Oxygen Supply to the Tropical North East Atlantic Oxygen Minimum Zone

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18.11.2013
1. The Oxygen Minimum Zone of the Tropical North East Atlantic (TNEA OMZ)

2. Diapycnal Oxygen Supply

3. Eddy-Driven Meridional Oxygen Supply
   3.1 Flux Gradient Parameterization
   3.2 Time Series Correlation
   3.3 Oxygen Flux Divergence

4. Summary and Outlook
1. Motivation

O$_2$ distribution at 600m obtained from the *Meteor* expedition 1925 – 1927 (Wattenberg, 1939)

Pocesses influencing the oxygen concentration in the open ocean

Karstensen et al. 2008
O₂ distribution at 400m, in µmol/kg

(Karstensen et al. 2008)
Low oxygen in the open ocean

O₂ distribution at 400m, in µmol/kg

(Karstensen et al. 2008)

Sensitivity of marine organisms to low oxygen

(Keeling et al. 2010, After Vaquer-Sunyer and Duarte 2008)
1. Motivation

Motivation

Low oxygen in the open ocean

O₂ distribution at 400m, in µmol/kg

(Karstensen et al. 2008)

Outgassing of supersaturated N₂O

(Suntharalingam 2000)
1. Motivation

O₂ distribution at 400m, in µmol/kg

(Karstensen et al. 2008)

Low oxygen in the open ocean

TNEA OMZ
Expanding and intensifying

(Stramma et al. 2008)
OMZs in model simulations

State-of-the-art global models not capturing distribution nor levels (300m concentrations, µmol/kg)

Oschlies pers. comm. 2013
State-of-the-art global models not capturing distribution nor levels (300m concentrations, μmol/kg)

In order to be able to better prognose future oceanic oxygen developments, it is necessary to understand involved physics and biology, in particular the OMZ response to circulation and ventilation.

(One major scientific question of SFB 754: 'Climate-Biogeochemistry Interactions in the Tropical Ocean')
1. Motivation

Oxygen Minimum Zone (OMZ) in the Tropical North East Atlantic (TNEA)

O₂ distribution and equatorial current system (300m - 500m depth)

Mean O₂ along 23W

Mean zonal currents

Brandt et al. (2010)
Oxygen Minimum Zone (OMZ) in the Tropical North East Atlantic (TNEA)

Average oxygen profile

- **CW** Central Water
- **AAIW** Antarctic Intermediate Water
**O₂ budget: Processes in density coordinates**

\[
\text{Source/sink} + \text{isopycnal supply} + \text{diapycnal supply} = \text{tendency/storage}
\]

The supply is the difference of fluxes into and out of the volume, i.e. flux divergence.
1. Motivation

O₂ budget: Processes in density coordinates

Source/sink + isopycnal supply + diapycnal supply = tendency/storage

The only important source/sink term in the deep ocean is consumption.
1. Motivation

O$_2$ budget for the TNEA OMZ region (mean profiles of budget terms)

\[ aOUR + R = 0 \]

Stationarity assumed

Quantify some of the missing supply terms
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Diapycnal processes

\[ \text{Consumption} + \text{isopycnal supply} + \text{diapycnal supply} = \text{tendency/storage} \]

\[ \text{Diapycnal advection} + (\text{double diffusion}) + \text{turbulent diapycnal diffusion} \]

Estimation method
McDougall 1991

Estimation method
St. Laurent and Schmitt 1999

Diapycnal flux

\[ F = -K \cdot \nabla c \]

Diapycnal supply to a volume (flux convergence)

\[ -\nabla F \]

Estimating diapycnal supply requires simultaneous data for K and c
2. Diapycnal O$_2$ Supply

Measurement programme (2008-2010)

- Tracer Release Experiment (TRE)
- Microstructure Profiles (MSS)
- Acoustic Current Profiles (ADCP)
- Oxygen Profiles (CTD-O$_2$)

Analysis box for this study: 6 to 15 N, 30 to 15 W.
The 3 methods to estimate diapycnal diffusivity $K$

**TRE**
Integrative in space and time. Only 1 $K$ value. 'Groundtruthing'.

**MSS**
Points in region and time. Vertical structures.

**ADCP**
Lines in region and time. Horizontal structures.
The 3 methods to estimate diapycnal diffusivity K

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Integrative in space and time.
Only 1 K value. ‘Groundtruthing’.

**MSS**

Points in region and time.
Vertical structures.

**ADCP**

Lines in region and time.
Horizontal structures.

All 3 methods work in an overlapping depth range.
Double diffusion is negligible here.
2. Diapycnal O₂ Supply

Diapycnal diffusivity $K$: intermediate results

\[ \left\langle F \right\rangle = -\left\langle K \cdot \nabla c \right\rangle = -\left\langle K \right\rangle \cdot \left\langle \nabla c \right\rangle \]

\[ \left\langle K \right\rangle_{TRE} = (1.2 \pm 0.2) \cdot 10^{-5} \frac{m^2}{s} \]

\[ \left\langle K \right\rangle_{MSS,ADCP} = (1.0 \pm 0.2) \cdot 10^{-5} \frac{m^2}{s} \]

MSS: $K$ is approximately constant with depth in the focus depth range 150 – 500m

$K$ and gradient $c$ are independent in each depth layer. The two properties simplify the merging of the 3 methods.

K from TRE and from MSS/ADCP agree in uncertainty limits

$K$ is substantially stronger than the expected background value
**2. Diapycnal O₂ Supply**

Concentration: flux: supply

\[ c \quad F = -K \cdot \nabla c \quad \nabla F \]

- Shallow Ox Min.
- Zonal currents
- Oxycline
- OMZ core

**Oxygen concentration**
**Diapycnal flux**
**Diapycnal flux in - Diapycnal flux out**
2. Diapycnal O$_2$ Supply

Concentration : flux : supply

\[ c \quad F = -K \cdot \nabla c \quad \nabla F \]

0 m
100 m
200 m
300 m
400 m

Oxygen concentration
Diapycnal flux
Diapycnal flux in - Diapycnal flux out

Shallow Ox Min.
Zonal currents
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2. Diapycnal \( O_2 \) Supply

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2. Diapycnal O₂ Supply

\[ \text{aOUR} + O_{2,\text{dia}} + R^{(1)} = 0 \]

- **aOUR**: Consumption
- **O₂, dia**: Diapycnal supply
- **R^{(1)}**: Isopycnal residual (advective + eddy supply)

Stationarity assumed

**Fischer et al. 2013**

![Graph showing O₂ budget](image)
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4. Summary and Outlook
Characteristic section cutting through the OMZ of the TNEA

Brandt et al. (2010)
3. Meridional O₂ Supply

Zonal mean and mesoscale velocity along 23°W

\[ \bar{u} \]

\[ \left| \langle u \rangle \right| \]

\[ U_e = \sqrt{\text{EKE}} = \frac{\sqrt{u^2 + v^2}}{2} \]
3. Meridional O₂ Supply

**Zonal mean and mesoscale velocity along 23°W**

*mean > mesoscale*

*mean < mesoscale*
Eddy-driven meridional O₂ Flux

Two methods

(I) Flux gradient parameterization
   → analysis based on repeated ship sections
   \[ F = -K_e \frac{dO_2}{dy} \]

(II) Correlation method
   → analysis based on mooring time series
   \[ F = \langle v' O_2' \rangle \]
1. Repeated ship sections along 23°W (1999 - 2011)

- **(I) Hydrography (CTD/O₂)**
  - average # cruises = 8
  - (> 500 profiles in upper 1000m)

- **(II) Velocity (ADCP)**
  - average # cruises = 10
  - (for depth range > 700m)

**Background:** O₂ distribution at 400m depth from *World Ocean Atlas 2009*.

**Photo:** A. Krupke

**Copyright:** GEOMAR Helmholtz Centre for Ocean Research Kiel

annual mean hydrography of the Tropical Atlantic

$O_2$ distribution at 400m depth from World Ocean Atlas 2009
Goal: estimate a mean $K_e$ profile

... to estimate eddy-driven meridional $O_2$ flux

$$F = -K_e \frac{dO_2}{dy}$$
Goal: estimate a mean $K_e$ profile

Basic approach:

$$K_e \propto U_e \tilde{L}$$

$\tilde{L}$ ... characteristic eddy length scale

$U_e$ ... characteristic eddy velocity

$$U_e = \sqrt{\text{EKE}} = \sqrt{(u'^2 + v'^2)} / 2$$
Goal: estimate a mean $K_e$ profile

1. Mixing length theory  
   $(\text{Armi and Stommel (1983), Ferrari and Polzin (2005))}$
   
   \[ K_e = c_e U_e L_e \]
   
   \[ L_e = \frac{O_2'}{\left| \nabla \sigma O_2 \right|} \]
   
   \[ U_e = \sqrt{EKE} = \sqrt{\left( u'^2 + v'^2 \right) / 2} \]
   
   \[ c_e = 0.16 \]

2. Rhines scale  
   $(Eden, 2007)$
   
   \[ K_e \propto U_e L_R \]
   
   \[ L_R = \sqrt{\frac{U_e}{2 \beta}} \]
   
   \[ U_e = \sqrt{EKE} = \sqrt{\left( u'^2 + v'^2 \right) / 2} \]
3. Meridional O₂ Supply

**mean $K_e$ profile**

TNEA: Hahn et al. (subm.)

GUTRE: Banyte et al. (2013)

NATRE: Ferrari and Polzin (2005)
Eddy-Driven Meridional O₂ flux along 23°W

\[ F = -K_e \frac{dO_2}{dy} \]
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Eddy-driven meridional O$_2$ Flux

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Moored observations along 23°W

Moored observations along 23°W
(O₂ distribution: update from Brandt et al. (2010))

Copyright Teledyne RD Instruments
Oxygen time series along 23°W

300 m

500 m
Oxygen and velocity time series at 5°N, 23°W

time series correlation:

\[ F = \langle v' O_2' \rangle \]

where

\[ v = \langle v \rangle + v' \quad O_2 = \langle O_2 \rangle + O_2' \]

(Reynolds decomposition)
Eddy-Driven Meridional O₂ flux along 23°W

\[ F = -K_e \frac{dO_2}{dy} \]

\[ F = \left\langle v'O_2 \right\rangle \]

northward O₂ flux at 400m-600m

dy

dO₂

mooring data, 5°N and 8°N

5°N, 23°W

8°N, 23°W

't et al. (2010)
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Eddy-driven meridional O₂ supply along 23°W

\[- \frac{dF}{dy} = \frac{d}{dy} \left( K_e \frac{dO_2}{dy} \right)\]

Meridional O₂ flux divergence

convergence of O₂ flux

divergence of O₂ flux

450m-600m: O₂ supply due to mesoscale (2.1 μmol kg⁻¹ yr⁻¹)

above 400m: bands with strong O₂ flux divergence/convergence → associated with mean zonal currents
### 3. Meridional O₂ Supply

**Equation:**

\[ aOUR + O_{2,\text{dia}} + R^{(1)} = 0 + R^{(2)} = 0 \]

**Diagram:**
- **Consumption:** Green line
- **Diapycnal supply:** Blue line
- **Residual = advective + zonal eddy supply:** Red line
- **Isopycnal meridional eddy supply:** Blue line

**Average between 350m - 570m:**

<table>
<thead>
<tr>
<th>Term</th>
<th>µmol kg⁻¹ yr⁻¹</th>
<th>% aOUR</th>
</tr>
</thead>
<tbody>
<tr>
<td>aOUR</td>
<td>-4.1</td>
<td>---</td>
</tr>
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<td>O₂, dia</td>
<td>0.9</td>
<td>~20%</td>
</tr>
<tr>
<td>O₂, y, eddy</td>
<td>2.4</td>
<td>~60%</td>
</tr>
<tr>
<td>R^{(2)}</td>
<td>0.8</td>
<td>~20%</td>
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3. Meridional O₂ Supply

**O₂ budget**

\[ aOUR + O_{2,\text{dia}} + O_{2,y,\text{eddy}} + R^{(3)} = \partial_t O_2 \]

- **aOUR** + diapycnal supply + meridional eddy supply + residual (advective + zonal eddy supply) = O₂ tendency (Brandt et al., 2010)

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Summary

Diapycnal diffusivity $K$ larger than expected, constant in 150 – 500m depth

Maximum diapycnal supply near OMZ core

Above 400m: bands with $O_2$ flux divergence/convergence associated with mean zonal currents

450m – 600m: homogeneous eddy-driven meridional $O_2$ supply

OMZ core depth: mainly diapycnal (up to 30%) and meridional eddy supply (>50%)

Above OMZ core depth: strong residual supply (associated with mean zonal currents)
Summary

Main oxygen supply processes in the TNEA OMZ
(recent interpretation)

- Advection
- Meridional Eddy Diffusion
- Diapycnal Diffusion

CW
AAIW
Outlook

Expand the analyses to 800m depth (AAIW)

Main missing term: mean zonal advection

Why is there that jump at 300m?

Tracer Release Experiment (OSTRE) in SFB phase II (2012 – 2015):
Measure integrative lateral diffusivity $K_e$ in OMZ core
Thank you for your attention

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European Ocean Observatory Network