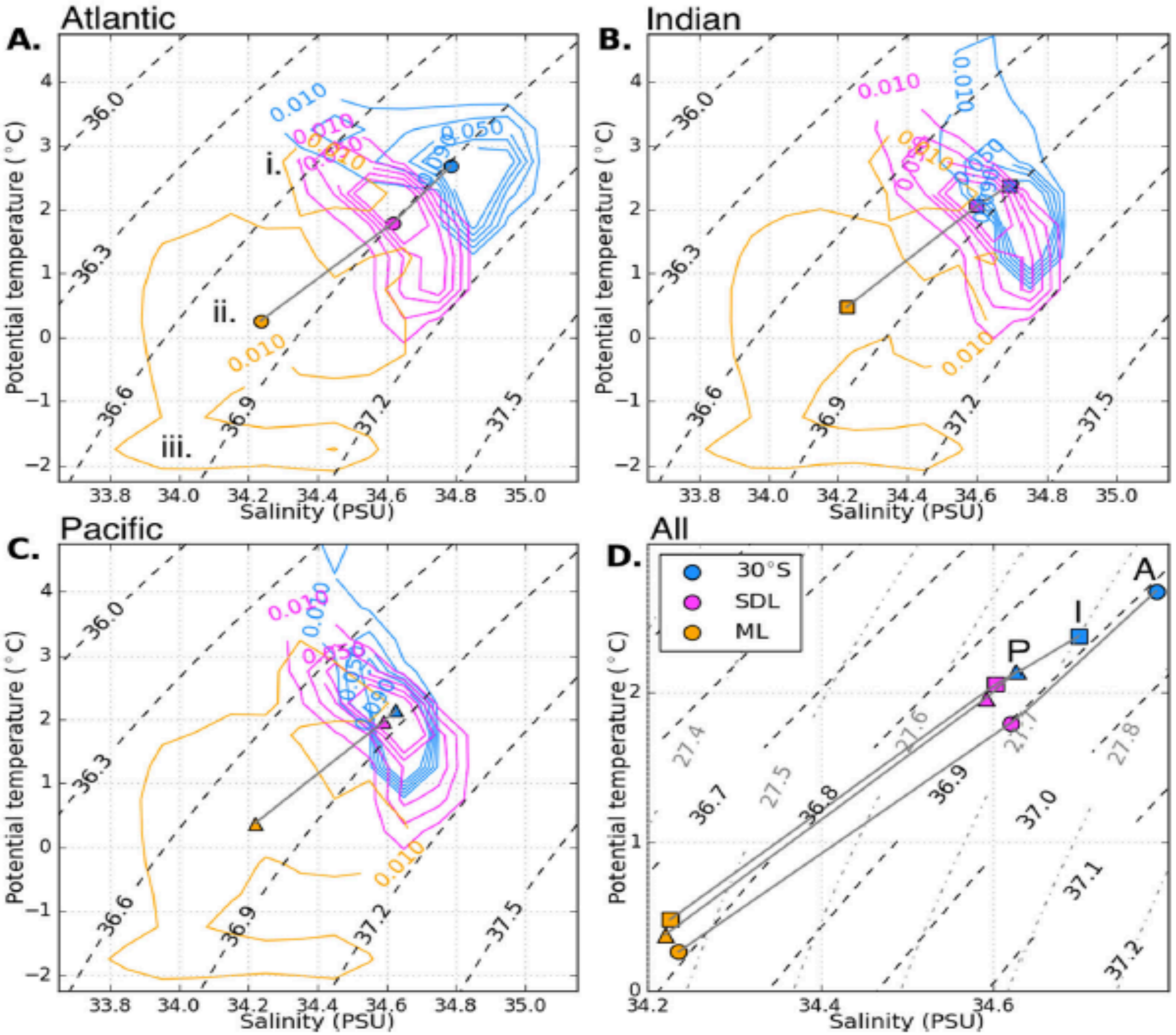


# Results

**Lagrangian water mass transformation in $\theta - S$**

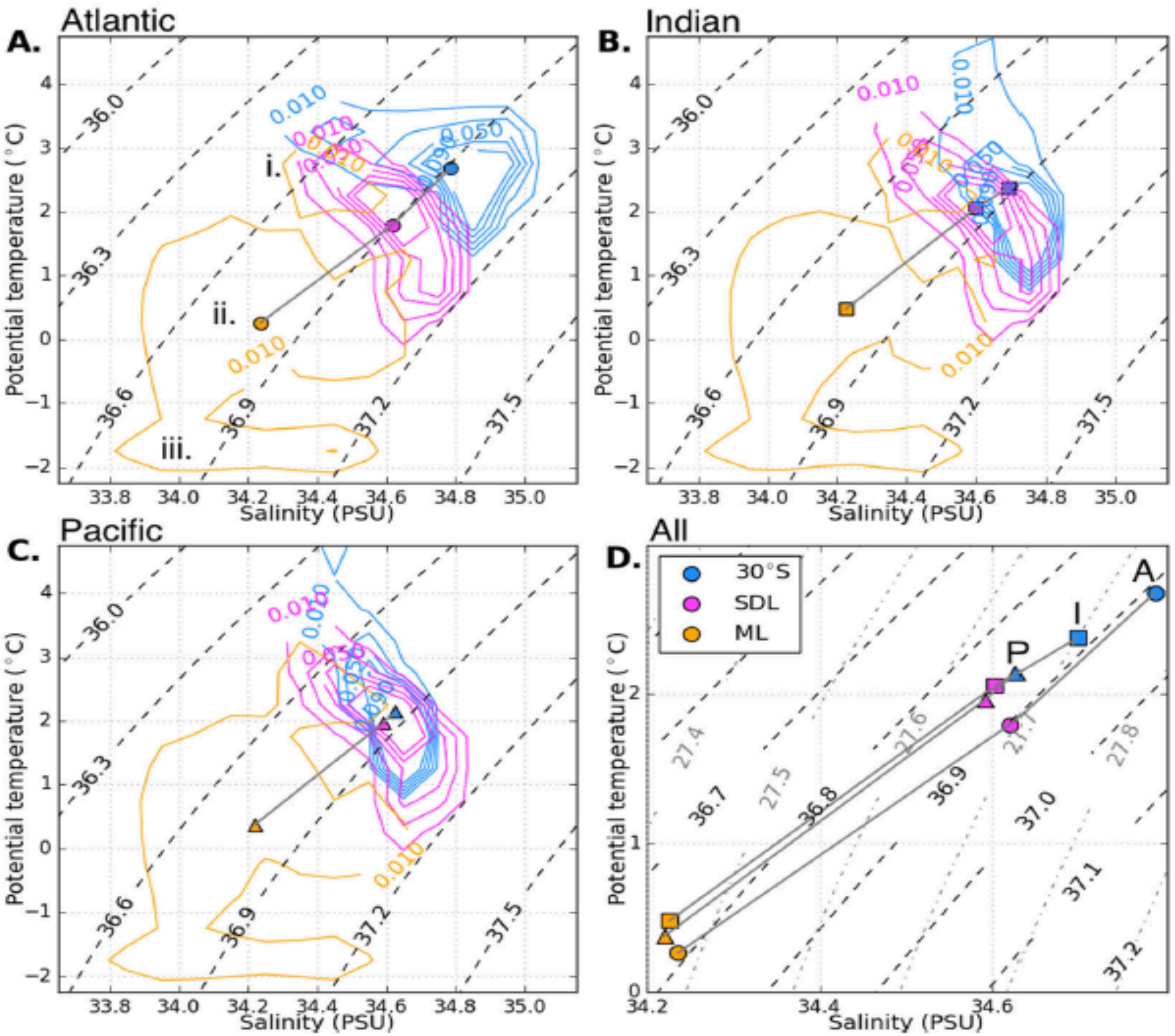
- SDL – ML -> thermohaline properties diverge into three different water masses
  - **i. Warm and salty waters upwelling in subtropical WBC.**
  - **ii. UCDW**
  - **iii. LCDW/AABW**

- Diapycnal mixing appears to be more important in the SDL-ML transition.

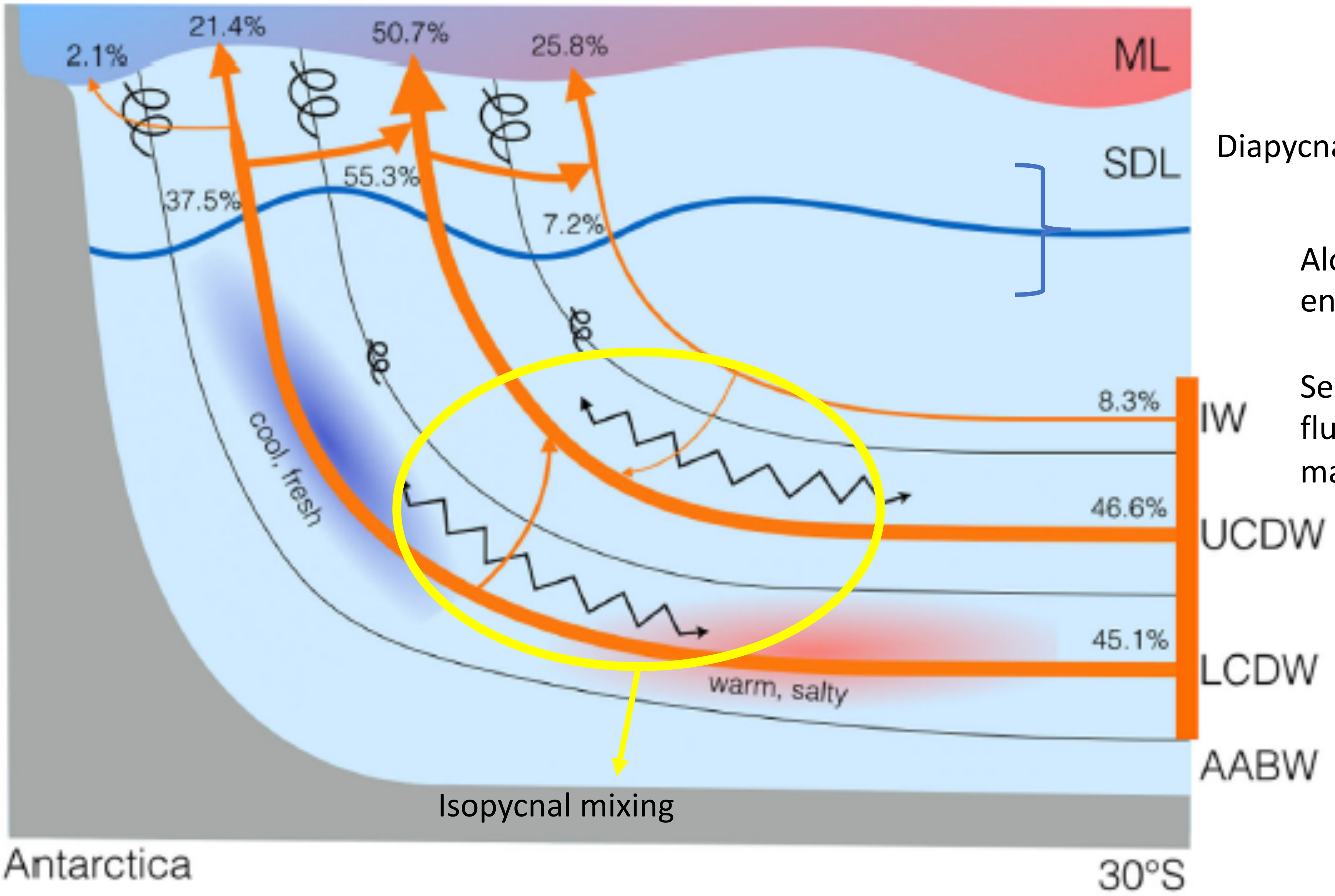


# Results

… the difference in center of mass of the particle distribution between the Atlantic and Indo-Pacific deep waters is preserved during upwelling. This is consistent with the results of Talley (2013) and others that find the signature of deep waters of Atlantic origin is found at a higher density (and below) Indian and Pacific deep waters.



# Summary




Diapycnal mixing

Along continental slope entrainment not resolved(?)

Seasonal cycle of freshwater fluxes affecting the water mass transformation (?)

Isopycnal mixing

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1. 3D upwelling pathways of deep water masses in the SO (Tamsitt et al. 2017, Nature communications).
   - Role of bottom topography and eddies.

2. Does the eddy field strength affect the upwelling timescales of deep waters? (Drake et al. 2018).
   - Lagrangian (upwelling and spiraling) timescales in a hierarchy of model resolution.

3. Transformation of Deep Water Masses along Lagrangian upwelling pathways in the SO (Tamsitt et al. 2018, JGR-Oceans).
   - How deep water transforms along the SO.
   - Where diapycnal mixing is important along the Lagrangian pathways.

4. Discussion

# Discussion

If we increase the model resolution, would the upwelling timescales asymptote?

How can we distinguish between the contribution of transient eddies vs standing eddies?

Seasonal cycle of freshwater fluxes affecting the water mass transformation (?)

What processes that are not represented in the model could account for a significant % of water mass transformation (Ruan et al., 2017).