ROLES OF THE OCEAN MESOSCALE IN THE LATERAL SUPPLY OF MASS, HEAT, CARBON AND NUTRIENTS TO THE NORTHERN HEMISPHERE SUBTROPICAL GYRE

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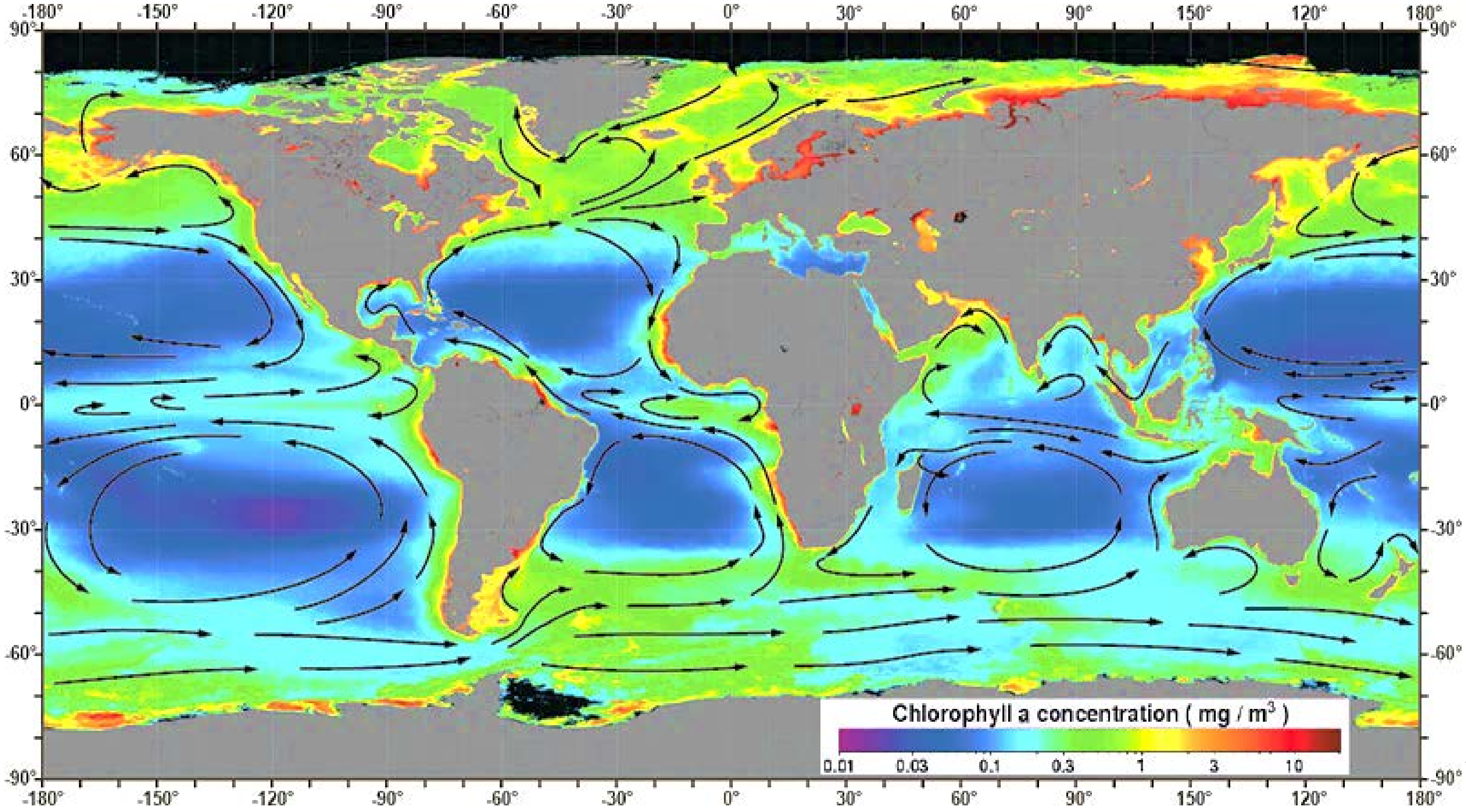
Subtropical gyres: "Ocean Desert"



Mean Annual concentration of phytoplankton chlorophyll from NASA MODIS http://www.rapid.ac.uk

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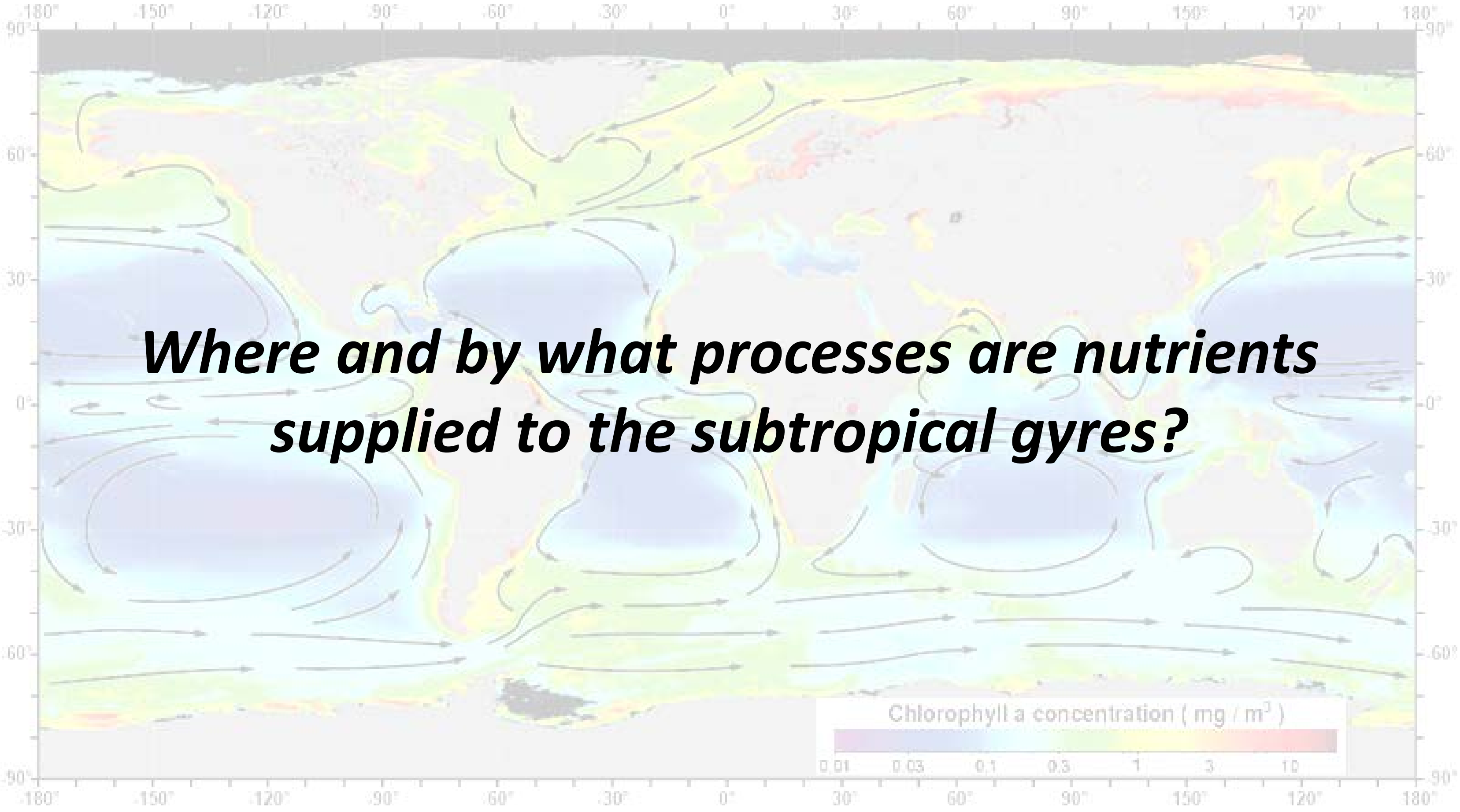

Where and by what processes are nutrients supplied to the subtropical gyres?

Mean Annual concentration of phytoplankton chlorophyll from NASA MODIS
http://www.rapid.ac.uk

Supply mechanisms of nutrients into the oligotrophic subtropical gyres

Vertical processes (e.g. mixing and upwelling from intermediate depths)

→ New production outpaced the known vertical supply of nutrients to the subtropical gyre euphotic zone (Mcgillicuddy Jr et al. 1998; Oschlies and Garcon 1998)

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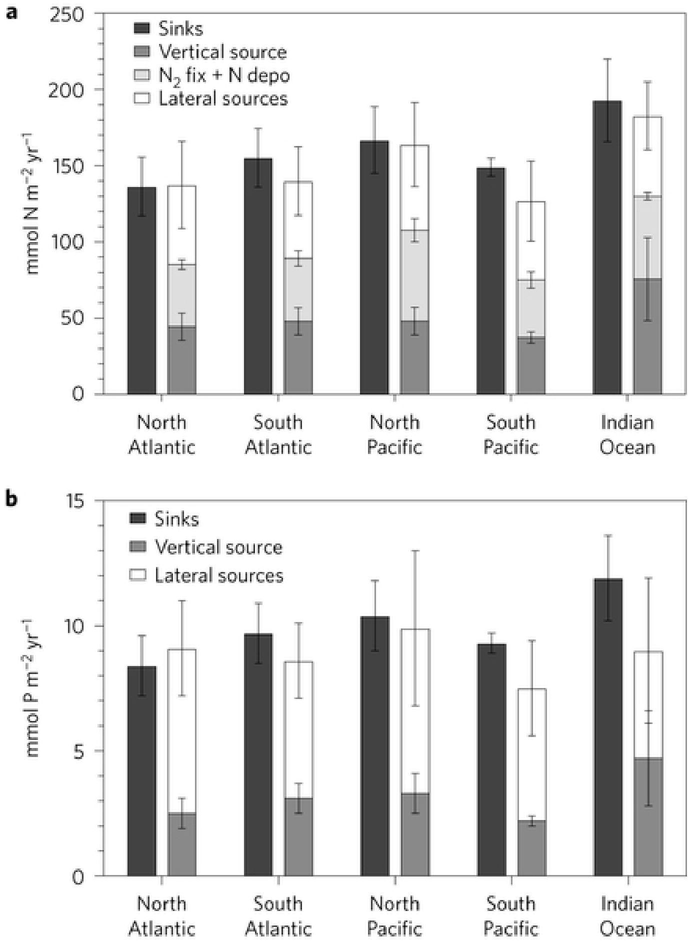


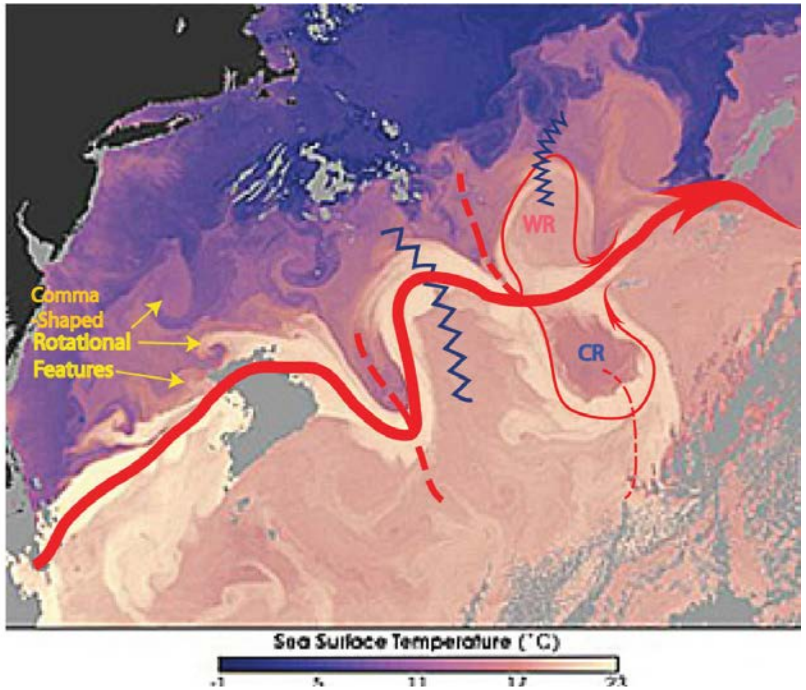
Lateral processes

- Recent studies have indicated the importance of lateral processes in supplying nutrients to the subtropical gyre from the neighbouring nutrient-rich subpolar gyres and tropics (e.g. Williams and Follows 1998,2003; Oschlies 2002; Ayers and Lozier, 2010)
- Letscher et al. (2016): Showed that roughly half of the dissolved inorganic phosphate is supplied by lateral transport by using the observationally-constrained coarse-resolution model

Importance of mesoscale eddies in WBCs

WBCs: Act both as "*blenders*" and "*barriers*" for cross-frontal tracer exchanges (Bower 1985)

- **Blender**:
  - Ekman transport driven by the strong down-front westerlies (e.g. Williams and Follows 1998)
  - Mesoscale eddies due to the heightened available potential energy (e.g. Samelson 1992; Qiu et al. 2007)
- **Barrier**: Jets suppress eddy-driven mixing at the shallower depths where the speed of the jet is much faster than the propagation speed of its meanders (e.g. Bower1985; Dufour et al. 2015)



What is the role of mesoscale motion in the lateral transport of mass and tracers into the subtropical gyres?

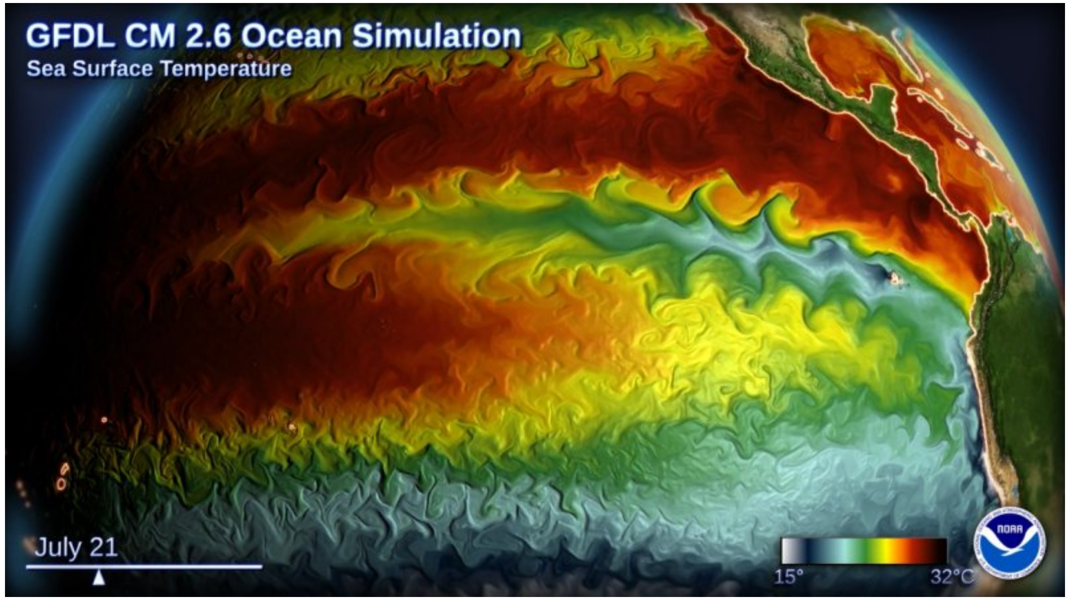
Goals of the study

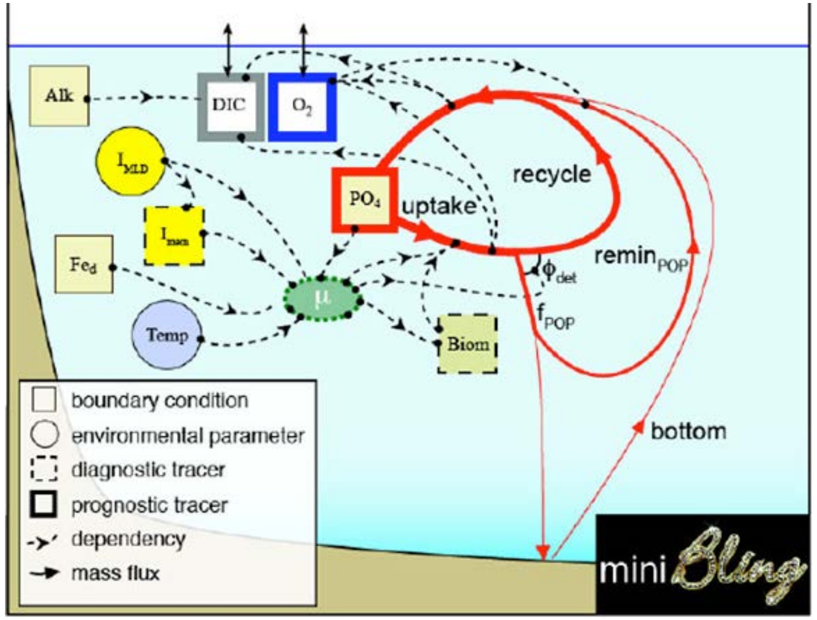
Quantify the transport of mass, heat, carbon, and nutrients into the North Pacific and North Atlantic subtropical gyres over an annual-mean timescale using an eddy-rich model coupled to a simplified prognostic biogeochemical model (CM2.6-miniBLING)

- Assess the physical mechanisms that control the lateral transport of these tracers into the interior of the subtropical gyres all along their boundaries
- Evaluate their importance in gyre heat, DIC, and nutrient budgets
- Understand the spatial variability of these transports, as well as any contrasts that emerge between the North Atlantic and the North Pacific subtropical gyres.

Methodology

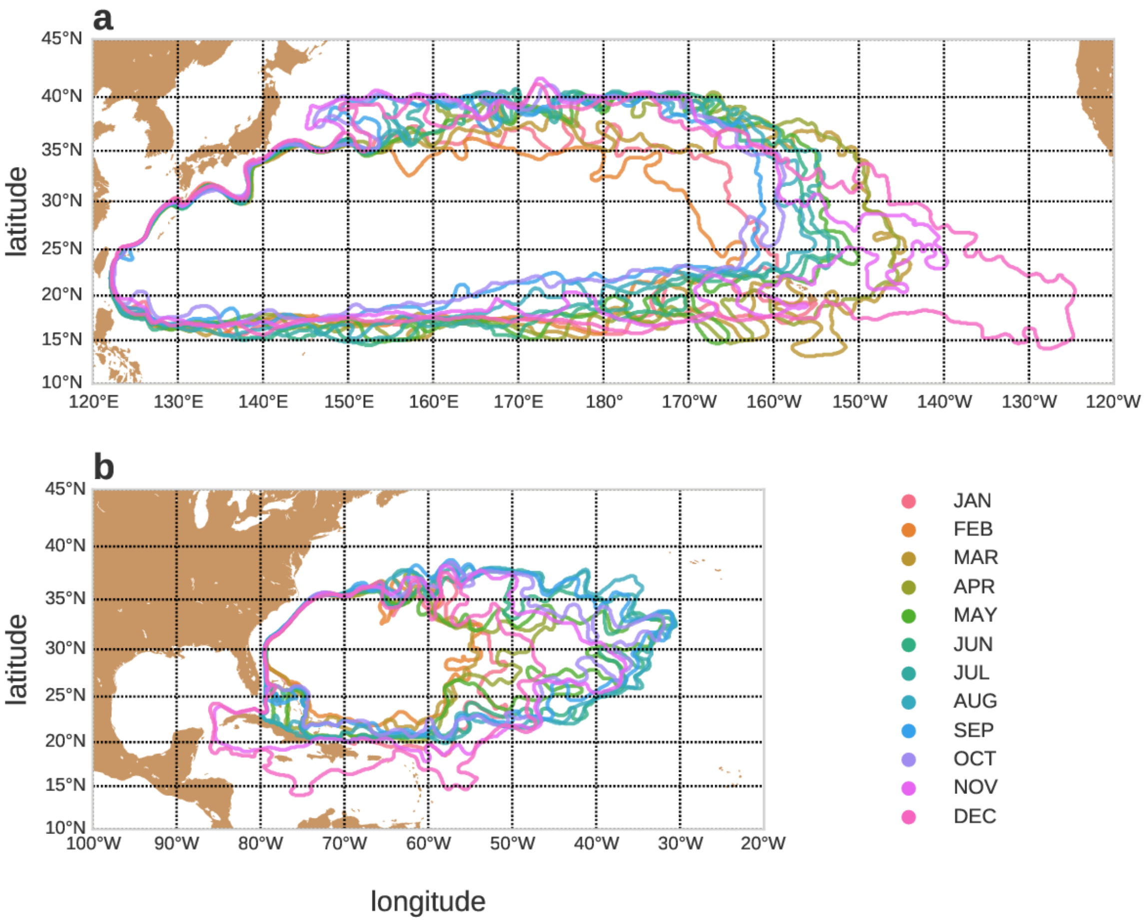
GFDL's ocean-atmosphere model *CM2.6* coupled with a simplified prognostic biogeochemical model *miniBLING*





- **CM2.6** (Delworth et al. 2012, Griffies et al. 2015): Resolves a large spectrum of oceanic mesoscale fluctuations with 0.1^{o} horizontal resolution for the ocean and the sea ice components
- **miniBLING** (Galbraith et al. 2015): Three prognostic tracers – DIC, O_2, average macronutrient "PO_4" ($PO_4/2+NO_3/32$)
- Years 191 – 200 are used among the 200 years of preindustrial control simulation

Definition of dynamically-defined subtropical gyres



Lateral Extent: Monthly mean 2D barotropic mass quasi-stream function integrated over the upper 1,000 m which encloses the largest closed areal extent →*western edges aligned with jets*

- N. Pacific: 20 Sv
- N. Atlantic: 25 Sv

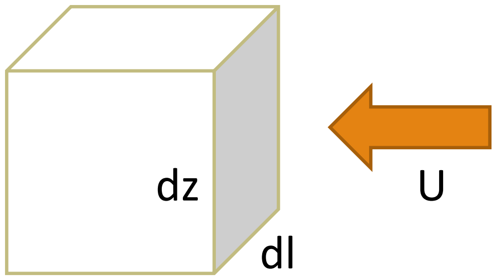
Vertical Extent: Ventilated pycnocline (Luyten et al. 1983)

- N. Pacific: $\sigma_\theta = 25.8 \text{ kg m}^{-3}$
- N. Atlantic: $\sigma_\theta = 26.6 \text{ kg m}^{-3}$

Decomposition of the transport into mean and eddy components (Griffies et al. 2015, Dufour et al. 2015)

The lateral transport of mass and tracer transport: $\Phi = \rho_0 dl\hat{n} \cdot \boldsymbol{U}C$,

where $\boldsymbol{U} = \boldsymbol{u}dz$



$$\Phi_{total} = \Phi_{mean} + \Phi_{eddy}$$

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$$\boxed{\begin{aligned}\Phi_{eddy} &= \Phi_{total} - \Phi_{mean} \\ &= \rho_o dl\hat{\boldsymbol{n}} \cdot (\overline{\boldsymbol{U}C} - \overline{\boldsymbol{U}}\bar{C})\end{aligned}}$$

→ The eddy term is dominated by ***mesoscale fluctuations*** (e.g., rings, jet meanders, etc.)

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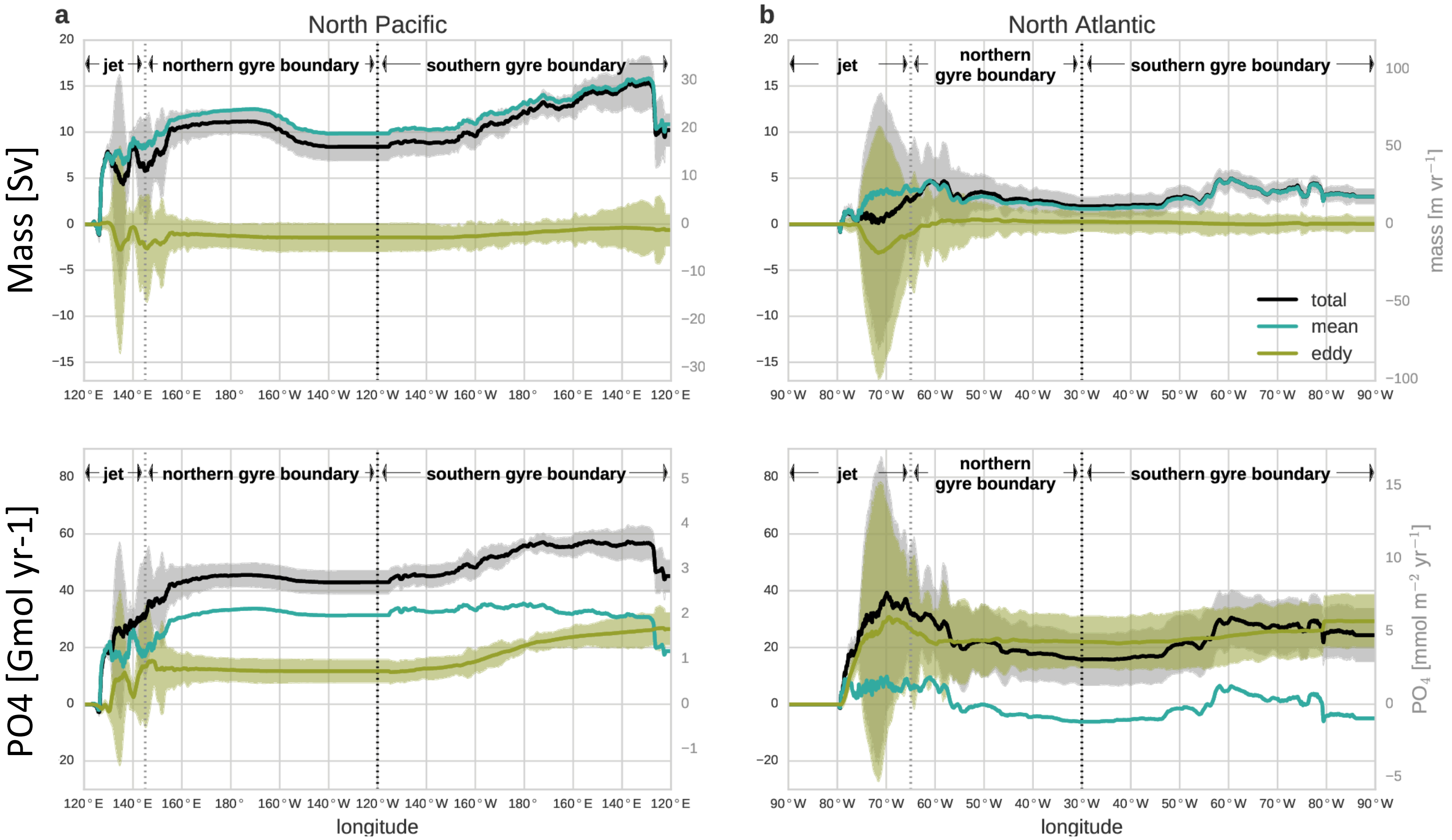
Two key processes associated with

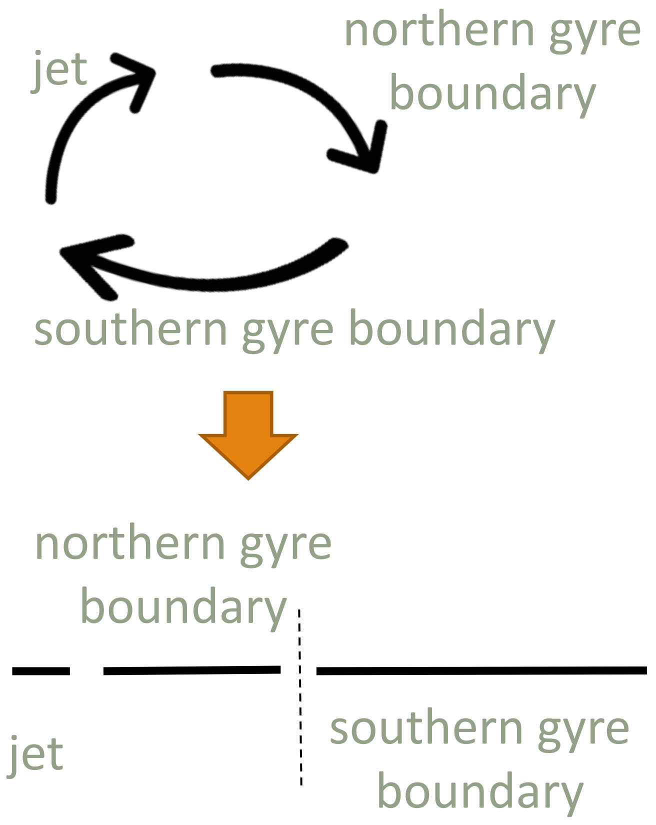
mesoscale eddies:

1. **Eddy-induced advective transport**: Act to convert heightened APE to KE (Gent et al. 1995) *acts up-gradient/down-gradient*
2. **Down-gradient isopycnal mixing** (commonly parameterized as tracer diffusion)

Results

Cumulative sum of annual-mean cross-boundary mass and nutrients input into the subtropical gyres





+ve transport = mass and tracer input to the gyre

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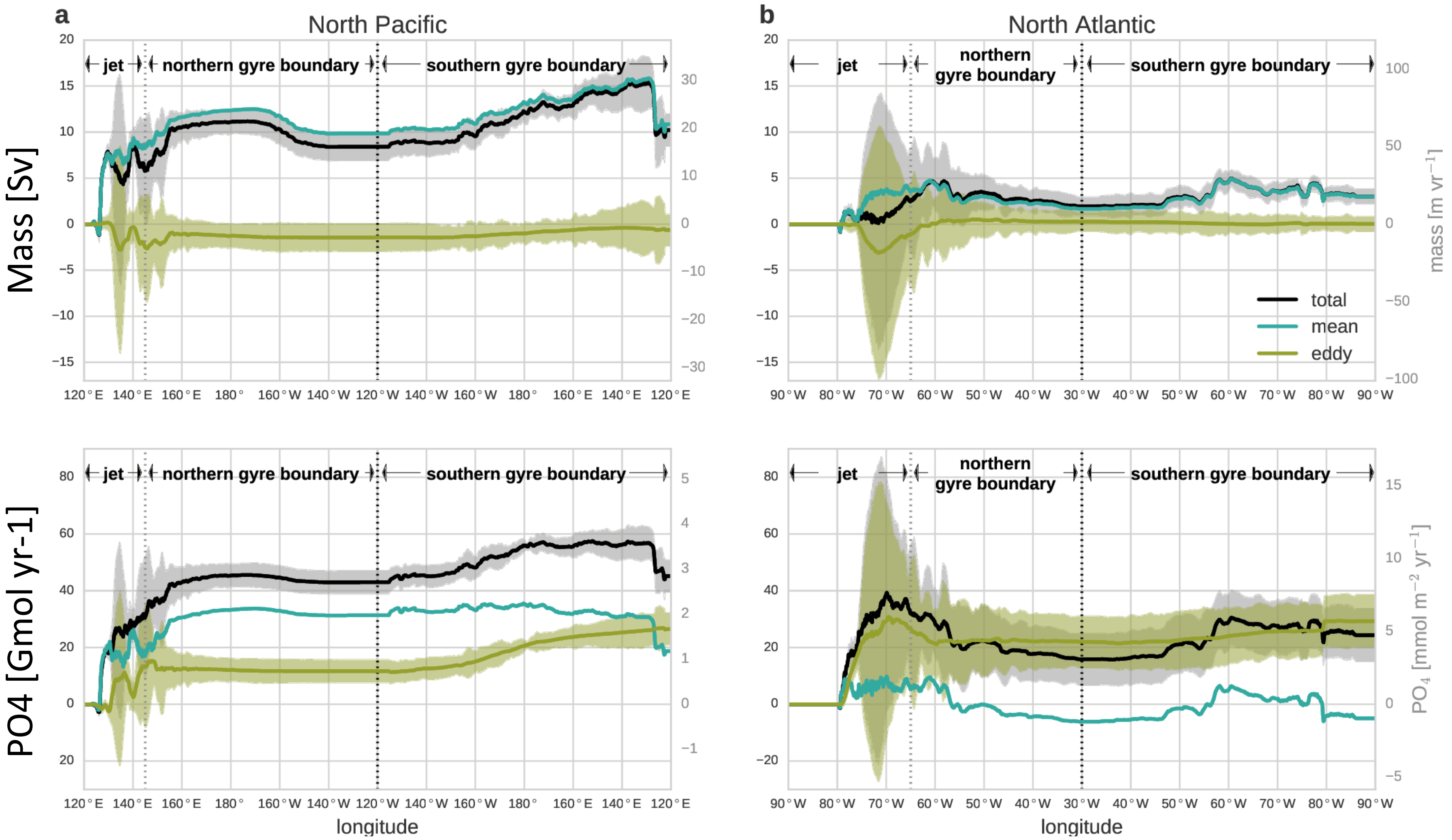

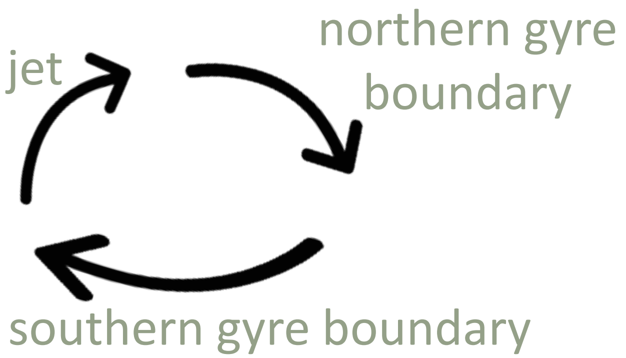

Gulf Stream and Kuroshio:

Act as gateways for mass and tracer cross-boundary transport

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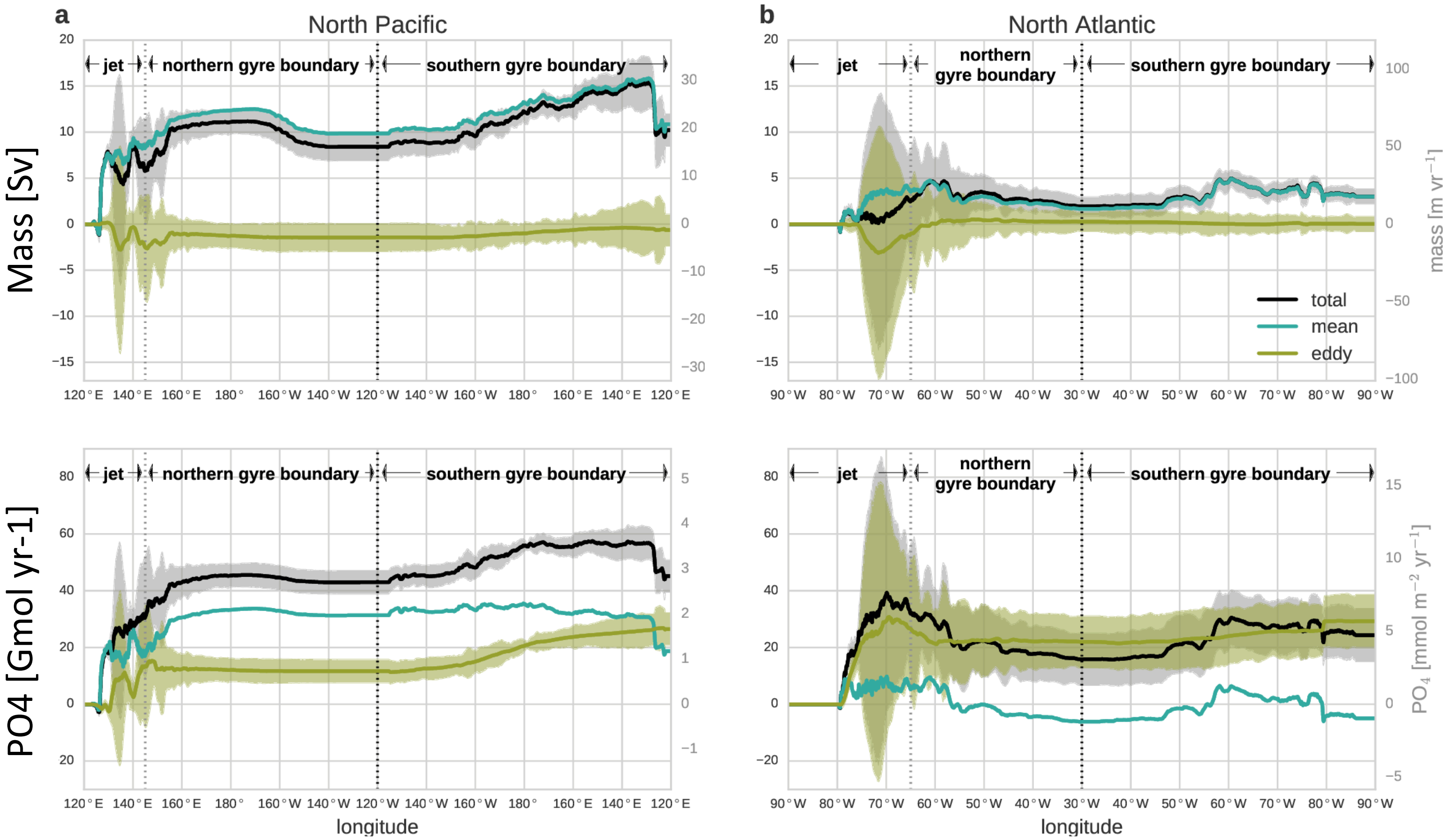
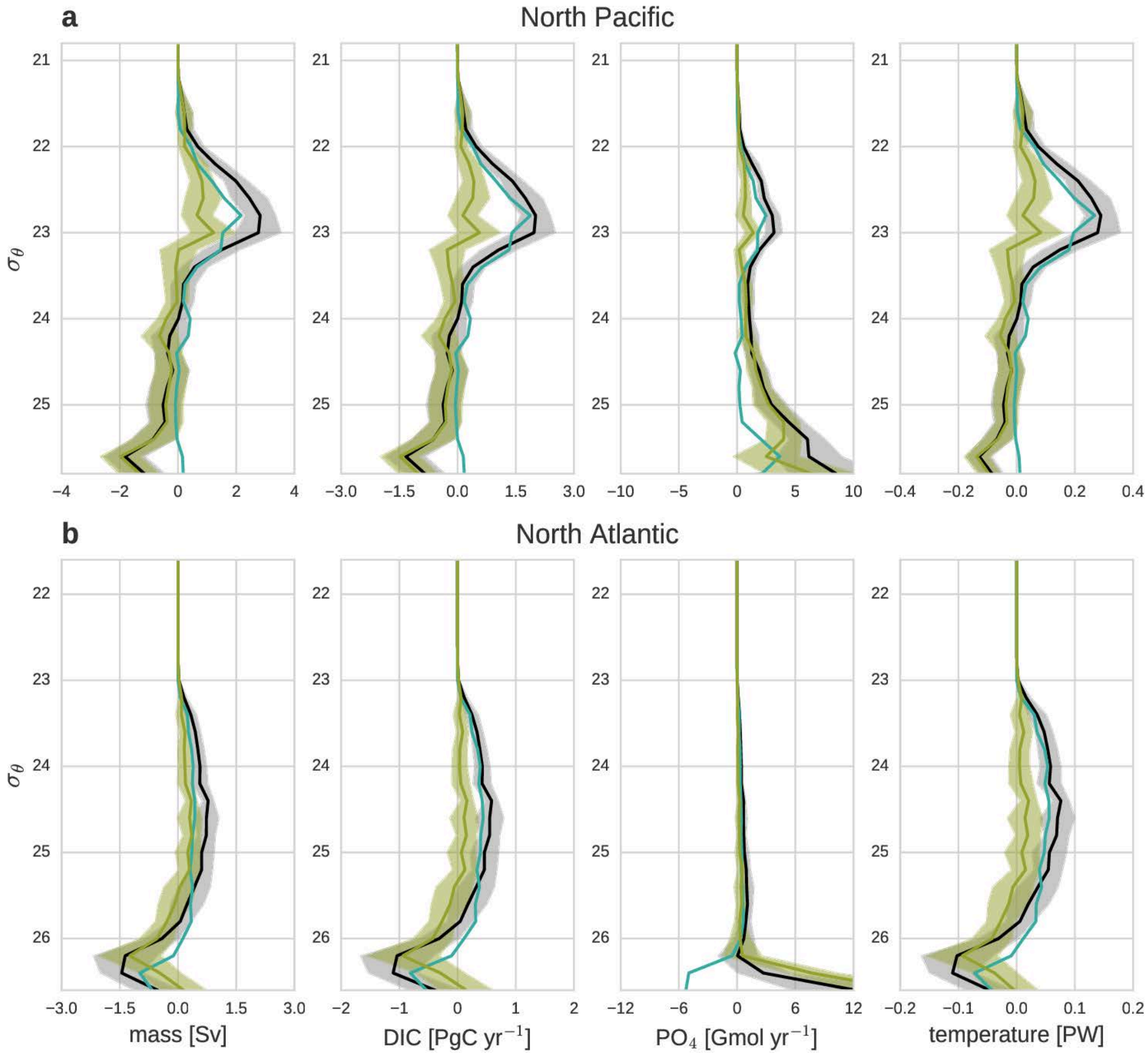


Mass:

- Dominantly supplied by the time-mean flow
- **Eddy** acts to remove mass
- Heat and DIC have similar along-boundary structure

Nutrients:

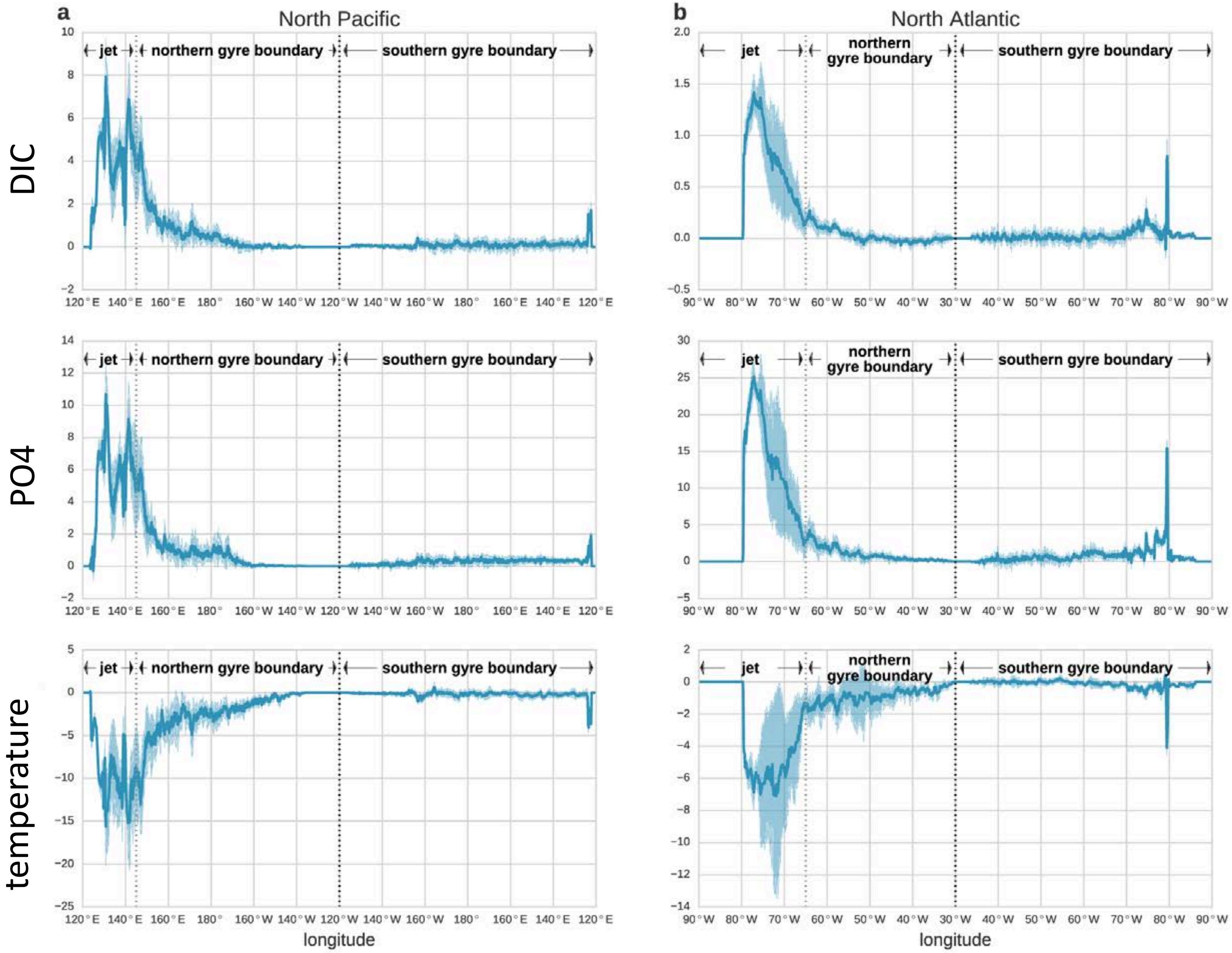
- Mainly supplied by the eddy component
- When normalised by the gyre area, ~2 times more lateral PO4 input into N. Atlantic



Vertical profile of cross-boundary tracer transport

- ❖ Mean input occurs at the shallower depths → Ekman input
- ❖ T and DIC have very similar profiles to that of mass → Eddy component mainly dominated by the **eddy-induced advective transport**
- ❖ **PO_4 at the base of the layer is elevated** → both the mean and eddy circulation induce the larger PO4 input/output at depths

However, mass advection cannot fully explain the behaviour of PO4 transport



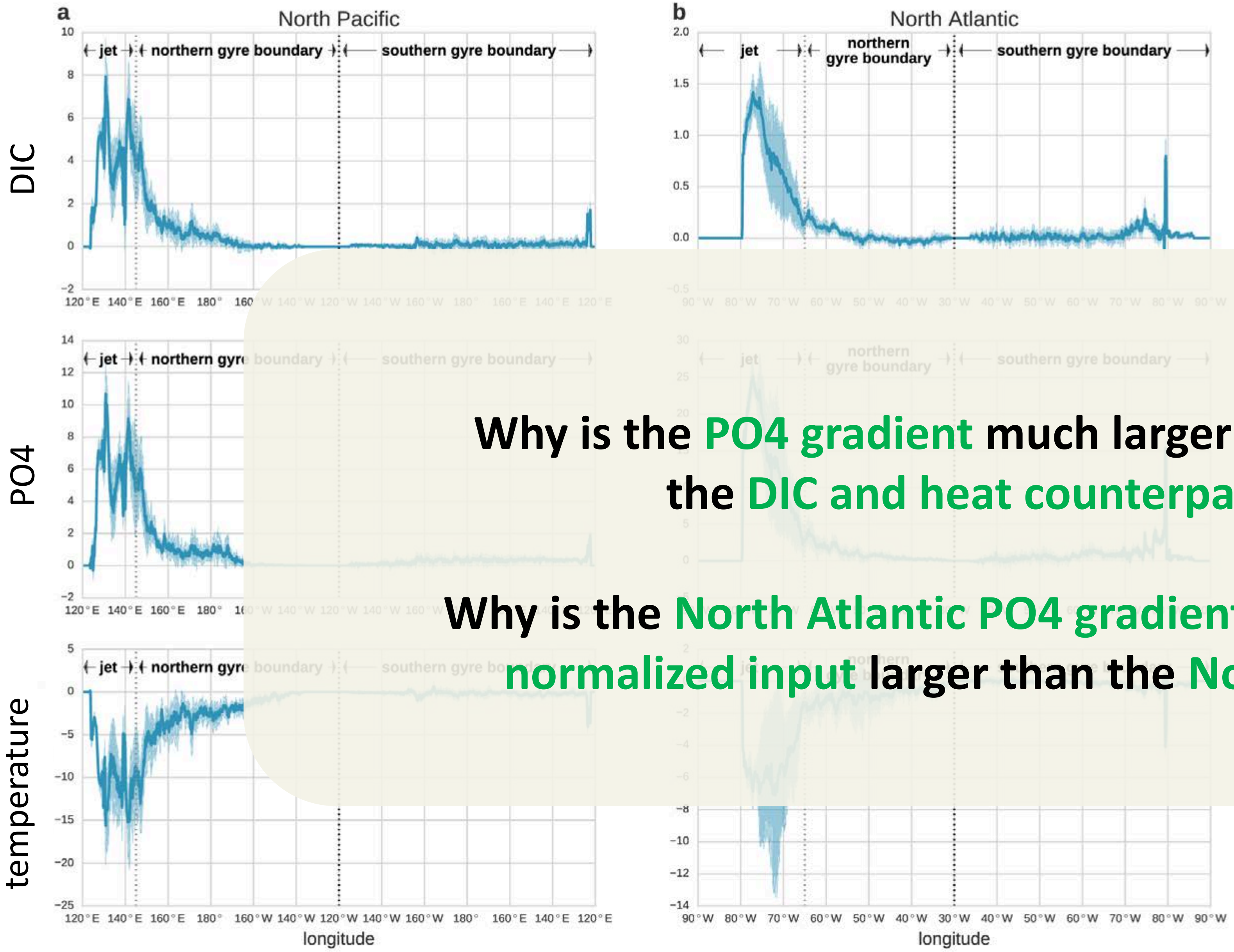
Cross-boundary tracer gradients

The down-gradient isopycnal tracer transport by the eddies:

$$\chi_c = -\rho_0 k\bar{h}(\nabla C) \cdot \boldsymbol{n}dl$$

- The most enhanced gradient across **Kuroshio** and **Gulf Stream**
- DIC and PO4 supplies nutrients by the **down-gradient eddy mixing**
  - PO4 gradient in N. Pacific (N. Atlantic) 1.5 times (10 times) larger than DIC gradient

+ve: higher concentration outside the gyre than the inside



Cross-boundary tracer gradients

Why is the PO4 gradient much larger compared to the DIC and heat counterparts?

Why is the North Atlantic PO4 gradient and the area-normalized input larger than the North Pacific?

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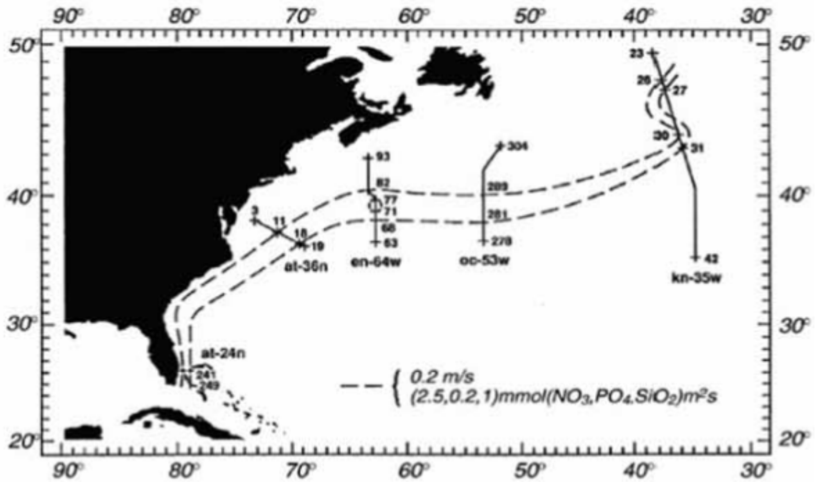
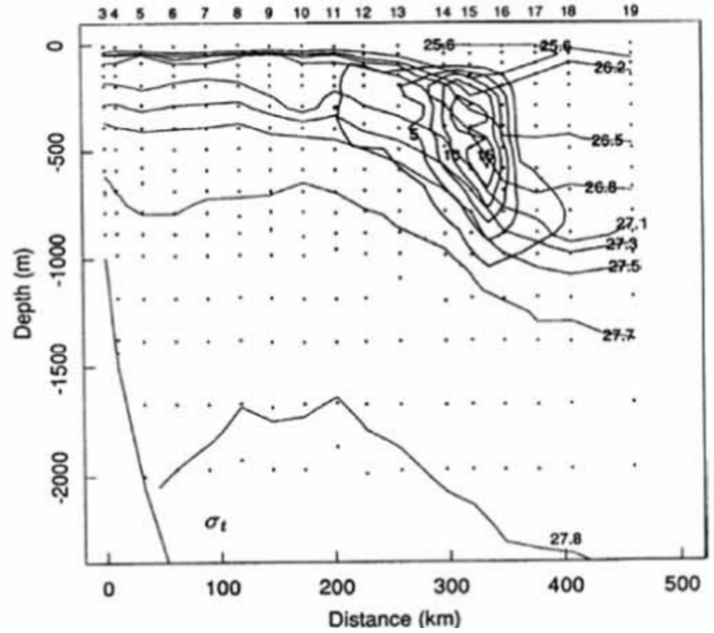
Why is the PO4 gradient much larger compared to the DIC and heat counterparts?

- Small DIC variations relative to background concentrations
- DIC and heat air-sea flux exchange, which smooth out the lateral tracer gradients
- Near complete depletion of PO4 in the subtropical gyres nearly to the base of the ventilated layer
- Presence of **Nutrient Stream** (Pelegri & Csanady 1991)





Excerpted from Pelegri & Csanady 1991

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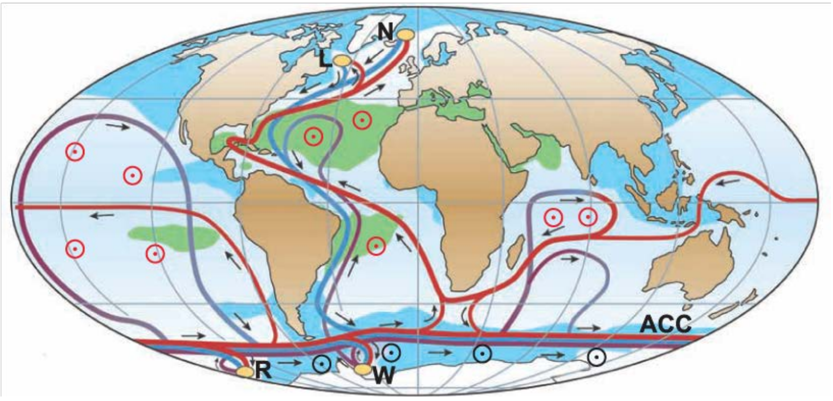
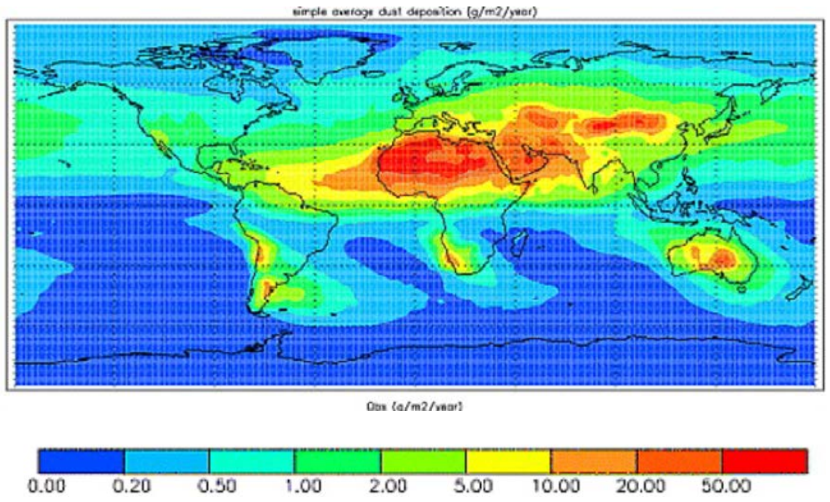


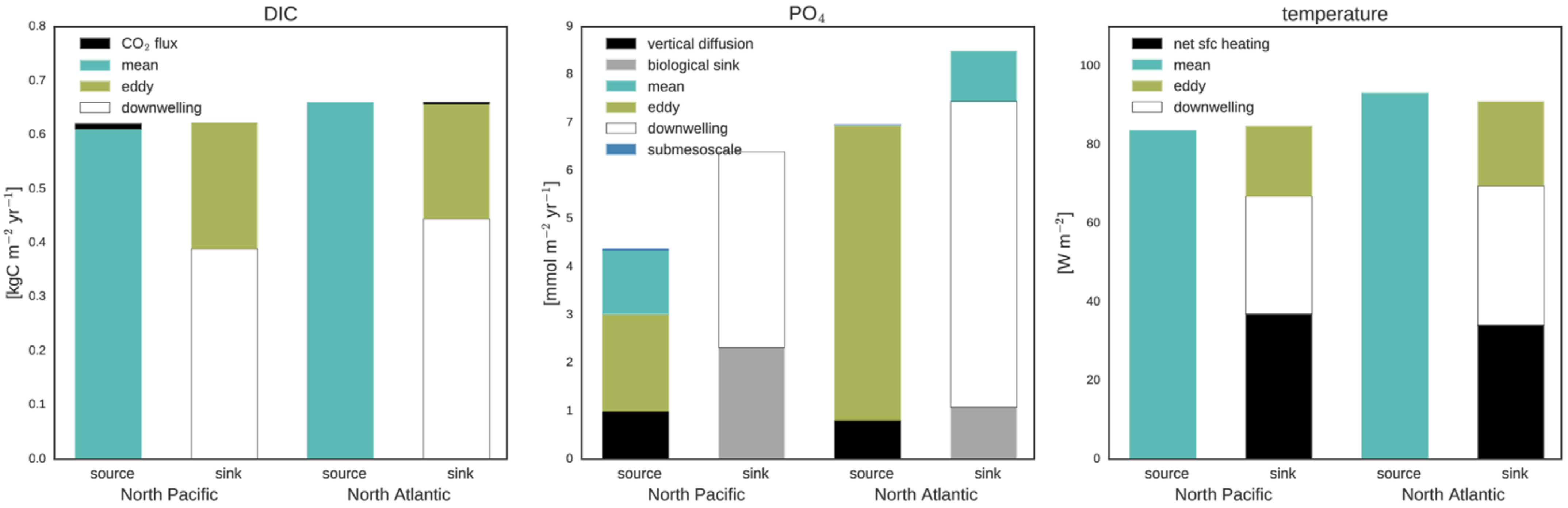
Excerpted from Kuhlbrodt et al., 2007

- Nutrient concentration in the Gulf Stream further enriched by the waters from the tropics and Southern Ocean, in the shallow return pathway of the AMOC (Palter and Lozier, 2008) →Gulf Stream nutrient concentration 4 - 5 times larger than the Kuroshio counterpart (Guo et al. 2012)
- Greater availability of iron in the subtropical North Atlantic due to the atmospheric deposition of iron-rich Saharan dust (Mahowald et al. 2005; Sedwick et al. 2005)



Excerpted from Mahowald et al. 2005

The importance of the lateral tracer transport in the respective subtropical gyre budget



DIC: Almost entirely supplied by the time-mean lateral transport, with 1/3 removed by the eddy

PO4: Dominantly supplied by the **eddy component**. Lateral transport explains > ¾ of the total supply

Heat: Eddy removal is in the same order of magnitude as air-sea heat flux → importance for the climate

Conclusion

Evaluation of **lateral transport** of mass, heat, carbon, and nutrients into the North Pacific and North Atlantic subtropical gyres, with a preindustrial simulation of an eddy-rich ocean-atmosphere model coupled with a simplified biogeochemistry model (CM2.6-miniBLING)

- **Kuroshio** and **Gulf Stream** act as main mass and tracer exchange gateways
- **Mass**, **DIC** and **heat** are supplied dominantly by the time-mean circulation, with the eddy component acts to remove them from the subtropical gyres (eddy-induced advective transport
- **PO4** is supplied primarily by the eddy component
- ***Lateral transport** of PO4 explains >3/4 of the total gyre PO4 supply*: roughly 1.5 times larger than the previous estimate by Letscher et al. (2016)