Biogeochemistry of Western Boundary Currents

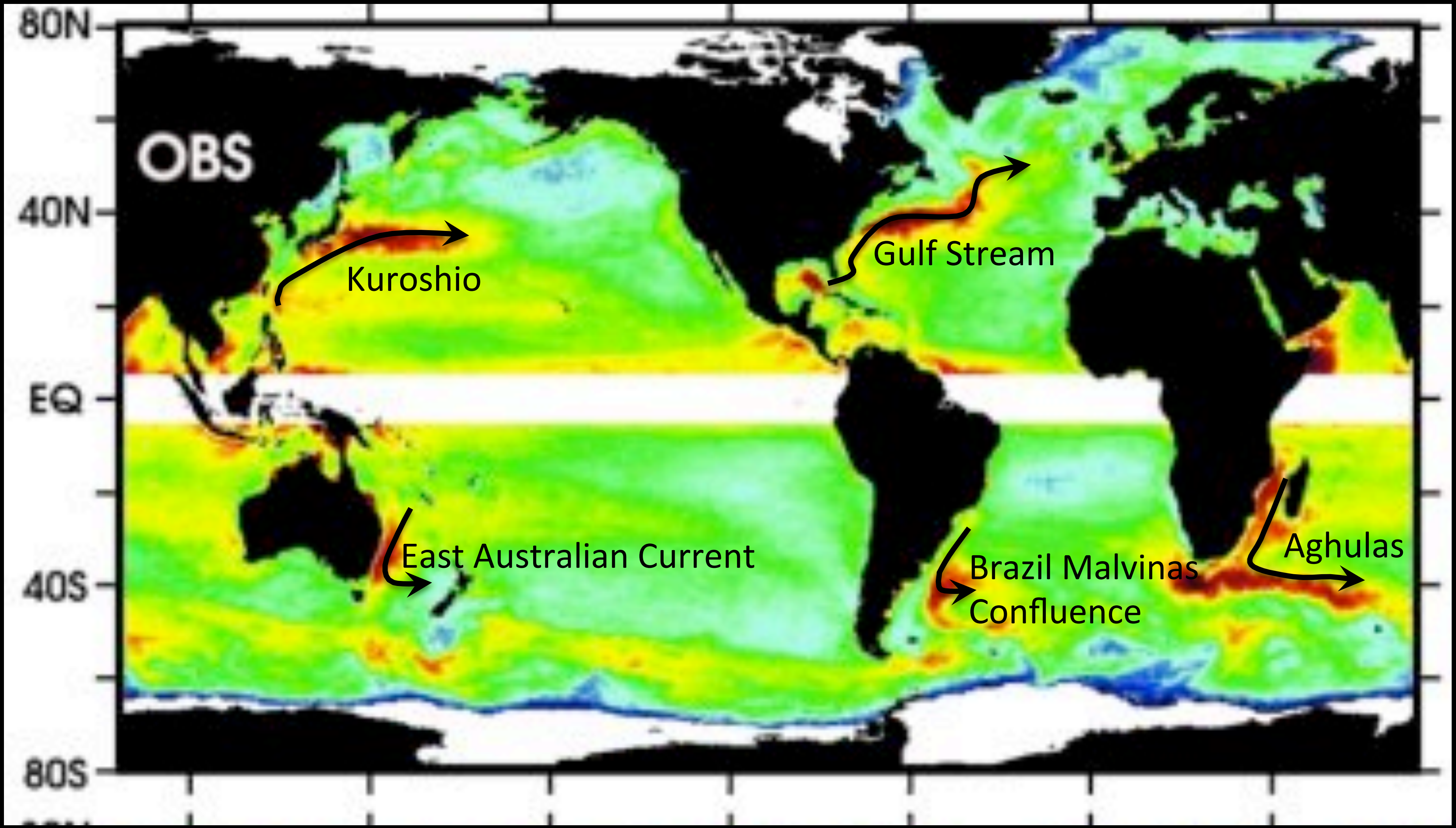
Jaime Palter, University of Rhode Island

September 25, 2017

Collaborators: Ayako Yamamoto, Tim Conway, Greg DeSouza, Julie Granger, Pia Moisander, Angel White, Elana Ames and many others

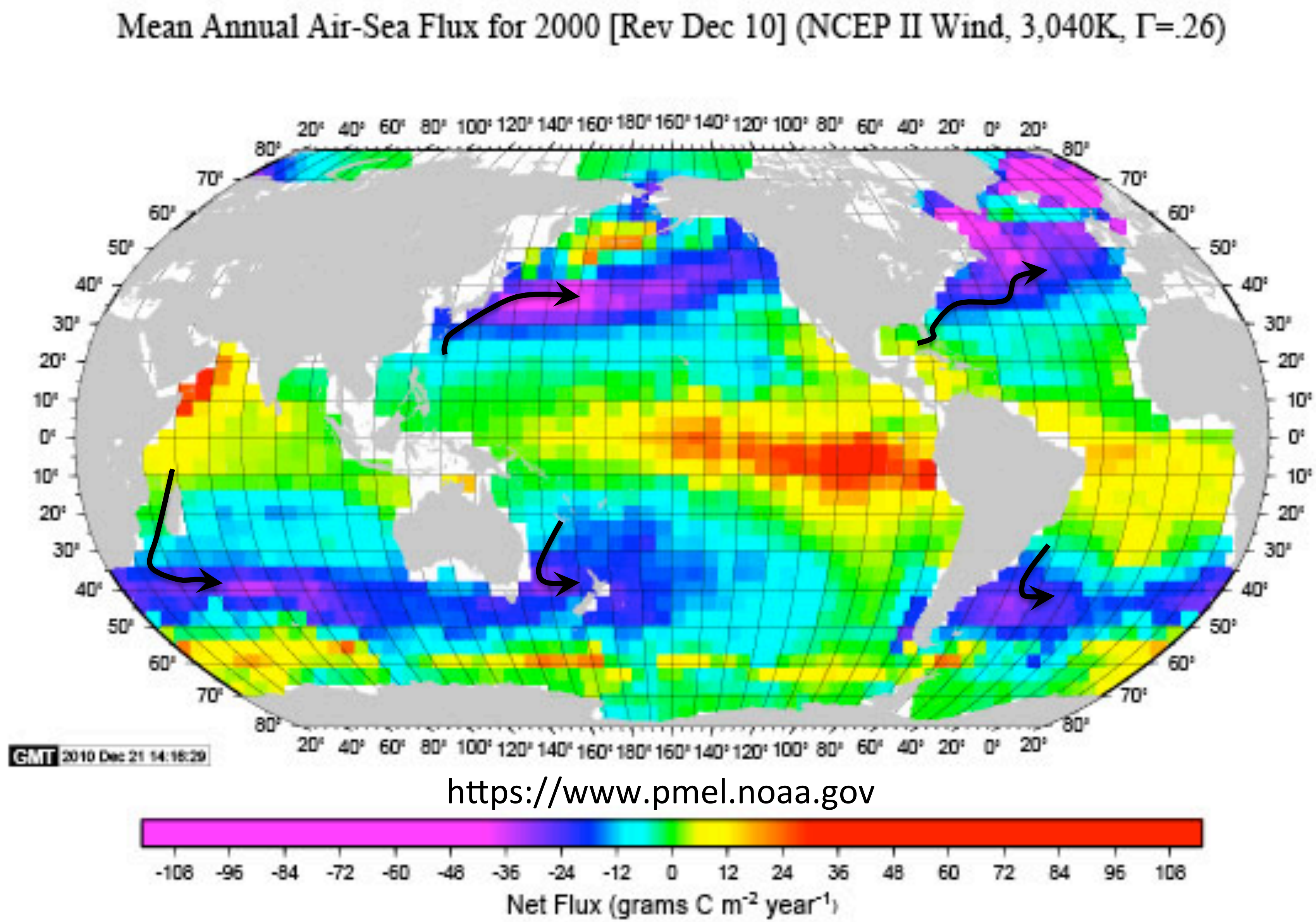
FIG. 173. — FRANKLIN'S CHART OF THE GULF STREAM.

Logarithm of Eddy Kinetic Energy



https://www.gfdl.noaa.gov/wcrp2011_poster_c37_dixon_th85b_eke/

Contemporary air-sea CO_2 flux



https://www.pmel.noaa.gov

Contemporary CO_2 exchange

- Sum of natural and anthropogenic carbon uptake
- Global patterns of contemporary CO_2 exchange are an emergent characteristic of the ocean-atmosphere system, and depend on ecology, chemistry, winds, and ocean circulation from the submesoscale to the global scale
- All of these themes are targets of the workshop, as they are implicated at WBC regions

LETTER

doi:10.1038/nature21068

Recent increase in oceanic carbon uptake driven by weaker upper-ocean overturning

Tim DeVries[1,2], Mark Holzer[3,4] & Francois Primeau[5]

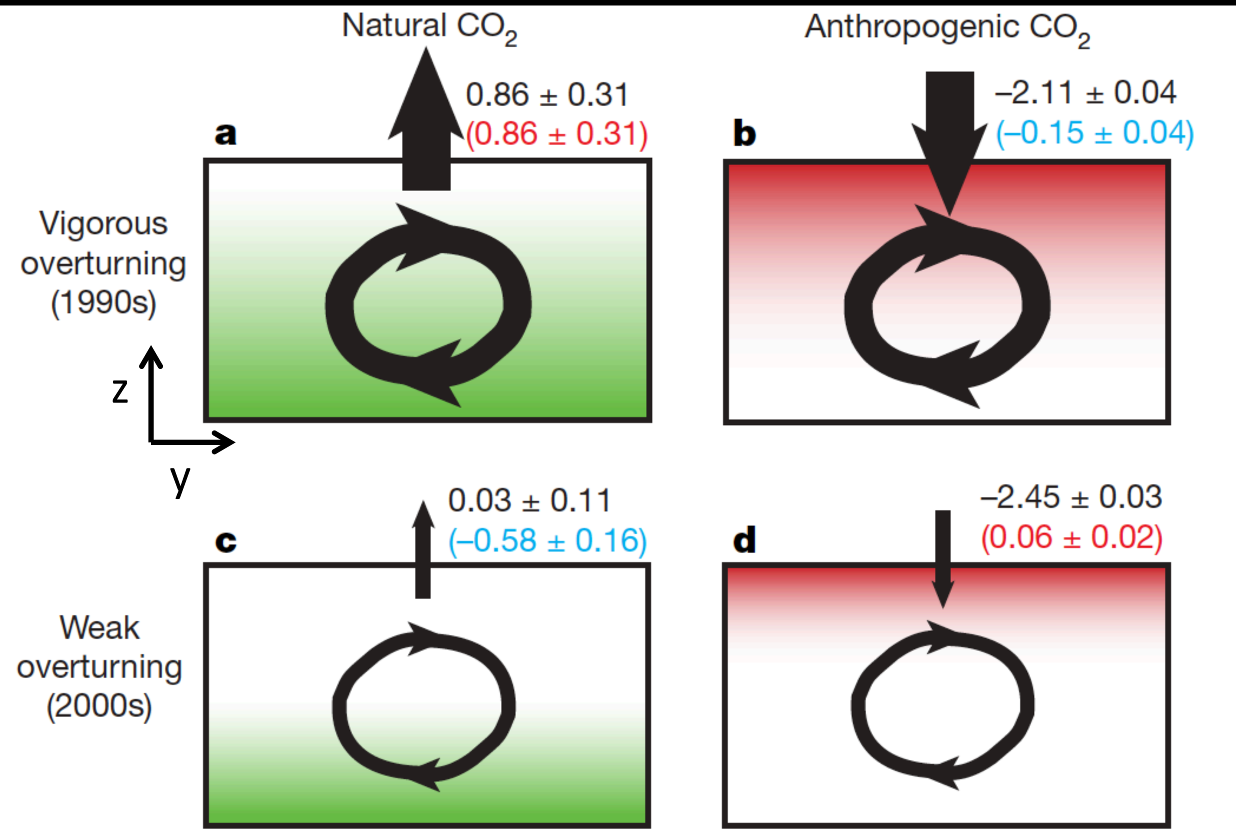
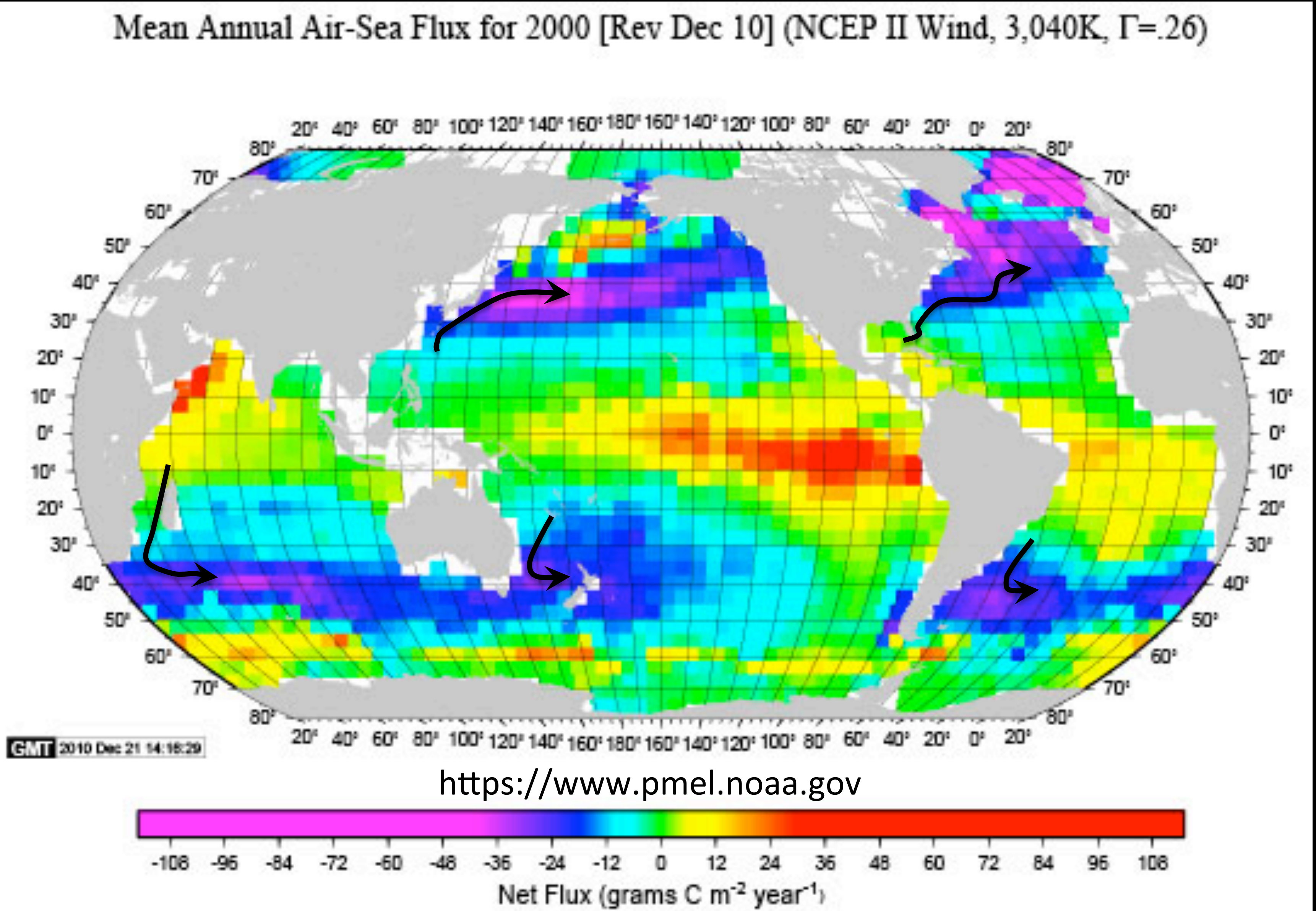


Figure 3 | Simplified conceptual diagram illustrating how changes in upper-ocean overturning circulation have affected the oceanic CO_2 sink. Vigorous overturning in the 1990s drove increased outgassing of

DeVries et al, 2017:

- Strengthened shallow overturning in the 1990s, caused enhanced outgassing of natural CO_2, and uptake of anthropogenic CO_2.
- In the 2000s, a sluggish upper-ocean overturning allowed the shallow overturning cells to retain their natural carbon at the expense of taking up more anthropogenic carbon

Contemporary air-sea CO_2 flux



https://www.pmel.noaa.gov

Workshop Questions

Three scientific questions:

1. How do mesoscale and submesoscale processes influence nutrient supply, biological activity, and air-sea CO_2 fluxes?
2. Do phytoplankton contribute to air-sea CO_2 exchange primarily through pCO_2 drawdown during mode water formation or carbon export via the biological pump?
3. How does natural variability modulate carbon export carried out by mode water formation and biological processes?

Workshop Questions/Talk Goals

Three scientific questions:

1. How do mesoscale and submesoscale processes influence nutrient supply, biological activity, and air-sea CO_2 fluxes?
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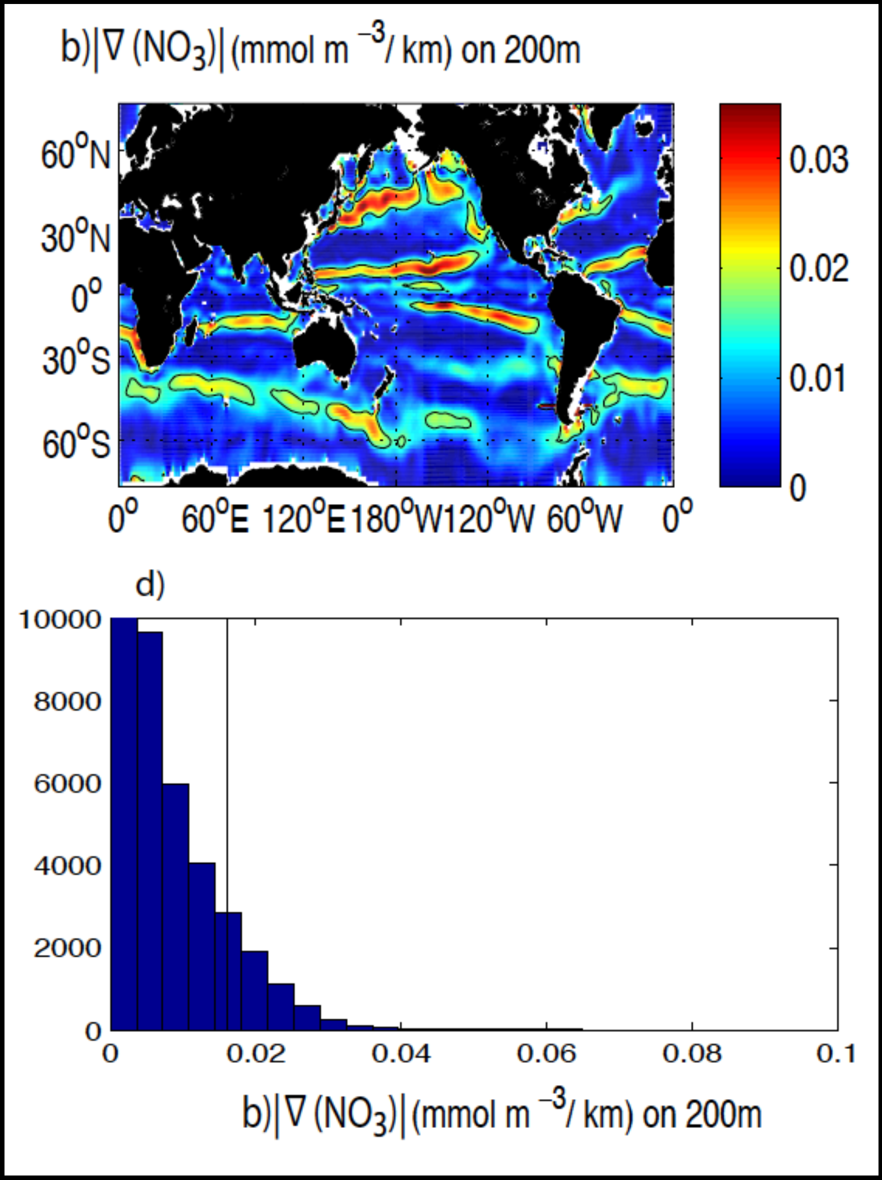
3. How does natural variability modulate carbon export carried out by mode water formation and biological processes?

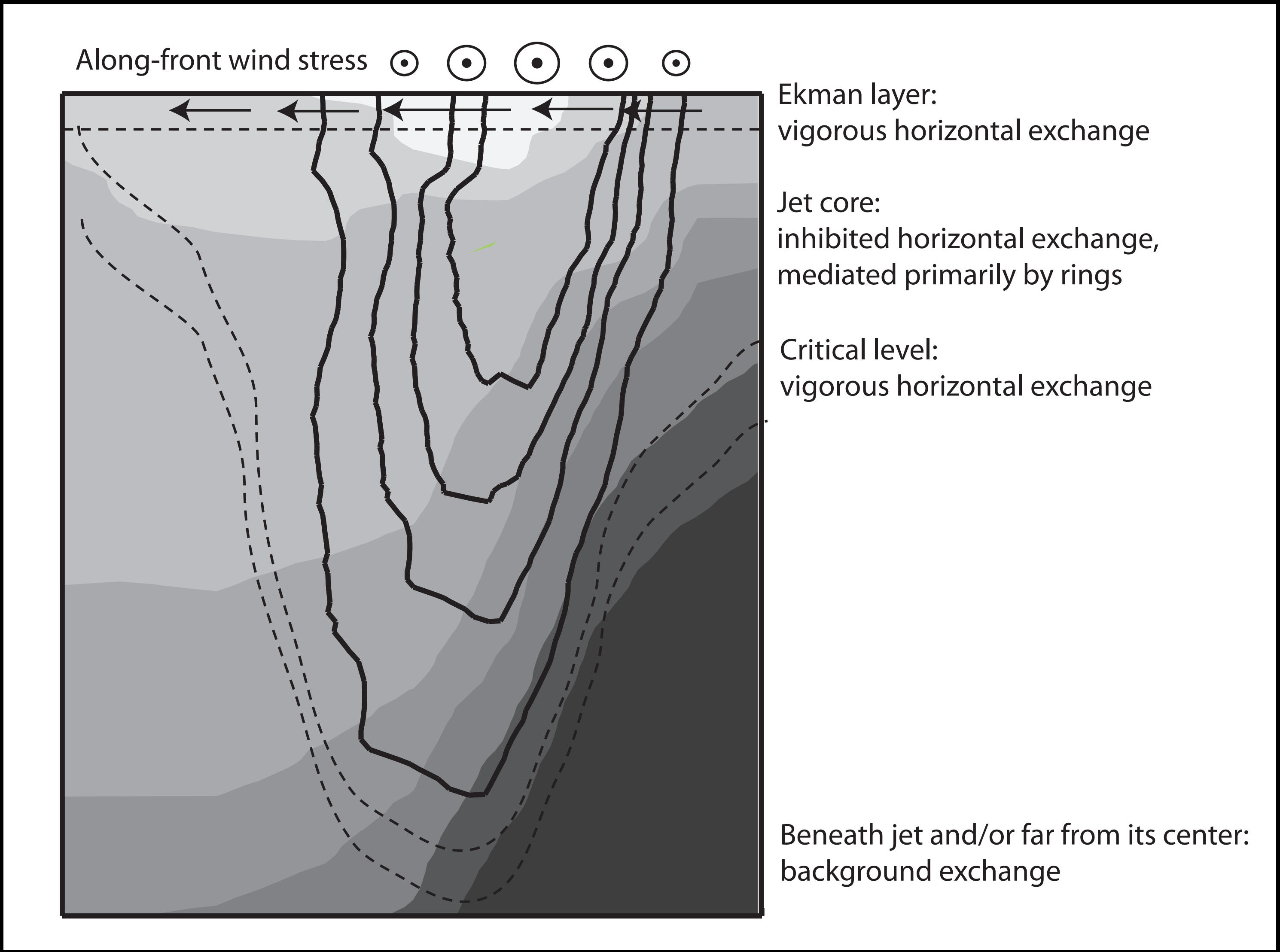
Nutrient and density gradients across WBCs are at least an order of magnitude stronger than elsewhere in the ocean



- Over most of the ocean and averaged over several eddy length and time scales, nitrate concentrations vary laterally by less than a 0.01 mmol m^{-3} per kilometer (a thousand times weaker than the vertical gradient).
- The distribution is strongly skewed, with high gradient regions organized into narrow fronts
- The gradients across these fronts are about a factor of 10-50 stronger than their surroundings
- Most nutrient fronts coincide with the ocean's strongest jets

Palter et al., 2013

WBCs: Blenders or barriers?



From Palter et al. 2013, based on Bower, 1991; Samelson, 1992; Rogerson et al., 1999; Abernathy 2009; Williams and Follows 2003

Bower et al, 1984

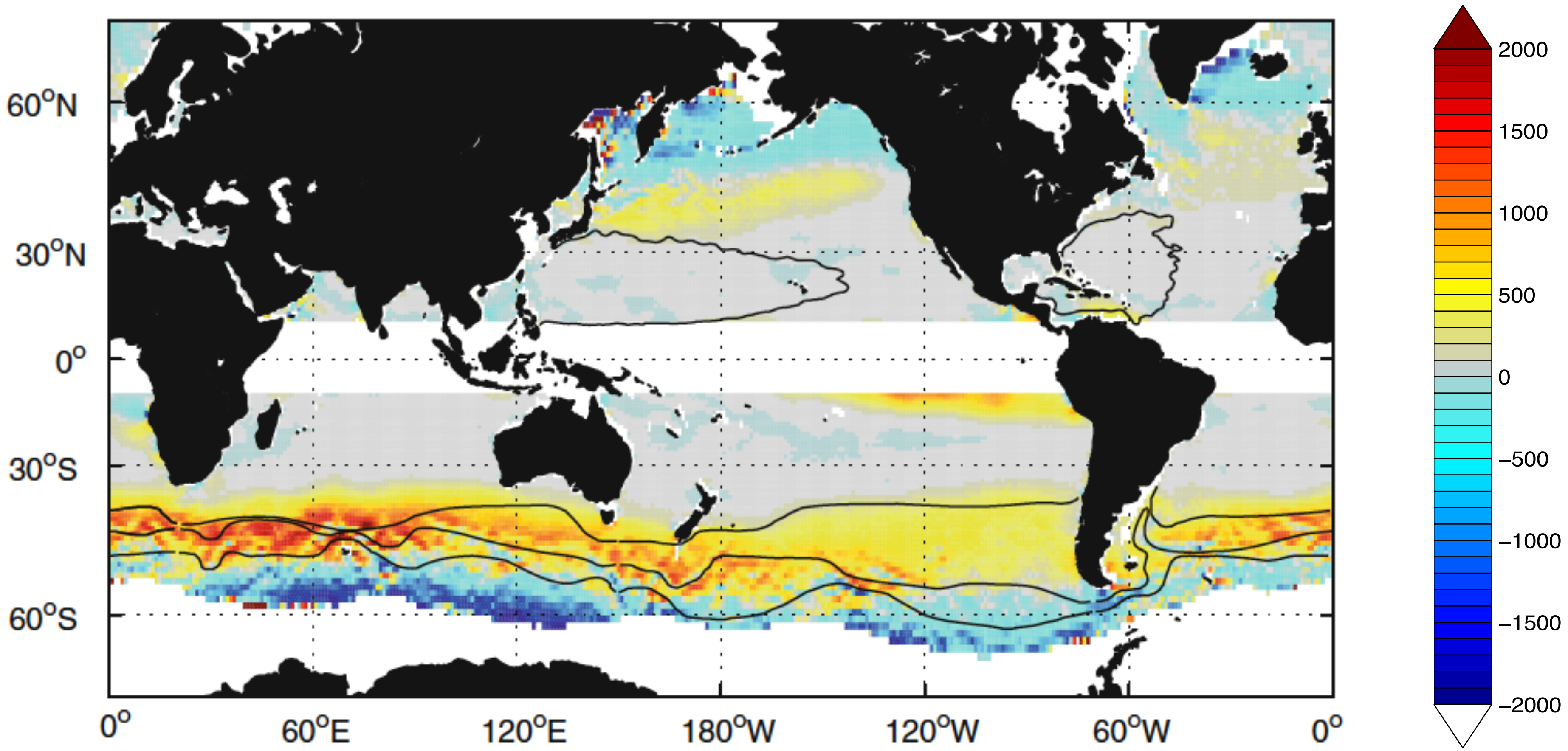
Blender or barrier?

1. Depends on what vertical layer under consideration
2. Is scale dependent – suggestions of vigorous exchange at the submesoscale
3. Answer has implications for ecology, productivity, and surface fluxes
4. Overall impact of transport across the WBC is tracer-dependent

Focus for this talk: Transport of nutrients across the WBCs and the impact on subtropical gyre productivity

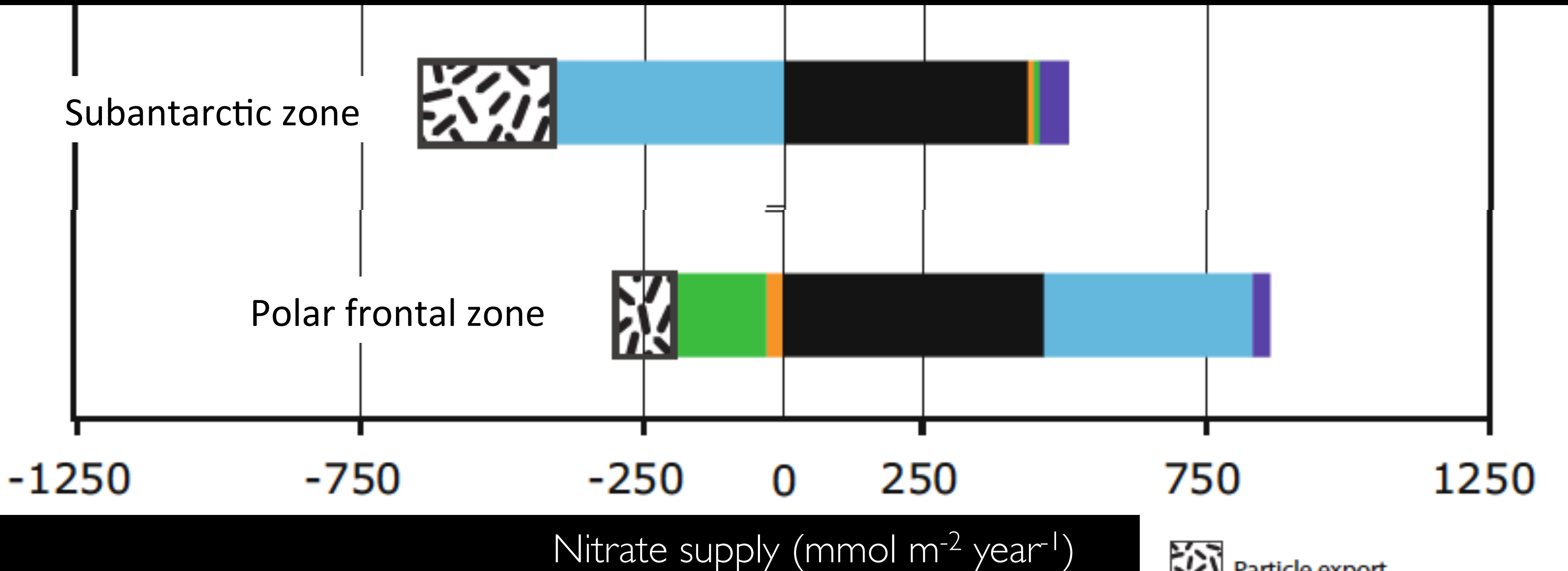
Mechanism 1: Ekman transport

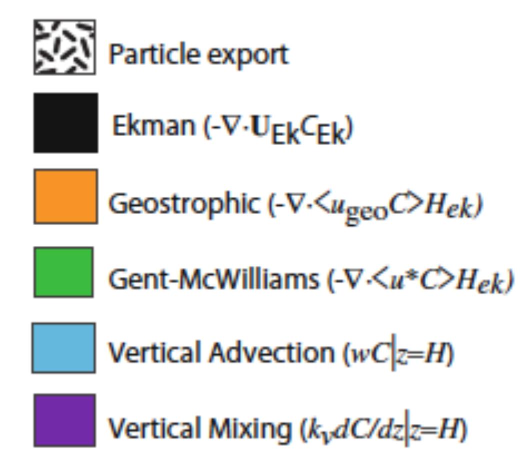
Total annual Ekman nitrate supply (mmol m^{-2} $year^{-1}$)

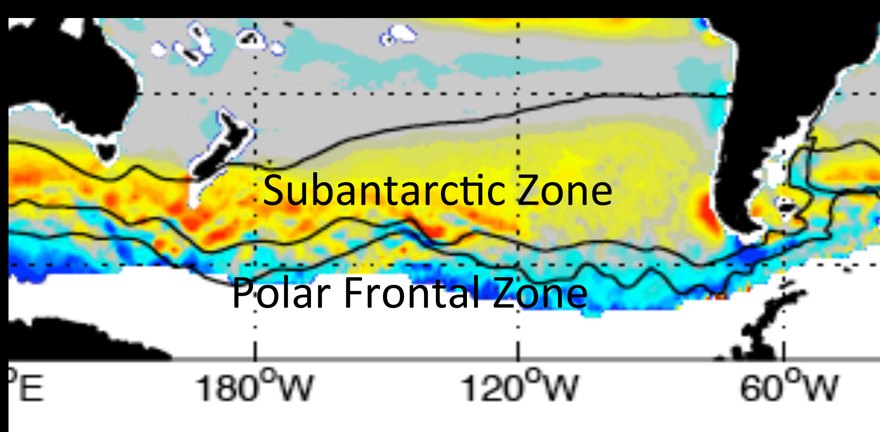


- Ekman supply of nutrients strongest in the Subantarctic zone

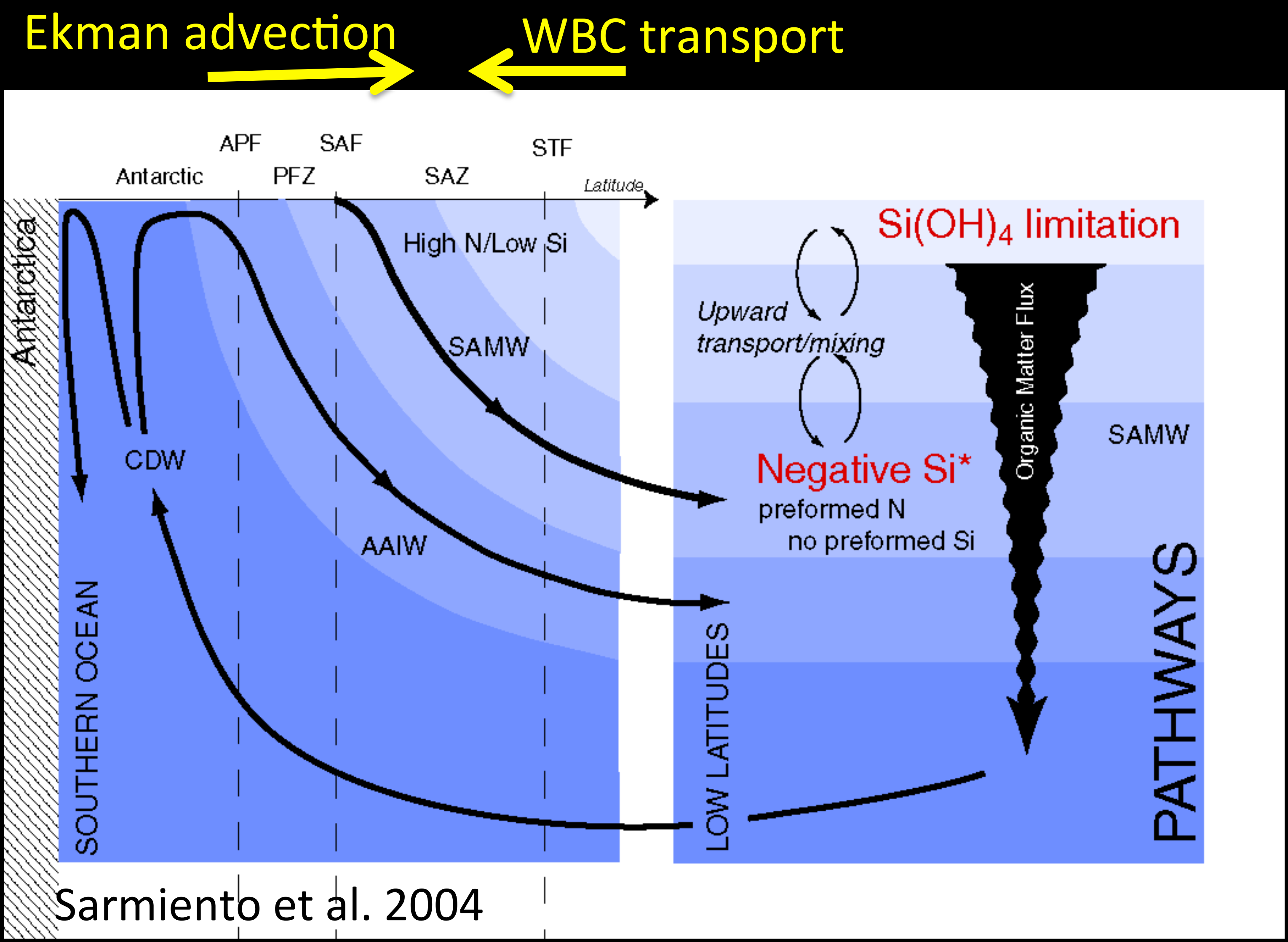
Nutrients upwelled in the Antarctic and Polar Frontal Zone are subducted in the Subantarctic Zone, the ultimate nutrient gateway







This view of the Ekman transport and subduction of nutrients in the Subantarctic agrees with the conceptual model provided by previous coarse-resolution models and tracer studies.



Sarmiento et al. 2004

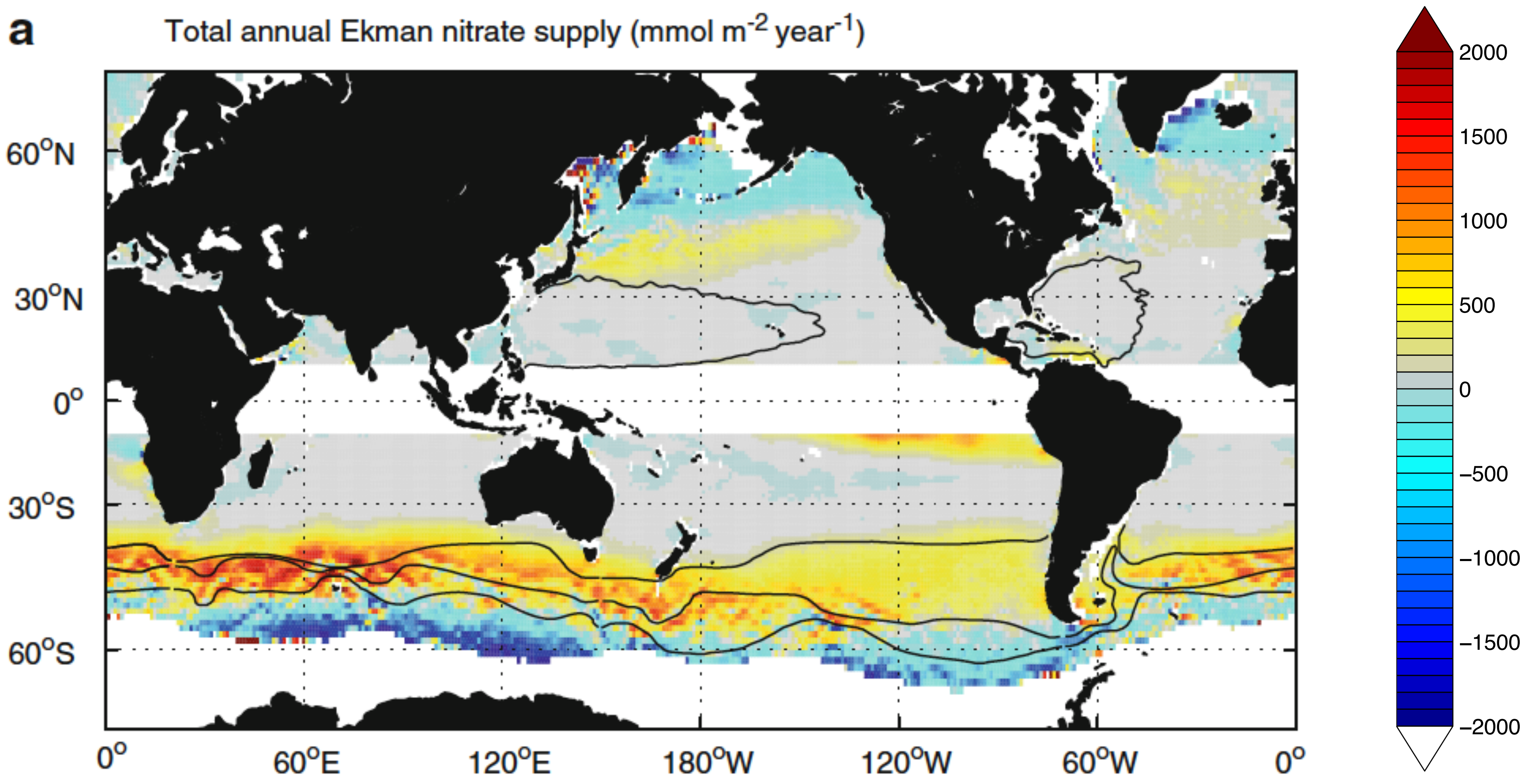
The Southern Ocean as a nutrient gateway

- Our coarse resolution simulations showed that the Southern Ocean provides the nutrients fueling 50-75% of low latitude productivity (30°S – 30°N).
- Thus, the Subantarctic is "the Mother of all nutrient gateways," as it is the only locale where nutrients are returned from the deepest isopycnal layers and restored to the thermocline
- These nutrients flood the thermocline in and below the 26.8 isopycnal (global average depth ~800 m)
- How do these nutrients ultimately reach the northern hemisphere subtropical gyres?

We proposed a two-step pathway:

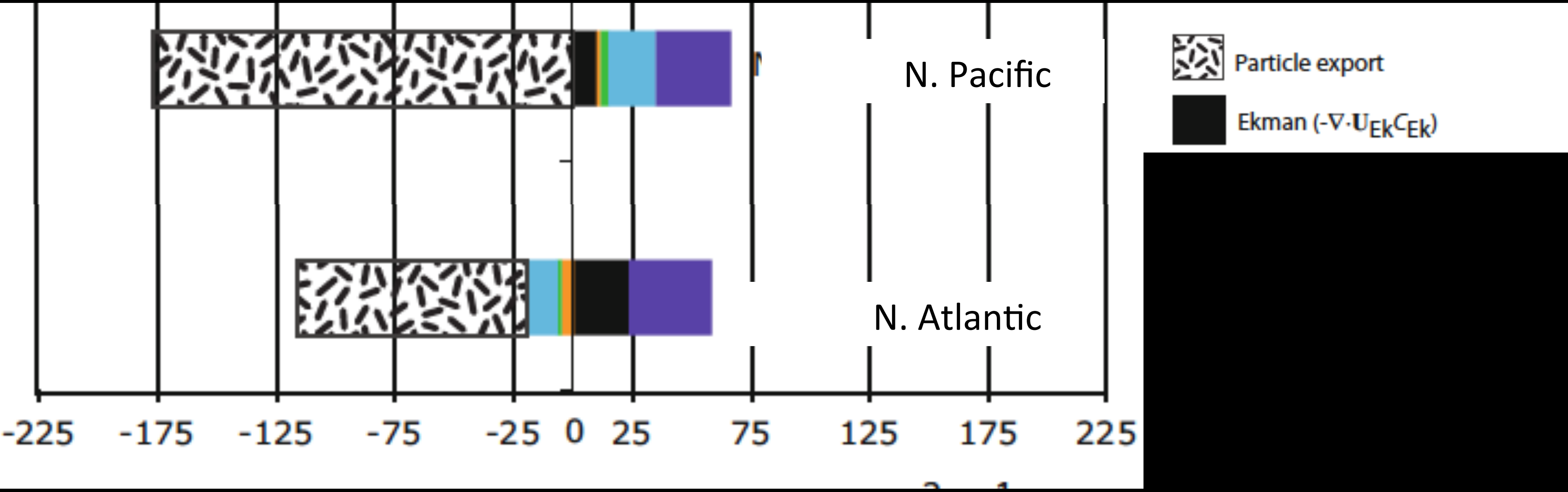
1. Mixing and upwelling outside of the subtropical gyres restores nutrients to shallower depths.

2. Advection and mixing across the WBCs transports nutrients into the gyres themselves.



Ekman transport is not a sufficient supply mechanism to support subtropical export productivity, particularly in the N. Hemisphere

Scale analysis of the terms in the nutrient budget (mmol m^{-2} year^{-1})



Data sources: Time-mean geostrophic velocities from AVISO altimetry; Particle Export from John Dunne based on Dunne et al. 2007; GM and vertical advection from the OCCA Atlas (from the ECCO data-assimilating model; Forget 2009). Winds (Risien and Chelton 2008). Vertical mixing with $K_v = 10^{-5}$ m^{2}s^{-1}.

Ekman transport falls short of what is needed to explain subtropical North Atlantic and Pacific export production.

Other mechanisms?

- Down-gradient mixing (from high concentrations outside the subtropics to low concentrations within) is the prime suspect, but mixing coefficients and isopycnal tracer gradients are highly uncertain.
- Turbulence can also lead to up-gradient tracer transport, as when the eddies oppose the Ekman transport (i.e. relax baroclinicity)
- Turbulent transfer of nutrients is essentially not quantifiable from observations alone.

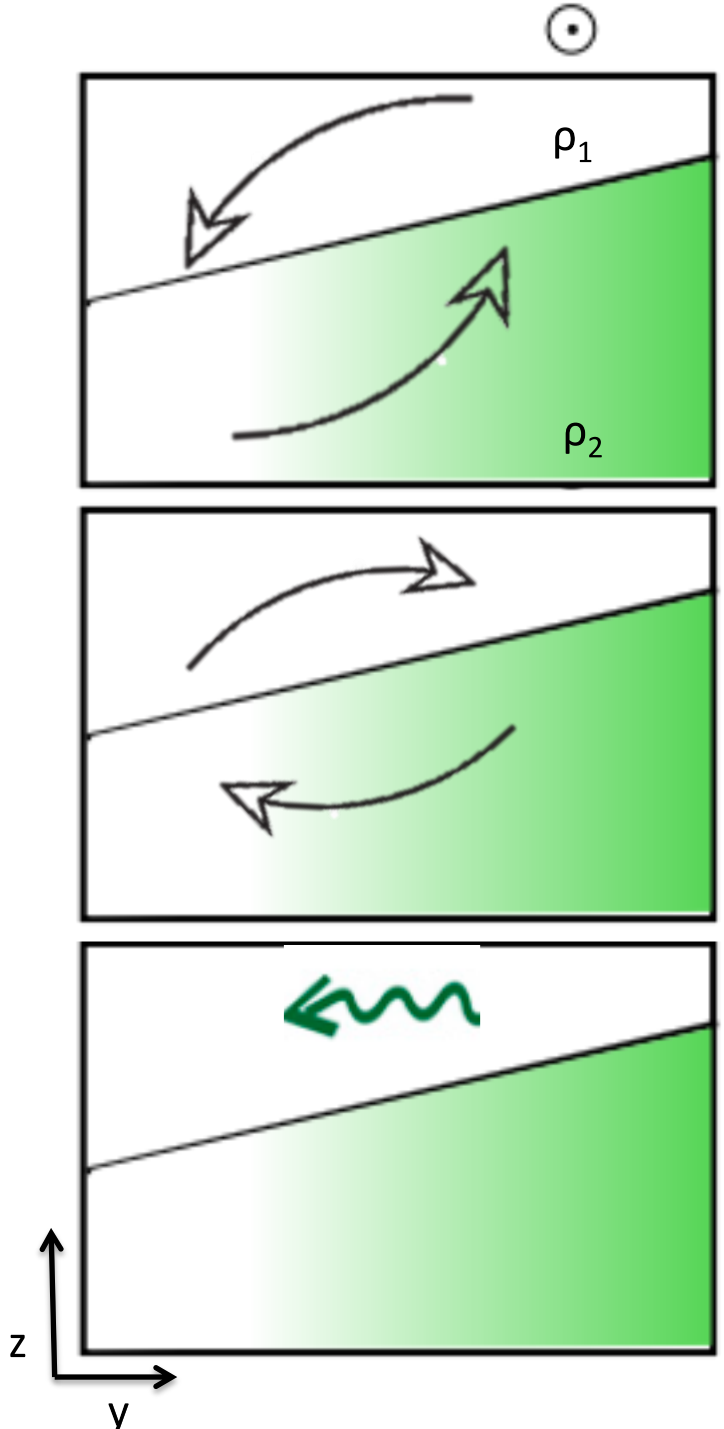
Ekman

Eddy mass transport:

$\overline{h'\mathbf{u}'}$

Down gradient turbulent mixing:

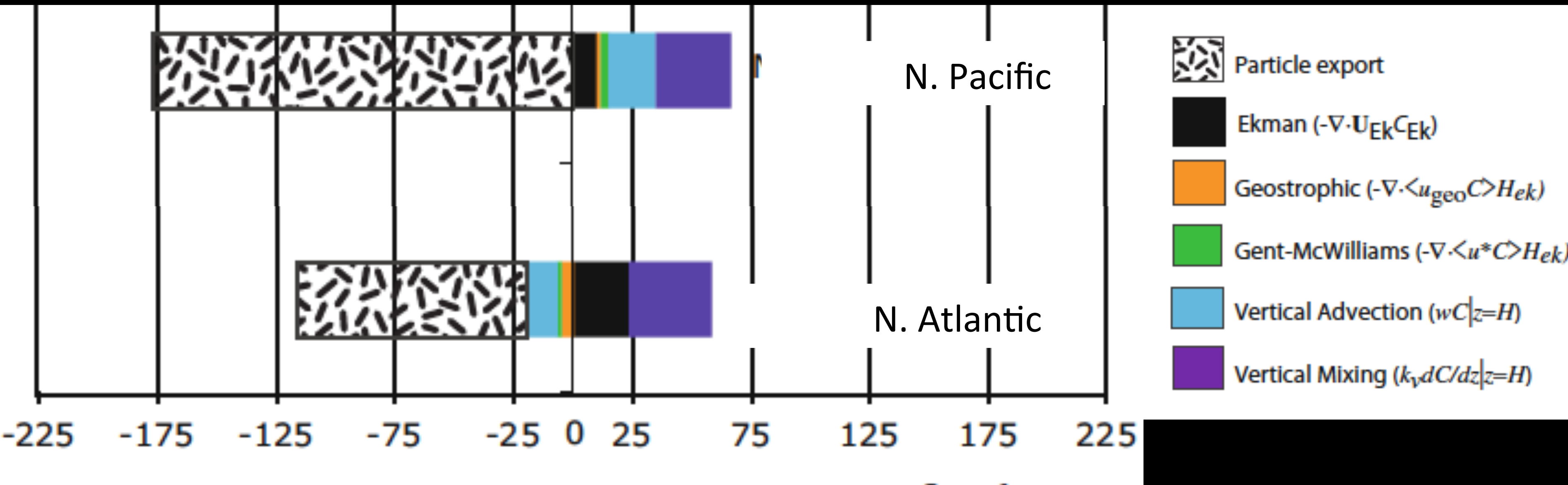
$\overline{\mathbf{u}'C'}$.



Mass transport by baroclinic eddies opposes Ekman transport and can flux nutrients up gradient (typically parameterized through the GM scheme).

Down gradient mixing—typically parameterized as diffusion—is another supply term.

Eddy mass transport removes nutrients from the gyres, but down-gradient mixing was too uncertain to include in an observation-based scale analysis



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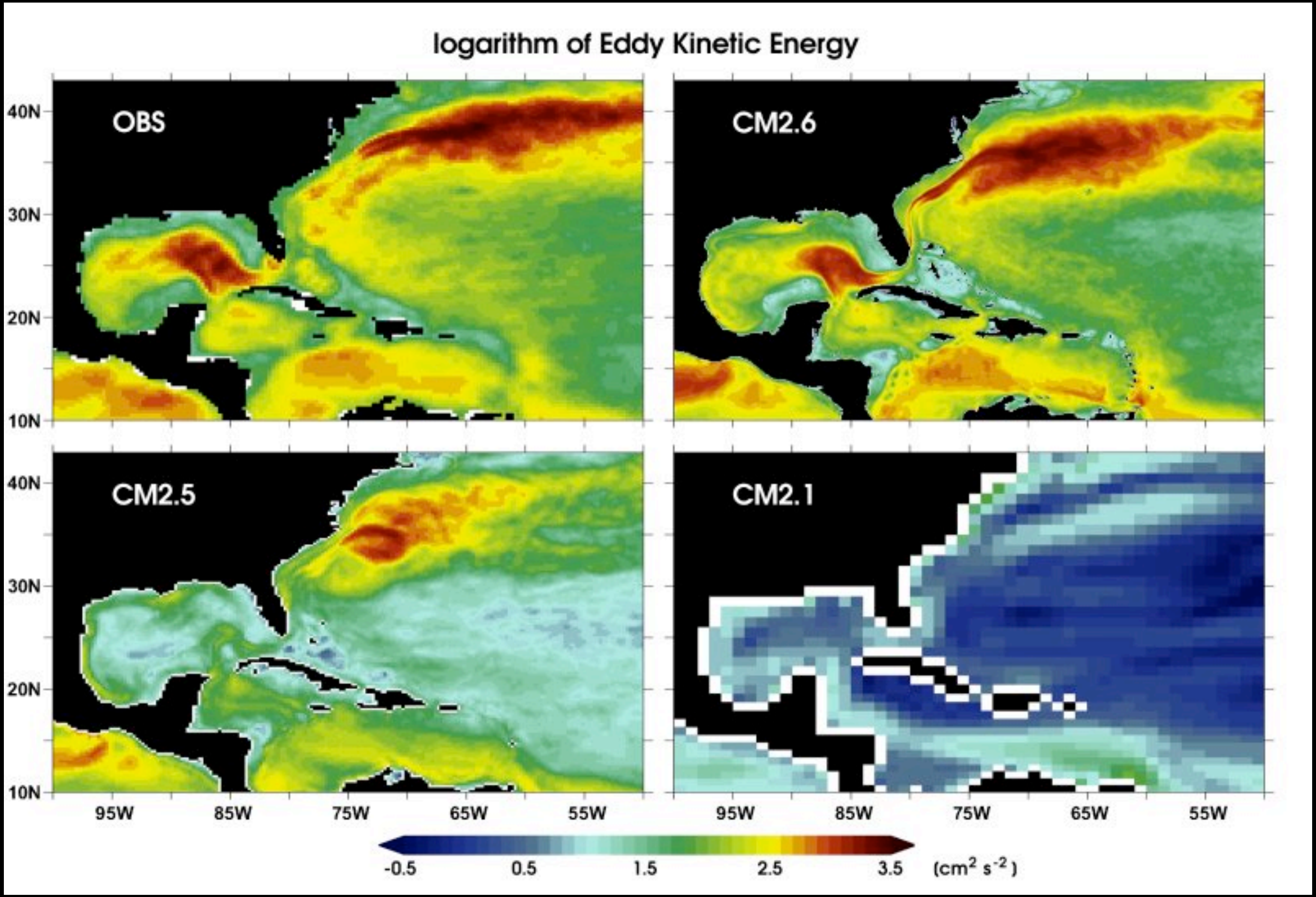
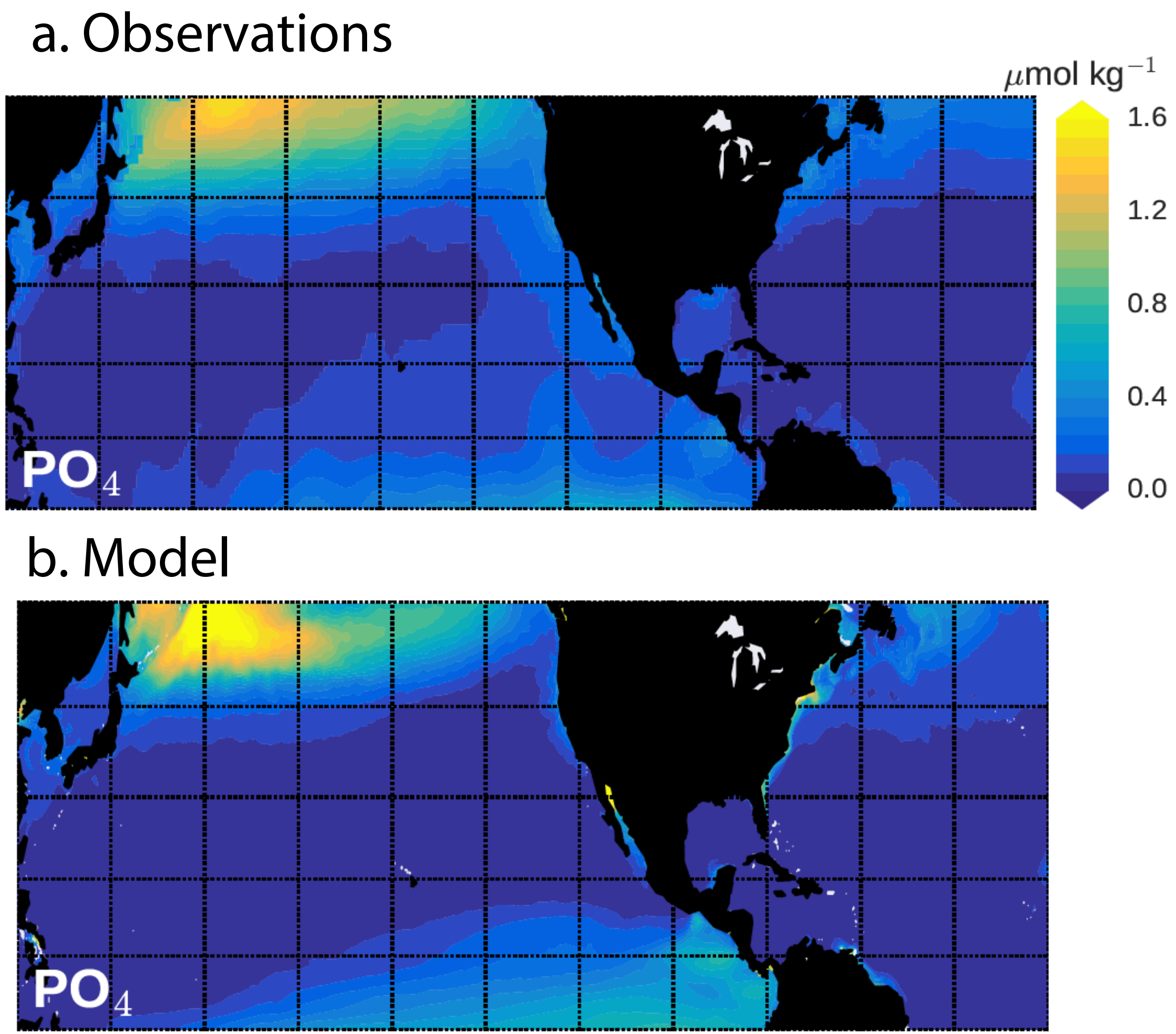
GFDL's CM2.6 provides a richly-eddying ocean simulation with biogeochemistry

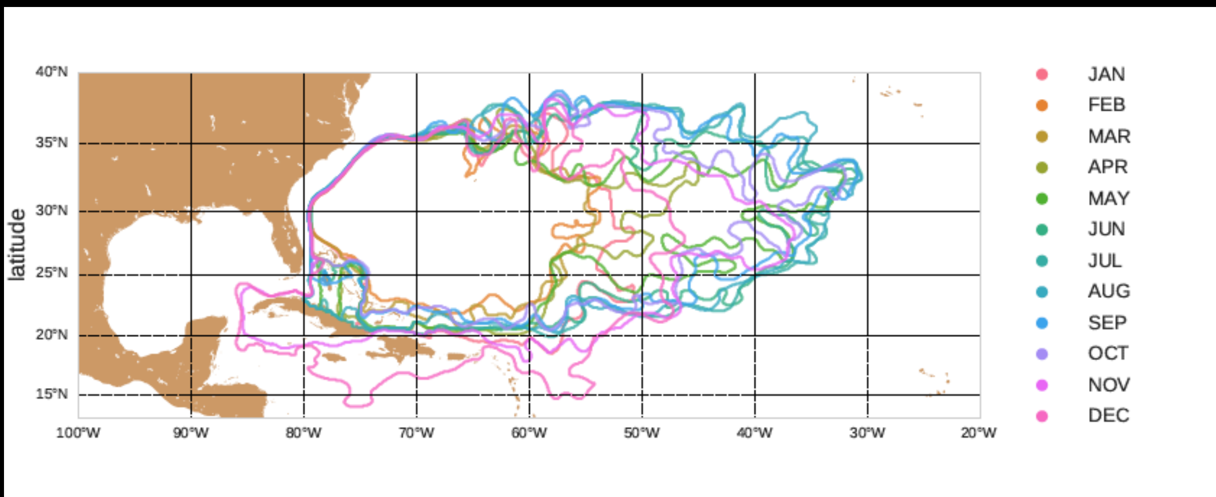


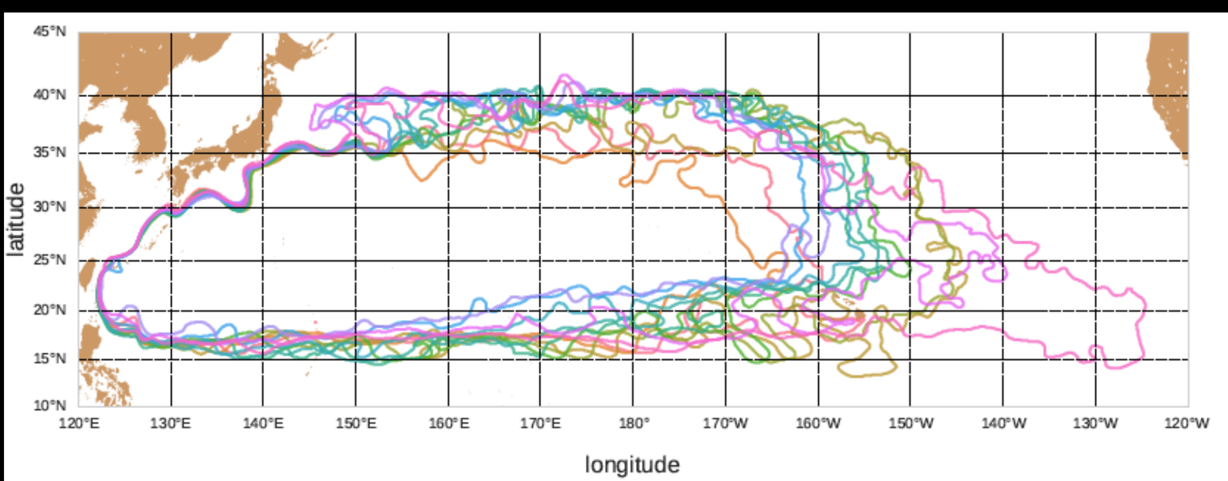
https://www.gfdl.noaa.gov/wcrp2011_poster_c37_dixon_th85b_eke/

The miniBLING model (Galbraith et al., 2015) simulates nutrient concentrations and gradients with skill, despite necessary simplifications



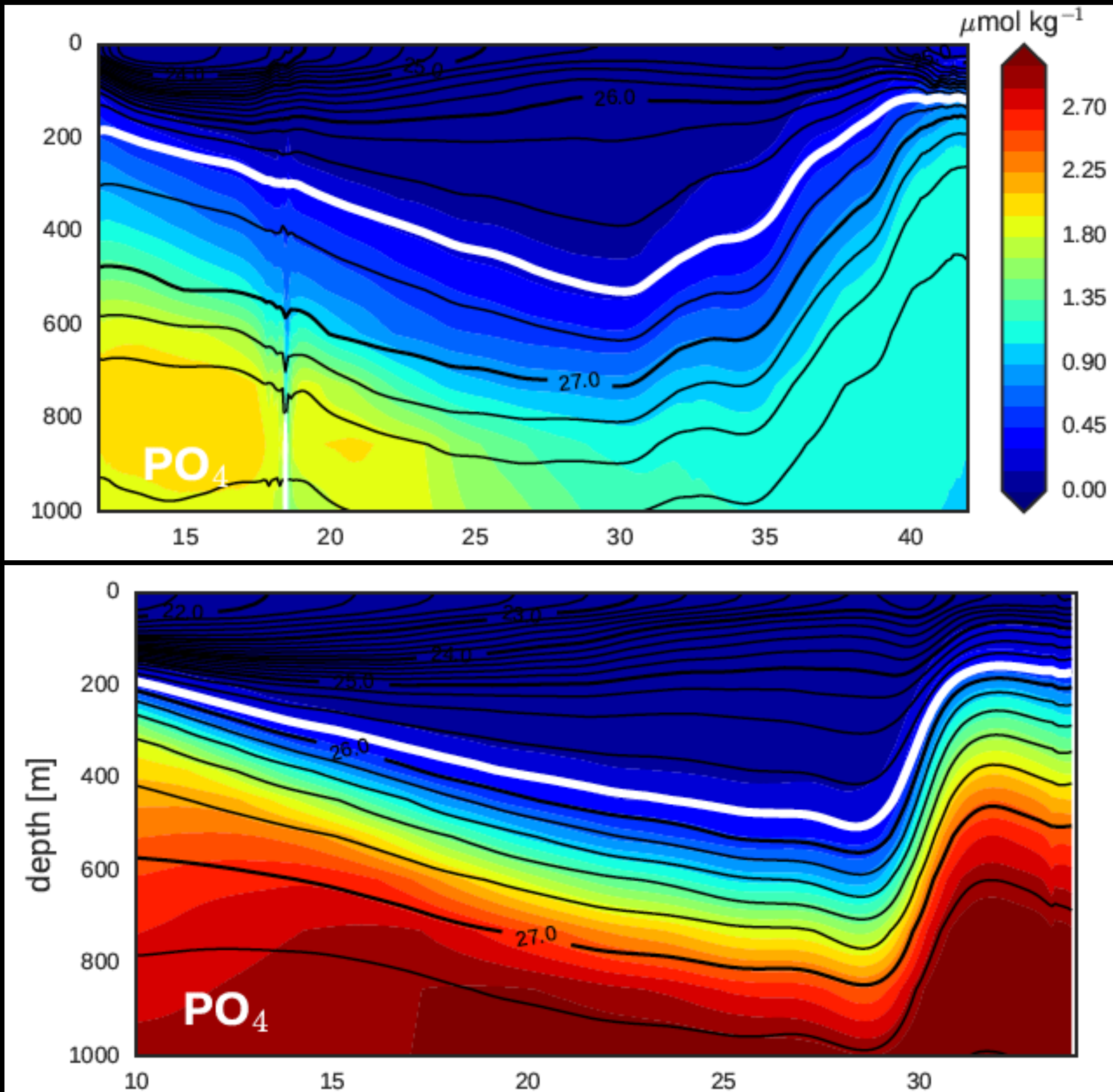
Yamamoto et al (submitted to JGR-Oceans) uses CM2.6 to mechanistically assess the flux of tracers into the Northern Hemisphere subtropical gyres





- Use the 10-year monthly mean 1000 m barotropic streamfunction to define the gyre boundary
- Transport evaluated normal to that boundary and above the isopycnal that forms the base of the deepest mixed layer (i.e. "the ventilated gyre")
- The total transport is decomposed into a time mean and "eddy" component
- The eddy is due to any temporal deviation from the 10-year monthly mean

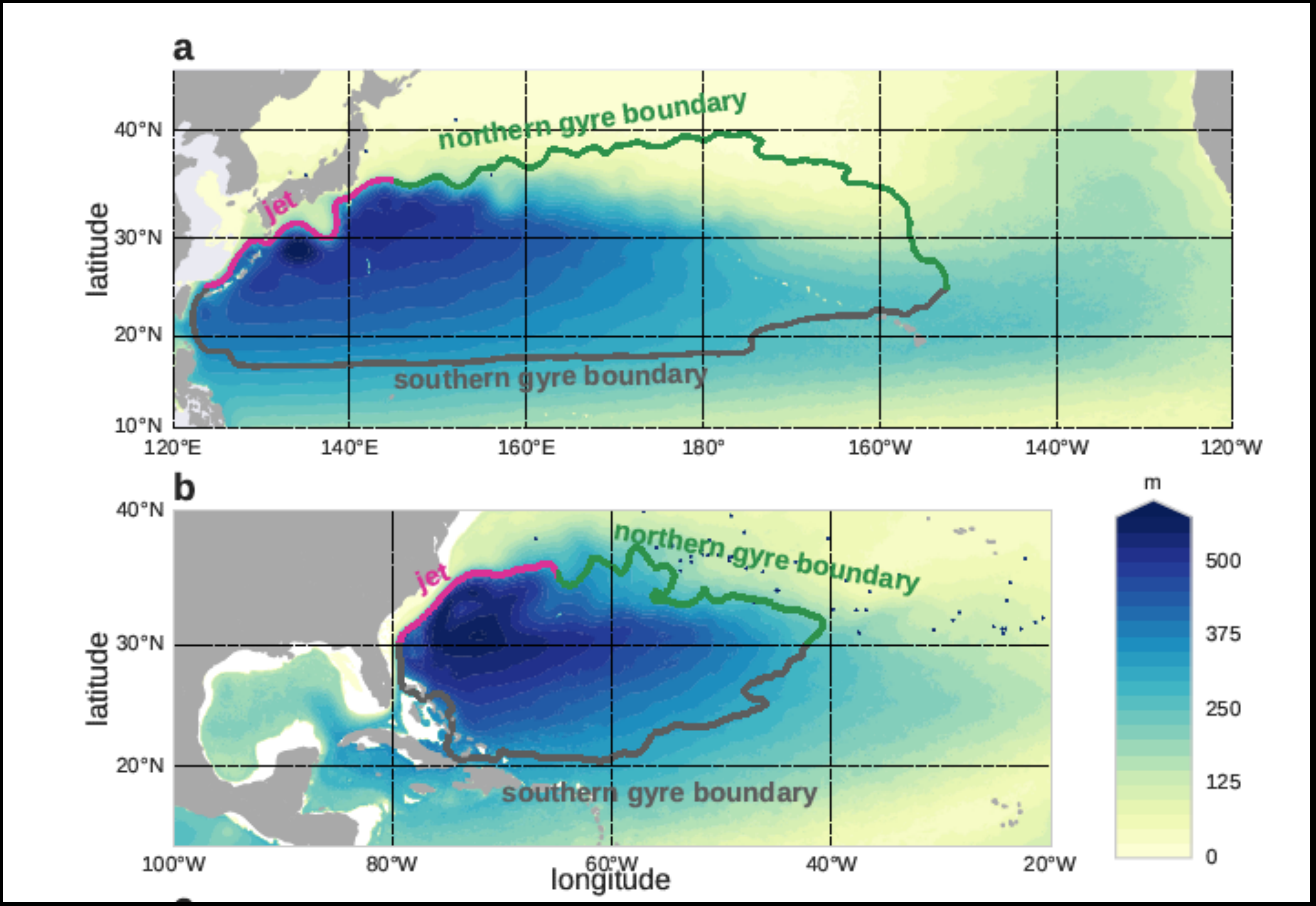
Phosphate in a slice through the gyres



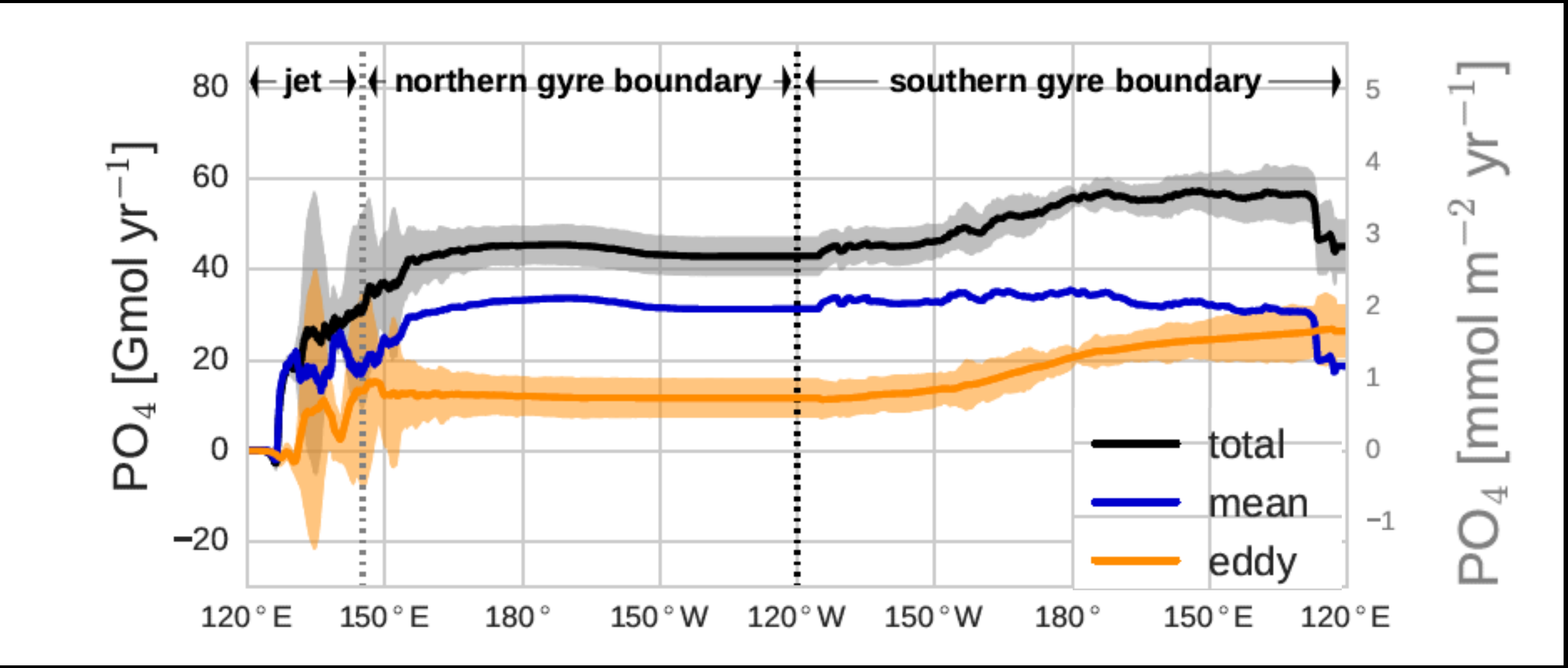
North Atlantic

North Pacific

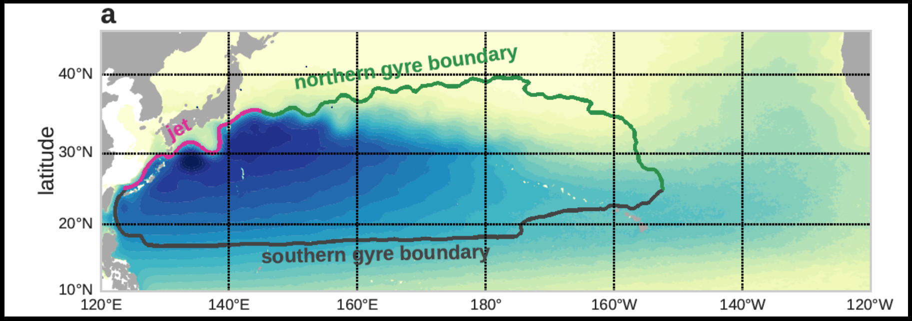
The vertical and lateral limits of the subtropical gyres: the ventilated layer bounded by the largest anticyclonic streamline



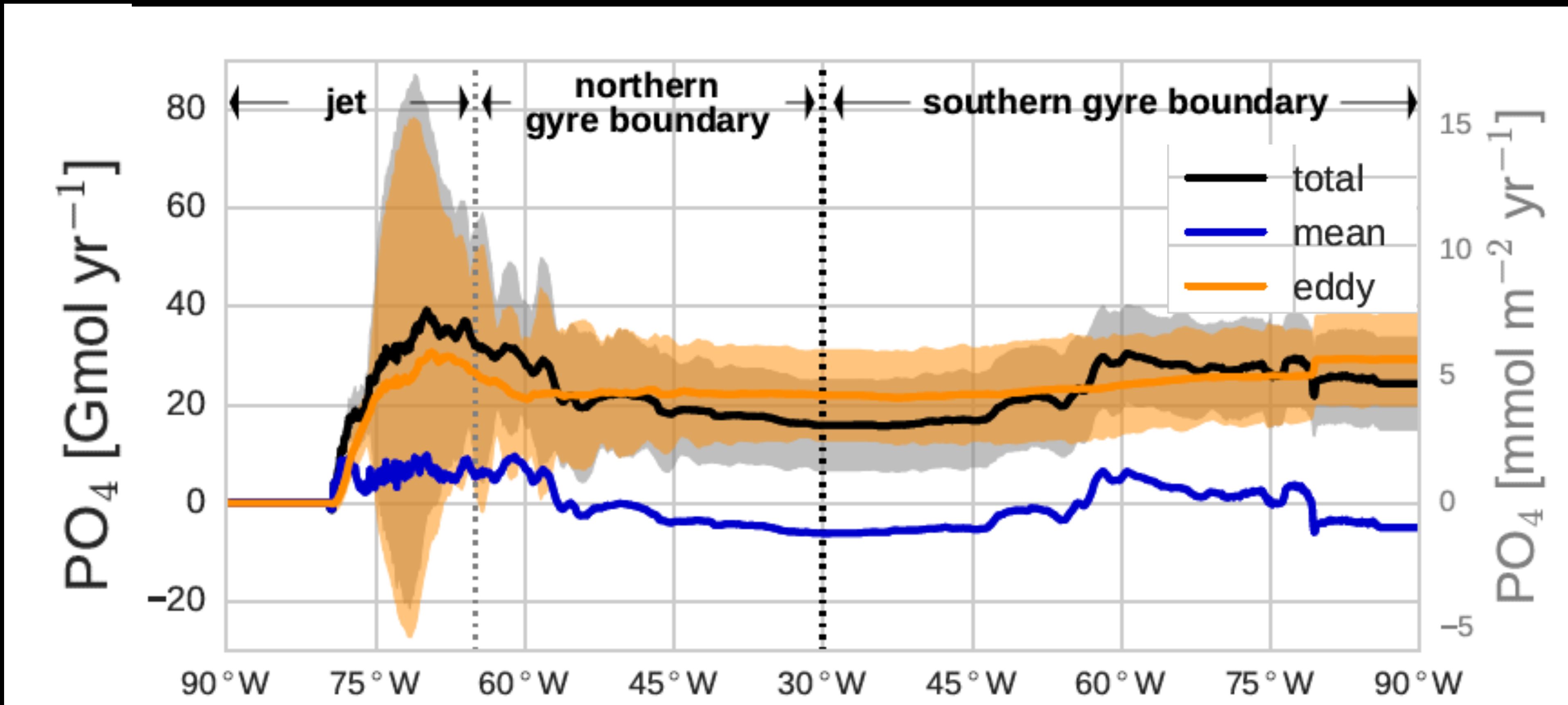
Cumulative sum of nutrient supply into the gyre as a function of distance around the gyre boundary

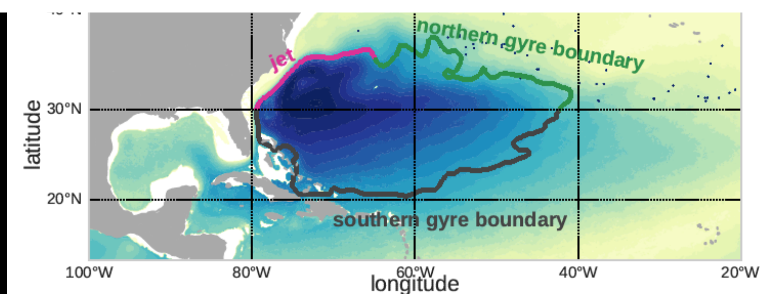


In North Pacific the eddies and mean are approximately equal players in the lateral PO_4 supply

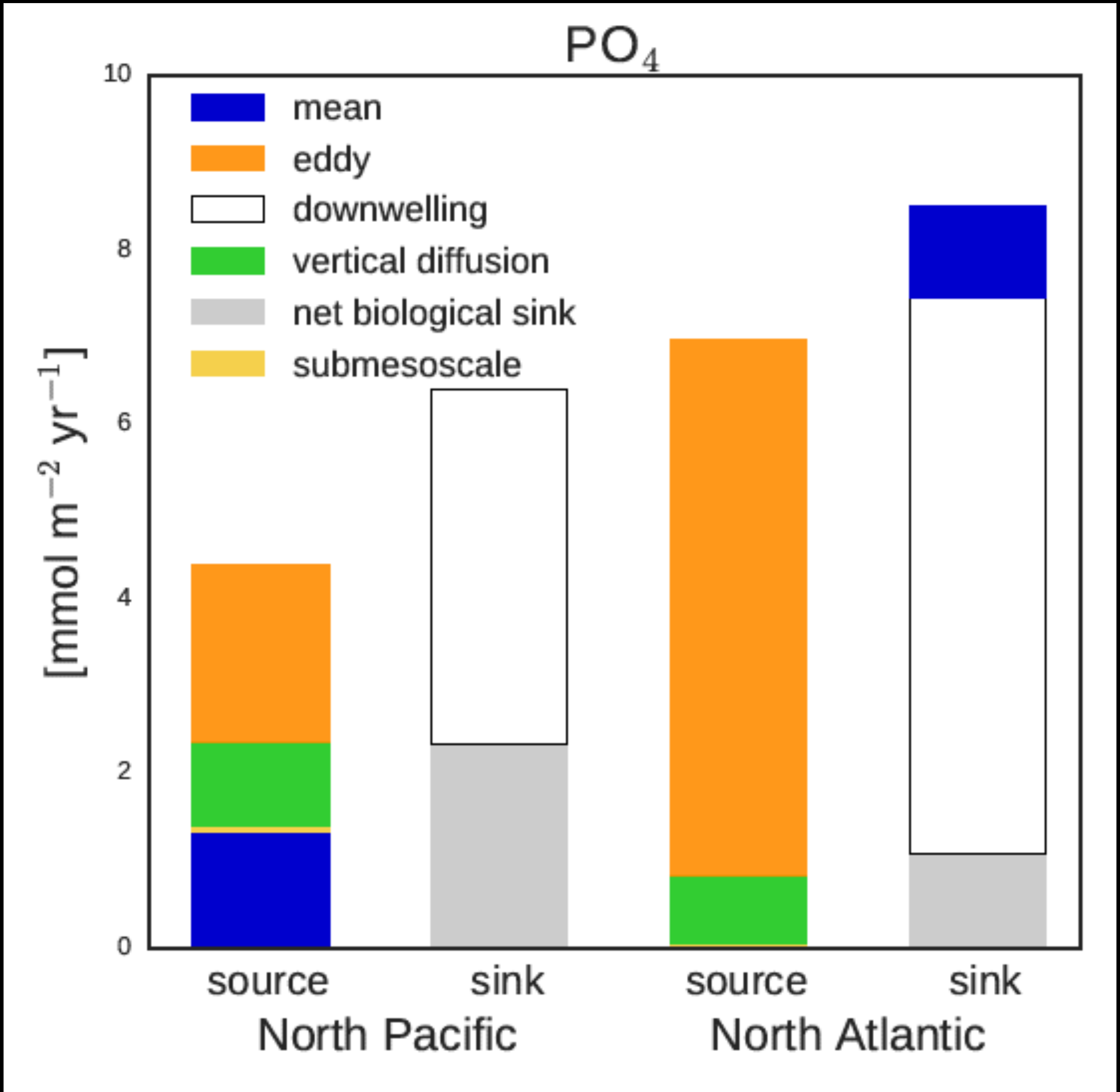


North Atlantic: eddies in the Gulf Stream dominate the lateral supply of nutrients to the gyre

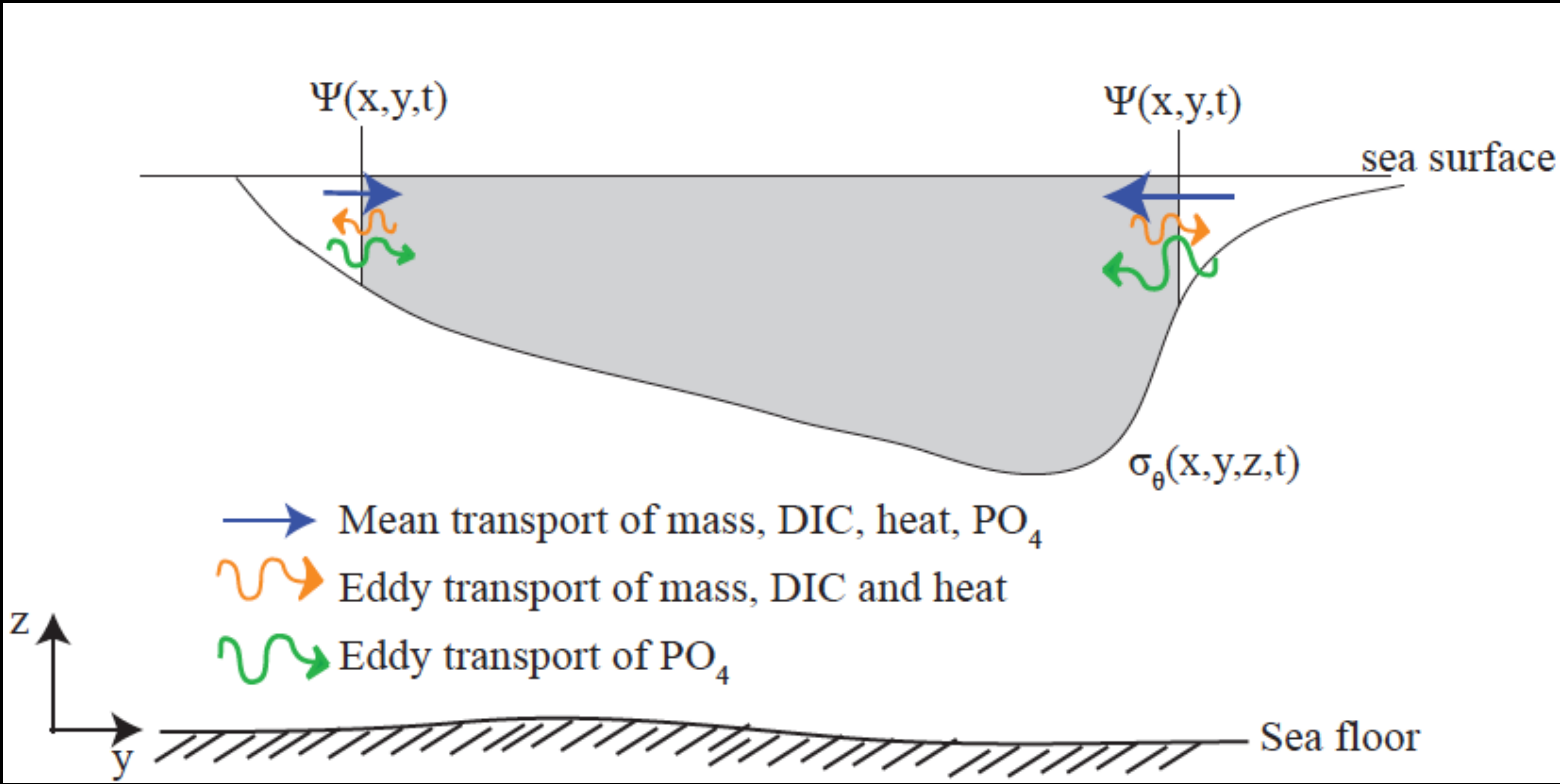




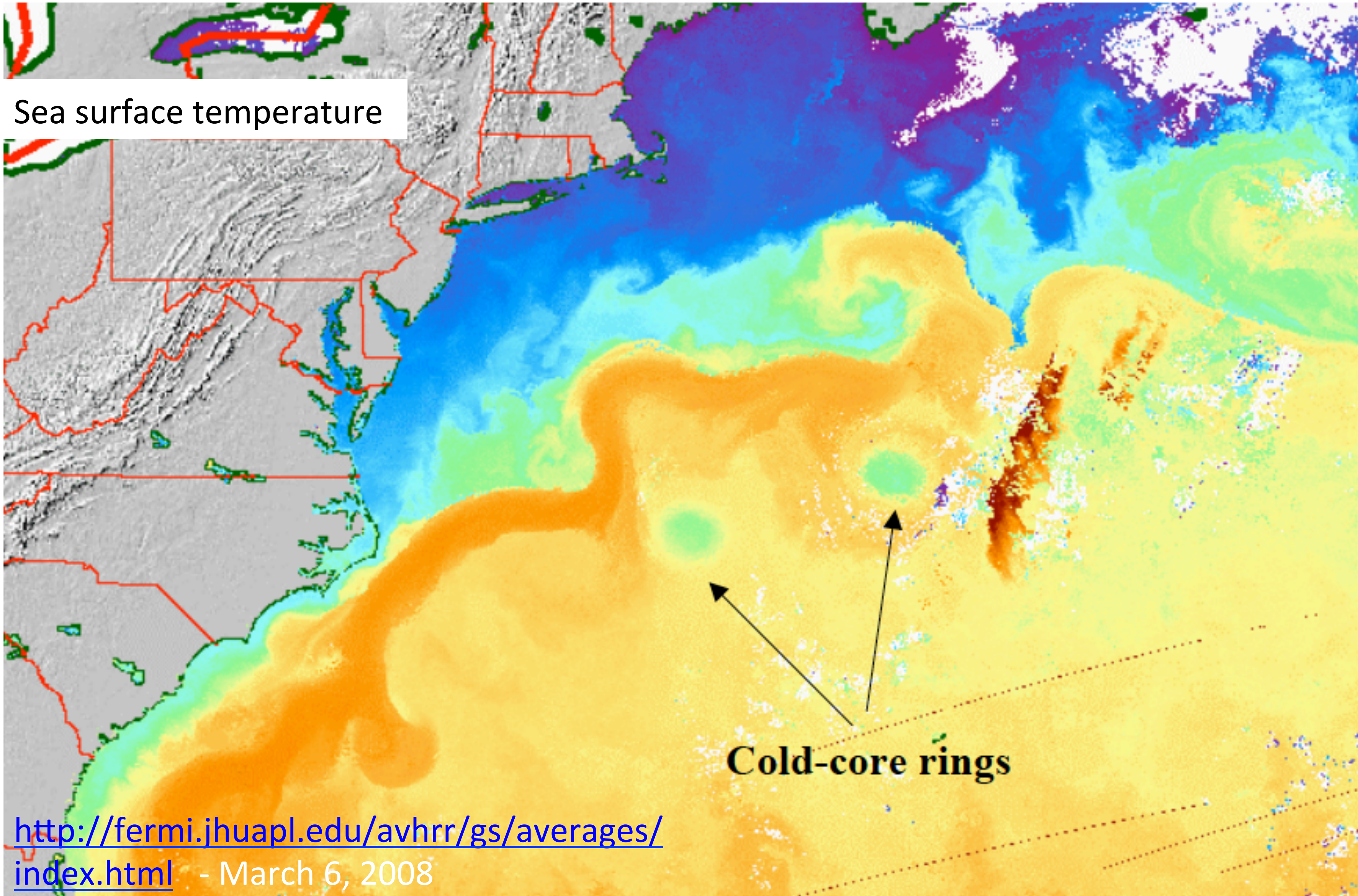
Dominant role of eddies in the PO_4 budget



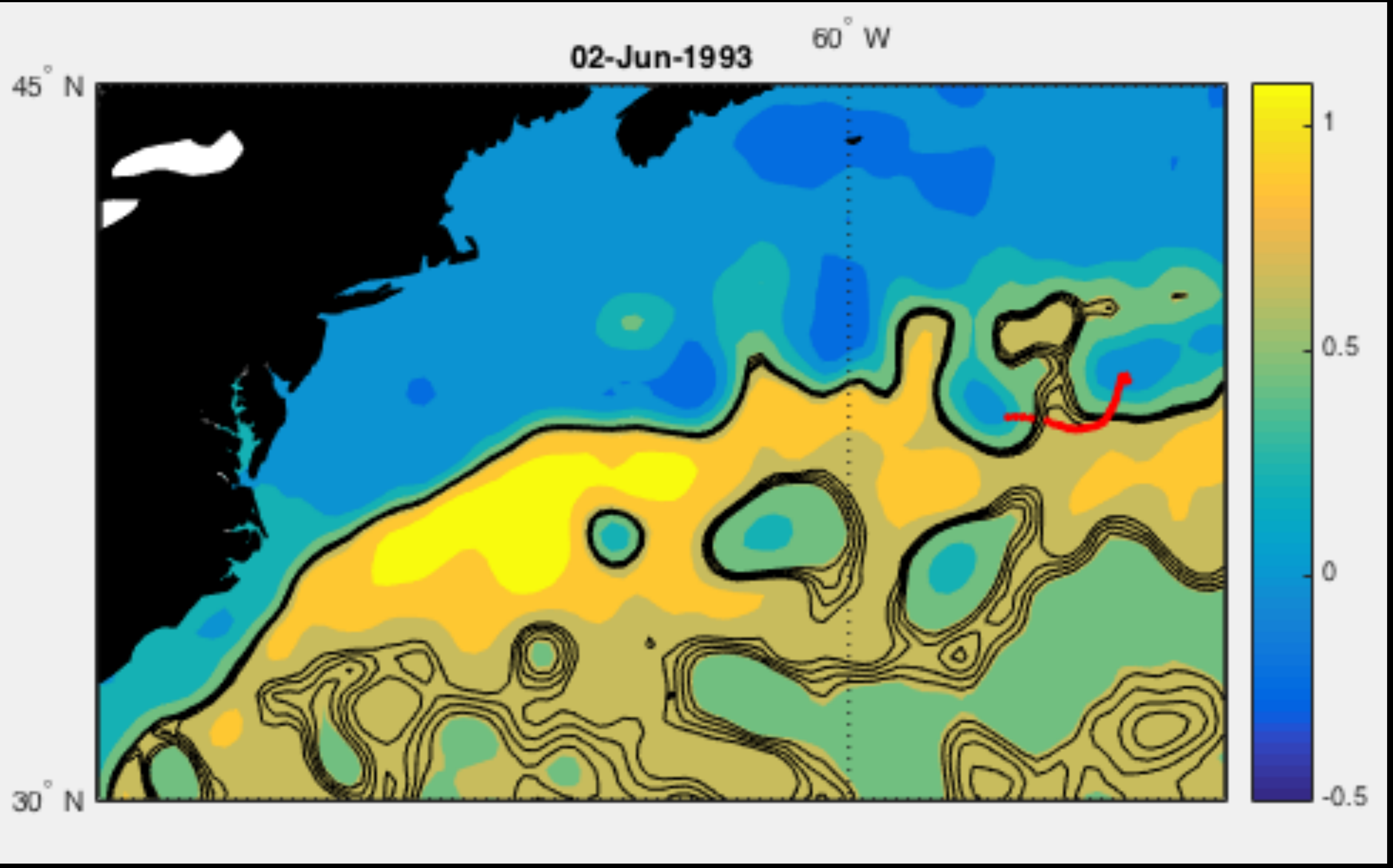
As hypothesized, down-gradient mixing is responsible for supplying a large share of nutrients to the gyre.



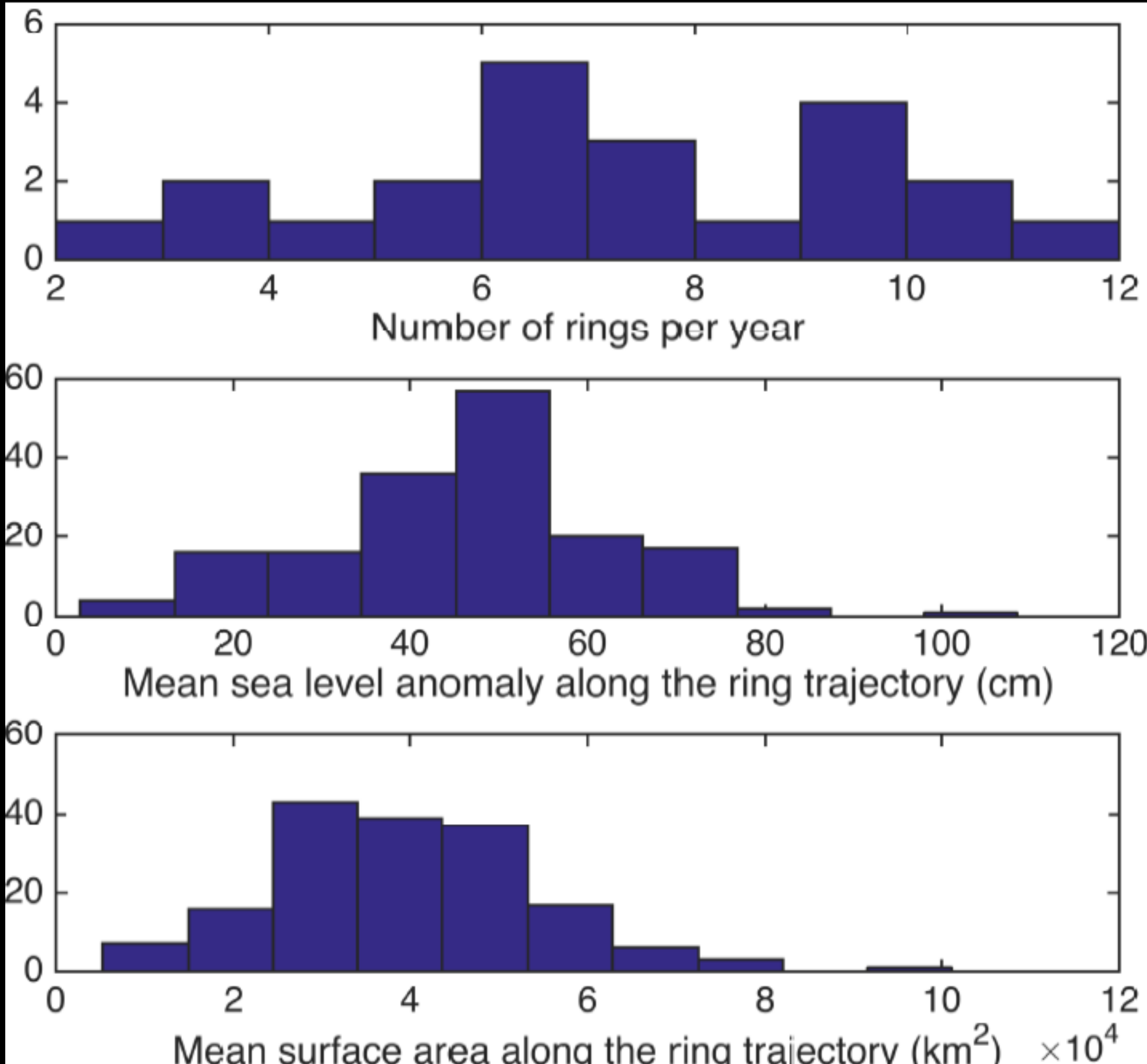
Gulf Stream, Kuroshio, (and ACC) are "leaky jets." One mechanism providing cross-jet transport: cold core rings, which can be tracked by satellite



http://fermi.jhuapl.edu/avhrr/gs/averages/index.html - March 6, 2008

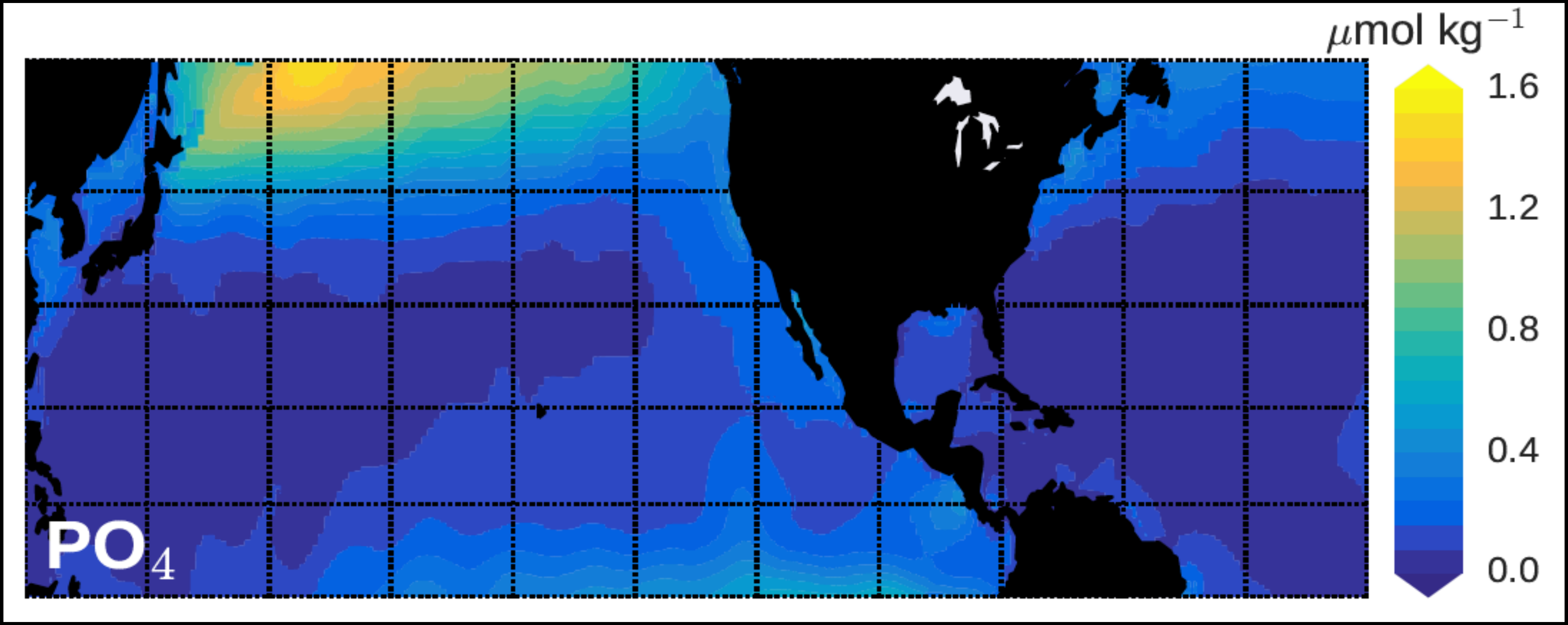


AVISO Sea Surface Height animation with eddy tracking from Faghmous et al., 2015.



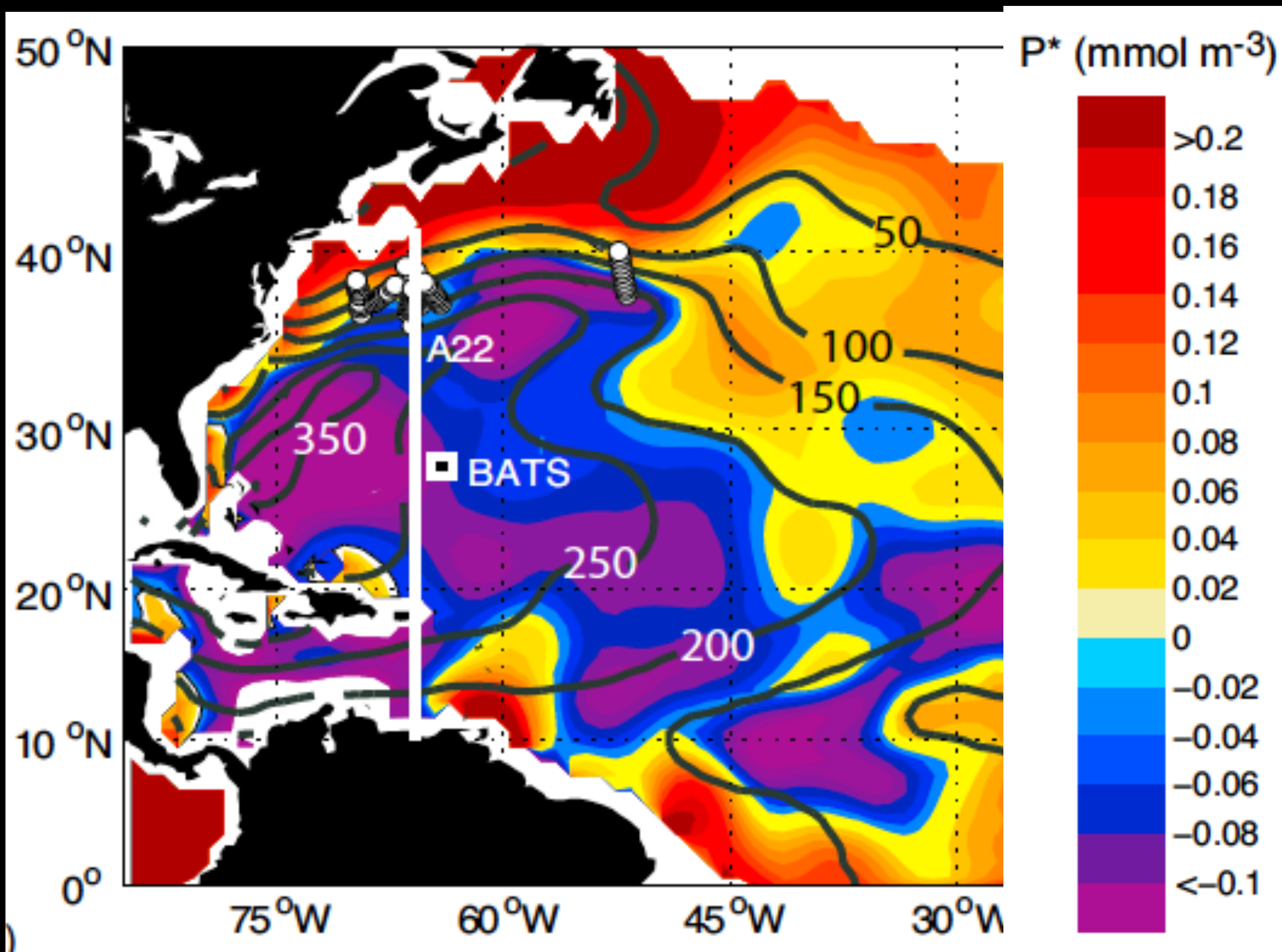
6
4
2
0
2
4
6
8
10
12
Number of rings per year
60
40
20
0
0
20
40
60
80
100
120
Mean sea level anomaly along the ring trajectory (cm)
60
40
20
0
0
2
4
6
8
10
12
Mean surface area along the ring trajectory (km^2) $\times 10^4$

Such rings could provide a substantial flux of phosphate



…and, P*, i.e. phosphate in excess of biological (Redfieldian) nitrogen demand:

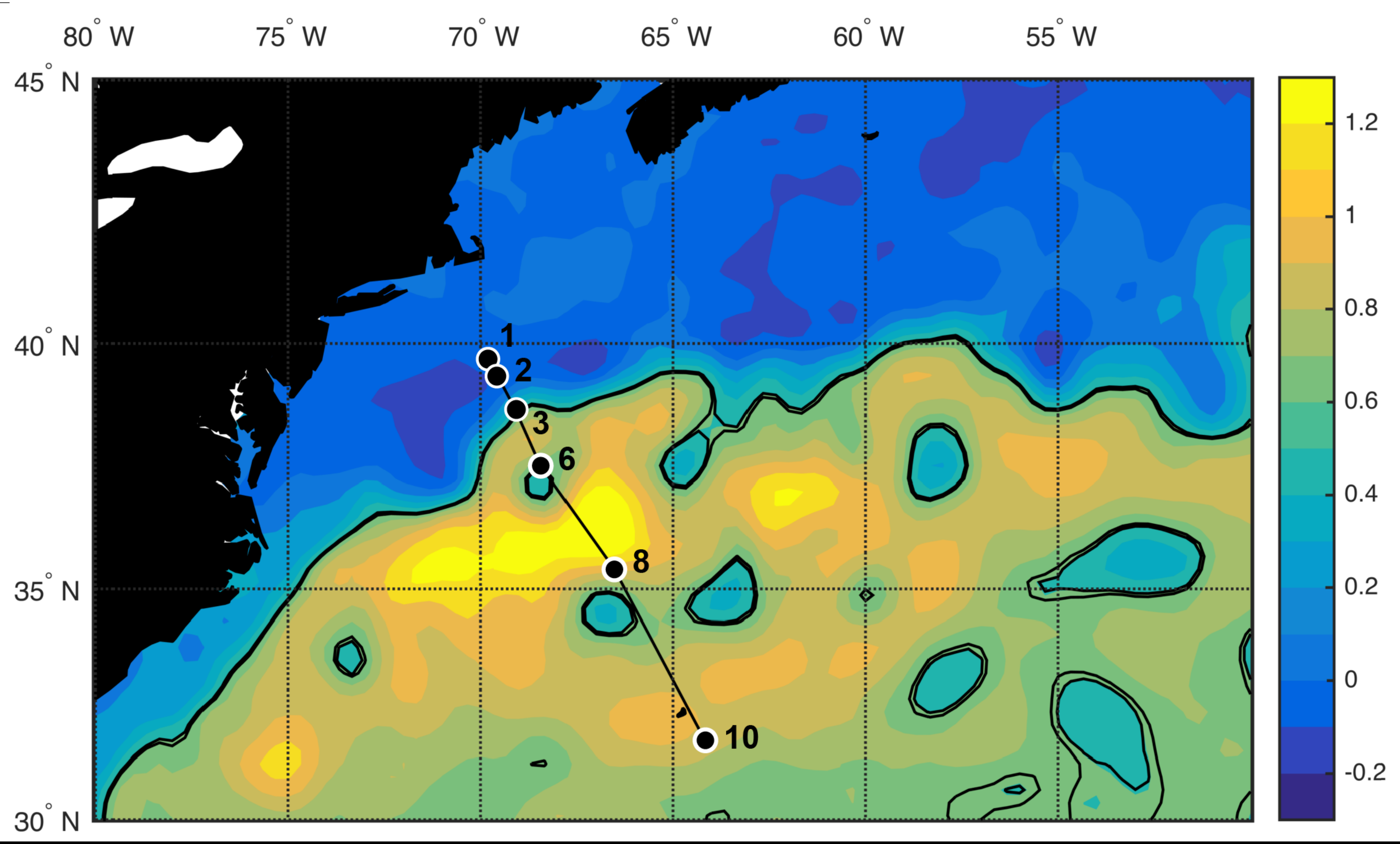
$$P^* = PO_4 - NO_3/16$$



- The Gulf Stream is a stark biogeochemical divide separating the P-rich Slope Sea from the P-depleted subtropics
- Exchange across this divide can support a community of N_2 fixing phytoplankton

Palter et al. 2012

…and iron (a nutrient that is scarce and even more scarcely measured).



Conway et al., submitted

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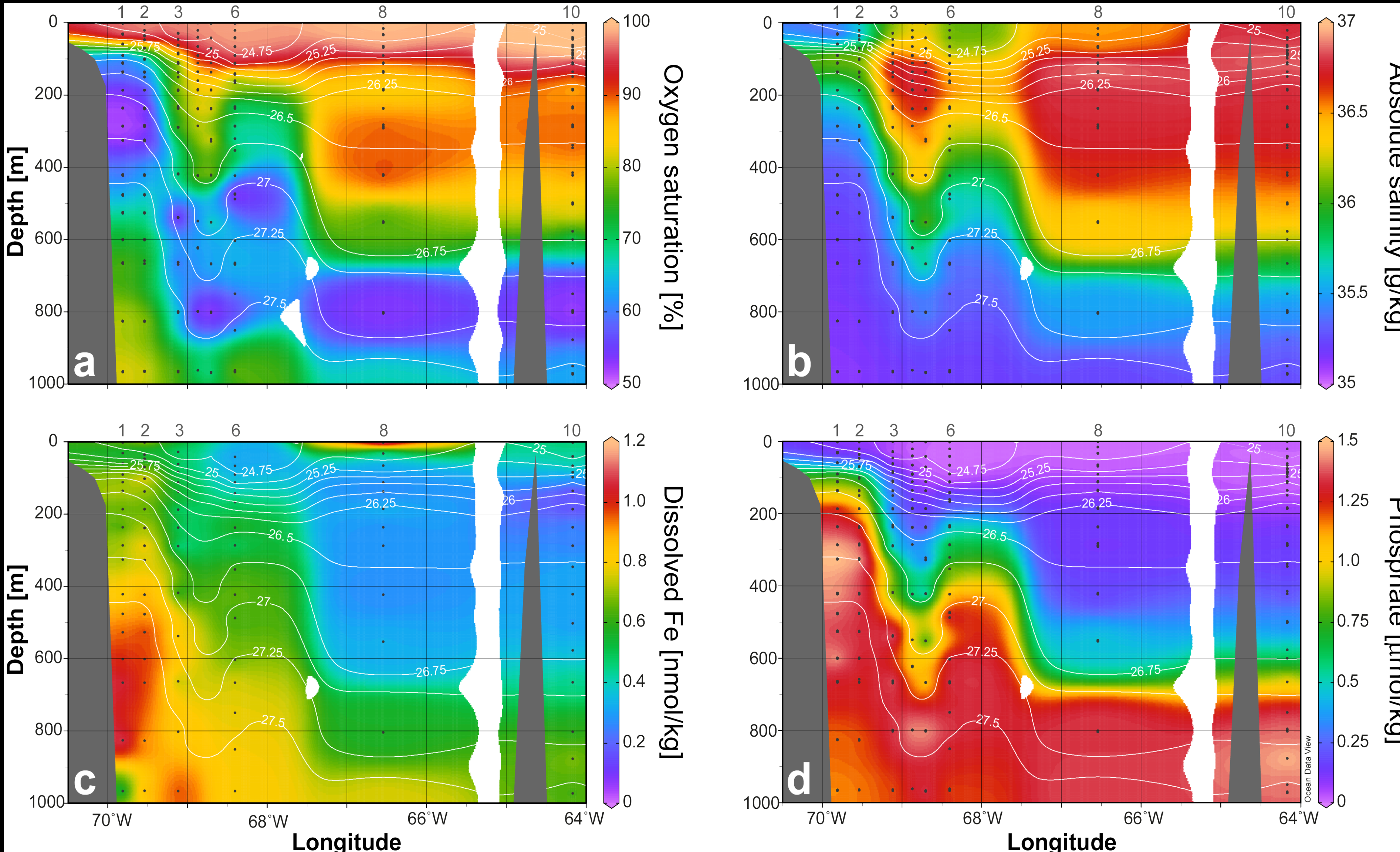
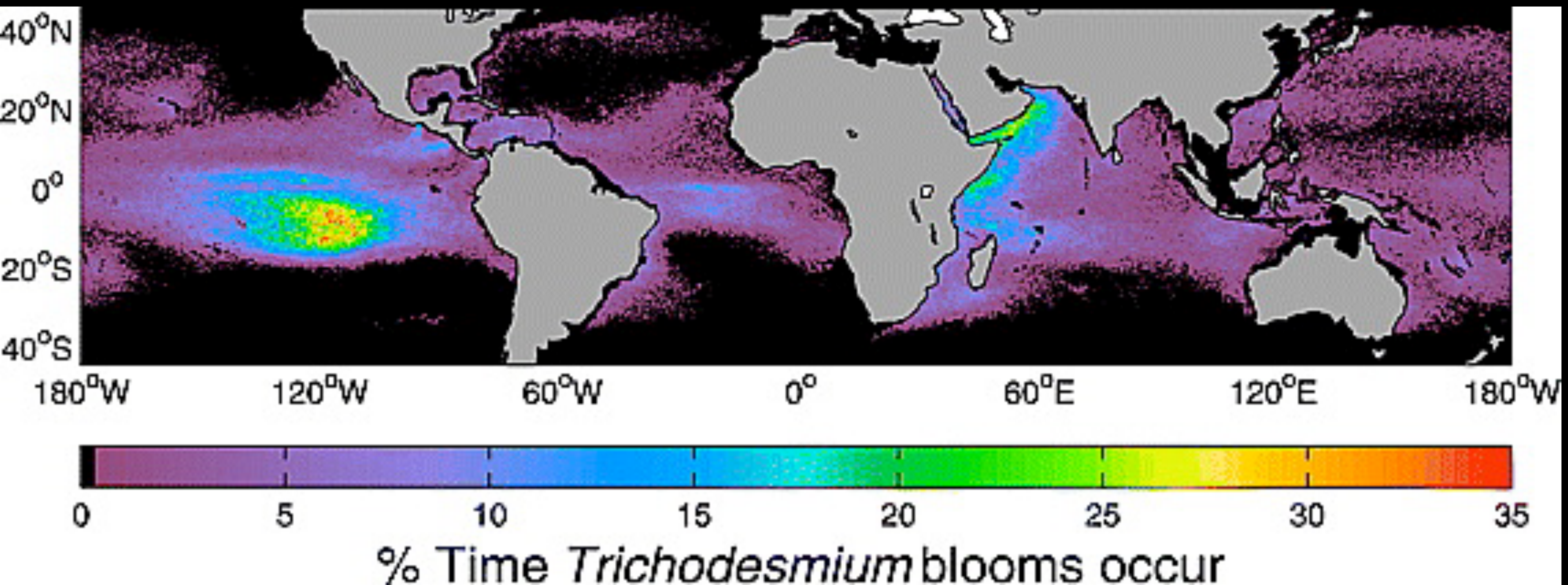


Conway et al., submitted

All the necessary ingredients for biological N_2 fixation should be present near the Gulf Stream



Westberry and Siegel 2006

Satellite images suggest *Trichodesmium* blooms as frequently along the path of the Gulf Stream as in the deep tropical N. Atl.

Testing the prediction: How much N_2 fixation in/near the Gulf Stream? Results due by the end of 2017.

Conclusions

nature geoscience
LETTERS
PUBLISHED ONLINE: 3 OCTOBER 2016 | DOI: 10.1038/NGEO2812

Nutrient budgets in the subtropical ocean gyres dominated by lateral transport

Robert T. Letscher*, François Primeau and J. Keith Moore

- The next step of the nutrient return journey – from the thermocline to the subtropical euphotic zone requires upwelling/vertical mixing outside the subtropical gyres and exchange across the WBCs
- Eddy-driven exchange closes the budget
- These eddy processes are difficult to resolve with traditional observations and coarse resolution models; satellite remote detection and tracking of coherent vortices has provided a timely solution to problem
- Next: apply these ideas to better understand carbon uptake


Thank you