Seasonal dynamics of the oxygen budget on the Namibian shelf: a model perspective

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**Large scale circulation**

- **South Atlantic Central Water (SACW)** is transported with the **poleward undercurrent (PUC)** onto the Namibian shelf
  - specific salinity and temperature signature
  - high nutrients and a low dissolved oxygen content

- **Eastern SACW (ESACW)** spreads northward with the **Benguela Current (BC)** along the southwest African shelf edge, by cross-shelf circulation onto the Namibian shelf
  - less saline and less nutrients and more oxygen than the PUC

**Large spatial and temporal variability of hydrographic conditions and currents: combination of locally and remotely forced processes**
Extended Oxygen Minimum Zone

Model results

field data: M57-3

Oxygen concentration [μmol/kg]

- The shape of the OMZ on the shelf is well reproduced
- BUT model overestimates extension of OMZ and field data show more variability

Hypoxic zone stretches in the near bottom water on the shelf

23°S in March 2003
Oxygen in the near bottom water

Field data, mooring off Walvis Bay: 120 m

Model results: 120 m

- Good simulation of hypoxic near bottom water (120 m) on the shelf
- Anoxic conditions correlate with an SACW fraction >55%

Shelf oxygen depends to a high extent on the water mass composition

Mohrholz et al. 2008
Outline and scope

• Working hypothesis:
  - The low oxygen water on the continental shelf off Namibia is primarily driven by physical advection and is only modified through local biogeochemical oxygen consumption.

• Tool:
  - Numerical simulation with a 3D coupled hydrodynamic-biogeochemical, regional ecosystem model: 1999-2013

• This presentation:
  - Relevant physical and biogeochemical processes controlling the oxygen budget on the Namibian shelf
  - Calculation of residence times to compare the relative importance of the physical and biogeochemical processes on the local oxygen concentration
SE Atlantic regional ecosystem model

**Hydrodynamic model:** MOM-5 (GFDL) with min ~8 km, max ~18 km resolution

**Vertical grid resolution:** 0-200 m depth 1.5-3 m, then increase to 300 m

**Model bathymetry:** ETOPO-5 and 30 arc-seconds version of the GEBCO data set

**Open boundaries/Initialisation:** ECCO global circulation model (sea level, currents, temperature and salinity); World Ocean Atlas (nutrients, oxygen)

**Realistic atmospheric forcings:** NCEP or ERA-interim reanalysis data, modulated scatterometer wind fields (QuikScat, ASCAT)
Coupled hydrodynamic-biogeochemical ecosystem model

3D Hydrodynamic Model
Modular Ocean Model (MOM-5, GFDL, USA)

3D Biogeochemical 'GENUS Model' (IOW, Germany)
Nutrient-Phytoplankton-Zooplankton-Detritus (NP$_3$Z$_3$D)-Model

Sediment Model (IOW, Germany)

- **Model currency:** nitrogen, coupled carbon, oxygen and sulfur cycles

- **Feedback OMZ and zooplankton:** reduced respiration at hypoxic conditions, zooplankton diel vertical migration regulates low O$_2$ availability in the OMZ

- **Nutrient cycling in the bottom sediment:** thin oxic and thick anoxic sediments with mats of large sulfur bacteria
**Relevant processes**

\[
\frac{\partial [O_2]}{\partial t} = \left( \frac{\partial [O_2]}{\partial t} \right)_{\text{dyn}} + \left( \frac{\partial [O_2]}{\partial t} \right)_{\text{bio}} + J_{\text{flux}}
\]

**Hydrodynamic transport**
- Meridional and zonal lateral advection
- Vertical advection

**Biogeochemical sources and sinks**
- Primary production
- Water column aerobic mineralisation of sinking detritus
- Aerobic mineralisation at the sediment
- Zooplankton respiration
- Nitrification

Exploring the physical and biogeochemical processes
Residence times on the Namibian shelf

- Division of the Namibian shelf (300 m shelf edge)
  - 16-28°S (Cape Frio/Kunene)
  - 19-22°S (Central Namibia)
  - 22-25°S (Walvis Bay)
  - 25-28°S (Lüderitz)

Relative importance of physical and biogeochemical processes in the 19-22°S box
Residence times on the Namibian shelf

- Division of the Namibian shelf (300 m shelf edge)
  - 16-28°S (Cape Frio/Kunene)
  - **19-22°S (Central Namibia)**
  - 22-25°S (Walvis Bay)
  - 25-28°S (Lüderitz)

Relative importance of physical and biogeochemical processes in the 19-22°S box

\[
\tau_{dyn} = \frac{O_2 \text{ inventory}}{\sum \text{oxygen transport fluxes into box}}
\]

\[
\tau_{bio} = \frac{O_2 \text{ inventory}}{\sum \text{biogeochemical fluxes within box}}
\]
PHYSICAL AND BIOGEOCHEMICAL PROCESSES
Local current patterns

**Volume transport flux budget [Sv]**
austral summer (DJF)

- **Off shelf** Ekman transport through the mixed layer
- **Poleward undercurrent** in sub-thermocline
- **Upwelling**, i.e. upward flux into mixed layer

**PUC dominates transport fluxes in the sub-thermocline, seasonal maximum in DJF**
Low oxygen water from the Angola Gyre

Model results

Field data: MSM 18/4

Oxygen concentration [μmol/kg]

Section through the Angola Gyre at 10°S in August 2011

Low oxygen source water of the PUC
Fingerprint of the PUC

Nitrate transport

Oxygen transport

AOU transport

Physical advection of nutrient-rich and oxygen-poor water
Air-sea oxygen flux

January 2004
- warm SST:
- $O_2$ release to atmosphere

July 2004
- flux towards ocean
- [mol/m²/d]

- **Shelf**: upwelling of cold water with low oxygen
- **Offshore**: seasonal differences driven by SST variation
- flux towards atmosphere

Shelf: upwelling of cold water with low oxygen
Biological oxygen consumption: water column

Oxygen consumption rates $[\text{mmol/m}^3/\text{d}]$

- Small zooplankton respiration, no diel vertical migration
- Large zooplankton respiration, diel vertical migration
- Nitrification
- Detritus mineralisation in the water column

$23^\circ S$, January 2004

Zooplankton respiration and nitrification are dominant processes
The biological oxygen budget in the water column

**Source and sinks:**
- Primary production (source)
- Zooplankton respiration (sink)
- Nitrification (sink)
- Detritus mineralisation in the water column (sink)

**Mixed layer depth**

**Net oxygen rates**

$[\text{mmol/m}^3/\text{d}]$

**23°S, July 2004**

Biological oxygen consumption most intense at mixed layer depth
Spatial pattern of oxygen flux into the sediment

Oxygen bottom flux [mmol/m²/d]

1. **High oxygen flux in shallow areas:**
   - oxygen flux into the sediment consumed by sulfur bacteria, i.e. no diffusion of oxygen into the sediment!

2. **Lower oxygen flux at intermediate depths:**
   - due to hypoxic or anoxic bottom water

3. **High oxygen flux at the shelf edge:**
   - no mats of sulfur bacteria and oxygen can penetrate into the sediment, supporting aerobic mineralisation of sediment detritus

January 2004
CALCULATION OF RESIDENCE TIMES:

19°S-22°S BOX OF THE NAMIBIAN SHELF (300 m)
Physical advection of oxygen

Seasonality in poleward undercurrent (PUC) and Bengula Current (BC)

zonal ($u$) transport from the West

Jan 2011: +6.2 Gmol/day
Jul 2011: +2.9 Gmol/day

Jan 2011: -3.7 Gmol/day
Jul 2011: -0.8 Gmol/day

Jan 2011: +2.7 Gmol/day
Jul 2011: +6.6 Gmol/day

meridional ($v$) transport from the North

Jan 2011: 12.6 Gmol/day
Jul 2011: 10.2 Gmol/day

meridional ($v$) transport from the South

Jan 2011: +6.2 Gmol/day
Jul 2011: +2.9 Gmol/day
Surface and sediment fluxes

Surface flux

-0.85 Gmol/day

+1.90 Gmol/day

Year 2011

Sediment flux

-0.42 Gmol/day

-0.22 Gmol/day

Year 2011

positive flux: into ocean

negative flux: into sediment

Small quantitative importance of vertical boundary fluxes
Biological oxygen evolution and consumption

Seasonality in primary production, but only small seasonality in $O_2$ consumption
Physical and biogeochemical residence times

### Physical advection of oxygen

- **January 2011**

\[
\tau_{dyn} = \frac{438.7 \text{ Gmol}}{12.6 \text{ Gmol/day}} = 35 \text{ days}
\]

- **July 2011**

\[
\tau_{dyn} = \frac{499.9 \text{ Gmol}}{10.2 \text{ Gmol/day}} = 49 \text{ days}
\]

### Biogeochemical oxygen consumption

- **January 2011**

\[
\tau_{bio} = \frac{438.7 \text{ Gmol}}{1.8 \text{ Gmol/day}} = 244 \text{ days}
\]

- **July 2011**

\[
\tau_{bio} = \frac{499.9 \text{ Gmol}}{2.5 \text{ Gmol/day}} = 200 \text{ days}
\]

Dominance of physical advection over biogeochemical consumption
The low oxygen water on the continental shelf off Namibia is primarily driven by physical advection and is only modified through local biogeochemical oxygen consumption.

Thank you very much for your attention!
The Benguela ecosystem model
Modeled processes at the (sediment) redoxcline

- Chemolithoautotrophic oxidation of $\text{H}_2\text{S}$ or $\text{S}^0$ with $\text{O}_2$ or $\text{NO}_3^-$

- $\text{NO}_3^-$ reduced to
  - $\text{N}_2$ (denitrification)
  - or
  - $\text{NH}_4^+$ (DNRA)

- $\text{NH}_4^+$ is biologically available, while $\text{N}_2$ is yy from the system!
**Coupled sediment model**

- **'thin' sediments**
  - Redoxcline within the sediment
  - low $\text{H}_2\text{S}$ –availability
  - Mats of sulfur bacteria DO NOT develop

- **'thick' sediments**
  - Redoxcline at the sediment surface or within the water column
  - high $\text{H}_2\text{S}$-availability
  - Mats of sulfur bacteria develop

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**Ventilation of the bottom water**

- $\text{O}_2$, $\text{NO}_3$
- Redoxcline
- Sulfur bacteria
- Sulfate reduction
- buried

**No ventilation of the bottom water**

- $\text{O}_2$, $\text{NO}_3$
- Redoxcline
- $\text{H}_2\text{S}$
- Sulfur bacteria
- Sulfate reduction
- buried
**Over-estimated hypoxia: possible reasons**

1. Too low oxygen content of the PUC or underestimated intensity of the PUC. This cannot be verified with the available field data.

2. Underestimated ventilation of the shelf with oxygen rich ESACW. Analysis of the composition of the shelf water from SACW and ESACW [Mohrholz et al., 2008] with newly available field data will help to resolve this issue.

3. Too low vertical and lateral mixing. Recent field studies with microstructure probes, [Mohrholz et al., 2014], have demonstrated the role of breaking internal waves, but also of breaking long wave swell for the mixing near the shelf edge. These processes are poorly represented in the model. Sub-mesoscale processes like eddies and filamental structures are also not well resolved.
Comparison of the four EBUS

Lachkar & Gruber 2012