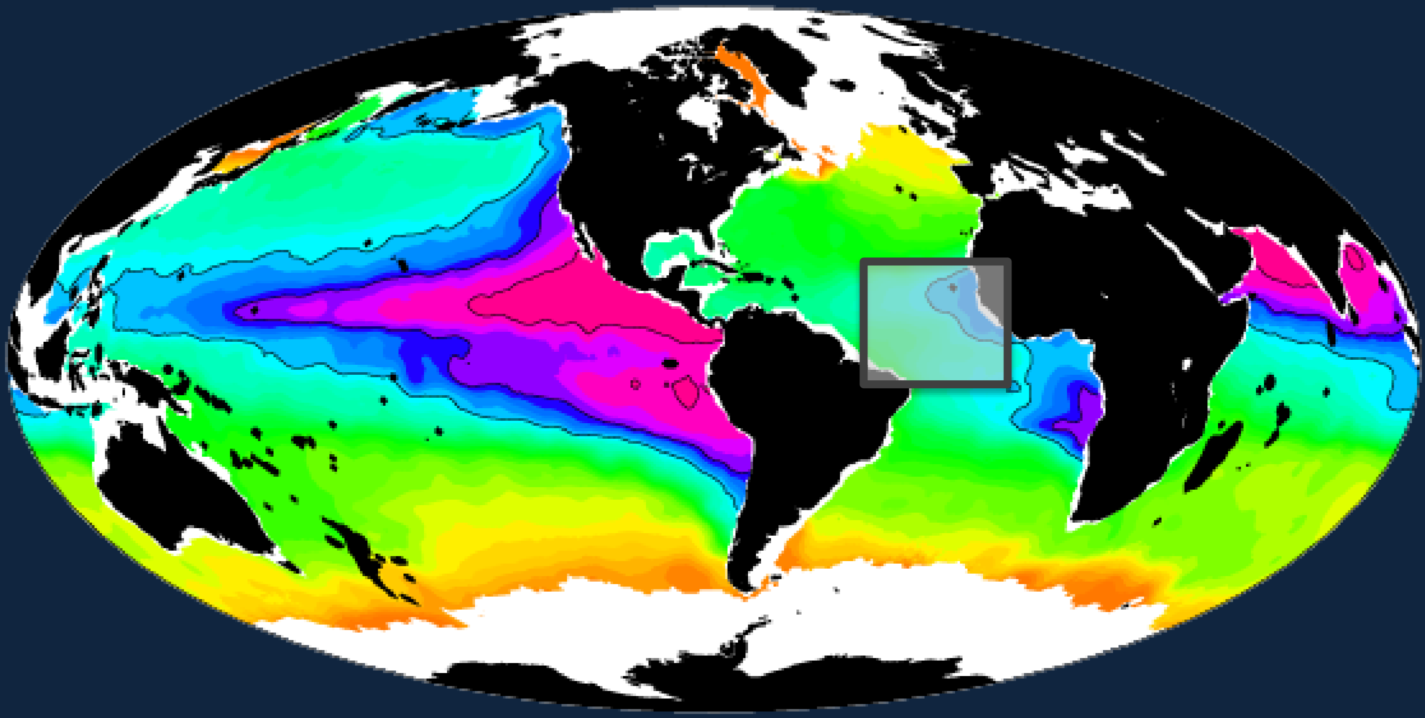

Eddy-driven oxygen supply to the eastern tropical North Atlantic

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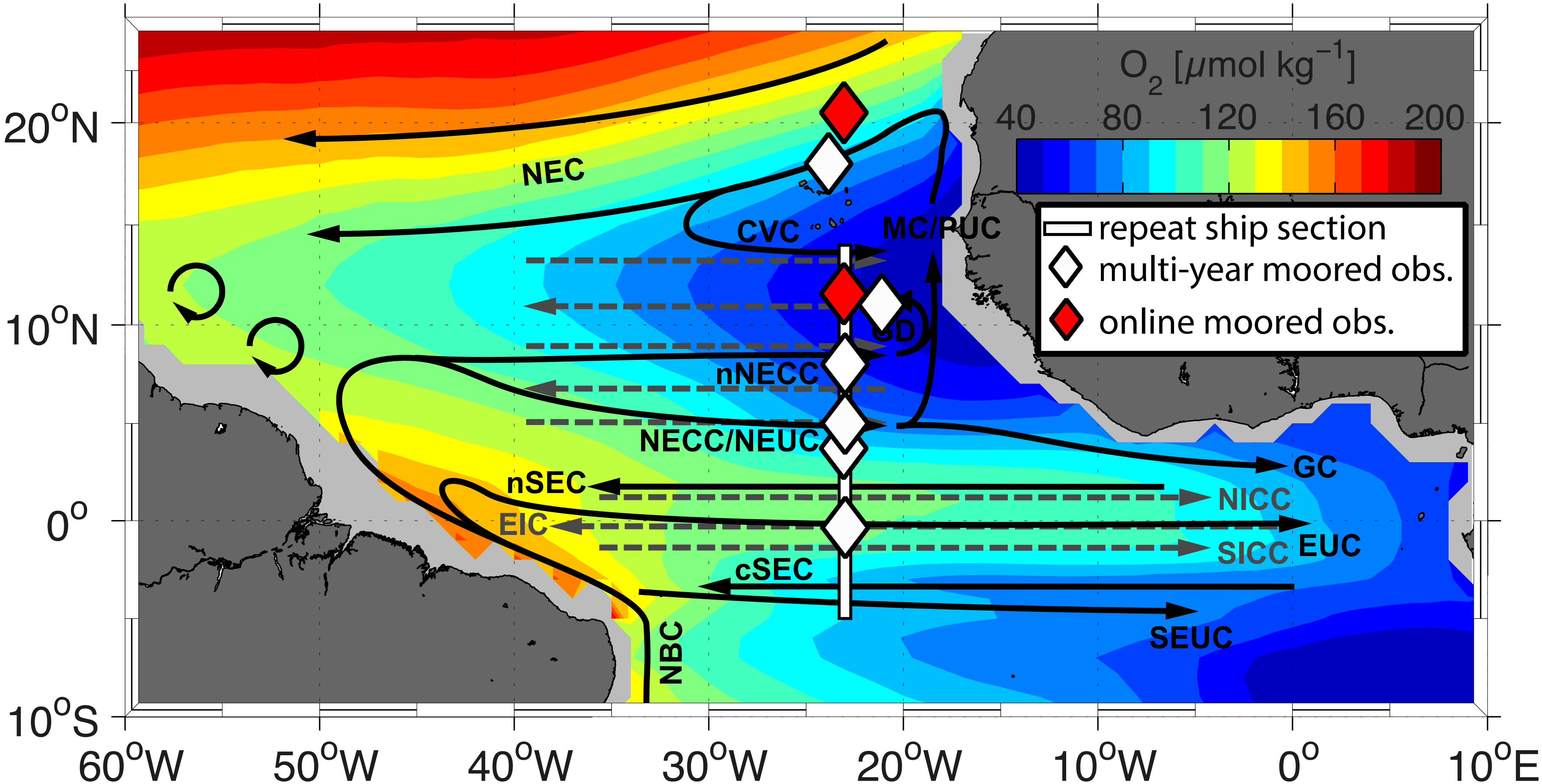
GEOMAR
Helmholtz Centre for Ocean Research Kiel

PIRATA-23 Meeting
Marseille
23.10.2018

SFB 754

Oxygen distribution and circulation in the tropical Atlantic

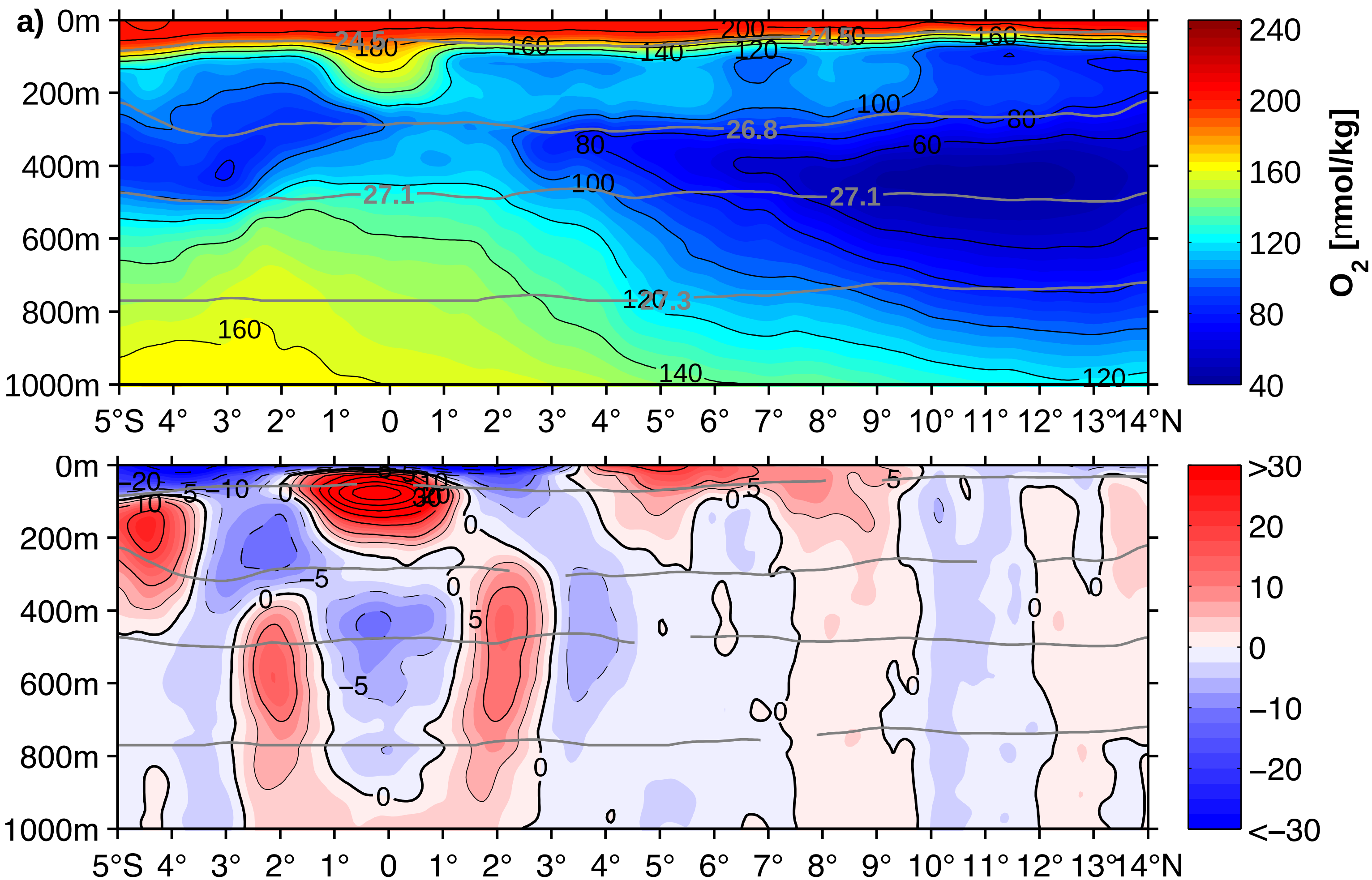


adapted from Hahn et al. (2017)

Oxygen distribution and circulation in the eastern tropical North Atlantic

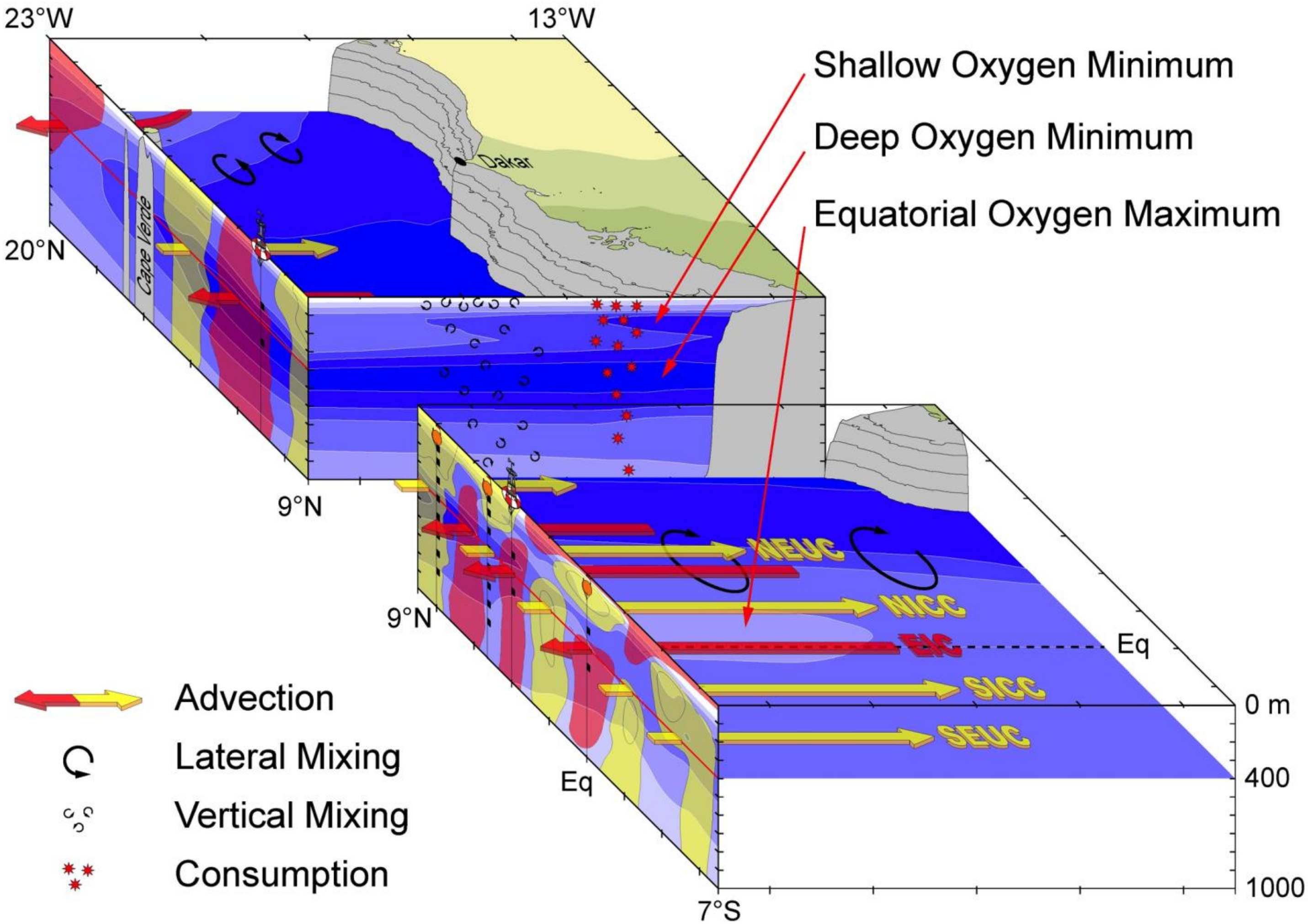
Oxygen

Zonal velocity



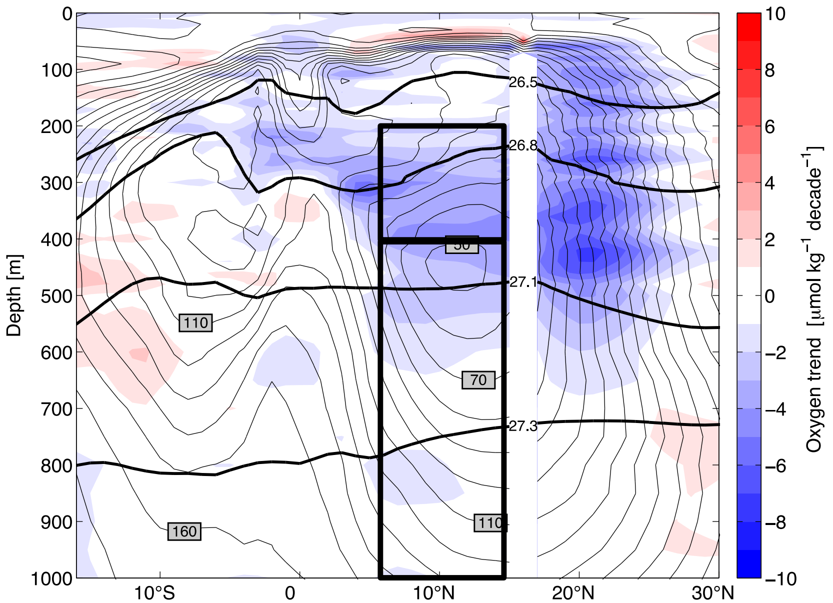
Brandt et al. (2015)

Ventilation pathways to the eastern tropical North Atlantic



Brandt et al. 2015

Multi-decadal and decadal O_2 trend along 23°W

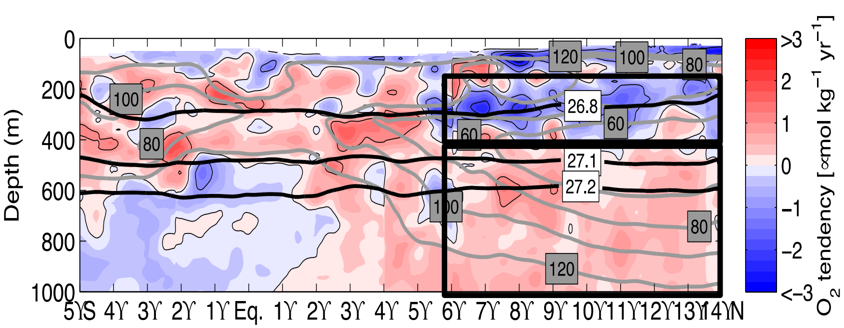


Brandt et al. (2015)

Multi-decadal (1972 – 2013):

200m – 400m: -2.9 µmol kg^{-1} $decade^{-1}$

400m – 1000m: -1.5 µmol kg^{-1} $decade^{-1}$



after Hahn et al. (2017)

Decadal (2006 – 2015):

200m – 400m: -6.2 µmol kg^{-1} $decade^{-1}$

400m – 1000m: +4.1 µmol kg^{-1} $decade^{-1}$

O_2 budget with multi-decadal (1972-2013) O_2 trend

$$C + K_\rho \partial_{zz} O_2 + K_e \partial_{yy} O_2 + (-\underline{u} \cdot \nabla O_2) = \partial_t O_2$$

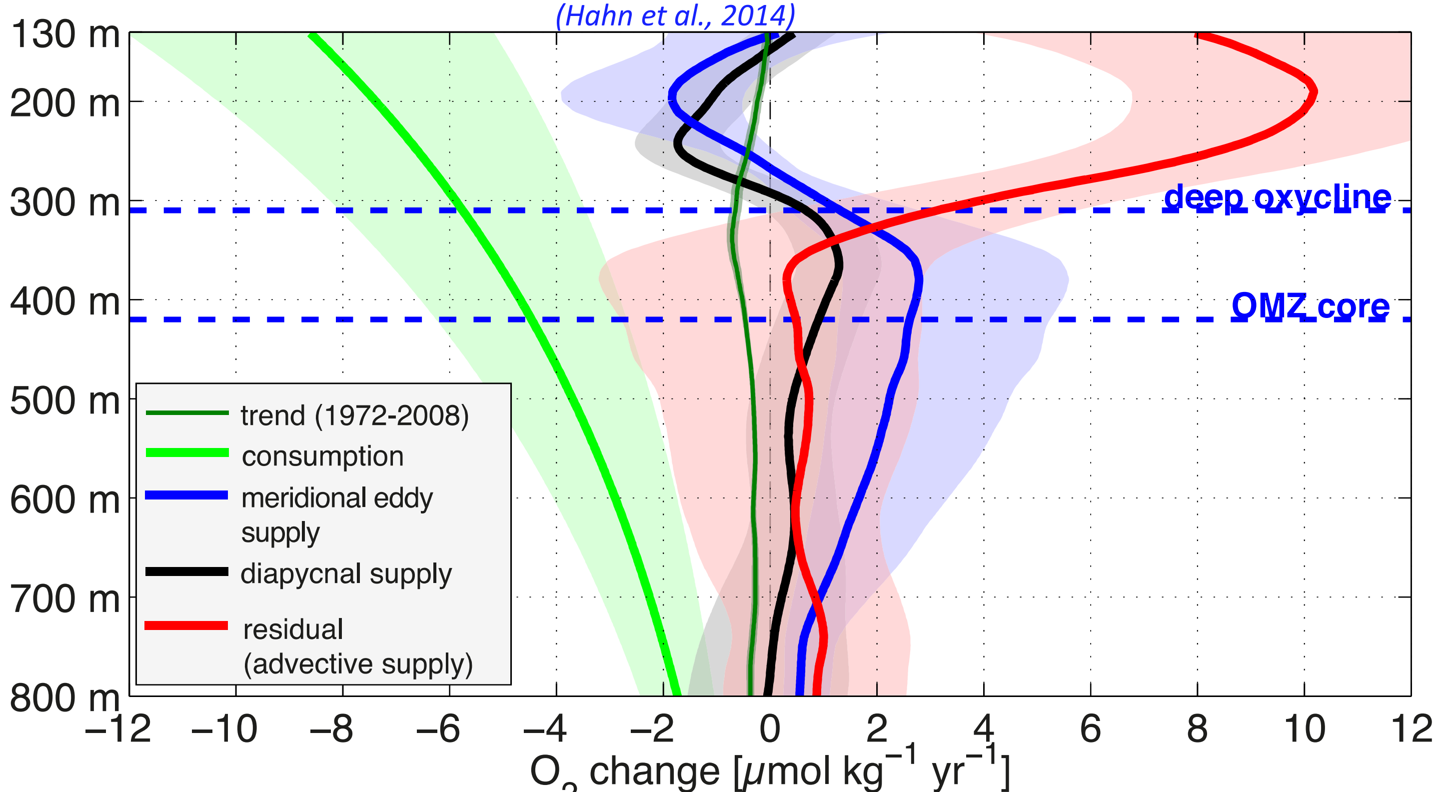
consumption (Karstensen et al., 2008)

diapycnal supply (Fischer et al., 2013)

meridional eddy supply (Hahn et al., 2014)

residual (advective supply) (Hahn et al., 2014)

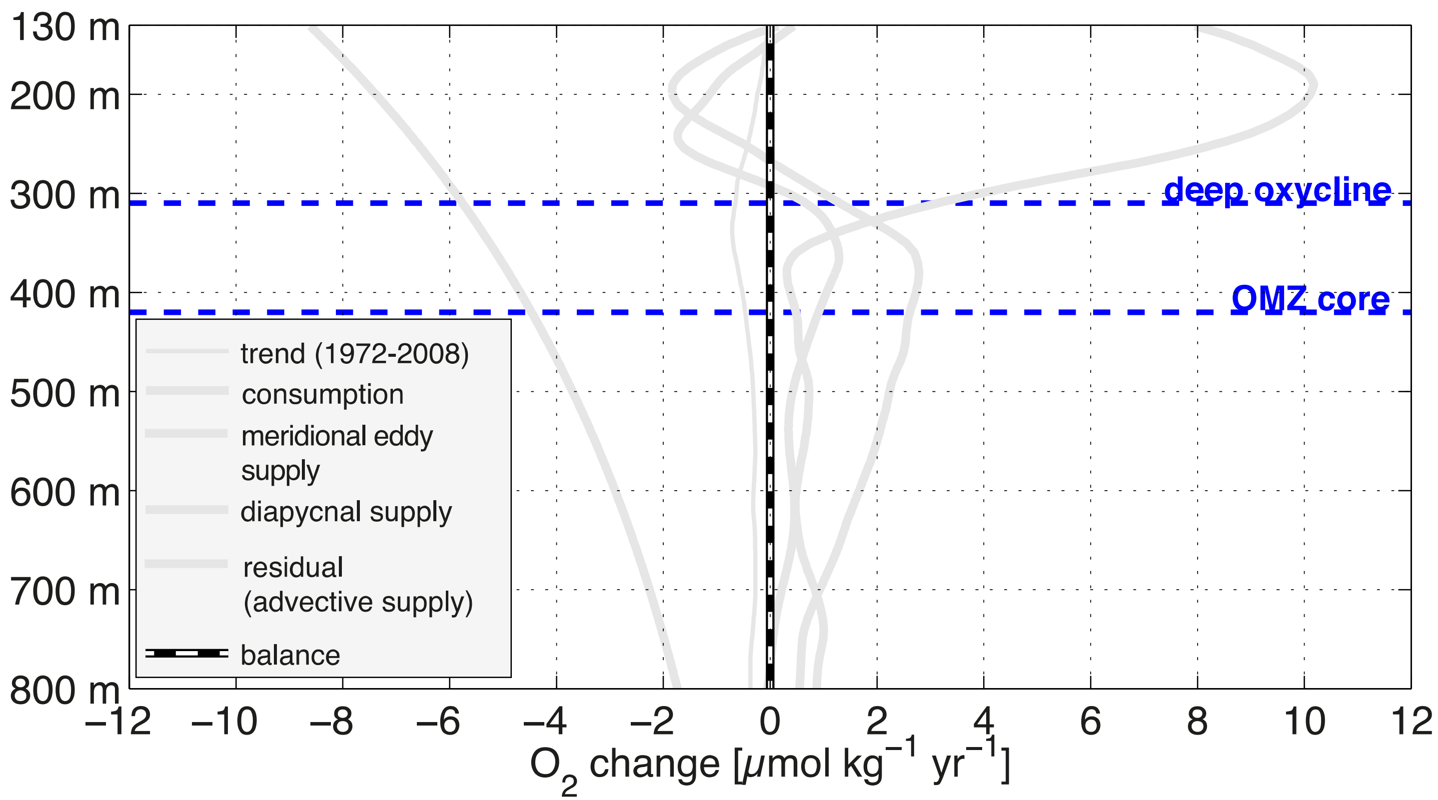
O_2 tendency (Brandt et al., 2010)



updated from Hahn et al. (2014) and Brandt et al. (2015)

O_2 budget with multi-decadal (1972-2013) O_2 trend

$$C + K_\rho \partial_{zz} O_2 + K_e \partial_{yy} O_2 + (-\underline{u} \cdot \nabla O_2) - \partial_t O_2 \overset{\text{def}}{=} 0$$ *(balance defined)*



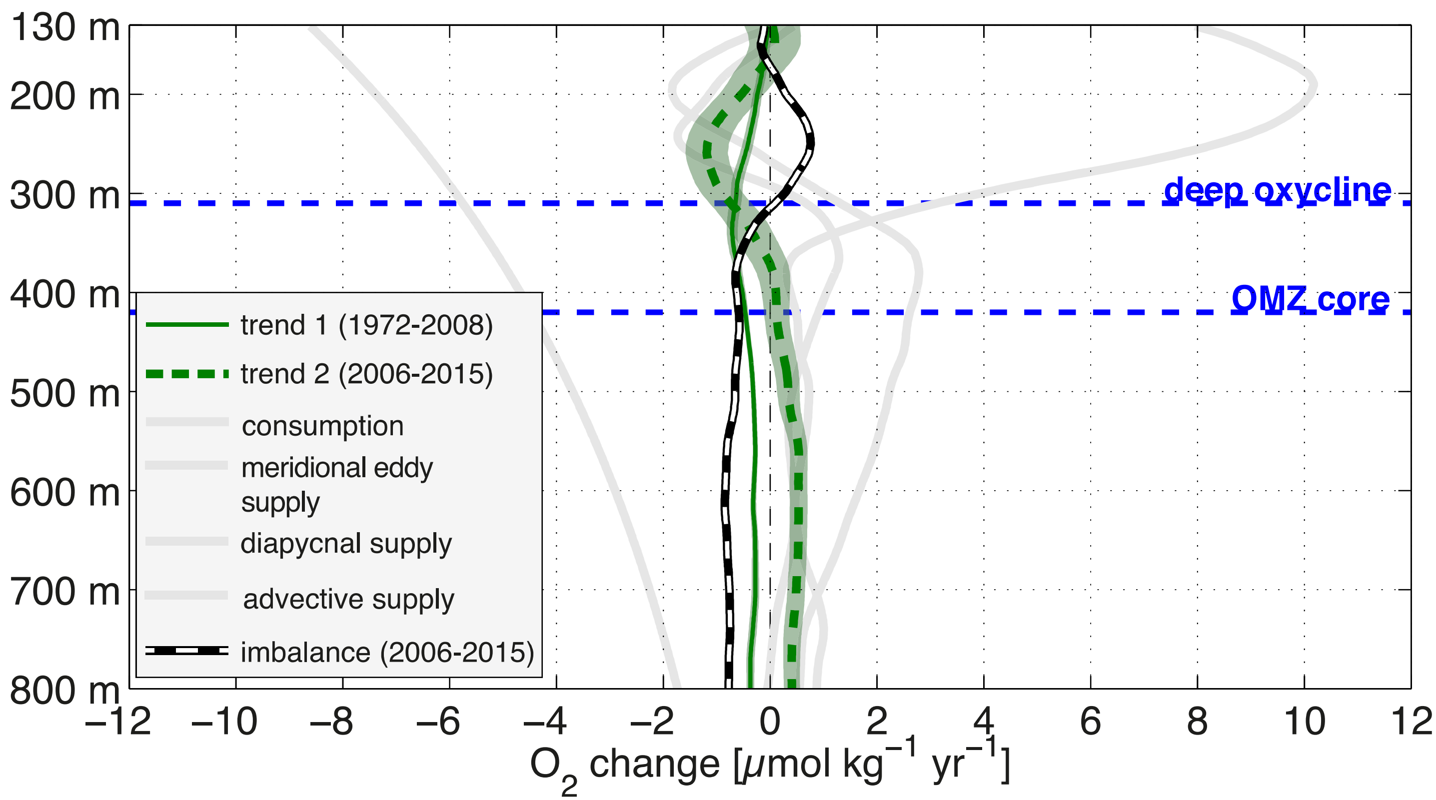
updated from Hahn et al. (2014) and Brandt et al. (2015)

O_2 budget (multi-decadal vs. decadal O_2 trend)

$$C + K_\rho \partial_{zz} O_2 + K_e \partial_{yy} O_2 + (-\underline{u} \cdot \nabla O_2) - (\partial_t O_2)^{(1)} \stackrel{\text{def}}{=} 0$$ *(balance defined)*

$$C + K_\rho \partial_{zz} O_2 + K_e \partial_{yy} O_2 + (-\underline{u} \cdot \nabla O_2) - (\partial_t O_2)^{(2)} \neq 0$$ *(imbalanced)*

(1) … period 1972-2008 (2) … period 2006-2015



adapted from Hahn et al. (2017)

O_2 budget (multi-decadal vs. decadal O_2 trend)

$$C + K_\rho \partial_{zz} O_2 + K_e \partial_{yy} O_2 + (-\underline{u} \cdot \nabla O_2) - (\partial_t O_2)^{(1)} \stackrel{\text{def}}{=} 0$$ *(balance defined)*

$$C^{(2)} + (K_\rho \partial_{zz} O_2)^{(2)} + (K_e \partial_{yy} O_2)^{(2)} + (-\underline{u} \cdot \nabla O_2)^{(2)} - (\partial_t O_2)^{(2)} \stackrel{?}{=} 0$$ *(consumption/ventilation changed?)*

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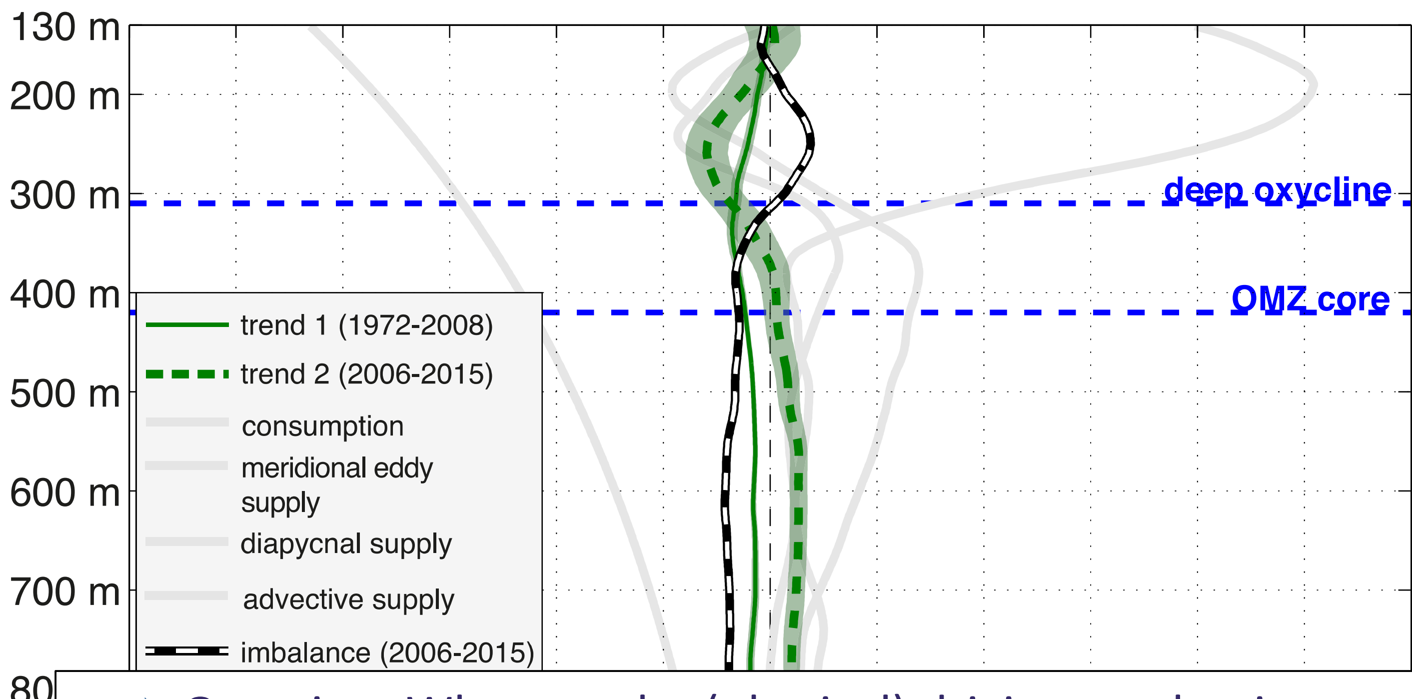

⇨ Question: What are the (physical) driving mechanisms for the decadal O_2 change?

O_2 budget (multi-decadal vs. decadal O_2 trend)

$$C + K_\rho \partial_{zz} O_2 + K_e \partial_{yy} O_2 + (-\underline{u} \cdot \nabla O_2) - (\partial_t O_2)^{(1)} \stackrel{\text{def}}{=} 0$$ *(balance defined)*

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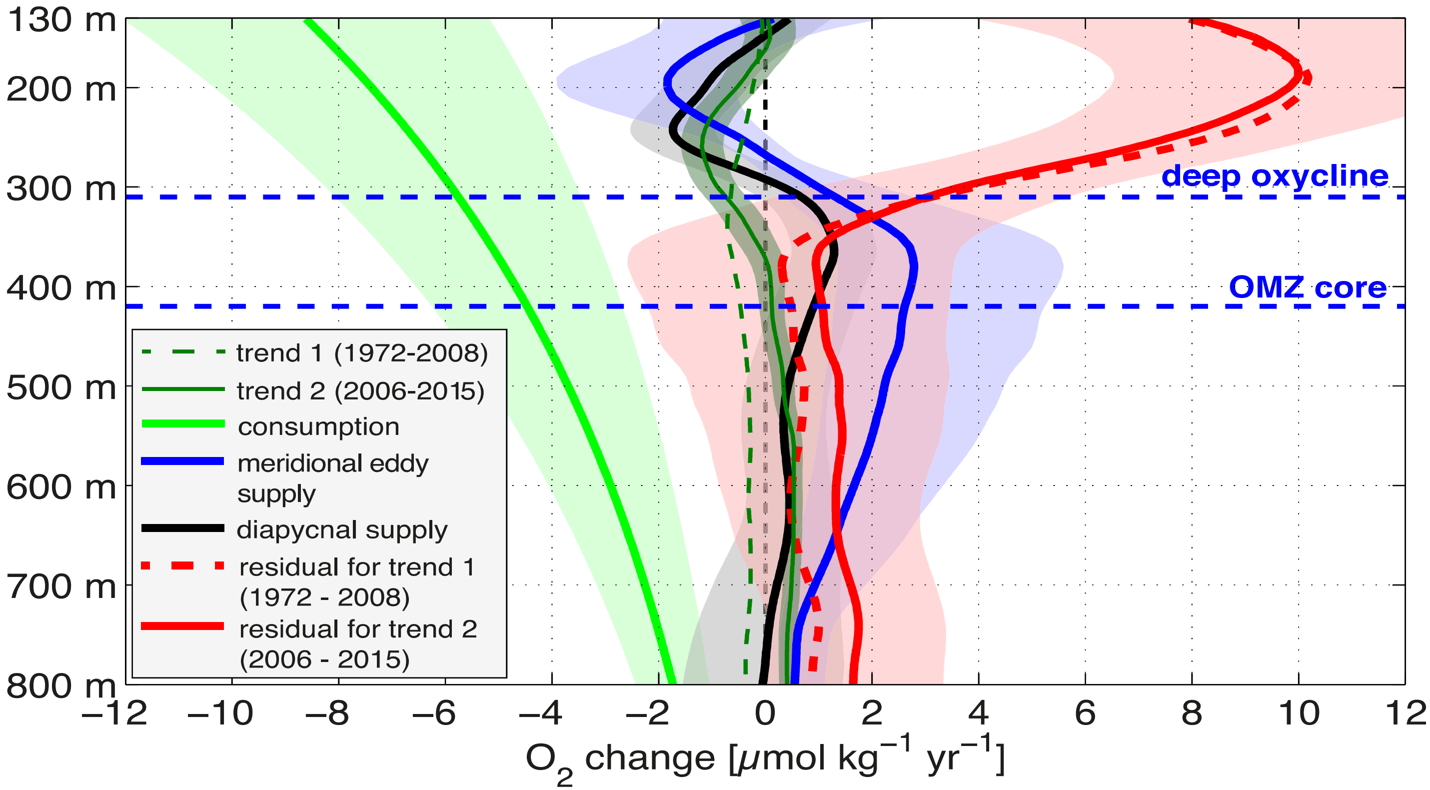

from Hahn et al. (2017)

O_2 budget (multi-decadal vs. decadal O_2 trend)

$$C + K_\rho \partial_{zz} O_2 + K_e \partial_{yy} O_2 + (-\underline{u} \cdot \nabla O_2) - (\partial_t O_2)^{(1)} \stackrel{\text{def}}{=} 0$$ *(balance defined)*

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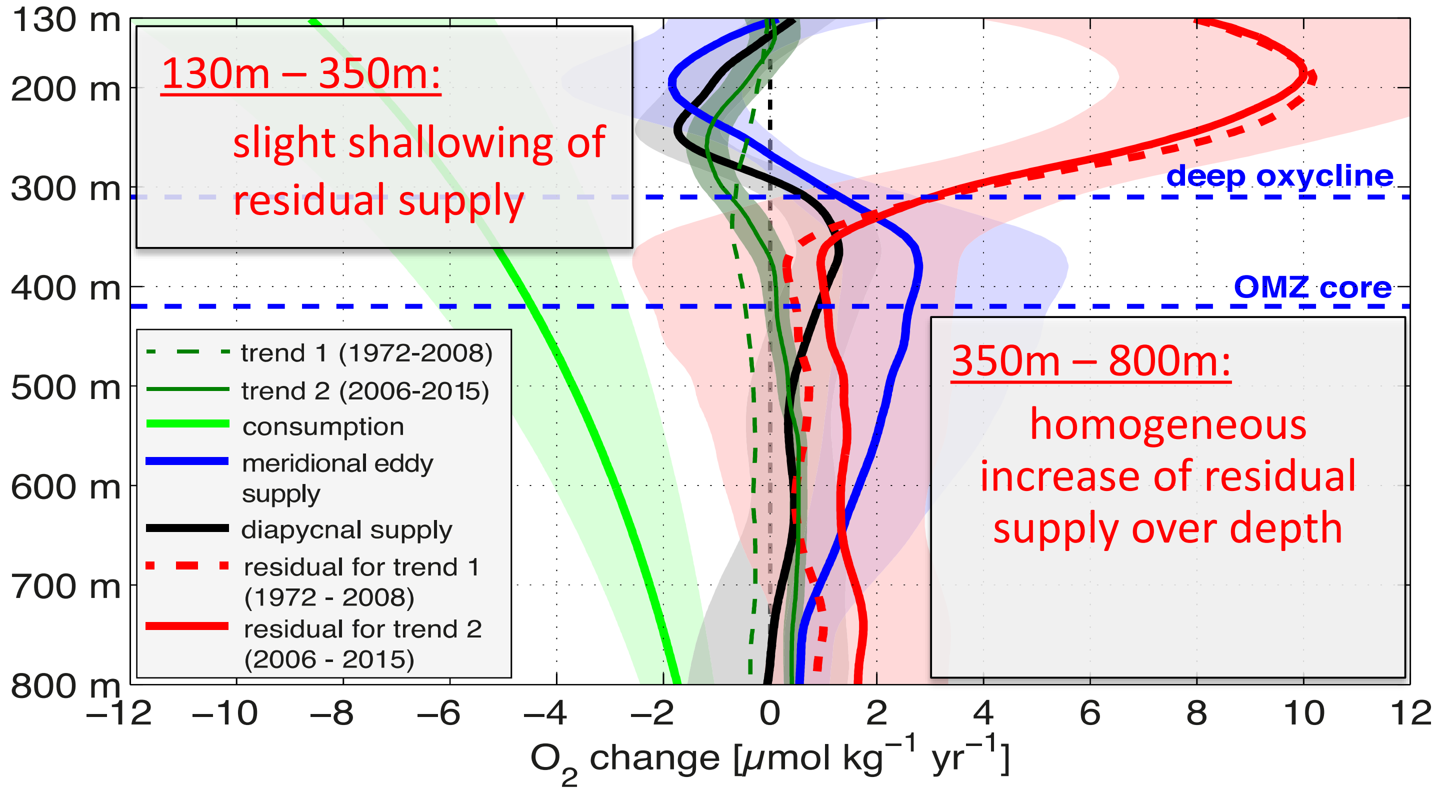

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O_2 budget (multi-decadal vs. decadal O_2 trend)

$$C + K_\rho \partial_{zz} O_2 + K_e \partial_{yy} O_2 + (-\underline{u} \cdot \nabla O_2) - (\partial_t O_2)^{(1)} \stackrel{\text{def}}{=} 0$$ *(balance defined)*

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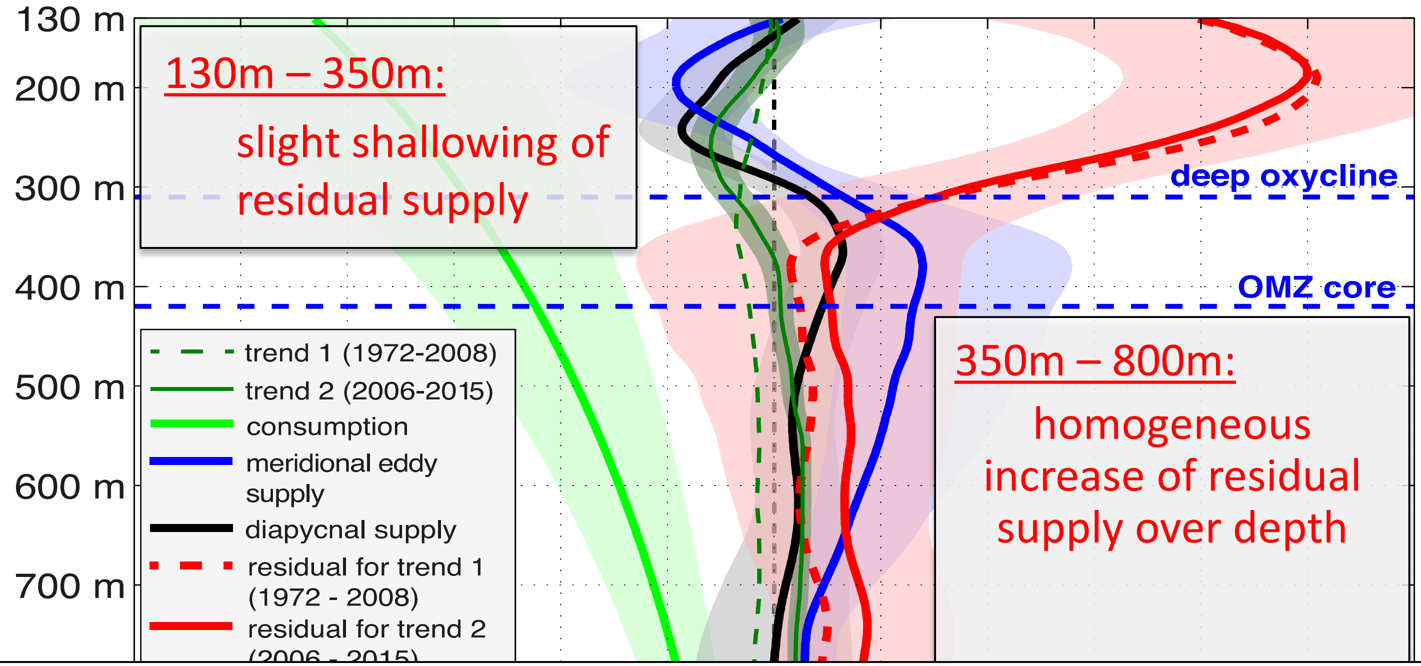

⇨ changes in advective oxygen supply have likely contributed to decadal oxygen change (but: high uncertainty!)

O_2 budget (multi-decadal vs. decadal O_2 trend)

$C + K_\rho \partial_{zz} O_2 + K_e \partial_{yy} O_2 + (-\underline{u} \cdot \nabla O_2) - (\partial_t O_2)^{(1)} \stackrel{\text{def}}{=} 0$ *(balance defined)*

$C^{(2)} + (K_\rho \partial_{zz} O_2)^{(2)} + (K_e \partial_{yy} O_2)^{(2)} + (-\underline{u} \cdot \nabla O_2)^{(2)} - (\partial_t O_2)^{(2)} \stackrel{?}{=} 0$ *(consumption/ventilation changed?)*

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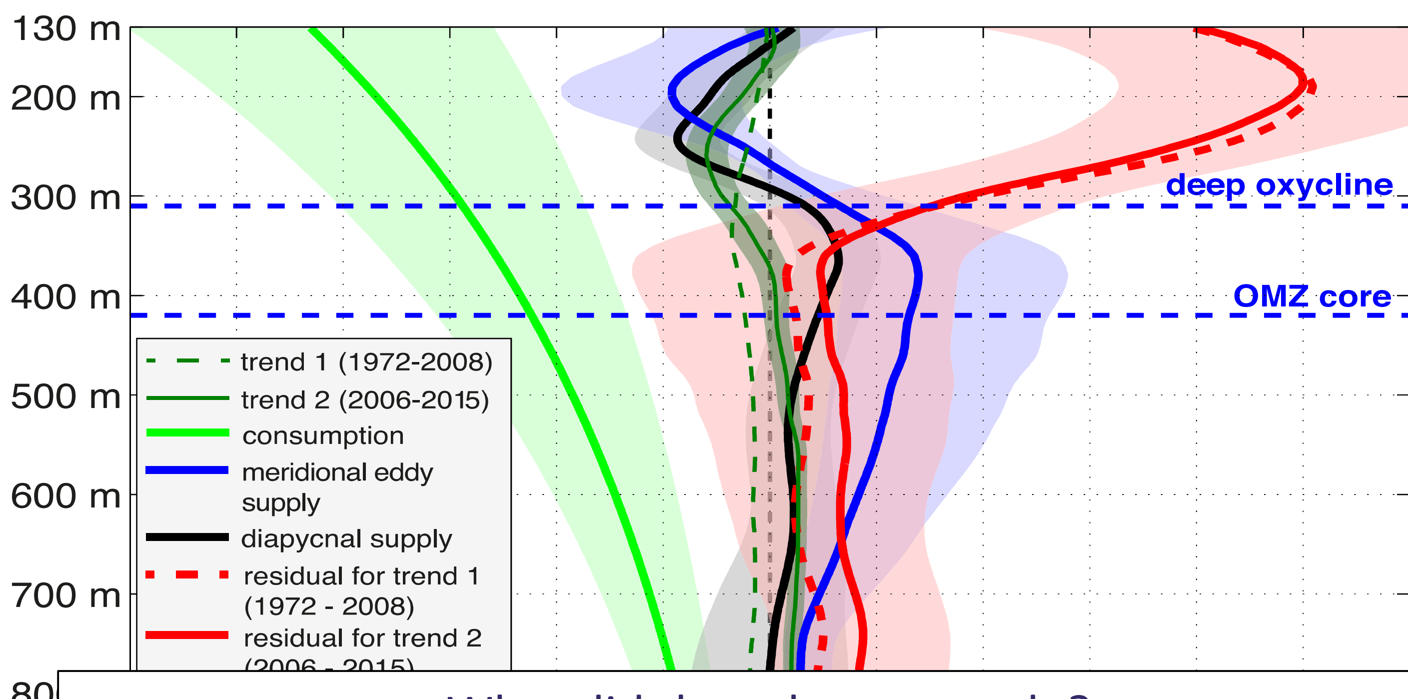


What did the other terms do?

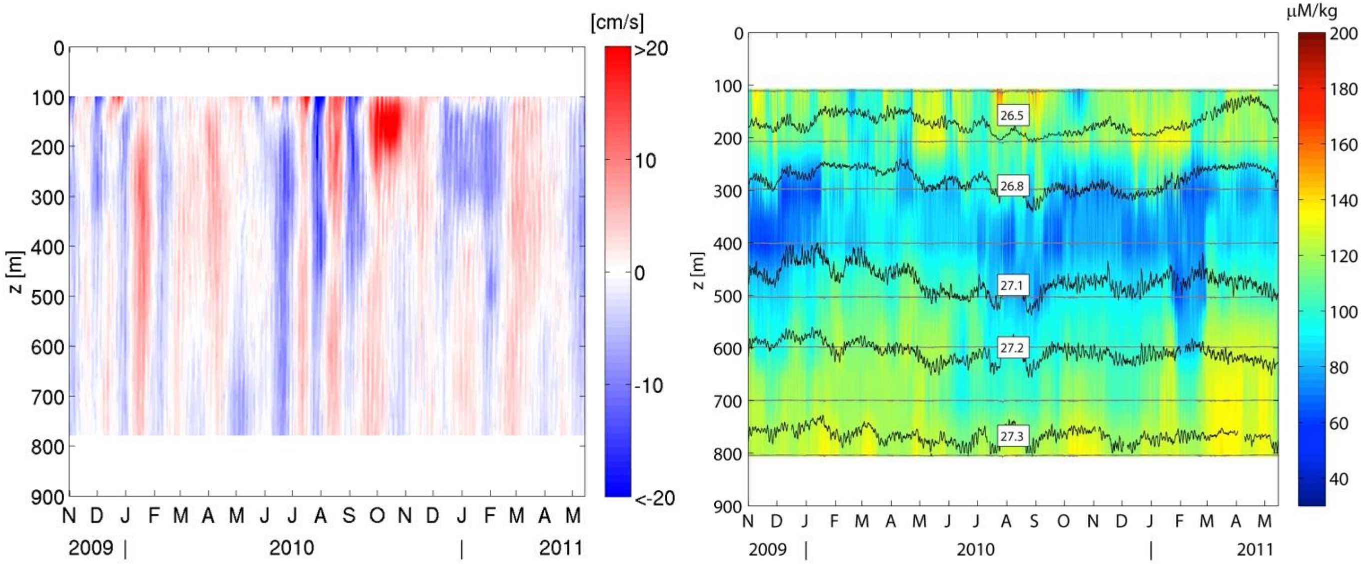
⇨ Here: Consider changes in eddy supply!

Two methods to estimate the eddy-driven oxygen flux (*Hahn et al. 2014*)

(I) Eddy flux correlation

$$F_{O_2}^{(1)} = \langle v' O_2 ' \rangle$$

→ analysis based on moored observations



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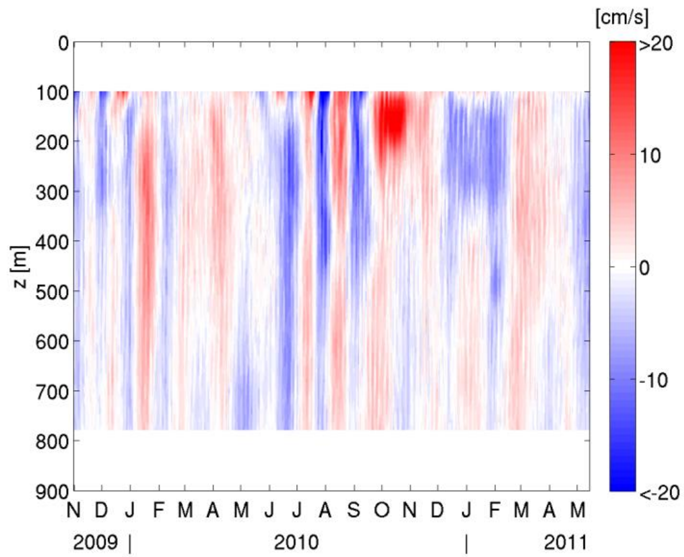
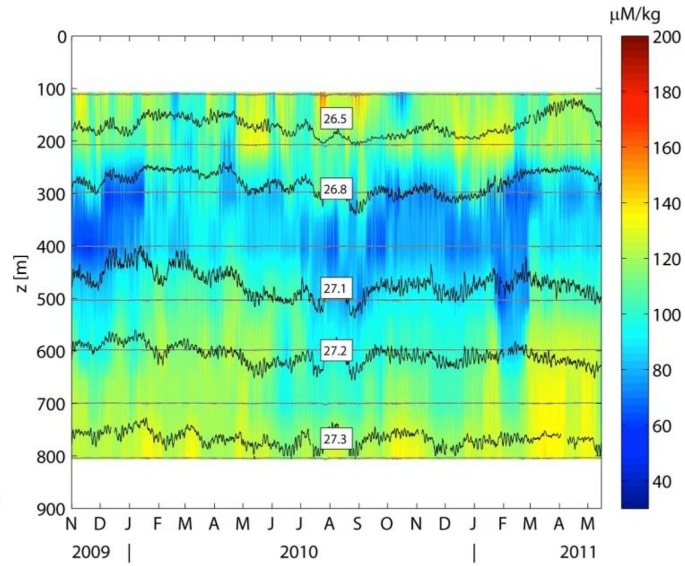
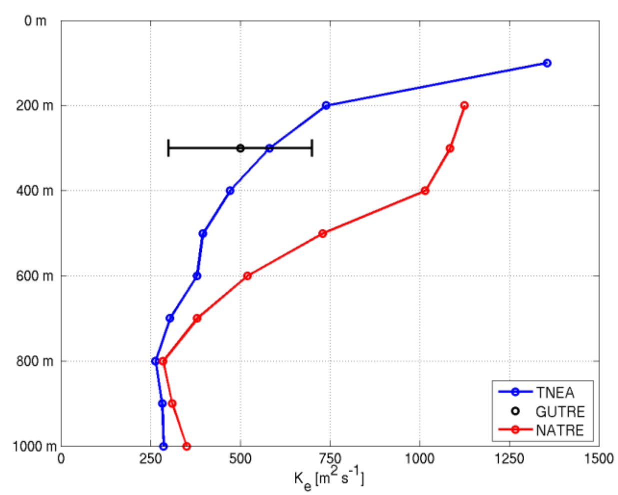


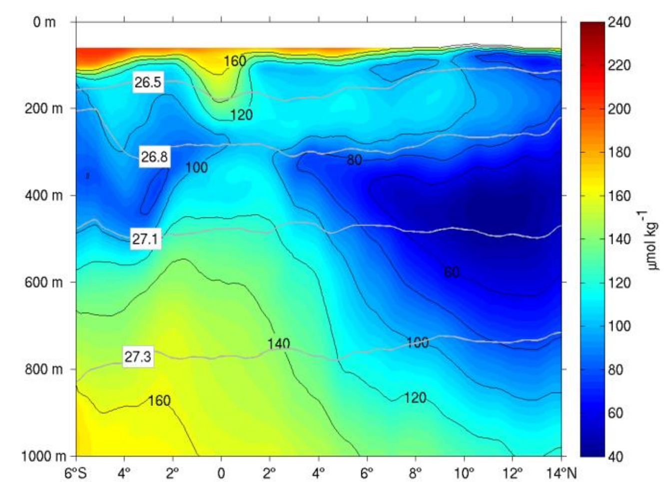


(II) Flux gradient parametrization

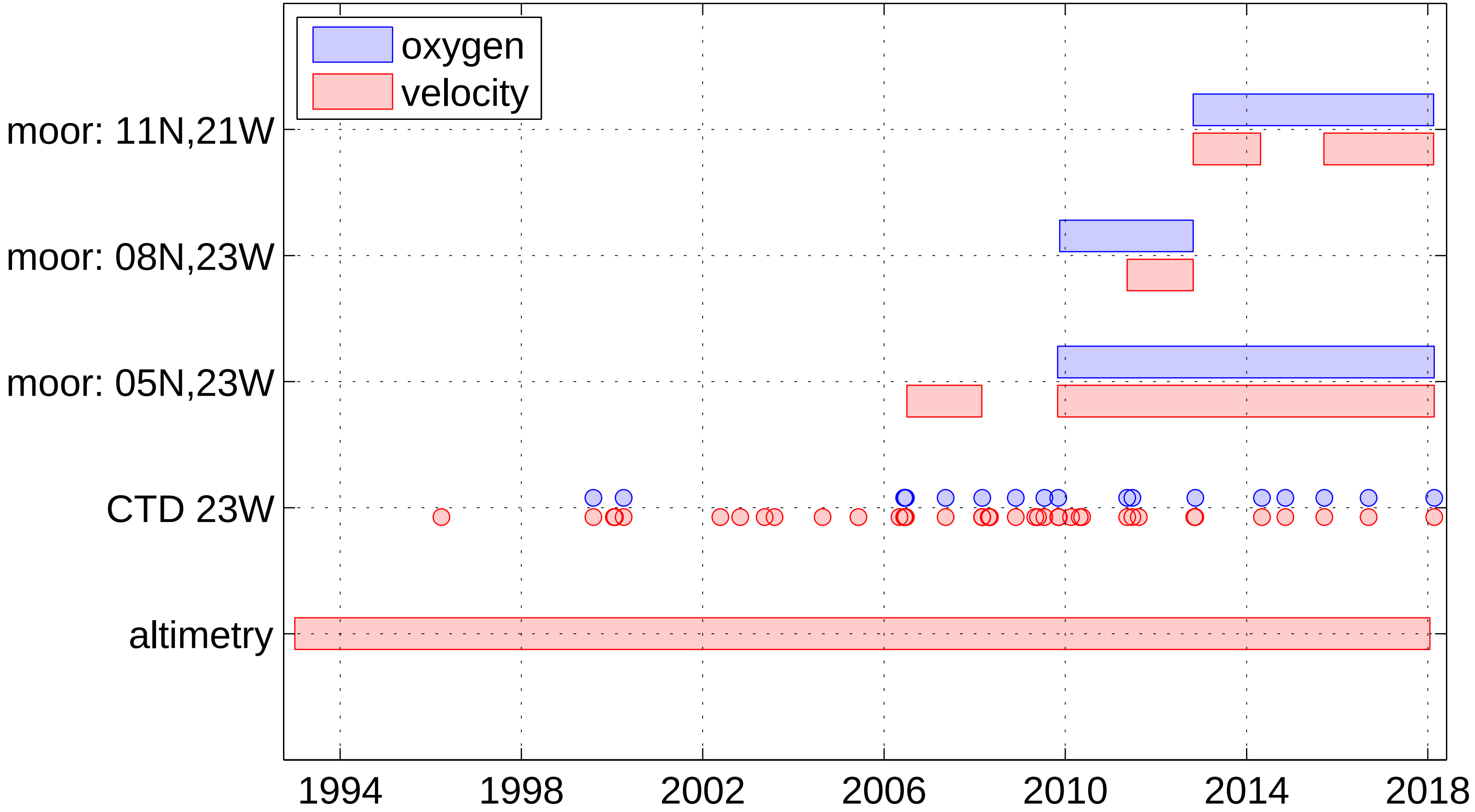
$$F_{O_2}^{(2)} = - K_e \frac{dO_2}{dy}$$

→ analysis based on repeat ship sections

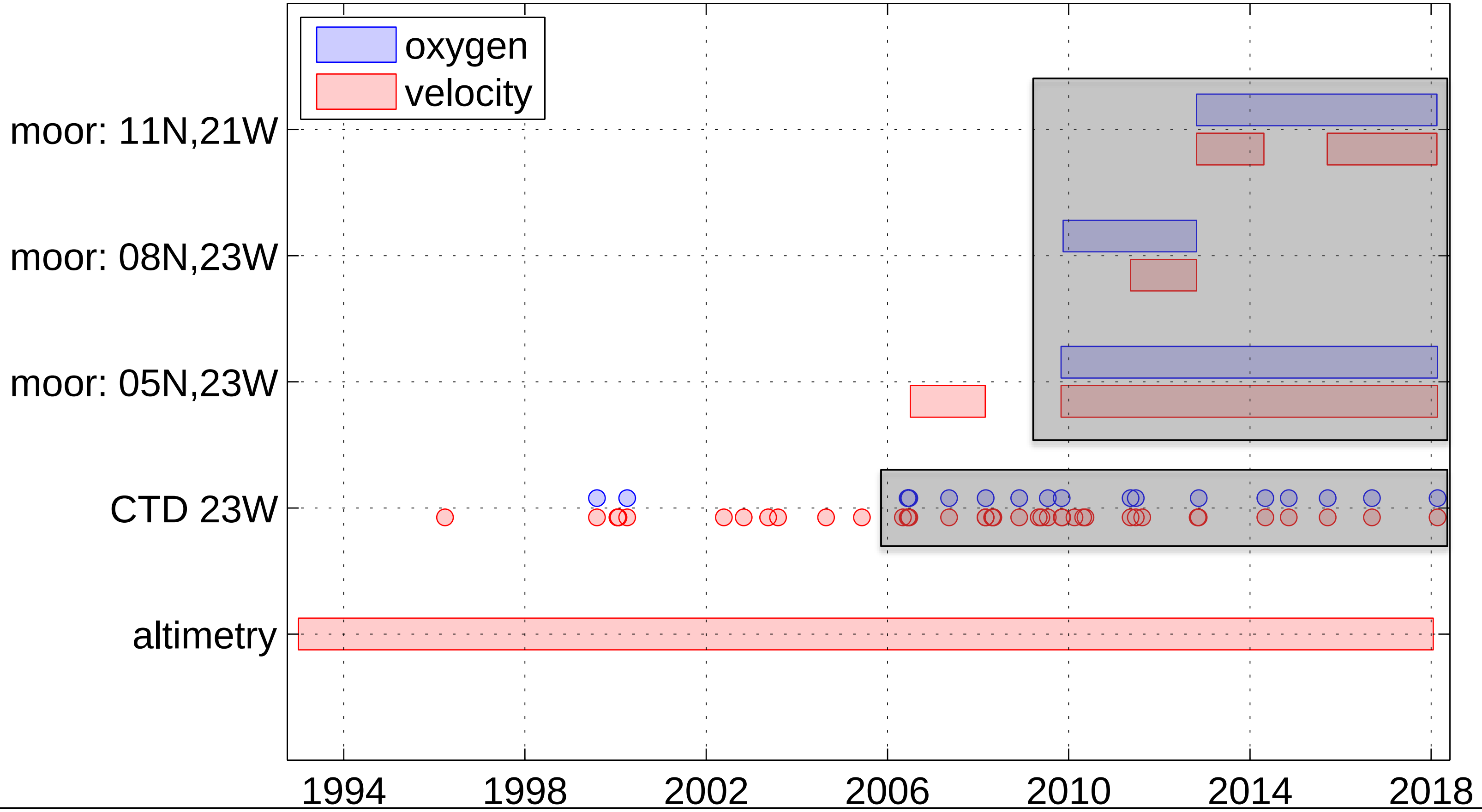




Temporal coverage of moored and shipboard observations

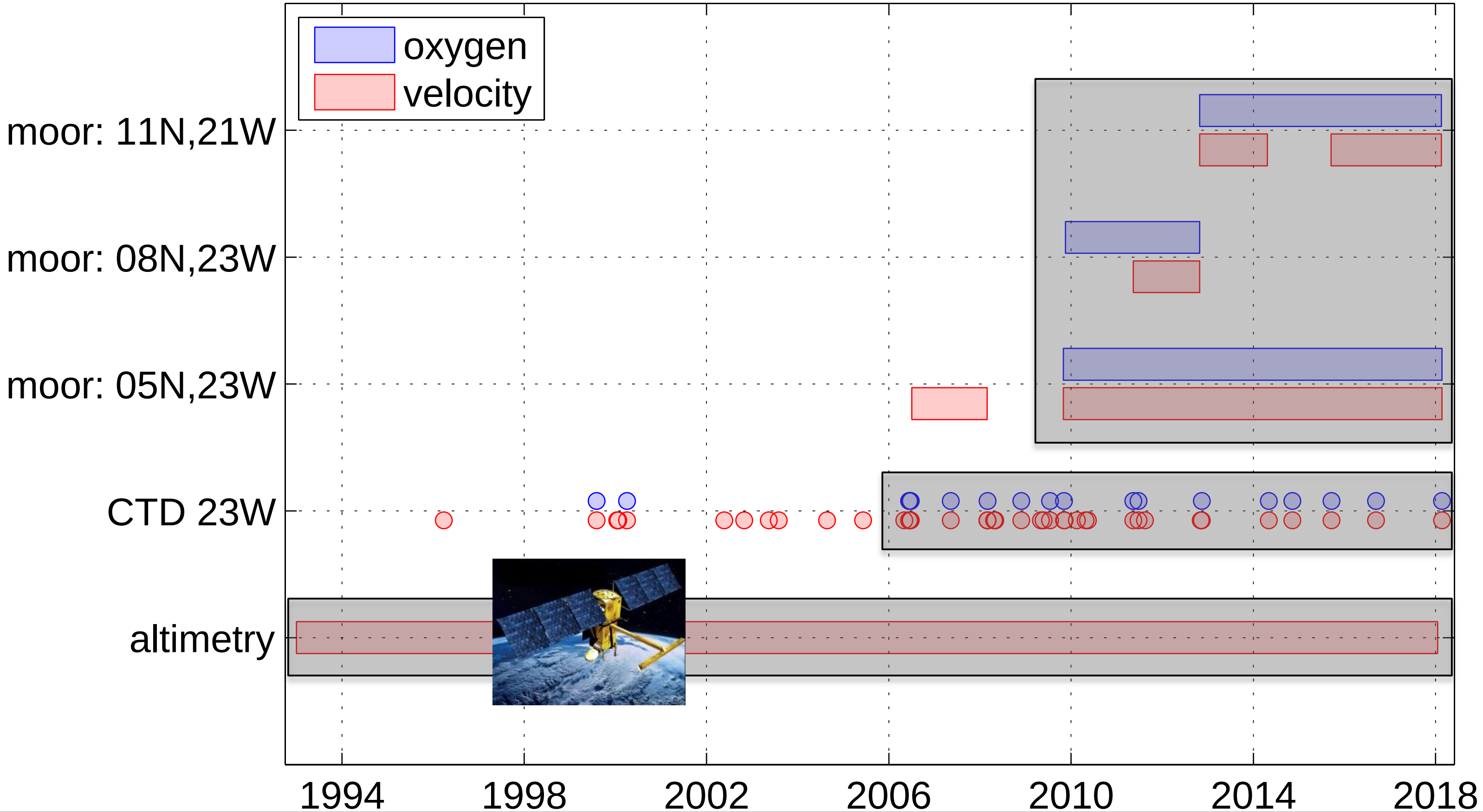


Temporal coverage of moored and shipboard observations



Moorings + shipsec ⇨ **time-mean** eddy-driven oxygen supply (after *Hahn et al. 2014*)

Temporal coverage of moored and shipboard observations



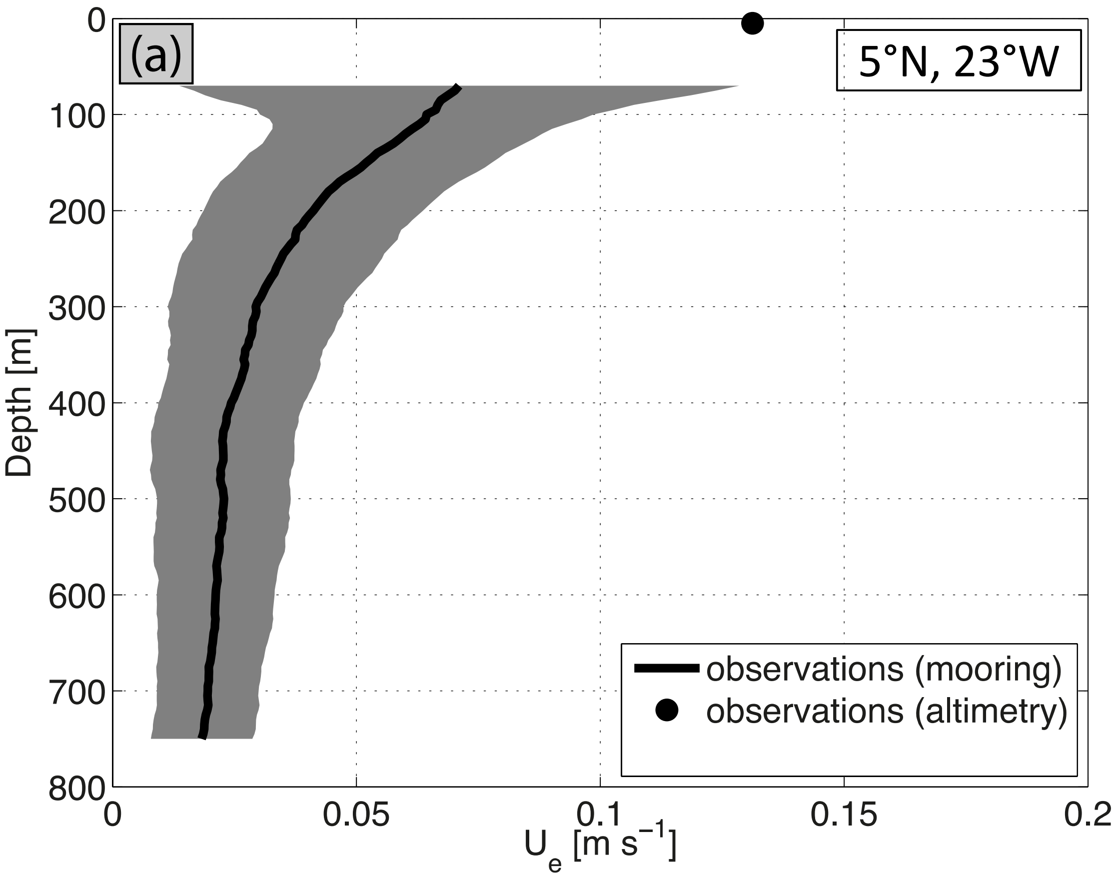
Moorings + shipsec ⇨ **time-mean** eddy-driven oxygen supply (after *Hahn et al. 2014*)

satellite observations ⇨ **temporally** varying eddy-driven oxygen supply (*here*)

Universal vertical structure of mesoscale eddies

$$H(z_s) = H_0 \cdot \sin(kz_s + \theta_0) + H_{ave}$$

(*Zhang et al. 2013*)



vertical structure function:

$$H(z_s)$$

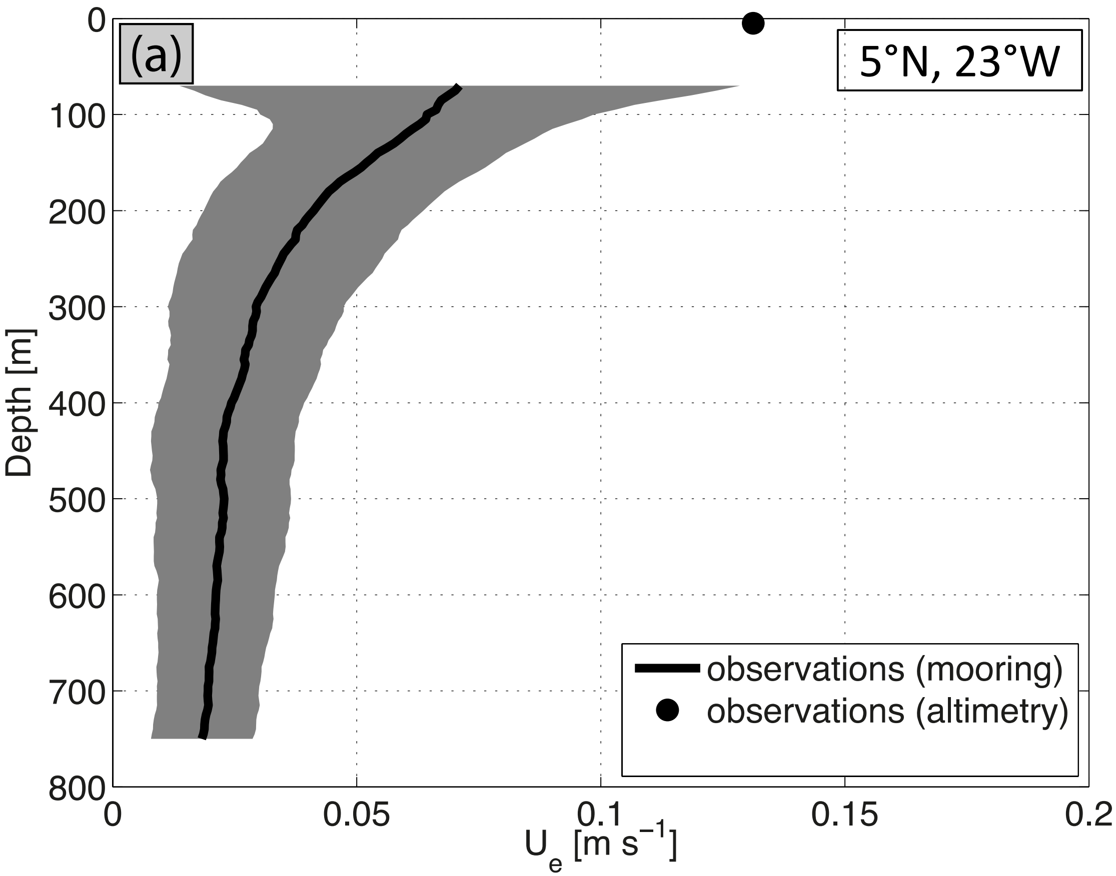
stretched coordinate:

$$z_s = \int_0^z (N/f)\,dz$$

Universal vertical structure of mesoscale eddies

$$H(z_s) = H_0 \cdot \sin(k z_s + \theta_0) + H_{ave}$$ (*Zhang et al. 2013*)

$$\propto U_e = \sqrt{EKE} = \sqrt{(u'^2 + v'^2)/2}$$



vertical structure function:

$$H(z_s)$$

stretched coordinate:

$$z_s = \int_0^z (N/f)\,dz$$

Characteristic eddy velocity:

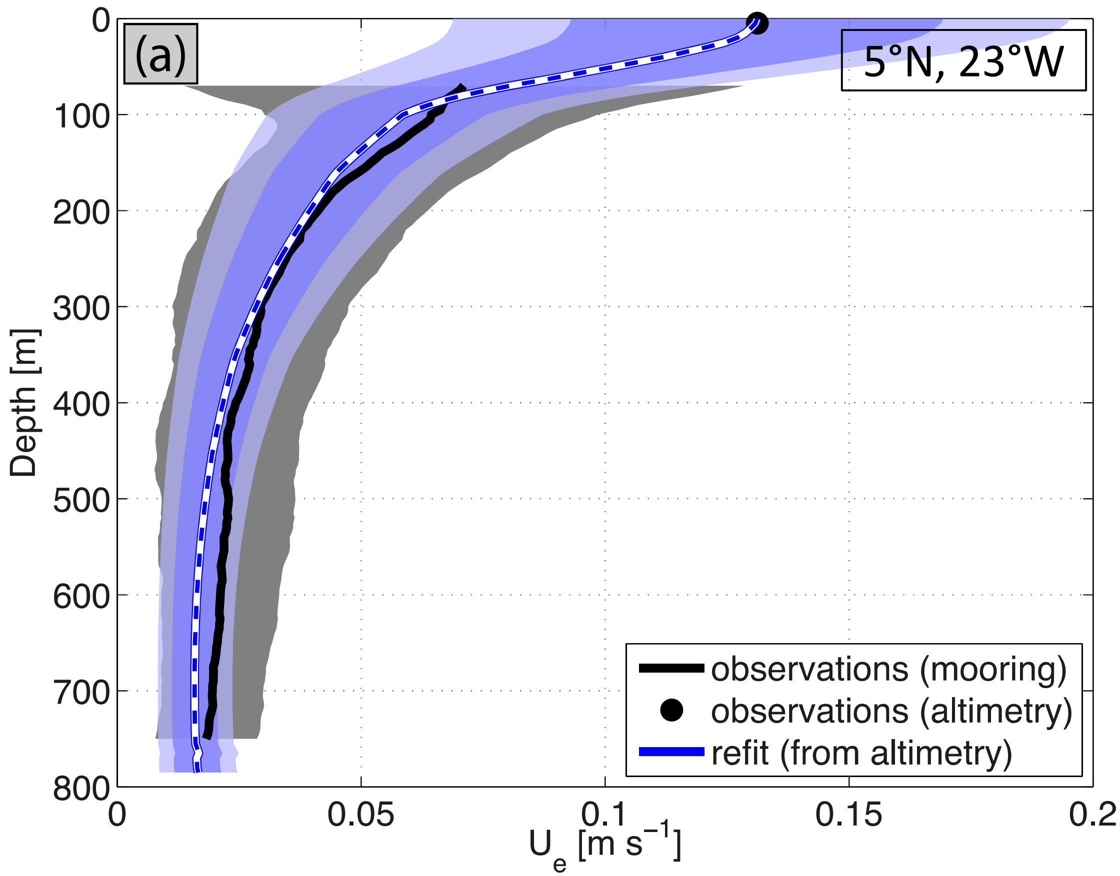
$$U_e$$

Universal vertical structure of mesoscale eddies

$$H(z_s) = H_0 \times \sin(kz_s + q_0) + H_{ave}$$

(*Zhang et al. 2013*)

$$\mu\, U_e = \sqrt{EKE} = \sqrt{(u'^2 + v'^2)/2}$$



<u>vertical structure function:</u>

$$H(z_s)$$

<u>stretched coordinate:</u>

$$z_s = \grave{\text{O}}_0^z (N/f)\,dz$$

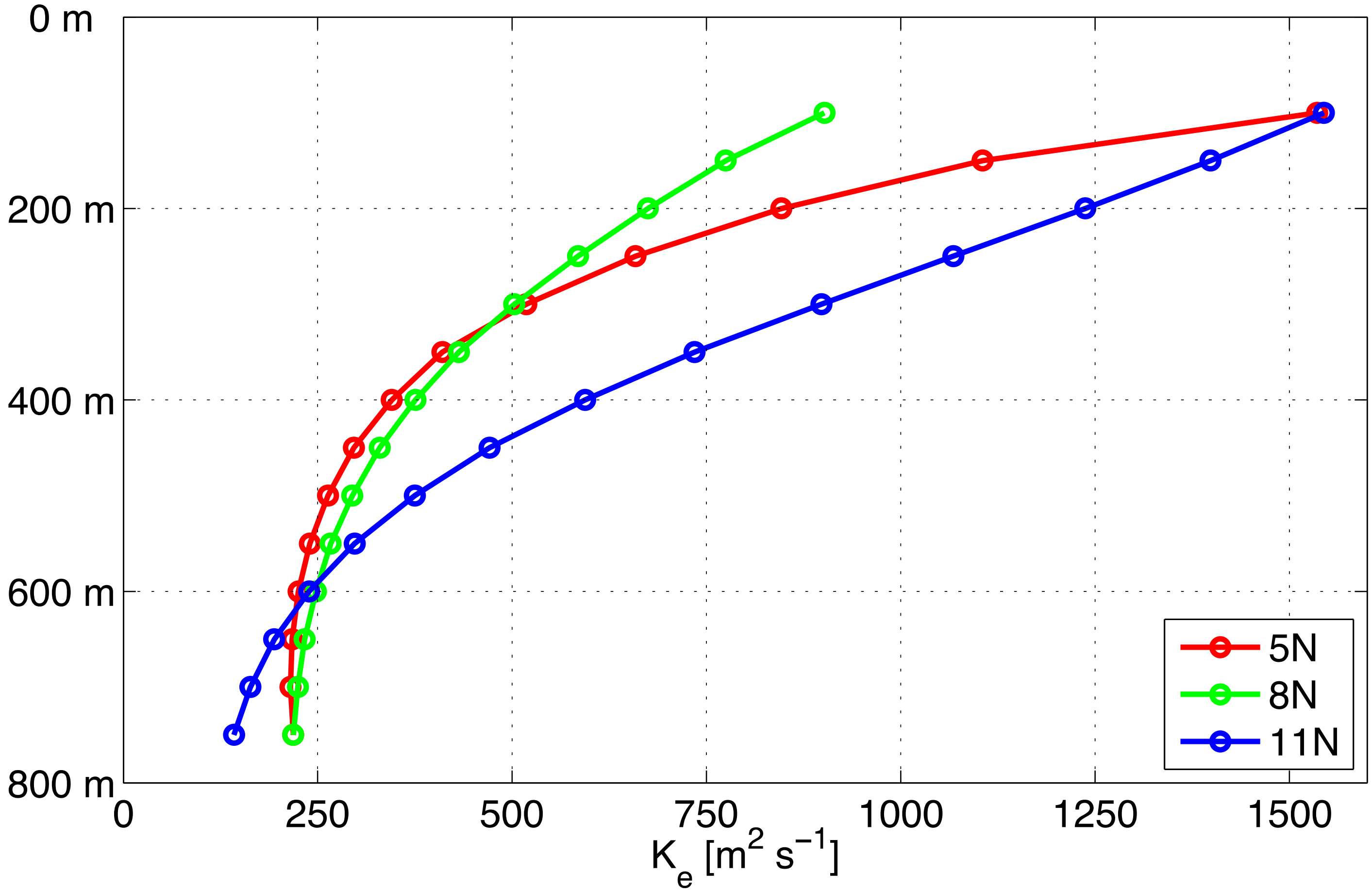
<u>Characteristic eddy velocity:</u>

$$U_e$$

Eddy diffusivity profiles from altimetry along 23°W

$$K_e = a\sqrt{U_e^3 / 2b}$$

(*Hahn et al. 2014*)



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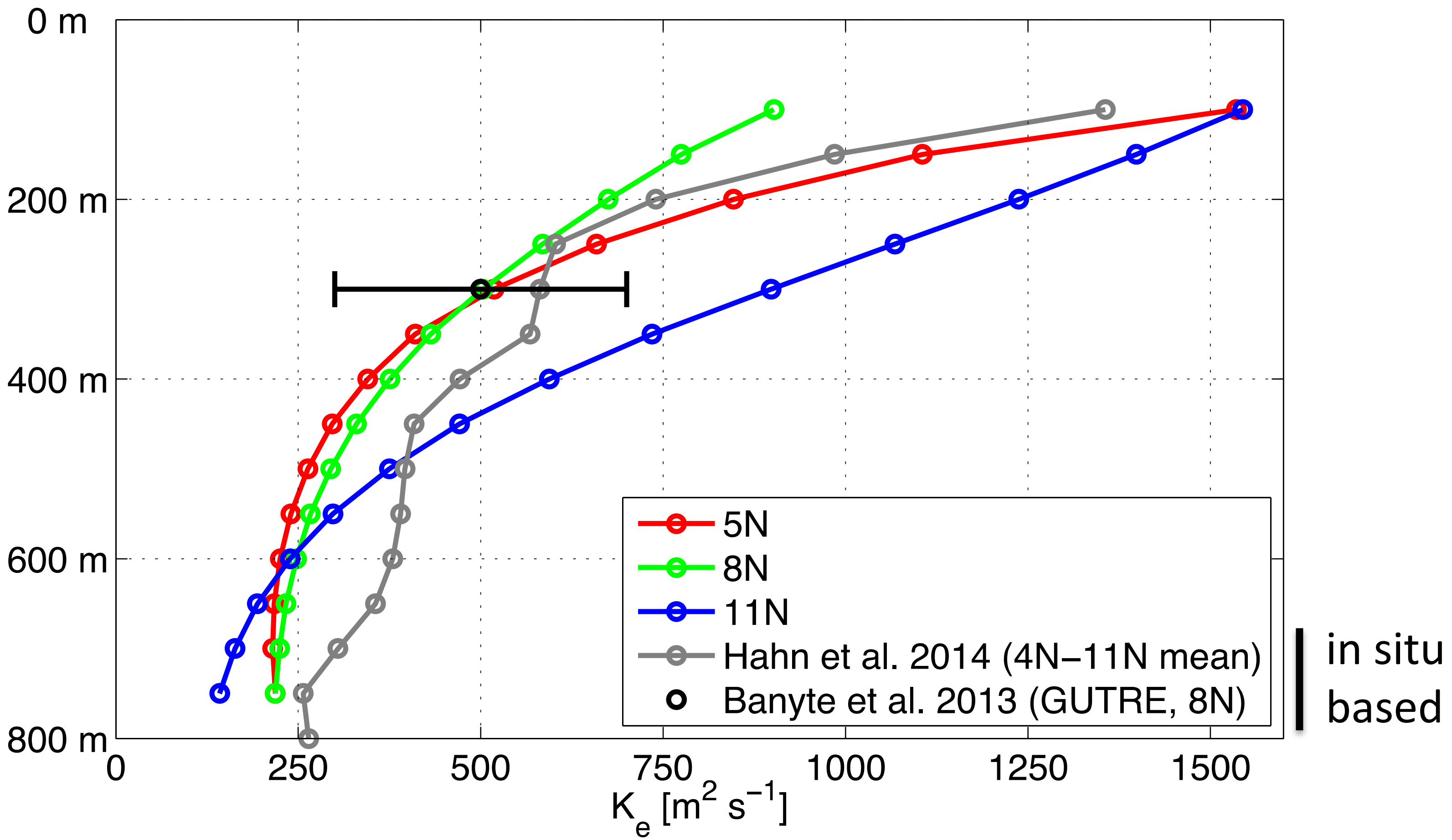
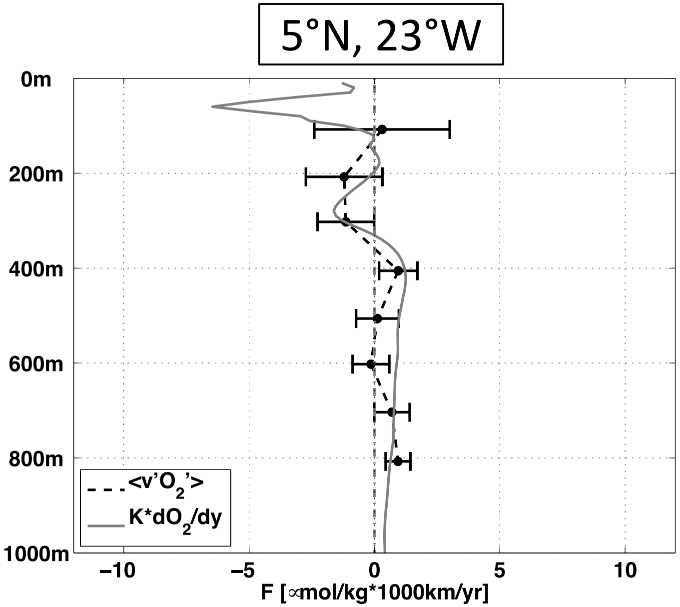


Meridional oxygen flux along 23°W

- two methods: (1) $F_{O_2}^{(1)} = \langle v' O_2' \rangle$ (2) $F_{O_2}^{(2)} = - K_e \frac{dO_2}{dy}$



$F > 0$ ⟹ northward flux

$F < 0$ ⟹ southward flux

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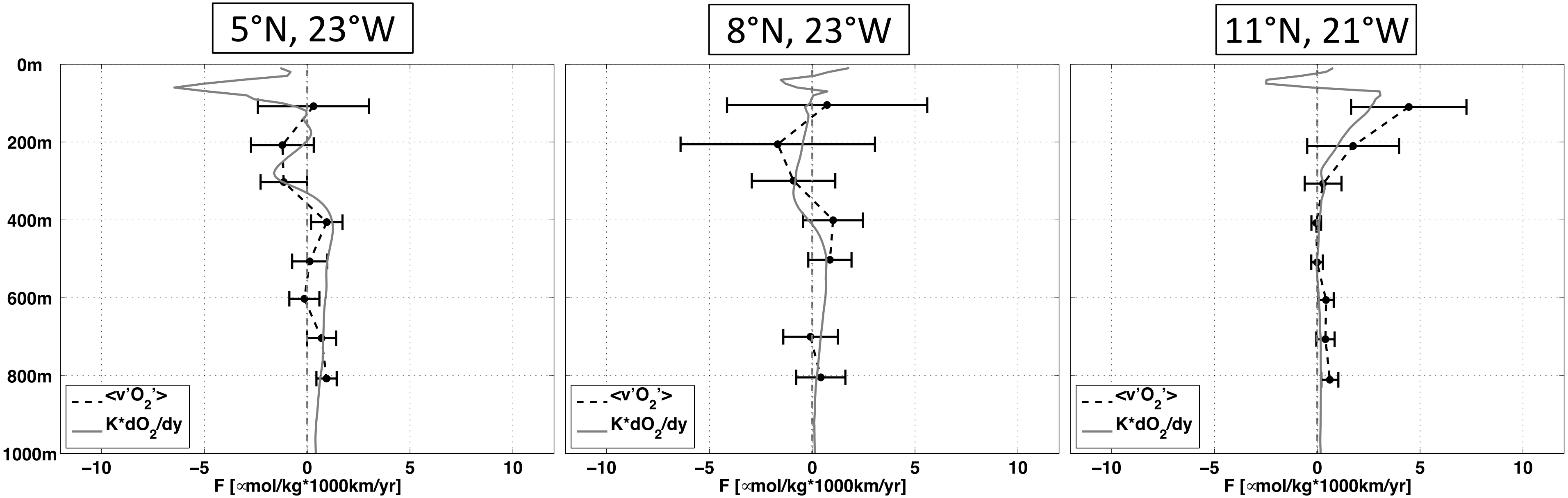


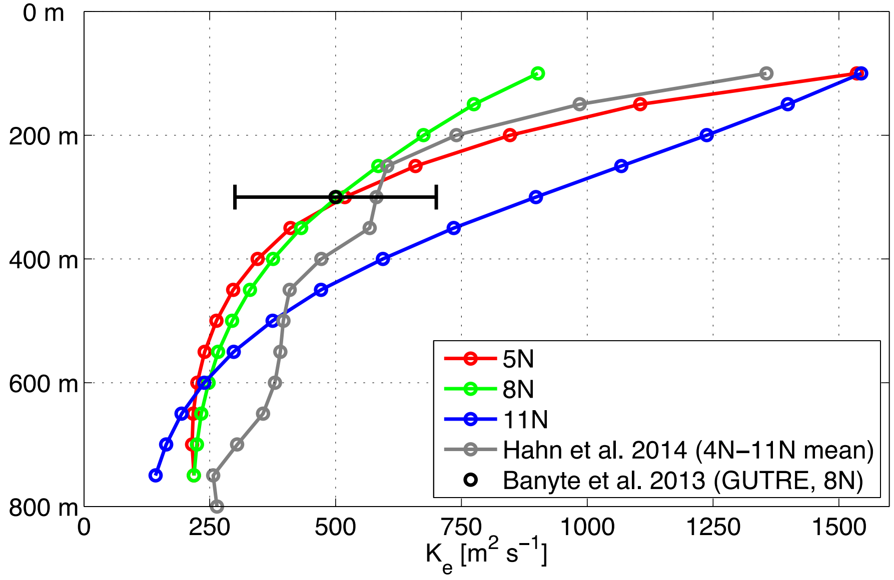
$F > 0$ ⟹ northward flux

$F < 0$ ⟹ southward flux

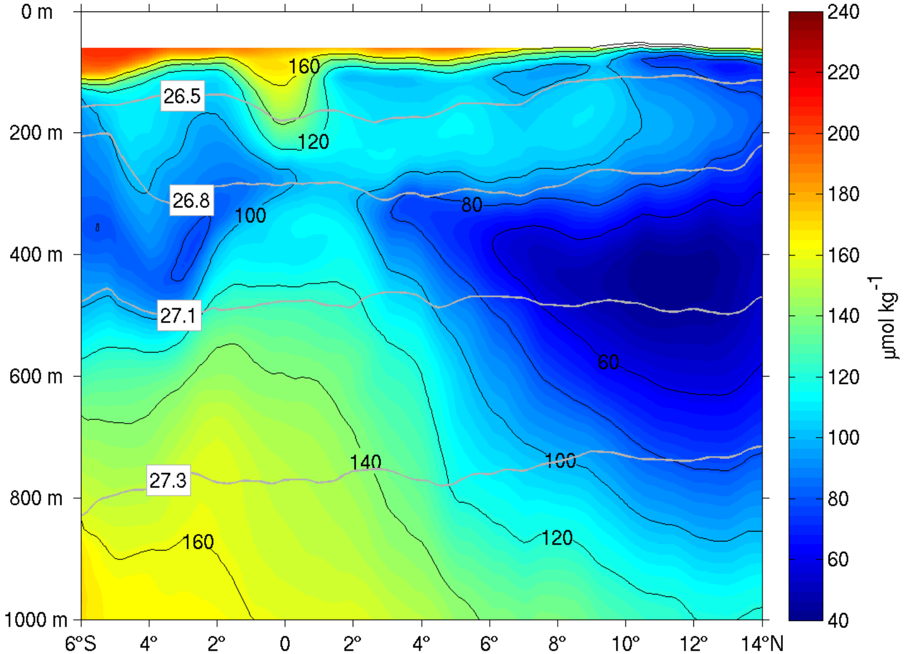
Time varying eddy-driven oxygen supply

- Flux divergence: $-divF_{O_2}(t,y,z) = K_e(t,y,z) \times \frac{d^2O_2(y,z)}{dy^2}$

K_e

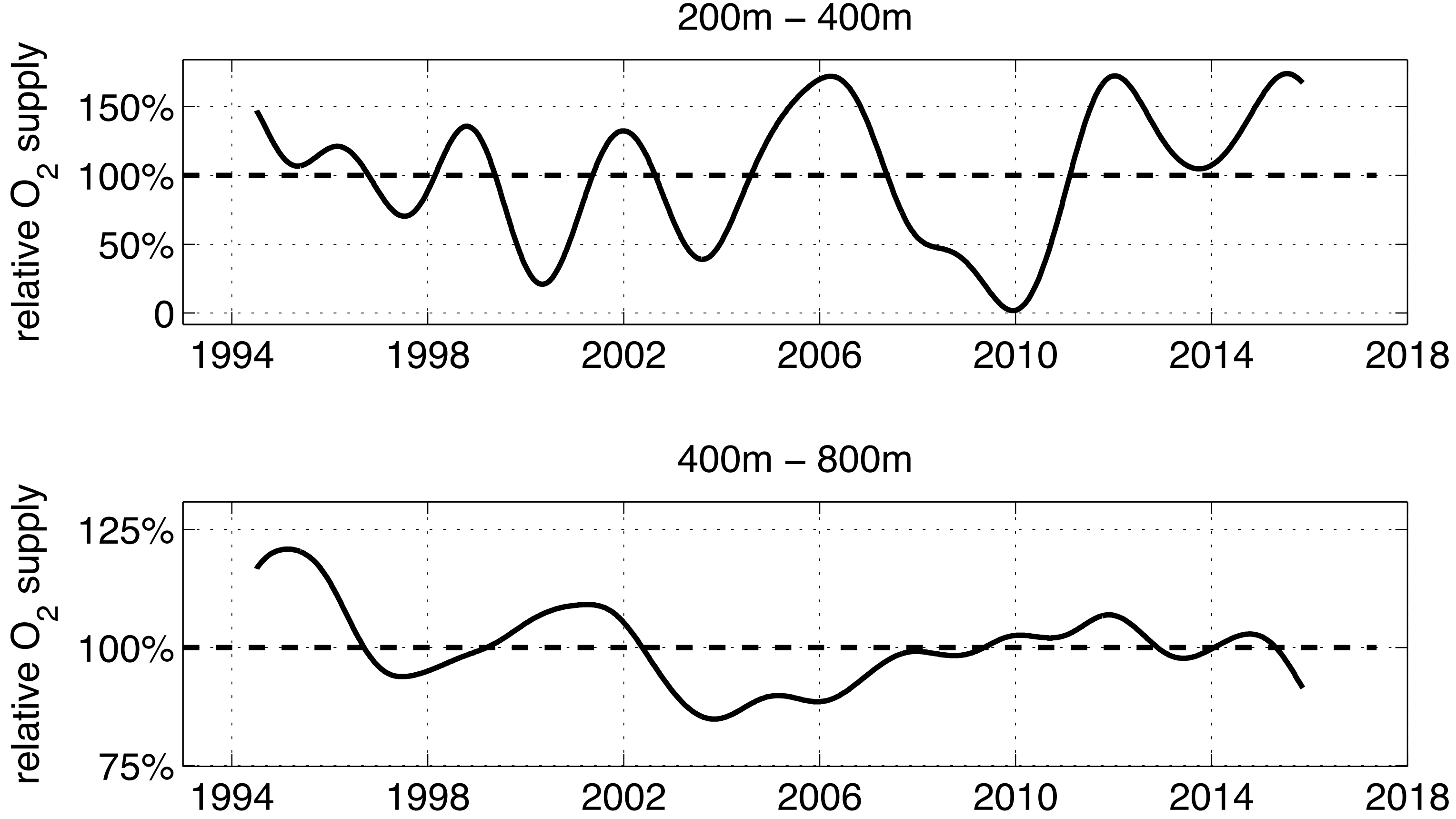


O_2



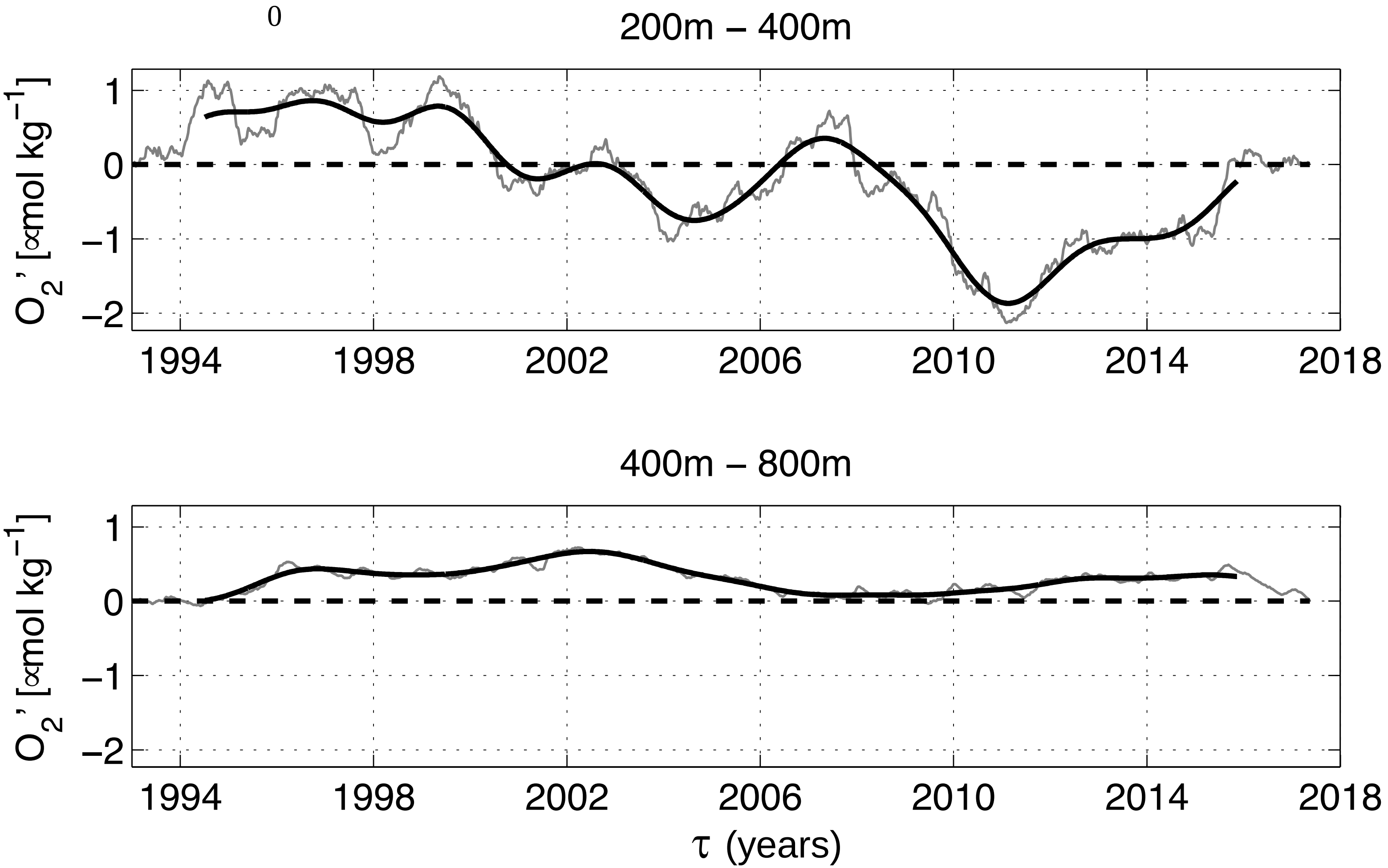
Time varying eddy-driven oxygen supply (average between 6°N-14°N)

$$divF_{O_2}(t) \Big/ \left\langle divF_{O_2}(t) \right\rangle$$



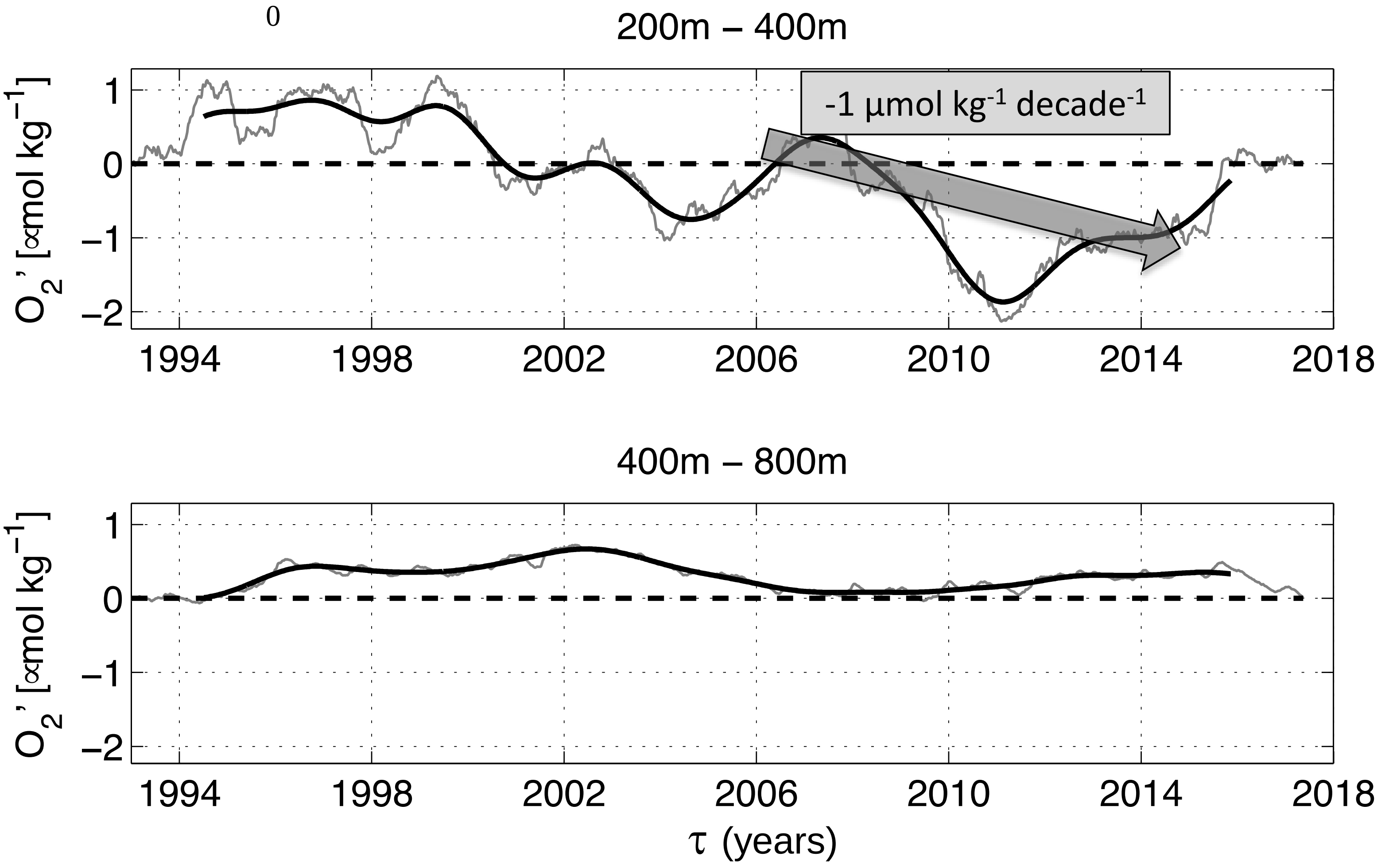
Anomaly of cumulative eddy-driven oxygen supply (average between 6°N-14°N)

- time integral: $\int_0^t -divF_{O_2}\,dt$ ⟹ eddy-driven oxygen variability



Anomaly of cumulative eddy-driven oxygen supply (average between 6°N-14°N)

- time integral: $\int_0^t -\,div F_{O_2}\, dt$ ⟹ eddy-driven oxygen variability



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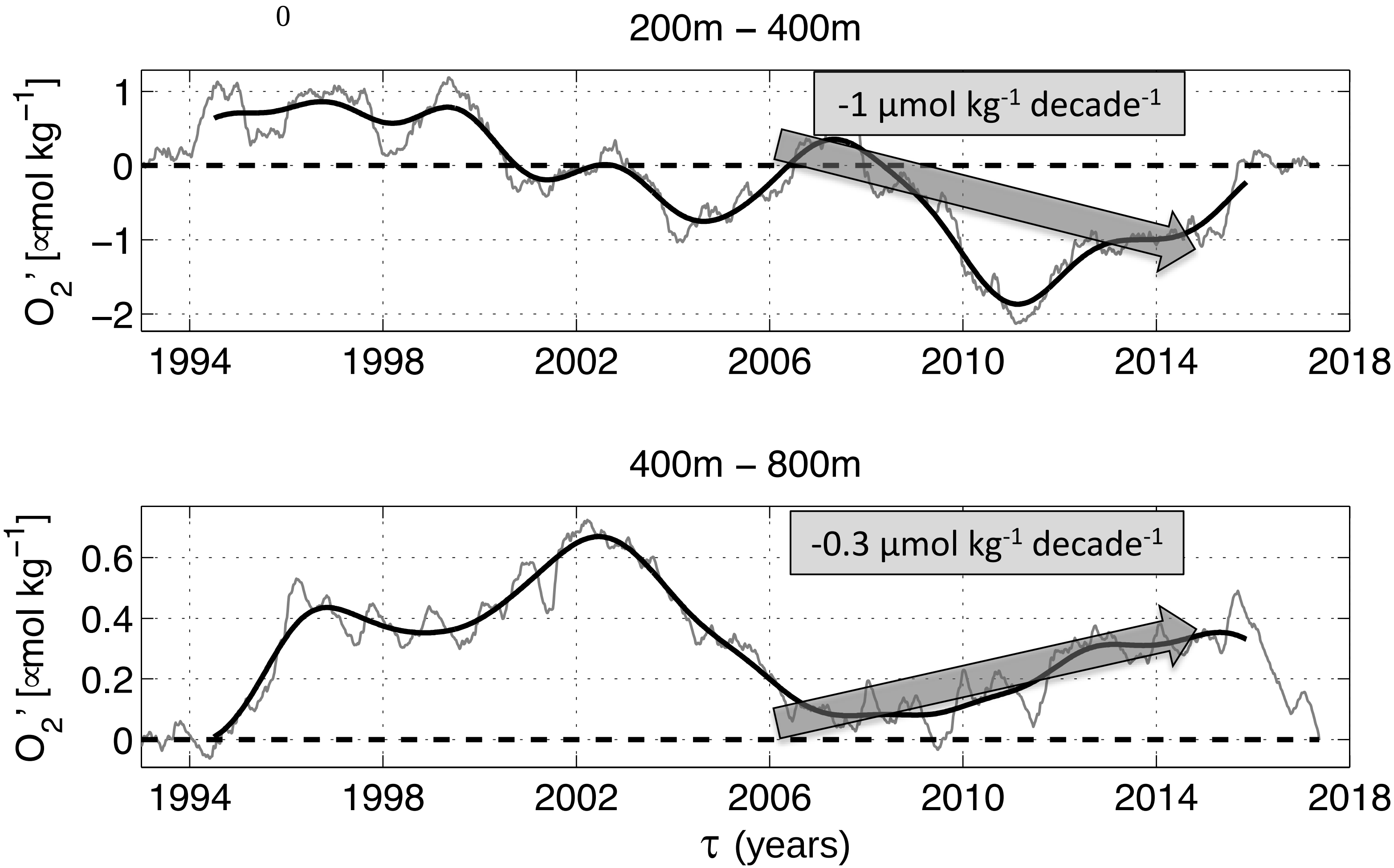

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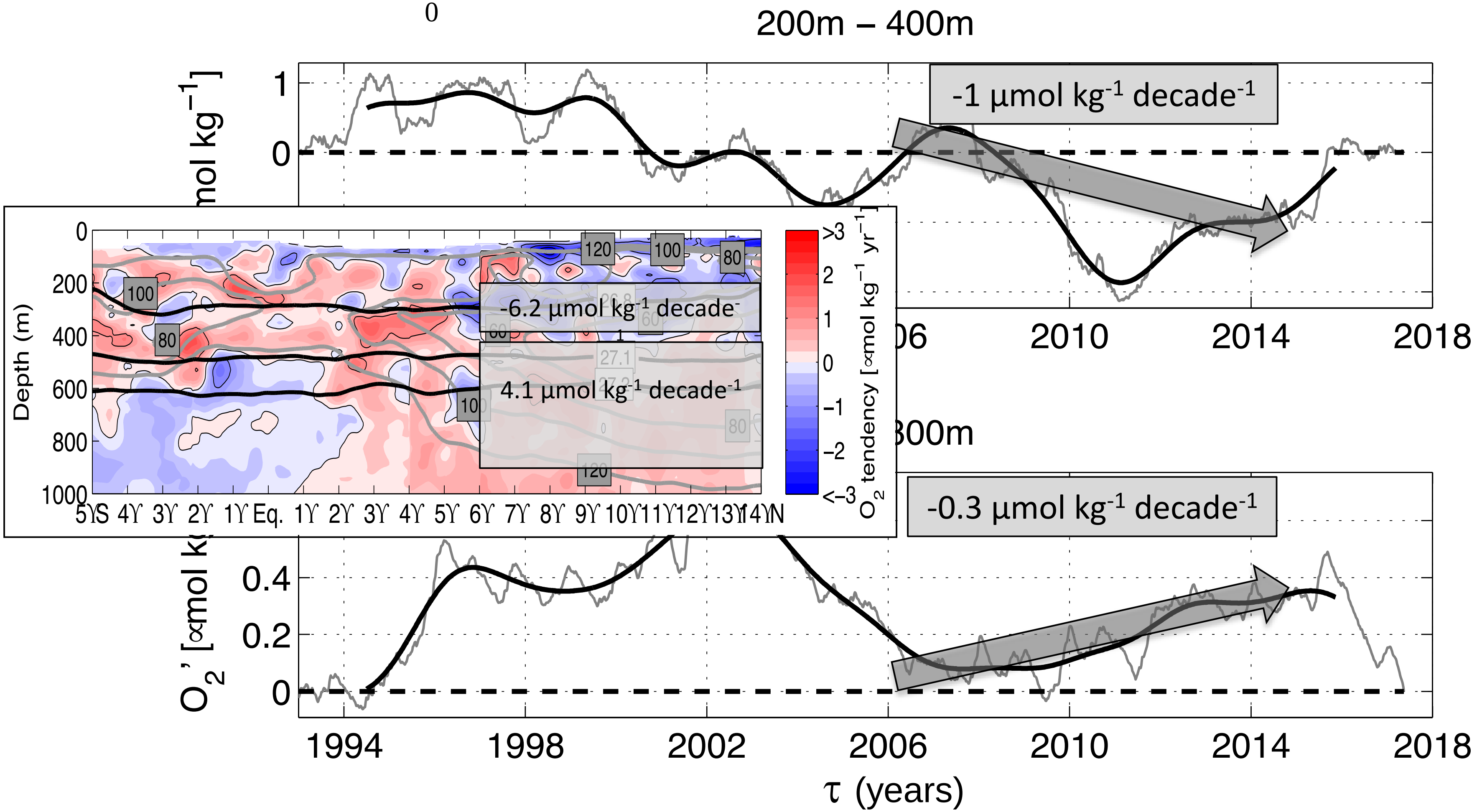
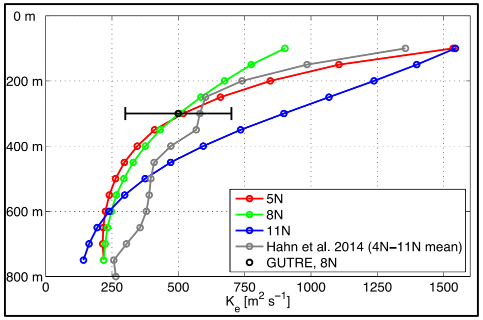


Summary

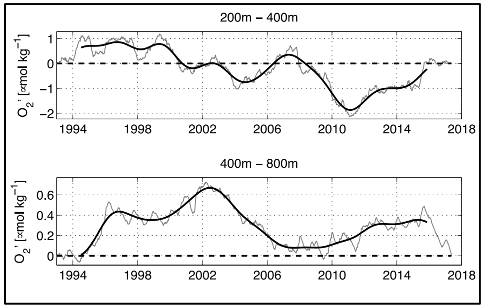
(1) Parametrization of EKE / Eddy-diffusivity:

- ⇨ regionally varying eddy diffusivity from moored observations and respective parametrization for satellite observations
- ⇨ estimate of time varying eddy diffusivity



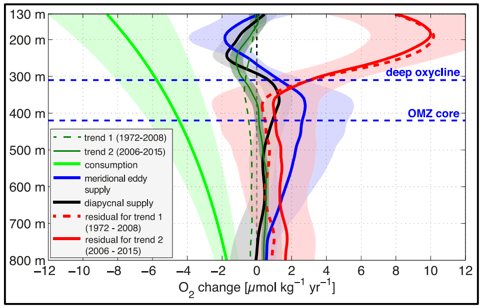
(2) Time varying eddy-driven O_2 supply:

- ⇨ interannual variability of eddy-driven O_2 supply is up to 50% of its average (smaller at depth)
- ⇨ anomaly of cumulated eddy-driven O_2 concentration is in phase with observed decadal O_2 change

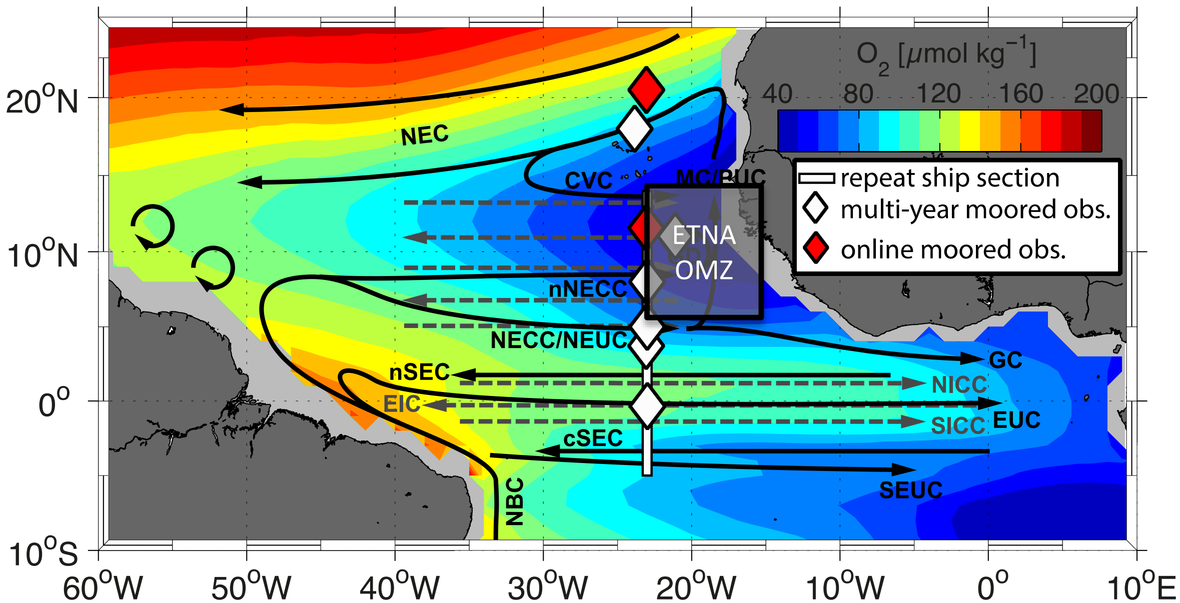


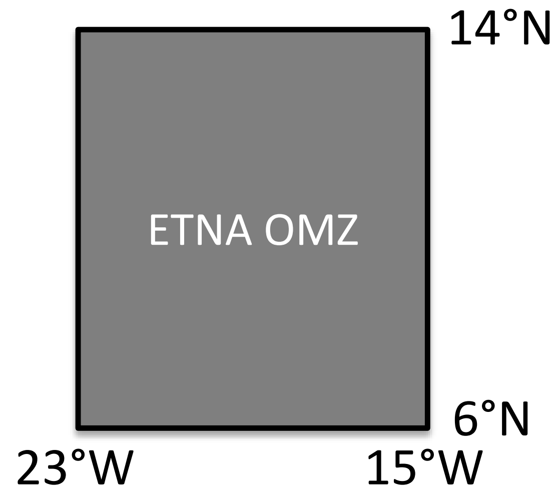
(3) Relative impact in time varying O_2 budget:

- ⇨ eddy-driven O_2 supply: has likely contributed to decadal O_2 change, but not major driving mechanism
- ⇨ advection: still seems major driver for decadal O_2 change



Changes in the advective oxygen supply





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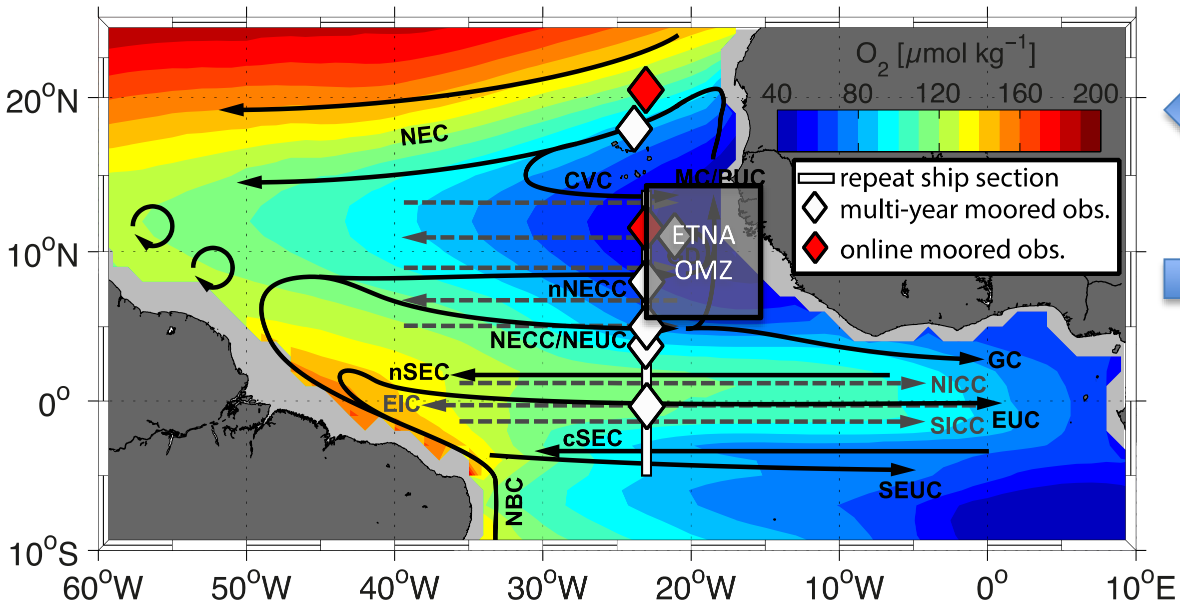
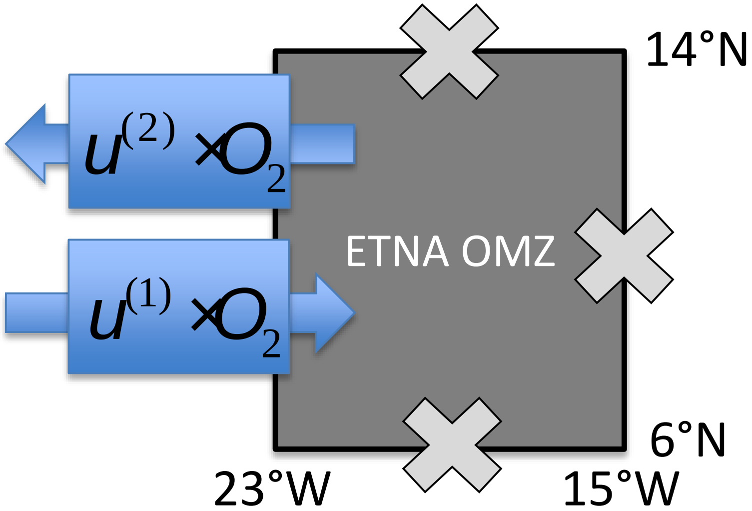
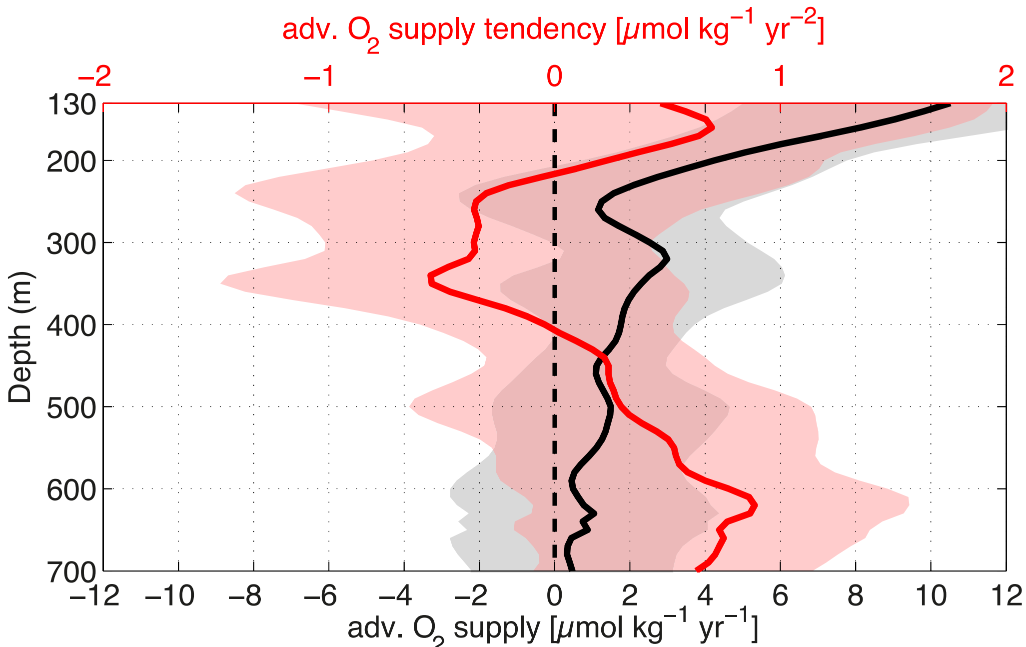




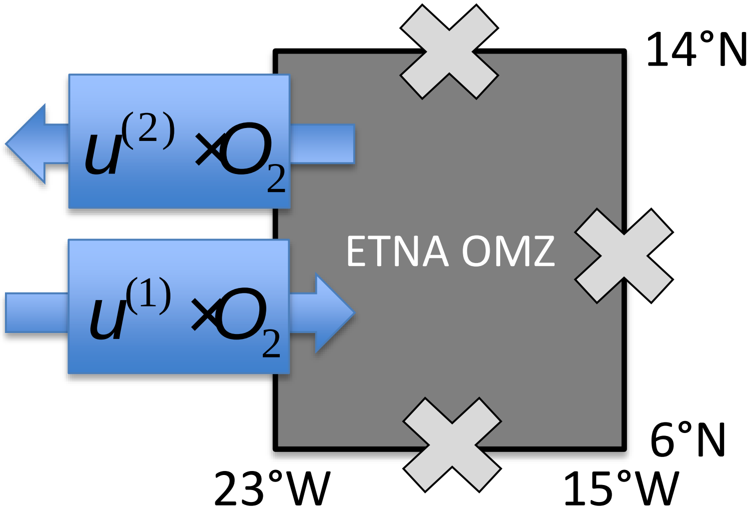
- advective O_2 flux across 23°W from 13 ship sections along 23°W (2006-2015)

⇨ rough estimate of advective O_2 supply to ‚ETNA OMZ' by considering respective box volume (*Hahn et al. 2017*)

Changes in the advective oxygen supply



Hahn et al. (2017)



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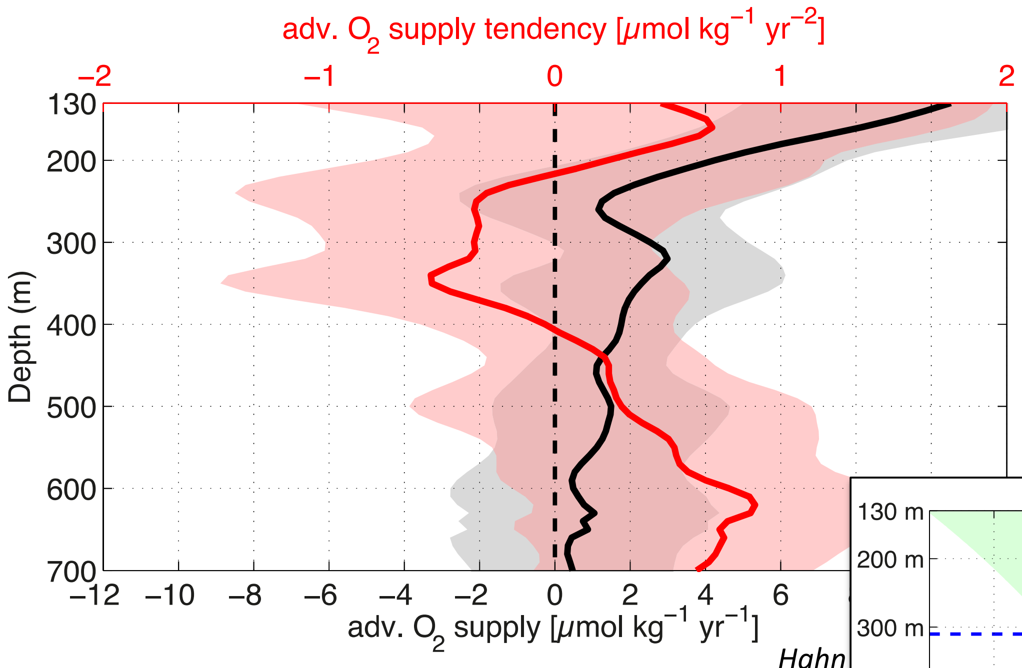
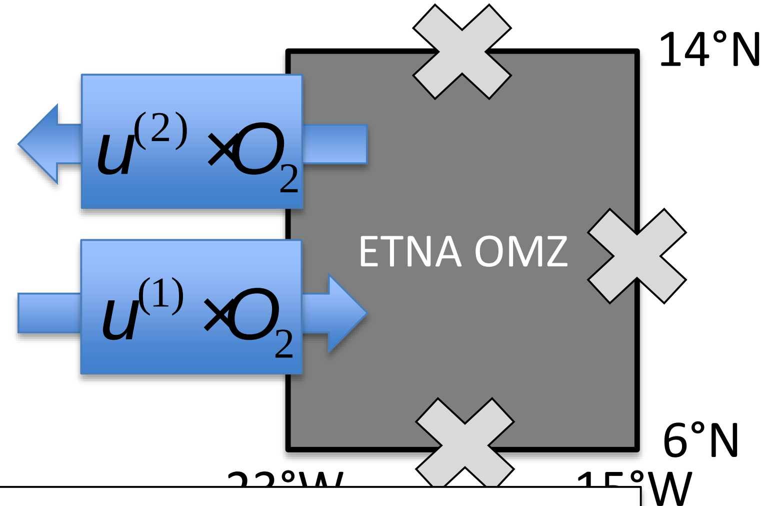
⇨ rough estimate of advective O_2 supply to ‚ETNA OMZ' by considering respective box volume (*Hahn et al. 2017*)

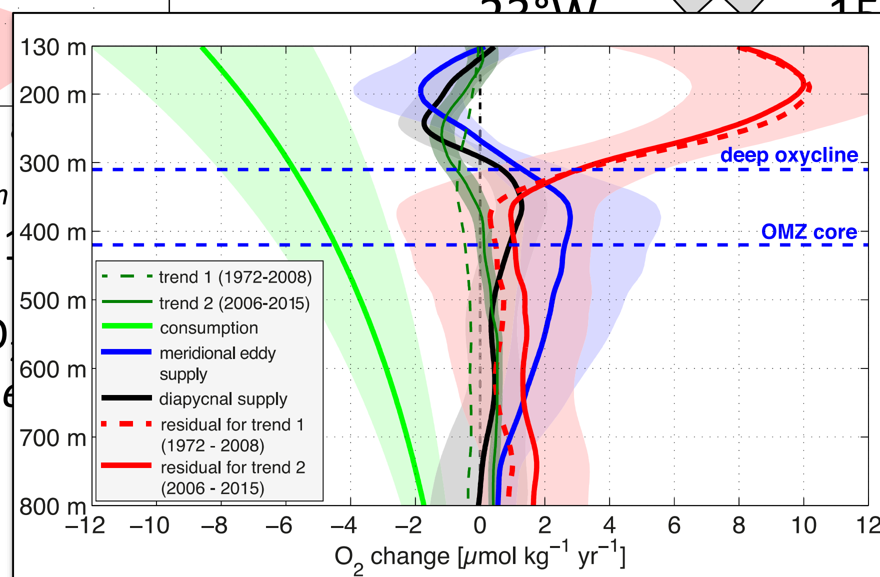
Changes in the advective oxygen supply





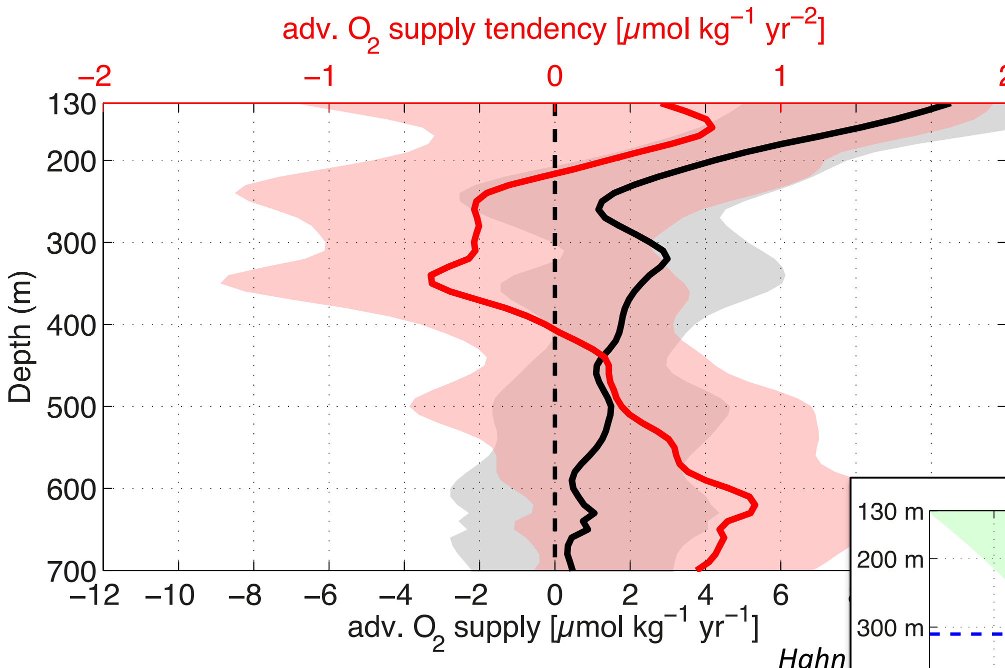
- advective O_2 flux across 23°W from 1

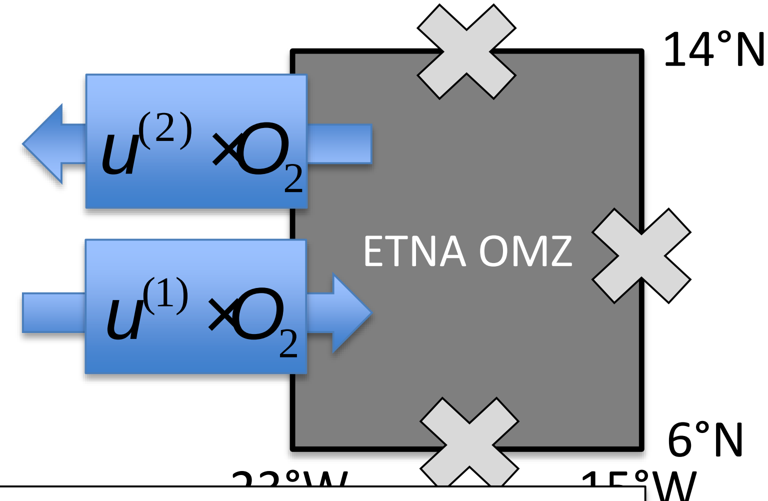
→ rough estimate of advective O
respective box volume (*Hahn e*



Hahn et al. (2017)

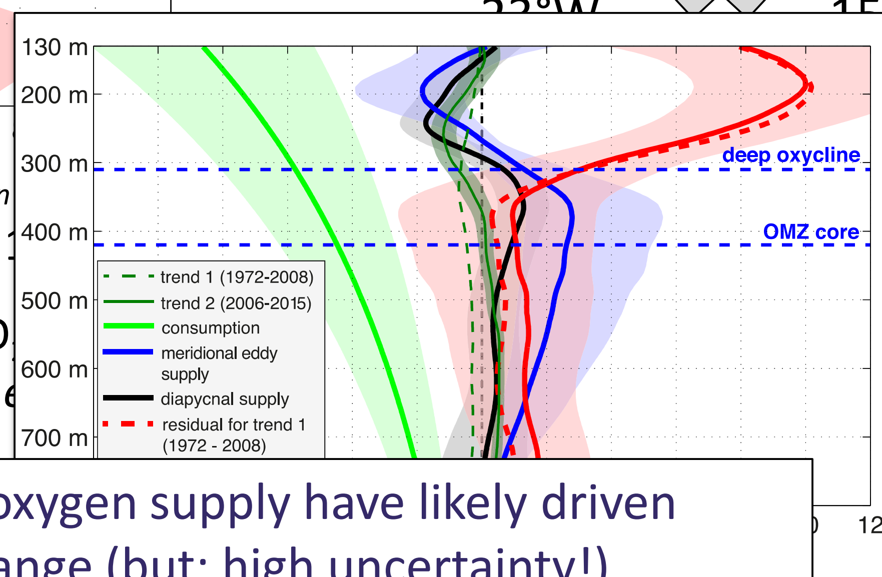
Changes in the advective oxygen supply





- advective O_2 flux across 23°W from 1

⇨ rough estimate of advective O_2
respective box volume (*Hahn e*



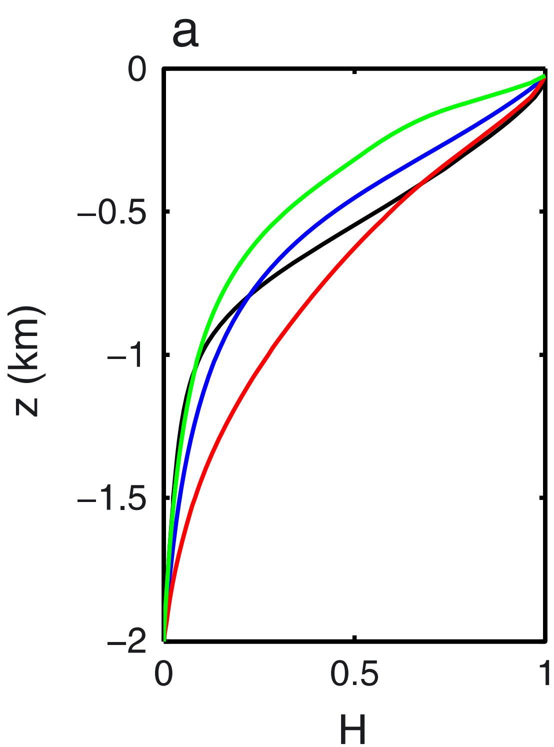
⇨ changes in advective oxygen supply have likely driven decadal oxygen change (but: high uncertainty!)

(2017)

Universal vertical structure of mesoscale eddies

- mesoscale eddies have universal vertical structure (*Zhang et al. 2013*) considering normalized pressure anomaly $p_n \sim H(z)$

$$p_n \mu H(z)$$

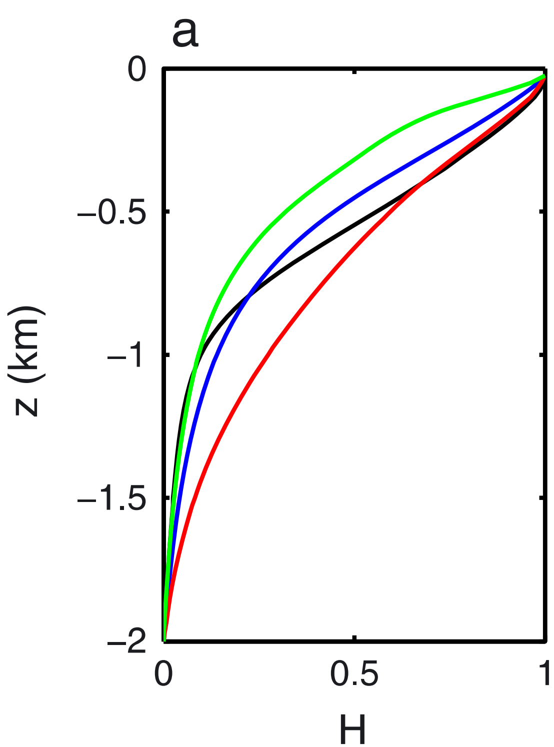


Zhang et al. (2013)

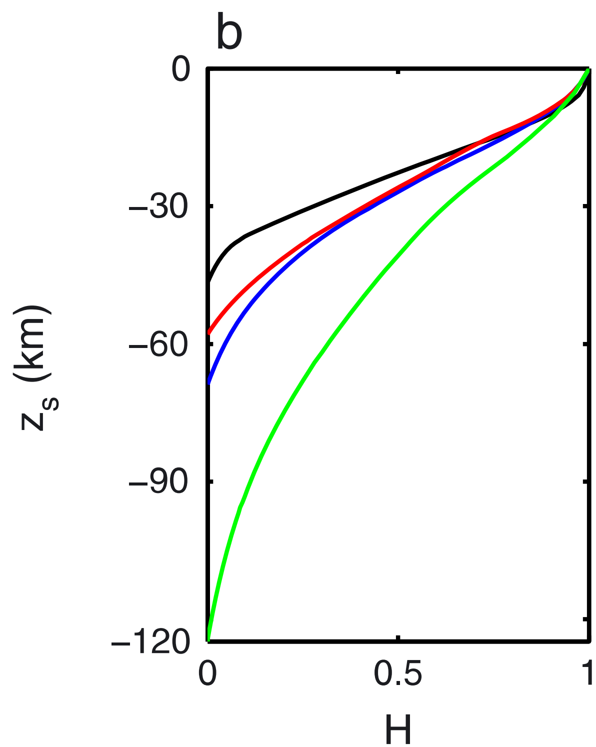
Universal vertical structure of mesoscale eddies

- mesoscale eddies have universal vertical structure (*Zhang et al. 2013*) considering normalized pressure anomaly p_n ~ *H(z)*

$$p_n \propto H(z) \qquad\qquad H(z_s)$$



Zhang et al. (2013)



Zhang et al. (2013)

<u>vertical structure function:</u>

$$H(z_s) = H_0 \cdot \sin(kz_s + \theta_0) + H_{ave}$$

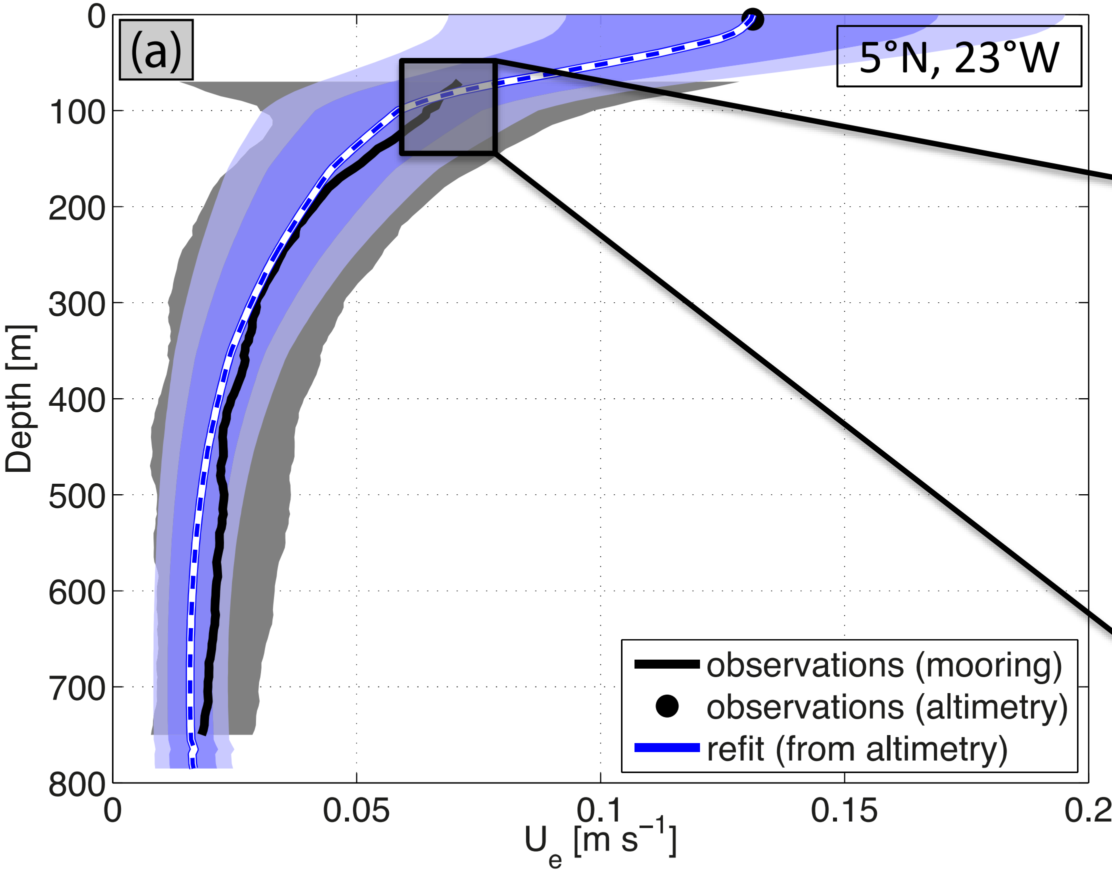
<u>stretched coordinate:</u>

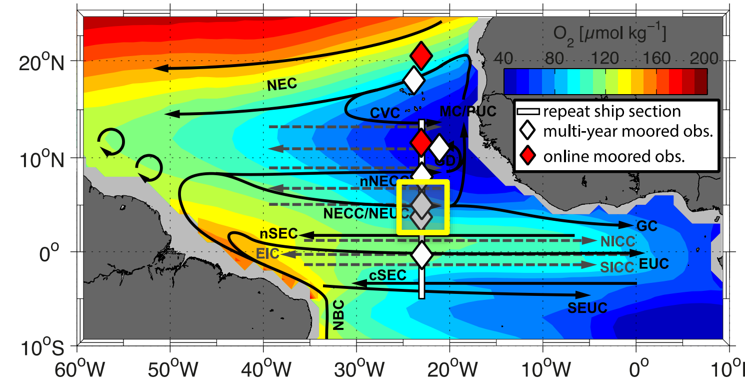
$$z_s = \int_0^z (N/f)\,dz$$

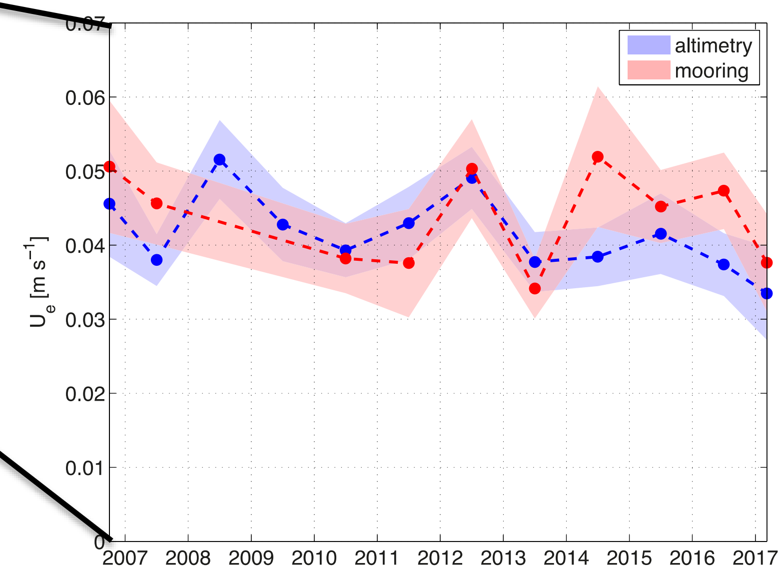
Universal vertical structure of mesoscale eddies

$$H(z_s) = H_0 \times \sin(kz_s + q_0) + H_{ave}$$

$$\mu\, U_e = \sqrt{EKE} = \sqrt{(u'^2 + v'^2)/2}$$







Universal vertical structure of mesoscale eddies

$$H(z_s) = H_0 \times \sin(kz_s + q_0) + H_{ave}$$

$$\mu \sqrt{U_e} = EKE$$