Modelling hypoxia and its impact on marine Good Environmental Status: The Black Sea case

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IWMO, Bologna, May 2016
1. Why?

2. Different Morphologies

3. Modelling Challenges

4. The Black Sea case
Oxygen Minimum Zones affects biogeochemistry

Decreasing oxygen level

Well oxygenated layer

Organic matter

Aerobic Respiration

CO₂

N₂, N₂O

Mn (II)

Fe (II)

H₂S

Climatic gases

NO₃ Reduction

Mn(IV) reduction

Fe(III) reduction

SO₄ reduction

Suboxia

Anoxia

(Mn) (Fe) (S)
Oxygen Minimum Zones affects biogeochemistry

Grégoire et al. (MAST,ULg)
Modelling Hypoxia & GES
IWMO, Bologna, May 2016
Oxygen Minimum Zones affects biology

(Rabalais and Turner., 2001)
Oxygen Minimum Zones affects biology

(Stramma et al., 2011)
1 Why?

2 Different Morphologies

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4 The Black Sea case
Oxygen Minimum Zones in the Open Ocean

Oxygen (µmol/kg) at 200 m

(Falkowski, 2011)
Oxygen Minimum Zones in the Open Ocean

Dissolved Oxygen at 400 m [μmol/kg]

(Stramma, 2008)
Oxygen Minimum Zones in the Open Ocean

Dissolved Oxygen at 400 m [μmol/kg]

(Stramma, 2008)
Oxygen Minimum Zones in permanently stratified basin

Baltic Sea, (Carstensen et al., 2014)
Oxygen Minimum Zones in permanently stratified basin

Black Sea, (Capet et al., 2016)
Oxygen Minimum Zones in coastal areas

Reported coastal dead zones (Diaz & Rosenberg, 2008)


- Seasonal or shorter stratification
- Sedimentation patterns
- Benthic-Pelagic coupling
Summary

- 7% of the global ocean total volume (Paulmier and Pino, 2009)
- Natural occurrence in some systems (e.g., high productivity, permanently stratified areas)
- The volume of OMZs is increasing (warming: stratification, decreased solubility, eutrophication)
- Pressure on Ecosystems: Habitat compression, mass mortality, affects benthos ecosystem functions
- Launch of the Global Oxygen Network (GO2NE) supported by IOC to integrate the various aspects of deoxygenation and to raise awareness
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Challenges for OMZ modelling

- Appropriately address the relevant processes.
- Valuate the impacts on ecosystem goods and services.

Key processes

- **General**: Suboxic Biogeochemistry
- **Coastal and shallow areas**: Benthic-Pelagic Coupling
- **Open Ocean & EBUS**: Meso- and Submeso- scales
- **permanently stratified basin**: Diapycnal ventilation processes
Challenges for OMZ modelling

- Appropriately address the relevant processes.
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Challenges for OMZ modelling

- Appropriately address the relevant processes.
- Valuate the impacts on ecosystem goods and services.

Connect Scales

Species → Patch → Habitat → Ecosystem → Societal relevance
1 Why?

2 Different Morphologies

3 Modelling Challenges

4 The Black Sea case
Northwestern Shelf
- Shallow
- Eutrophic
- Seasonal Hypoxia

Open Sea
- Deep (2000 m)
- Stratified
- Permanent Anoxia
Shoaling oxycline in the central part

Oxygen - [μM]

[Image of a graph showing oxygen penetration depth and oxycline depth over time from 1960 to 2010, with SHIPS and ARGO data indicated.]

Well-Oxygenated
Oxycline
Suboxic
Anoxic

Murray et al., 2014

[Diagram showing layers of the water column with oxygen and sulfide concentrations.]
Seasonal hypoxia on the northwestern shelf

Rivers and land inputs
Fresh water, nutrients...

Atmosphere
Gas exchanges, precipitation-evaporation, wind mixing, ...

Hydrodynamic Model
Temperature, salinity, circulation, mixing, ...

Biogeochemical model
- Autotrophs
- Heterotrophs
- Detritus
- Dissolved gases: O₂, CO₂, Nutrients NO₃, NH₄, PO₄

Benthos
Seasonal hypoxia on the northwestern shelf

[Map showing hypoxic areas]

[Graph showing hypoxic areas from 1985 to 2010 with data from Mee 2006, Capet et al., 2013, and UkrSCES 2002]

[Bar chart showing hypoxic areas with categories for Eutrophication and Climate]

[Graph showing nitrogen discharge by rivers with data for past years (1981-2009) and projected years (2015-2020)]

[Graph showing nitrate discharge from 1960 to 2010 with peaks in the 1980s and a decline in recent years]
Ecological Processes
- Bioturbation
- Feeding
- Reproduction
- Mobility
- Growth

Ecosystem Functions
- Nutrient recycling
- Sediment Stability
- Resilience
- Carbon sequestration
- Decomposition

Ecosystem goods and services
- Climate regulation
- Sediment formation and stability
- Storing and cycling nutrients
- Production of food
- Cleaning water and air

VALUATION
Going further: A functional approach

Morphological, physiological or phenological characteristics defined at the level of the species

<table>
<thead>
<tr>
<th>Biological Traits Species</th>
<th>Feeding mechanisms</th>
<th>Adult Longevity</th>
<th>Relative Adult Mobility</th>
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<td></td>
<td>SF</td>
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<td>GB</td>
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<td>Mya arenaria</td>
<td>2</td>
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</tr>
<tr>
<td>Mytilius galloprovincialis</td>
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<td>0</td>
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Southwood hypothesis (1977)

The habitat provides the template on which evolution forges characteristic life history strategy. This means that biological traits can be related to the physical and biogeochemical properties of the environment.
**Going further: A functional approach**

**Traits, (Violle et al., 2007 Oikos)**

Morphological, physiological or phenological characteristics defined at the level of the species

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### Biological Traits

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**Southwood hypothesis (1977)**

The **habitat** provides the template on which evolution forges characteristic life history **strategy**. This means that biological traits can be related to the physical and biogeochemical properties of the environment.
EROS21 dataset, August 1995, (Wijsman et al 1999)
RLQ analysis, (Legendre and Legendre, 2012; Dray et al., 2014)

Grégoire et al. (MAST,ULg)

Modelling Hypoxia & GES

IWM0, Bologna, May 2016

20 / 30
RLQ analysis, (Legendre and Legendre, 2012; Dray et al., 2014)

Stations

Traits

Species

Environment

?
RLQ analysis, (Legendre and Legendre, 2012; Dray et al., 2014)

Grégoire et al. (MAST,ULg)
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Species

Environment + Model outputs

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RLQ analysis, (Legendre and Legendre, 2012; Dray et al., 2014)

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**Environmental + Model outputs**

- **Species**
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Results for trait related to mobility

Significance (p-value) of the bivariate associations between traits and environmental variables (results from the fourth-corner tests). Significant associations correspond to p values <0.05

- Mean summer bottom shear stress
- Annual range of $[O_2]_{\text{bottom}}$
- Total Phosphorus in the sediments
- Water Depth
Mapping of Ecological Traits

LOCAL Trait-environment relationships

Map- ECOSYSTEM

?
Mapping of Ecological Traits

LOCAL Trait-environment relationships

Map - ECOSYSTEM

?  Temperature  Currents  Oxygen  Salinity  ...

TRAITS MAPS

Grégoire et al. (MAST,ULg)  Modelling Hypoxia & GES  IWMO, Bologna, May 2016
Mapping of Ecological Traits: Mobility

**Mobility**

- Oxygen range
- Shear stress
- Total Phosphorus
- Depth

- Degree of Attachment
- Adult Mobility
- Adult life habit

3D Ocean model

SOM Analysis of significantly correlated variables

**Graphs:**
- Depth [m]
- Range [O₂] [mmol/m³]
- Summer Mean τ [N/m²]

**Legend:**
- High Mobility, Free living, Crawler, No Att.
- Burrower, Temporary attached
- Sessile, tube-dwelling, attached, no mobility

Grégoire et al. (MAST,ULg)
Modelling Hypoxia & GES
IWMO, Bologna, May 2016
Mapping of Ecological Traits: Mobility

**Mobility**

- Oxygen range
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Degree of Attachment | Adult Mobility | Adult life habit

3D Ocean model → SOM Analysis of significantly correlated variables

Graphs showing:
- Depth in meters
- Range of oxygen in mmol/m³
- Summer mean stress in N/m²

**Map**

Mobility gradient
Stress gradient

Grégoire et al. (MAST, ULg)
Modelling Hypoxia & GES
IWMO, Bologna, May 2016
From Traits to Ecological Processes

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Increasing activity

Increasing impact on the sediment turnover
From Traits to Ecological Processes

Per capita effect of each species on sediment mixing (Solan et al. 2004)

\[ BP_i = \sqrt{B_i \cdot M_i \cdot R_i} \]

### Per capita effect of each species on sediment mixing

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Community-level bioturbation potential

\[ B_{Pc} = \sum_{i=\text{species}} \sqrt{B_i \cdot M_i \cdot R_i} \]
Multiple linear regression

\[
\log(BP_c) = f(\text{OrgC}, \text{Hypoxia index}, \tau, \text{depth})
\]

\[
(R^2 = 0.77)
\]
Multiple linear regression

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Variability of biogenic mixing length
Multiple linear regression

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\( R^2 = 0.77 \)

Variability of biogenic mixing length

Inclusion in the model \( \rightarrow \) revised shelf budgets
BENTHOX: Impact of low oxygen concentrations on Biogeochemistry and biodiversity

Field Experiments and laboratory analyses

- **Benthic Fluxes:** Incubation, microprofiling
- **Macrobenathos:** Van Veen grabs
- **Diagenesis:** Porewater profiles, solid phase
- **Sediment cores analyses:** reconstructing the past

Model development and simulations

Scenarios Management recommendations

- **Methodology and diagnostics definition** for assessing the Good Environmental Status of marine waters.
- **Projections at the horizon 2020 and 2050**

Habitat modeling
Thanks for your attention ... ... and questions

More info on:

- Seasonal hypoxia on the northwestern shelf:
  Capet et al, 2013, *Biogeosciences*

- Benthic-Pelagic coupling in the model:
  Capet et al, 2016, *Ocean Modelling*

- Decline of the Black Sea oxygen inventory:
  Capet et al, 2016, *Biogeosciences*