AMOC Lagrangian Mass, Heat & Salt Transport
(preliminary work)

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Goal of Lagrangian analysis applied to ECCO

1. Quantify the paths of mass, heat and salt for the large-scale ocean circulation
2. Quantify the spatial distribution of property-transformations
3. Quantify the transit-transit time distributions between target locations
4. Understand the contribution of individual processes to mass, heat and salt fluxes

Tracer analysis is an alternative to Lagrangian analysis (Ichiro's talk)

Pros and cons of Lagrangian versus Eulerian tracer analysis

A. Lagrangian analysis allows to solve tracer advection with no diffusion. Numerically, cannot solve $\partial_t T + \nabla \cdot (\mathbf{v}T) = 0$, but can solve

$$\dot{\mathbf{x}} = \mathbf{v}(\mathbf{x}, t)$$

B. With no diffusion, transport of **mass** (volume) can be quantified

C. Advective transport of θ, S is computed tracking properties along Lagrangian trajectories

D. Diagnosing transformation of $\sigma_n(\theta, S)$ with complicated EoS is simple: $\dfrac{D\sigma_n}{Dt} = \mathscr{D}_{\sigma_n}$. Just record $\sigma_n(\theta, S)$ along trajectories at discrete time intervals to get $D\sigma_n/Dt$. Tracers need $\dfrac{\partial \sigma_n}{\partial \theta}|_S \mathscr{D}_\theta + \dfrac{\partial \sigma_n}{\partial S}|_\theta \mathscr{D}_S$ (complicated).

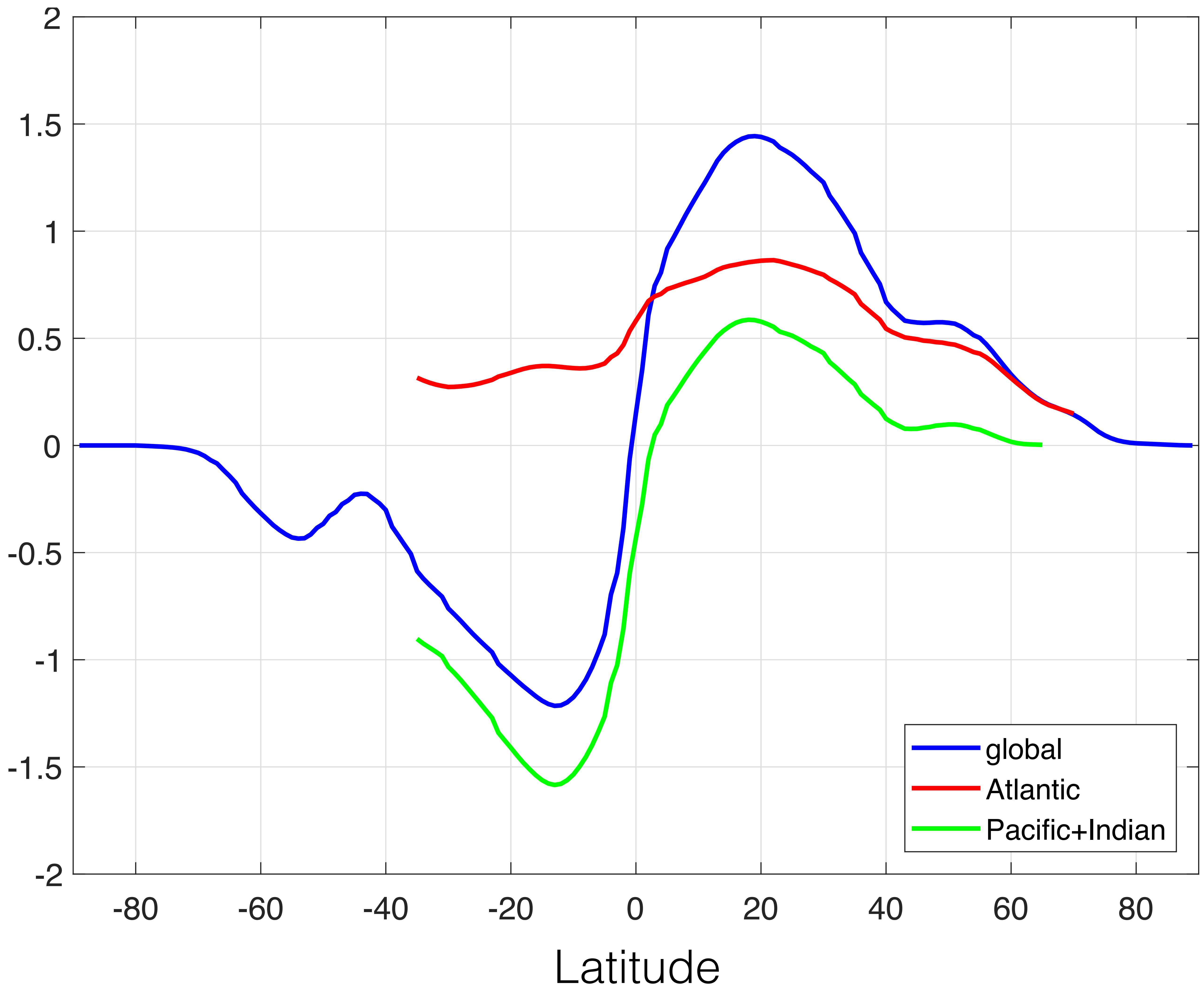
E. $\dot{\mathbf{x}} = \mathbf{v}$ is computationally more efficient for localized injections: no need to solve equations at empty wet-points (~ 2.4×10^6 wet-points in ECCO). Lagrangian time-steps are longer (5 hours) than tracer time steps (1 hour) for high-order schemes (e.g. Runga-Kutta 4th).

F. The diffusive transport is omitted, but can be calculated from $\dfrac{DT}{Dt} = \mathscr{D}_T$ (complicated)

Review of ECCO climatology and motivation

Can individual components of heat transport be isolated?

Time-mean heat transport 1992-2017 ECCOV4r4 (PW)

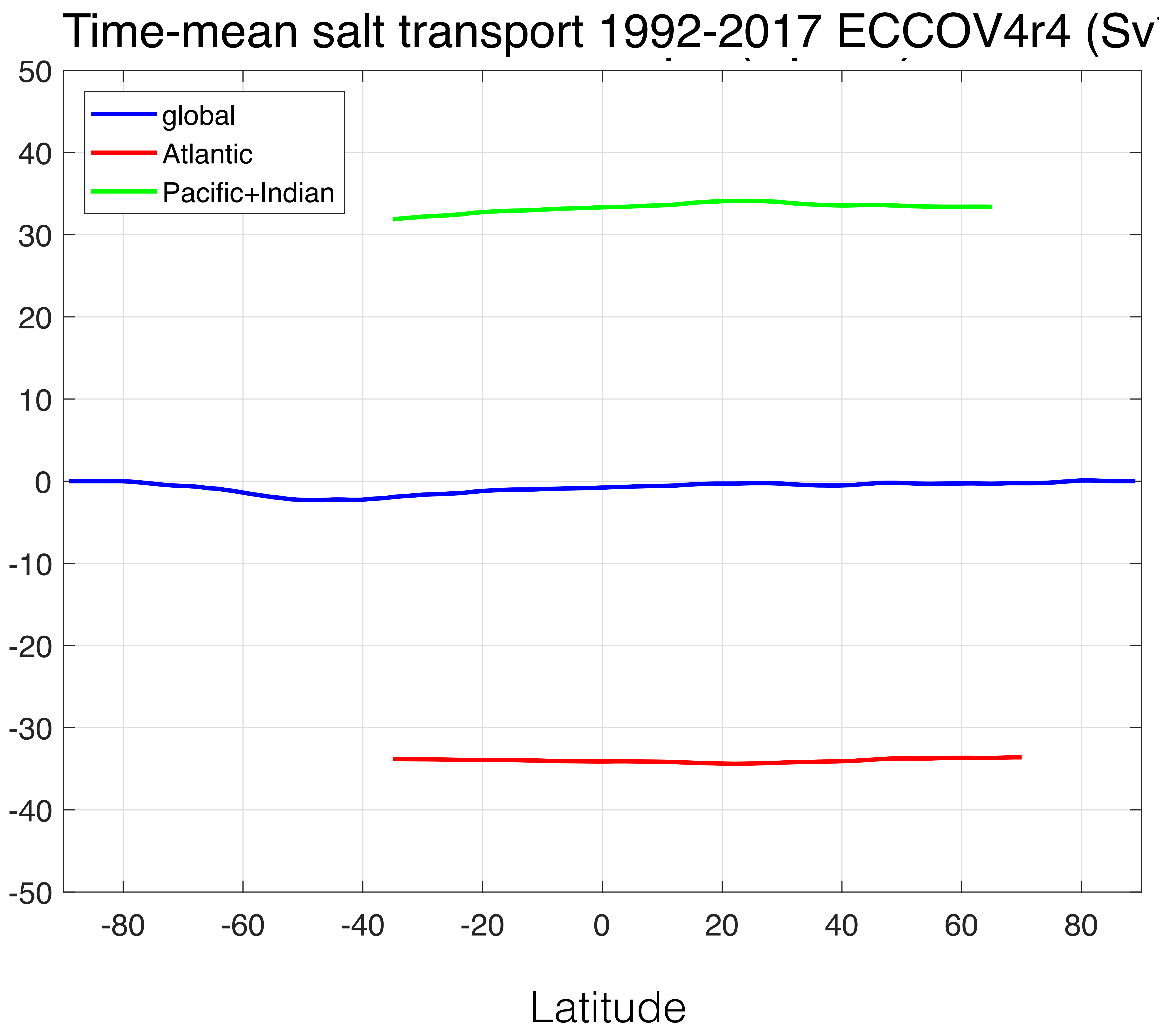


1. Atlantic heat transport is everywhere northward because of AMOC.

2. Can we quantify how much is due to MOC versus gyres?

3. Is it a sensible question, or are the gyres and MOC completely intertwined?

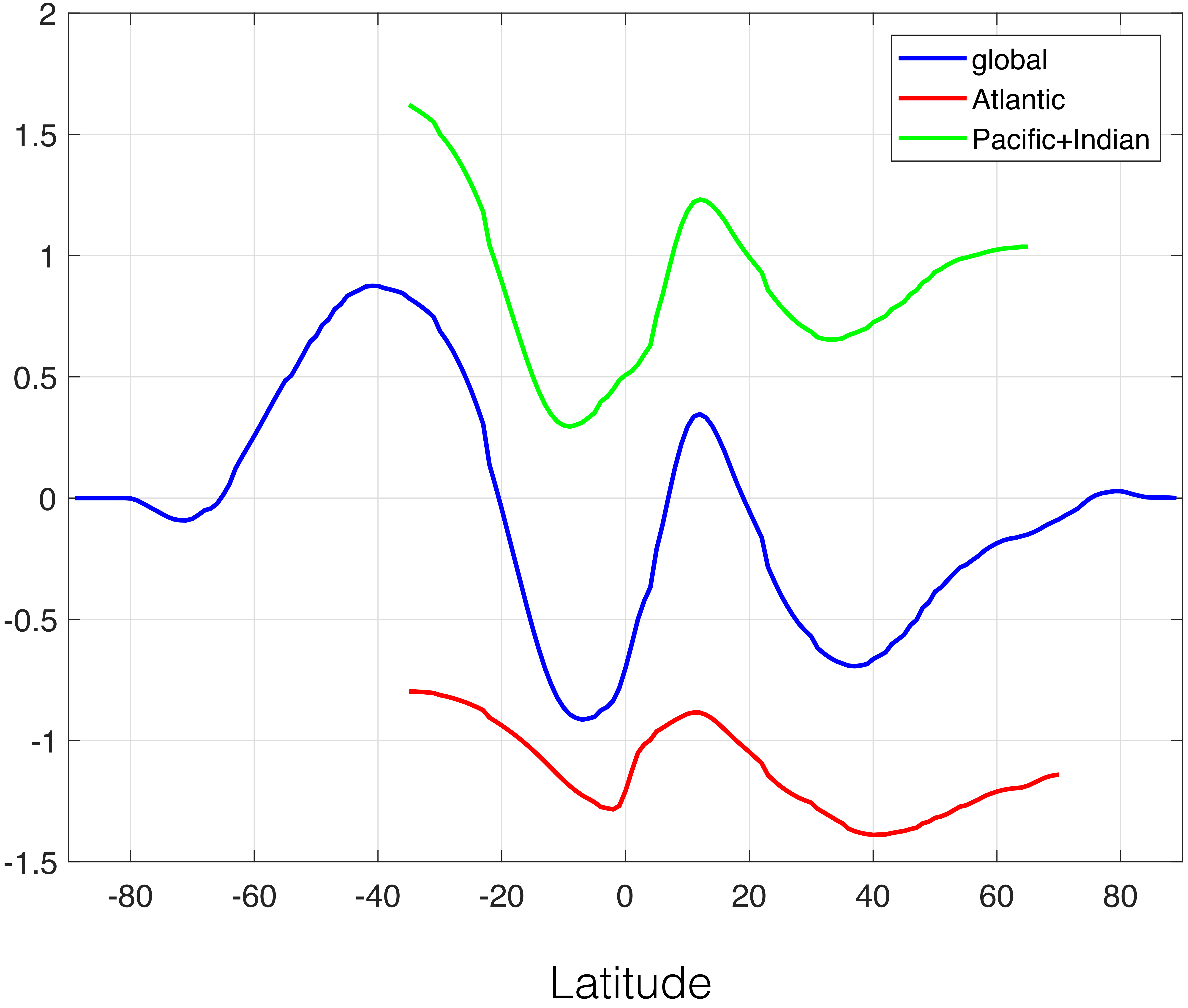
Can individual components of salt transport be isolated?



1. Northward Atlantic salt transport by the AMOC is deemed essential for its stability (salt-advection feedback).
2. Salt transport is obscured by the volume transport of reference salinity (about 1Sv*35PSU)

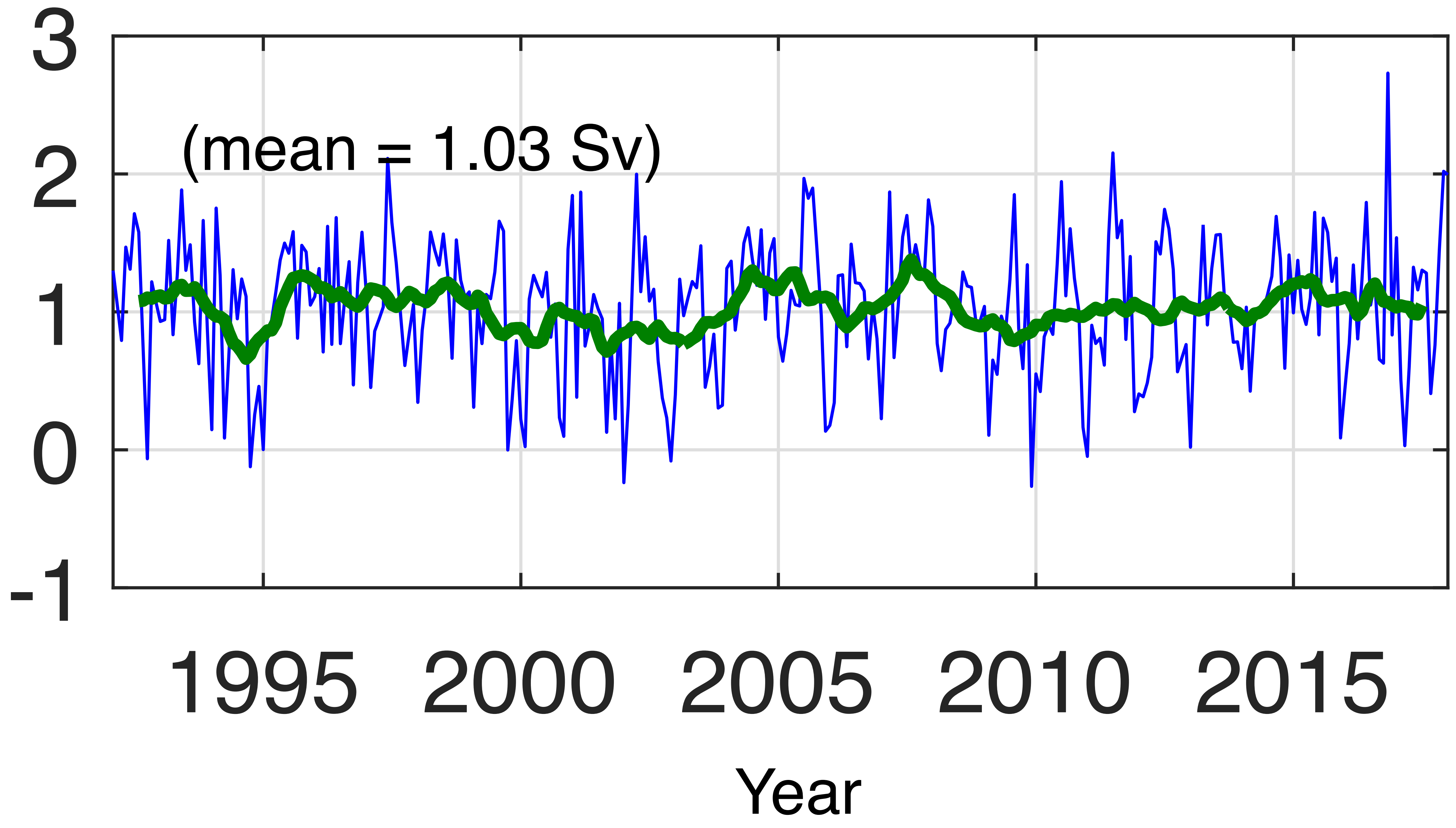
Can individual components of volume transports be quantified?

Time-mean volume transport 1992-2017 ECCOV4r4 (Sv)



1. 0.9 ± 0.7 Sv flows northward in Indo-Pacific
2. -1.1 ± 0.3Sv flows southward in Atlantic
3. Volume transport is due to surface E-P-R + Bering Strait through flow (**BST**~ 1Sv).

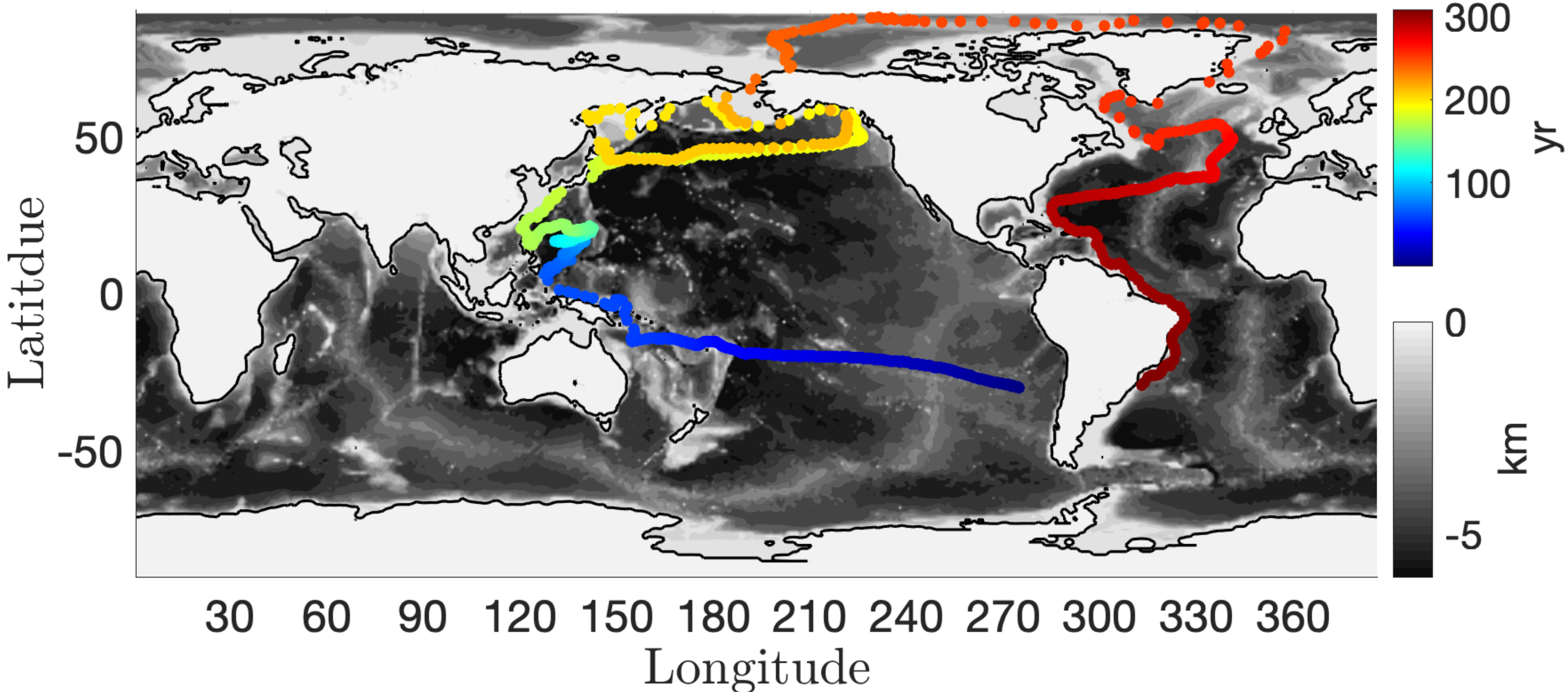
BST 1992-2017 ECCOV4r4 (Sv)



End of Review

Easy process to isolate: the BST component of the overturning cell

1. Seed 200000 Lagrangian parcels across Bering Strait
2. Track forward and backwards in time to **30^{o}S in Atlantic and 30^{o}S Indo-Pacific**
3. Record volume transport, temperature, salinity on trajectories.

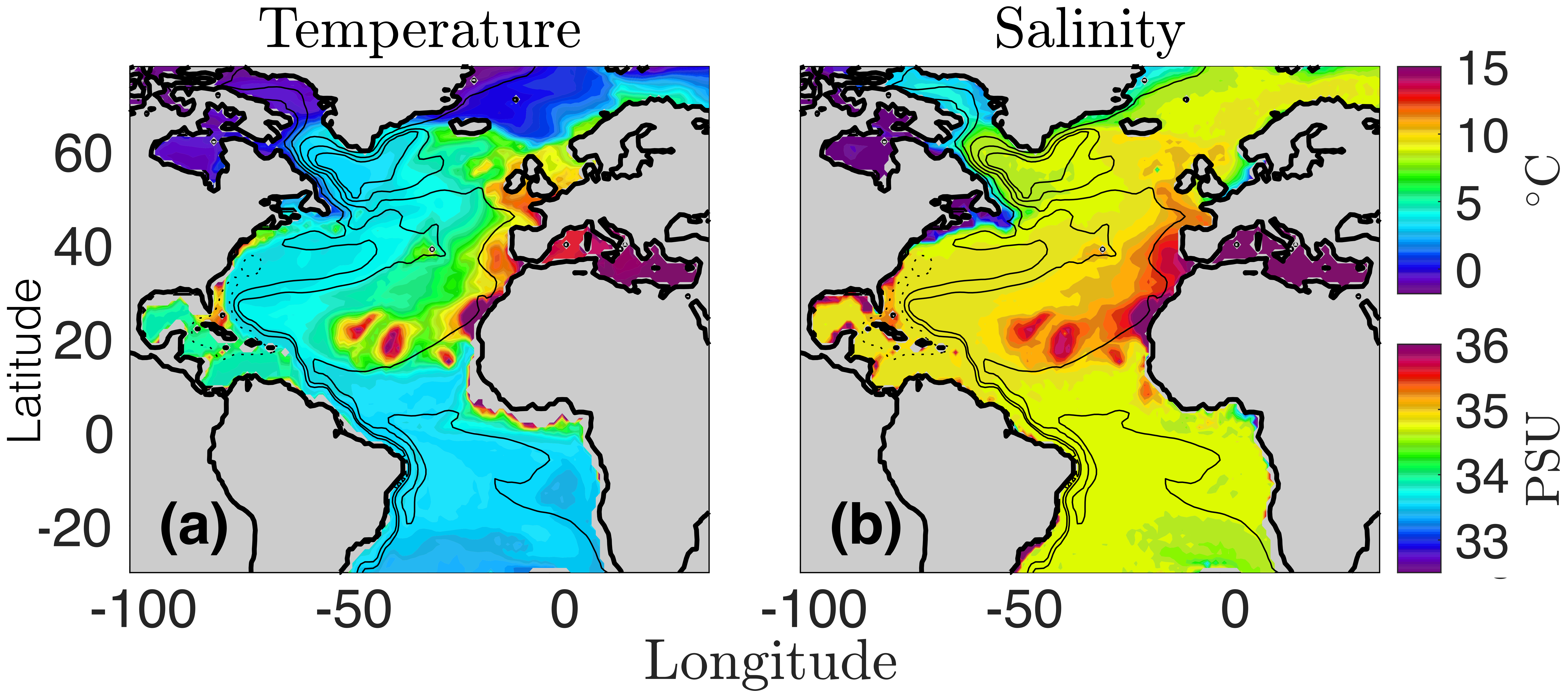


Northward flow: South Pacific —> Bering Strait

1. Typical temperatures are 4-7°C: **AAIW-Upper waters**
2. Typical salinities are 34.2PSU: **AAIW-Upper waters**
3. Parcels flow along the gyres at intermediate/surface depths
4. Ensemble average in lat-lon bins (transport black contours, $\theta - S$ colors)

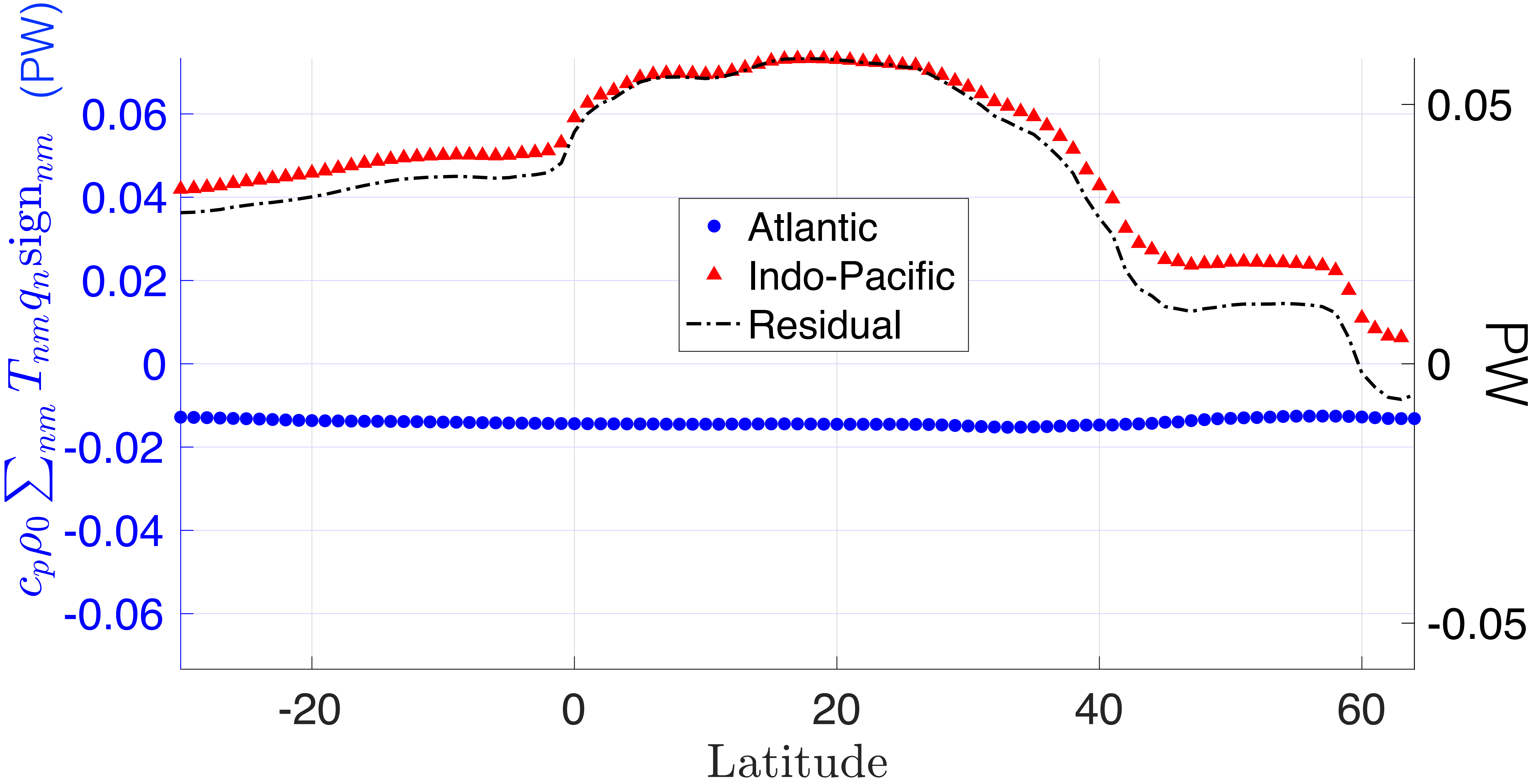
Southward flow: Bering Strait—> South Atlantic

1. Typical temperatures are 3°C: **NADW**
2. Typical salinities are 34.8PSU: **NADW**
3. Parcels flow in Deep Western Boundary Current (not uniformly spread)
4. Ensemble average in lat-lon bins (transport black contours, $\theta - S$ colors)



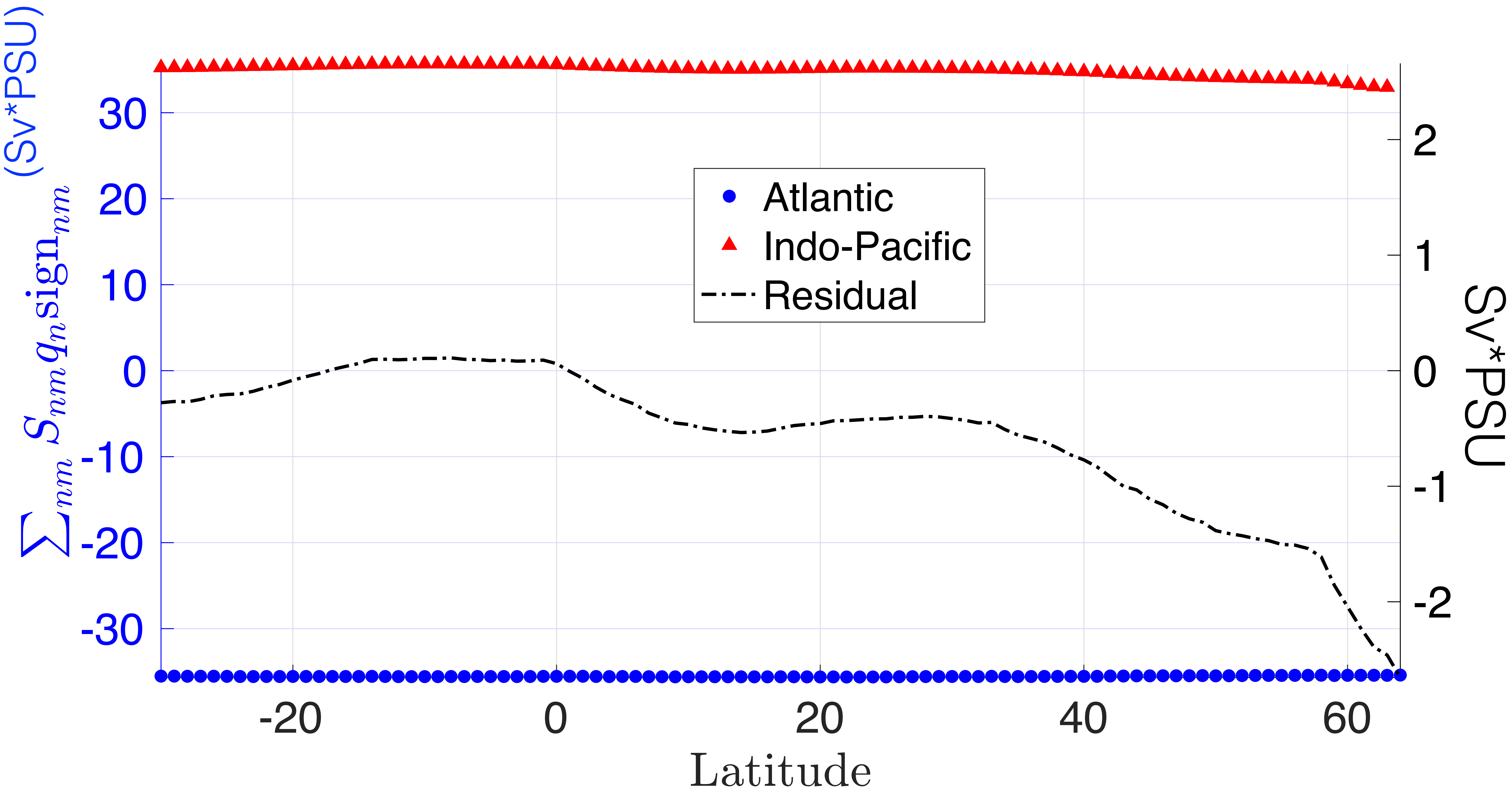
Heat transport carried by Bering Straight Throughflow (BST)

1. BST carries heat **northward in SH**, just like the AMOC
2. BST carries heat **southward** for lat> 60°N (small)
3. Northward branch is in Indo-Pacific, southward branch in Atlantic
4. About 1/10th of AMOC heat transport (1Sv mass transport)
5. BST flow is part of the AMOC, closed in Pacific.



Salt transport carried by Bering Straight Throughflow

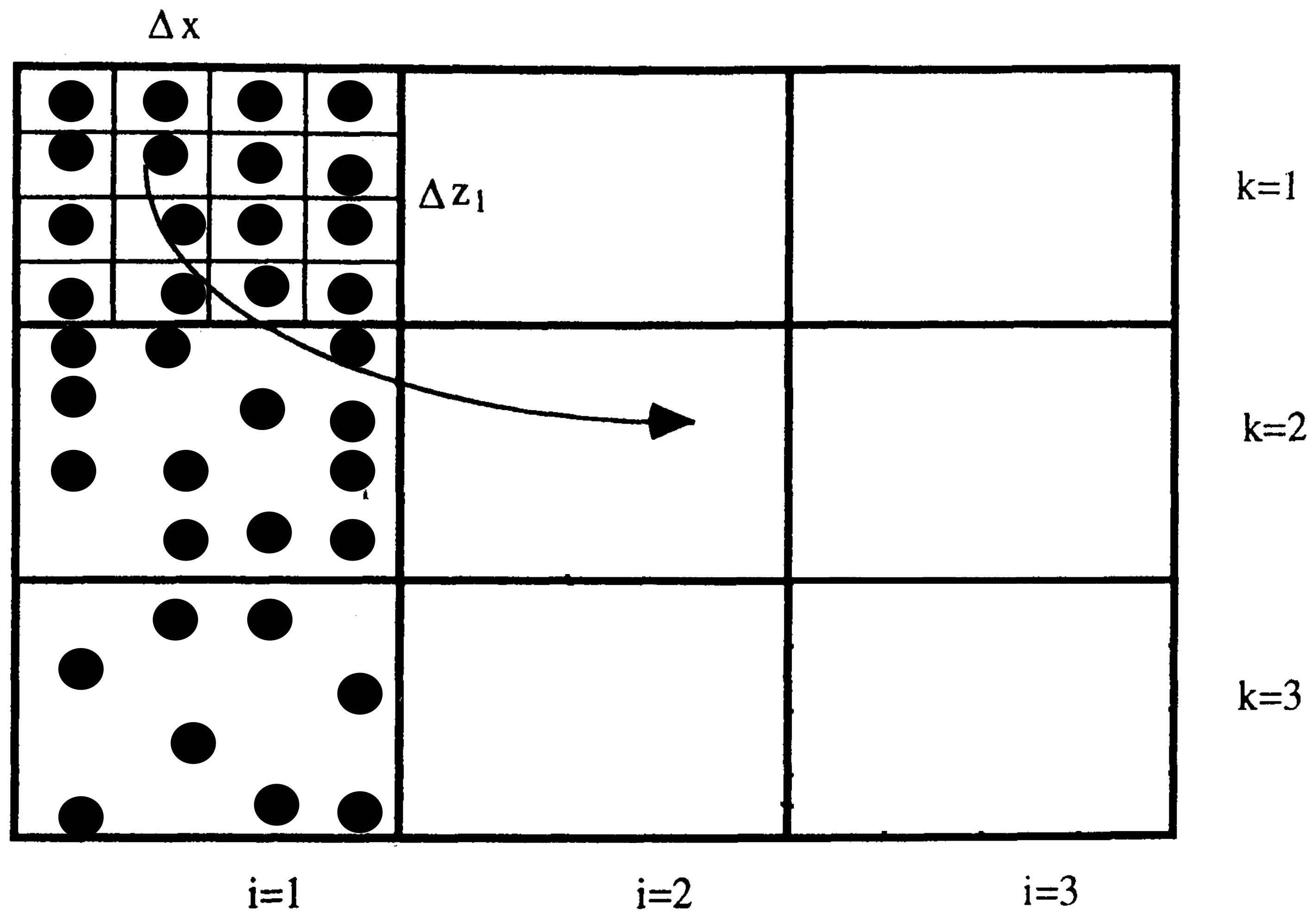
1. BST carries salt **southward**, opposite to the AMOC
2. Northward branch is in Indo-Pacific, southward branch in Atlantic
3. BST opposes the salt-advection feedback of the AMOC and stabilizes it



Discussion

1. Global circulation of the BST is part of the mid-depth overturning cell (MOC)
2. BST component of MOC has lower branch in Atlantic and upper branch in Pacific
3. The MOC has an extra-Atlantic component with substantial heat and salt fluxes
4. Salt transport of BST larger than temperature transport (in density space)
5. Salt transport of BST weakens the salt-advection feedback in accord with OGCMs studies with open/closed Bering Strait

Recipe for quantitative analysis of Lagrangian analysis (using parcels)



1: "Paint" a grid-face $\Delta x_o \, \Delta z_o$ of initial section with "dye" for a short-time Δt
2: The amount of dye will be proportional to $\Delta y_o = V(x_o, y_o, z_o, t_o)\Delta t$
3: There is more dye where $V(x_o \,.\, y_y, z_o)$ is larger ("flux-weighitng")
4: With no diffusion the initial painted volume is conserved (stretched and folded)

$$\frac{D\, V(x_o, y_o, z_o, t_o)\Delta x_o \Delta z_o \Delta t}{Dt} = 0$$

5: For constant Δt the initial transport is conserved following the dye

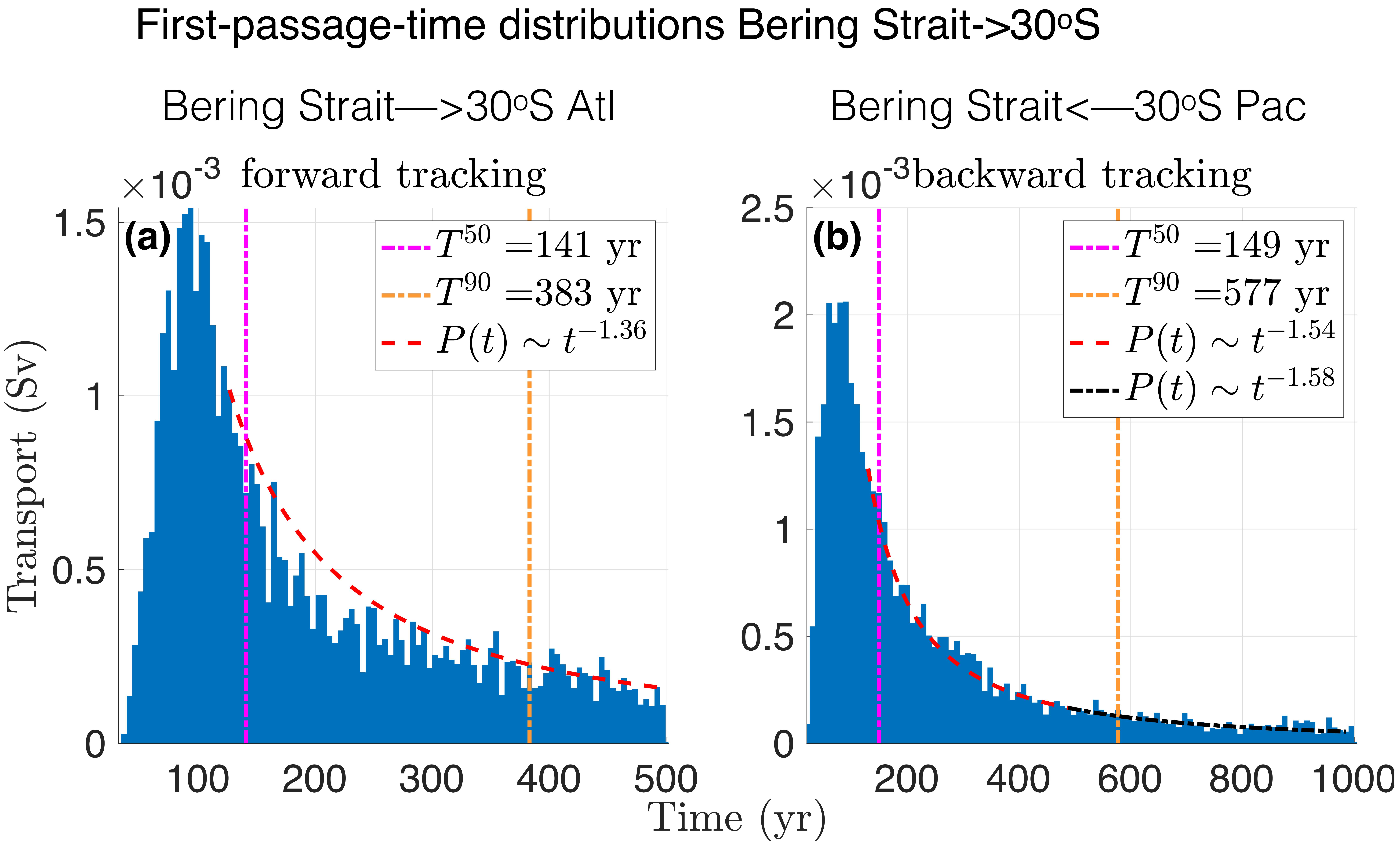
6: Use N parcels release, instead of dye (easier to conserve numerically)

Each parcel will have a transport $T_n = V(x_o, y_o, z_o, t_o)/N$

7: Repeat for each grid-face of the section
8: Record position, time, temperature and salinity along trajectories.

Downstream, calculate transports of volume, $C_n = 1$, temperature, $C_n = \theta$, and salinity, $C_n = S$, as:

$$\sum_n T_n C_n(x, y, z, t)$$



First-passage-time distributions Bering Strait->30ºS
Bering Strait—>30ºS Atl
Bering Strait<—30ºS Pac
×10^-3 forward tracking
×10^-3 backward tracking
(a)
(b)
T^{50} =141 yr
T^{90} =383 yr
$P(t) \sim t^{-1.36}$
T^{50} =149 yr
T^{90} =577 yr
$P(t) \sim t^{-1.54}$
$P(t) \sim t^{-1.58}$
Transport (Sv)
Time (yr)
0
0.5
1
1.5
2
2.5
100
200
300
400
500
600
800
1000