DEOXYGENATION IN THE GLOBAL AND COASTAL OCEAN: CHALLENGES OF OBSERVING AND MODELLING LOW OXYGEN ZONES.

GO$_2$NE

THE GLOBAL OCEAN OXYGEN NETWORK

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GO$_2$NE working group
Low Oxygen waters are found in the coastal, open ocean and (semi)-enclosed seas.

Some numbers:

* > 500 coastal sites

* ~ several millions km$^3$ where O2 < 2mg/l

Breitburg et al., 2018
Open Ocean

From 1960, the global oxygen loss amounts to 1-2% of total ocean oxygen inventory (~ a loss of 70 billions tons since 1960) (Bopp et al., 2013; Schmidtko et al., 2017).

Hot spots of changes

- Tropical and North Pacific Ocean, Southern Ocean, South Atlantic Ocean, Arctic Ocean (> 60% of the oxygen loss)

- Largest loss observed in the main thermocline 100-300m, as well as from 1000m to the bottom

Schmidtko et al., 2017
GLOBAL OXYGEN BUDGET

FLOWS IN PMOL O₂/YEAR

STOCKS IN PMOL

NET LAND SOURCES 0.07

FOSSIL FUEL BURNING 0.68

O₂ 37000

WEATHERING AND VOLCANISM 0.01

Manning and Keeling, 2006; Schmidtko et al., 2017.

Keeling et al., 1993
FOSSIL FUEL BURNING 0.68

OΔ2 227

NET LAND SOURCES 0.07

WEATHERING AND VOLCANISM 0.01

Keeling et al, 1993

Manning and Keeling, 2006; Schmittko et al., 2017.

O2 37000

GLOBE LACK SOURCES

O2 227

PHOTIC LAYE 75-100M

GLOBAL OXYGEN BUDGET

FLOWS IN PMOL O2/YEAR

STOCKS IN PMOL

BURIAL

OMZ

1000M
WHY IS DEOXYGENATION ONGOING?

Warming-induced solubility change can only explain 15% of the trend.

What about the other 85%?
**Why is deoxygenation ongoing?**

**What about the other 85%?**

- Slowdown of the meridional overturning circulation
- Reduced ventilation due to the reduction in deep convection & mixed layer subduction (intermediate layer).
- Natural climate variability (Duteil et al., 2018)
**WHY IS DEOXGENATION ONGOING?**

**What about the other 85%?**

Slowdown of the meridional overturning circulation

Reduced ventilation due to the reduction in deep convection & mixed layer subduction (intermediate layer).

Natural climate variability (Duteil et al., 2018)

*Models are needed in order to gain a mechanistic understanding of the importance of these processes.*

Gilbert, 2017
The number of recorded hypoxic zones (O$_2$ < 2mg/l) started to approximately double every ten years starting in the 1960s (Diaz and Rosenberg, Science, 2008).
Most are related to increased N and P loads and subsequent eutrophication.
PERSISTENT TO PERIODIC AND OCCASIONAL EVENTS
BOTTOM LAYER (BENTHIC-PELAGIC)
HUMAN-CAUSED

+ REDUCED SOLUBILITY AS IN THE OPEN OCEAN

Phytoplankton sinks to the bottom

DIC

$\mathrm{O}_2$

$\mathrm{H}_2\mathrm{S}$

Pycnocline
OCEAN NITROGEN BUDGET
FLOWS IN Tg N yr\(^{-1}\) (10\(^{12}\) g N yr\(^{-1}\))

- **Atmospheric Deposition**: NO\(_3\) and NH\(_4\) \(10 + 40\)
- **N2-Fixation**: \(140\)
- **(De)Nitrification**: N\(_2\O\) \(4\)
- **Denitrification**: N\(_2\) \(195-350\)

**Burial**: 25

**Riverine**: 30 + 50

**Total Nitrogen**: 210 000 000 TGN

** Reactive Nitrogen**: 4 200 000 TGN (2%)

Numbers from Gruber and Galloway, 2008, Somes et al., 2016
OCEAN NITROGEN BUDGET FLOWS IN Tg N yr$^{-1}$

- Atmospheric deposition of NO$_3$ and NH$_4$: 10 + 40 Tg N yr$^{-1}$
- N$2$-fixation: 140 Tg N yr$^{-1}$
- (De)nitification of N$_2$O: 4 Tg N yr$^{-1}$
- Denitrification of N$_2$: 195-350 Tg N yr$^{-1}$

Numbers from Gruber and Galloway, 2008, Somes et al., 2016

ATMOSPHERIC DEPOSITION NO₃ AND NH₄⁺ 10 + 40

N₂-FIXATION N₂ 140

(DE)NITRIFICATION N₂O 4

DENITRIFICATION N₂ 195-350

LOSS OF REACTIVE NITROGEN IMPACT ON PRIMARY PRODUCTION?
IMPACT ON THE REDFIELD N/P RATIO?

RIVERINE

30 + 50

BURIAL

25

OMZ

OCEAN NITROGEN BUDGET FLOWS IN Tg N yr⁻¹


OCEAN NITROGEN BUDGET FLOWS IN Tg N yr⁻¹

N$_2$-fixation requires high amounts of iron and phosphate.

Impact of deoxygenation.

Ocean nitrogen budget flows in Tg N yr$^{-1}$.

Numbers from Gruber and Galloway, 2008, Somes et al., 2016.
The marine phosphorus cycle is crucial in stabilizing the marine nitrogen cycle.
**O₂ IS A KEY STANDARD OCEANOGRAPHIC VARIABLE**

**Ship data**

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<thead>
<tr>
<th>Period</th>
<th>Maps</th>
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</thead>
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<tr>
<td>1950-1954</td>
<td><img src="image1" alt="Maps" /></td>
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<tr>
<td>1955-1959</td>
<td><img src="image2" alt="Maps" /></td>
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<td><img src="image12" alt="Maps" /></td>
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<tr>
<td>2010-2014</td>
<td><img src="image13" alt="Maps" /></td>
</tr>
</tbody>
</table>

Schmidtko et al., 2017

**BGC-ARGO**

~30 profiles/year at ~75 depths

**Table 1. Profiles to depth > 900 m.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ship Profiles per year (2001-2010)</th>
<th>BGC-Argo Profiles per year (2016)</th>
<th>BGC-Argo /Ship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>1730</td>
<td>11332</td>
<td>6.5</td>
</tr>
</tbody>
</table>

Claustre and Johnson, 2017, GOOS webinar

Source: US NODC, ARGO GDAC
BUT OXYGEN SENSORS CAN DRIFT …

The drift can render problematic the assessment of the long term change in oxygen... e.g. Takeshita et al., 2013

Correction of ex-situ and in-situ drift: in-situ calibration at the float deployment and during its life time is needed.

Oxygen trend
@ 300 m (1960-2010): -0.066 µmol/kg/yr (Stramma et al. 2012)
100-1000m (1970-1992): -0.042 µmol/kg/yr (Helm et al., 2011)

Stramma et al., 2012
BEST PRACTICES FOR OXYGEN SENSORS: IN AIR CALIBRATION

- **In Air calibration:** achievable accuracy $\sim 1 \mu\text{mol} / \text{kg}$ over the lifetime of a float.
- Correction of non-calibrated floats (already deployed) seems challenging.
- Delivering of Near-real time data for operational purposes (NRT-DT products)

Oxygen optodes mounted on the top caps of floats:

Bushinsky et al. 2016
Accurate measurement of O2 in the LOZs is critical for the correct estimation of N budget.

Estimations of the extent and evolution of Anoxic Marine Zones (AMZs) are still uncertain.

Specific monitoring is needed for LOZs: short response time (gradient), accuracy of ultra-low concentrations (a few nm if the detection of anoxic zone is targeted).

Accurate measurement of O2 in the LOZs is critical for the correct estimation of N budget.
THE VOLUME OF OMZ IS STILL UNCERTAIN

Oxygen biases of the gridded WOA05 product is of the order of 6.4 mmol O2/m3

Table 2. Volume (10^6 km^3) of Suboxic Waters for the Major OMZs in the Indian and Pacific Oceans for Two Oxygen Limits (20 and 5 mmol m^-3)^a

<table>
<thead>
<tr>
<th></th>
<th>North Pacific</th>
<th>South Pacific</th>
<th>Indian Ocean</th>
<th>Global</th>
</tr>
</thead>
<tbody>
<tr>
<td>WOA05</td>
<td>O_2 &lt; 20 mmol m^-3</td>
<td>8.8</td>
<td>1.5</td>
<td>2.6</td>
</tr>
<tr>
<td>Objective mapping 1</td>
<td>11.6</td>
<td>2.3</td>
<td>3.4</td>
<td>17.3</td>
</tr>
<tr>
<td>Objective mapping 2</td>
<td>12.0</td>
<td>2.5</td>
<td>3.6</td>
<td>18.1</td>
</tr>
<tr>
<td>Corrected WOA05</td>
<td>12.0</td>
<td>1.9</td>
<td>3.2</td>
<td>17.1</td>
</tr>
<tr>
<td>WOA05</td>
<td>O_2 &lt; 5 mmol m^-3</td>
<td>0.67</td>
<td>0.04</td>
<td>0.34</td>
</tr>
<tr>
<td>Objective mapping 1</td>
<td>2.37</td>
<td>0.45</td>
<td>0.86</td>
<td>3.68</td>
</tr>
<tr>
<td>Objective mapping 2</td>
<td>2.41</td>
<td>0.61</td>
<td>1.11</td>
<td>4.13</td>
</tr>
<tr>
<td>Corrected WOA05</td>
<td>1.64</td>
<td>0.13</td>
<td>0.68</td>
<td>2.45</td>
</tr>
</tbody>
</table>

^aThe data sets shown are gridded WOA05, GLODAP data mapped using the procedure described by Gandin [1963], GLODAP data mapped using the procedure described by Barnes [1964], and gridded WOA05 with an empirical linear correction based on GLODAP in situ measurements.
Profiling floats with oxygen and bio-optical sensors allow to investigate biogeochemical processes at the oxic-anoxic interface.

Particle maximum likely consists of chemoautotrophic bacterial populations oxidizing sulfide and the sinking MnOx particles acting as a redox shuttle.

Stanev et al., 2018.
Nitrite accumulation
Manganese accumulation
Impact on nitrogen fixation
Very important to constraint

Canfield and Thamdrup, 2009
PREDICTING OXYGEN: MODELLING LOZ IS CHALLENGING
Current IPCC models consistently predict that deoxygenation will continue (1.8-3.5%)
Contrasting conclusions for the evolution of OMZs at the end of the 21st century ....

CMIP5 models disagree in their predictions of the volume of waters with oxygen values lower than 100 µmol/l (They even disagree on the sign).
The global role of mesoscale eddies in shaping OMZs remain unclear. Some eddies contribute to the ventilation of LOZs by injecting rich oxygen water by stirring mechanisms. (ETNP)

Low oxygen submesoscale coherent vortices, contribute to maintain the OMZs in the ETNA

Bettencourt et al., 2015

Shütte et al., 2016

High respiration rate 0.1 µmol/kg /day, Karstensen et al., 2015
**REGIONAL SEAS: FORECASTING OXYGEN**

**Black Sea**
Forecasting center

PU-BIO
ULiege

Grégoire et al., 2008; 2011

Capet et al., 2016

**PU-PHYSICS**
(CMCC, USOFIA)

**HZG**
PU-WAVES

Hypoxic records - [%]
(<6 mmol O/m³)

[O₂] – [mmol/m³]

Quality control procedure (QUID)

Link with MSFD (D5)

Capet et al., 2013;
During the past 60 years, the vertical extent of the Black Sea’s oxygenated layer has narrowed from 140m to ~80m.
COPERNICUS MARINE SERVICE
OCEAN MONITORING INDICATORS

Knowing more about:

- **the program**: copernicus.eu
- **the service**: marine.copernicus.eu
- **the entrusted entity**: mercator-ocean.eu
Oxygen Loss can alter:

- Behavior & Migrations
- Vision
- Metabolism
- Reproduction
- Growth/Size
- Mortality

Ecosystem structure
- Composition
- Abundance
- Biodiversity

Gallo and Levin, 2018

<table>
<thead>
<tr>
<th>One liter of Air</th>
<th>Overall Mass</th>
<th>Oxygen</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3g</td>
<td>0.3g</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>One liter of Water</th>
</tr>
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<tbody>
<tr>
<td>1000g</td>
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</table>

- 0.008g (100% sat)
- 0.004g (50% sat)
- 0g (anoxic)
WHAT IS THE OXYGEN LIMIT TO MARINE LIFE?

OXYGEN CONTROLS TAXONOMIC COMPOSITION

Crustacean & fish intolerance to hypoxia induces mass mortality

Fish and Crustaceans are the first to die under hypoxia

Benguela Lobster Walkout

BUT Adaptation: from laboratory to the field (up to a certain limit).
Predicting the impact of deoxygenation: From physiology to biogeography

From observations in the Lab. to field habitat mapping:

\[ \Phi = \frac{\text{Oxygen Supply}}{\text{Organism's } O_2 \text{ demand}} \]

\[ = A_0 B^n \frac{pO_2}{\exp\left(\frac{-E_0}{k_B T}\right)} \]

Deutsch et al., 2015. Science
From observations in the Lab. to field habitat mapping:

\[ \Phi = \frac{Oxygen \ Supply}{Organism's \ O_2 \ demand} \]

\[ = A_0 B^n \frac{pO_2}{\exp\left(-\frac{E_0}{k_B T}\right)} \]

Deutsch et al., 2015. Science

- Global reduction of the metabolic index on averaged 21 %
- 1/3 is due to O2 loss
From physiology to biogeography

\[
\phi = \frac{\text{Oxygen Supply}}{\text{Organism's } O_2 \text{ demand}}
\]

\[
= A_0 B^n \frac{P_{O_2}}{\exp\left(\frac{-E_0}{k_BT}\right)}
\]

Habitat loss from 1971-2000 to 2071-2100

Change in metabolic index from 1971-2000 to 2071-2100

- Global reduction of the metabolic index on averaged 21%
- 1/3 is due to O2 loss

Deutsch et al., 2015. Science

Cod
Blue marlin with tag

15% habitat loss between 1960-210

Maximum daily dive depth;

DO in ml/l

Stramma et al., 2012.
Modeling the Population Effects of Hypoxia on Atlantic Croaker (Micropogonias undulatus) in the Northwestern Gulf of Mexico: Part 1—Model Description and Idealized Hypoxia

Kenneth A. Rose¹,² · Sean Creekmore¹ · Peter Thomas³ · J. Kevin Craig⁴ · Md Saydur Rahman⁵ · Rachael Miller Neilan⁶

Modeling the Population Effects of Hypoxia on Atlantic Croaker (Micropogonias undulatus) in the Northwestern Gulf of Mexico: Part 2—Realistic Hypoxia and Eutrophication

Kenneth A. Rose¹,² · Sean Creekmore¹ · Dubravko Justič¹ · Peter Thomas³ · J. Kevin Craig⁴ · Rachael Miller Neilan⁵ · Lixia Wang¹ · Md Saydur Rahman⁶ · David Kidwell⁷
Modeling Strategy

A succession of modelling approaches

- Exposure-Effect sub models

- Individual Based models: 7 development stages

- Coupled hydrodynamical-biogeochemical model
Trade-off between food and hypoxia

- 25% nutrient
+ Hypoxia

No Hypoxia

Hypoxia

Model Year

Age 2+ (millions)
So far, the success of hypoxia management is mitigated

**Gulf of Mexico**


**Baltic Sea**

**Black Sea**

**WHY?**

- Need a dual N and P reduction (Conley et al., 2009)
- Variability of the physics has to be taken appropriately into account (Fennel and Laurent, 208)
- Sediment inertia
- Climate warming?
Global ocean oxygen climatology does not yet incorporate Argo Oxygen data but the recommendation for in-air calibration has the potential to deliver data of sufficient quality for assessing oxygen trends.

A global coordinated assessment of deoxygenation in the coastal and regional ocean is missing. International efforts are needed to promote the inclusion of regional data in international data bases and to build climatology for the global coastal zone and EBUS.

A Socat-like product for oxygen would improve our estimation of deoxygenation in the global and coastal ocean. Higher level of quality check (e.g. extending CARINA) with a special focus on OMZ would be beneficial.
High quality data is needed (e.g. in AMZs) in order to derive robust parameterization of biogeochemical models and to deliver reliable thresholds for biogeochemistry. This will allow to better estimate the consequences of LOZs on the cycling of essential elements like C, N, P, Fe.

Predictions of the effects of deoxygenation at spatial, temporal and ecological scales most relevant to the ecosystem services are needed including error estimation on the prediction (e.g. ensemble approaches).

Regional models have abilities to represent the oxygen dynamics at monthly to weekly time scales (Rose et al., 2017) but their performances can be hampered by the quality of their boundary conditions.
Ongoing Activities

- Produce a technical brief (soon published)
- Produce peer-reviewed scientific articles: paper published in Science in January 2018 + several reviews in preparation.
- GO2NE Summer School, Xiamen China, September 2019, ..
- Align with the activities of existing networks, (e.g. GOOS, GOA-ON, IGMETS, IOC-HAB);
- Raising awareness, develop a communication strategy;
Ocean Deoxygenation: Drivers and Consequences
Past • Present • Future

INTERNATIONAL CONFERENCE KIEL
GERMANY

SAVE THE DATE 3 – 7 September 2018
Thank you!
Members

Denise Breitburg (Co-chair, Smithsonian Environmental Center; USA)
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Denis Gilbert (DFO; Canada)
Dimitri Gutierrez (Instituto del Mar del Peru; Peru)
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