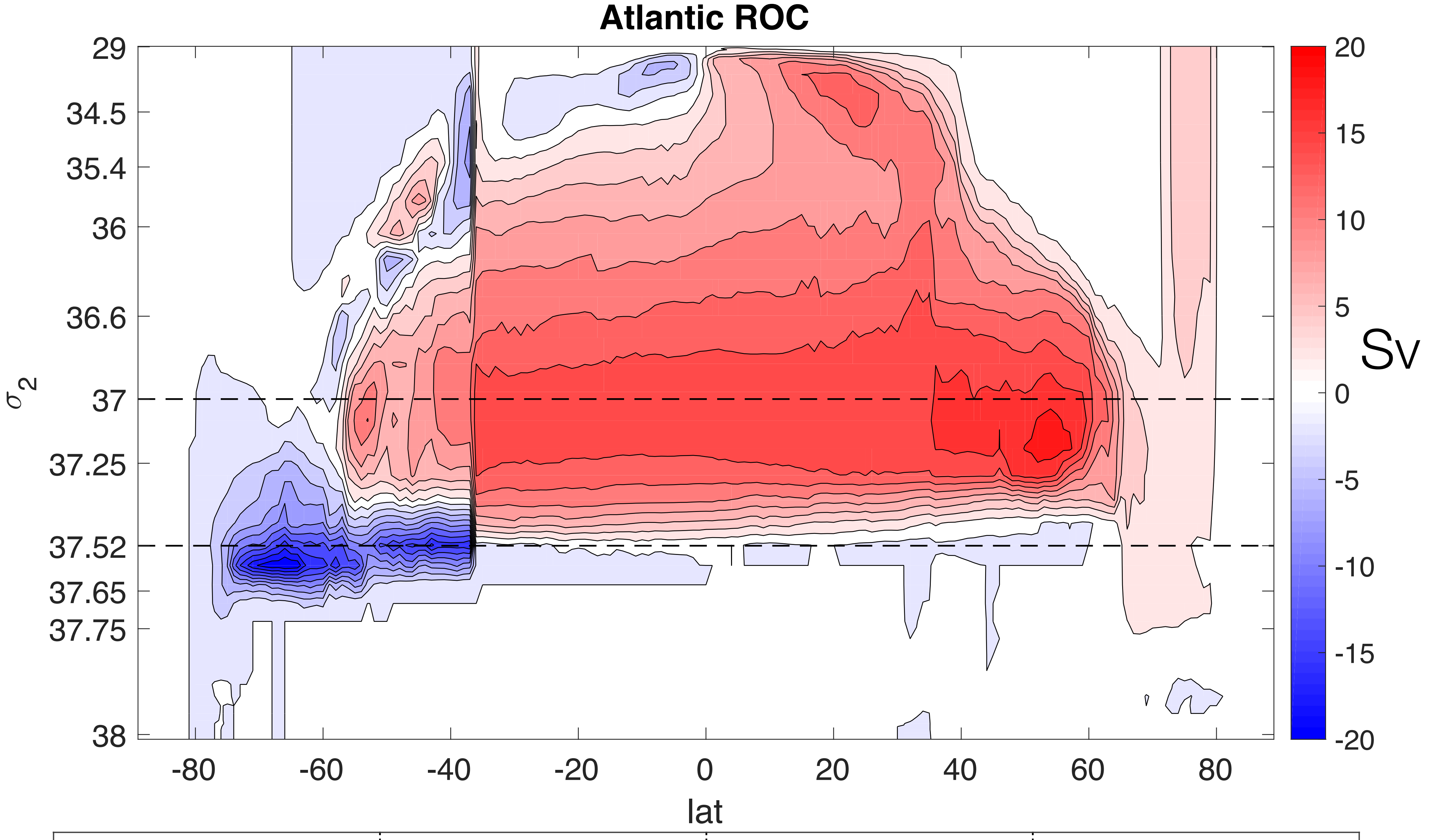
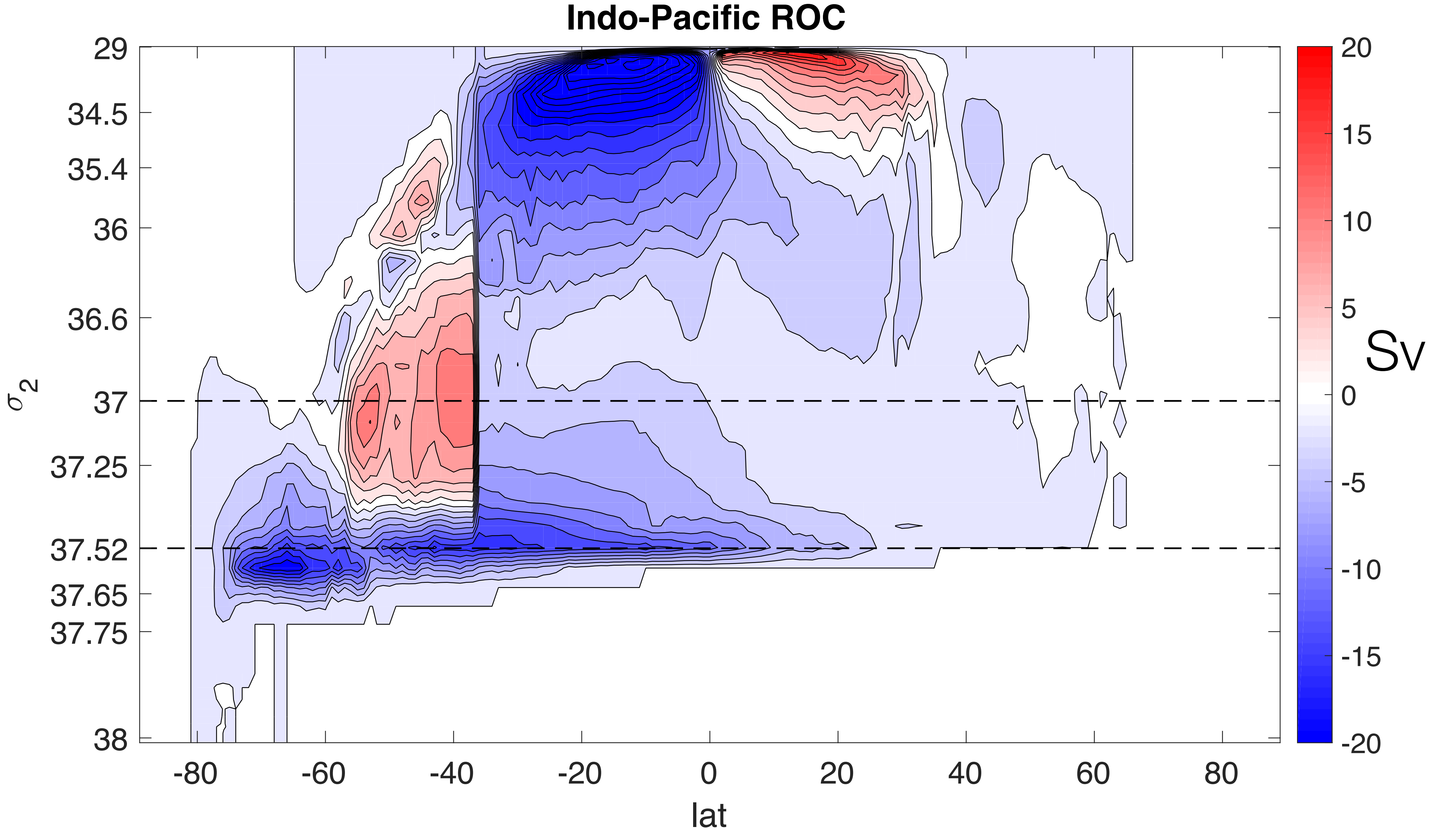
The Global Overturning Circulation: theories and estimates

Paola Cessi
Scripps Institution of Oceanography
University of California, San Diego

The residual overturning circulation (ROC) according to ECCO4





Estimate	Data	30°S transport	Max transport
ECCO4	Hydrography,Argo, SST,altimeter,geoid, MITgcm	15Sv	19Sv
Lumpkin& Speer 2007	Hydrography+inverse	12Sv	17Sv
Talley 2013	Hydrography	18Sv	26Sv
SAMBA	direct velocity	15Sv	

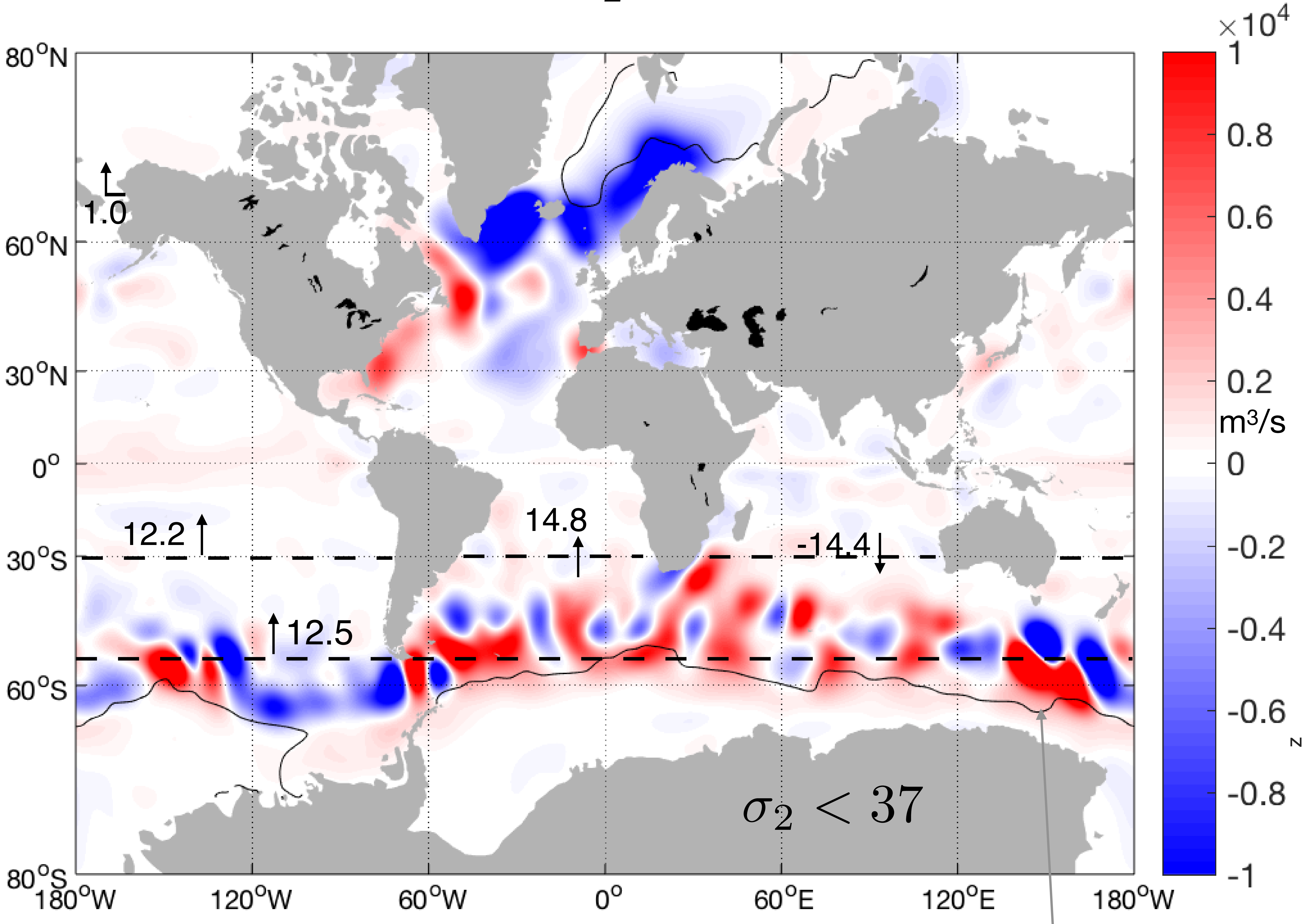
Estimate	Data	30°S transport	Max transport
ECCO4	Hydrography,Argo, SST,altimeter,geoid, MITgcm	17Sv	19Sv
Lumpkin& Speer 2007	Hydrography+inverse	21Sv	21Sv
Talley 2013	Hydrography	29Sv	29Sv
Kunze 2017	Diapycnal mixing from IGW (strain)		20Sv
DeLavergne&et al. 2016	Diapycnal mixing from IGW (tides) +leeW		10-20Sv

Meridional velocity (Eulerian + GM) vertically integrated to 50 σ_2 surfaces
Time and zonally averaged by sector
Measures the diapycnally-induced overturning

STILL NOT GREAT AGREEMENT AMONG ESTIMATES…

A horizontal look at the upper branch of the ROC

Mass (Euler+bolus) budget above σ_2 =37: smoothed diapycnal velocity (colors) for ECCO4

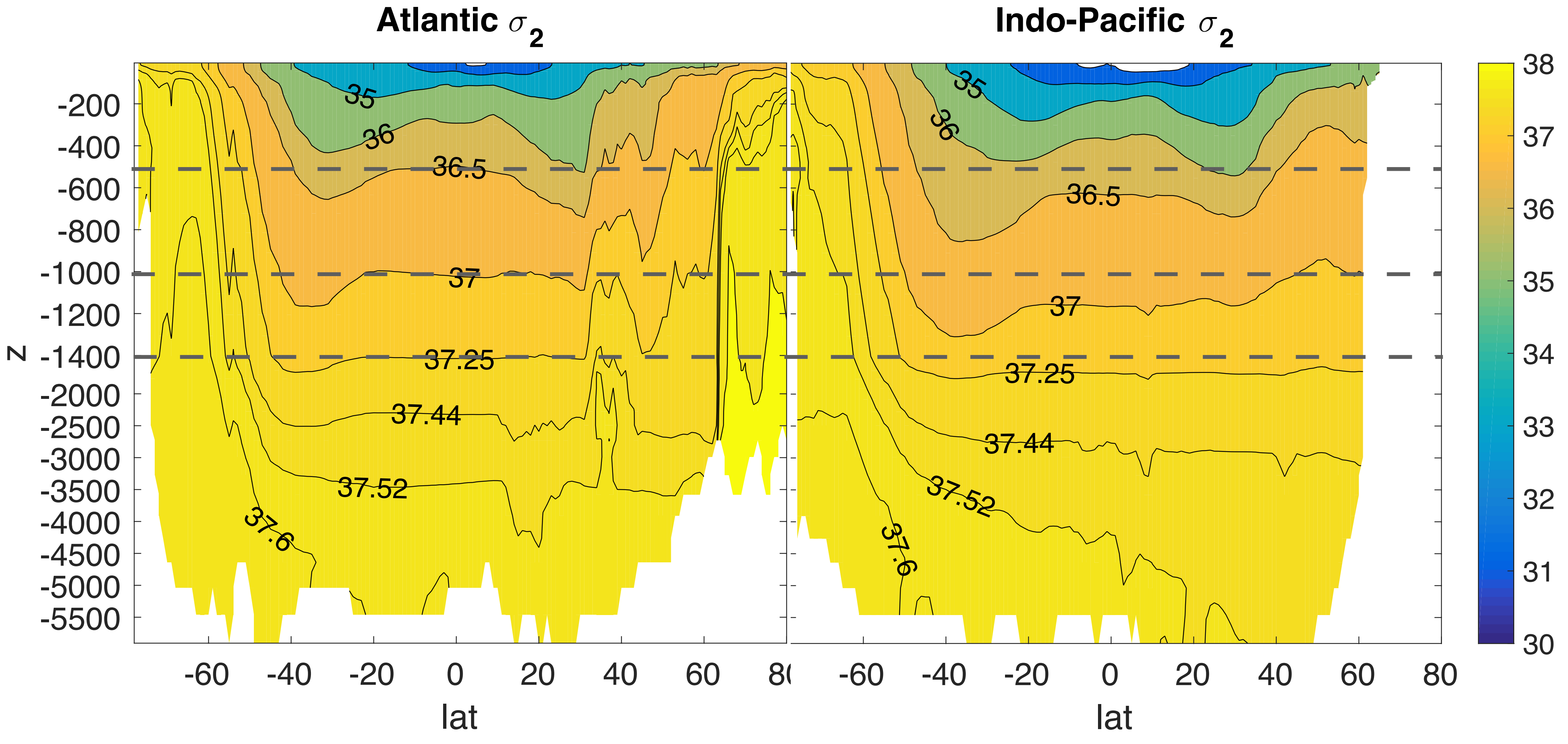


Section transport above σ_2 =37 in Sv →

Climatological outcrop of σ_2 =37

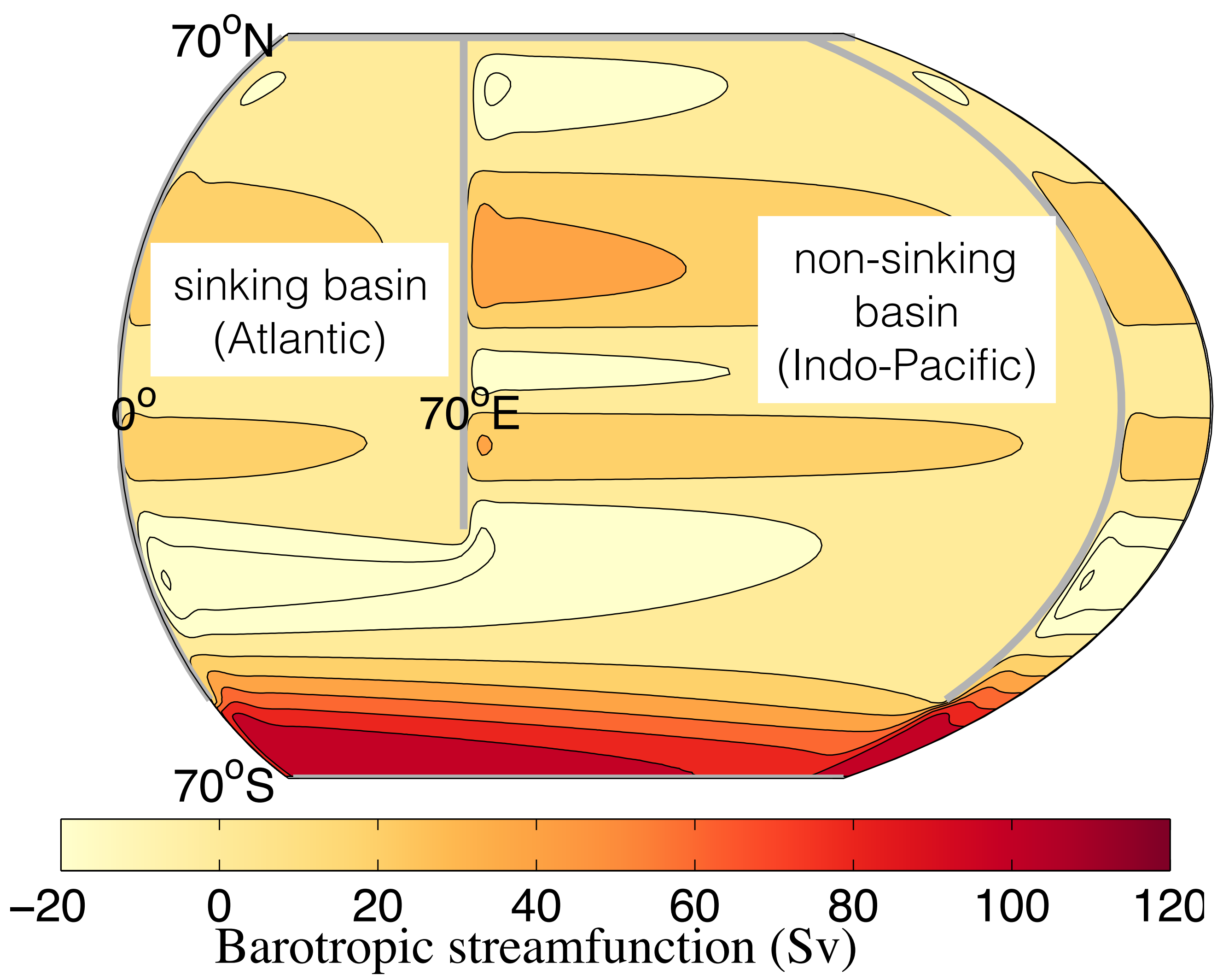
12.5 Sv ageostrophic transport enters at 54°S
+ 2.2 Sv geostrophic out of Indo-Pacific
=14.8Sv geostrophic into Atlantic

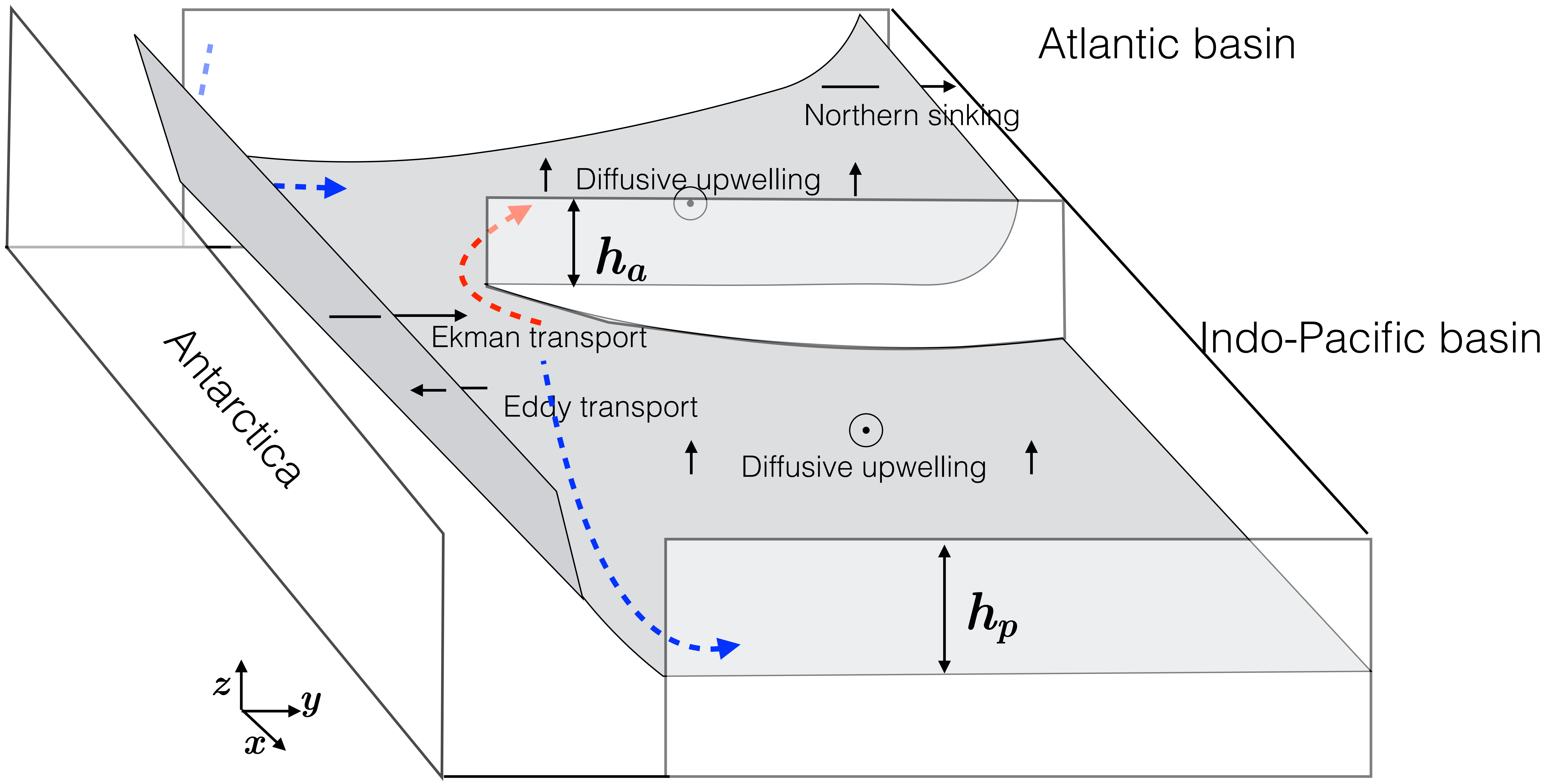
Balanced by pressure and isopycnal-depth differences between Atlantic and Indo-Pacific



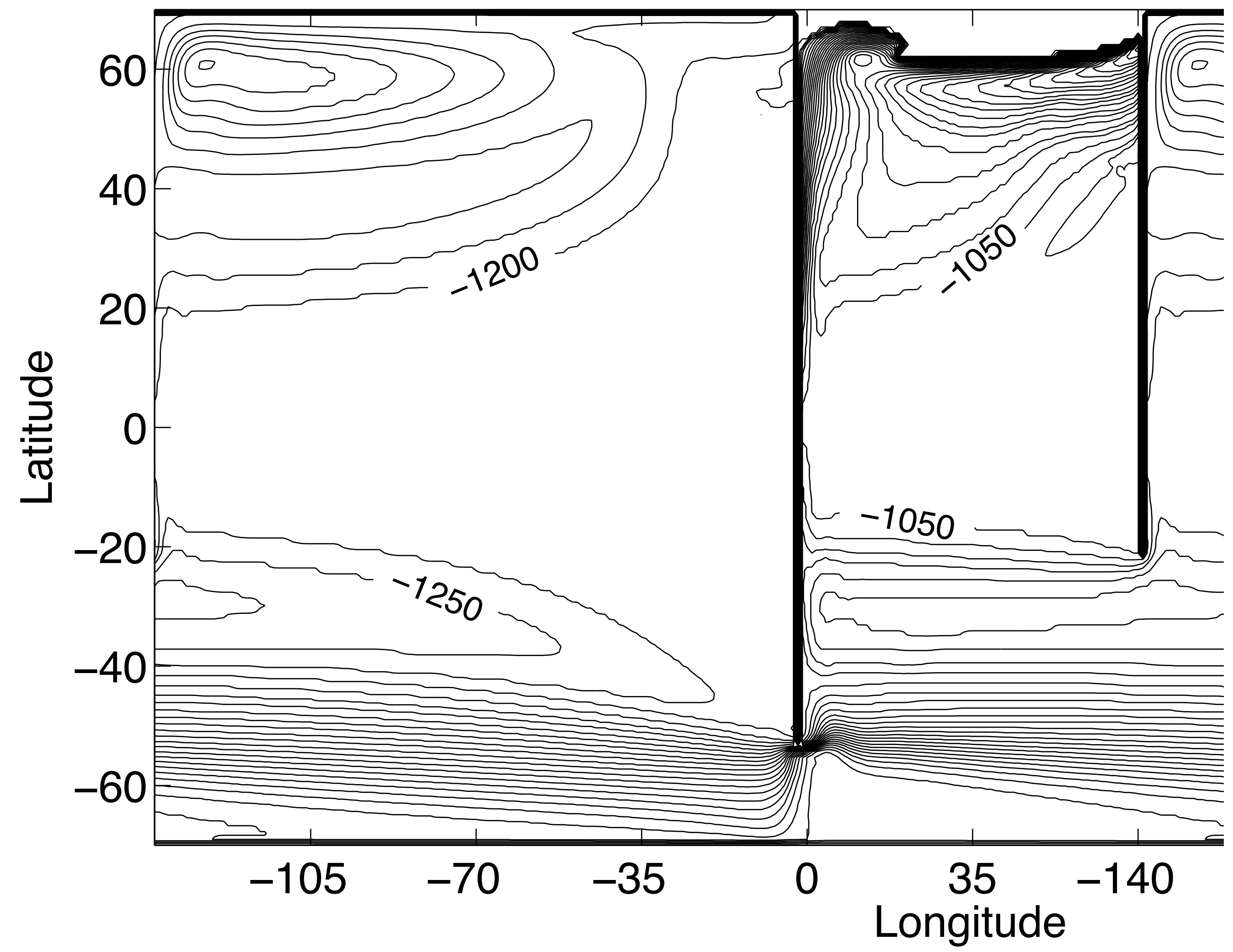
Zonally averaged σ_2 from ECCO4

Isopycnal depth difference explained in the context of simple models (Jones & Cessi, 2016)





Depth of isopycnal

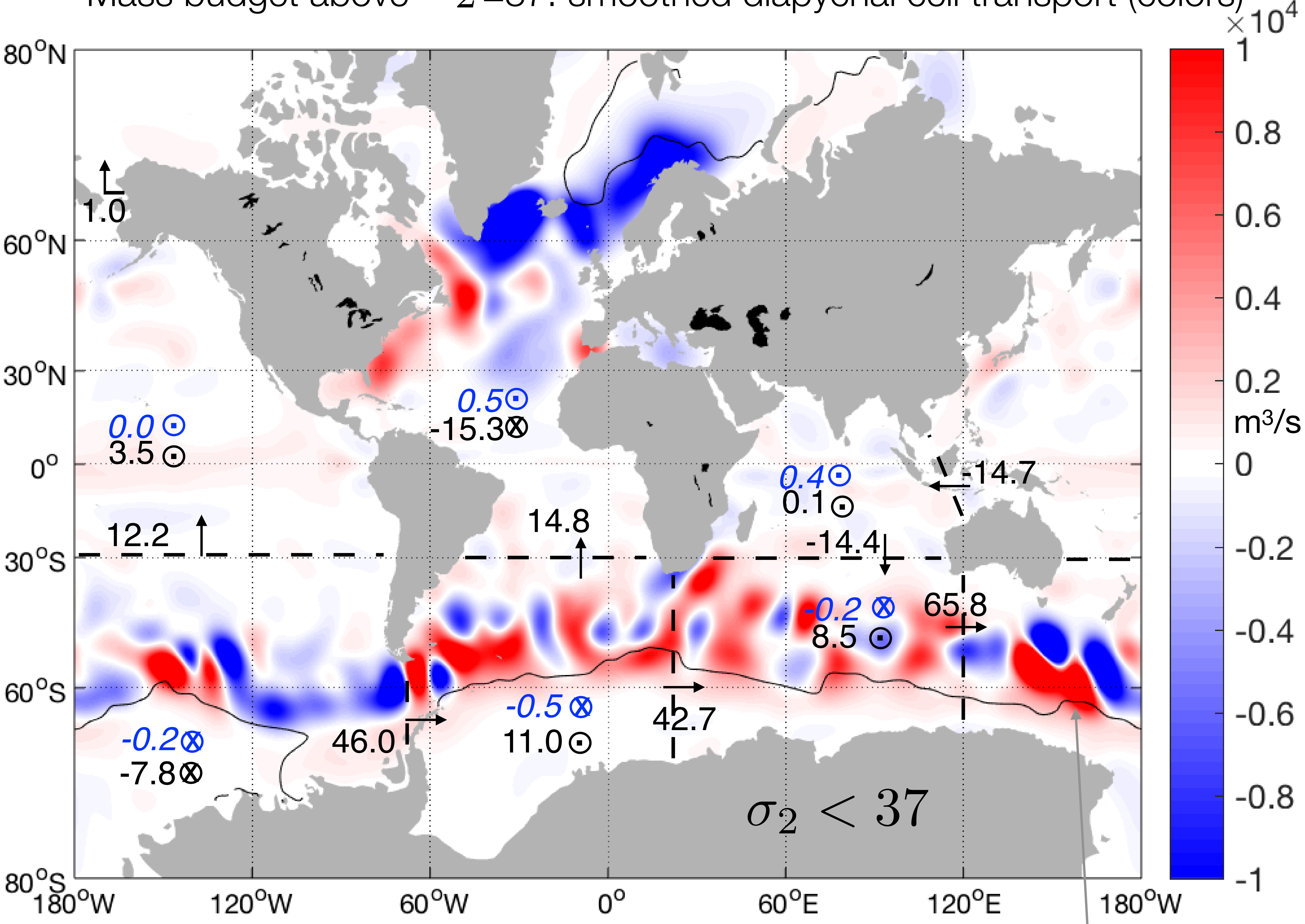


$$\frac{\Delta b}{2f_s}(h_a^2 - h_p^2) = \text{Ekman transport - Eddy transport + Diffusive upwelling}$$

- Wind-driven upwelling in the Southern Ocean (SO) pumps waters up & north
- Diffusive upwelling in all oceans pumps deep water up
- Deep water formation occurs in North Atlantic, but not North Pacific
- **How is water entering the Indo-Pacific returning to the Atlantic (warm versus cold route)?**

Interbasin exchanges in the Southern Ocean: upper branch of the ROC

Mass budget above σ_2=37: smoothed diapycnal cell transport (colors)



Surface freshwater transport in Sv ⊙
Diapycnal area transport across σ_2=37 in Sv ⊙
Section transport above σ_2=37 in Sv ⟶

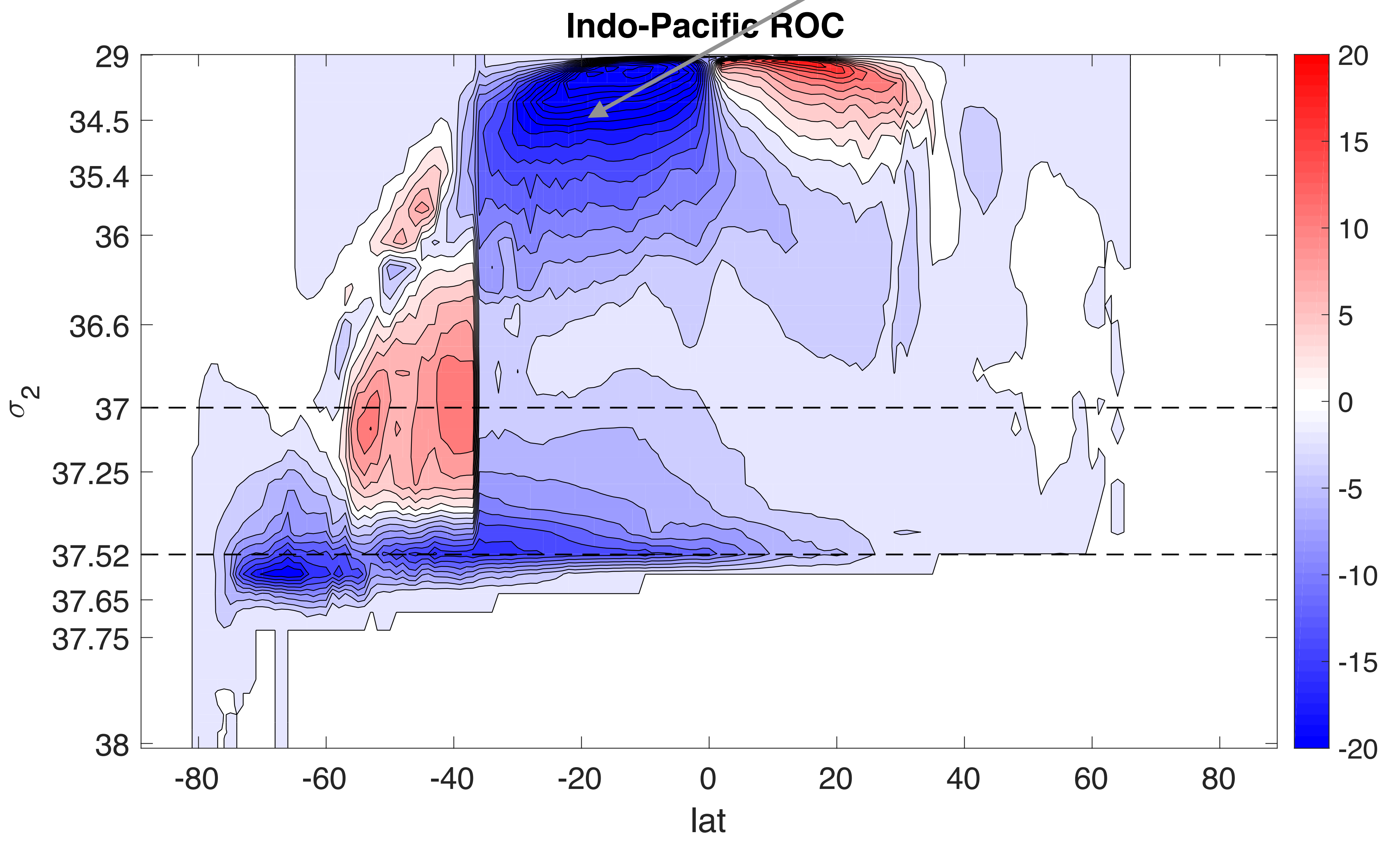
Climatological outcrop of σ_2=37

Large transformations in Southern Ocean

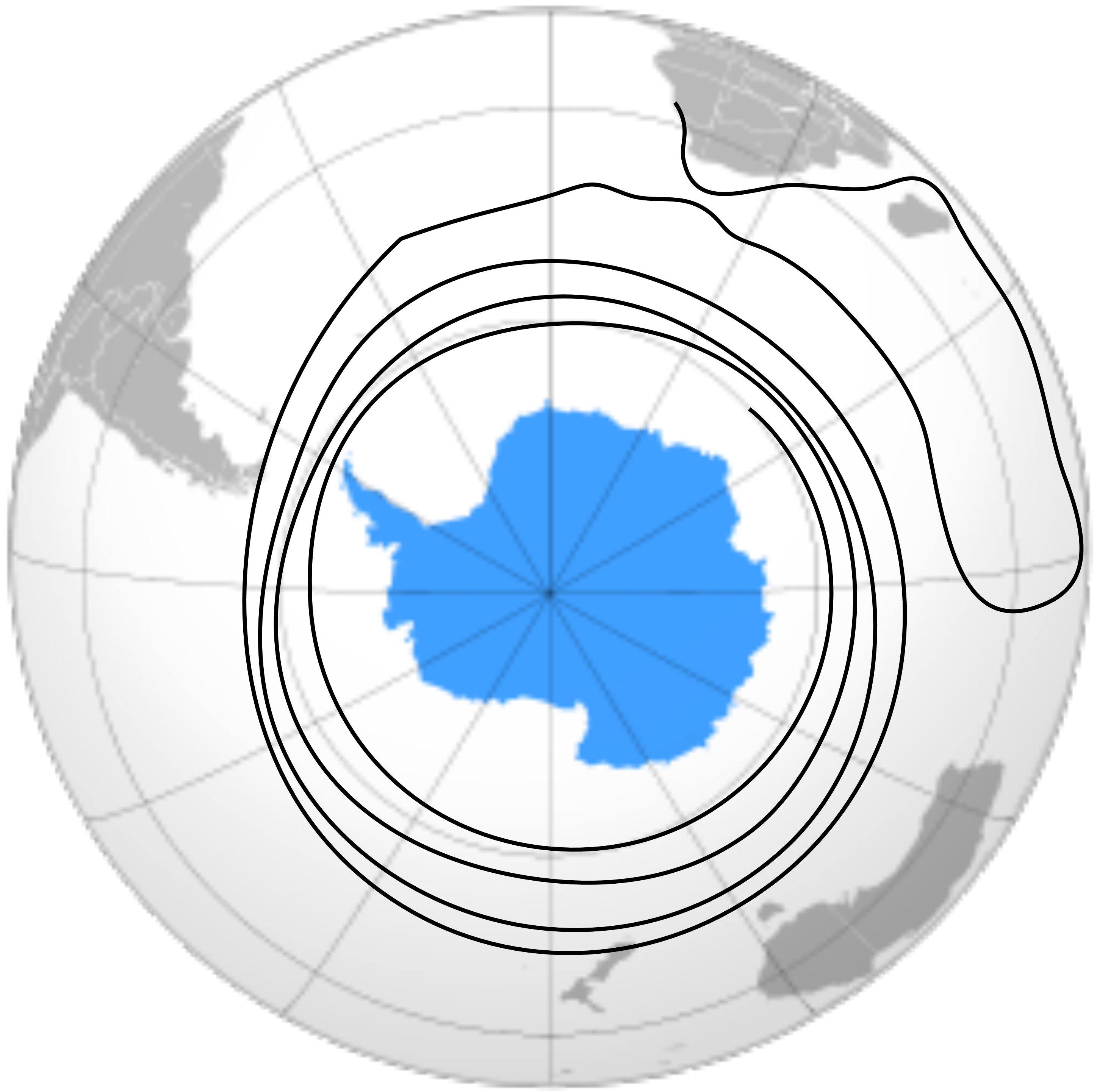
Cold-route vs. warm-route: obscured by ACC

Indonesian through-flow: obscured by supergyre

Tasman leakage: obscured by supergyre and ACC



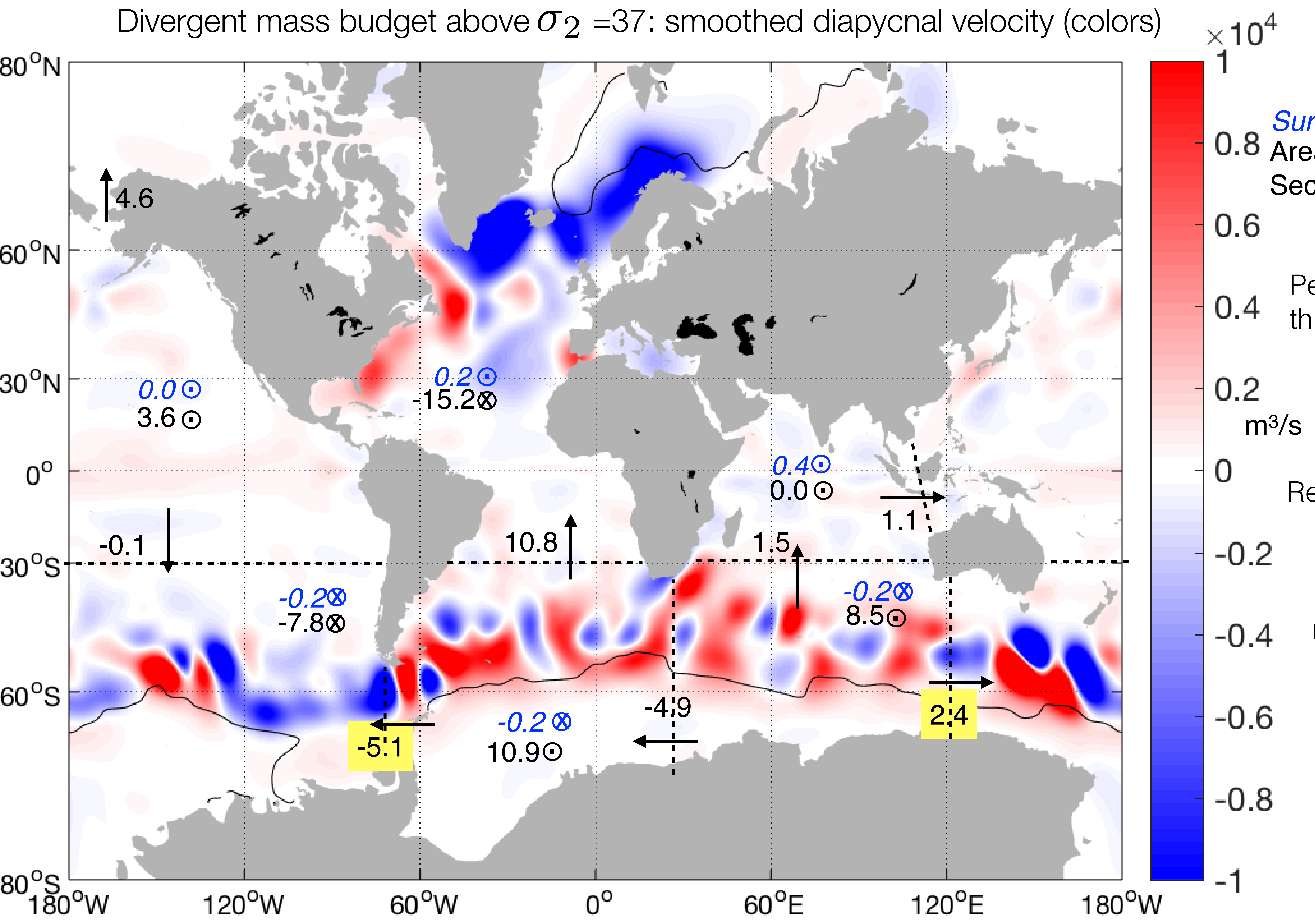
Particles circle tens of times before exiting into one sector



Schematic of a particle path with net eastward flow through warm route.

How does one focus on the net exchanged component of the transport?

Helmholtz decomposition on isopycnals: upper branch of the ROC



Surface freshwater fluxes in Sv ⊙

Area integrated diapycnal velocity at σ_2=37 in Sv ⊙

Section transport above σ_2=37 in Sv ⟶

Perform a Helmholtz decomposition on thickness integrated horizontal velocity[1]

$$\int_{h(\rho_2)}^{h(\rho_1)} (u, v)\,\mathrm{d}z = \mathrm{e}^3 \times \nabla_{\mathrm{h}}\psi + \nabla_{\mathbf{h}}\phi\,.$$

Recirculating component+Divergent component

$$\nabla\cdot\nabla_{\mathbf{h}}\phi = \varpi$$

minimizes energy norm — diapycnal velocity

Cold-route is negative!

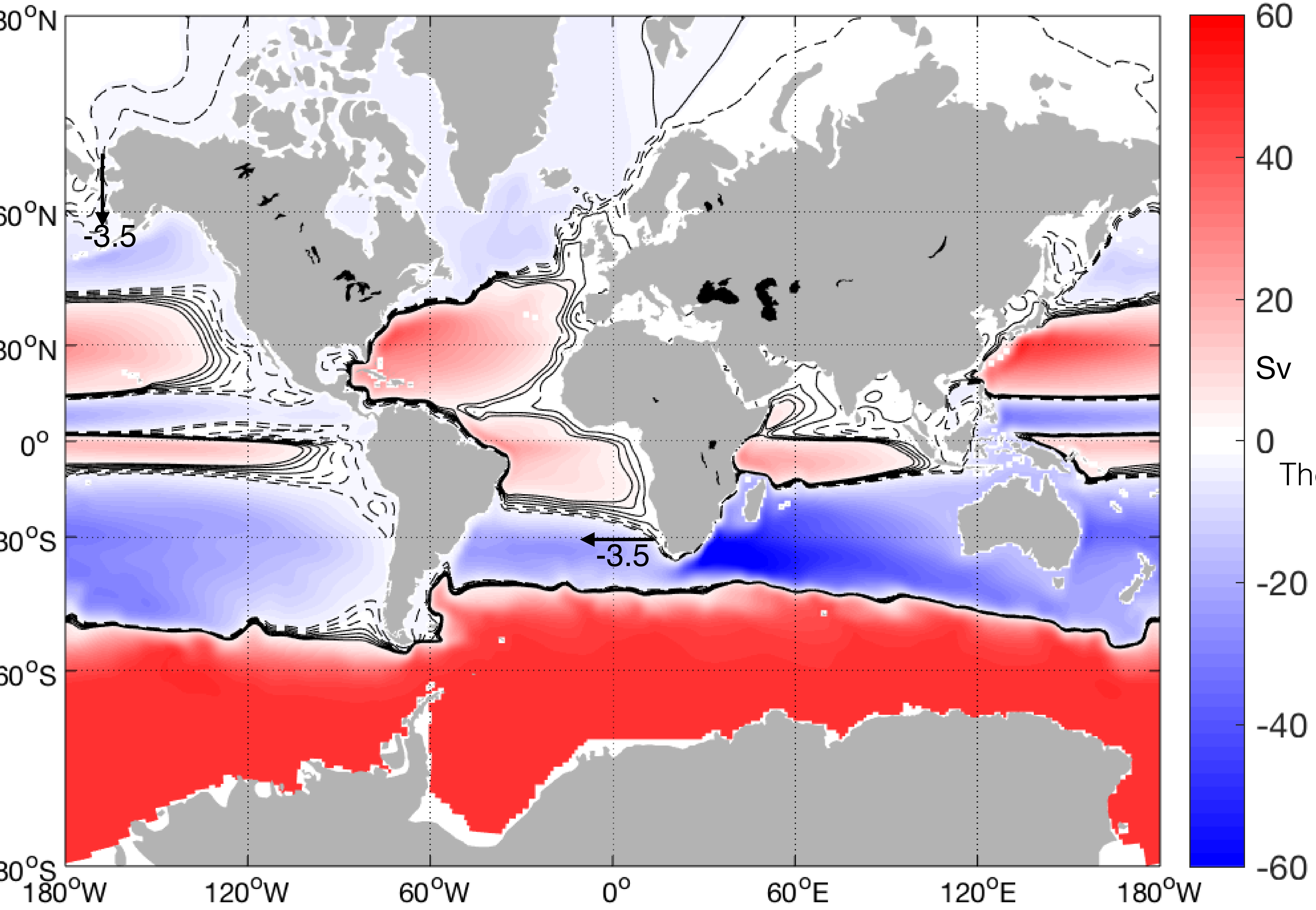
Tasman leakage is positive!

Is it meaningful? Need to compare with other methods, e.g. particle paths that carefully conserve volume, with unbiased starting points

[1]Young (JPO, 2012) shows how to do vector calculus in density coordinates: abandon orthogonality and use dual vectors.

Helmholtz decomposition on isopycnals: upper branch of the ROC

Streamfunction transport above σ_2 =37



Perform a Helmholtz decomposition on 50 thickness integrated horizontal velocities[1]

$$\int_{h(\rho_2)}^{h(\rho_1)} (u, v)\, \mathrm{dz} = \mathrm{e}^3 \times \nabla_\mathrm{h}\psi + \nabla_\mathbf{h}\phi\,.$$

Recirculating component+Divergent component

The recirculating component is a large gyre around the world

Inter-basin exchange: 0Sv through cold route

Inter-basin exchange: 3Sv through warm route

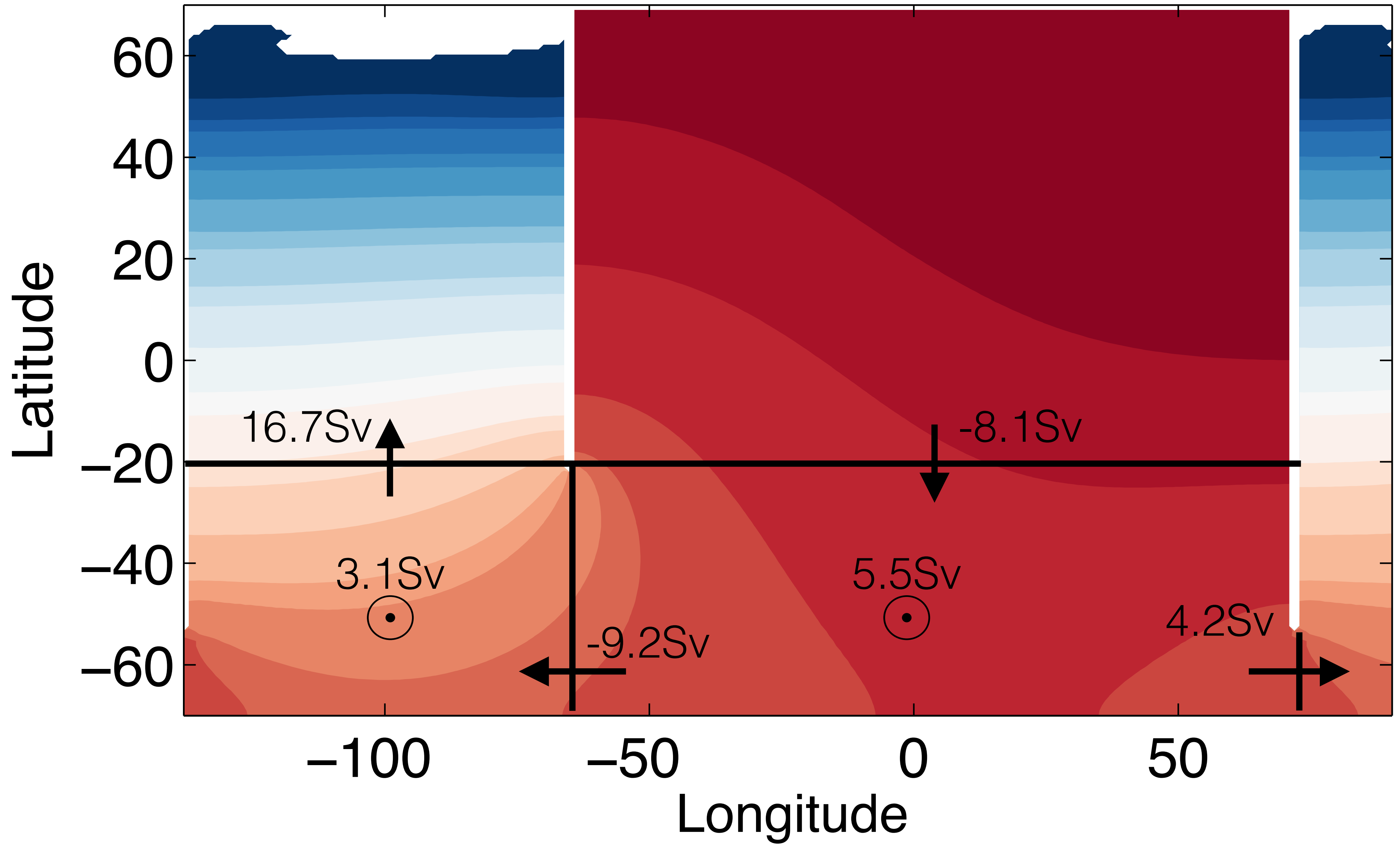
Super gyre max transport: 72Sv

Is it meaningful? Need to compare with other methods, e.g. particle paths that carefully conserve volume, with unbiased starting points

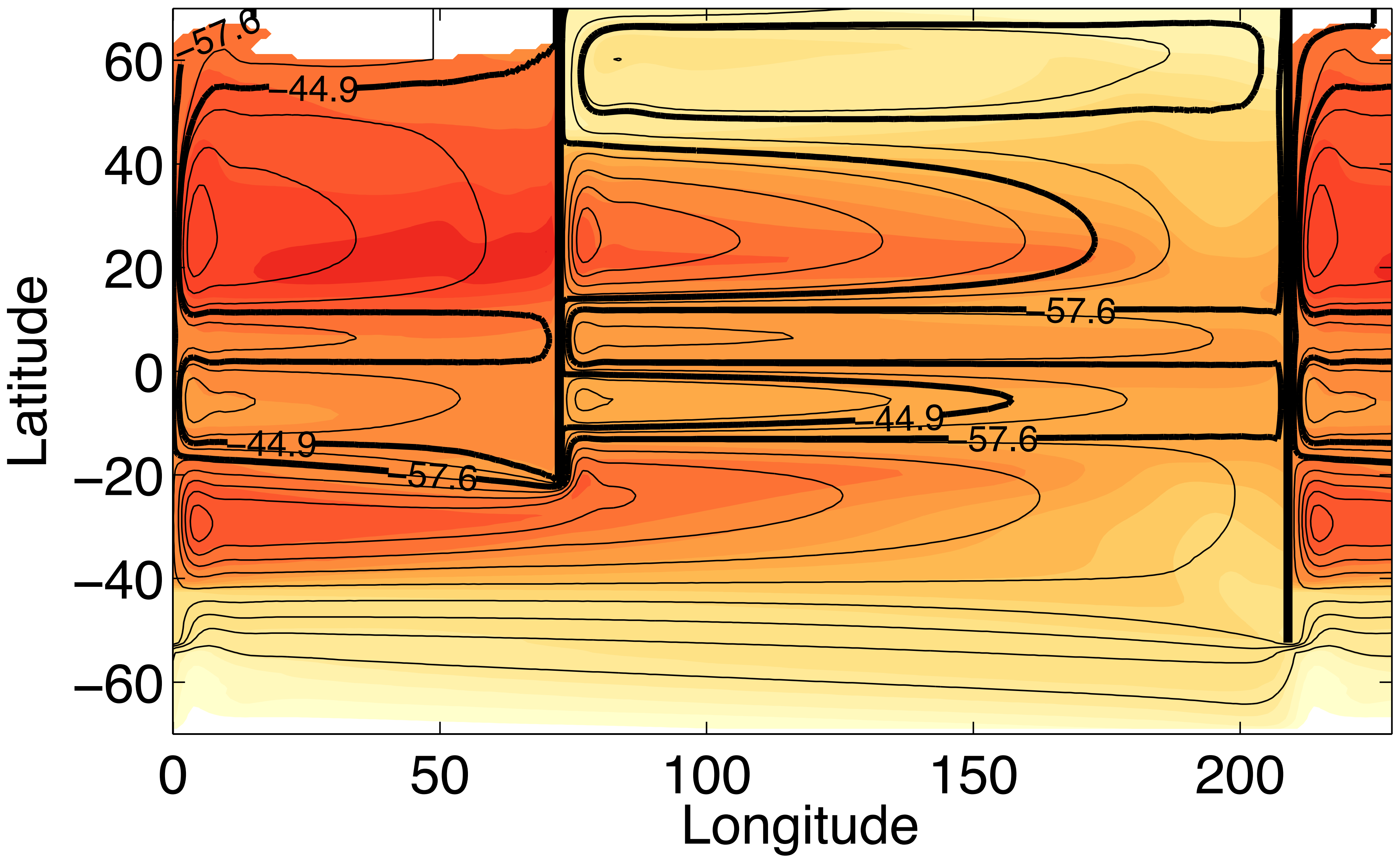
Neither components of Helmholtz decomposition show Indo-Pacific intermediate+thermocline water going **eastward** through the cold route
At least -4.9-3.5=-8.4 Sv are going **westward** through warm route.

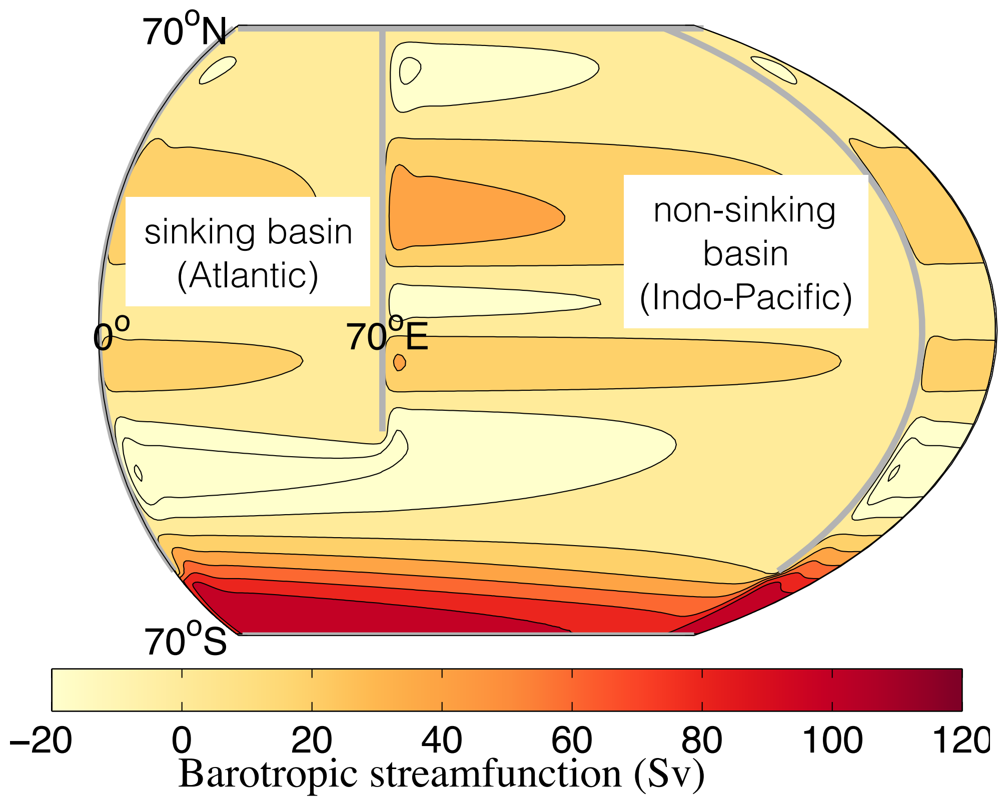
Helmholtz decomposition versus particle tracking in a simple model (Cessi&Jones 2017, Jones&Cessi 2018)

Velocity potential of divergent velocity (colors) and transport



Pseudo streamlines (contours) and salt (colors)





Particle paths and pseudo-streamlines show ZERO transport through cold route and about -15Sv through warm route.

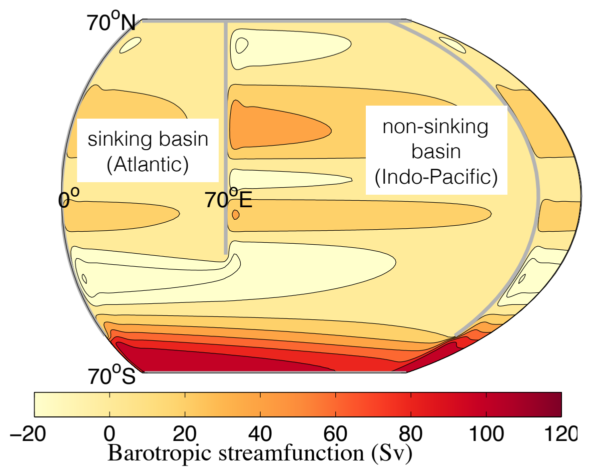
Velocity potential distributes the transport between routes to minimize u^2+v^2

It appears that streamfunction is more faithful to particle paths (for weak divergence)

All transports are calculated using sum of Eulerian+bolus velocity: very different answer with Eulerian only! Indicates importance of eddy transport.

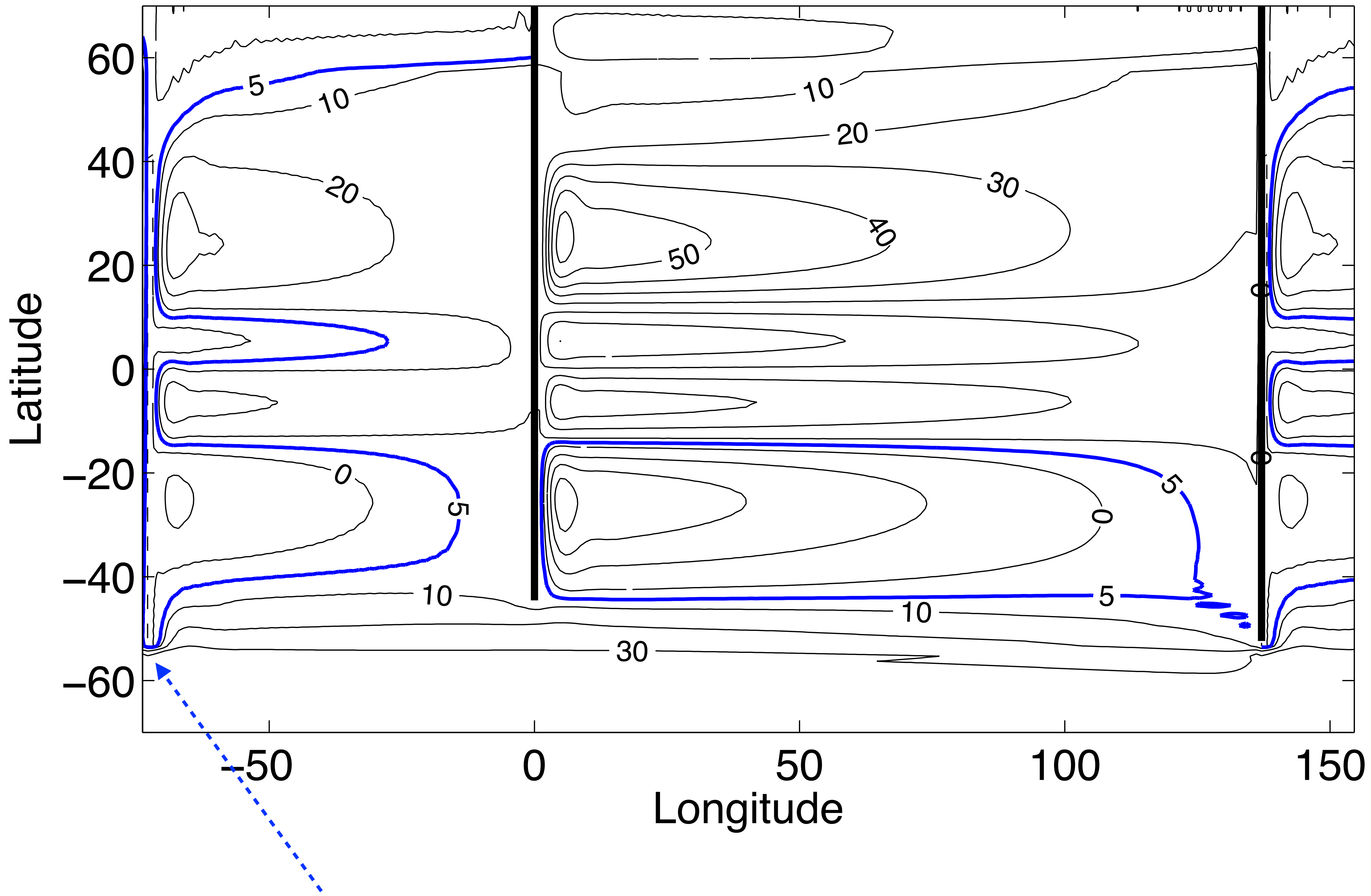
Need to apply these diagnostics to complex/high resolution models and data sets to quantify exchanges.

Simple models need to lengthen S. Africa to 45^{o}S for cold route (Cessi&Jones 2017, Jones&Cessi 2018)



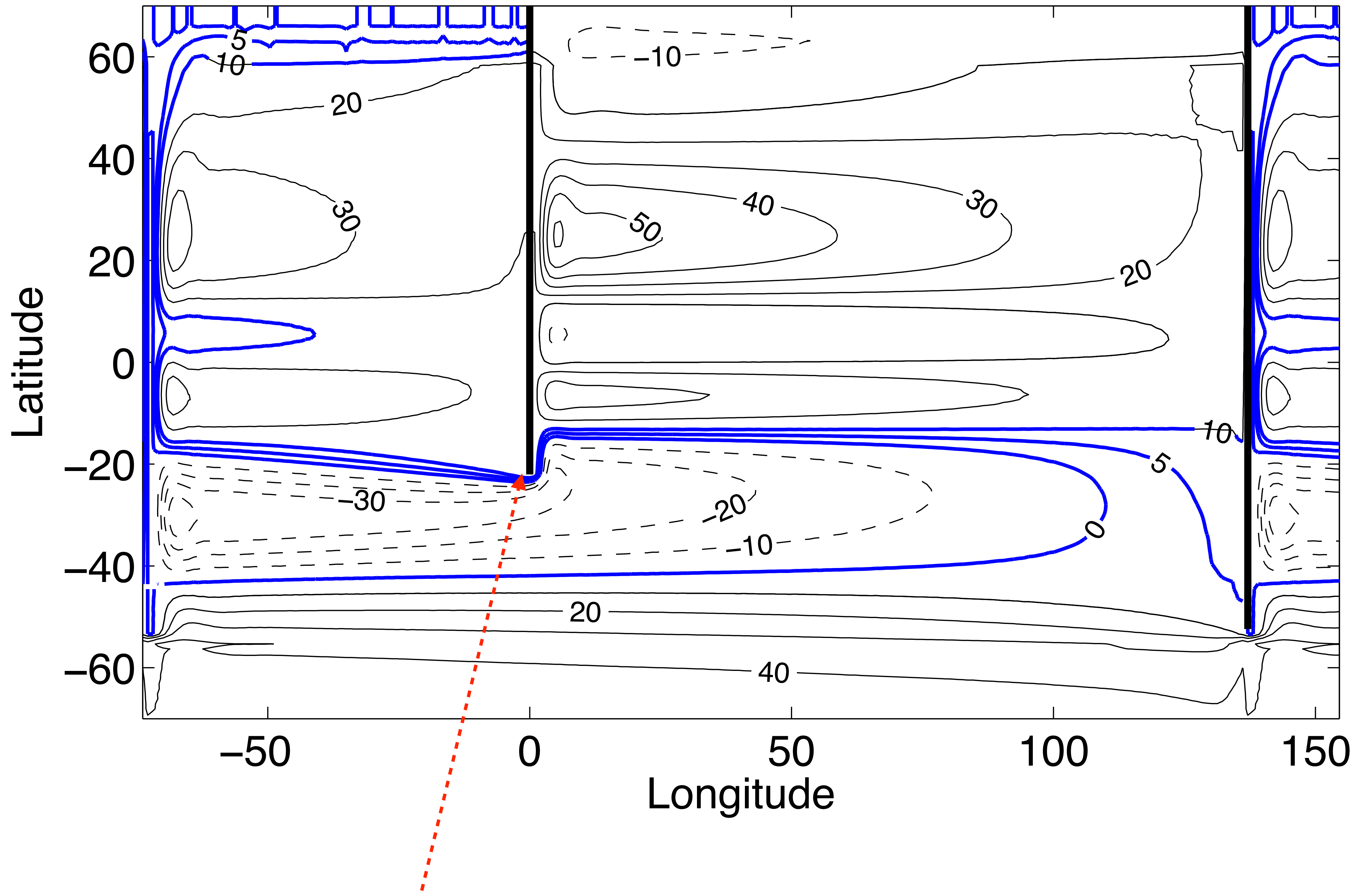
Long continent **always** ends at 52S

Short continent ends at **45S**



Cold route

Short continent ends at **21S**



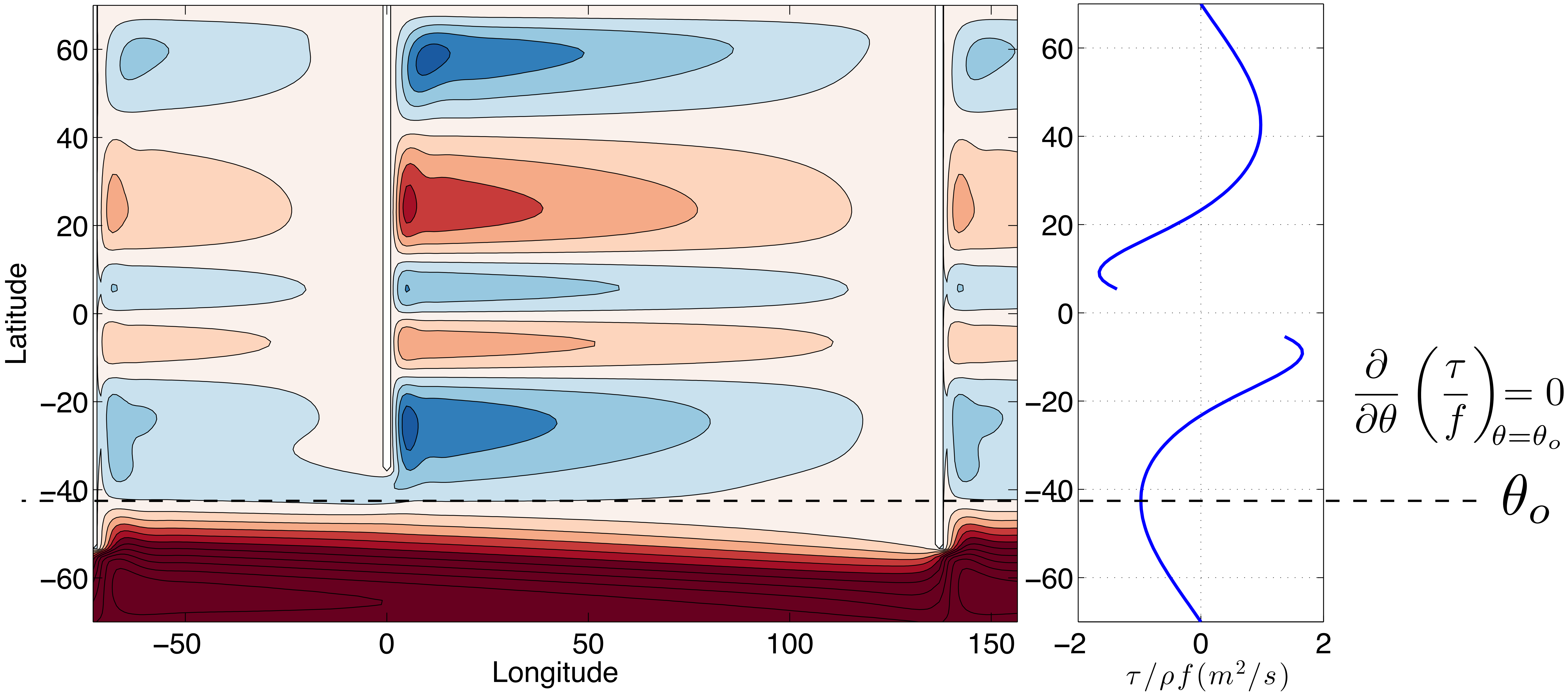
Warm route

Particle paths and pseudo-streamlines show ZERO transport through warm route if S. Africa is at 45^{o}S or 53^{o}S

Particle paths and pseudo-streamlines show ZERO transport through warm route if S. Africa is at 35^{o}S or 21^{o}S

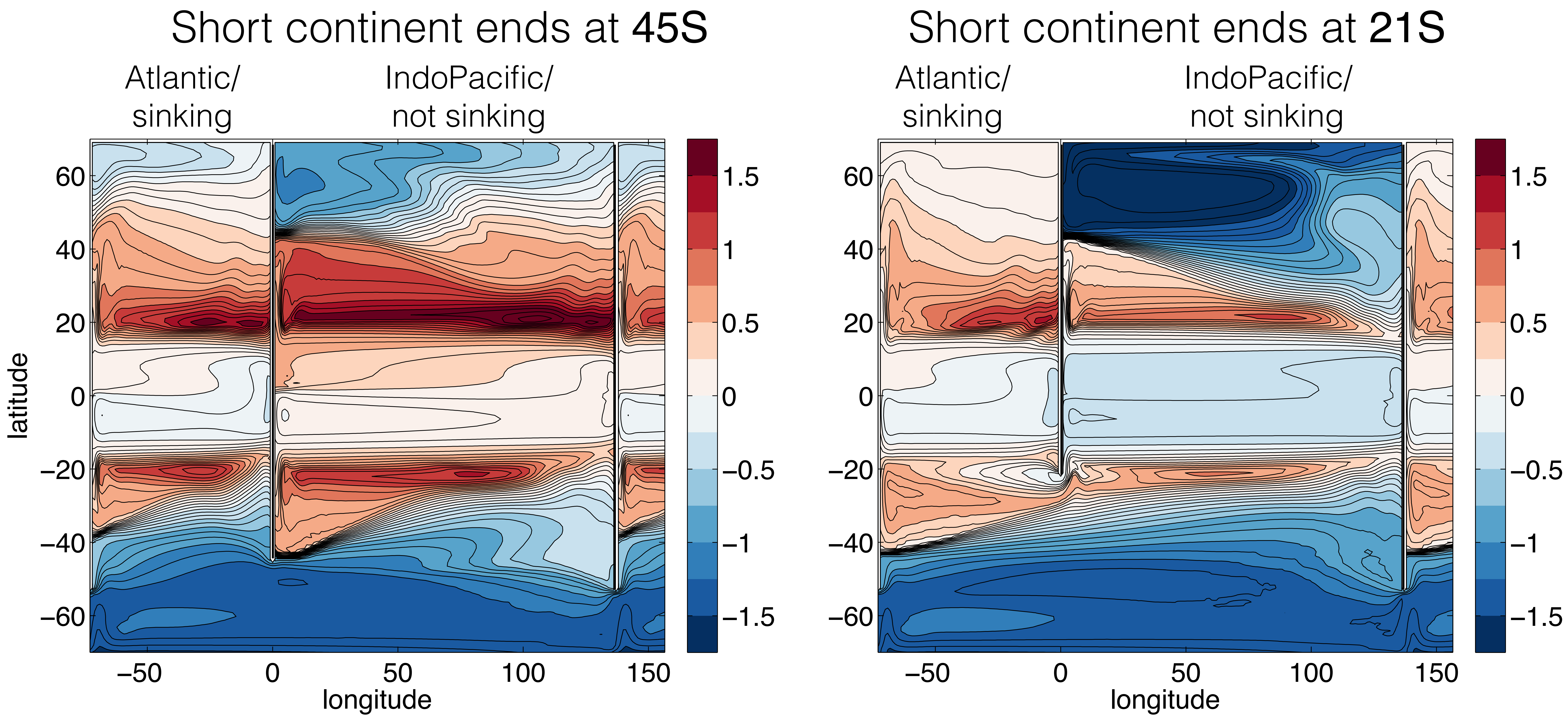
Zero Ekman pumping latitude θ_o sets warm vs. cold route

Barotropic streamfunction from GCM



- North of θ_o there are gyres
- South of θ_o the flow is cyclonic and circumpolar (periodic)
- If continent ends **north** of θ_o: **a single SUPERGYRE**
- If continent ends **south** of θ_o: **two separate gyres**

Surface salinity for different continent lengths



Narrow sinking in both configurations, but **qualitative** difference in salinity:

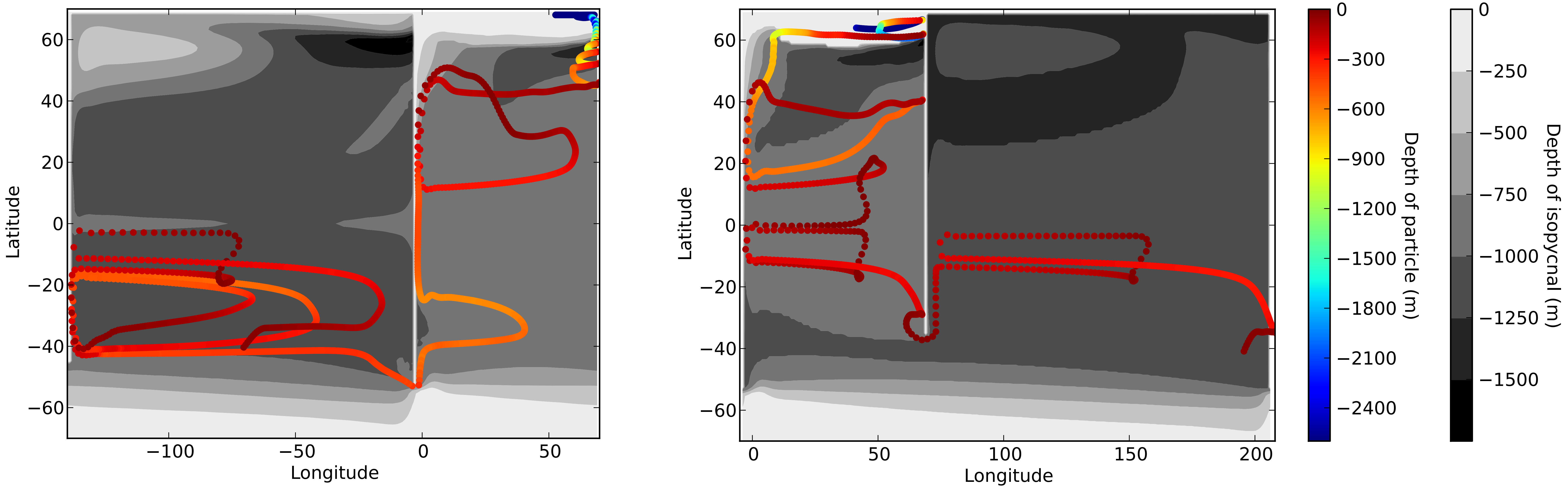
Short continent at 45S: SSS is saltier only in far north of sinking basin

Short continent at 21S: SSS is saltier everywhere in sinking basin

Examples of particle paths in 3D (biweekly dots)

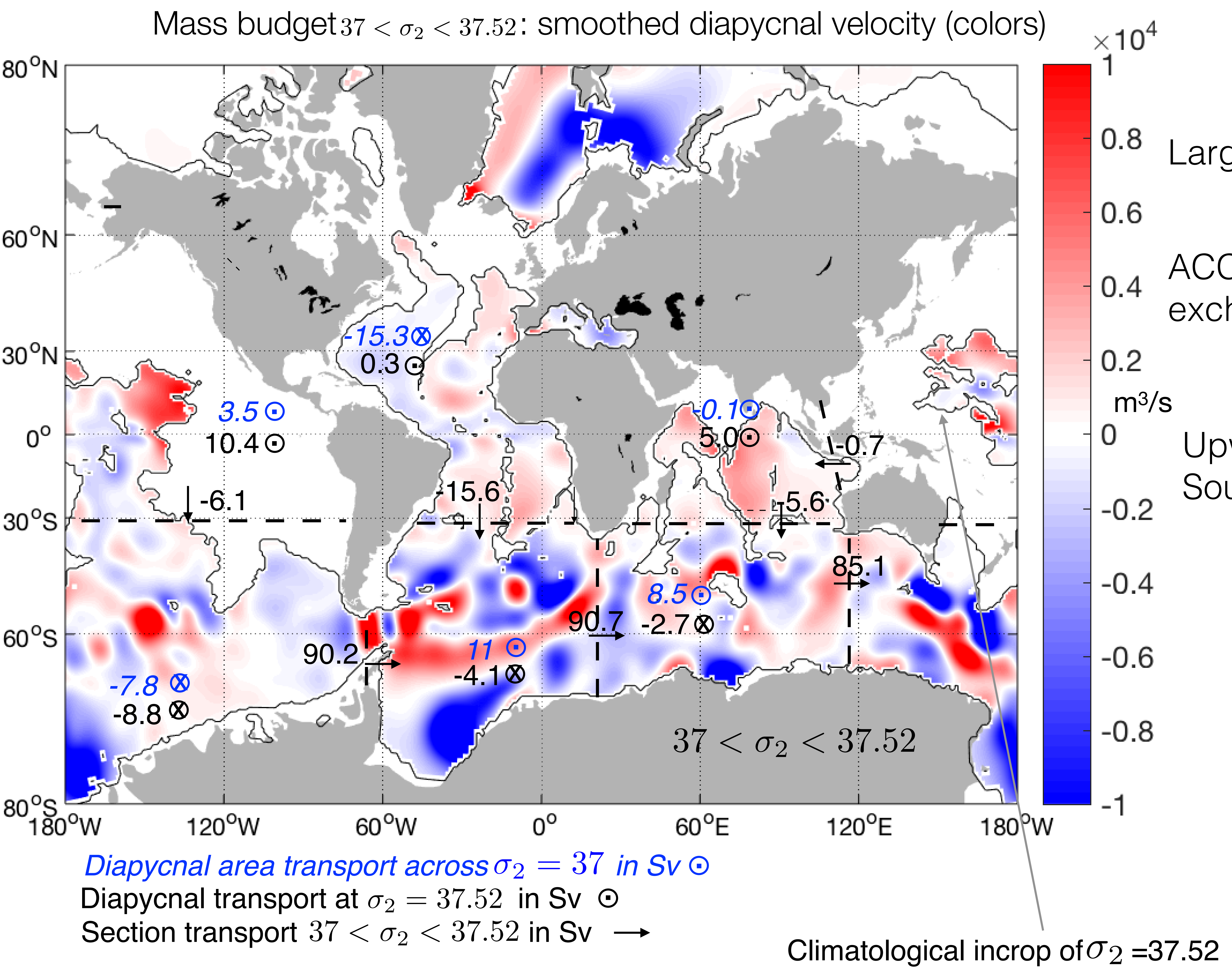
Short continent ends at 45S

Short continent ends at 35S



Short continent ends at 45S	Short continent ends at 35S
Pushed northward by Ekman transport	Pushed northward by Ekman transport
Subducts & goes around subtropical gyre	Subducts & goes around subtropical gyre
Exits in subpolar region	Exits in subtropical region
Enters active basin in subpolar region	Enters active basin in subtropical region
Spirals around gyres	Spirals around gyres
Drains out of the isopycnal	Drains out of the isopycnal
Cold route follows cyclonic circumpolar flow	Warm route follows anticyclonic supergyre

How much NADW is recycled through the abyssal cell before upwelling?



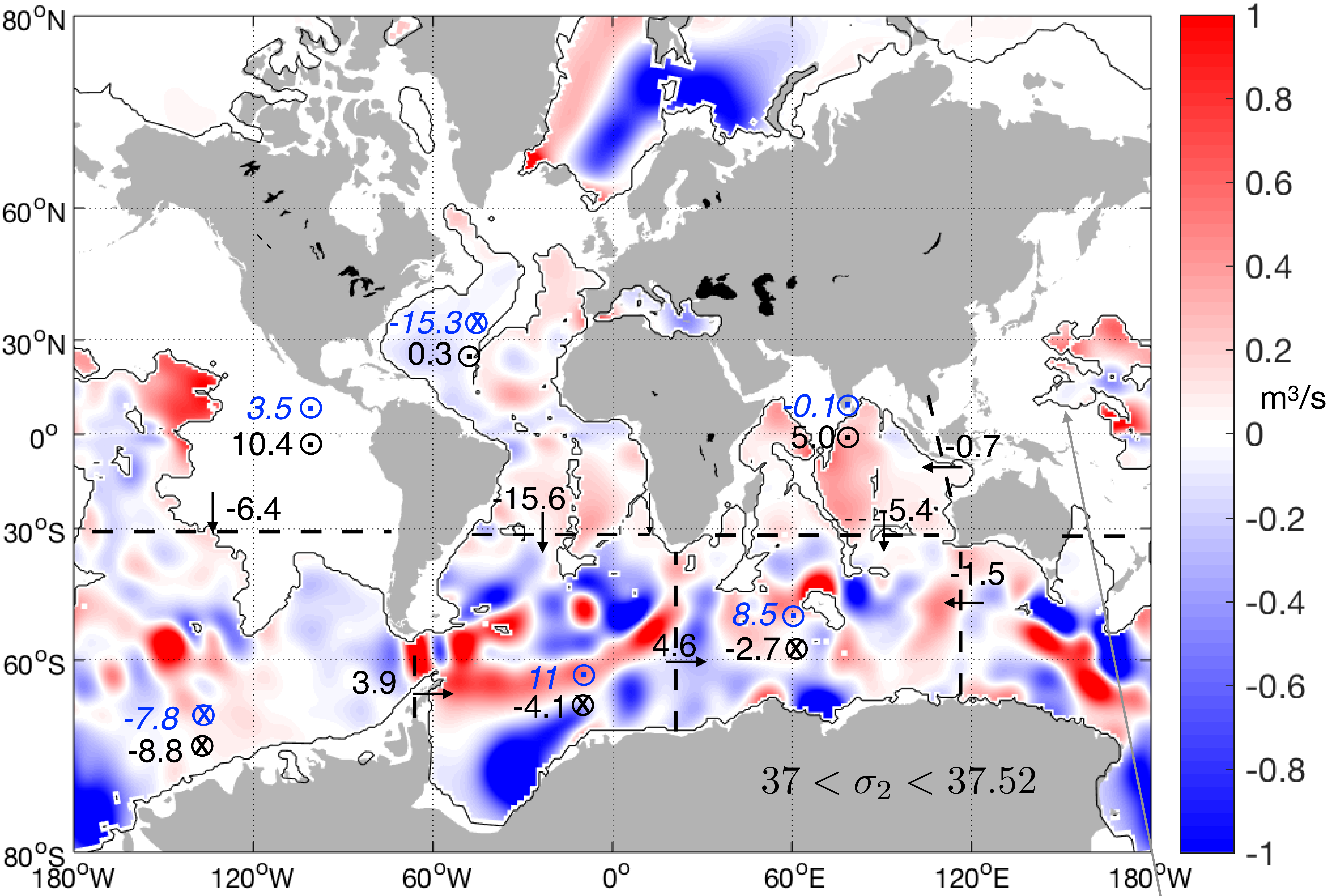
Large transformations in Southern Ocean

ACC transport is much larger than interbasin exchanges

Upwelling in Atlantic and Indian sectors of Southern Ocean

Helmholtz decomposition on isopycnals: NADW branch of the ROC

Divergent mass budget $37 < \sigma_2 < 37.52$: smoothed diapycnal velocity (colors)



Diapycnal area transport across $\sigma_2 = 37$ in Sv ⊙

Diapycnal transport at $\sigma_2 = 37.52$ in Sv ⊙

Section transport $37 < \sigma_2 < 37.52$ in Sv ⟶

Climatological incrop of σ_2 =37.52

Several possible interpretations: with different degrees of recycling of NADW in the abyssal cell

Need some guidance from particle paths (mass) and numerical tracer release experiments

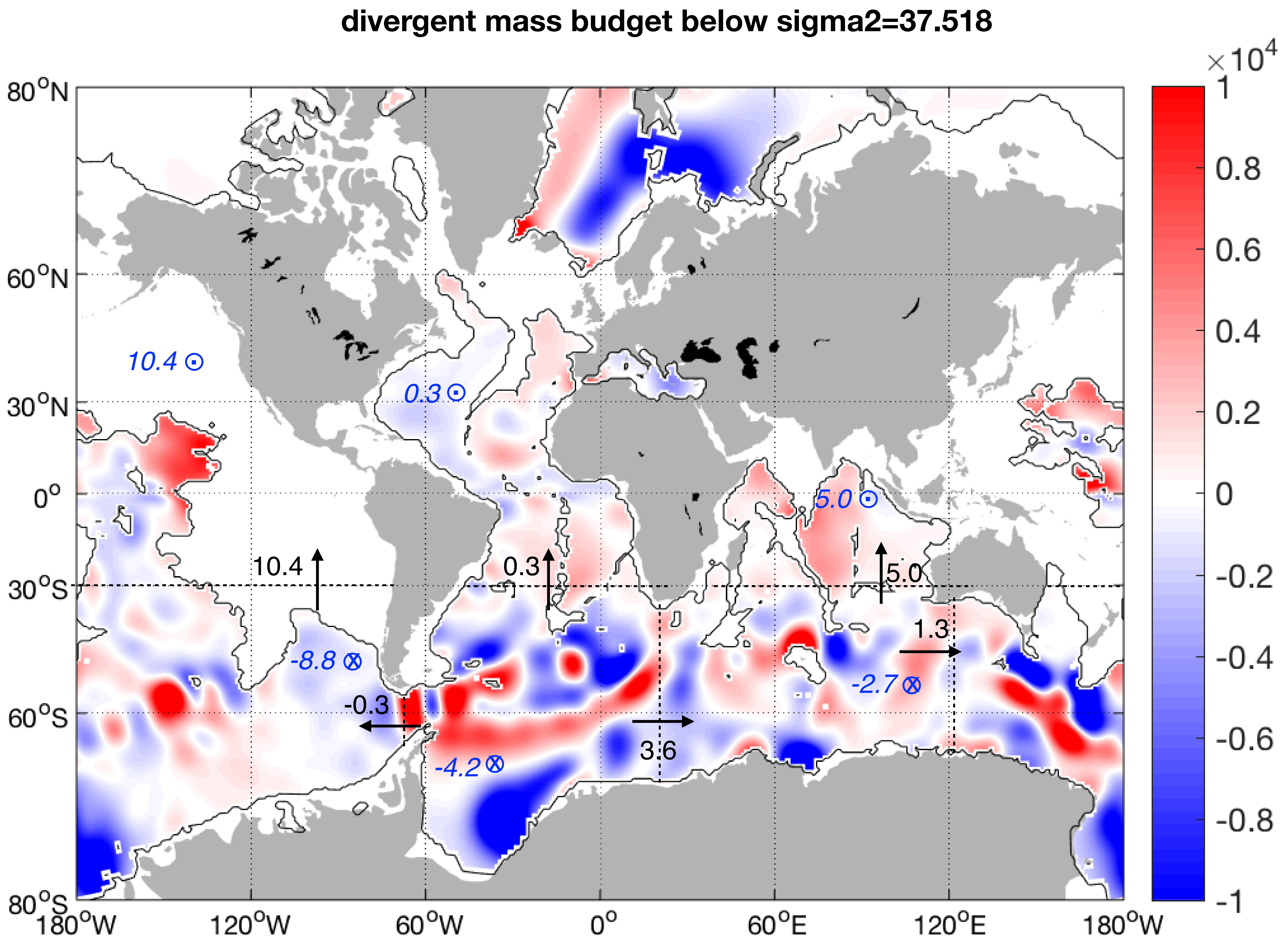
Estimate	Data	30°S transport	%recycled into AABW
ECCO4	Hydrography,Argo, SST,altimeter,geoid, MITgcm	17Sv	28%-100%
Lumpkin& Speer 2007	Hydrography+inverse	21Sv	70%
Talley 2013	Hydrography	29Sv	100%

Some fake news debunked

- ECCO4 24 years not equilibrated in abyss: ECCO4 is adjoint not a forward model.
- Only altimeter anomalies are used: full altimetry with geoid model using GRACE data.
- Eddy and diapycnal coefficients specified: 3-D fields part of the optimized parameters.

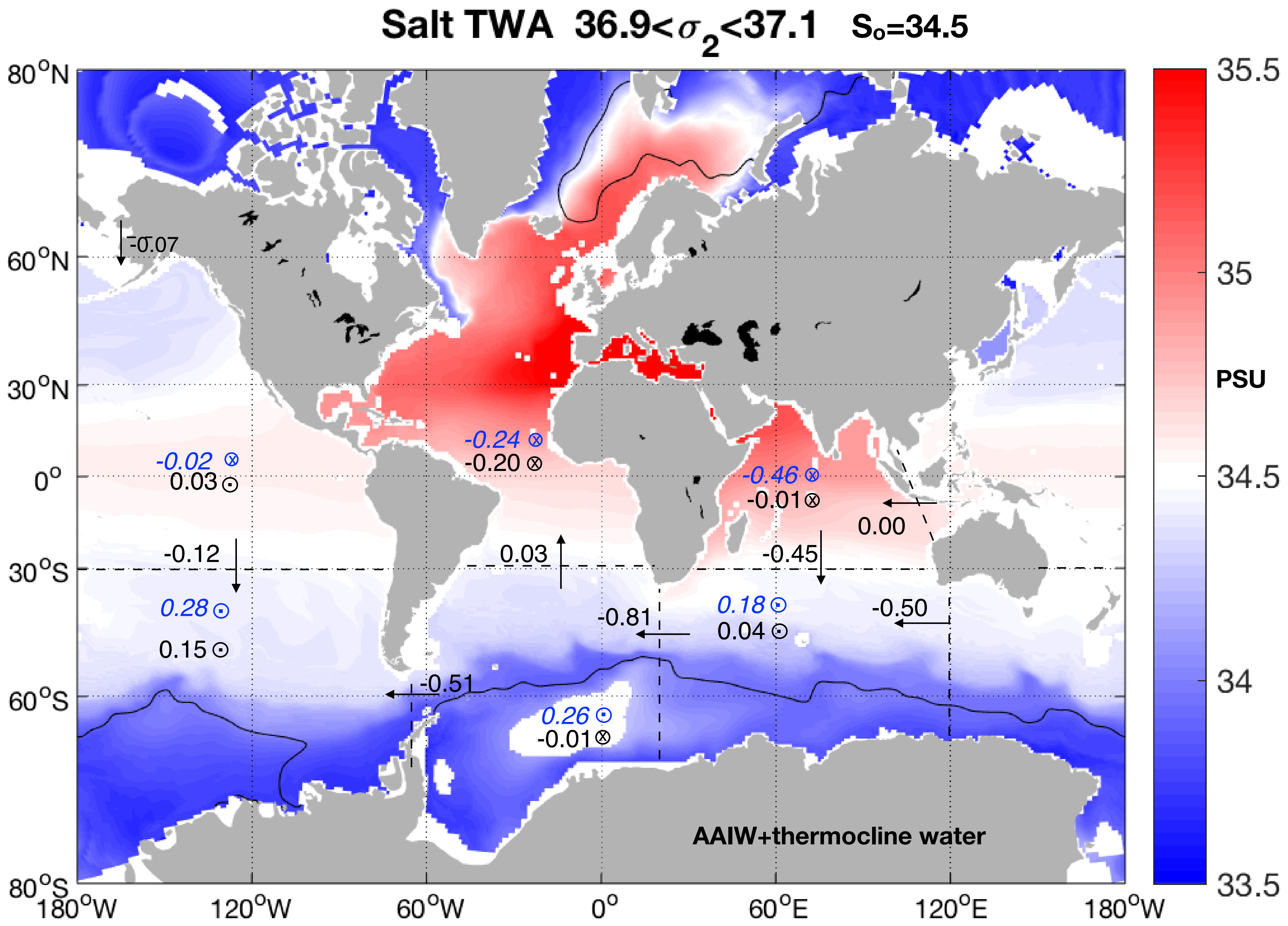
Conclusions

- Data estimates of residual overturning circulation differ quantitatively
- Interbasin exchange of ROC is geostrophically balanced leading to isopycnal depth differences
- Neither simple models nor ECCO4 estimate show cold-route exchange in upper ROC
- Theory suggests that cold-route requires Cape Horn in subpolar wind-stress regime
- Interbasin and intercell exchanges obscured by the large recirculation of ACC and super gyre
- Need to apply diagnostics (Helmholtz decomposition and particle tracking) to eddy-resolving models to quantify inter-basin and inter-cell exchanges.
- How do these methods compare quantitatively with traditional water-mass diagnostics from hydrography?

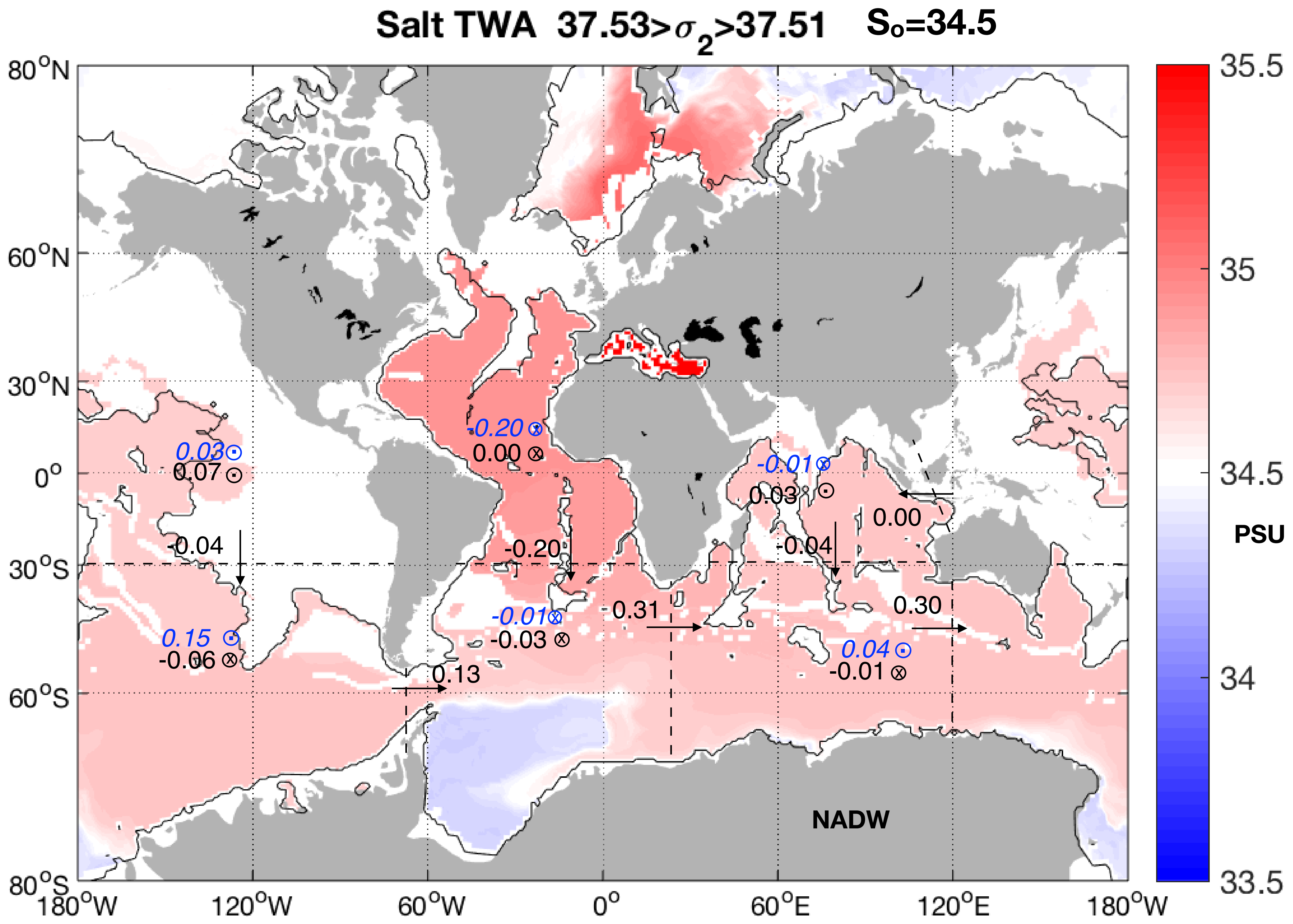


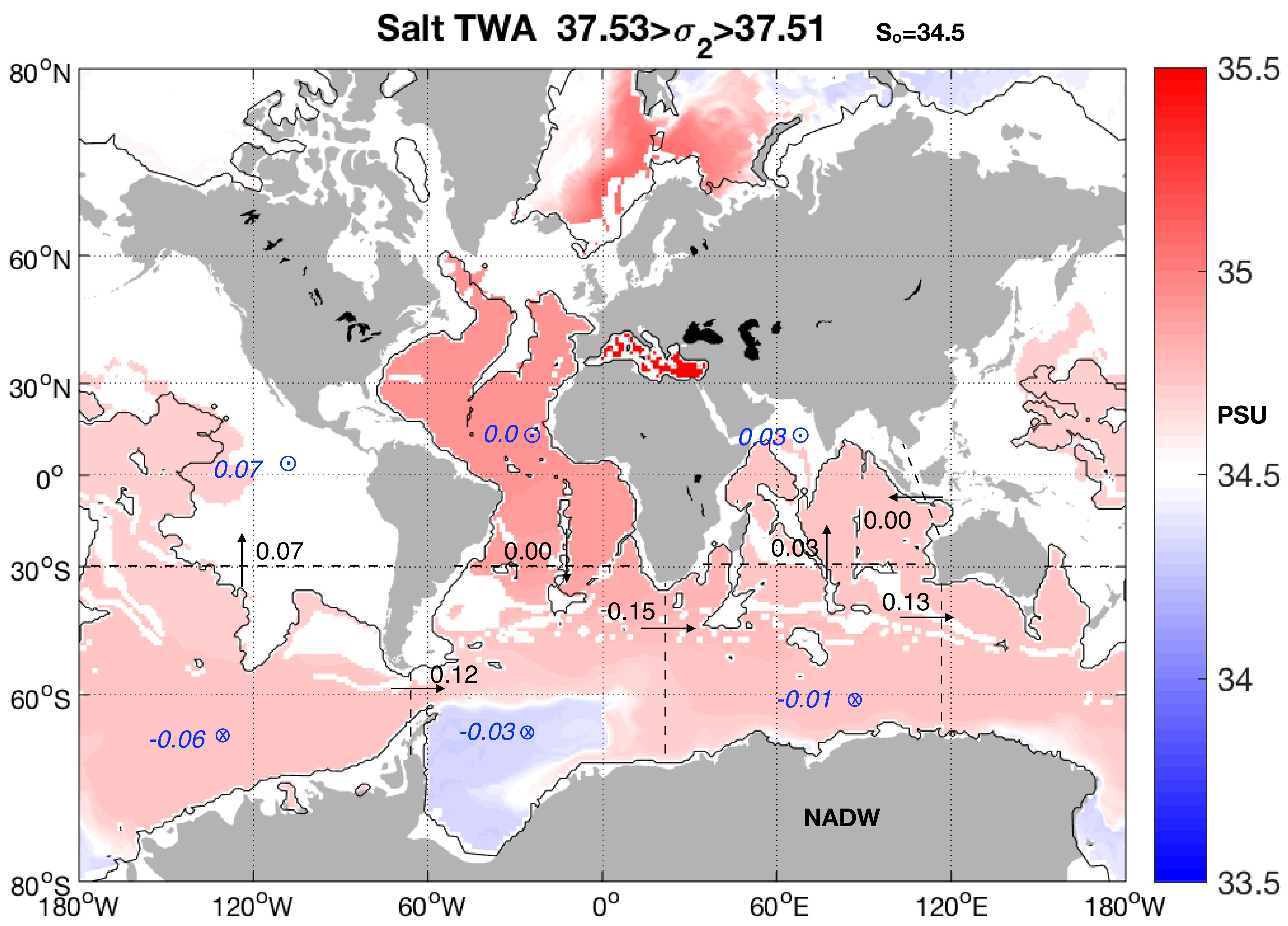
divergent mass budget below sigma2=37.518
80°N
60°N
30°N
0°
30°S
60°S
80°S
180°W
120°W
60°W
0°
60°E
120°E
180°W
×10^4
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
10.4
0.3
5.0
10.4
0.3
5.0
1.3
-8.8
-2.7
-0.3
3.6
-4.2

salt budget above sigma2=37. referenced to S_o



salt budget for NADW 37.52>sigma2>37 referenced to S_o




Salt TWA 37.53>σ2>37.51
So=34.5
80°N
60°N
30°N
0°
30°S
60°S
80°S
180°W
120°W
60°W
0°
60°E
120°E
180°W
35.5
35
PSU
34.5
34
33.5
0.07
0.0
0.03
0.07
0.00
0.03
0.00
0.15
0.13
0.12
-0.06
-0.03
-0.01
NADW