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From Scylla to Charybdis: Eutrophication and climatic drivers of hypoxia in the Black Sea northwestern Shelf
What is hypoxia?

Hypoxic threshold: $[O_2] < 62 \text{ mmol/m}^3 (2 \text{ mg/l})$
Why does hypoxia occurs?
Deep basin: permanent anoxia below ~150/200 m
Seasonal Hypoxia

Hypoxic threshold: $[O_2] < 62 \text{ mmol/m}^3 \ (2 \text{ mg/l})$
Seasonal Hypoxia

Phytoplankton growth

Respiration

Hypoxic threshold: \([O_2] < 62 \text{ mmol/m}^3 (2 \text{ mg/l})\)
Seasonal Hypoxia in the BS-NWS

Fig 15. Expansion of seasonal hypoxic and anoxic zones on the north-western shelf (from Zaitsev, 1992a).
Recovery?

Oxygen records
(World ocean atlas, Seadatanet, Black Sea Commission data)

Hypoxic records
(<62 mmol O/m³)
Studying Hypoxia with a 3D model
GHER 3D biogeochemical model

River inputs
(nutrients, freshwater, suspended matter)

Atmospheric model & data
GHER 3D biogeochemical model

River inputs (nutrients, freshwater, suspended matter)

Atmospheric model & data

Surface fluxes (heat, momentum, nutrients, oxygen, freshwater)

Hydrodynamics → Currents, mixing, T, S

[Diagram showing hydrodynamics with images for April, May, and June]
GHER 3D biogeochemical model

River inputs (nutrients, freshwater, suspended matter)

Atmospheric model & data

Surface fluxes (heat, momentum, nutrients, oxygen, freshwater)

Hydrodynamics → Vertical and lateral transport, T°

36 state variables

3 phyto. Groups
4 zoo groups.

C, N, P, Si, O
GHER 3D biogeochemical model

Atmospheric model & data

River inputs (nutrients, freshwater, suspended matter)

Hydrodynamics → Vertical and lateral transport, $T^\circ$

Surface fluxes (heat, momentum, nutrients, oxygen, freshwater)

36 state variables

C, N, P, Si, O

Light penetration

Photosynthesis, respiration, Bacterial loop, Chemistry

3 phyto. Groups

4 zoo groups.

Anoxic Chemistry
GHER 3D biogeochemical model

Atmospheric model & data

River inputs (nutrients, freshwater, suspended matter)

Hydrodynamics → Vertical and lateral transport, $T^\circ$

Surface fluxes (heat, momentum, nutrients, oxygen, freshwater)

36 state variables

3 phyto. Groups
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C, N, P, Si, O

Light penetration

Photosynthesis, respiration, Bacterial loop, Chemistry

Organic matter deposition.

Resuspension by waves and bottom stress.

Benthic diagenesis → Diffusive fluxes.

(Stanev and Kandilarov, 2012; Soetart, 2000)

Anoxic Chemistry
Model validation

Does the model adequately resolve ...

- the horizontal distribution
- the seasonal distribution
- the interannual distribution
- the vertical distribution
- the specific occurrence of hypoxia

... reflected by in situ observations?
Model validation

Does the model adequately resolves ...

- the horizontal distribution
- the seasonal distribution
- the interannual distribution
- the vertical distribution
- the specific occurrence of hypoxia

... reflected by in situ observations?

Yes, yes, yes, yes, yes and yes
Model Validation : Point-to-point

Merged by months → validation of the seasonal cycle

Hypoxic records- [%]
(<62 mmol O/m³)

[O₂] – [mmol/m³]

b)
Interannual variability

[Graph showing interannual variability with time series data from 1980 to 2010. The y-axis represents [O²] - [mmol/m³] with values ranging from 200 to 350. Two lines are plotted: one for observations (red dotted line) and one for a model @ observations (blue dotted line).]
Interannual variability
The H-index

An Index to quantify the intensity of hypoxia as an environmental pressure on ecosystems

The H-index express the spatial extension of hypoxia..
.. modulated by the duration of hypoxia
Interannual variability of Hypoxia
Interannual variability of Hypoxia

What are the drivers of this interannual variability?
Interannual variability of Hypoxia

Eutrophication and climate

(1) High nitrogen riverine discharge.
(2) High sedimentary organic carbon content.
(3) Warm springs.
(4) Warm summers.

36 %
27 %
82 %

Explained variance (R²)
36 %
27 %
82 %
Can we exploit this knowledge for management purposes?
Hypoxia response to N discharge

Includes the year specific influences of climatic and sediments drivers
Hypoxia response to N discharge

Response curve for average atmospheric conditions (1980-2009)

Area affected by hypoxia [$10^3 \text{ km}^2$]

Nitrogen discharge by the rivers - [Gmol N /yr]

Past years (1981-2009)

Average atmospheric conditions (1980-2009)
These average atmospheric conditions are not valid anymore.
Hypoxia as a function of N

Area affected by hypoxia [10^3 km^2]

Nitrogen discharge by the rivers - [Gmol N/yr]

- Past years (1981-2009)
- 1981-2009
- 2015-2020
The cost of warming

![Graph showing the relationship between hypoxia and nitrogen loads.]
The cost of warming

Current Nitrogen loads

Environmental cost
20% increase of Hypoxia

(= +3% of the shelf area)
The cost of warming

Current Hypoxia level

Economical cost
24% reduction of nutrient loads

Nitrogen loads
Conclusion

Climate warming strongly enhances the threat of hypoxia.
Climate warming strongly enhances the threat of hypoxia.

→ The management of hypoxia through restriction of nutrient loads should account for climate warming.
Climate warming strongly enhances the threat of hypoxia.

→ The management of hypoxia through restriction of nutrient loads should account for climate warming.

= Adaptive Policies
Interannual variability of Hypoxia

(1) High nitrogen riverine discharge enhance the influx of organic matter to bottom waters
(2) High sedimentary organic carbon content enhances the benthic oxygen consumption.
(3) Warm springs reduce the ventilation and set summer bottom temperature.
(4) Warm summers extend the duration of the stratified period.

Oxygen exchange with Atmosphere

Depth - [m]

Jan  Feb  Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec
Take-home Messages (3)
Take-home Messages (1/3)

Hypoxia is still ongoing in the Black Sea NWS

Monitoring should be focused on the area, months and depth of known hypoxia occurrence
Take-home Messages (2/3)

Hypoxia is intensified by year-to-year accumulation of organic matter in the sediments.

Systems with decreasing N $\rightarrow$ inertia in the recovery process.
Systems with increasing N $\rightarrow$ increase of the H/N ratio. *(Turner, 2008)*
Take-home Messages (3/3)

Climate impacts almost as much as eutrophication.

Nutrient reduction policies should account for realistic climatic scenarios.
Thank you for your attention.
... and questions!

Organic matter accumulates in the sediments

C - [mmolC/m²]

- C from 3D model
- parametric model based on N history ($R^2 = 0.95$)

N → $N_{eq}$

$C_{eq}$ - [mmolC/m²]

5 10 15 25 40 60 80

Model Validation: Point-to-point
\[ D = \frac{1}{\max A(t)} \int_{\text{year}} A(t) \, dt, \]

\[ H = \frac{1}{D} \int_{\text{year}} A(t) \, dt, \]
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Recovery?

1980-1987
5826
<2mg/l: 50

1988-1995
7647
127

1996-2002
981
0

2003-2009
339
0

Hypoxic areas - [10^3 km^2]

Mee 2006
present study
UkrSCES 2002

Recovery?

1980-1987

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0

a)

b)

Hypoxic areas - [10^3 km^2]


Mee 2006

present study

UkrSCES 2002
The Model

**36 States variables**

- **Physics (5)**
  - Currents, T°, Salinity, Surface elevation, Turbulence

- **Oxygen and Dissolved Inorganic Carbon (2)**

- **Inorganic nutrients (5)**
  - SiO, NO₃, NH₄, PO₄, "Reducers"

- **3 Phytoplankton (6) (free C/N)**
  - Diatoms, Flagellates, Small Flagellates

- **Zooplankton (2)**
  - Micro-, Meso-

- **Gelatinous zooplankton (2)**
  - Omnivorous, Carnivorous

- **Detrital matter (8)**
  - Particulate, Semi-labile and Labile forms
  - Silicious Detritus, Aggregates

- **Bacteria (1)**

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**Monthly RIVERS fluxes and nutrients flows** (from L. Wolfgang & A. Cociasu)

31 double-sigma layer

6h-atmospheric forcings from ECMWF (1.125°)

(from ERA40)
Model's Specificity

- **No data assimilation**: Necessity to construct specific Bosphorus representation to ensure conservation of volume and total salt content.

- **Anoxic waters**: The biological model explicitly includes anoxic chemistry through the use of a variable 'Oxygen demanding Units', as a proxy for reducers acting in the anoxic zone.

- **Sediments compartment**

- **Light absorption scheme**