# An eddy-driven mechanism for partitioning the AMOC deep limb into the DWBC and an Interior Pathway

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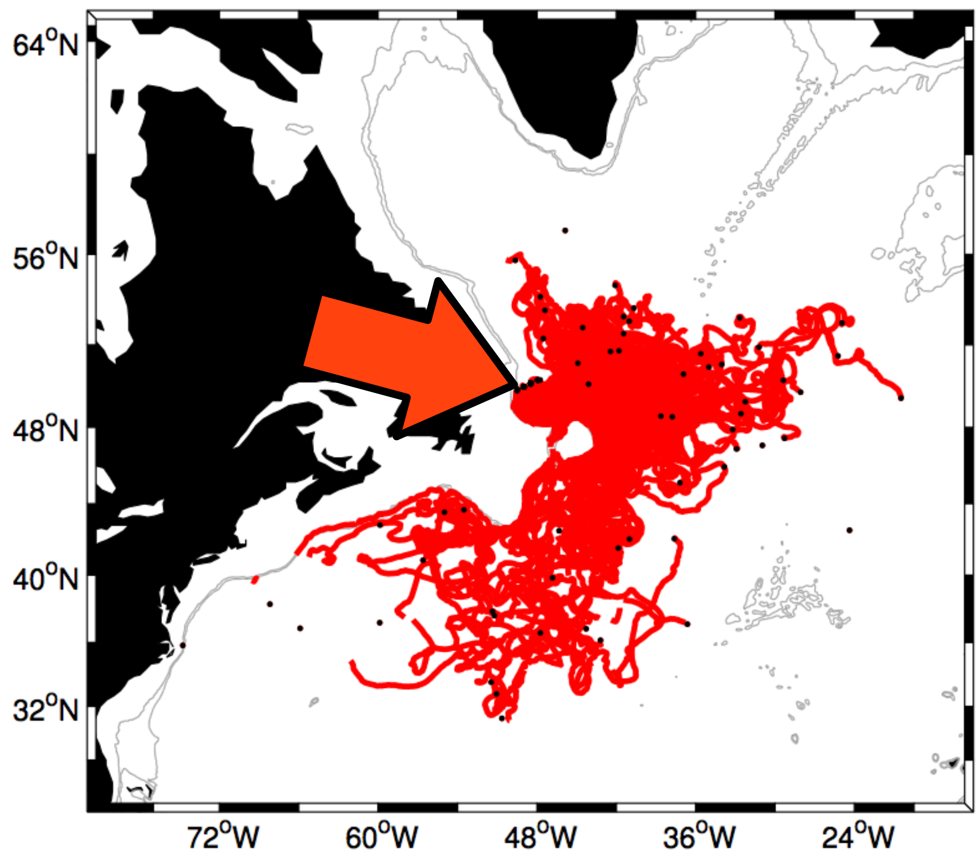


55 RAFOS floats with mission dates spanning 2003 to 2007 launched at 700 and 1500 m (*Bower et al.*, in press).

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German Academic Exchange Service

Annnapolis, MD, First US AMOC Annual Meeting, May 4, 2009

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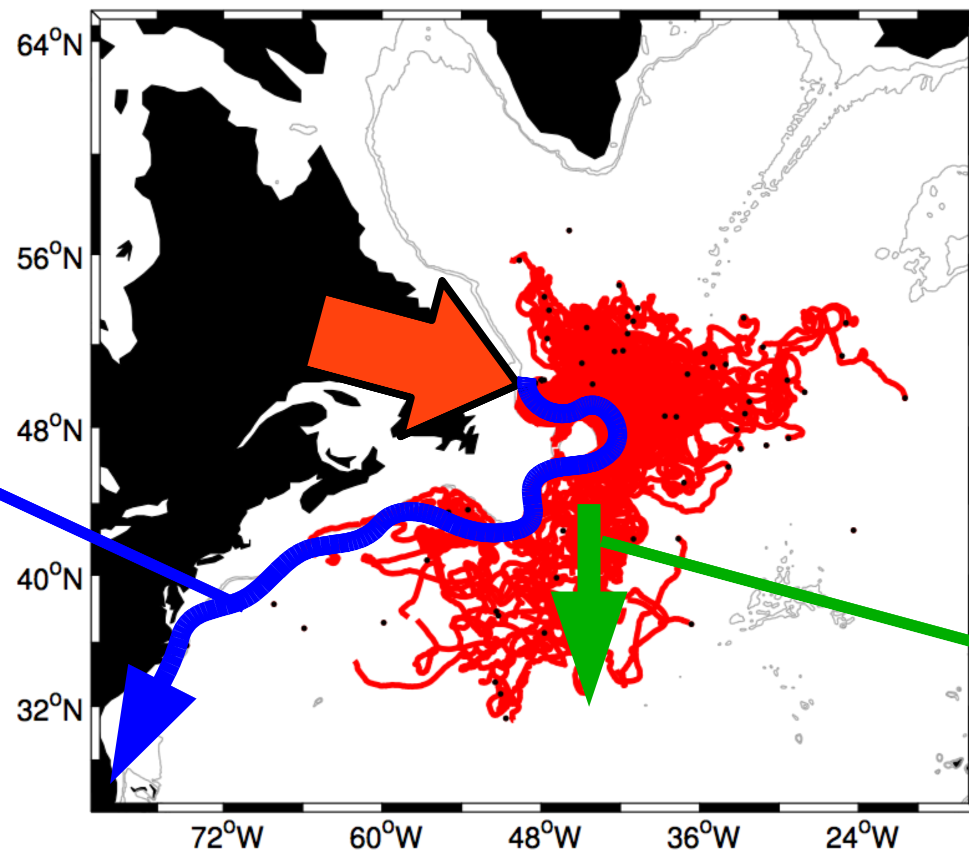
Fast, concentrated **DWBC** is the expected pathway

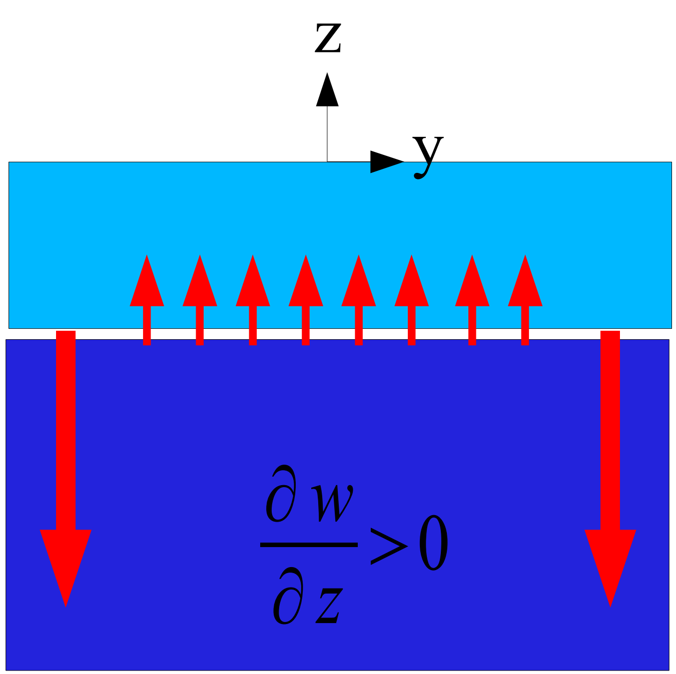


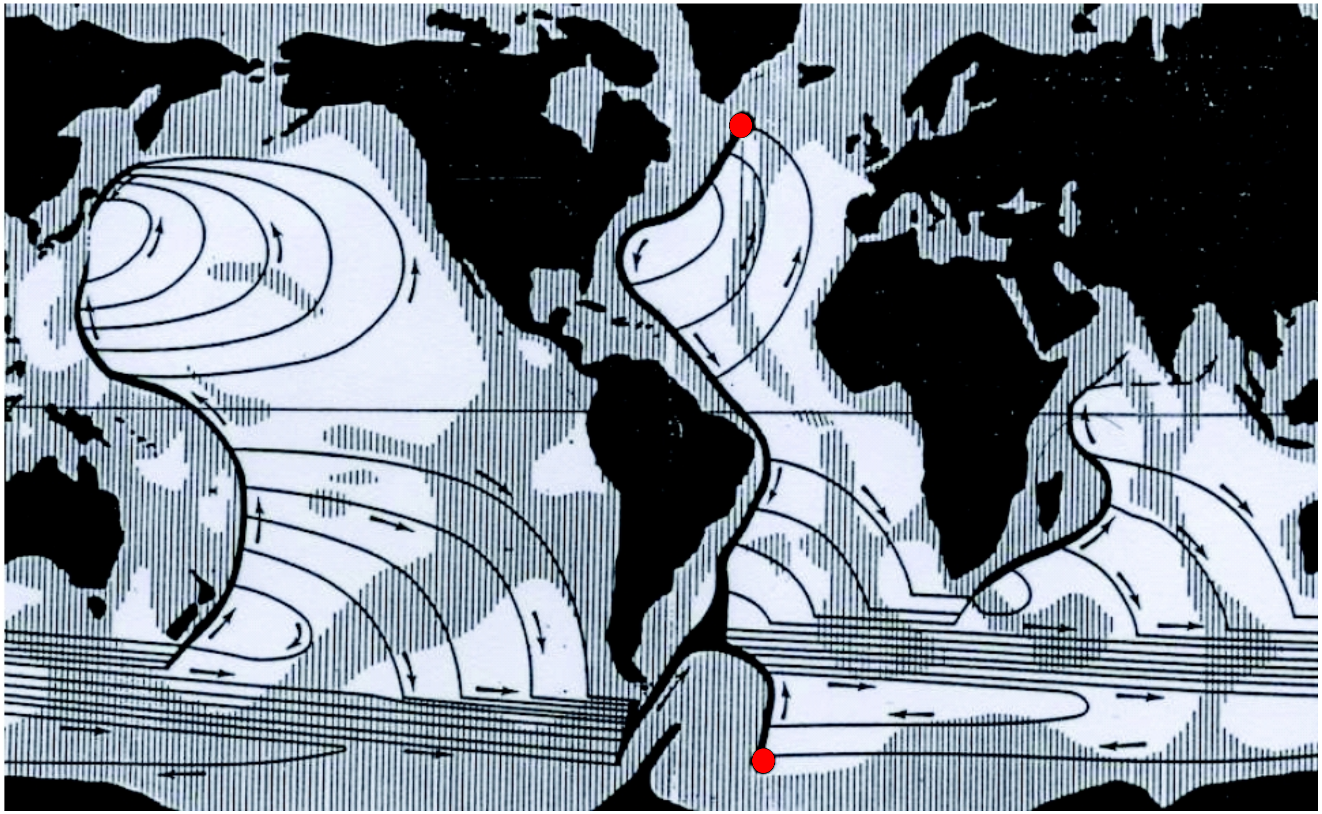

Slow, broad **Interior Pathway**

# Why is this important? Stommel's Model

**What does the vorticity balance** $\boxed{\beta v = f \frac{\partial w}{\partial z}}$ **suggest about large-scale abyssal circulation?**

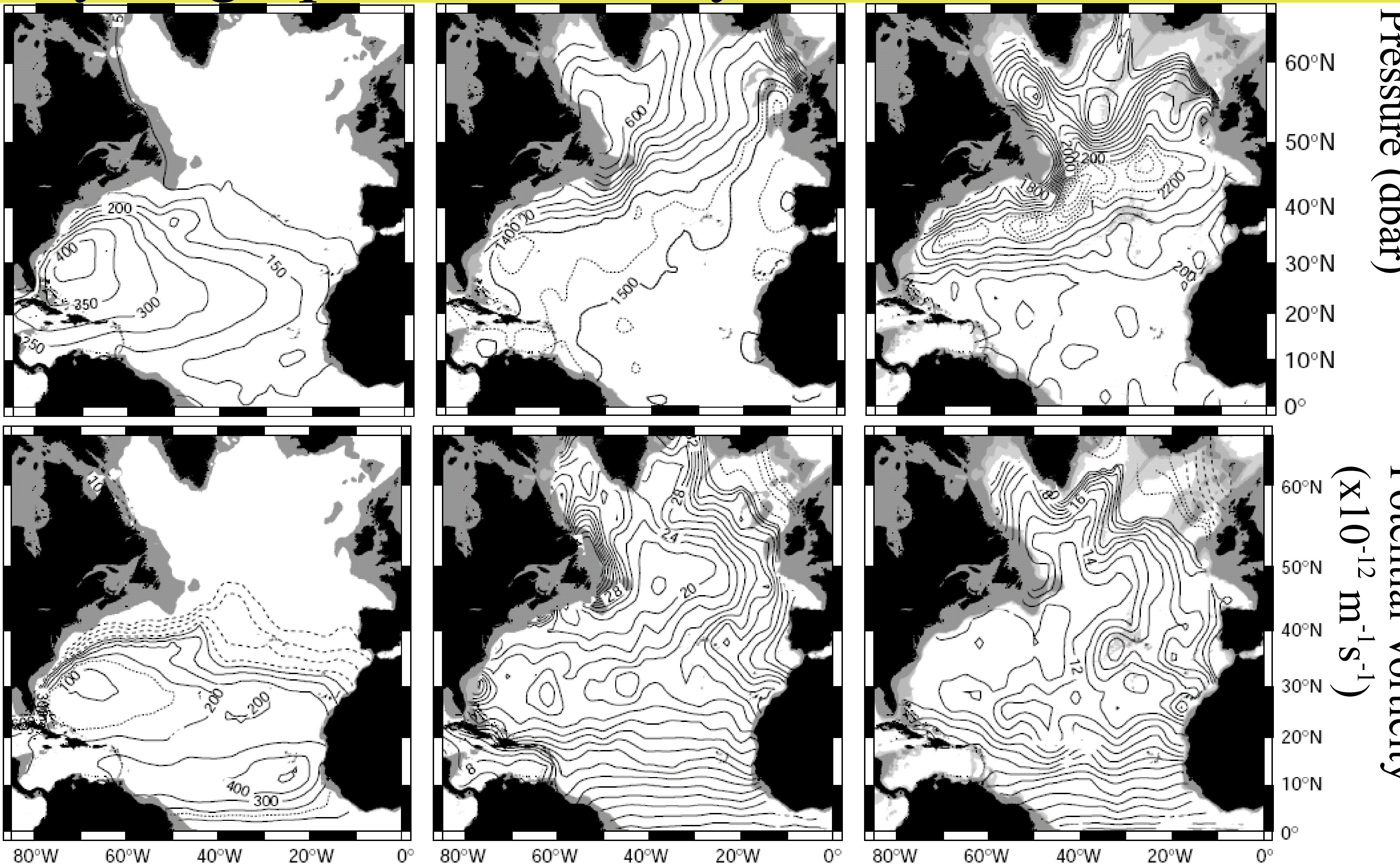
(1) Two sources: NADW and AABW
(2) ...must be balanced by upwelling from the abyssal layer.
(3) Interior flow is poleward
(4) ...and a DWBC is proposed to maintain continuity in the abyssal layer.



(*Stommel*, 1958)

# Suggestion of a possible mechanism from hydrographic data: eddy-driven recirculations




$\sigma_0 = 26.50$ $\sigma_{1.5} = 34.60$ $\sigma_2 = 36.95$ (*Lozier*, 1997)

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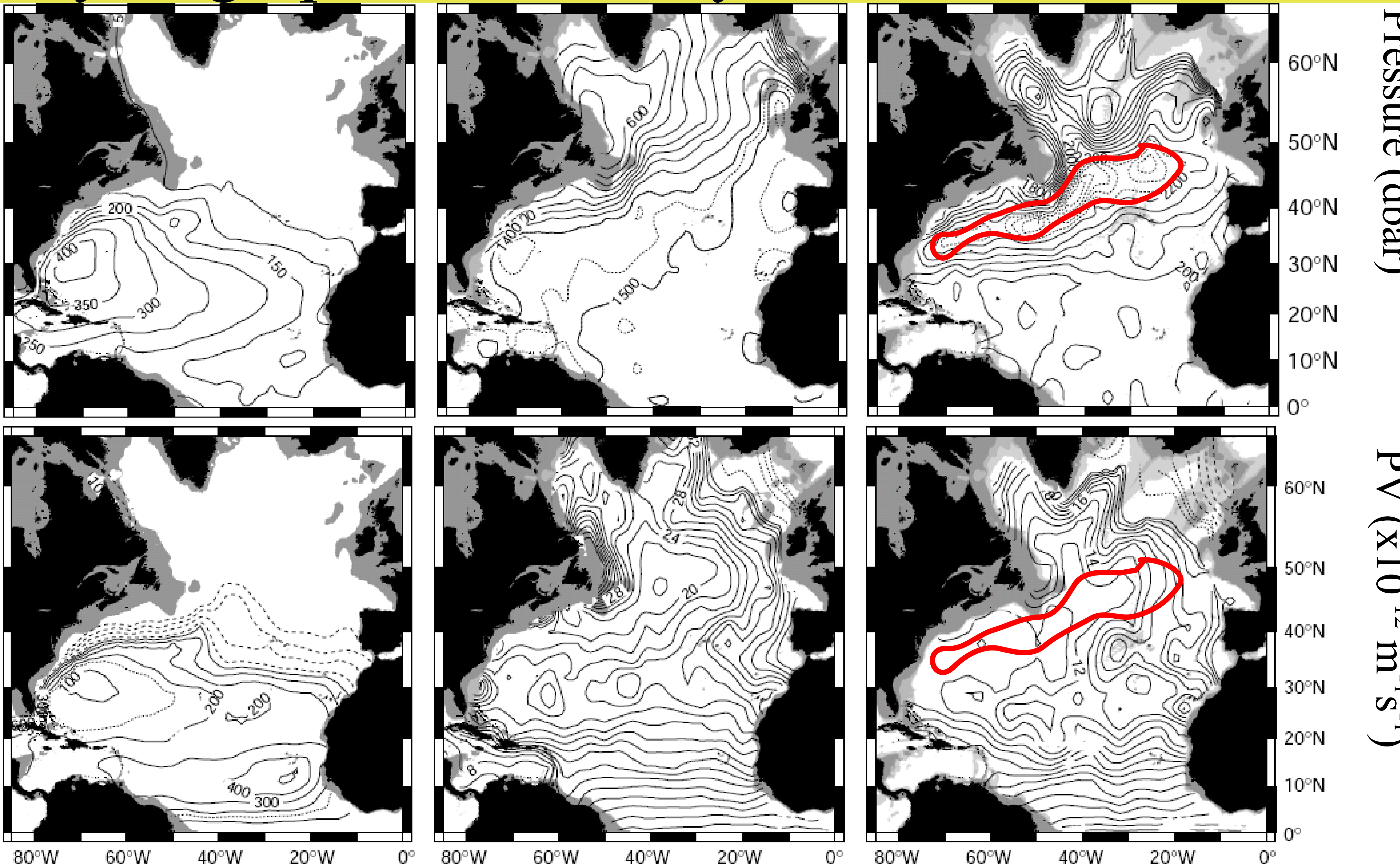


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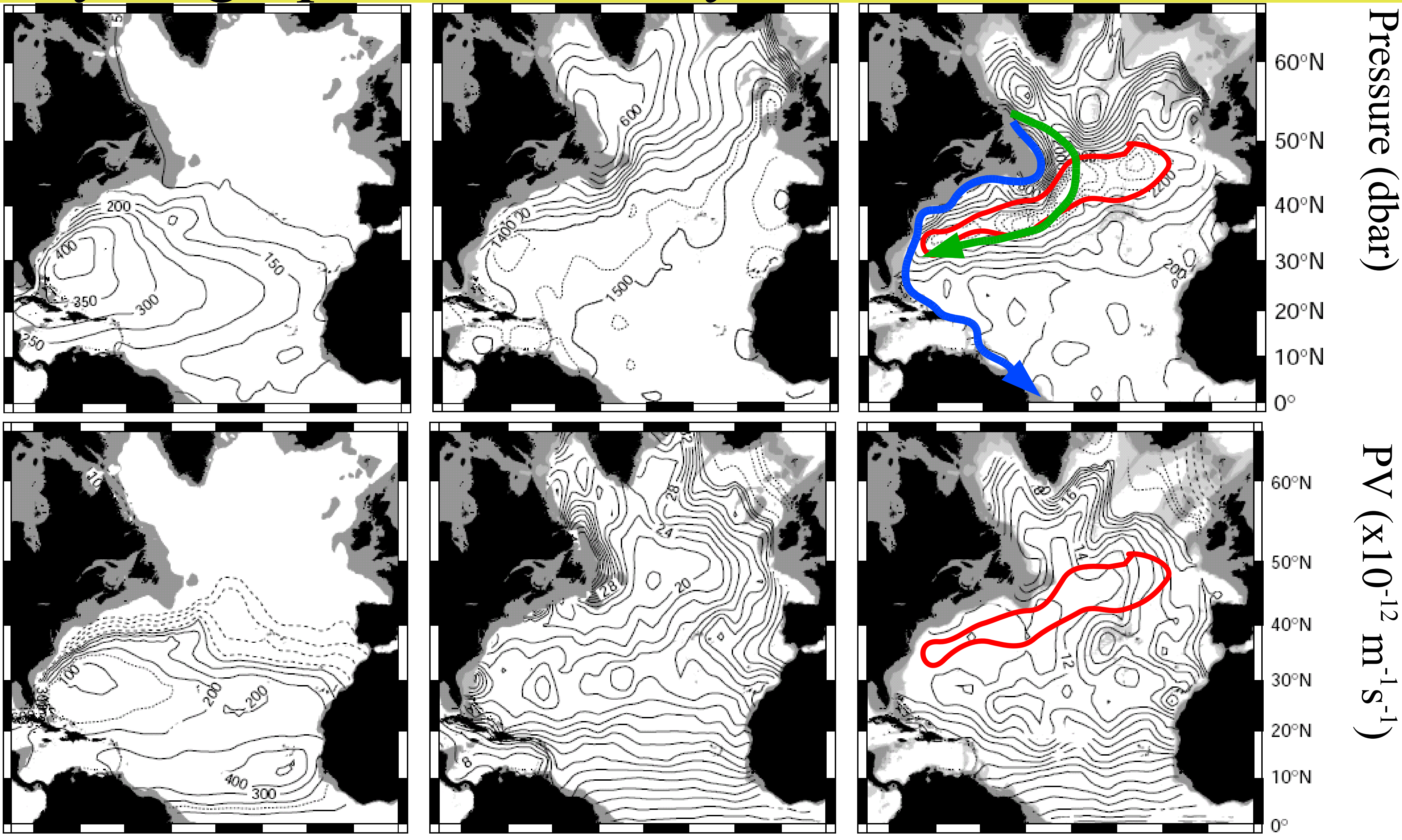


$\sigma_0 = 26.50$ $\sigma_{1.5} = 34.60$ $\sigma_2 = 36.95$ (*Lozier*, 1997)

# Focus

Are the signatures of eddy-driven flow inferred from hydrographic data commensurate with the behavior of eddies in ocean models?

- Hydrographic data cannot resolve absolute velocities or eddy scales.
- Model output is an estimate of the envelope of possible states of the ocean at high spatial and temporal resolutions.

**OPEN QUESTIONS:**

Are deep eddy-driven recirculations present in the models?

How well do they match patterns in observations?

To what extent do the eddy-driven pathways influence the export of waters from the subpolar to subtropical gyres?

# Models Used: Spinup and Forcing

Global models, 46 z-levels, partially filled bottom cells, new advection scheme, ice model (*DRAKKAR Group*, 2007), (*Biastoch et al.*, 2008):

**ORCA05** **1/2° resolution**

- Climatological 20 year spin-up and then 1958-2004 hindcast.
- CORE* forcing (30d freshwater reduced by 15-20% north of 30°N)

**ORCA025** **1/4° resolution**

- Started with hindcast forcing, 1958-2004
- CORE forcing (6h NCEP, 1d ISCCP, 30d freshwater)

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Regional model of the North Atlantic, 45 z-levels (*Böning et al.*, 2006)

**FLAME** **1/12° resolution**

- Spun up for 10 years and then hindcast 1990-2004
- ECMWF wind/heat climatologies with NCEP anamolies
- Open boundaries at the north and south.

# Lagrangian Drifters: Expectations

**(1) FLAME 1/12$^{o}$**

- Highest Resolution => eddy resolving
- Floats move away from boundary in a strong, broad interior pathway
- Strongest signs of deep recirculation gyres

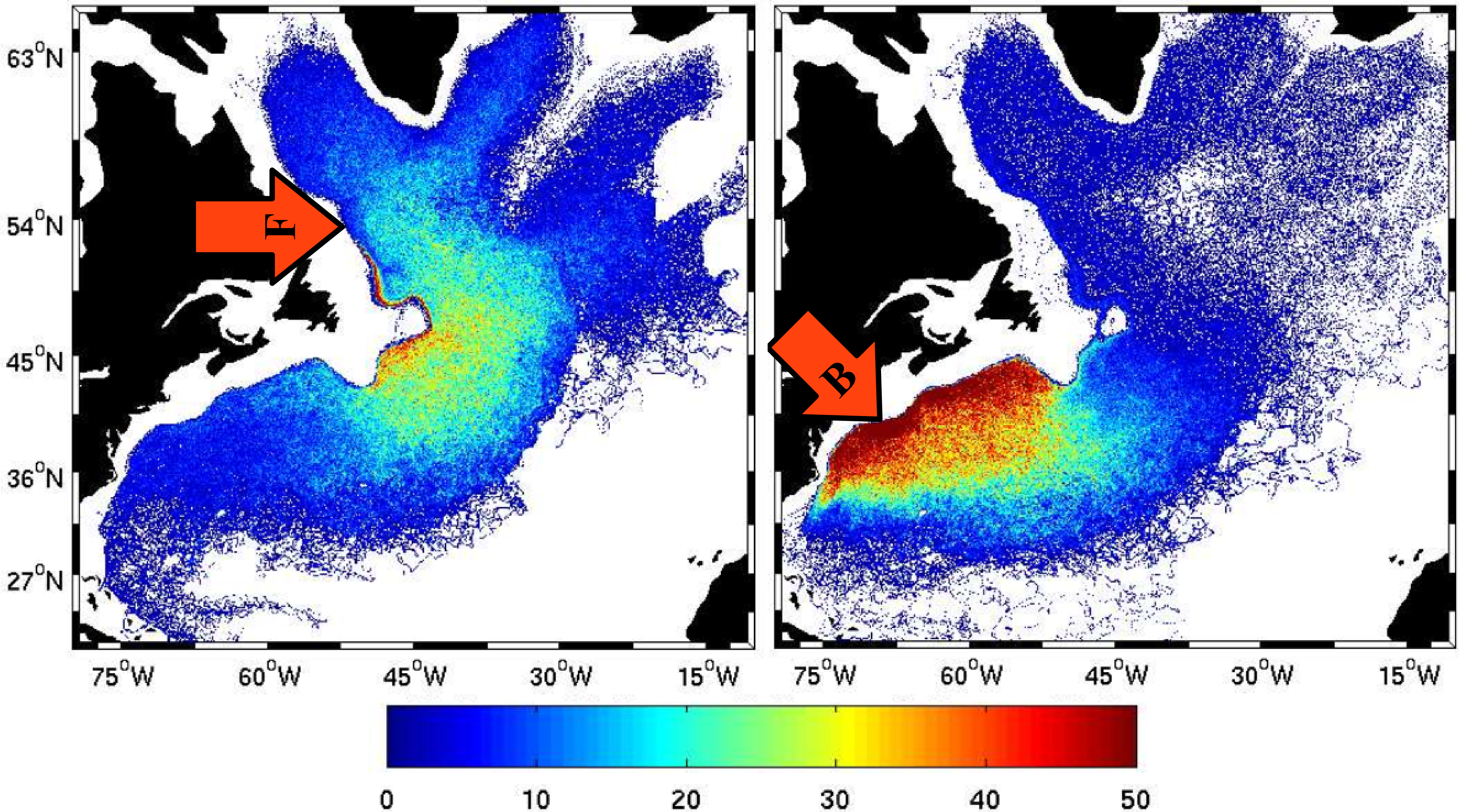
**(2) ORCA05**

- Low Resolution => not eddy permitting, not eddy resolving
- Floats go down the DWBC in a well-defined pathway
- No deep recirculation gyres

**(3) ORCA025**

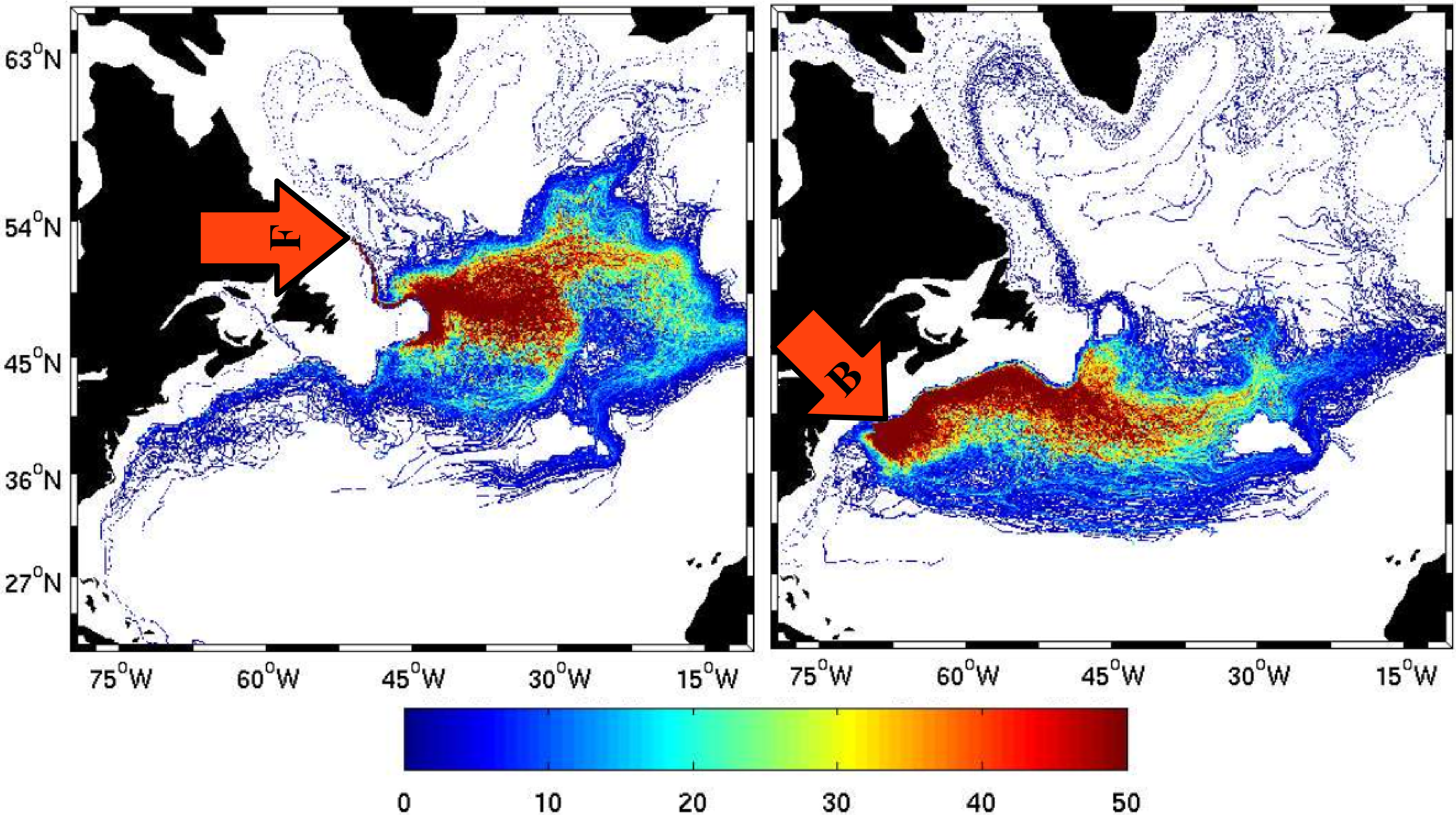
- Intermediate Resolution => eddy permitting
- Floats are split between the DWBC and the interior pathway
- Recirculation gyres are present but weaker

# Where do the floats go in FLAME?



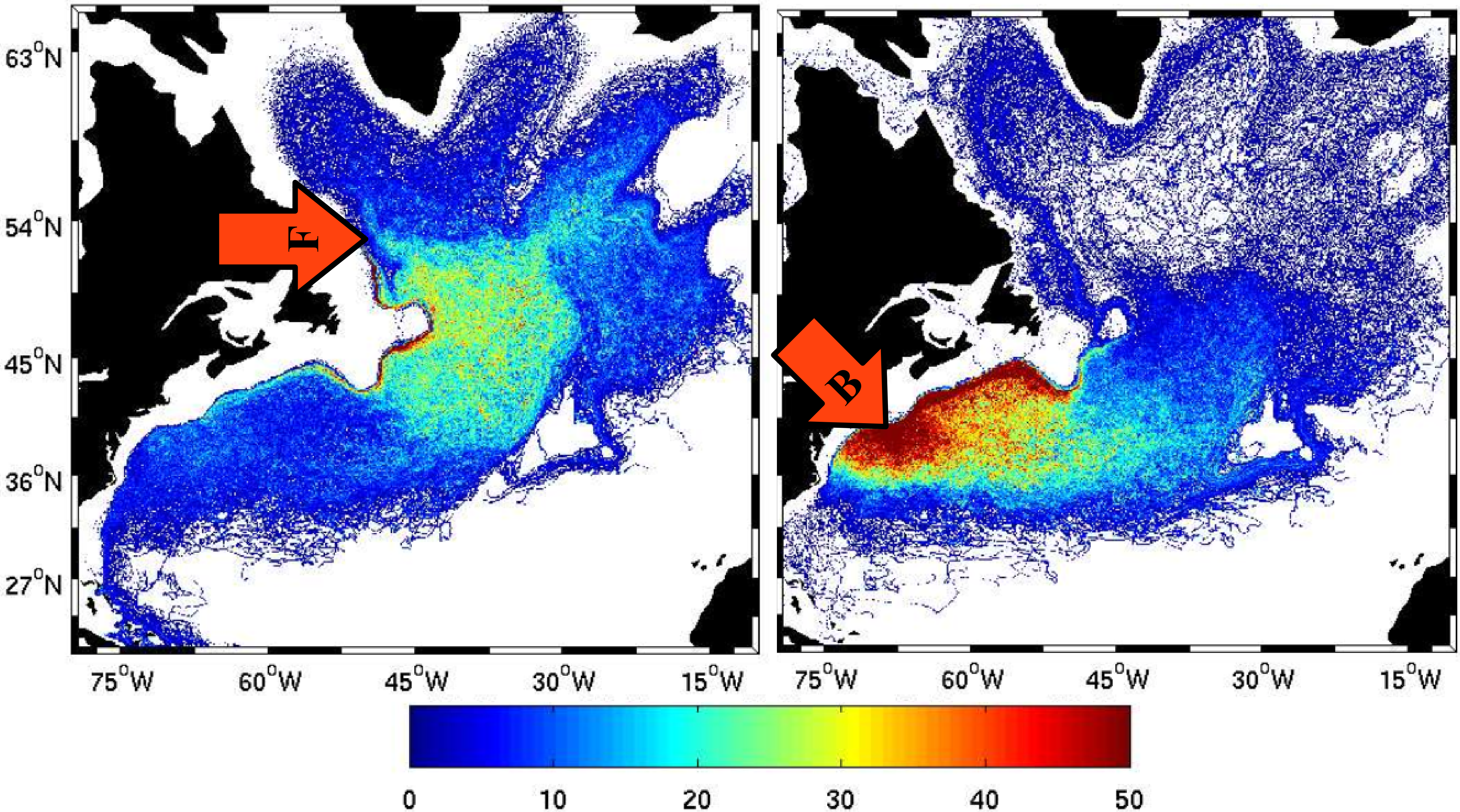

Position histograms of 1560 e-floats from 3-daily snapshots of FLAME '92-'04 velocity field for 13 year **Forward** (left) and **Backward** (right) trajectories, [# floats]. Arrows indicate launch site. All floats were launched at 1500 m.

# Where do the floats go in ORCA**05**?




Position histograms of 1560 e-floats from 5-day averages of ORCA05 '92-'04 velocity field for 13 year **Forward** (left) and **Backward** (right) trajectories, [# floats]. Arrows indicate launch site. All floats were launched at 1500 m.

# Where do the floats go in ORCA**025**?




Position histograms of 1560 e-floats from 5-day averages of ORCA025 '92-'04 velocity field for 13 year **Forward** (left) and **Backward** (right) trajectories, [# floats]. Arrows indicate launch site. All floats were launched at 1500 m.

# Are these eddy-driven flow? Eulerian View

On a constant density surface, potential vorticity is quasi-conserved:

$$\frac{Dq}{Dt} = F + \Delta \approx 0$$

where:

$F$ = forcing $\quad\zeta$ = local vorticity

$\Delta$= dissipation $\quad f$ = planetary vorticity

$$q = \frac{(\zeta + f)}{\sigma_n}\frac{\partial \sigma_n}{\partial z}$$

After rearrangements and time averaging, we obtain the enstrophy ( $\overline{q'^2}$ ) equation

$$\frac{1}{2}\overline{\frac{Dq'^2}{Dt}} = -\overline{\boldsymbol{u}'q'}\cdot\nabla Q + \overline{F'q'} + \overline{\Delta q'}$$

Negligible at depth

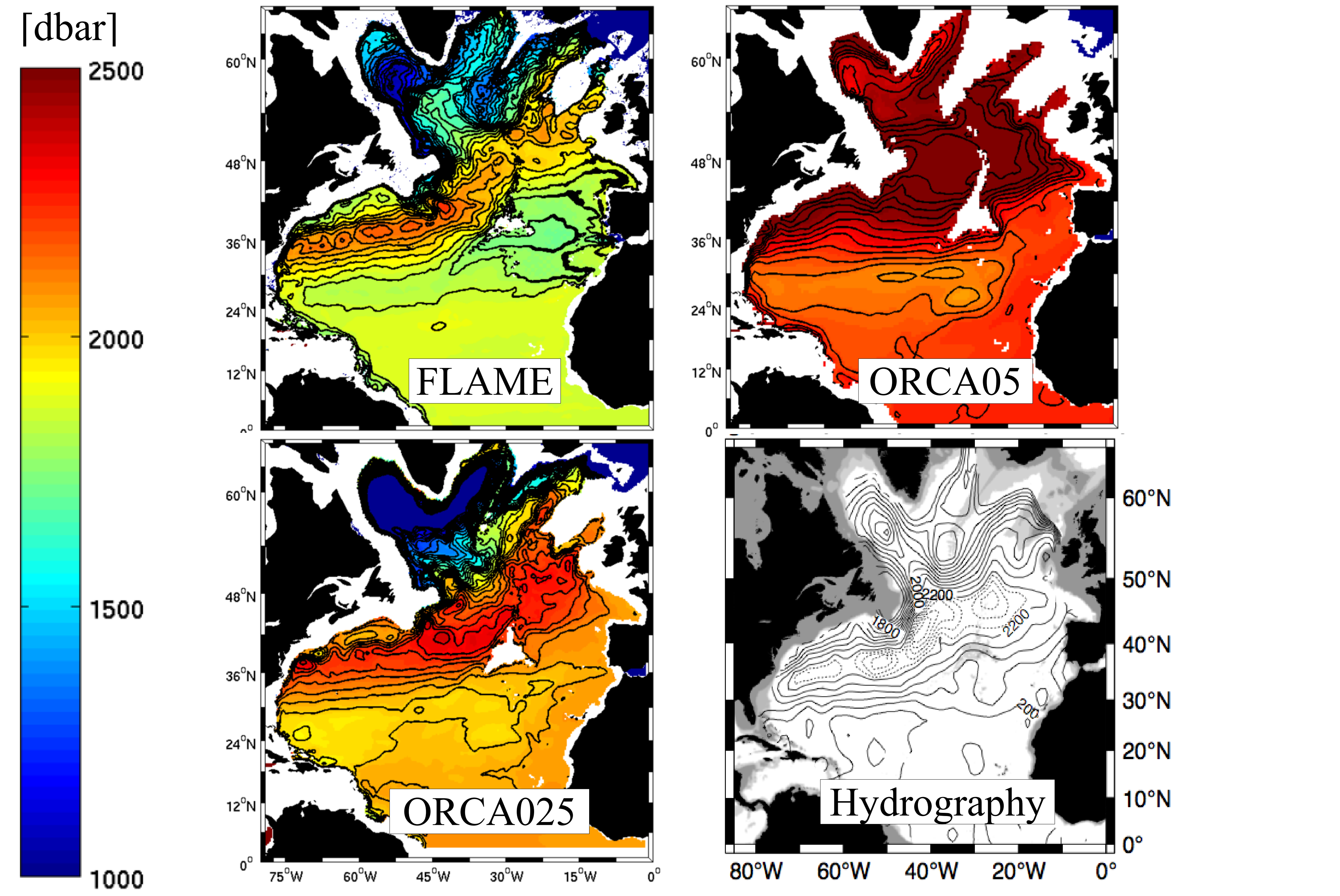
( - ) sink

Enstrophy can be maintained only if eddy fluxes are down the mean gradient of $Q$.

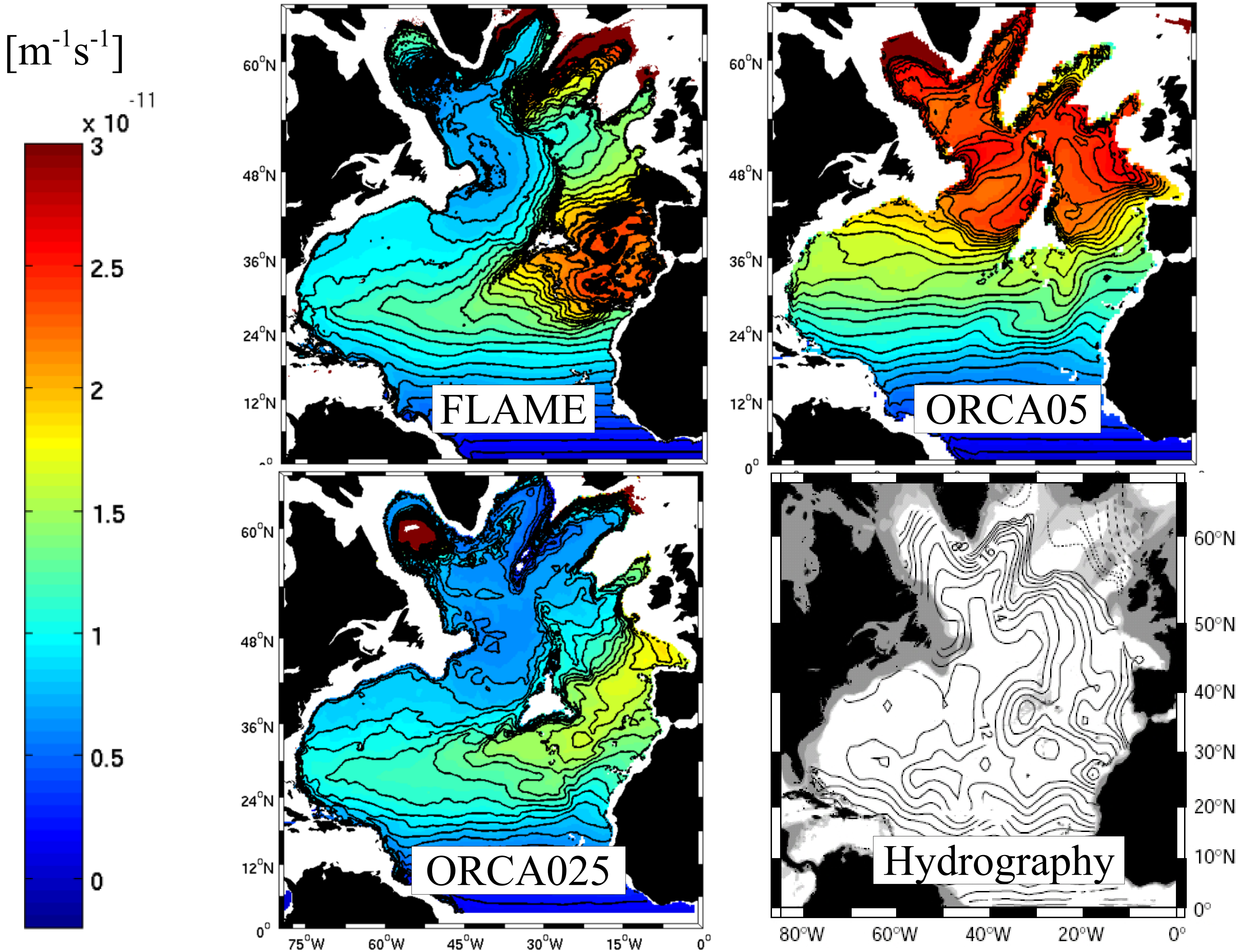
where $q = Q + q'$

(*Rhines and Holland*, 1979)

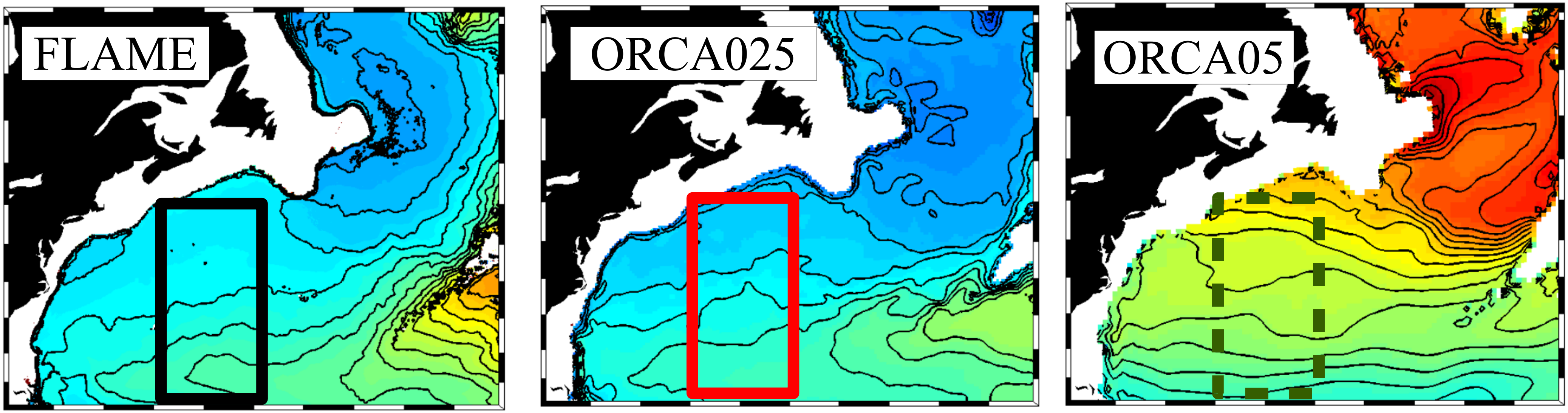
# Pressure on $\sigma_2 = 36.95$ isopycnal



# Potential Vorticity on $\sigma_2 = 36.95$ isopycnal



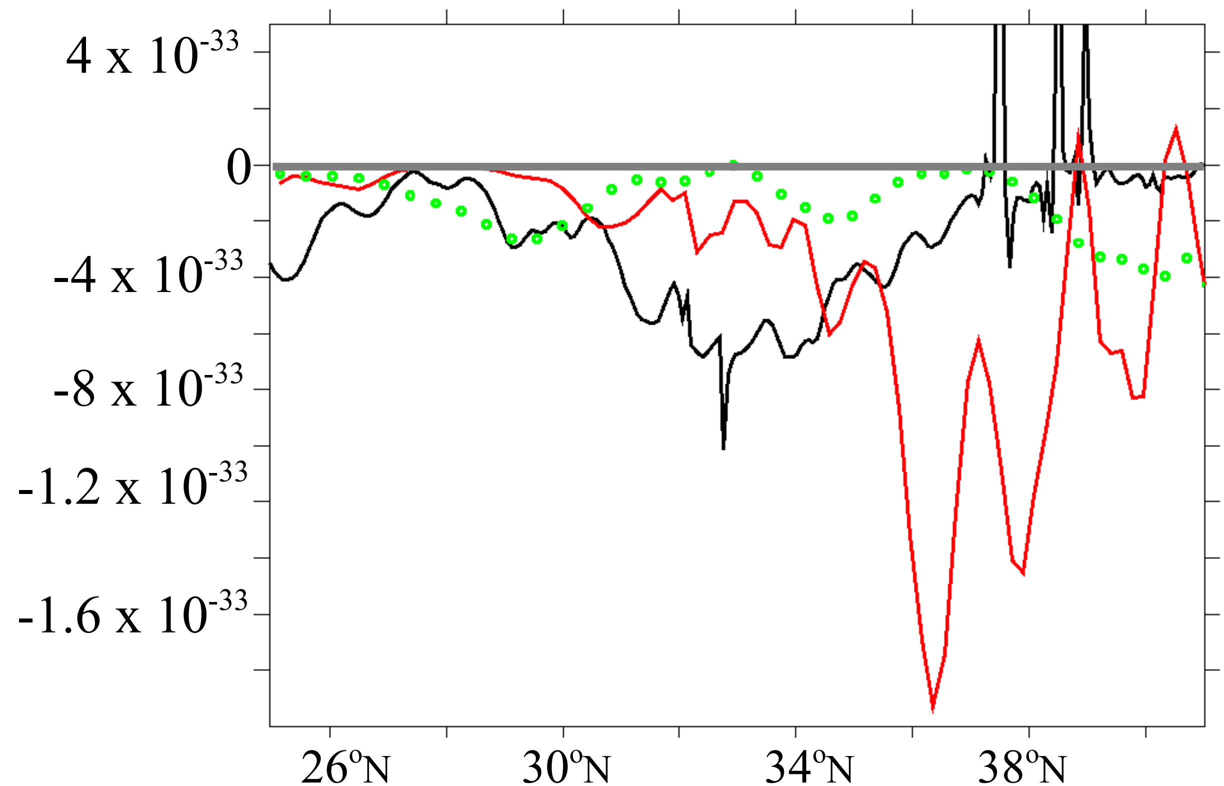
# Comparison of down-gradient eddy fluxes



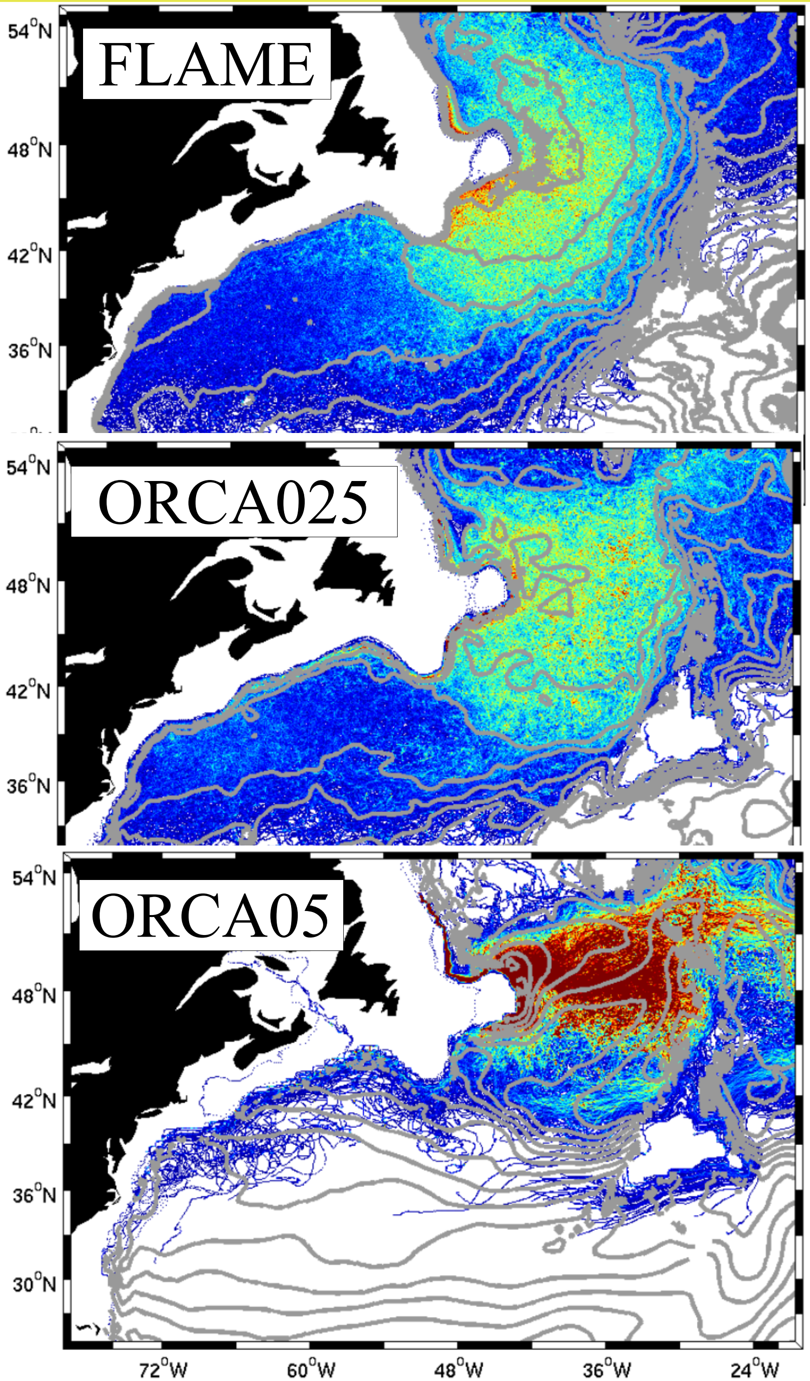

**TOP:** Mean potential vorticity ($Q$) on $\sigma_2 = 36.95$ isopycnal in models [$1e^{-12}\ m^{-1}s^{-1}$]

**BOTTOM:** Zonal average (65°-55°W) of

$$\overline{\boldsymbol{u}'q'}\cdot\nabla Q$$



# Lagrangian & Eulerian Synthesis, Summary




(1) We propose that a system of linked, deep, eddy-driven recirculation gyres is a mechanism enabling deep limb AMOC transport in an interior pathway.

(2) In eddy-permitting and eddy-resolving models, Lagrangian drifters follow an interior pathway.

(3) The Eulerian signatures of eddy-driven gyres are similar in both hydrographic observations and eddy-resolving and eddy-permitting models.

(4) Lagrangian pathways as determined from trajectories are in agreement with Eulerian analysis of eddy effects.

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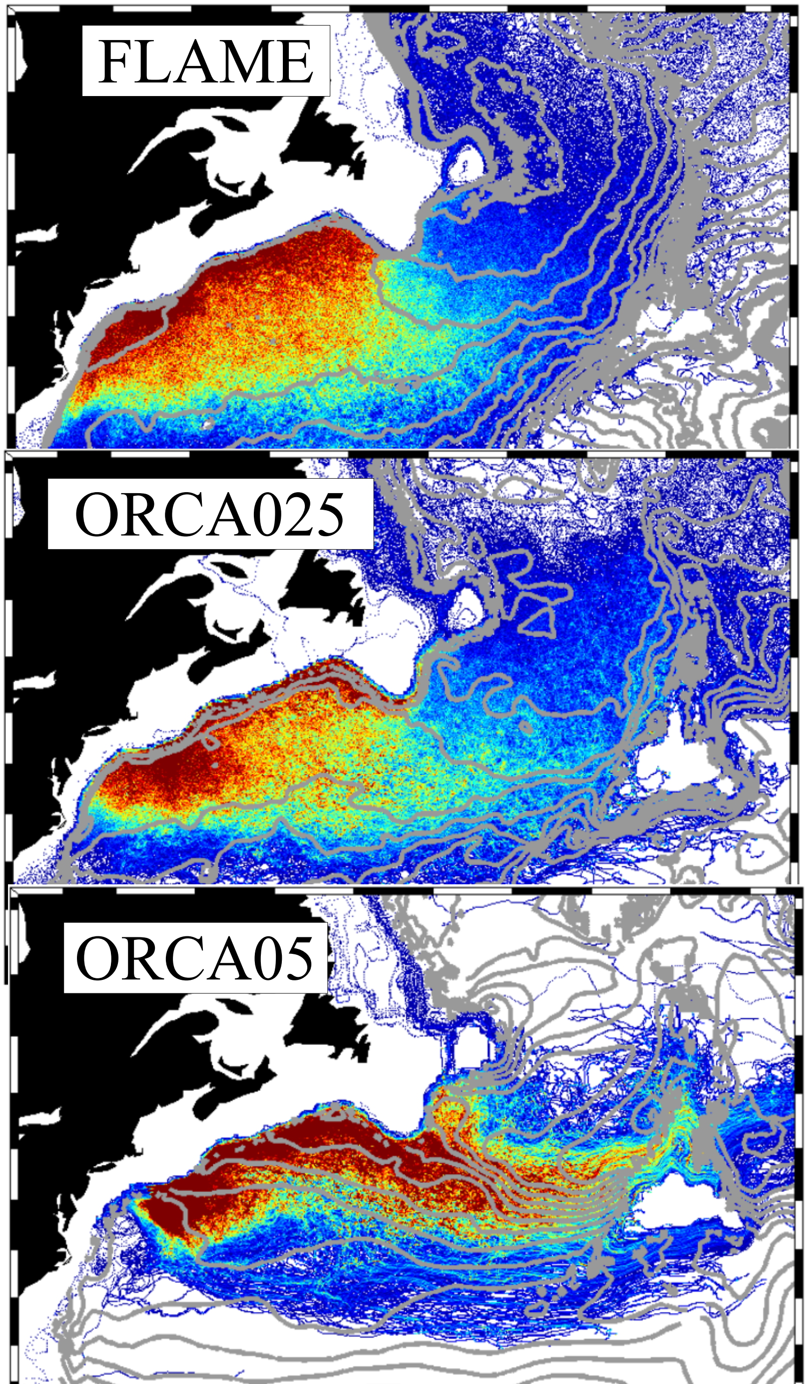


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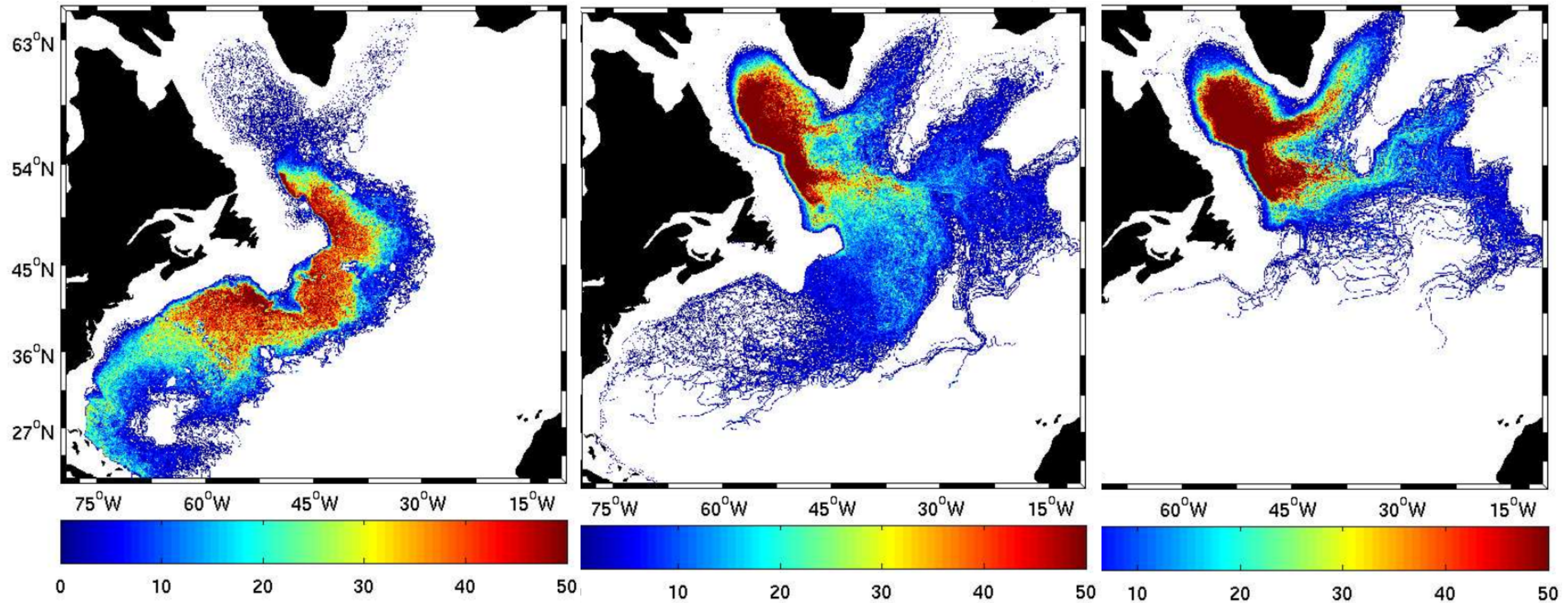
# Deep Floats (3500m)



# Expectations of Eulerian Fields

**(1) FLAME 1/12°**

- Highest Resolution => eddy resolving
- Regions of homogenized mean potential vorticity ($Q$)
- Eddy fluxes down the gradient of $Q$
- Floats' recirculations coincide with homogenized $Q$

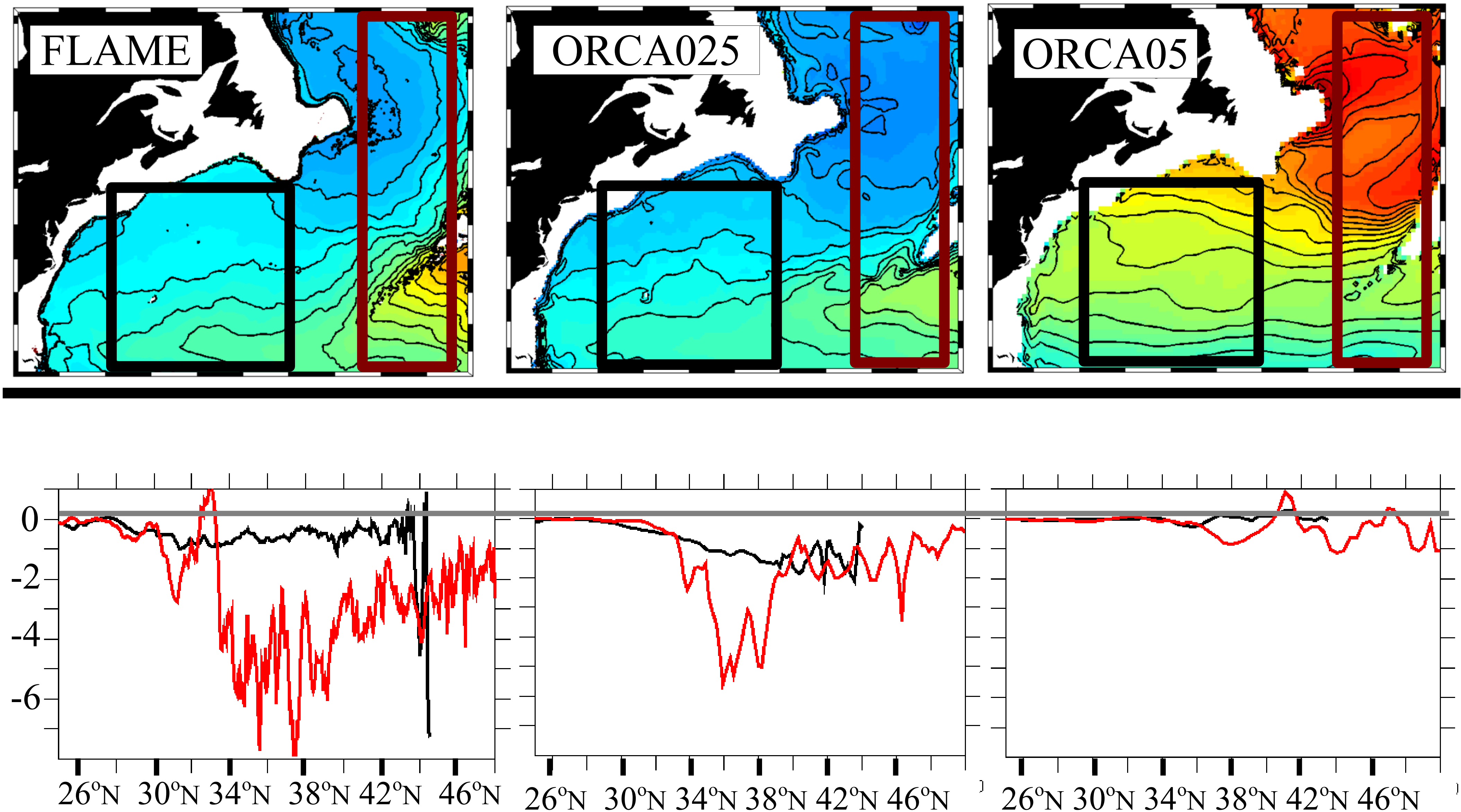
**(2) ORCA05**

- Low Resolution => not eddy permitting or eddy resolving
- No deep eddy-driven recirculation gyres
- No homogenized $Q$
- No down-gradient eddy fluxes

**(3) ORCA025**

- Intermediate Resolution => eddy permitting
- Eddy effects similar to FLAME are present but they are weaker.

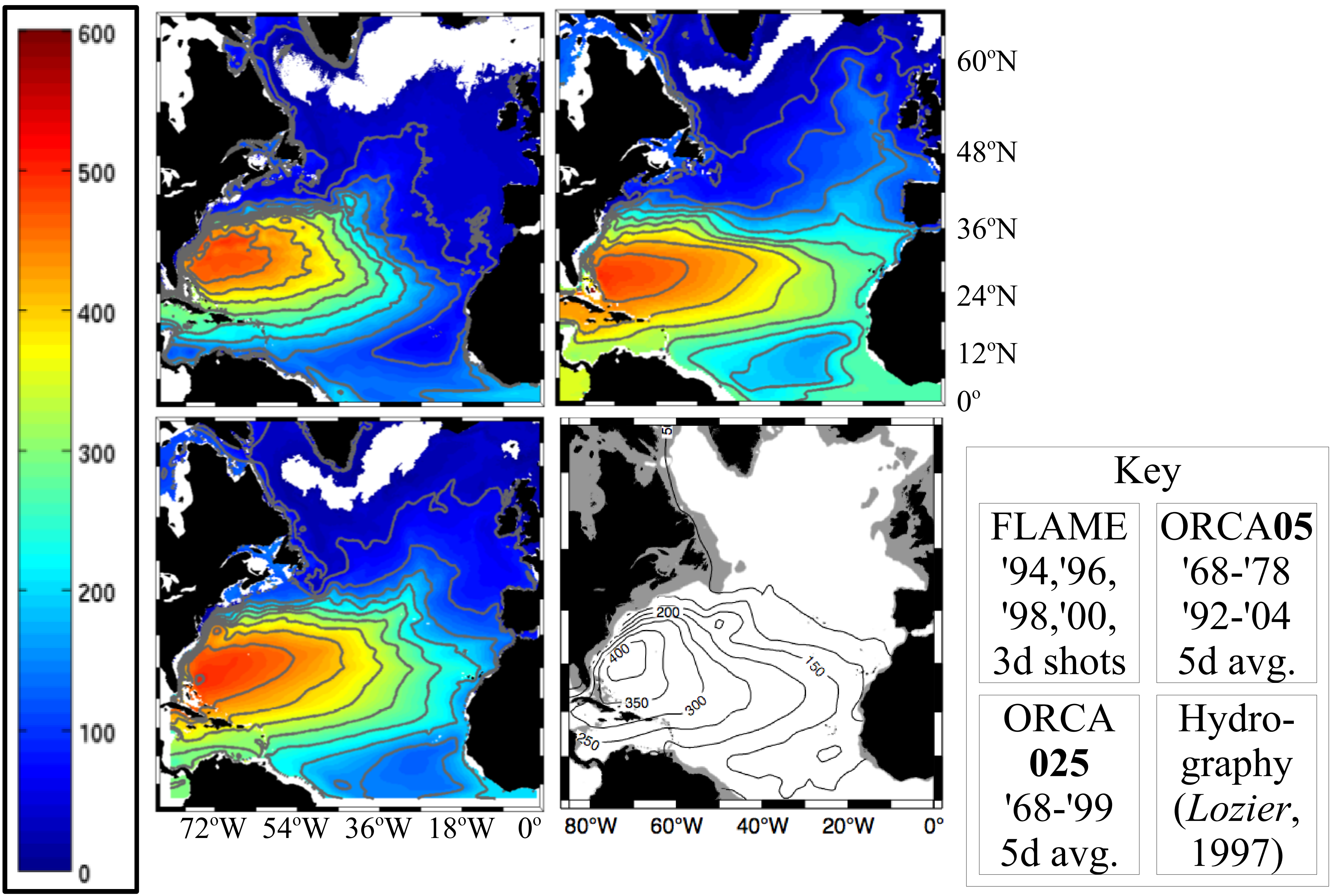
# Comparison of down-gradient eddy fluxes



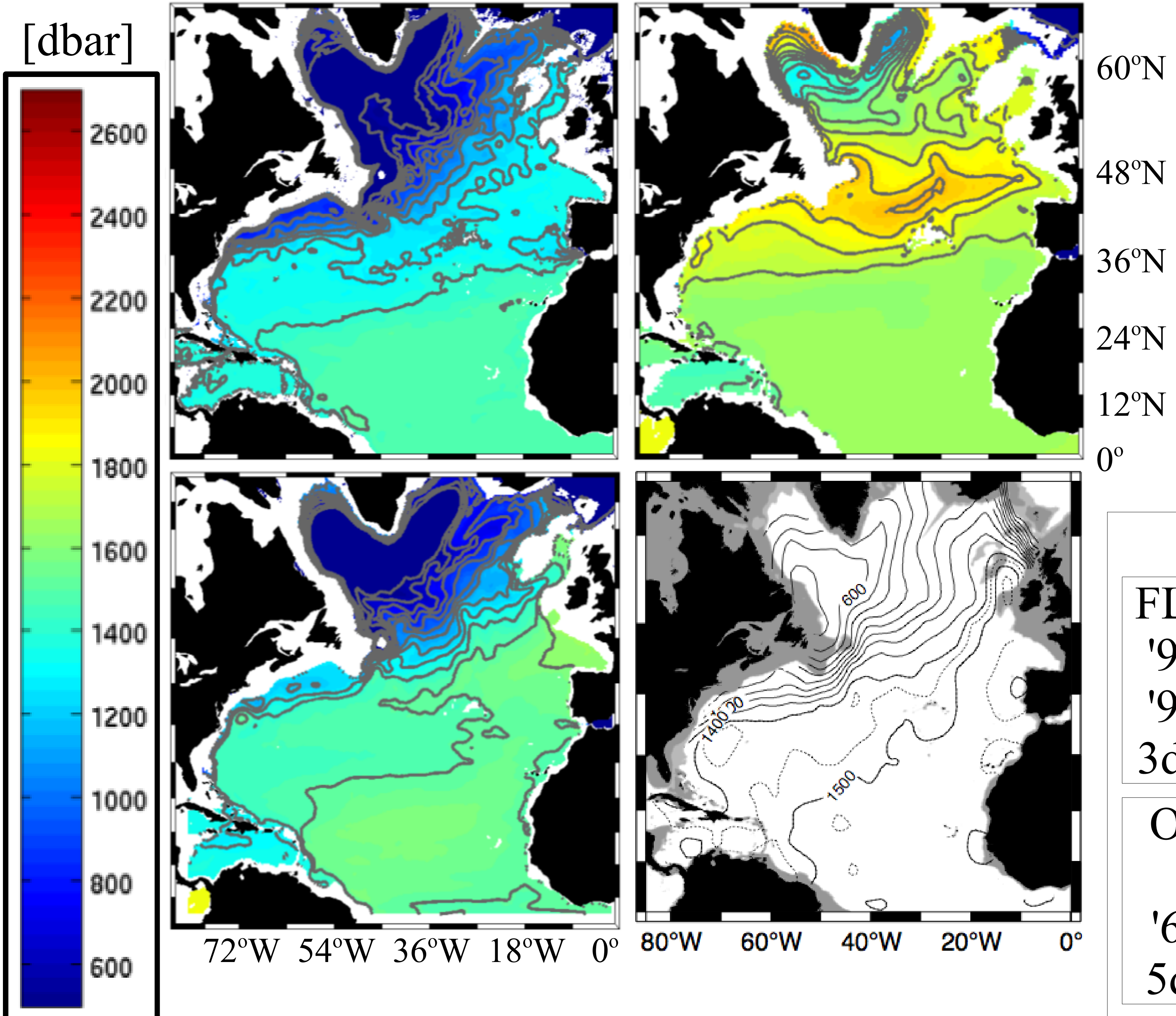

**TOP:** Mean potential vorticity ($Q$) on $\sigma_2 = 36.95$ isopycnal in the models.

**BOTTOM:** Zonal average of $\overline{\boldsymbol{u}'q'}\cdot\nabla Q$, 70°-50°W (red) 44.5°-33°W (black)

# Pressure on $\sigma_0 = 26.50$ isopycnal



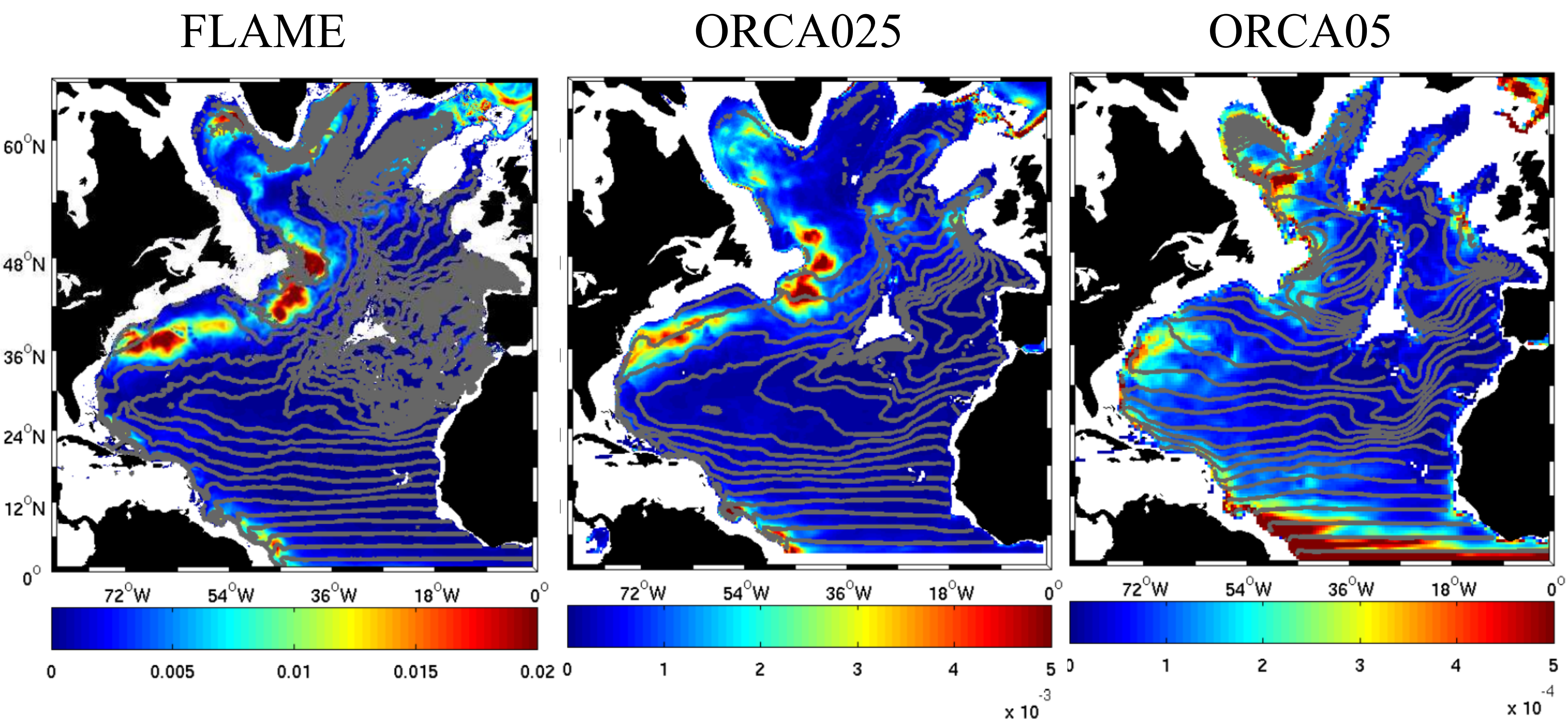
# Pressure on $\sigma_{1.5} = 34.60$ isopycnal




Key

| | |
|---|---|
| FLAME '94,'96, '98,'00, 3d shots | ORCA**05** '68-'78 '92-'04 5d avg. |
| ORCA **025** '68-'99 5d avg. | Hydro-graphy (*Lozier*, 1997) |

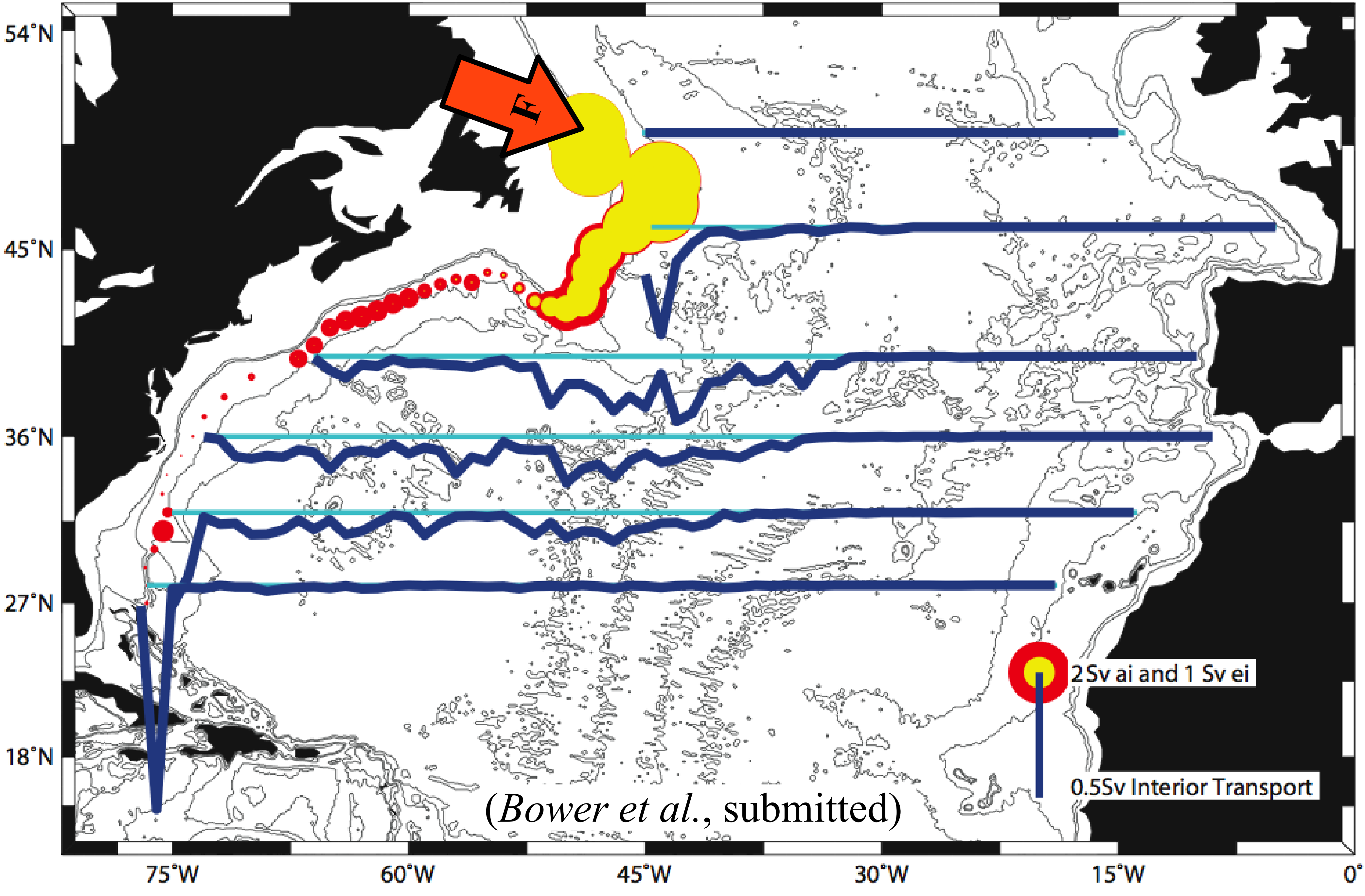
# EKE and $Q$ on $\sigma_2 = 36.95$ isopycnal




Map of eddy kinetic energy (EKE) [$m^2/s^2$] and mean potential vorticity ($Q$) contours [$(ms)^{-1}$] on $\sigma_2 = 36.95$, for:

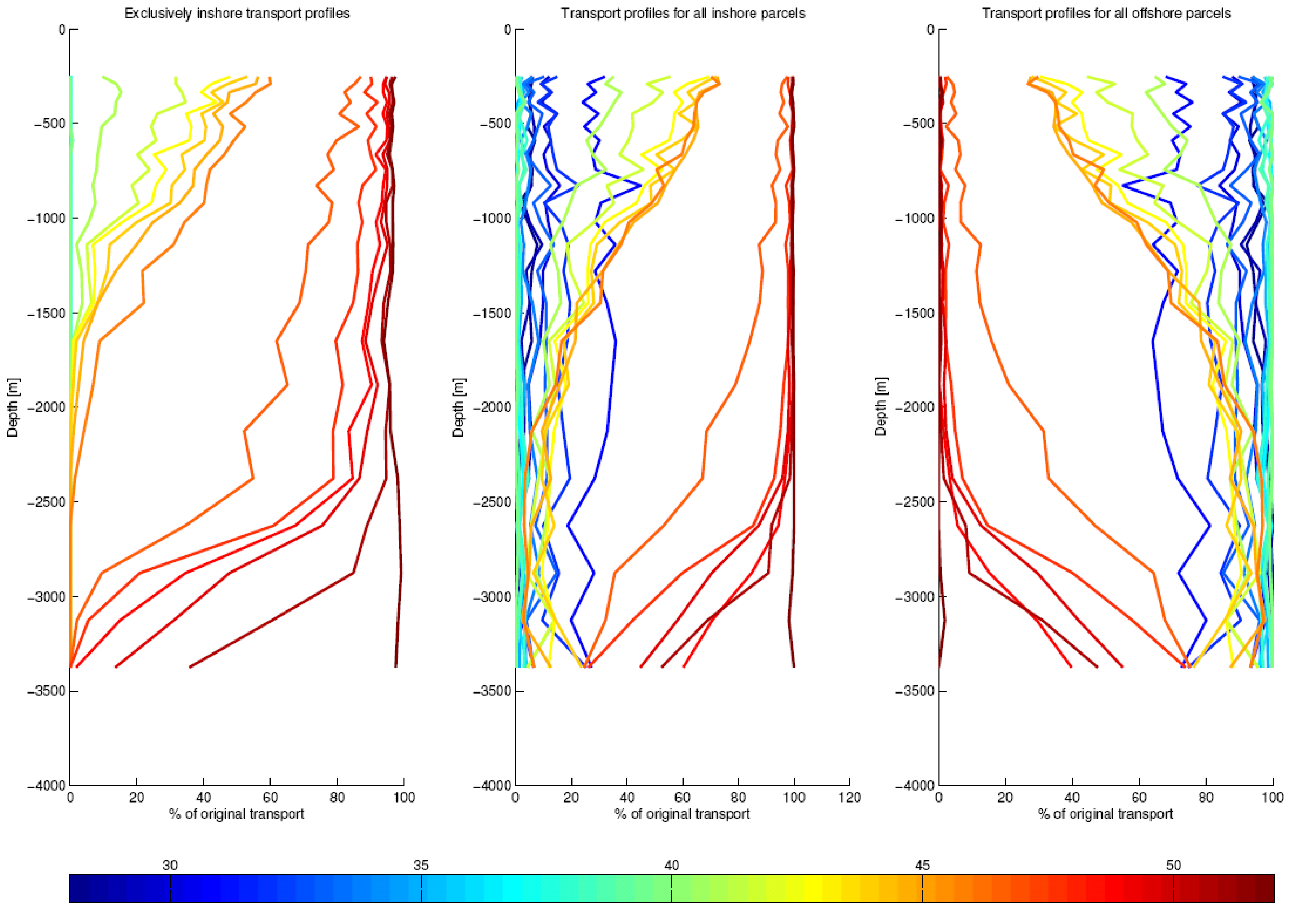
FLAME averages over 1994, 1996, 1998, and 2000 3-daily snapshots,
ORCA05 averages over 1968-1978 and 1992-2004 5-daily averages
ORCA024 averages over 1968-1999 5-daily averages.

# Deep Limb AMOC Transport Fate

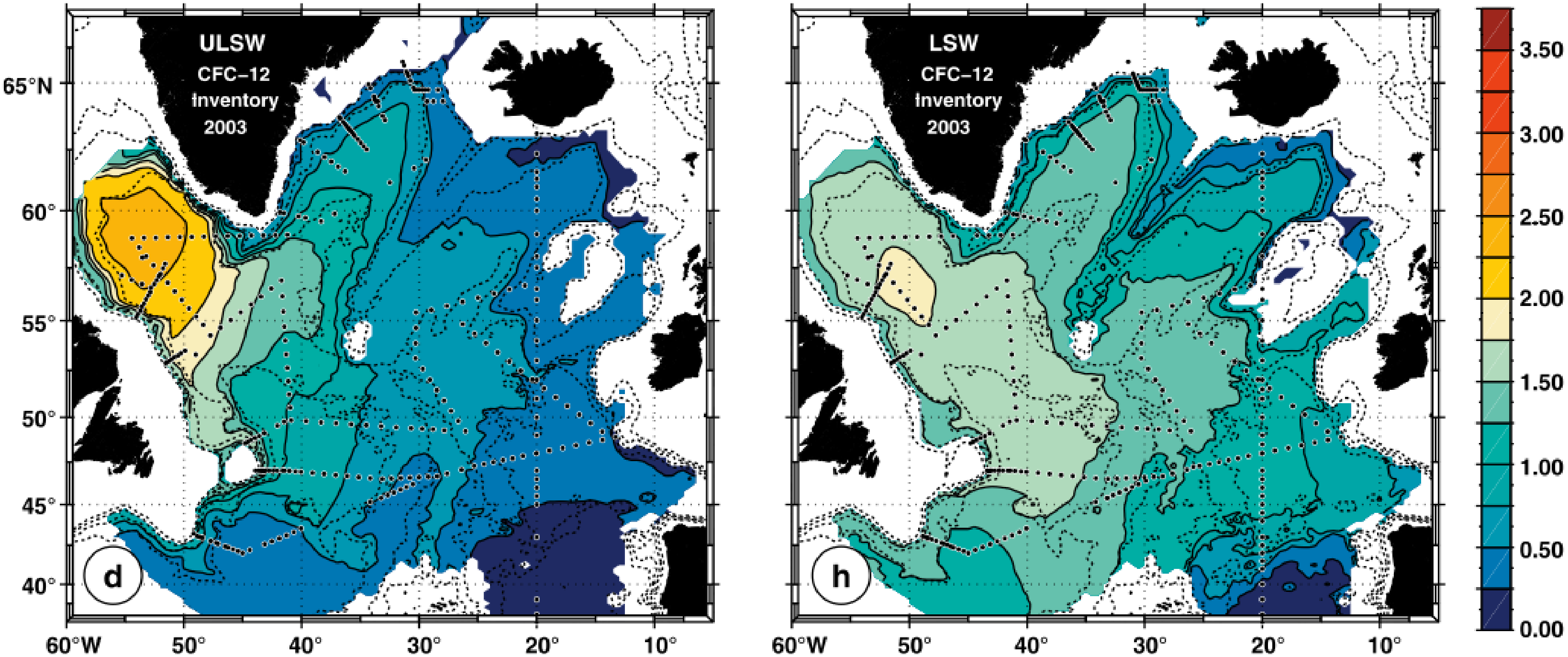



(*Bower et al.*, submitted)

# Transport in Deep Limb AMOC



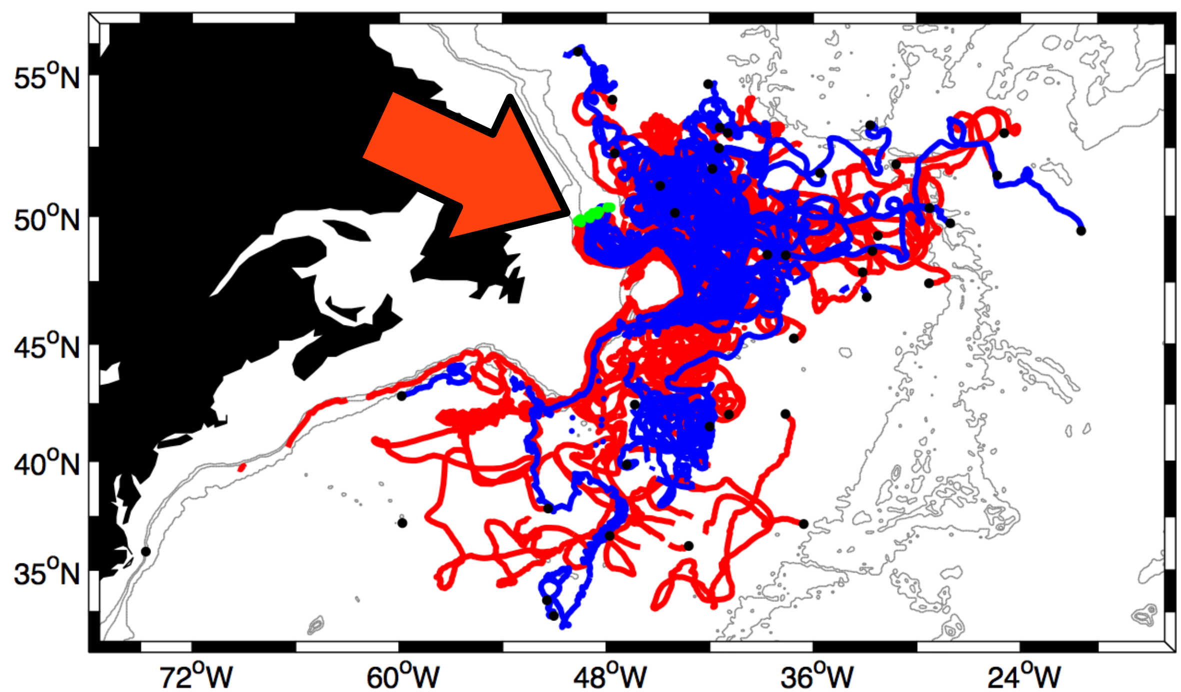
# Context: Drifters and Tracers




More tracer along the boundary but there is also tracer in the interior.

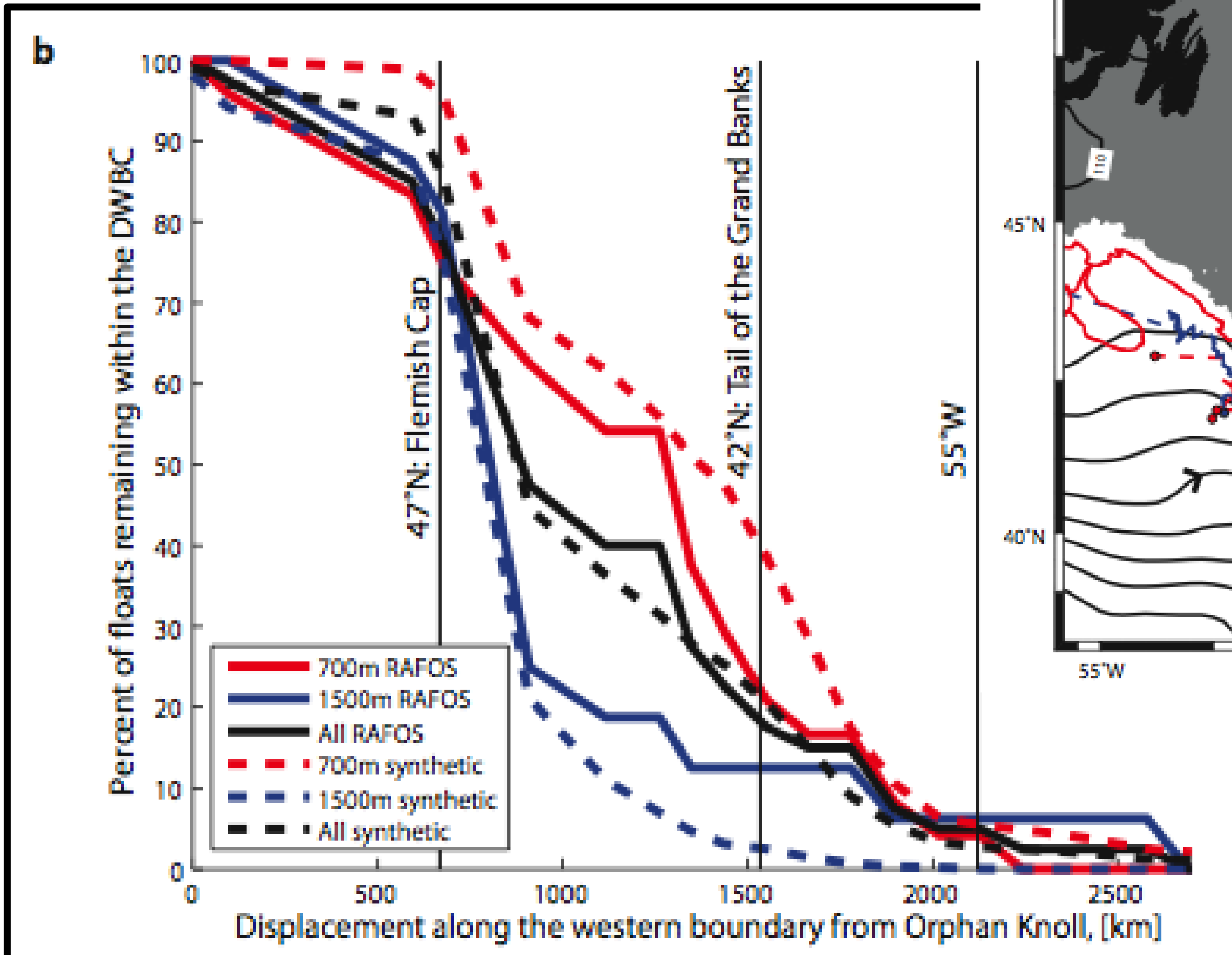
CFC inventory 2003, $\sigma_\theta$=27.68-27.80 kg/m$^3$ [moles/km$^2$] (*Kieke et al.*, 2007)

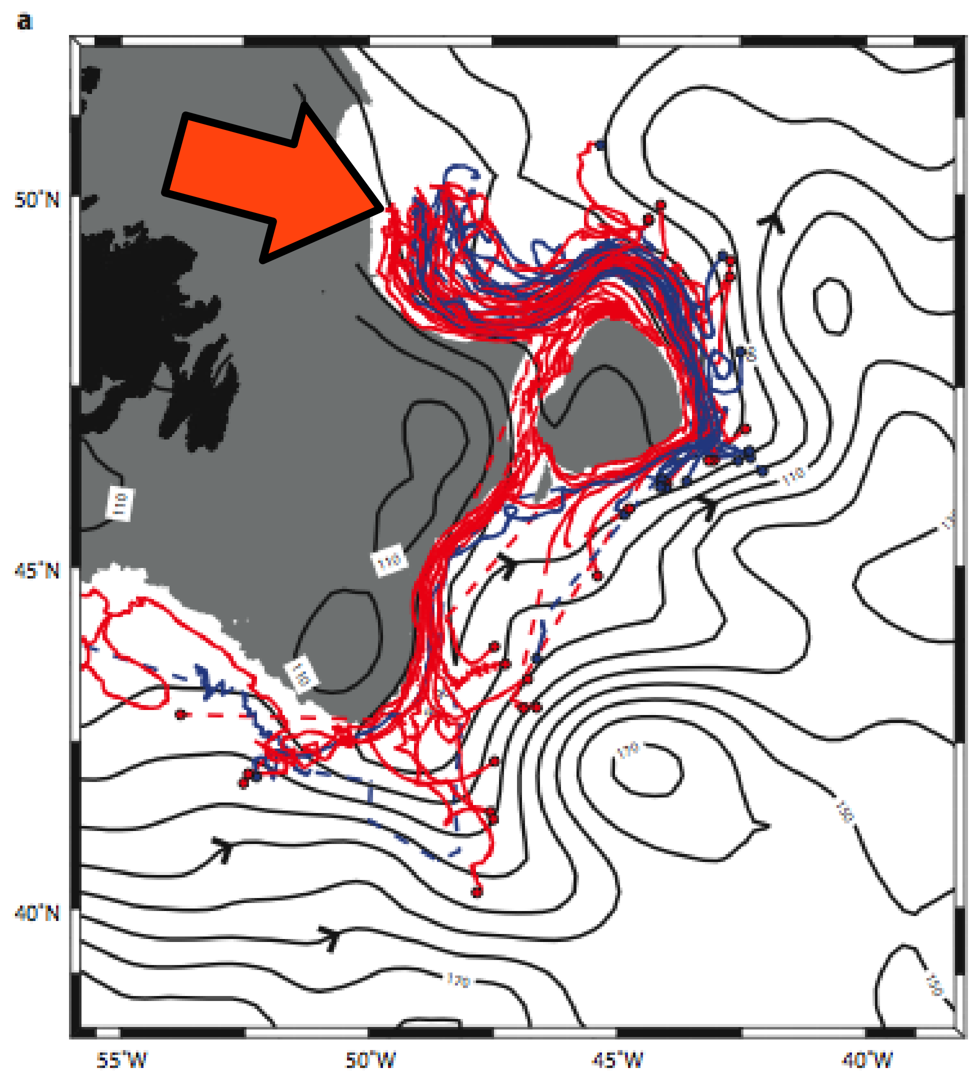
40 2003-2007 RAFOS trajectories
Red = 700m, Blue = 1500m
(*Bower et al.*, submitted)



# Exits from the DWBC during the first 2 years

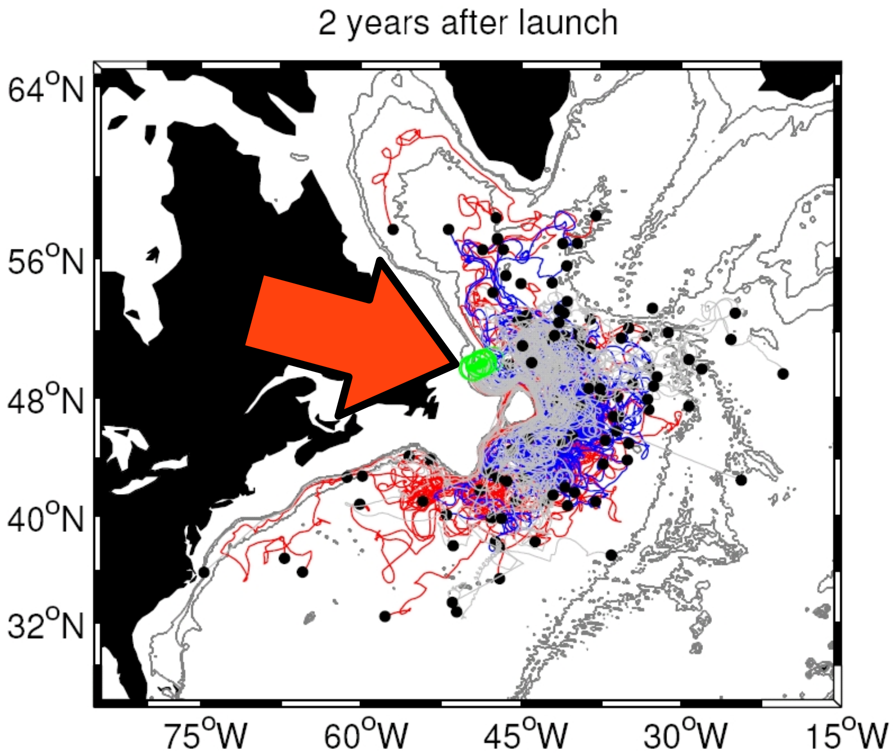
Percent of RAFOS and synthetic (FLAME) floats that stay inshore of the 4000m isobath.
(*Bower et al.*, submitted)

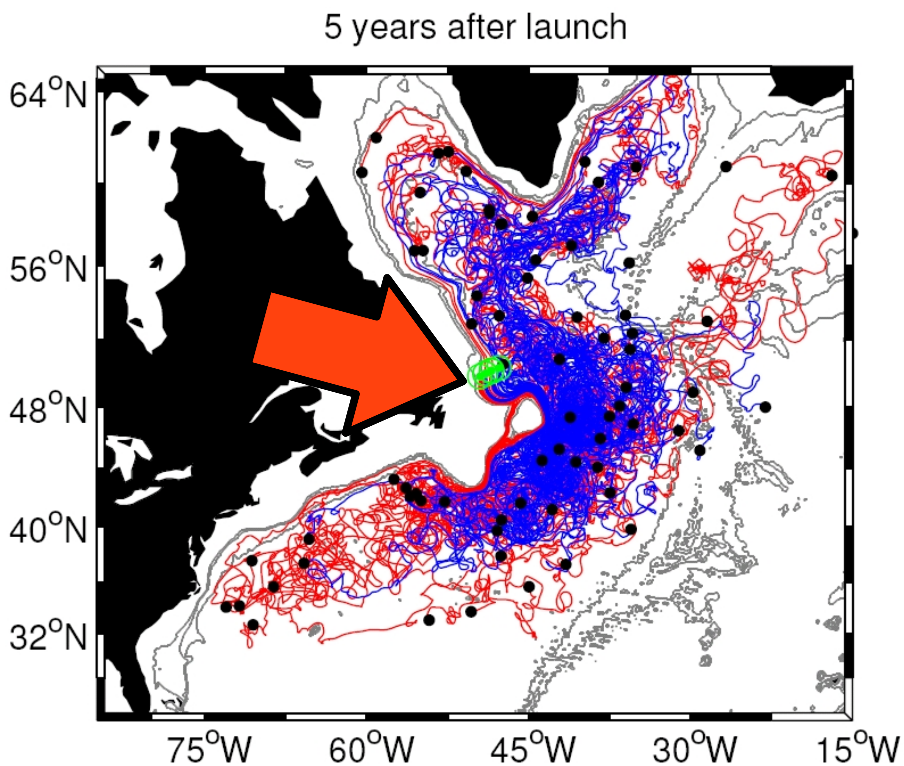


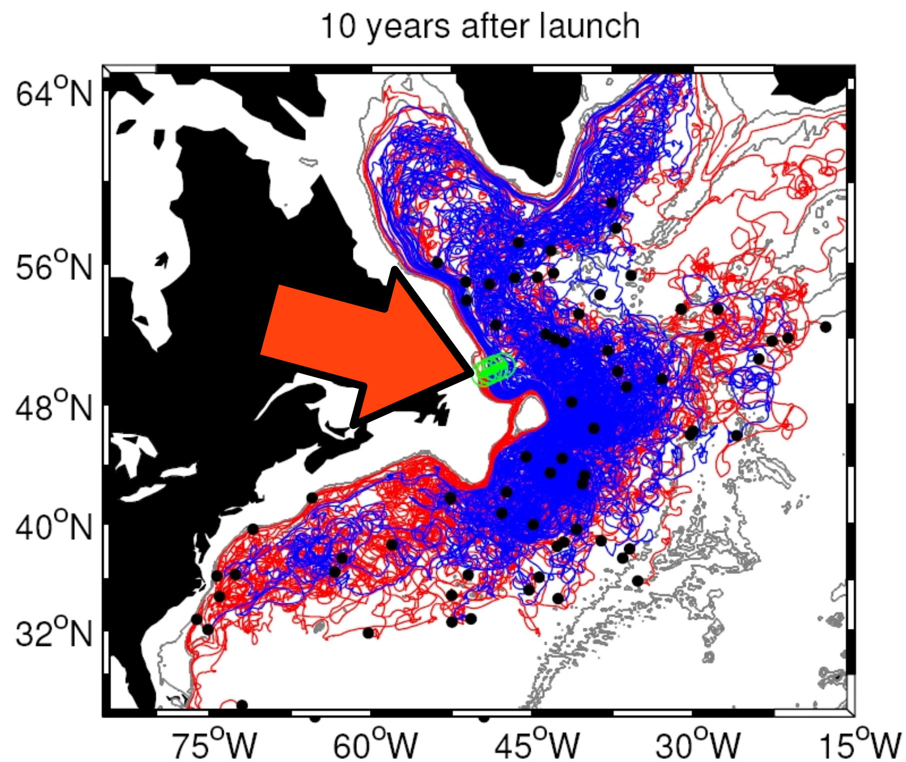




RAFOS trajectories plotted to the point of separation (*Bower et al.*, submitted).

# Where do the floats go in FLAME?

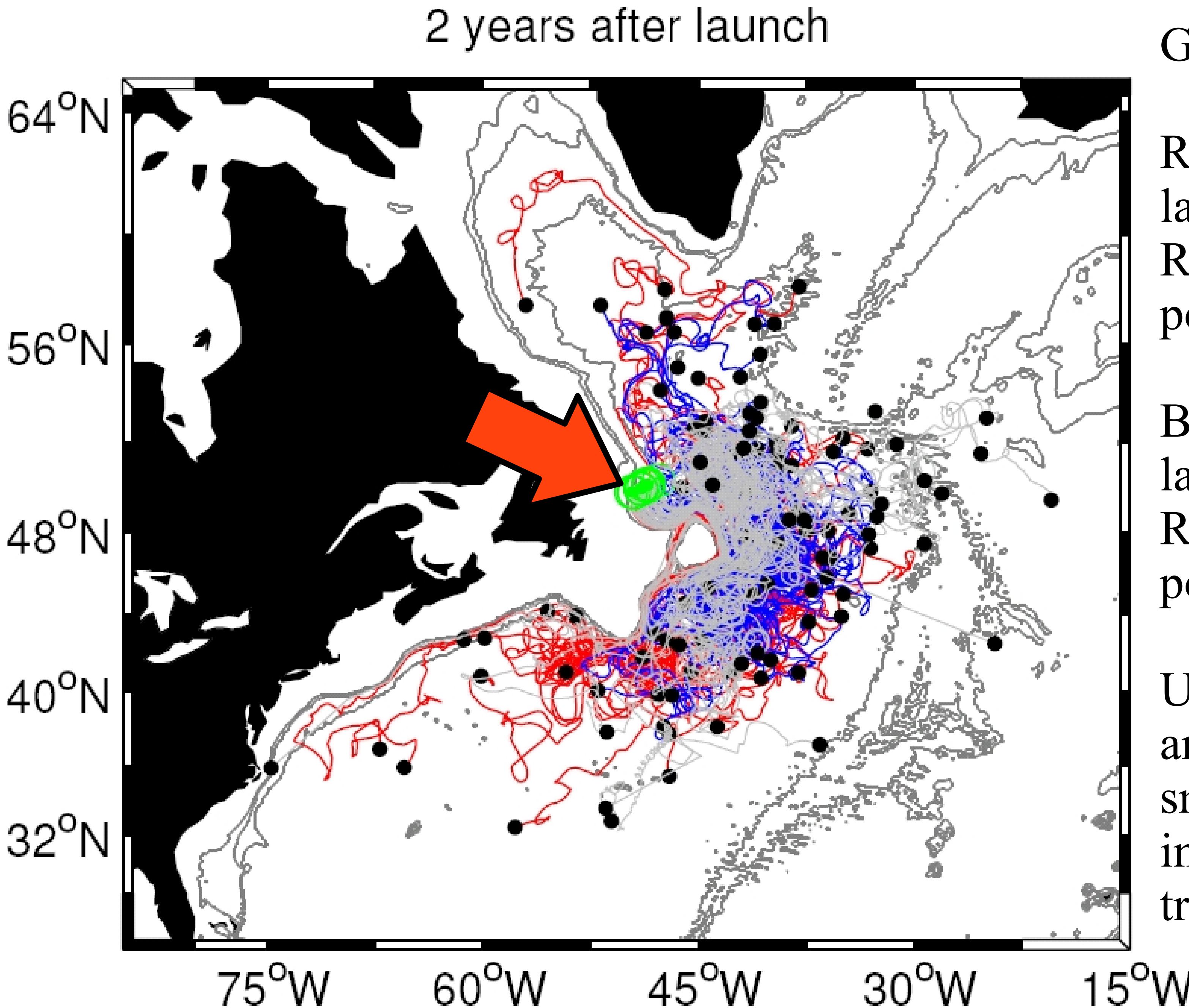



Real (grey) and synthetic (red = 700m, blue = 1500m) trajectories. E-floats were launched in the same locations as real floats but run on 3-daily snapshots of '94, '96, and '98 FLAME model velocity fields (*Bower et al.*, submitted).

# Where do the floats go in FLAME?




Gray = RAFOS traj.

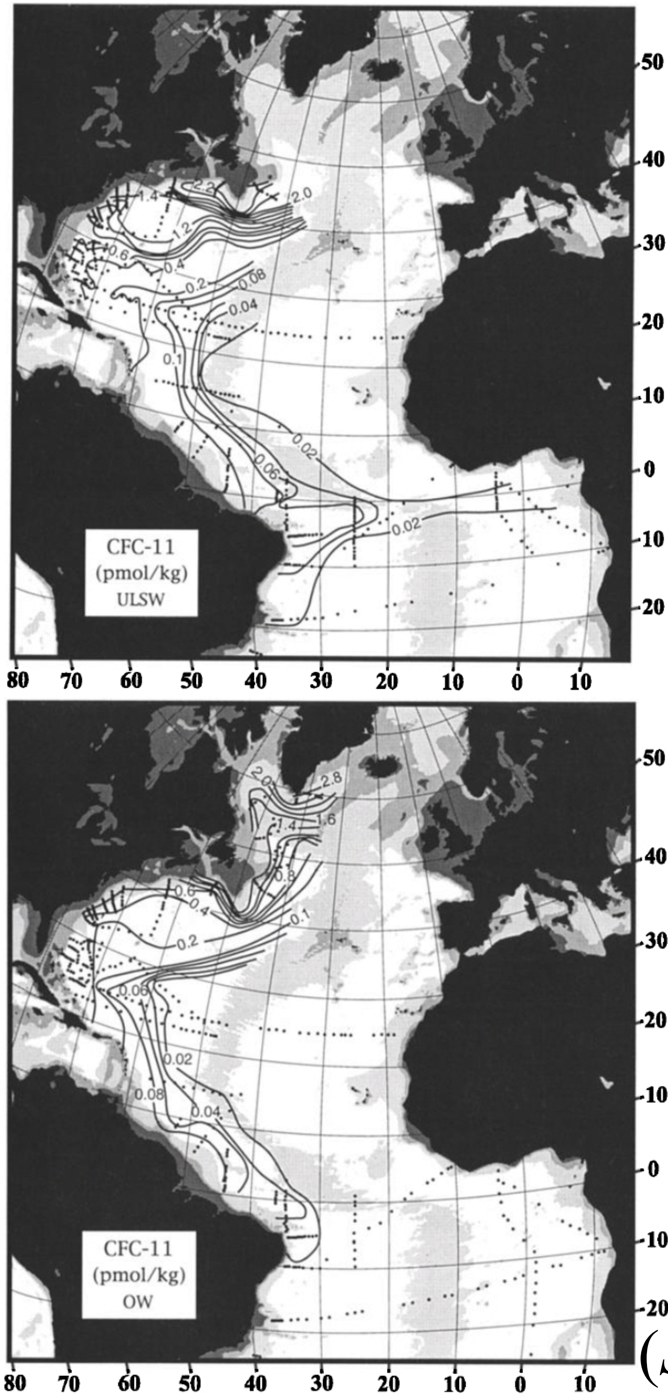
Red = FLAME traj. launched at 700m RAFOS floats' positions

Blue = FLAME traj. launched at 1500m RAFOS floats' positions.

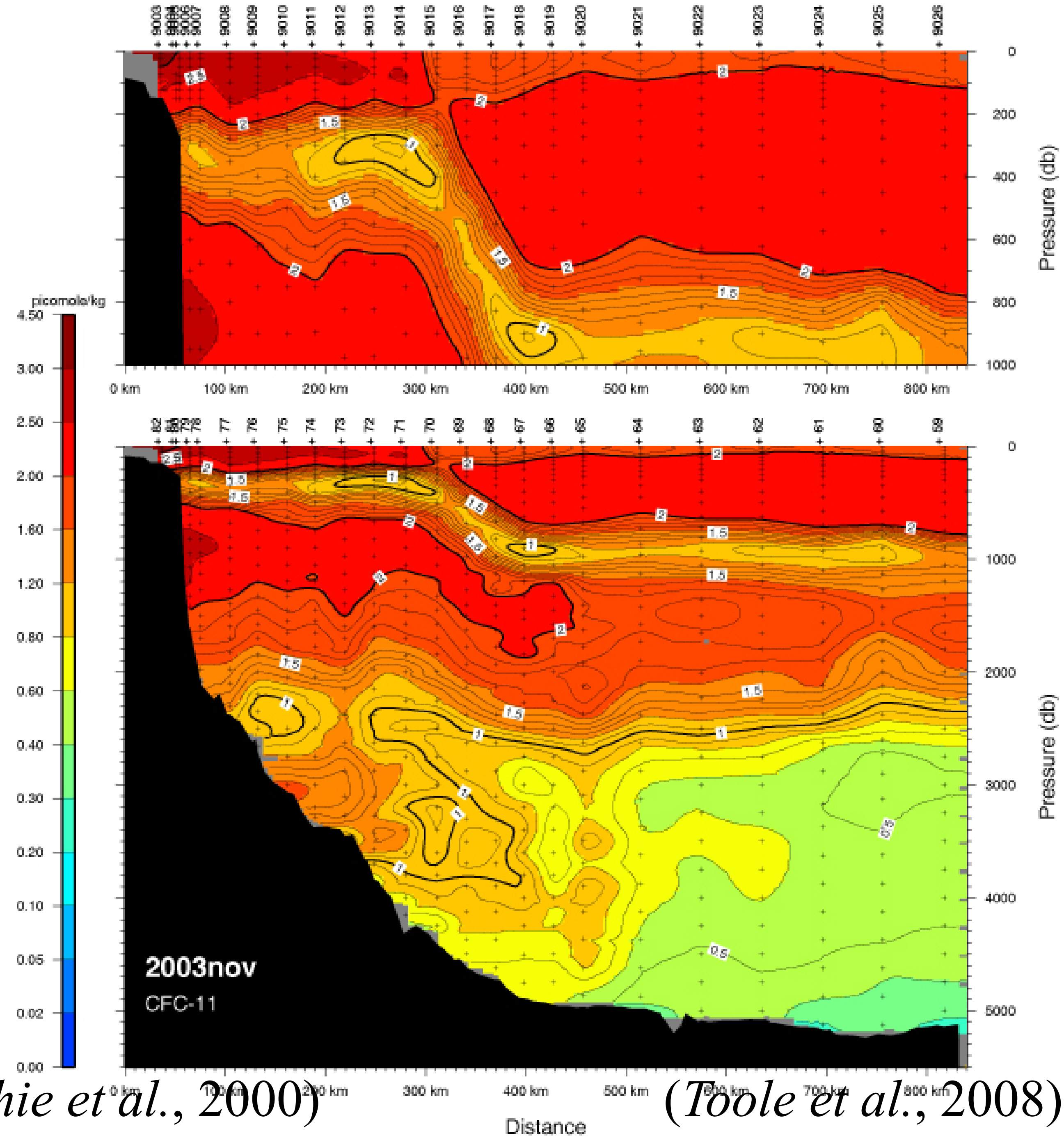
Used 1994, 1996, and 1998 3-daily snapshots to integrate 3D trajectories.

(*Bower et al.*, submitted)

# Context: Tracers



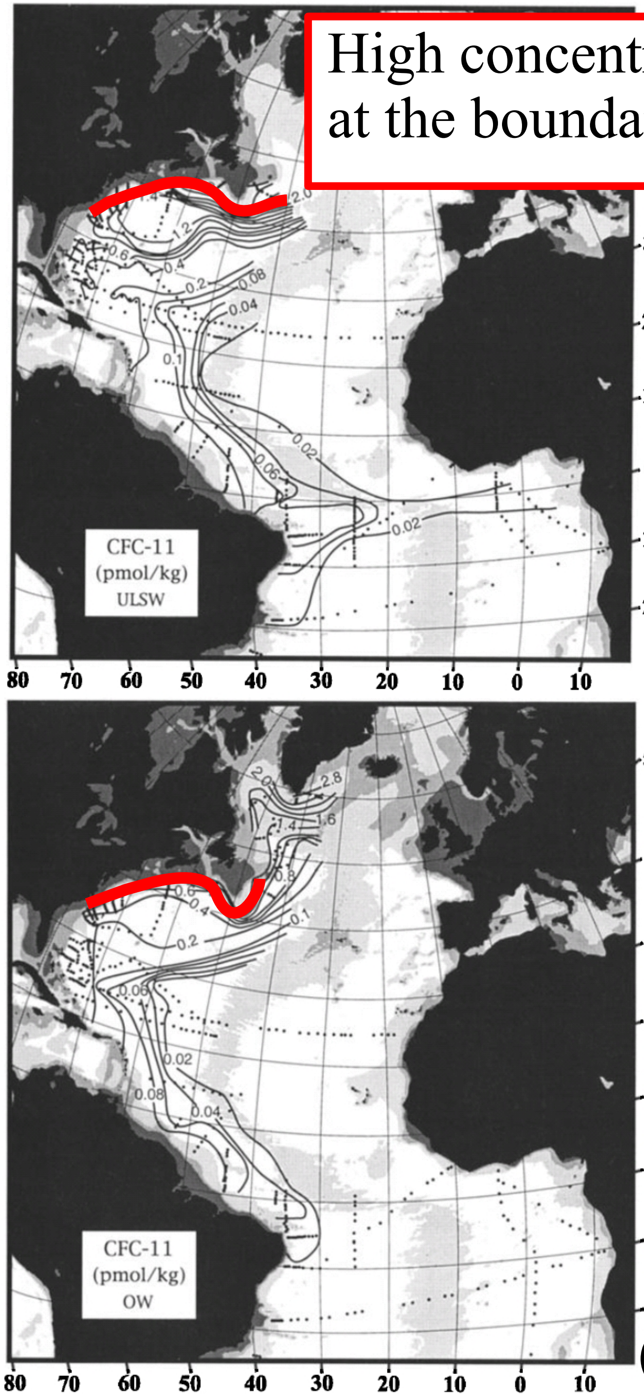

(*Smethie et al.*, 2000)



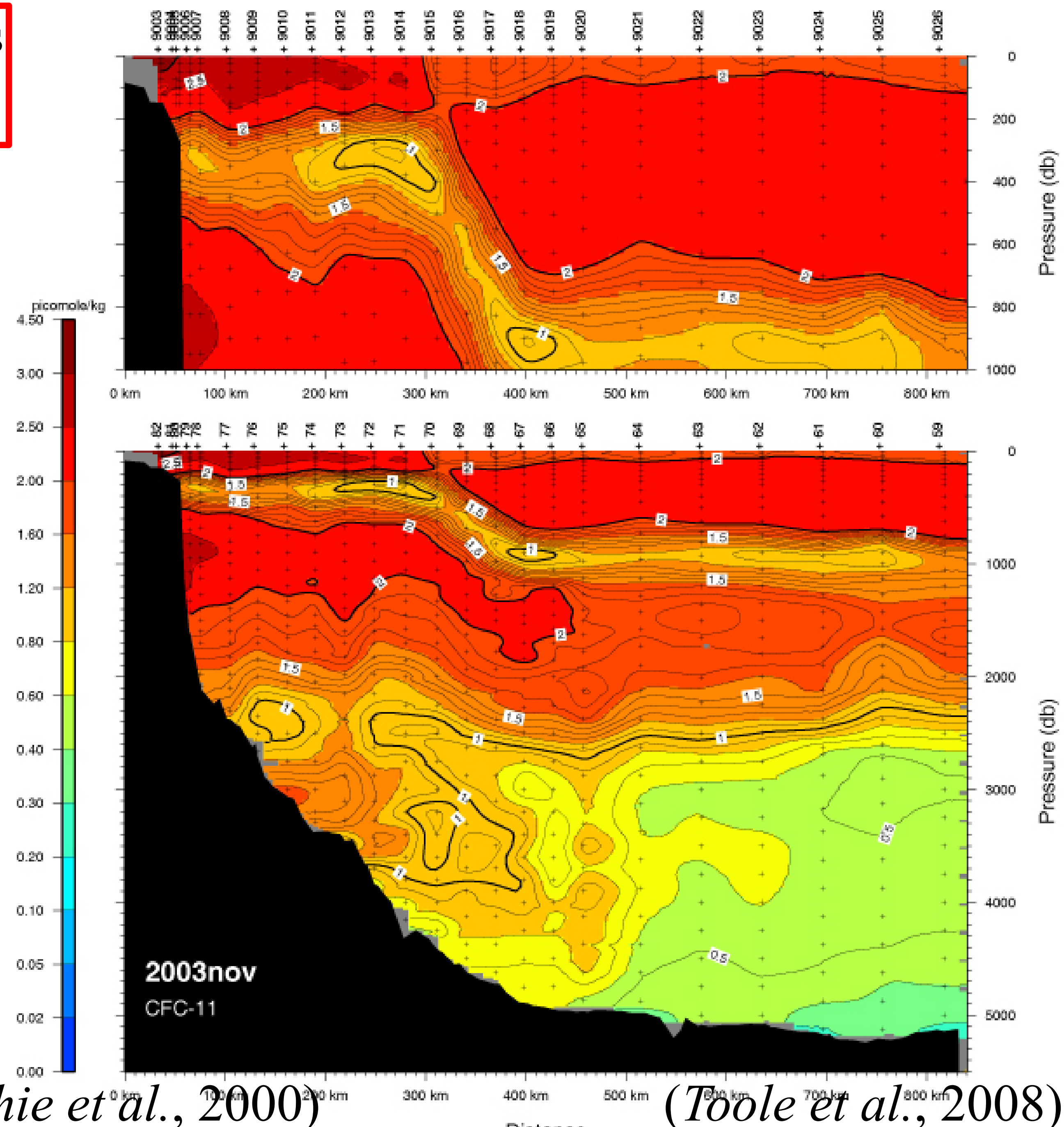

(*Toole et al.*, 2008)

# Context: Tracers

High concentrations at the boundary




(*Smethie et al.*, 2000)




(*Toole et al.*, 2008)

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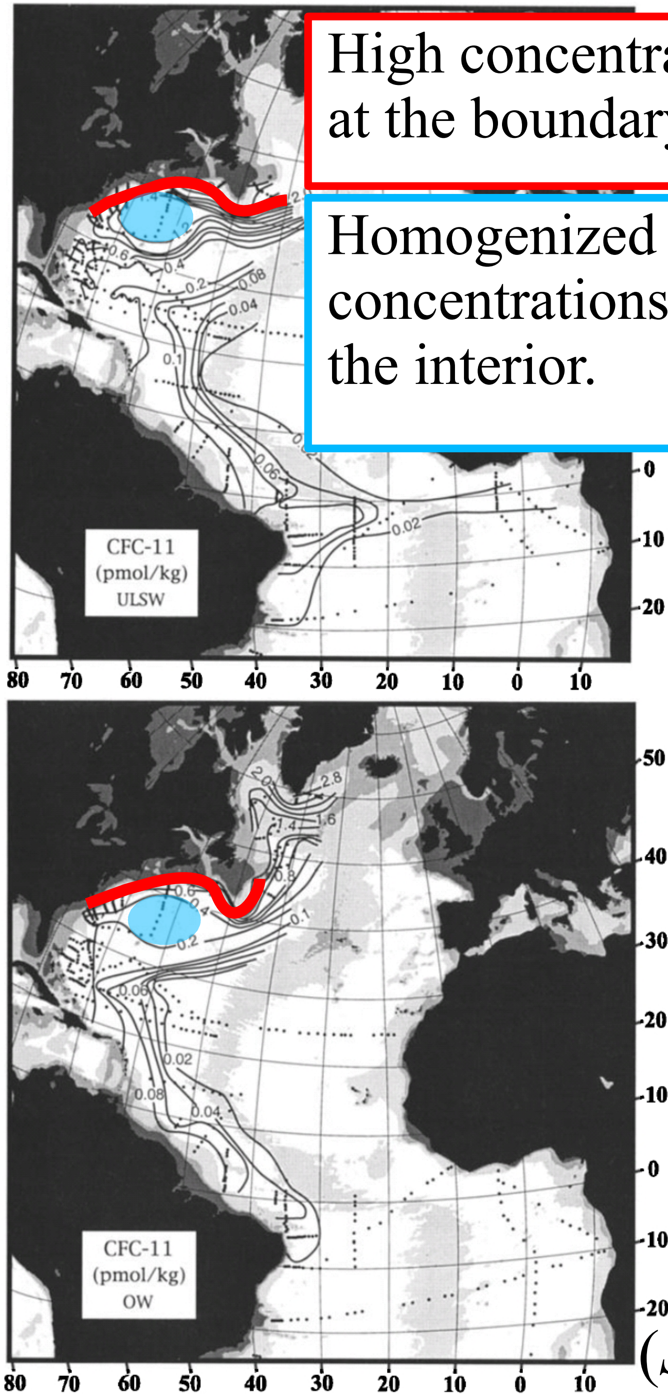
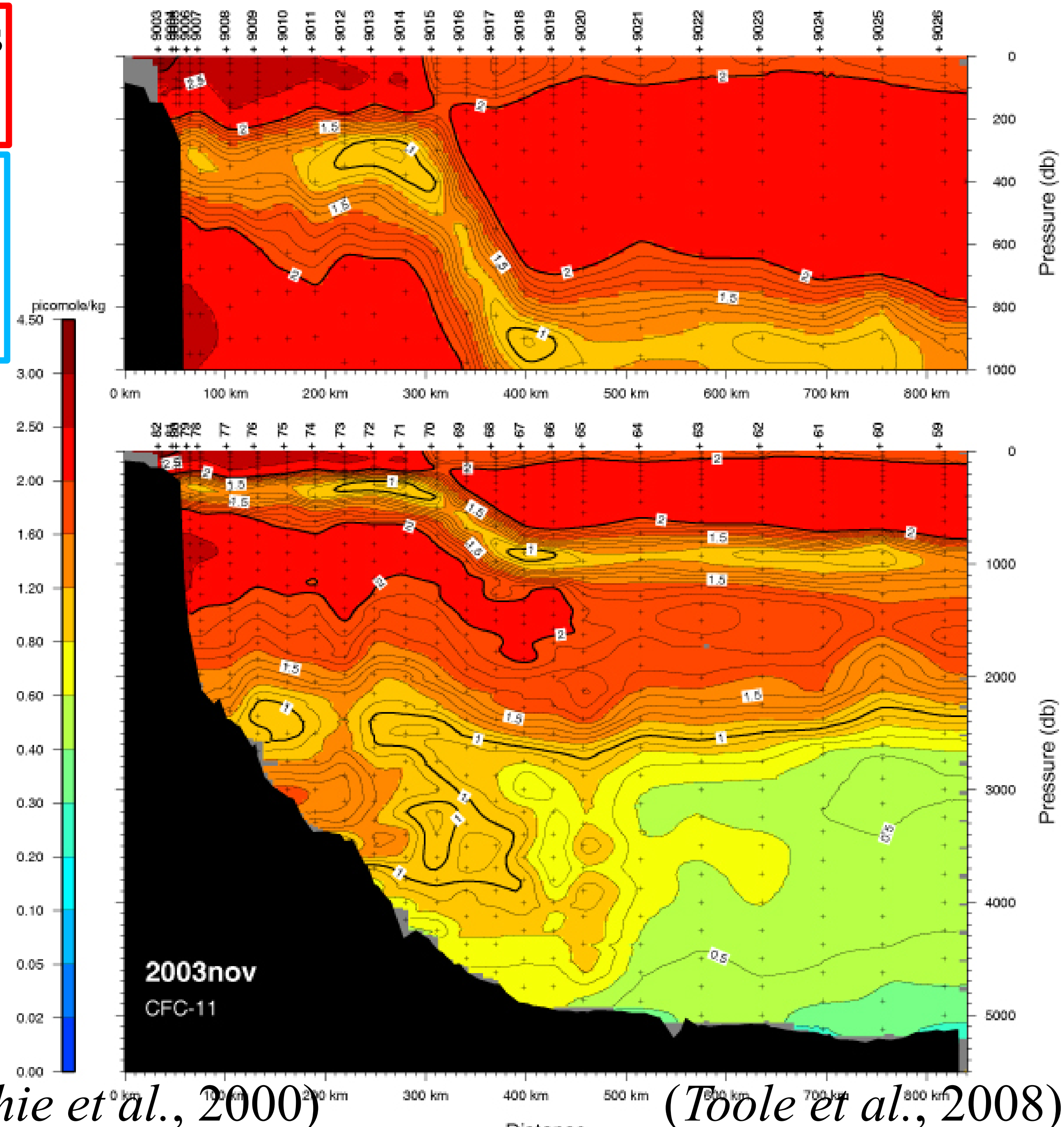



High concentrations at the boundary

Homogenized concentrations in the interior.

(*Smethie et al.*, 2000)




(*Toole et al.*, 2008)

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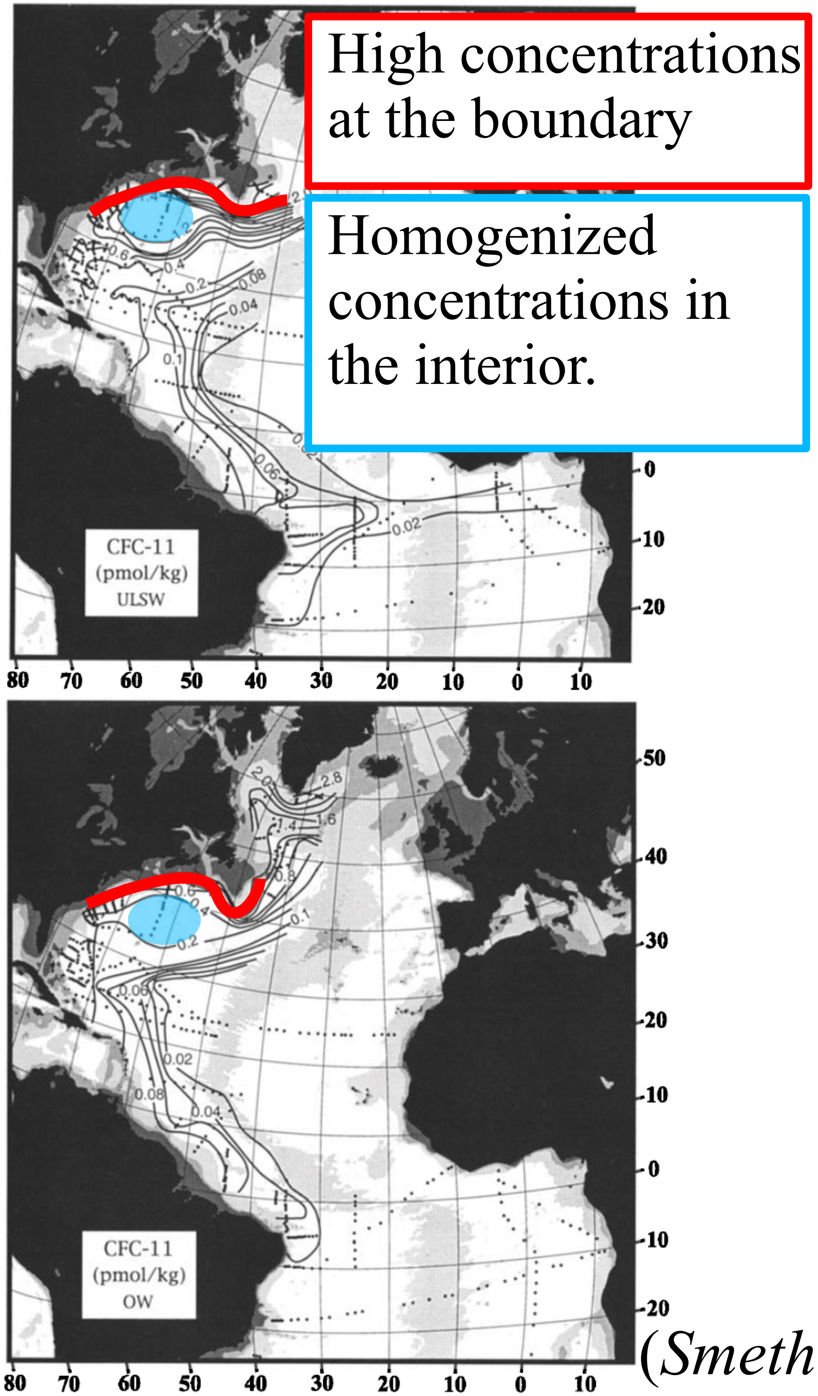
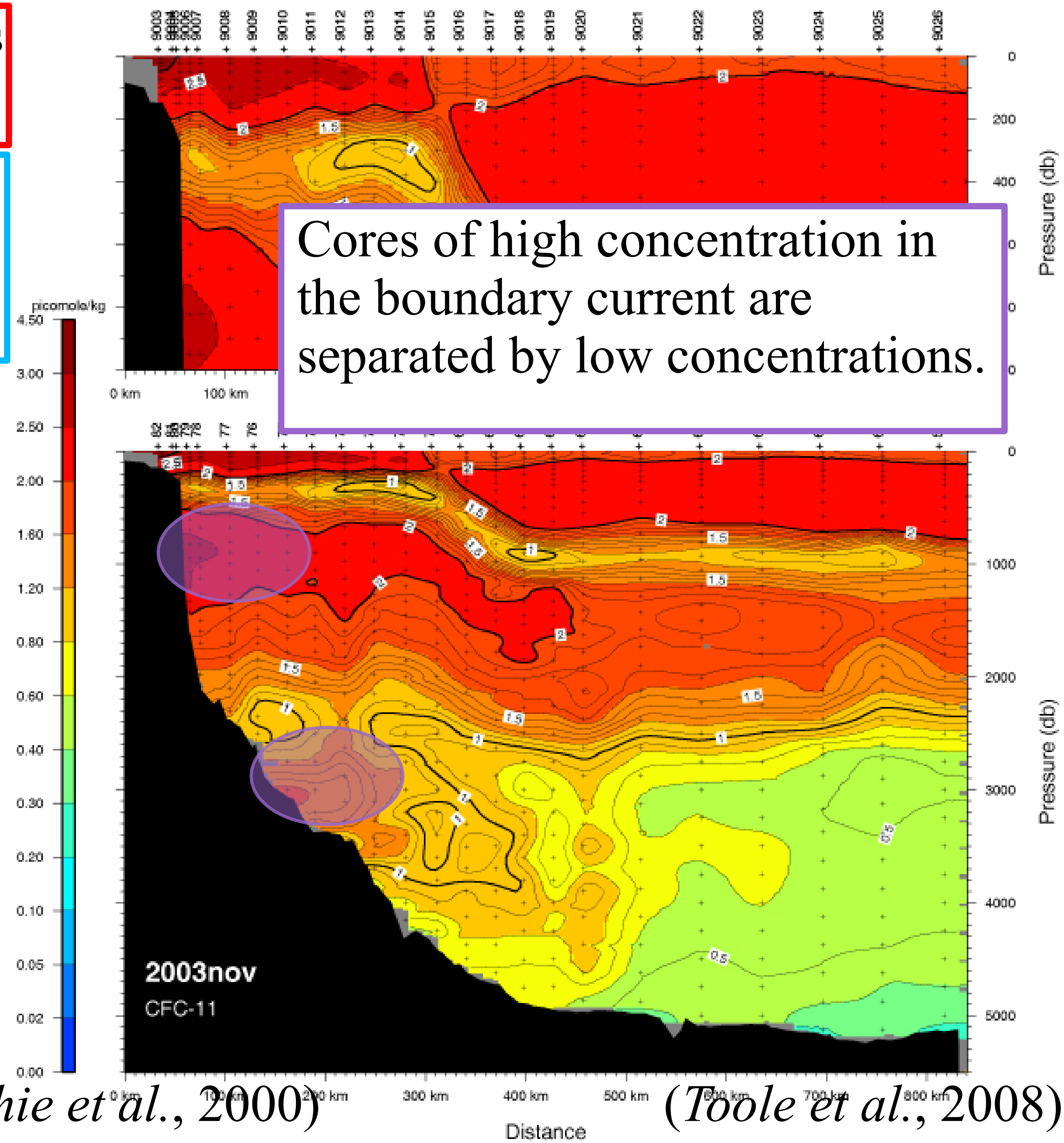
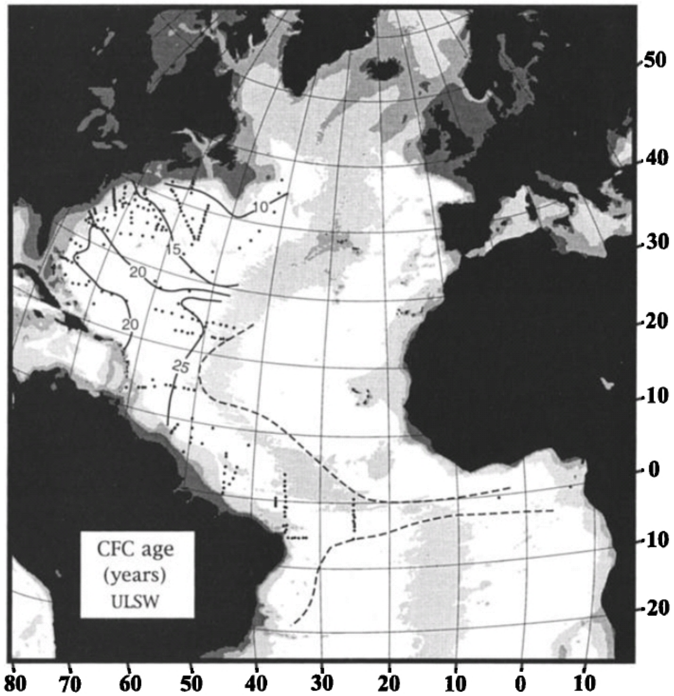


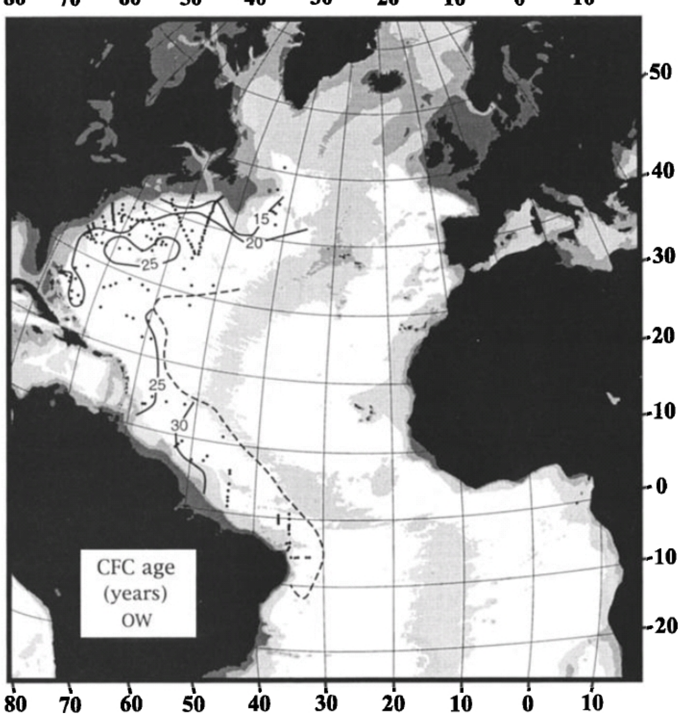

(*Smethie et al.*, 2000)




(*Toole et al.*, 2008)

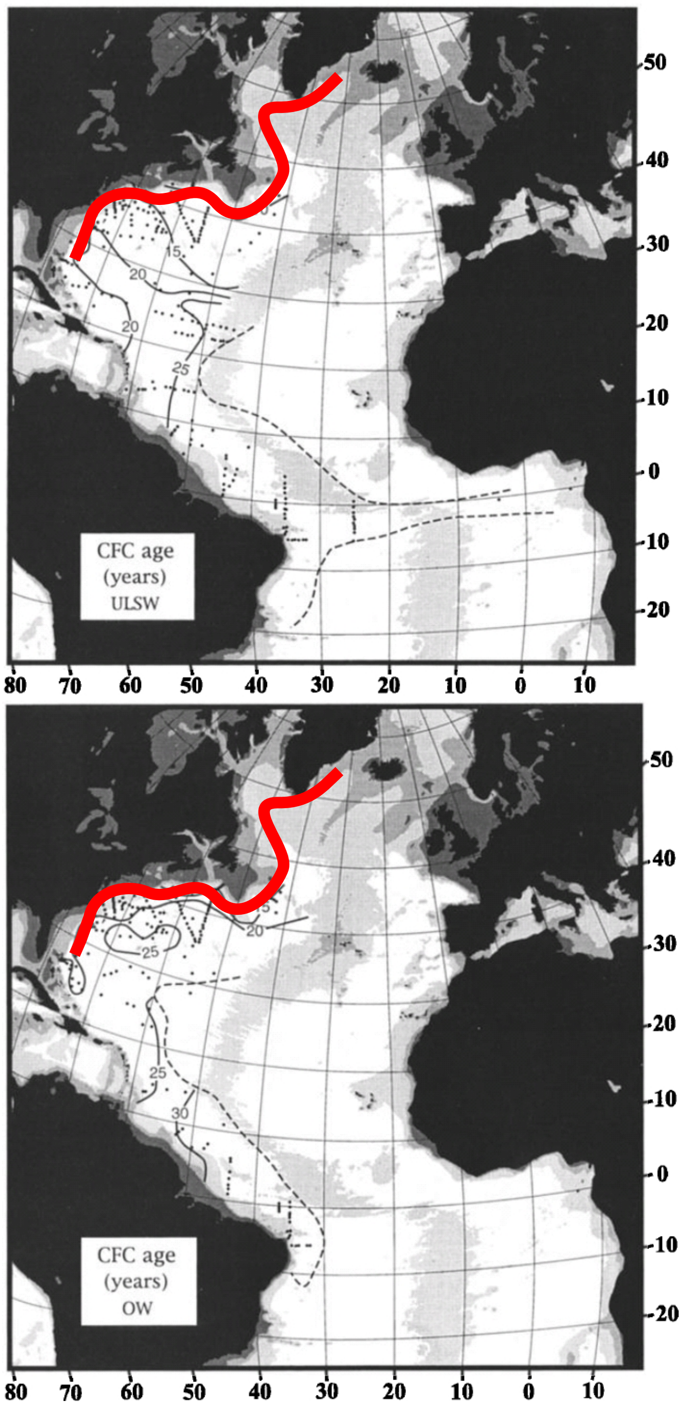
# Passive Tracers




Tracer age maps by comparing CFC concentrations in the water to the known atmospheric timeseries (*Smethie et al.*, 2000) 4000 km/20 years = ~1cm/s.

# Passive Tracers

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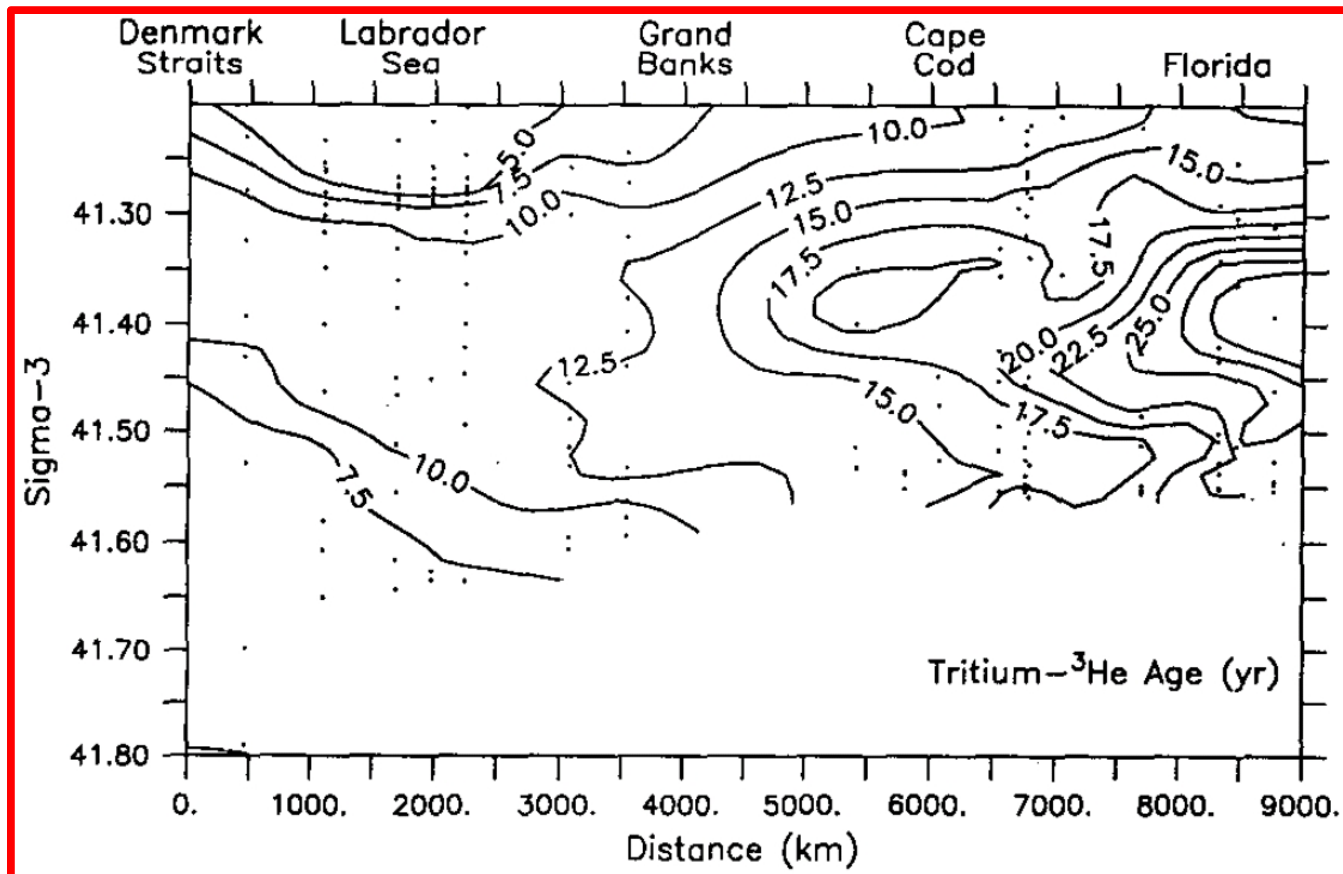
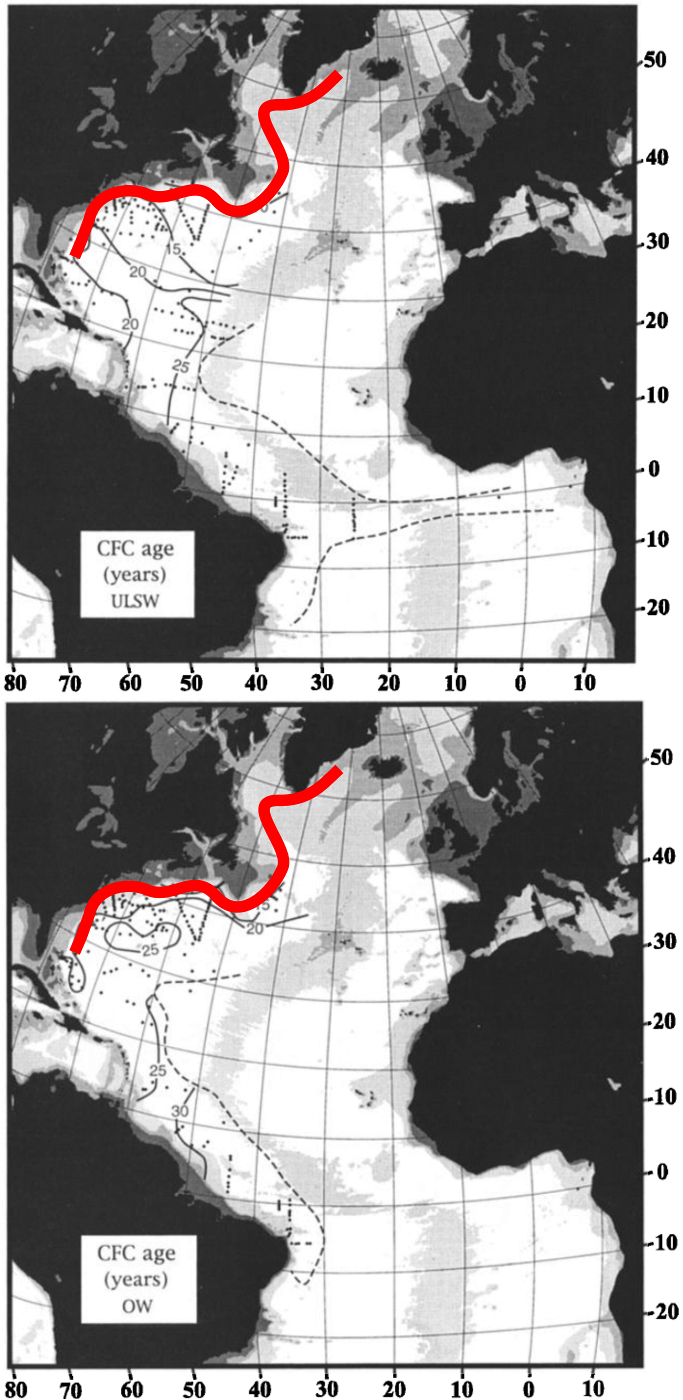
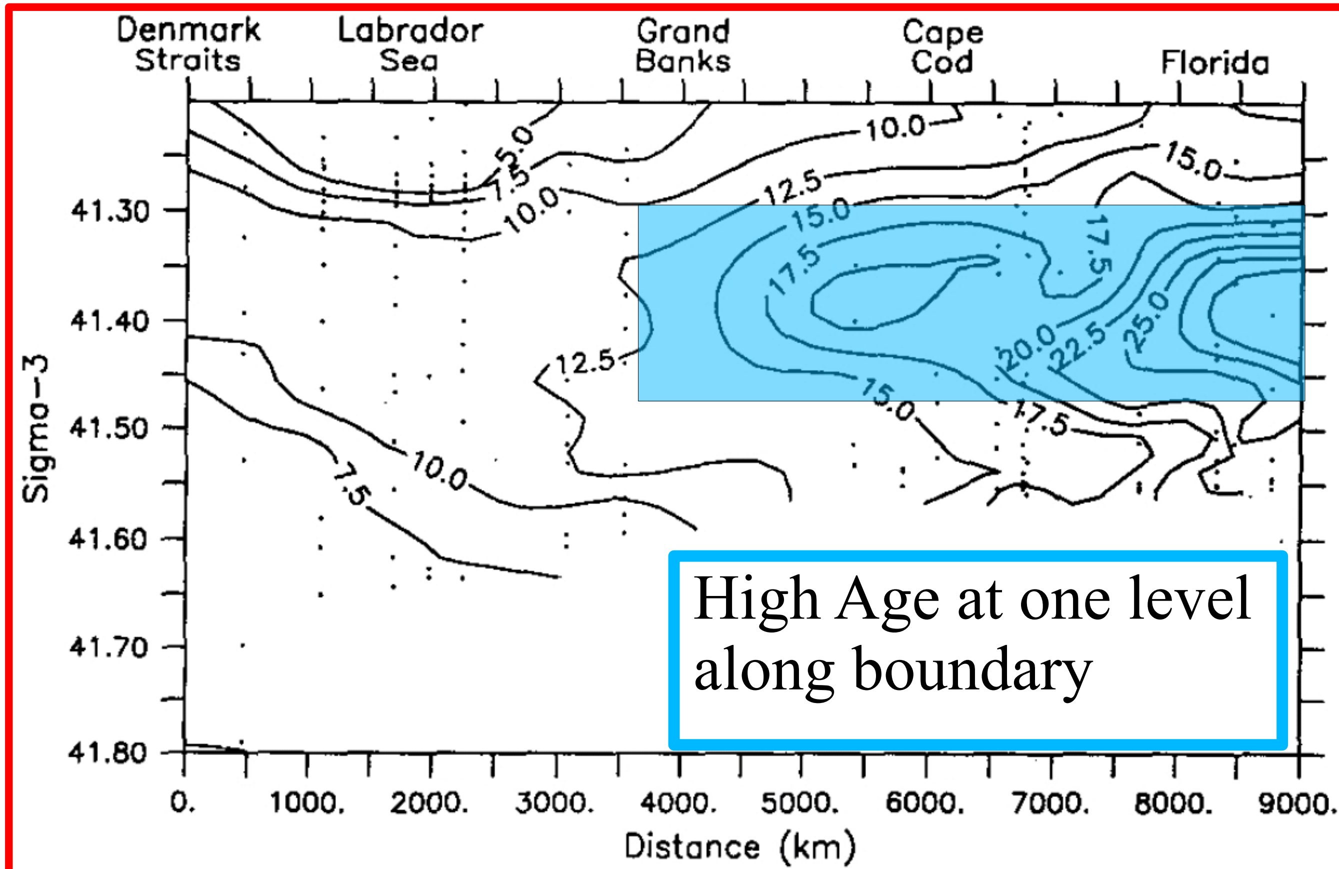



Meridional section of tracer age along the western boundary (*Doney and Jenkins*, 1994)

# Passive Tracers



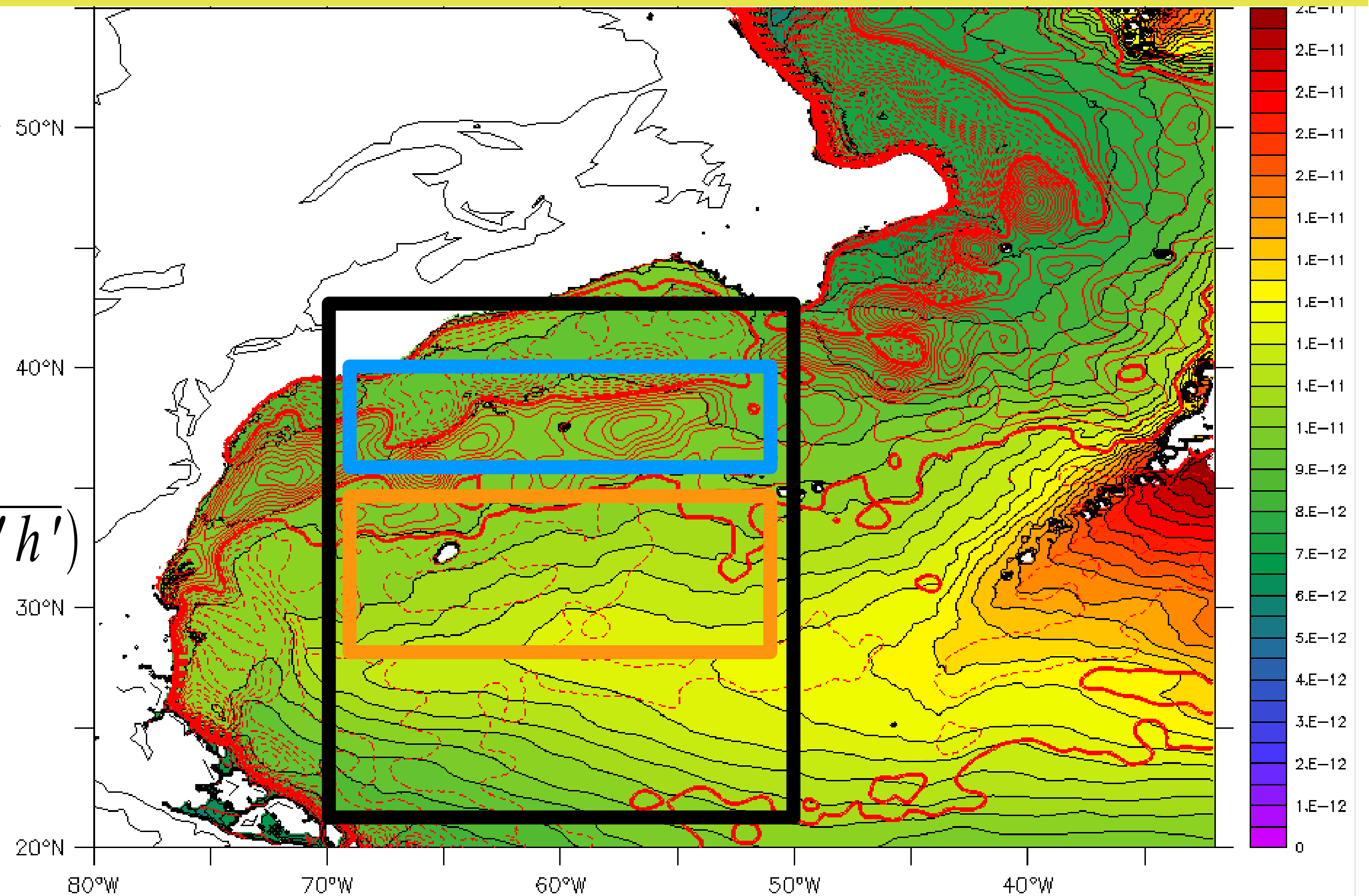

Tracer age maps by comparing CFC concentrations in the water to the known atmospheric timeseries (*Smethie et al.*, 2000) 4000 km/20 years = ~1cm/s.




Meridional section of tracer age along the western boundary (*Doney and Jenkins*, 1994)

# Results : Eddy fluxes in FLAME

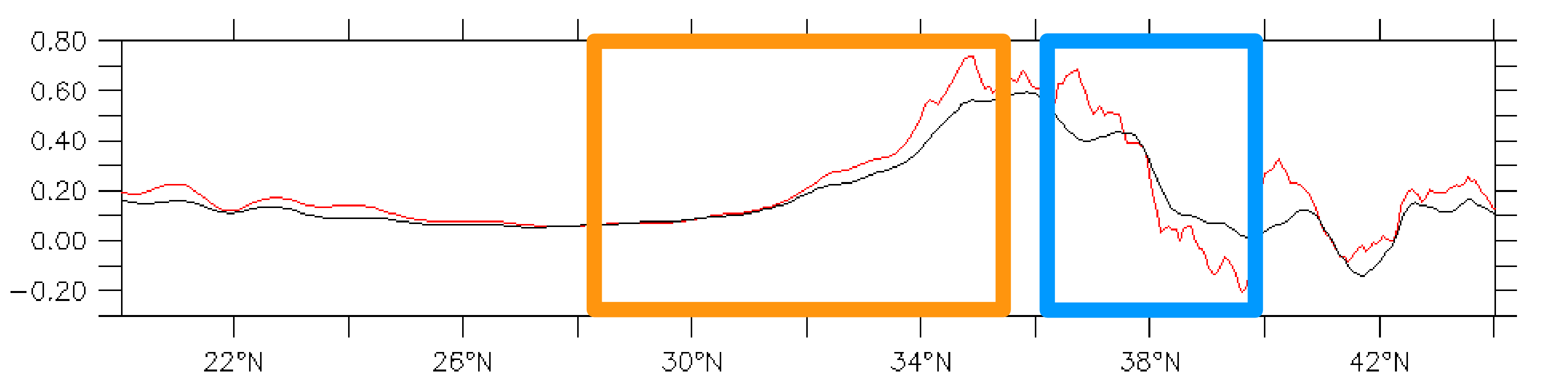
Streamfunction, Ψ, (0.01 $m^2/s$ intervals) on the $\sigma_2$ = 36.95, from 15 years of monthly mean FLAME velocity fields overlaid on mean $q$.




$$\overline{w_i} = \frac{D\bar{h}}{Dt} = \bar{\boldsymbol{u}} \cdot \nabla \bar{h} + \nabla \cdot (\overline{\boldsymbol{u}'h'})$$

$$\overline{w_{ie}} = \frac{\partial}{\partial y}(\overline{v'h'})$$

$$(\overline{v'h'})_{(70W-50W)}$$



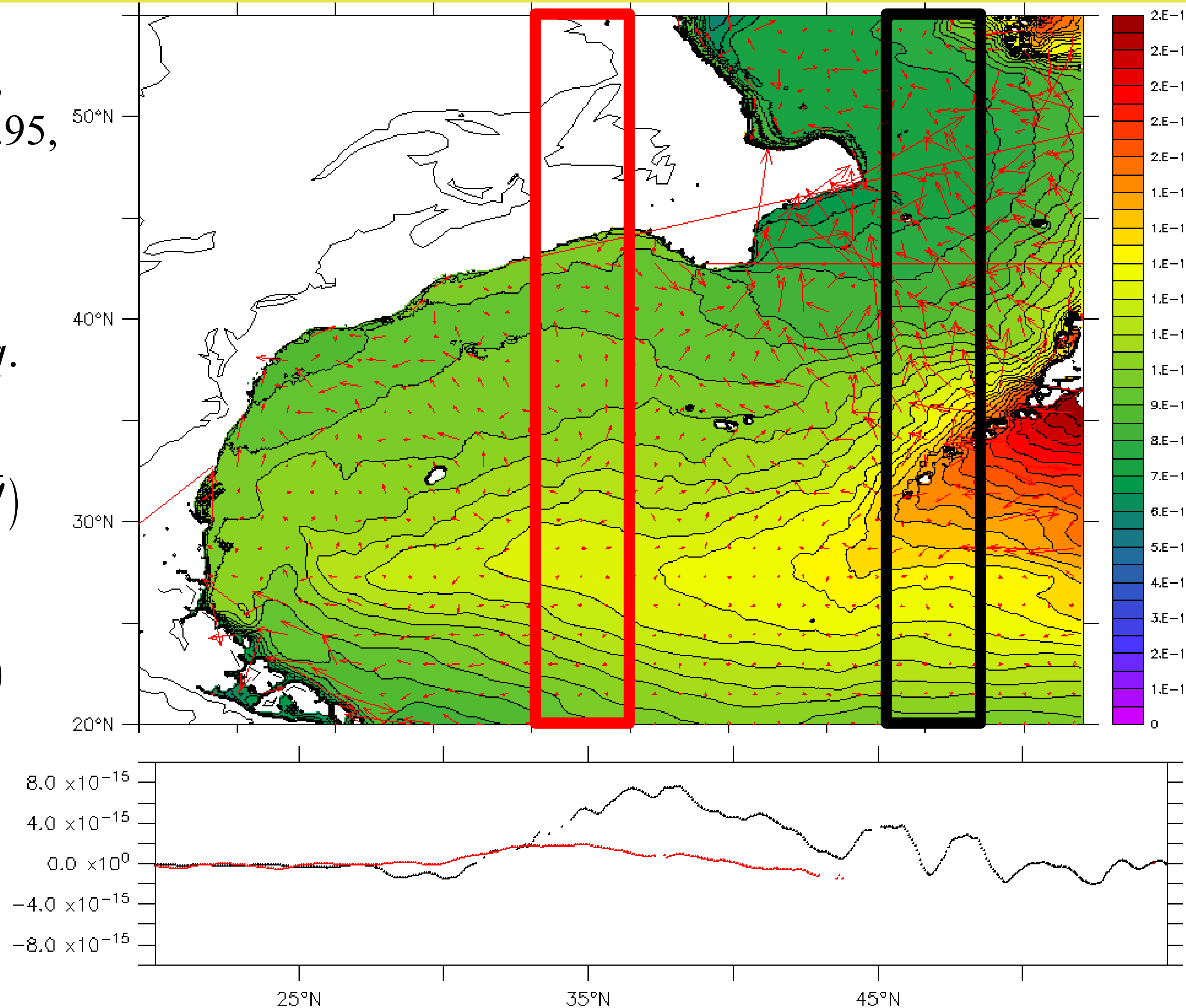
# Results: Eddy fluxes in FLAME

Eddy fluxes of potential vorticity, $\langle \boldsymbol{u}'q' \rangle$, on $\sigma_2 = 36.95$, from 15 years of monthly mean FLAME velocity fields with mean $q$.

$$\frac{D\overline{Q}}{Dt} = -\nabla \cdot \left(\overline{\boldsymbol{u}'q'}\right)$$

$$\overline{V}\frac{\partial \overline{Q}}{\partial y} = \frac{-\partial}{\partial y}\left(\overline{v'q'}\right)$$

$$\left(\overline{v'q'}\right)_{(5^o\, strip)}$$

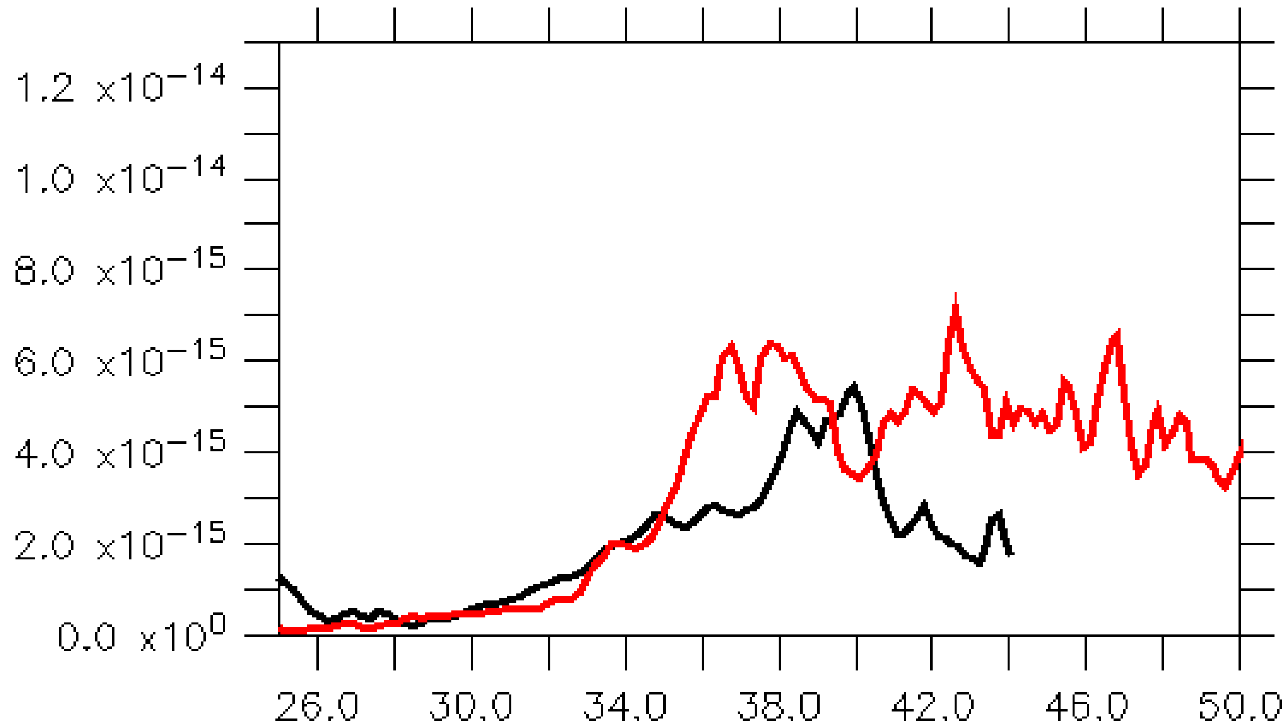


# Magnitude of Eddy fluxes

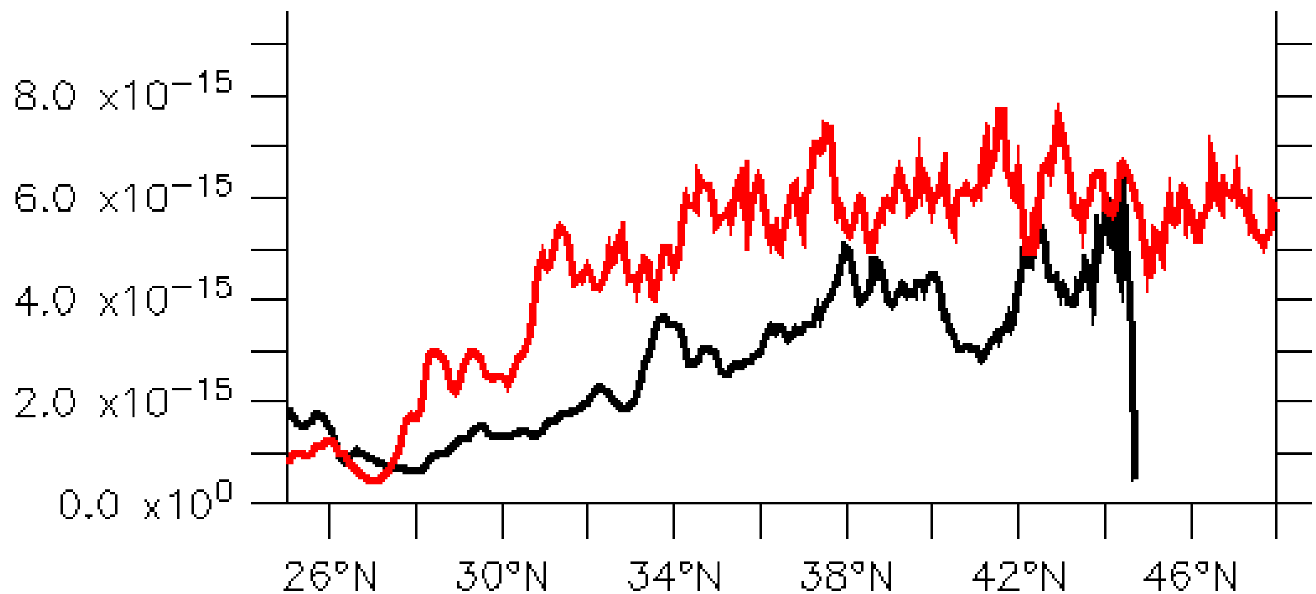
Zonal average
(black = 70°W to 50°W)
(red = 44.5°W to 32°W)
magnitude of eddy fluxes

$$\left|\overline{\boldsymbol{u}'q'}\right|$$

[(s)$^{-2}$] on $\sigma_2 = 36.95$
isopycnal in:




**TOP:**
ORCA025 ('68-'99
5-daily averages)




**BOTTOM:**
FLAME ('94, '96, '98, '00
3-daily snapshots)