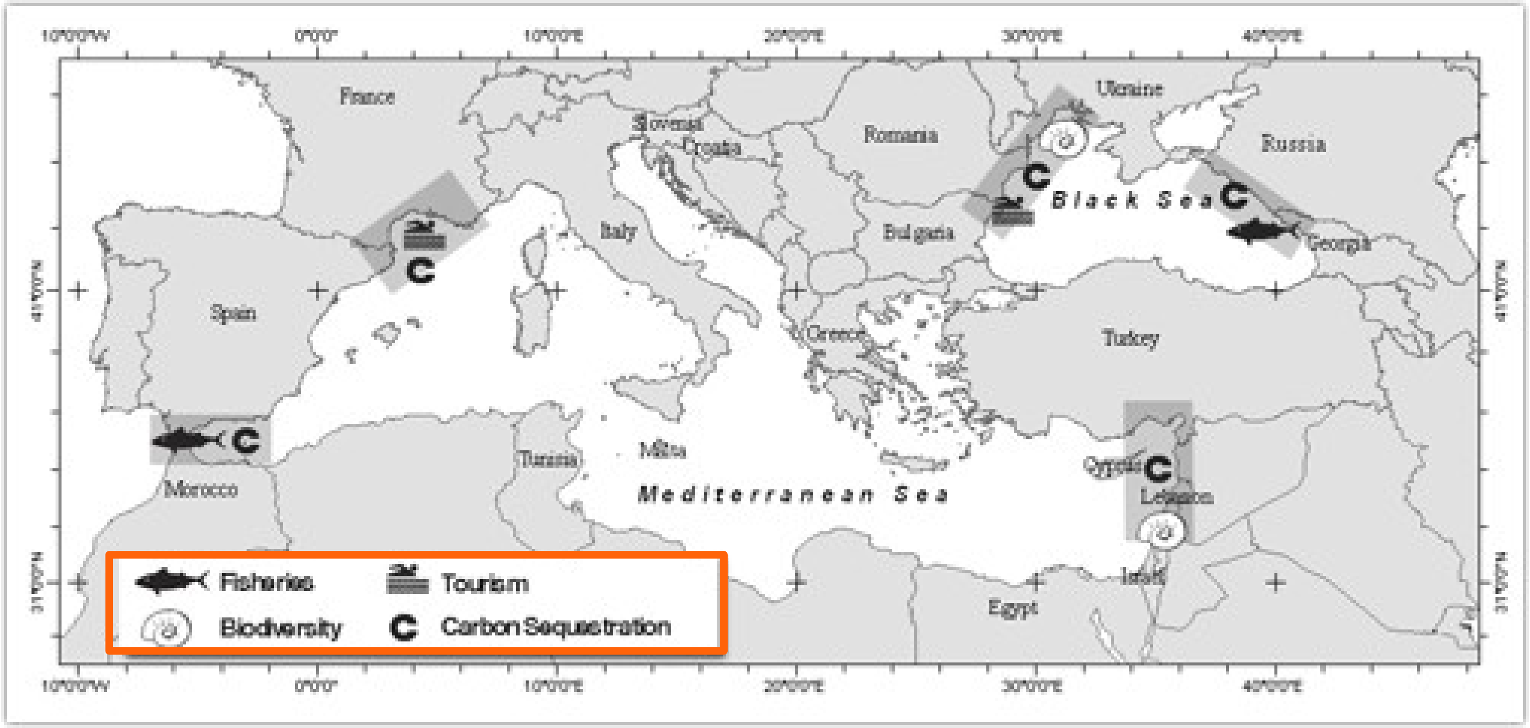
Variability of the Black Sea hydrodynamics and biogeochemistry system.

Arthur Capet; IMEDEA April 2014

Study of the multi-decadal evolution of the **Black Sea** hydrodynamics and biogeochemistry using mathematical modelling

Study of the multi-decadal evolution of the **Black Sea** hydrodynamics and biogeochemistry using mathematical modelling



SESAME
Southern European Seas: Assessing and Modelling Ecosystem changes

Enviromental resources: marine Goods and Services

Study of the multi-decadal evolution of the **Black Sea** hydrodynamics and biogeochemistry using mathematical modelling

The capacity to deliver

Goods and Services

depend on

Environmental status

Goods and Services

- Fisheries
- Biodiversity
- Tourism
- Carbon sequestration
- ...

Environmental status

Study of the multi-decadal evolution of the Black Sea **hydrodynamics** and biogeochemistry using mathematical modelling

Physics

Circulation and mixing of water masses.

Goods and Services

- Fisheries
- Biodiversity
- Tourism
- Carbon sequestration
- ...

Environmental status

- **Hydrodynamics**

Study of the multi-decadal evolution of the Black Sea hydrodynamics and **biogeochemistry** using mathematical modelling

Chemistry and Biology

Cycles of the basic elements of life:

Carbon, **N**itrogen , **O**xygen, **P**hosphorus, **Si**licate

Transport and transformation

- Inorganic (nutrients)
- Living (planktons)
- Detritial (dead cells, faeces)

Goods and Services

- Fisheries
- Biodiversity
- Tourism
- Carbon sequestration
- ...

Environmental status

- Hydrodynamics
- **Biogeochemistry**

Study of the **multi-decadal evolution** of the Black Sea hydrodynamics and biogeochemistry using mathematical modelling

Dynamic system

→ **Physical** and **biogeochemical** characteristics are **variables** in **Space** and **Time**

Multi-decadal: from 1960 to present

External forcings:

- Atmospheric conditions
- Riverine inputs

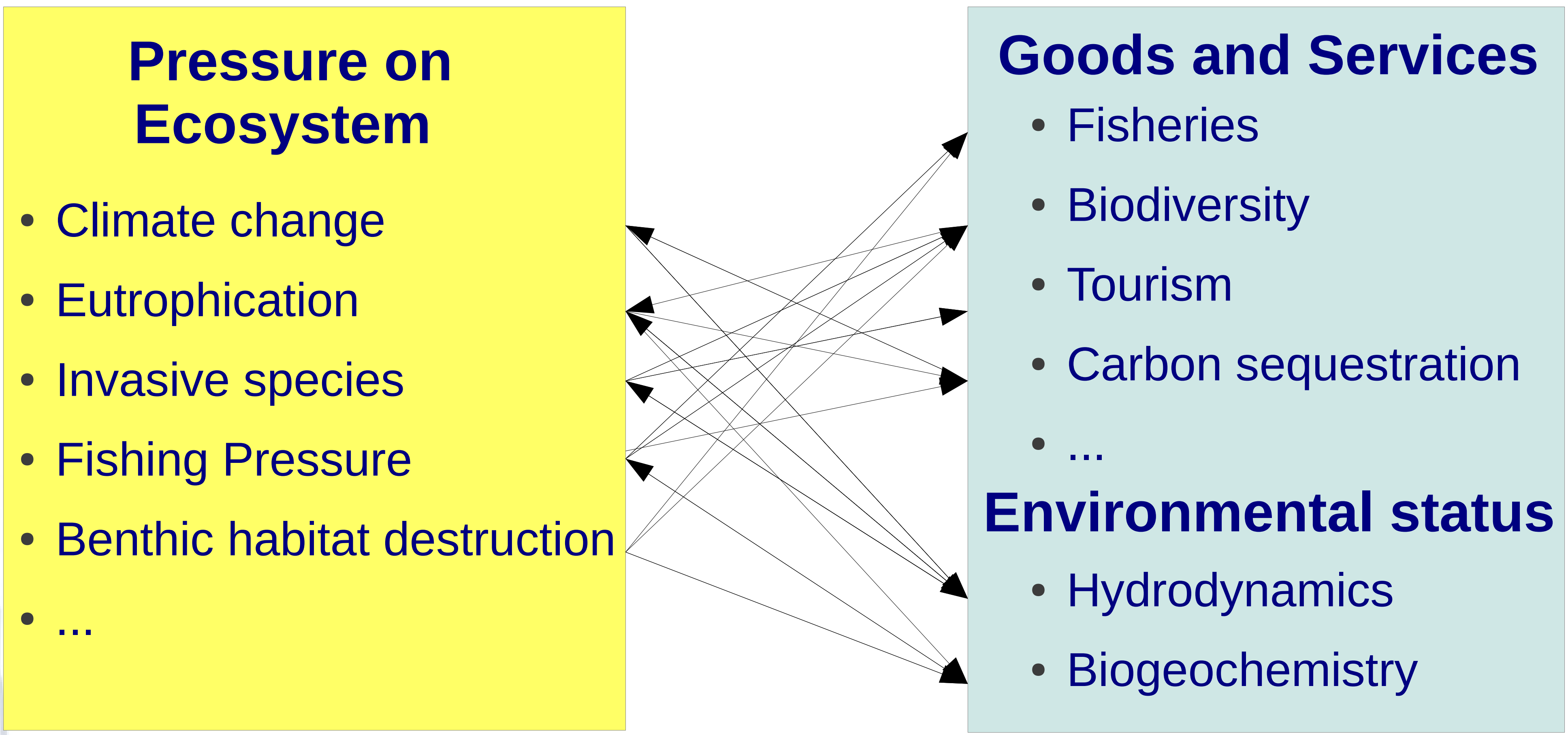
Goods and Services

- Fisheries
- Biodiversity
- Tourism
- Carbon sequestration
- ...

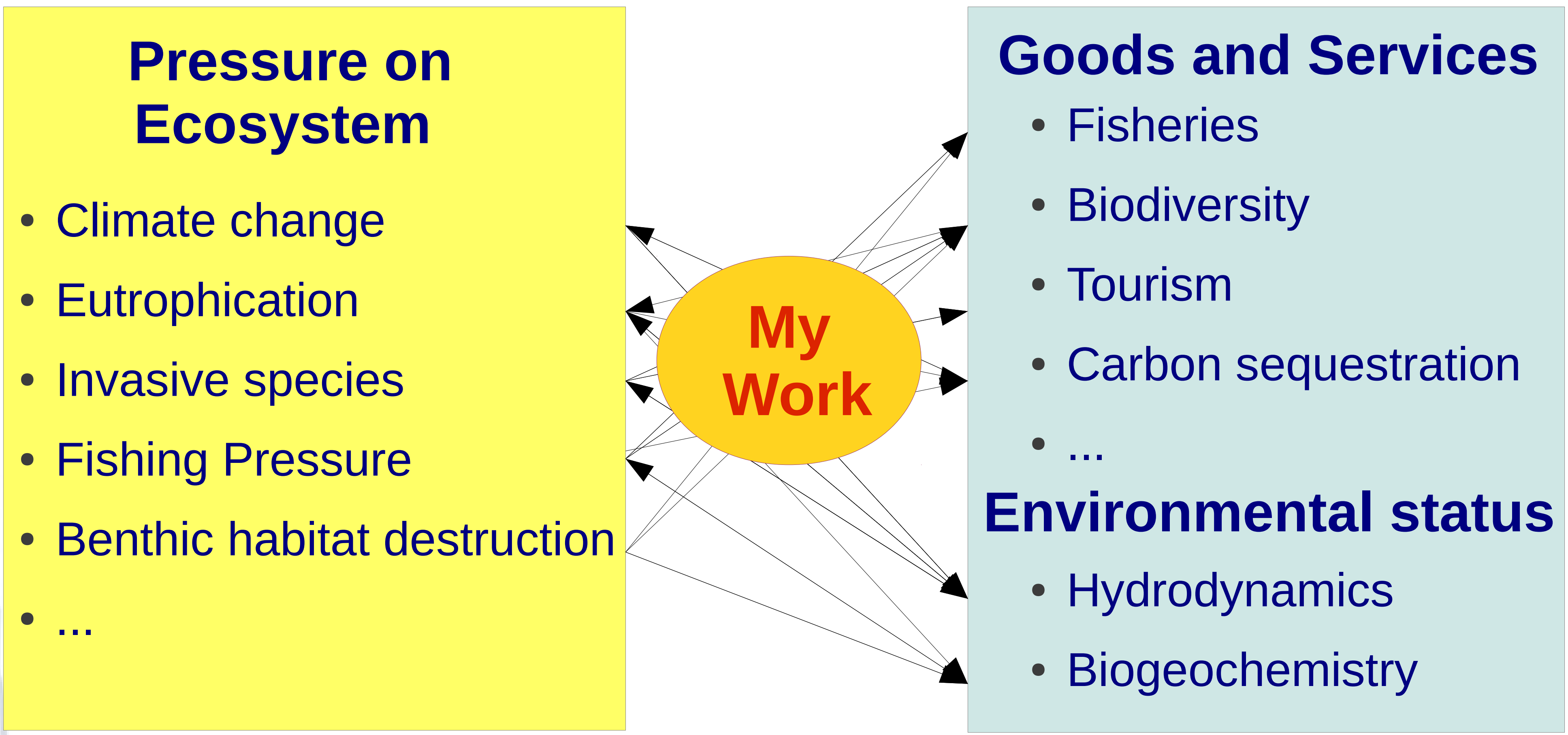
Environmental status

- Hydrodynamics
- **Biogeochemistry**

Study of the **multi-decadal evolution** of the Black Sea hydrodynamics and biogeochemistry using mathematical modelling



Study of the multi-decadal evolution of the Black Sea hydrodynamics and biogeochemistry using **mathematical modelling**



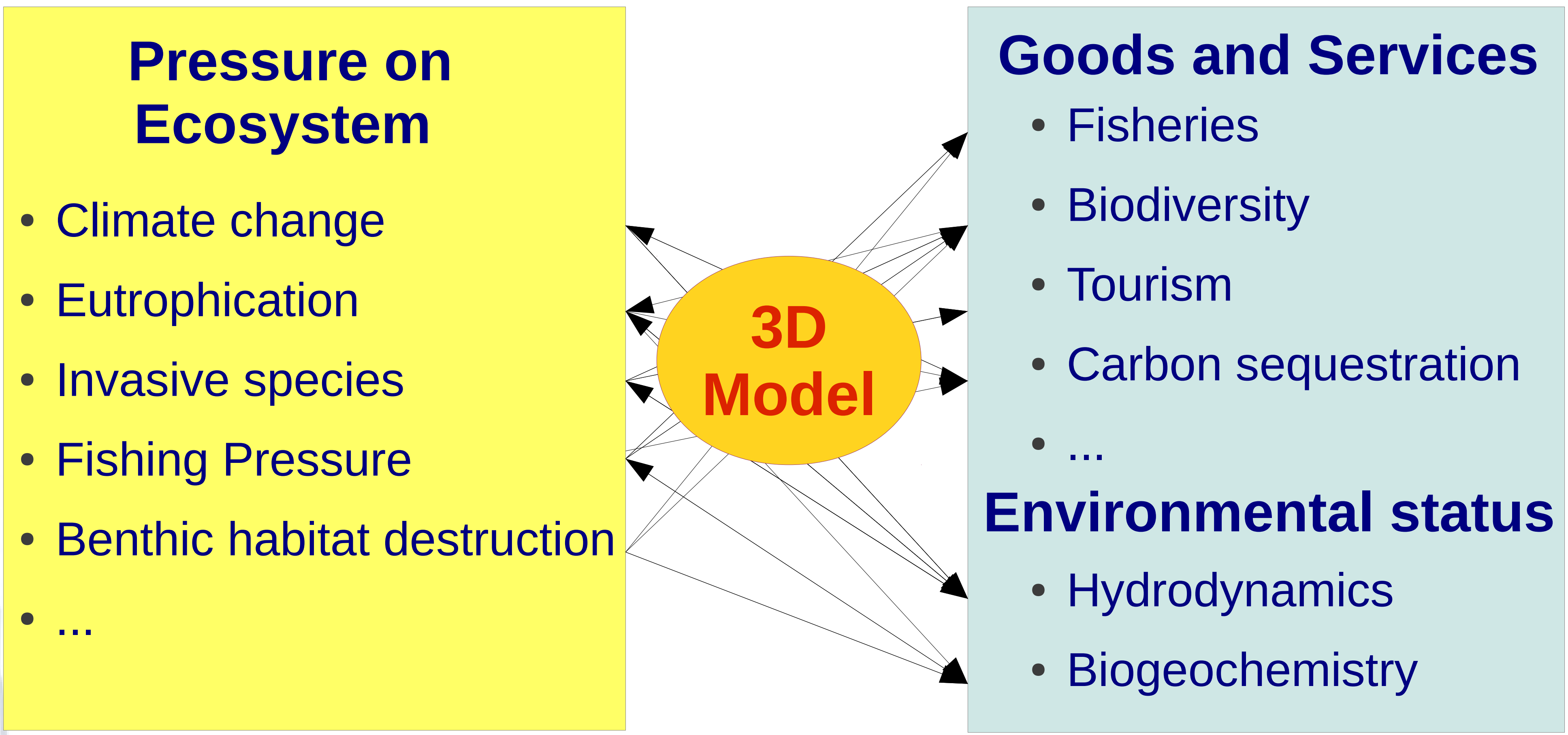
Study of the multi-decadal evolution of the Black Sea hydrodynamics and biogeochemistry using **mathematical modelling**

A computer software to reproduce the dynamics of the Black Sea ecosystem

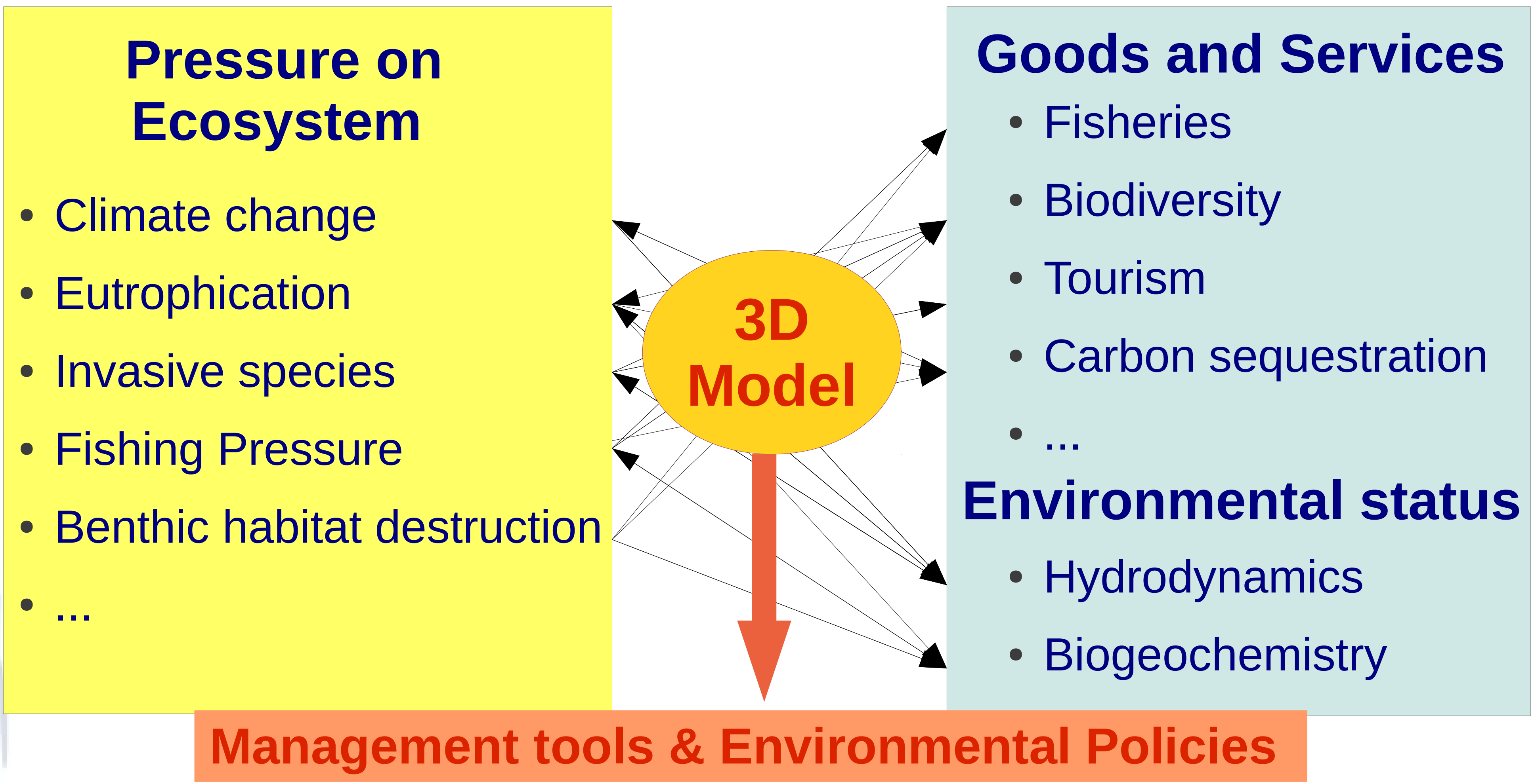
My Work

3D mechanistic model

Study of the multi-decadal evolution of the Black Sea hydrodynamics and biogeochemistry using **mathematical modelling**



Study of the multi-decadal evolution of the Black Sea hydrodynamics and biogeochemistry using **mathematical modelling**



Outline

Hydrodynamics

- Introduction: The Black Sea structure
  - Variability from observations: describe
  - Variability from model: resolve and explain

Biogeochemistry

- Introduction: Hypoxia in the Northwestern shelf
  - Model requirements
  - Dynamics of hypoxia

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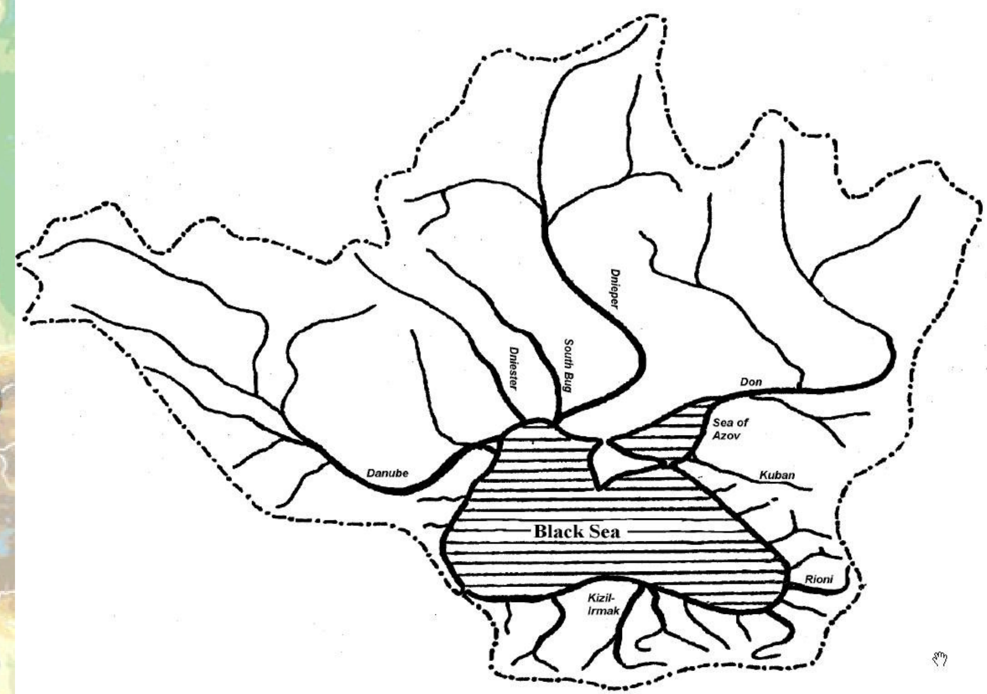
A quasi enclosed basin

The Bosphorus Strait

A large drainage area

→ Large riverine inputs: fresh water and nutrients

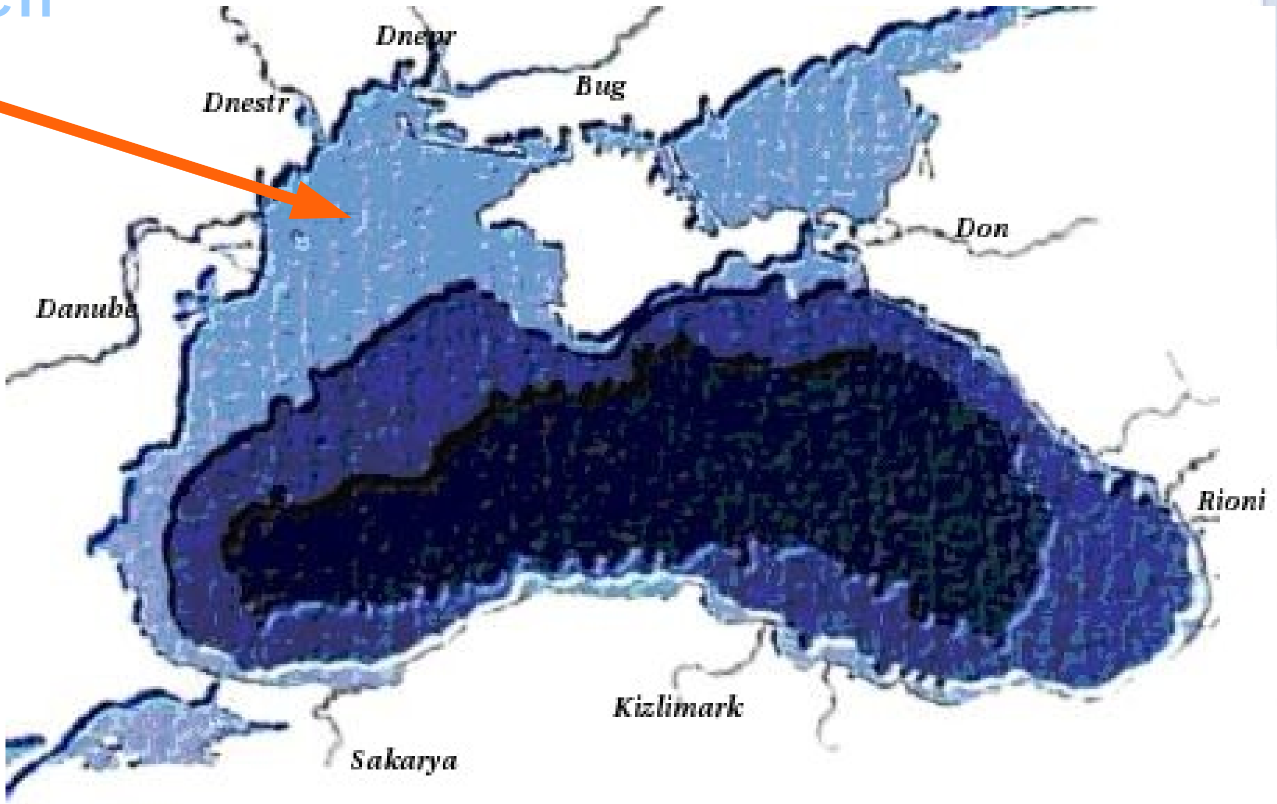


A large drainage area

→ Large riverine inputs: fresh water and nutrients

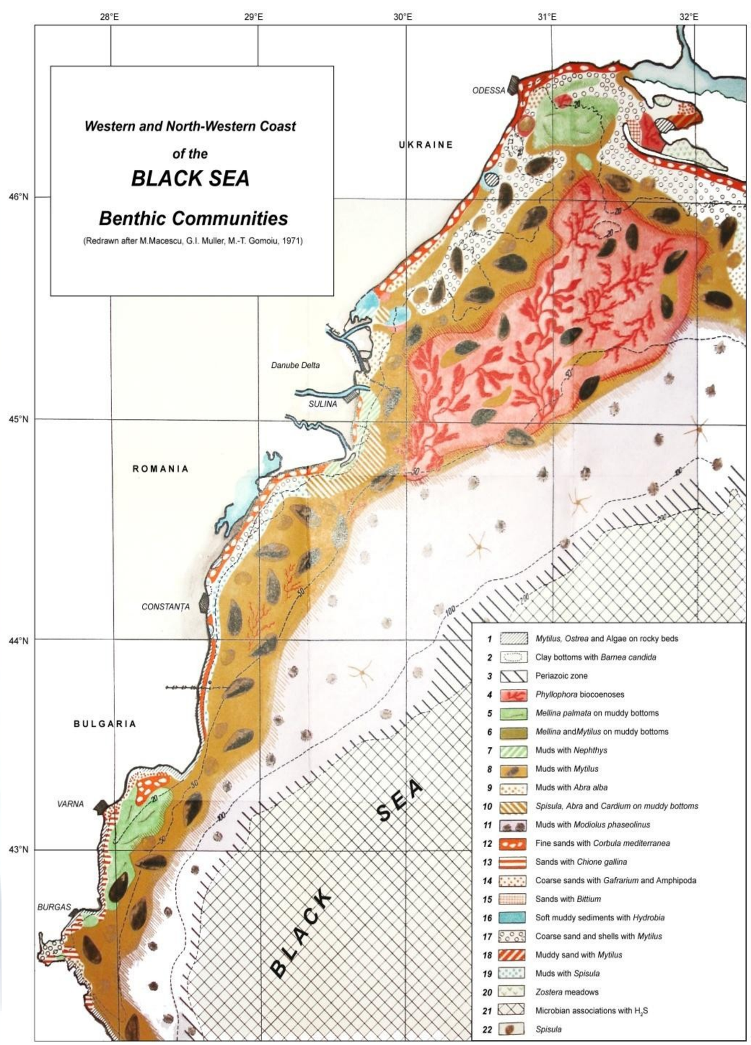
Northwestern Shelf

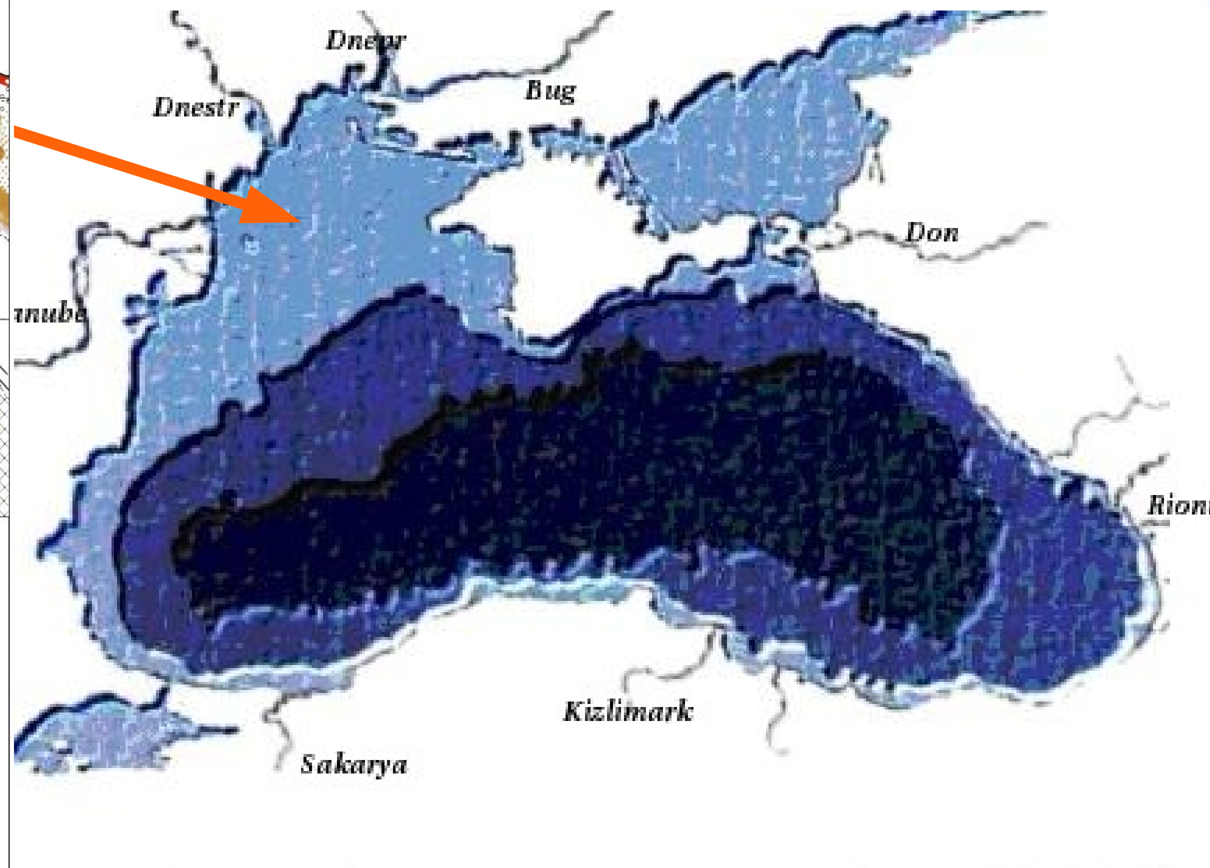
- Shallow (<120 m)
- Rich in nutrients
- Rich ecosystem



A large drainage area

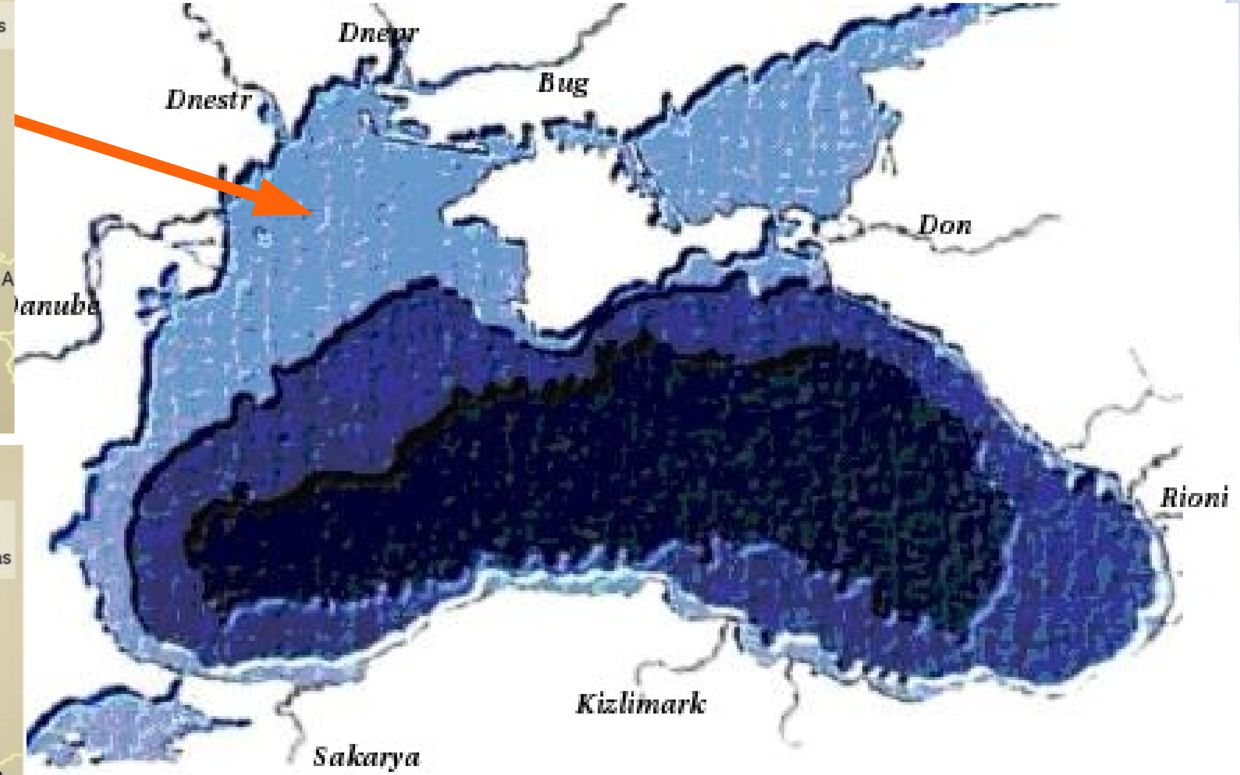
→ Large riverine inputs: fresh water and nutrients





A large drainage area

→ Large riverine inputs: fresh water and nutrients

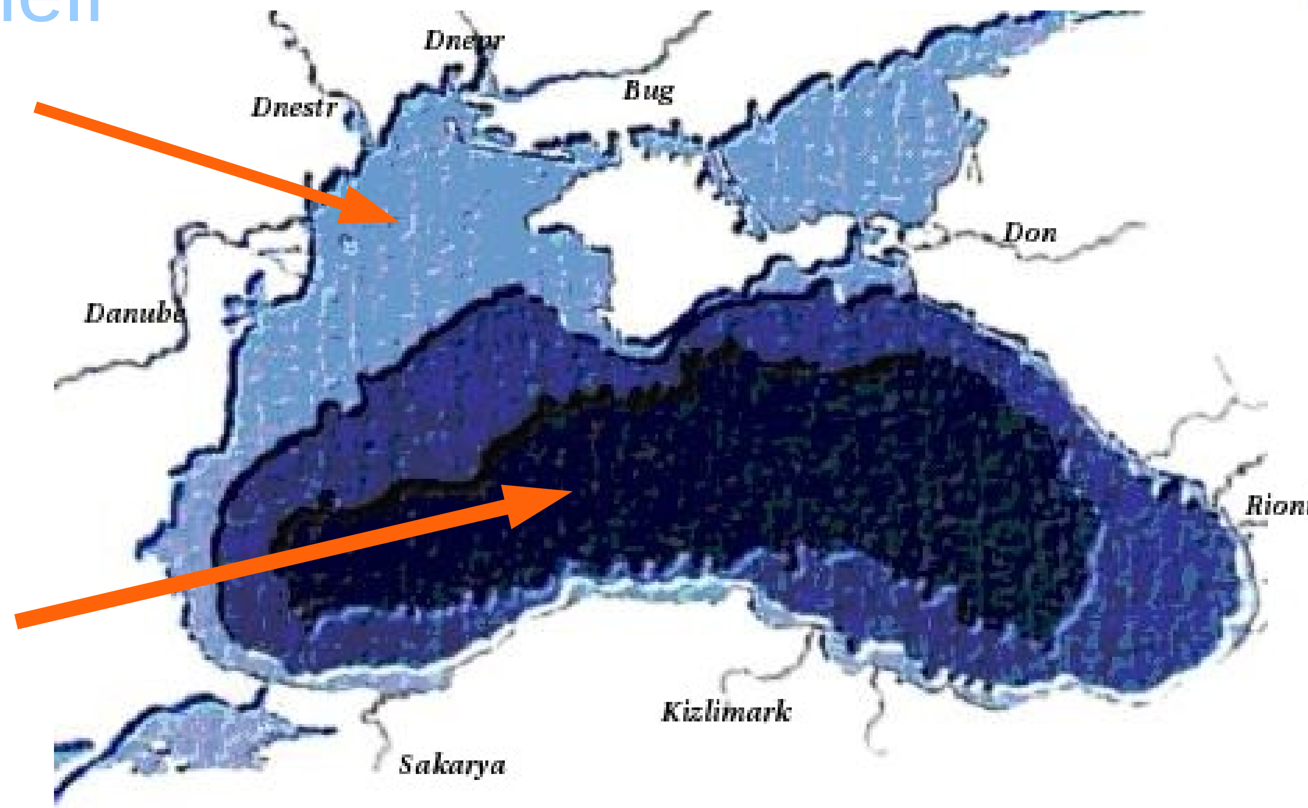


A large drainage area

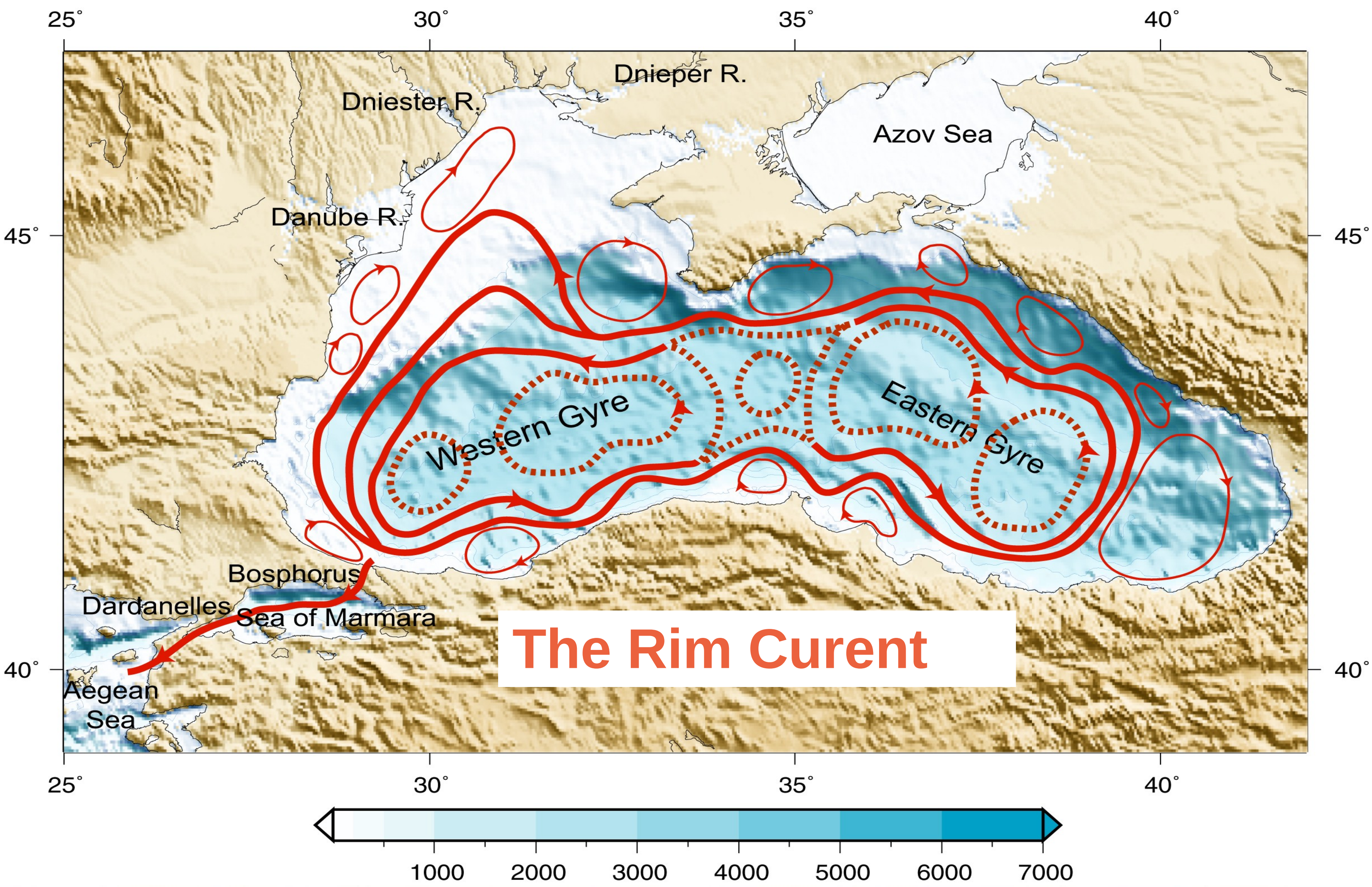
→ Large riverine inputs: fresh water and nutrients

Northwestern Shelf
- Shallow
- Rich in nutrients
- High biodiversity

Central basin
- Deep (>2000m)
- Poor in nutrients

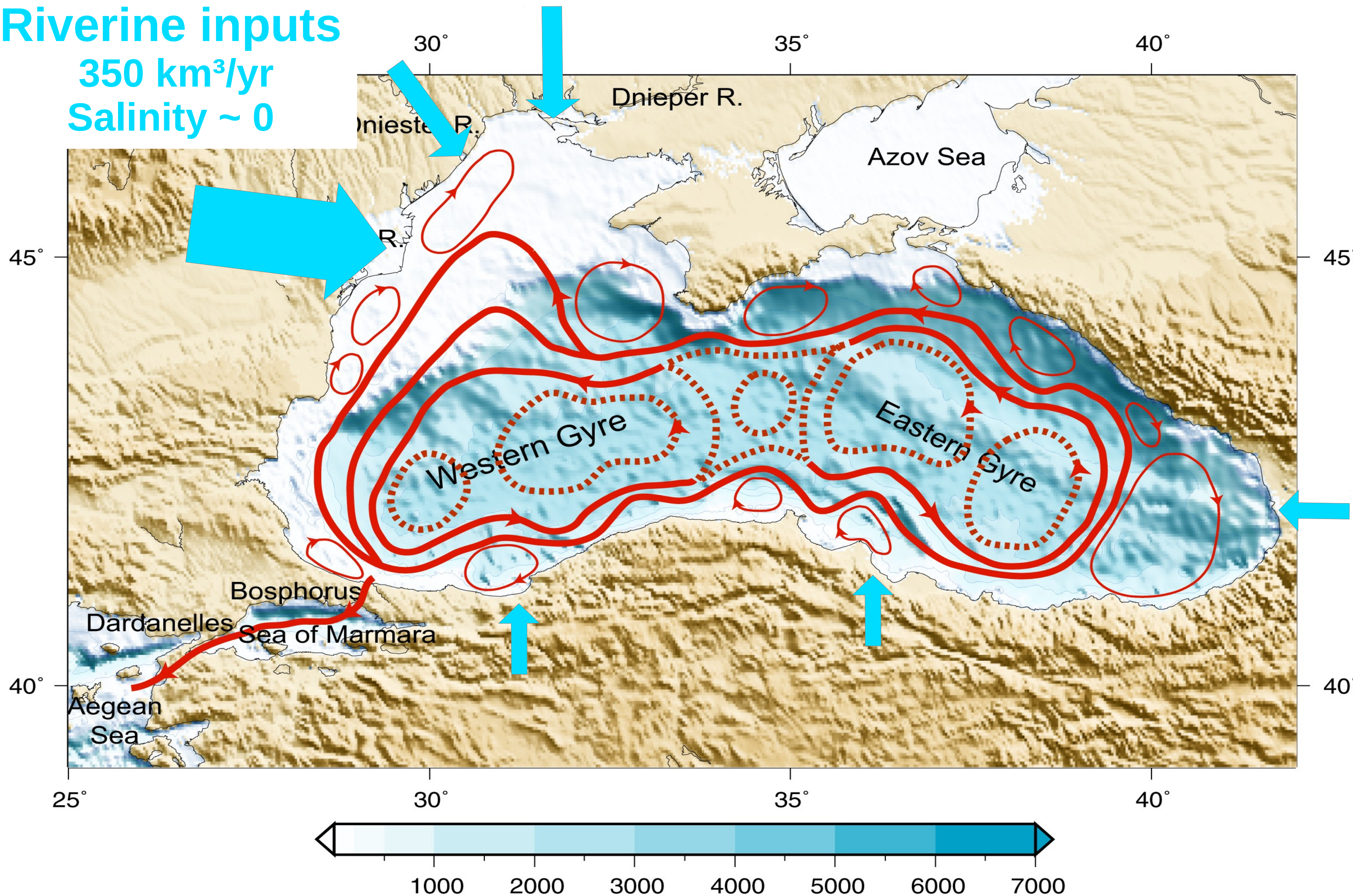


Circulation



Circulation

Riverine inputs
350 km³/yr
Salinity ~ 0



Circulation

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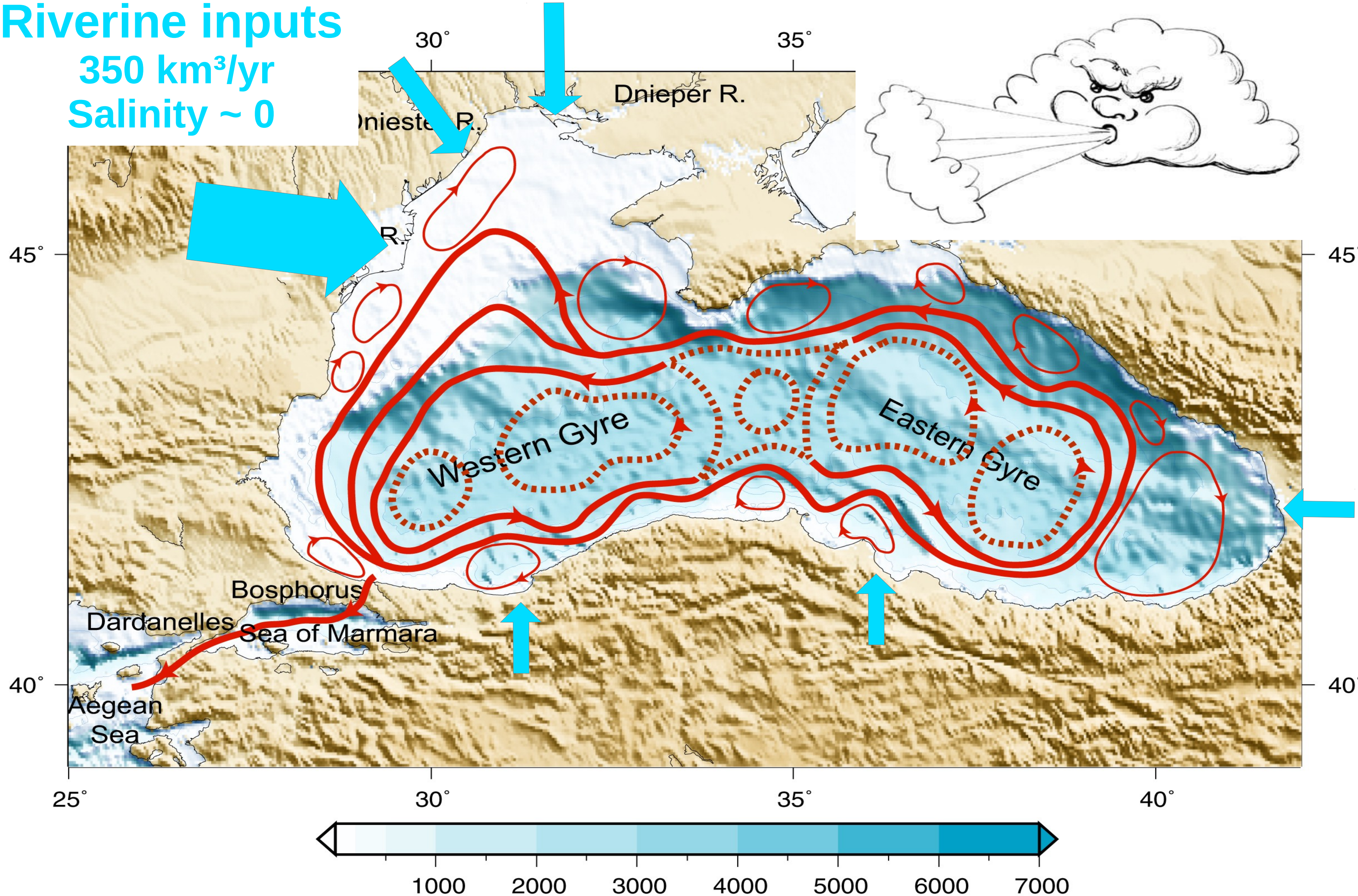
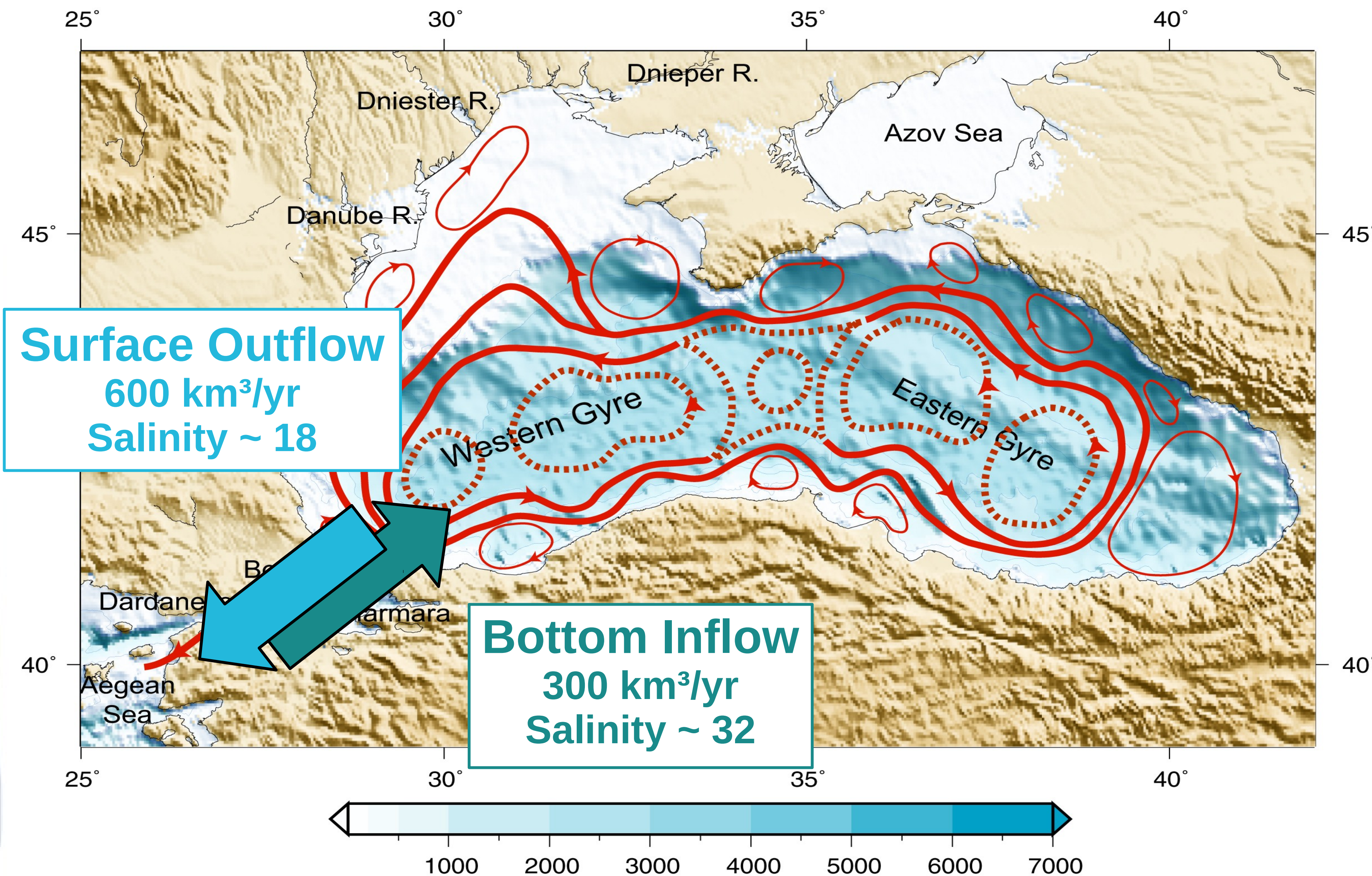
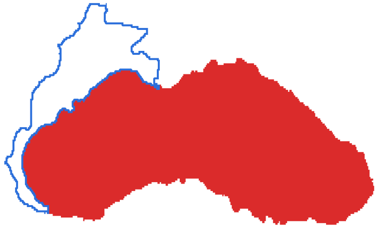
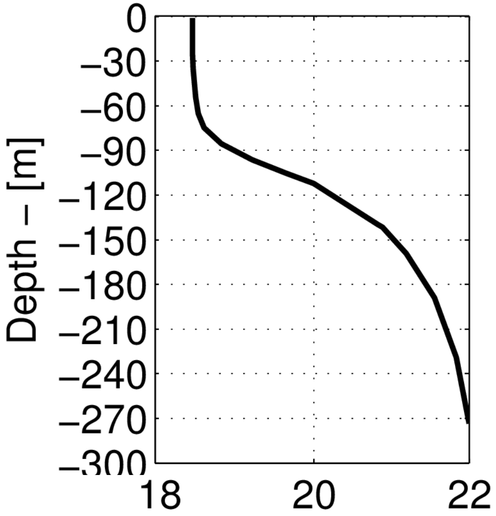


Circulation



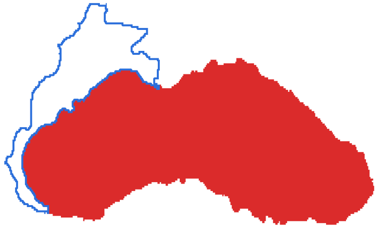
Vertical structure

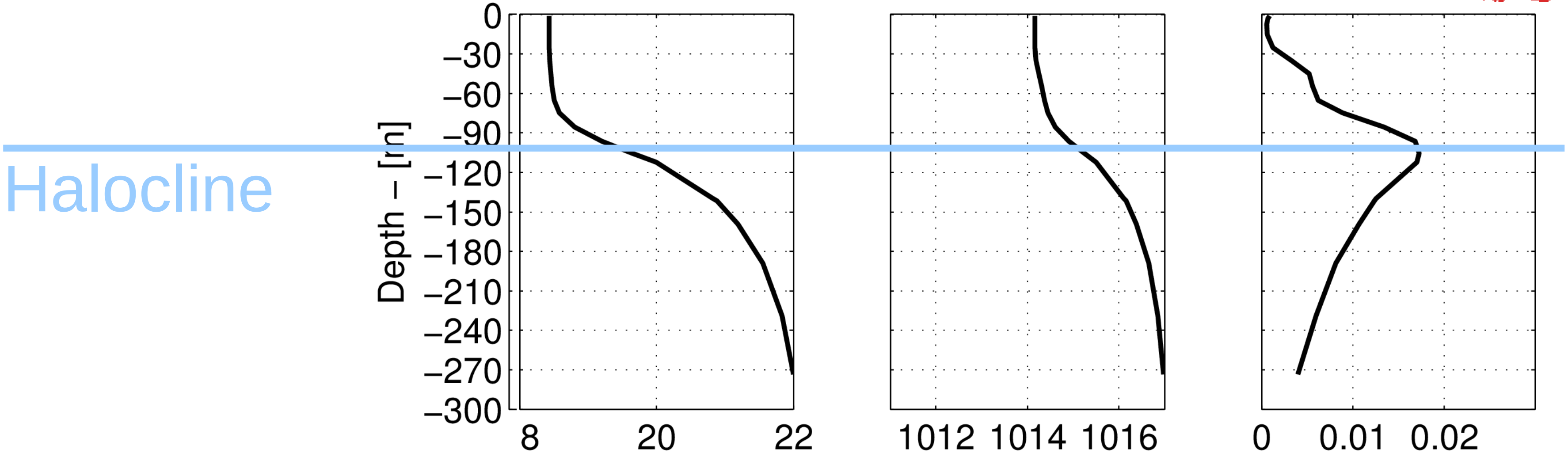




Salinity
[psu]

Vertical structure



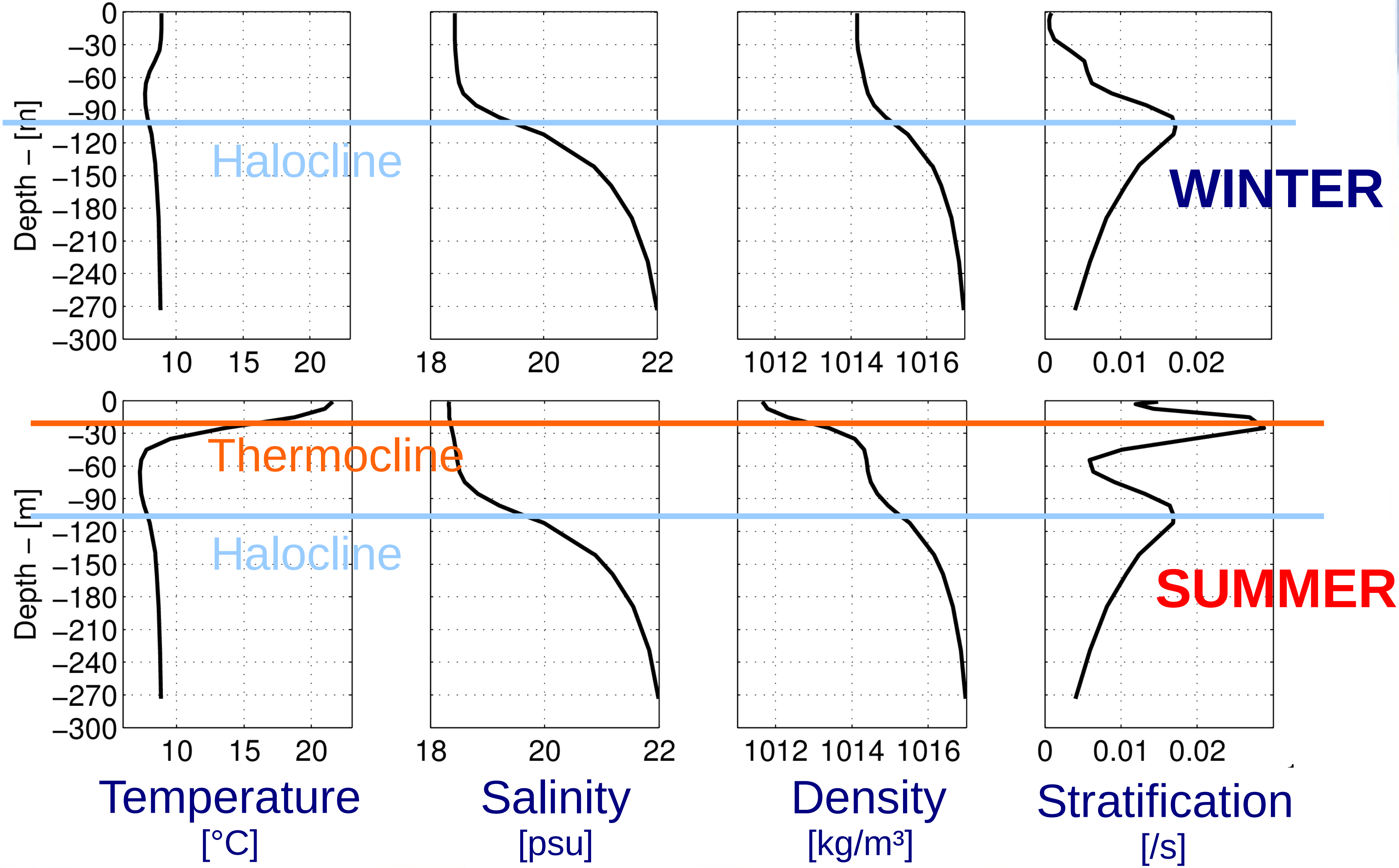


Salinity
[psu]

Density
[kg/m³]

Stratification
[/s]
(Brunt Vaiasala frequency)

Vertical structure



Vertical structure

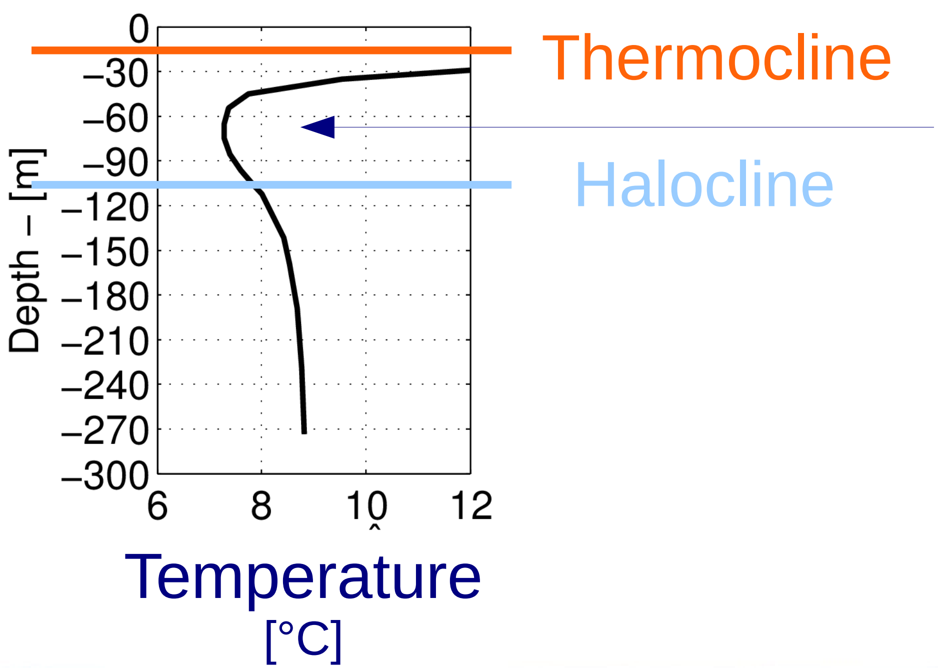
Dense water formation

↓

Convective sinking
blocked by the Halocline

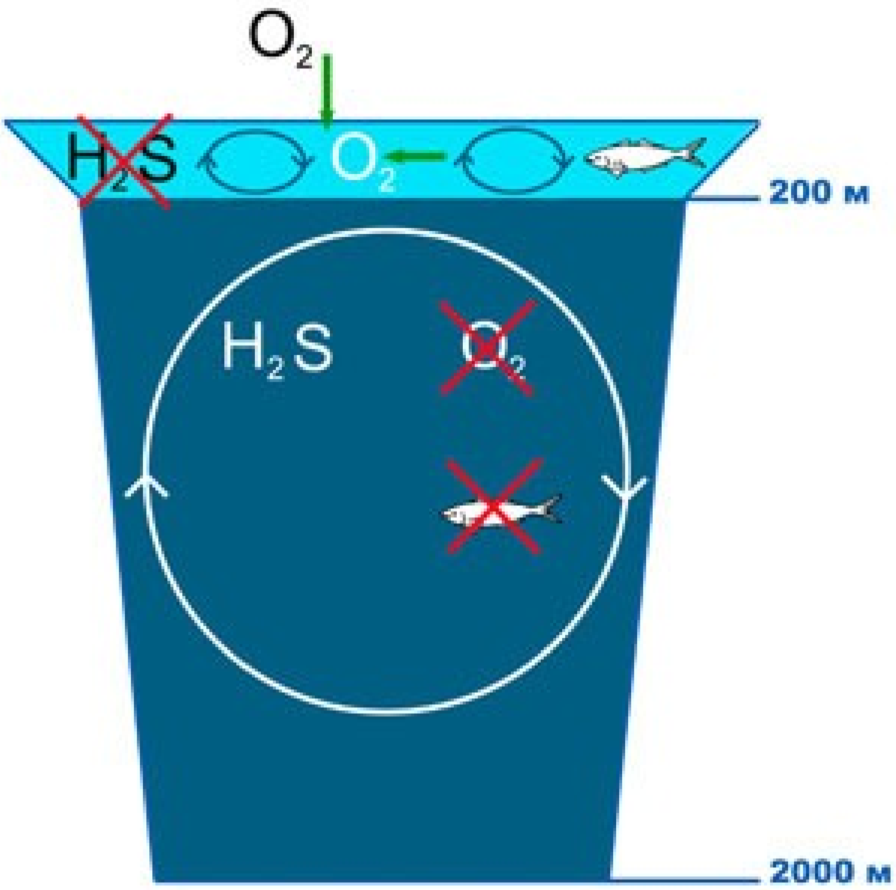
↓

Cold Intermediate Layer



Vertical structure

→ No mixing between surface and deep waters.
→ No oxygen below 200 m



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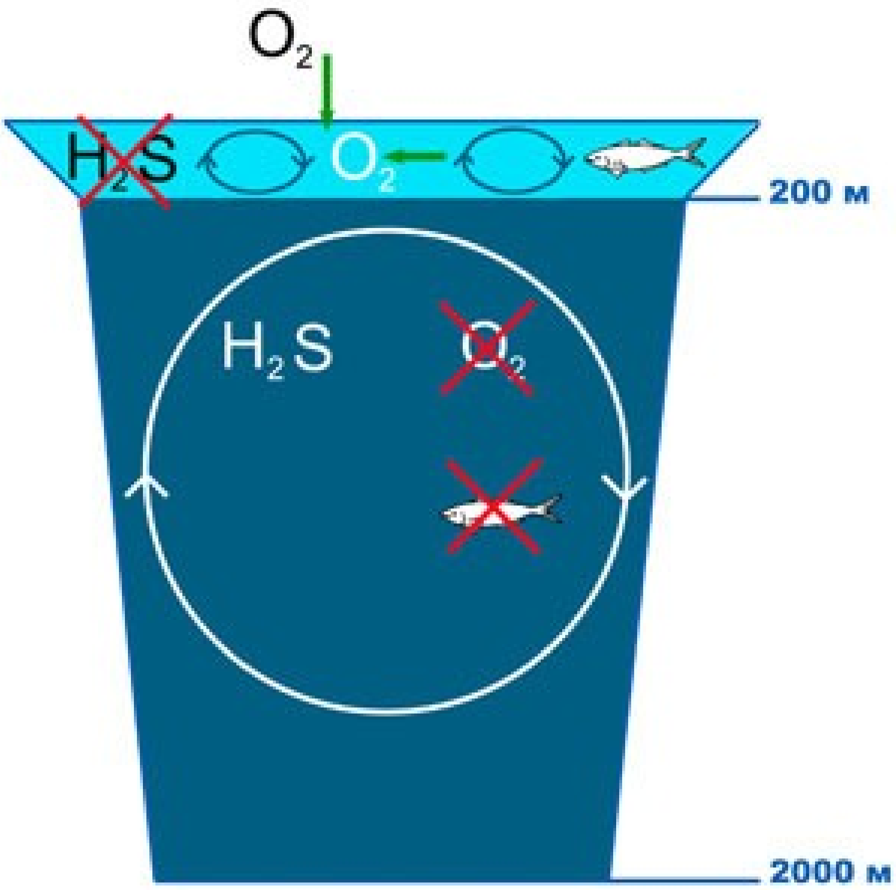

Small active volume
+
Large influence Area
=
Sensitivity to changing external forcings

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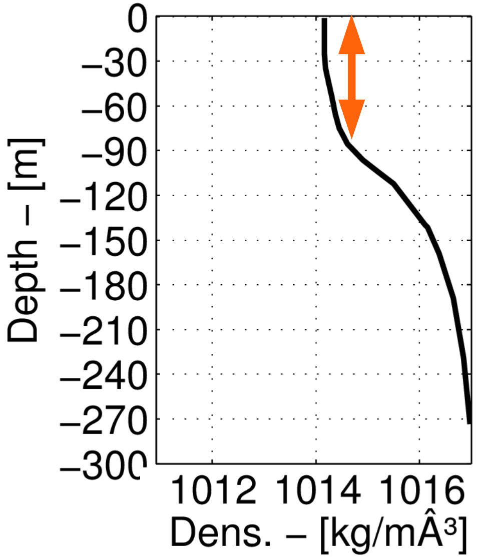
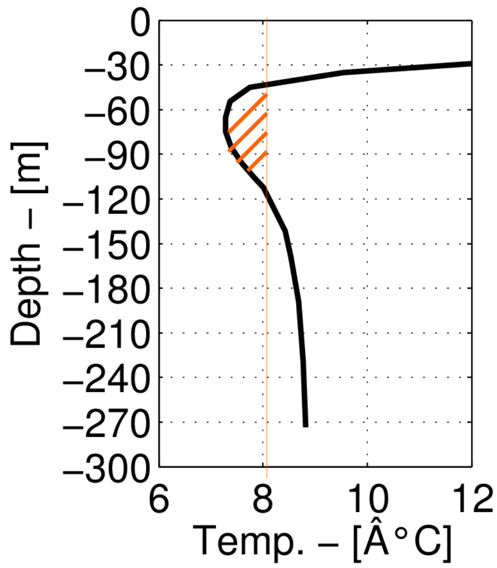
(Capet et al. 2014, Ocean Dynamics)

Vertical profiles → Diagnostics



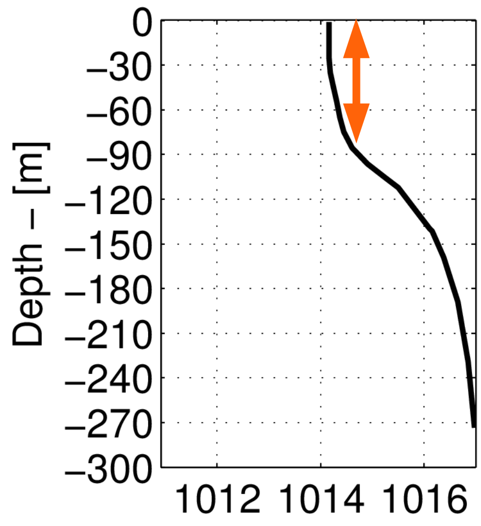
Mixed Layer Depth



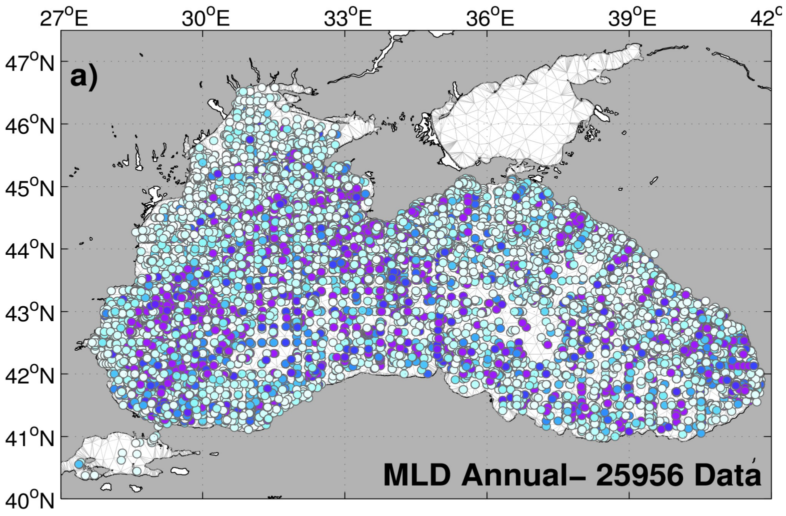
Cold Intermediate layer
cold content

(Capet et al. 2014, Ocean Dynamics)

Vertical profiles → Diagnostics → Spatial variability

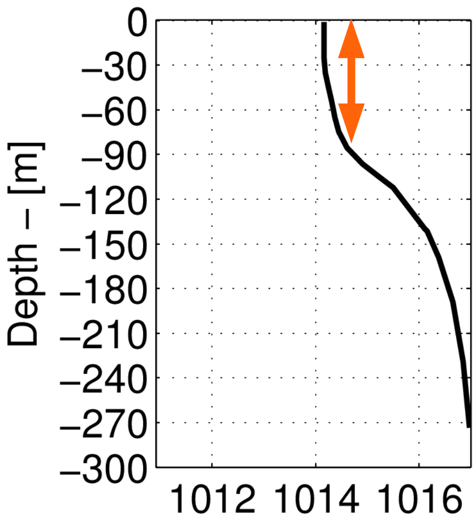


Mixed Layer Depth

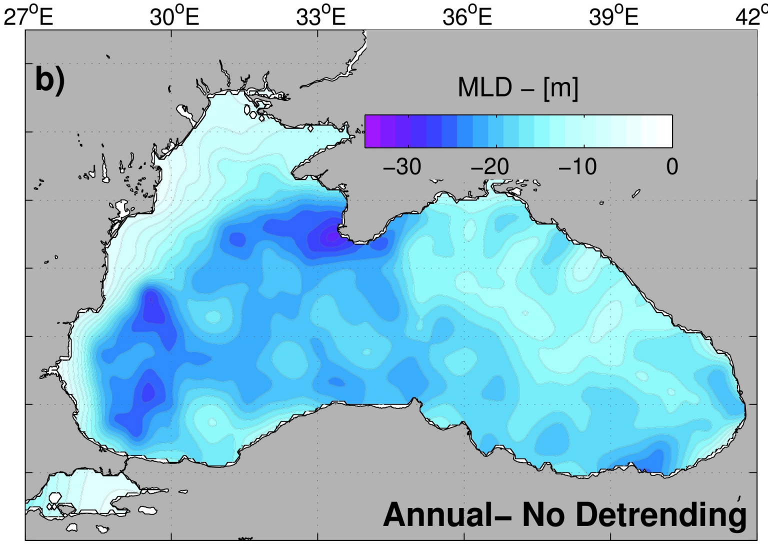


(Capet et al. 2014, Ocean Dynamics)

Vertical profiles → Diagnostics → Spatial variability

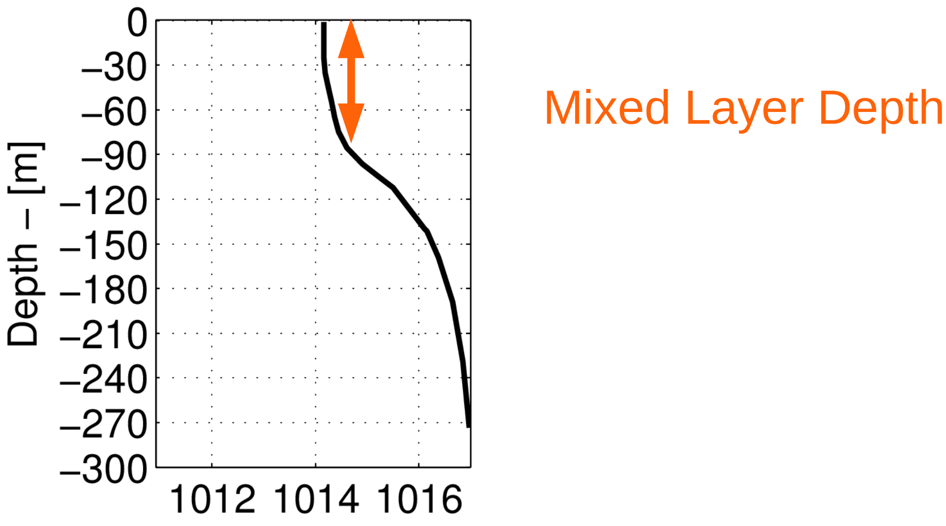


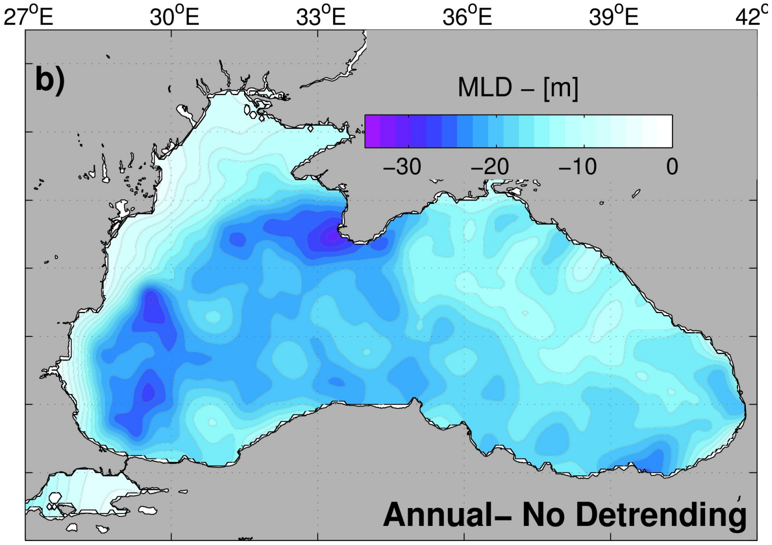
Mixed Layer Depth

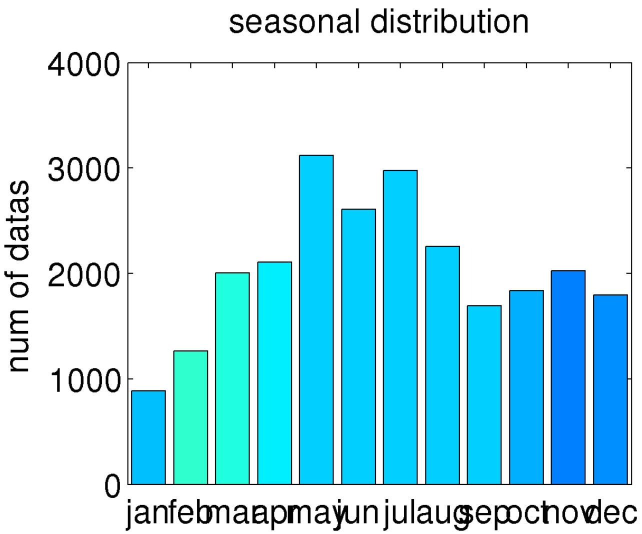


(Capet et al. 2014, Ocean Dynamics)

Vertical profiles → Diagnostics → Spatial variability



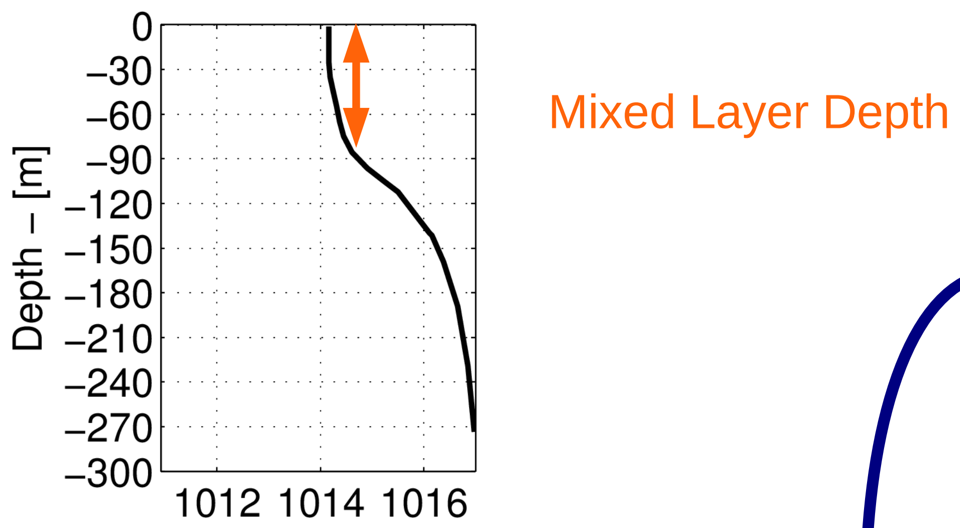


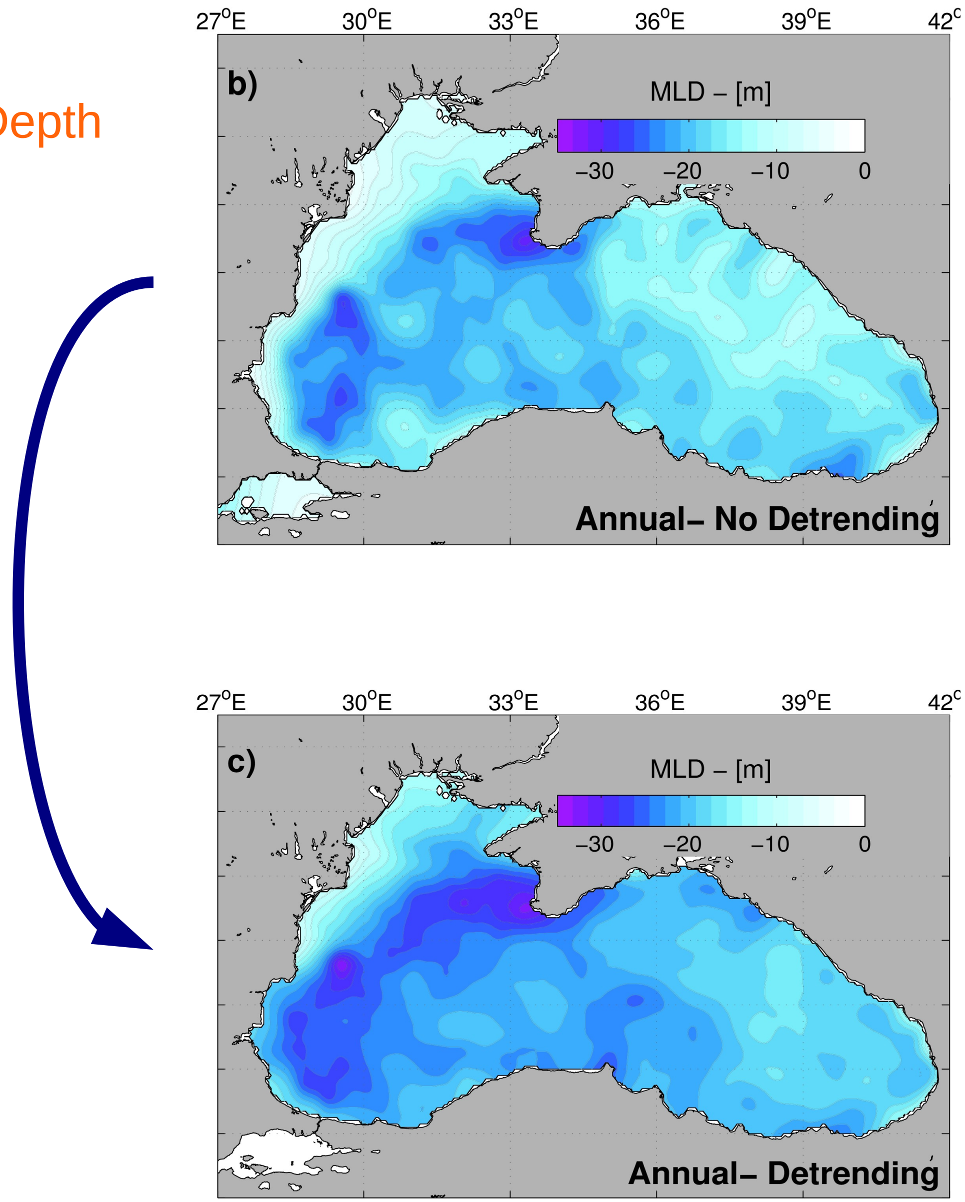


The uneven distribution of data alters the **apparent** variability.

(Capet et al. 2014, Ocean Dynamics)

Vertical profiles → Diagnostics → Spatial variability



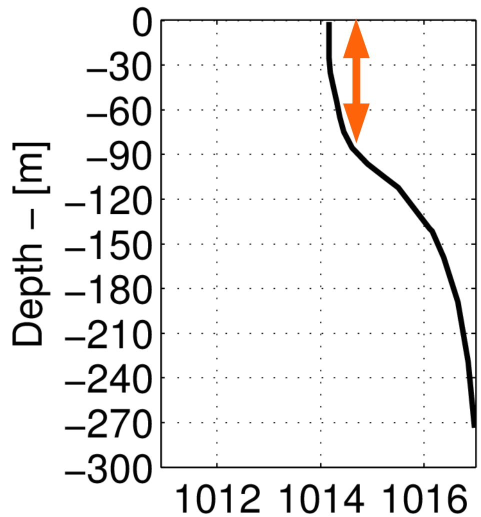


DIVA detrending analysis

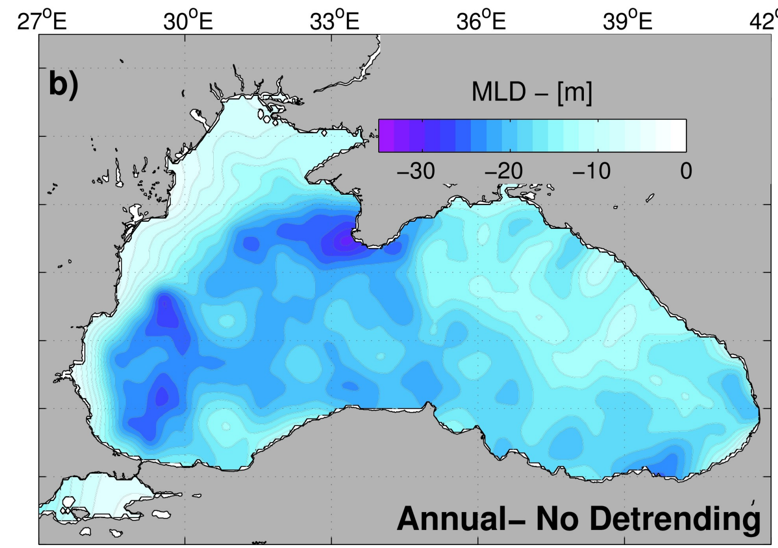
Correct the bias induced by
uneven distribution

(Capet et al. 2014, Ocean Dynamics)

Vertical profiles → Diagnostics → Spatial variability



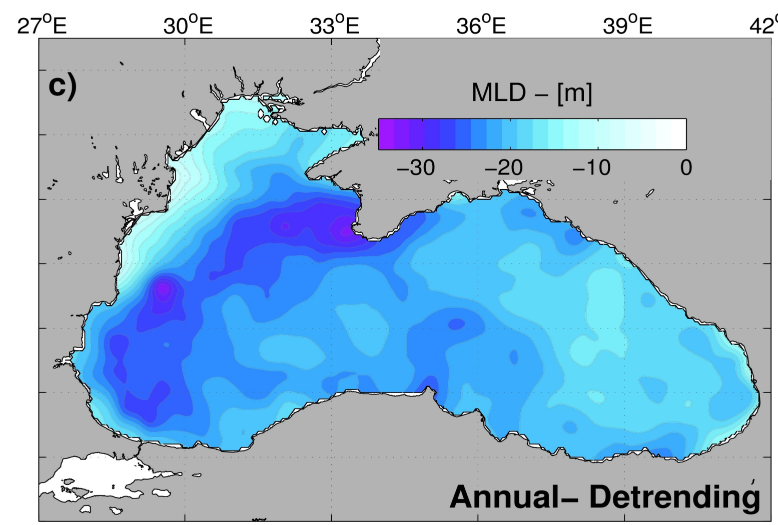
Mixed Layer Depth



DIVA detrending analysis

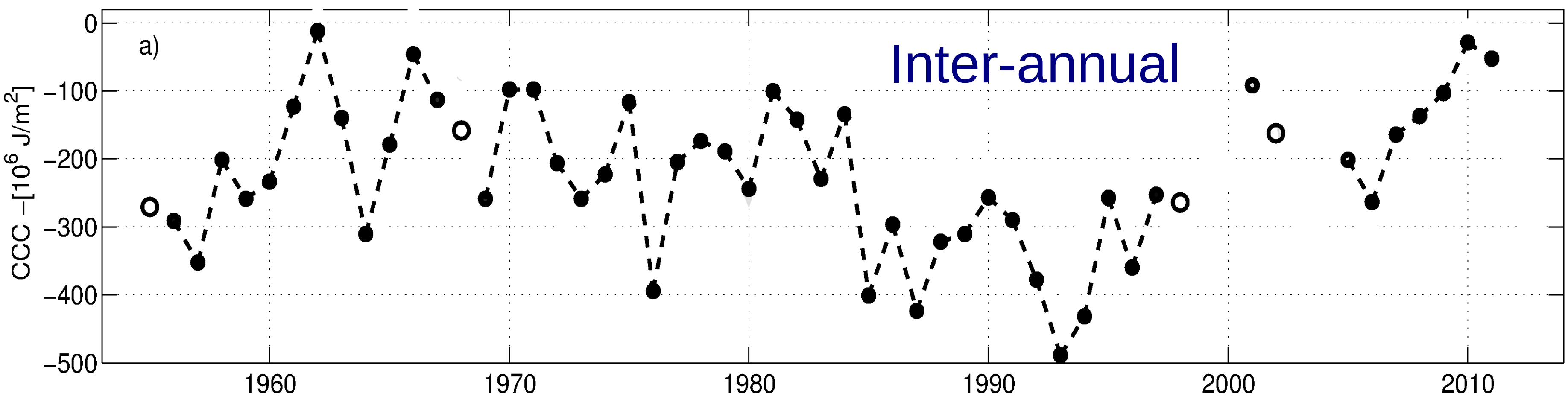
Correct the bias induced by uneven distribution

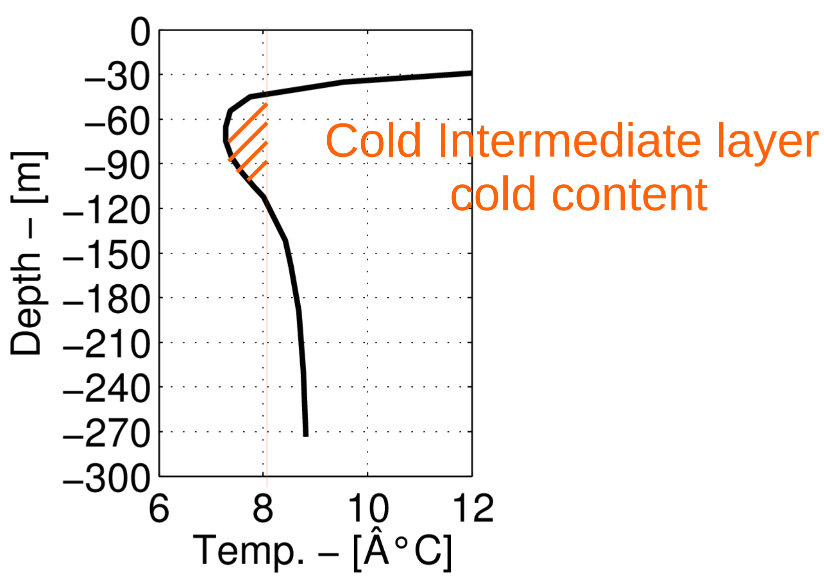
→ Montlhy climatologies of MLD and CCC

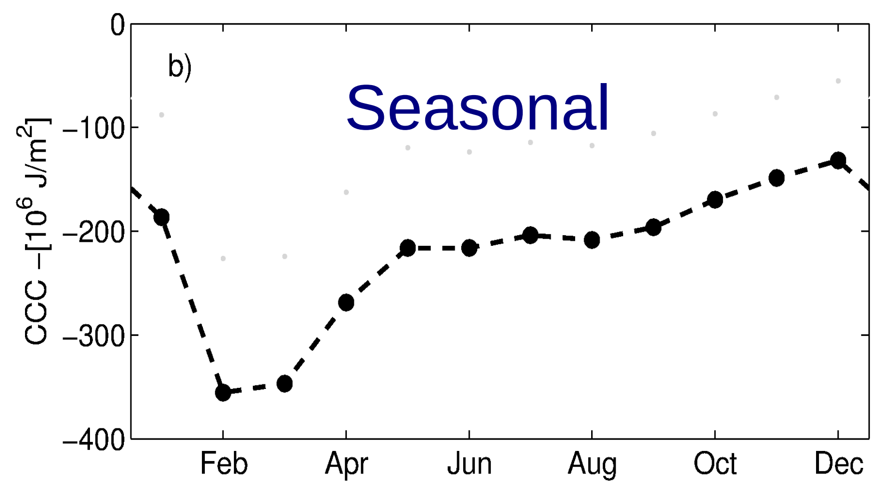


(Capet et al. 2014, Ocean Dynamics)

Temporal variability

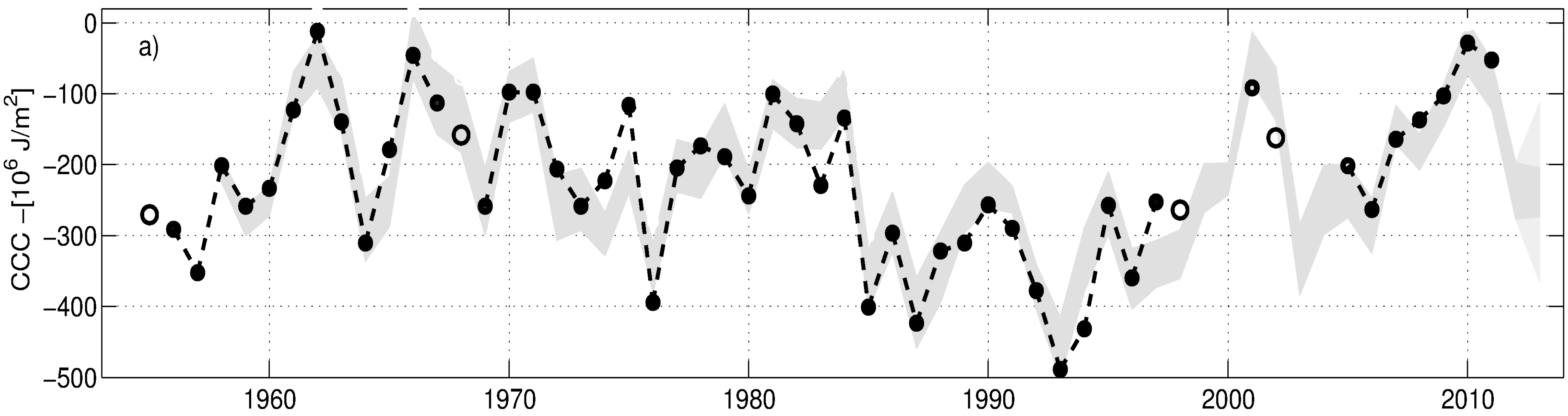


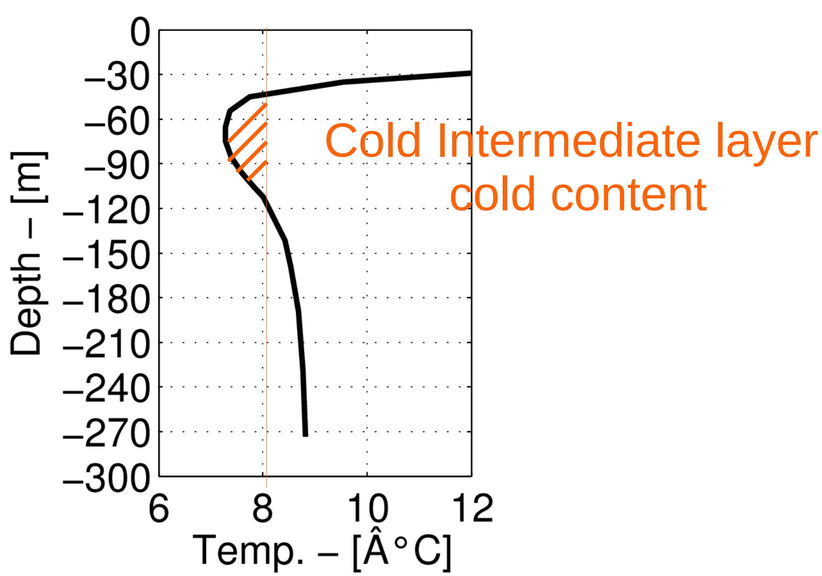




(Capet et al. 2014, Ocean Dynamics)

Temporal variability





Explained by the anomaly of **winter air temperature** cumulated over the 4 past years

(Capet et al. 2014, Ocean Dynamics)

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- Introduction: The Black Sea structure
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- Introduction: Hypoxia in the Northwestern shelf
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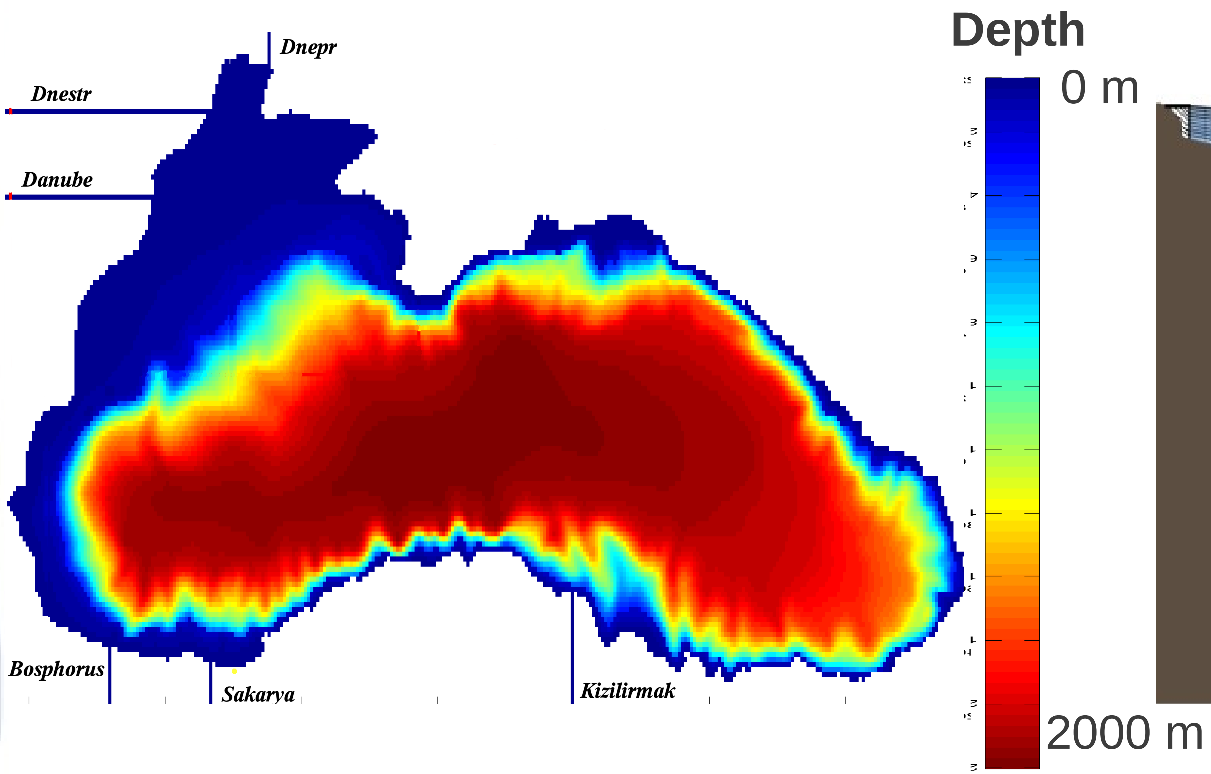
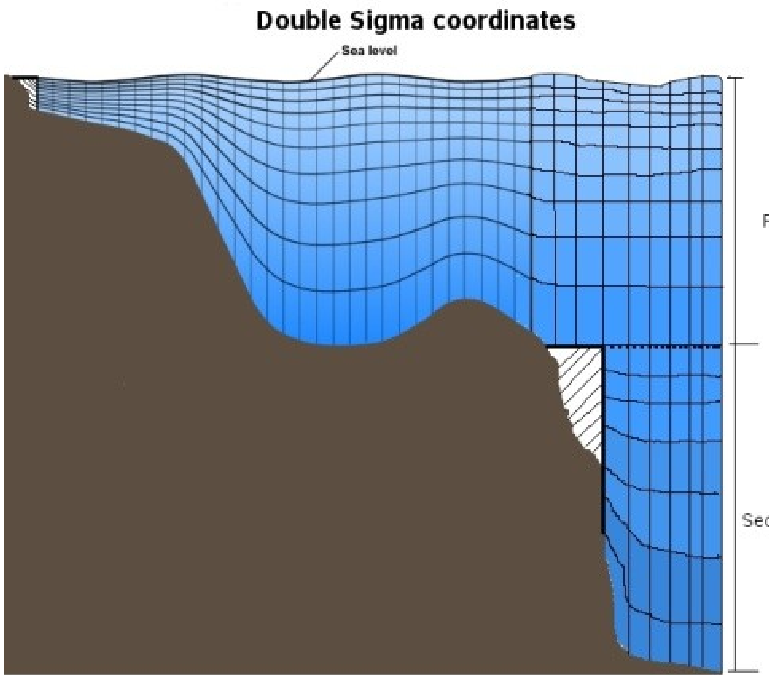
  - Dynamics of hypoxia

To build a hydrodynamic model you need ...

- Domain: Bathymetry, open boundaries.
- State variables: Temp., Sal., Currents, Elevation, Internal turbulence
- Hydrodynamic equations
- External forcings: River flows, Atmospheric conditions





Model experiment

Objective: Relate the variability of the Black Sea structure to the variability of atmospheric conditions

Long term simulation with realistic forcings: 1960-2000

(Capet et al. 2012, Deep-Sea Research II)

Model Diagnostics

- Surface
  - Sea surface temperature (SST)
- Water column
  - Mixed layer depth (MLD)
  - Cold intermediate layer Cold content (CCC)
  - Mean kinetic energy (MKE)

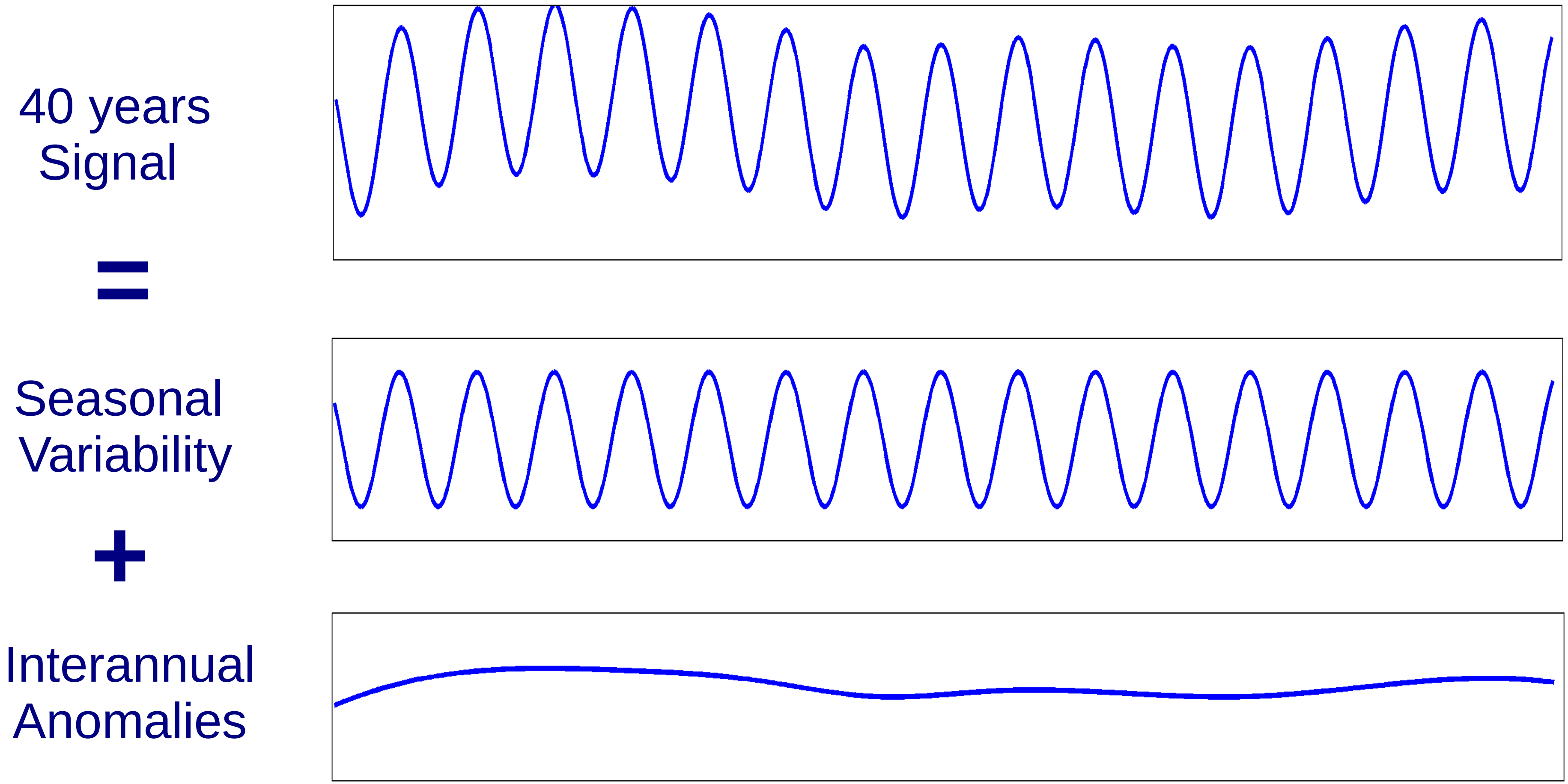
(Capet et al. 2012, Deep-Sea Research II)

Model Diagnostics

- Surface
  - Sea surface temperature (SST) **Satellite**
- Water column
  - Mixed layer depth (MLD)
  - Cold intermediate layer Cold content (CCC)
  - Mean kinetic energy (MKE)

(Capet et al. 2012, Deep-Sea Research II)

Interannual Anomalies



(Capet et al. 2012, Deep-Sea Research II)

Interannual Anomalies

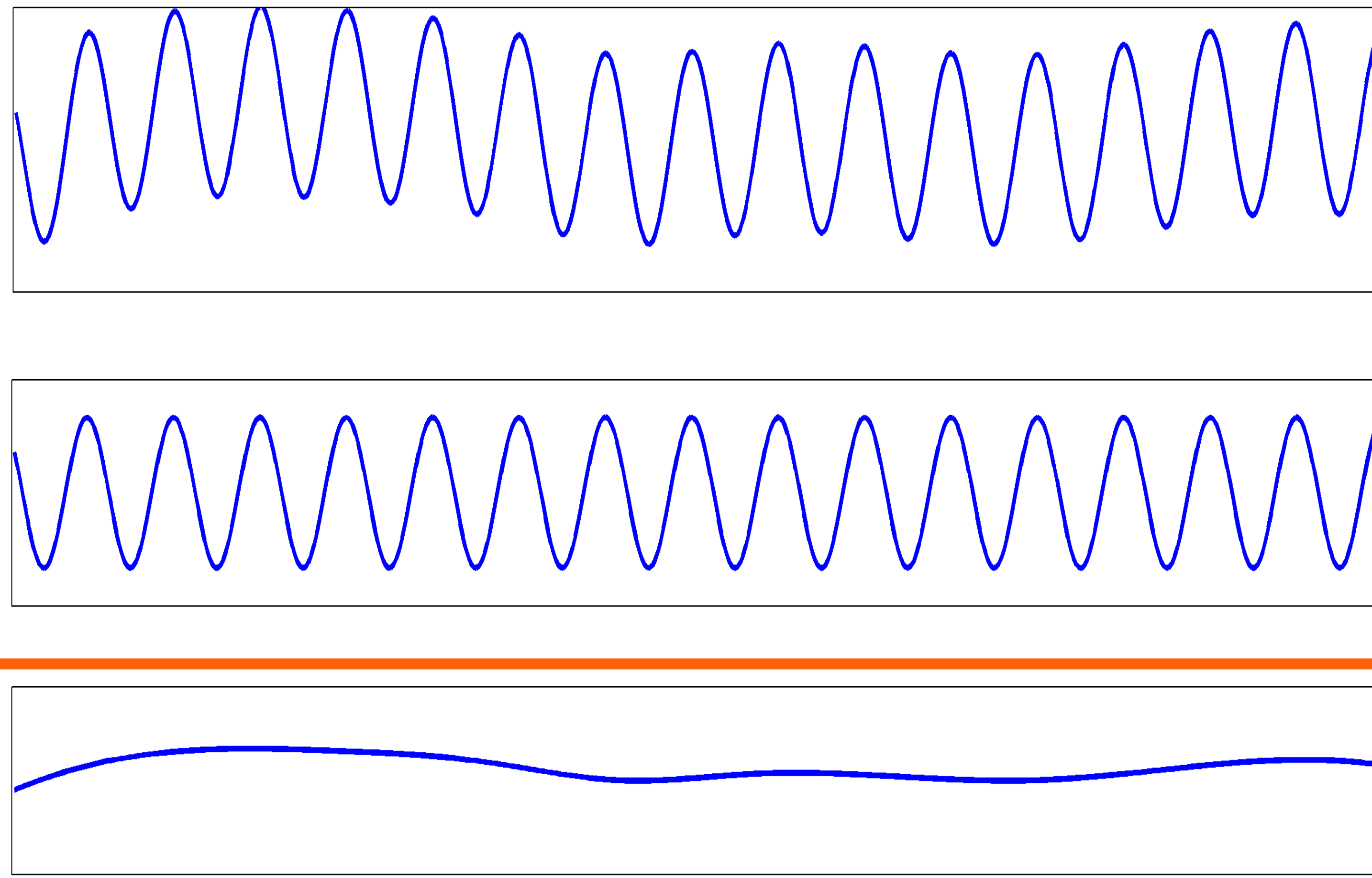
40 years Signal

=

Seasonal Variability

+

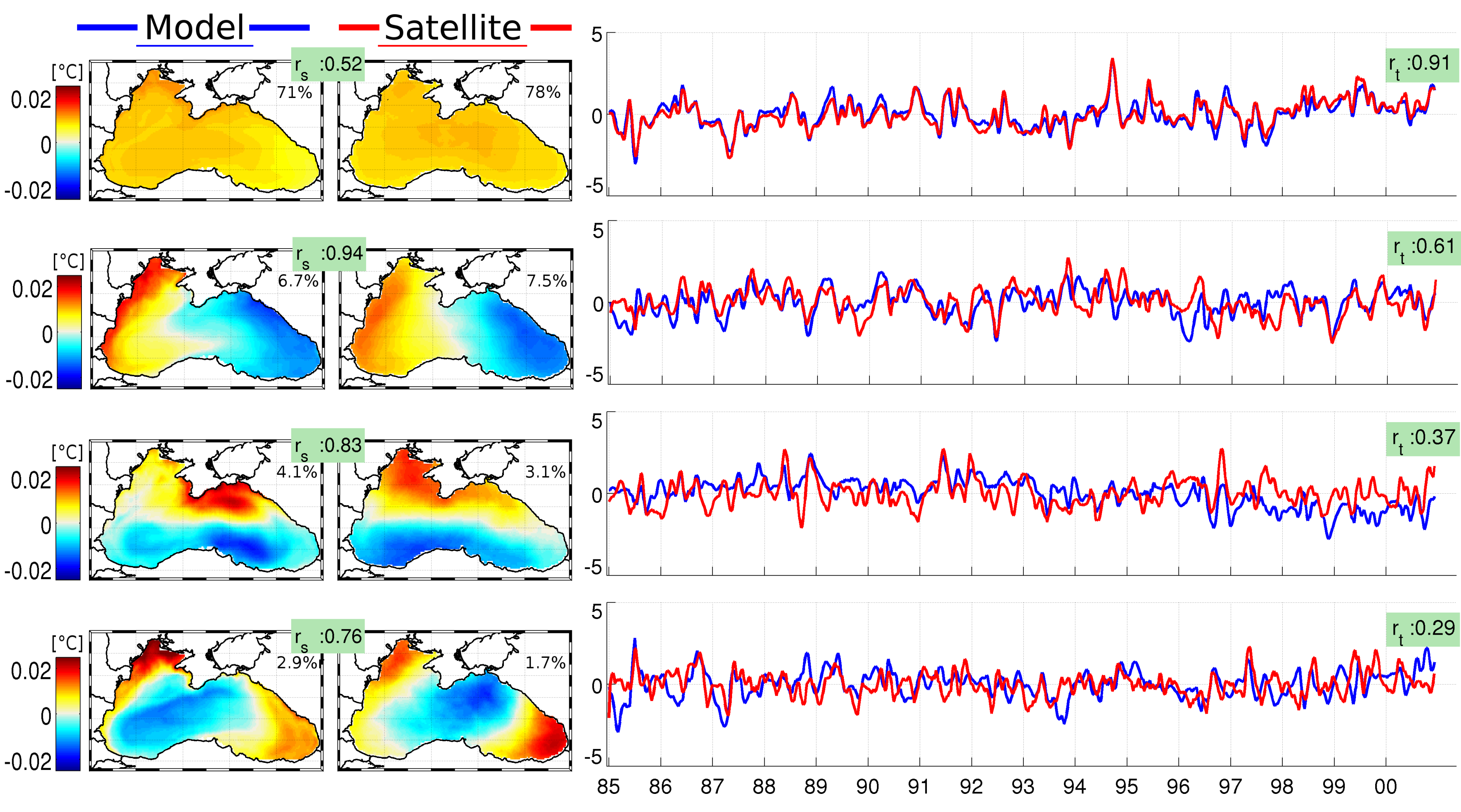
Interannual Anomalies



(Capet et al. 2012, Deep-Sea Research II)

Sea Surface Temperature anomalies

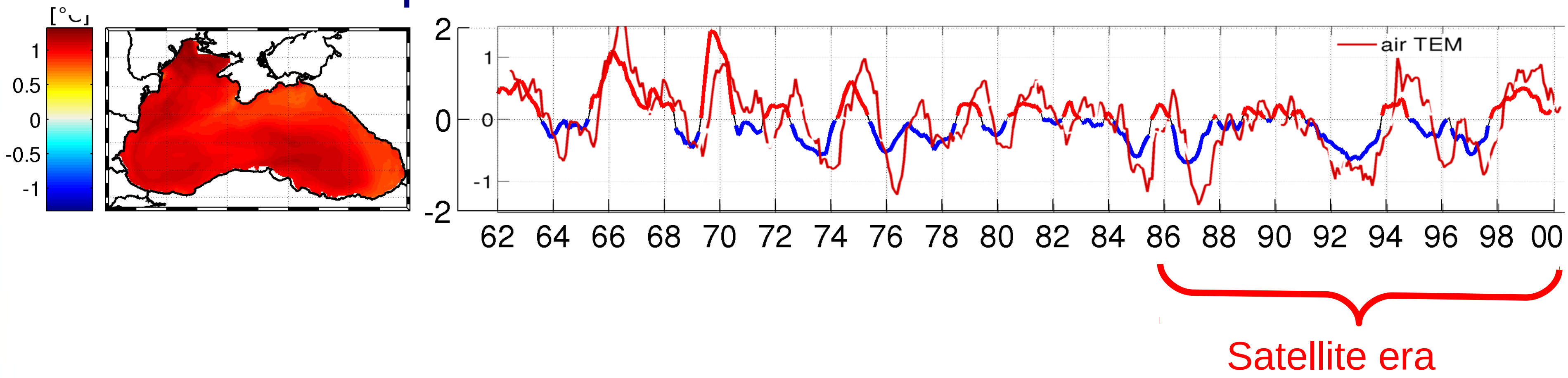
Model VS Satellite (1985-2000)



(Capet et al. 2012, Deep-Sea Research II)

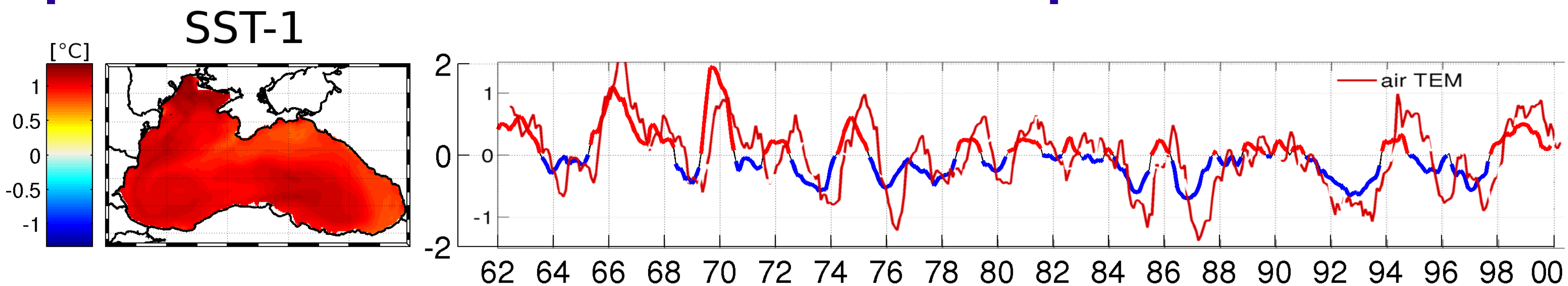
The model allows to go back in time

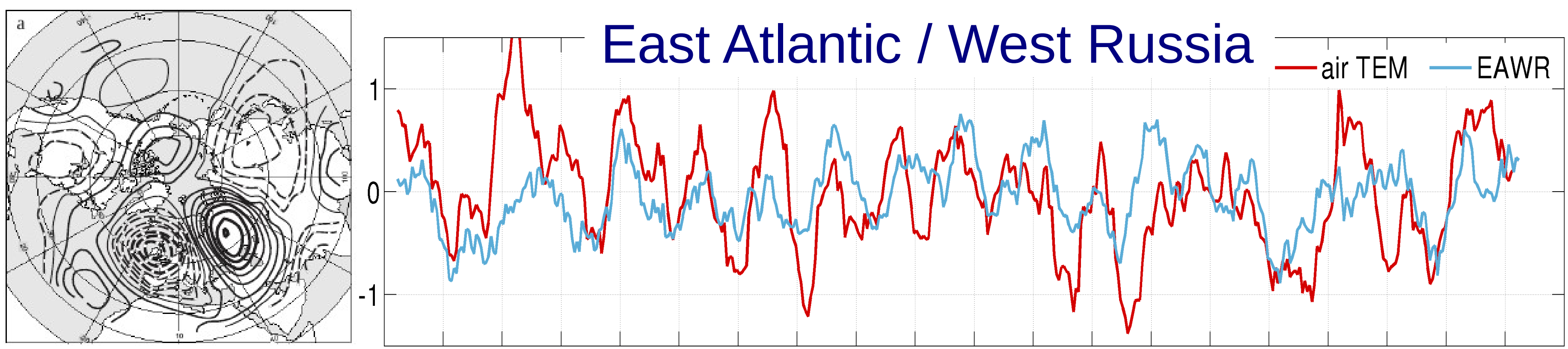
Surface Temp.

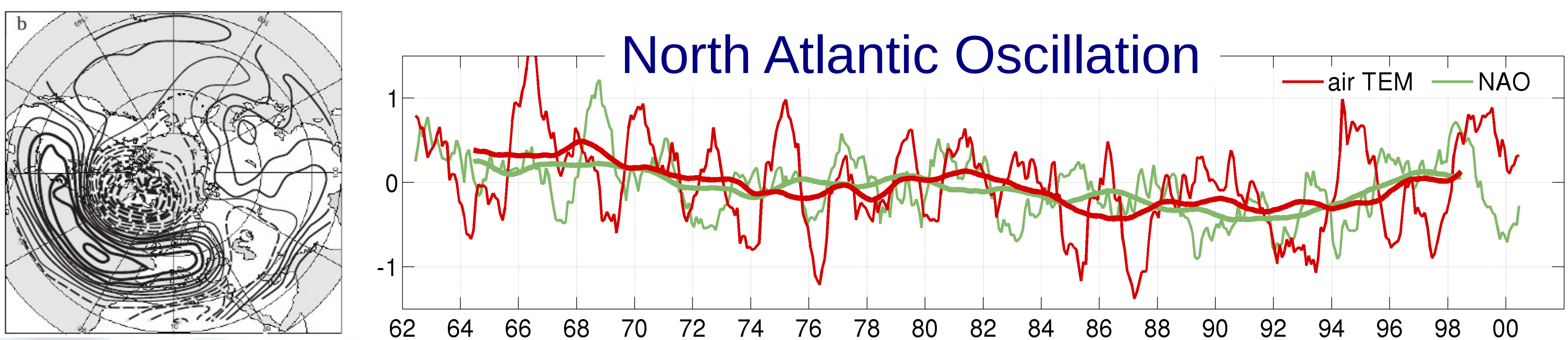


(Capet et al. 2012, Deep-Sea Research II)

SST respond to large teleconnection patterns with various temporal scales

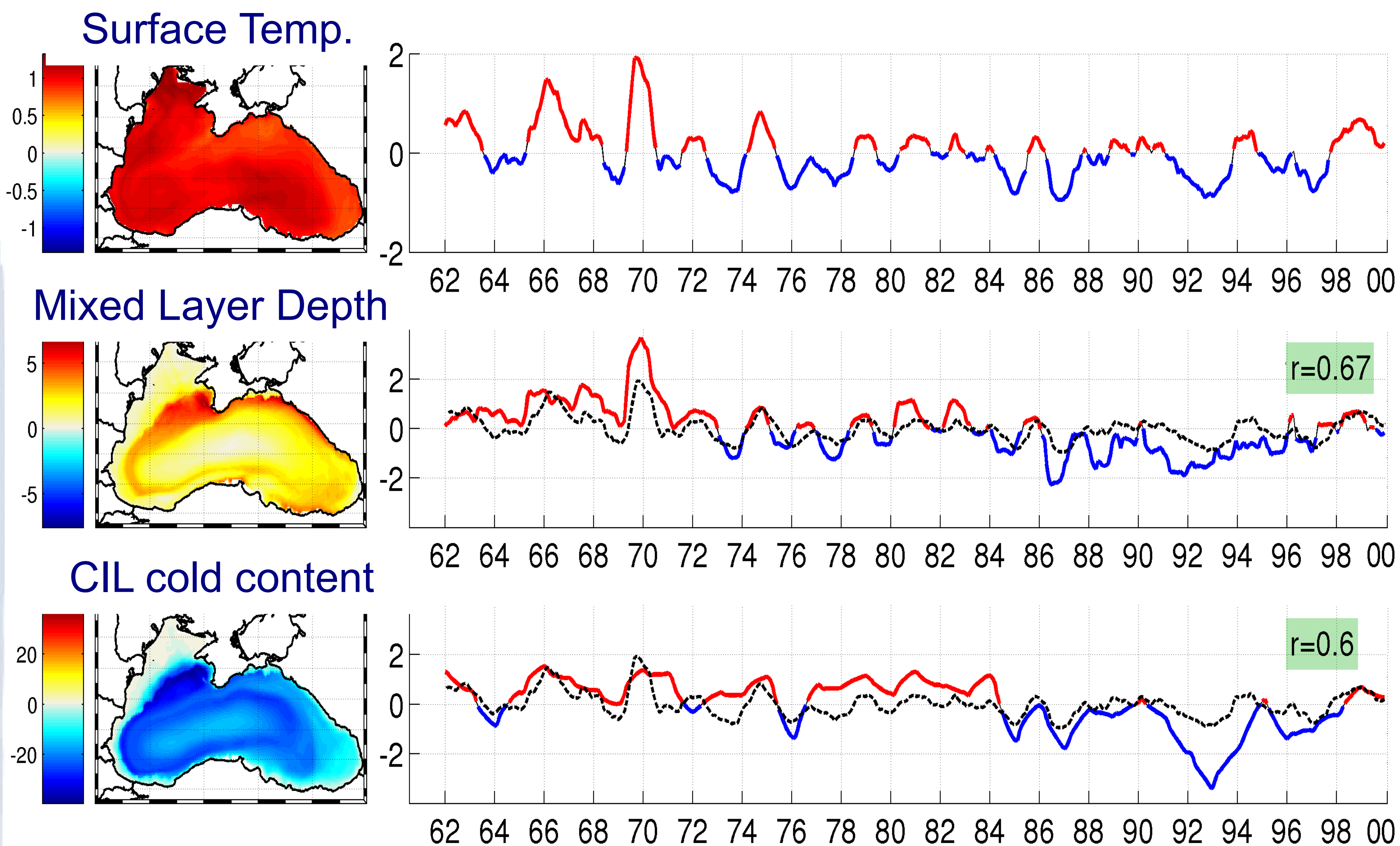






(Capet et al. 2012, Deep-Sea Research II)

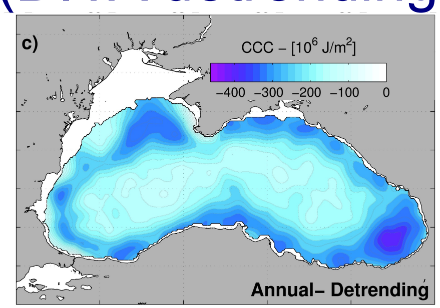
The model allows to go underwater



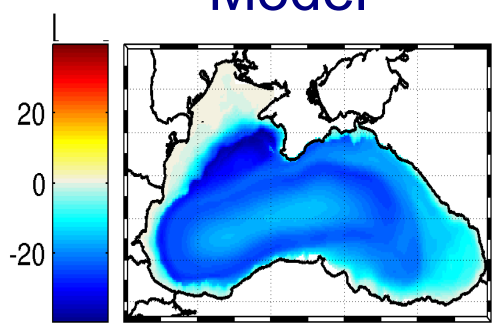
(Capet et al. 2012, Deep-Sea Research II)

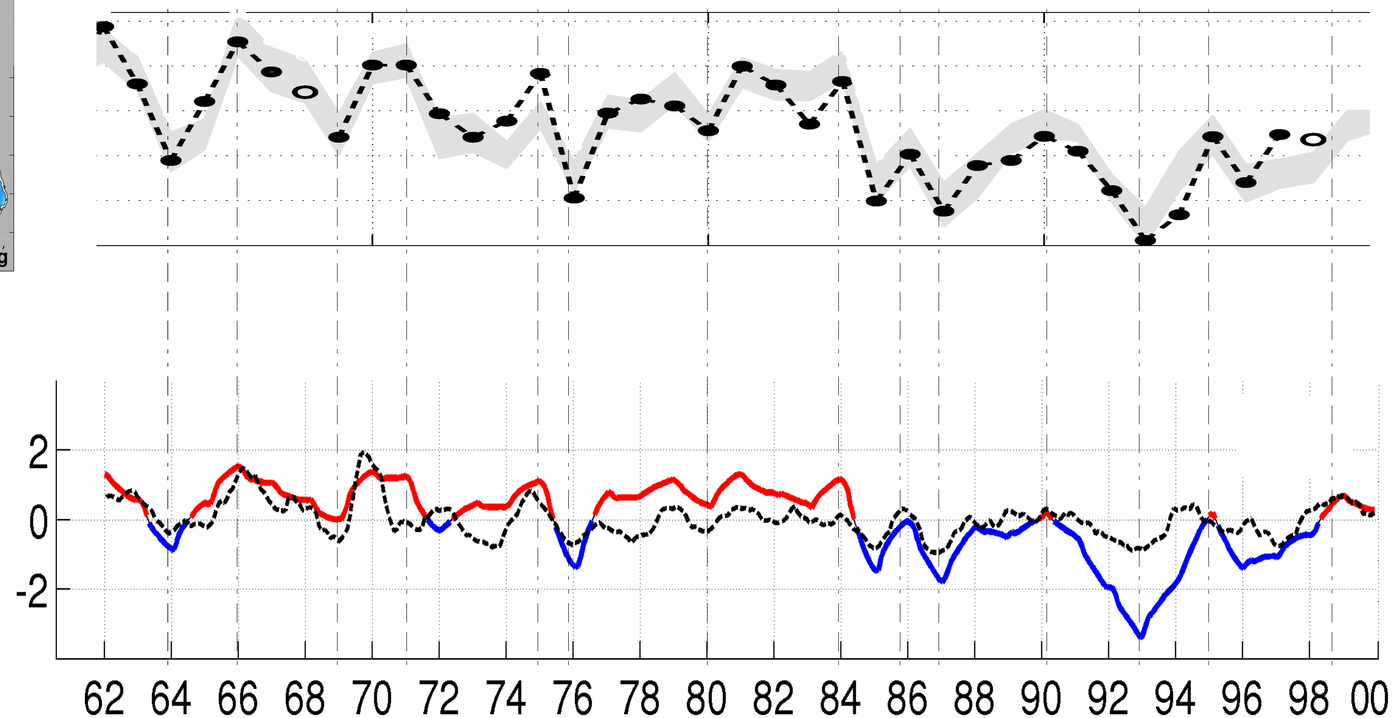
CIL cold content : Model VS Profiles

Vertical profiles
(DIVA detrending)



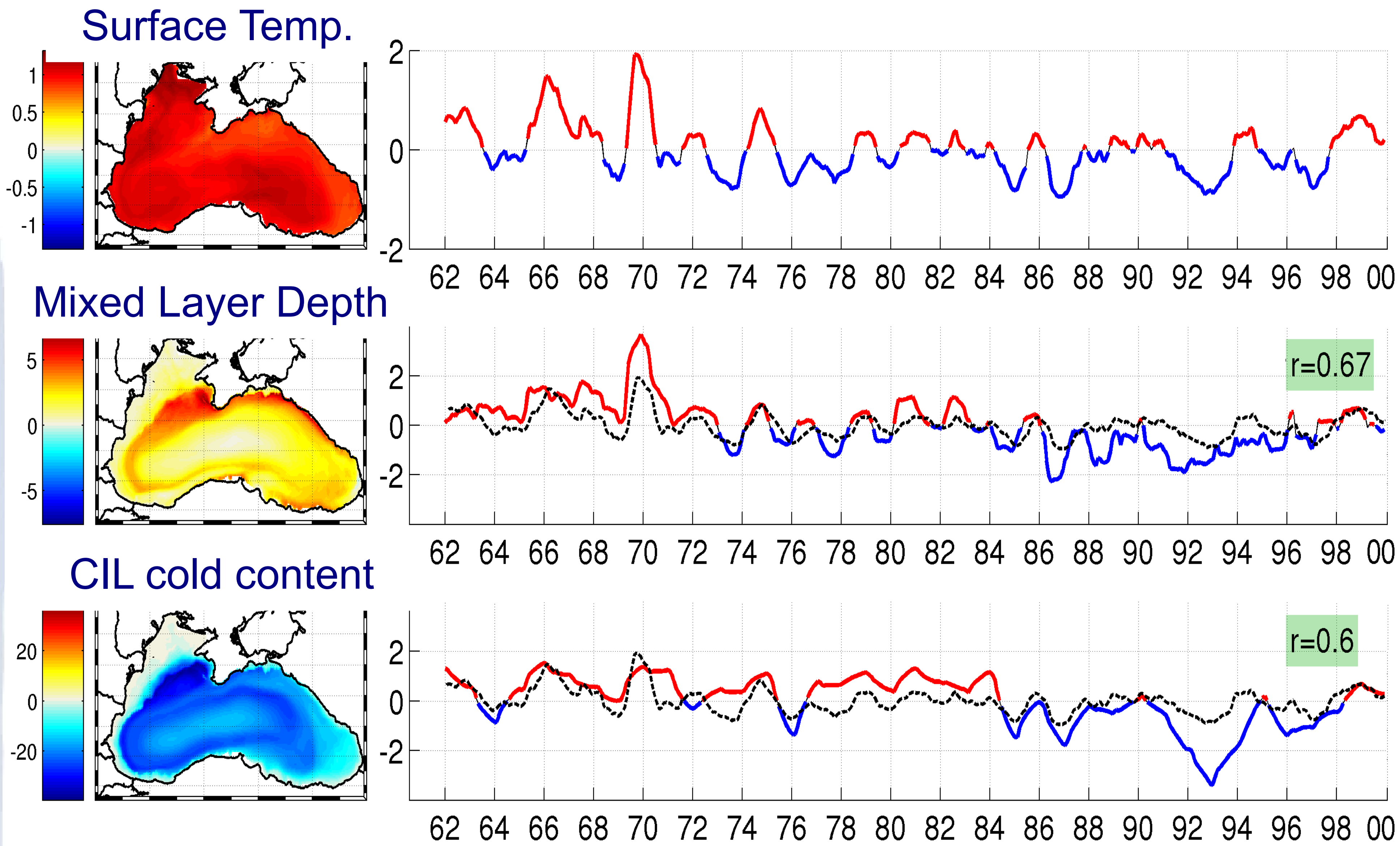
Model





(Capet et al. 2012, Deep-Sea Research II)

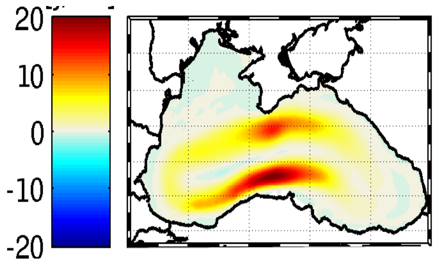
The model allows to go underwater

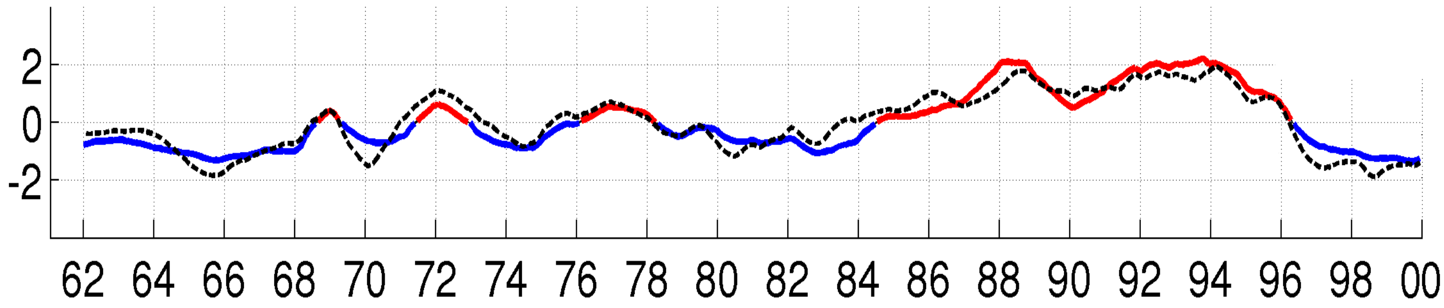


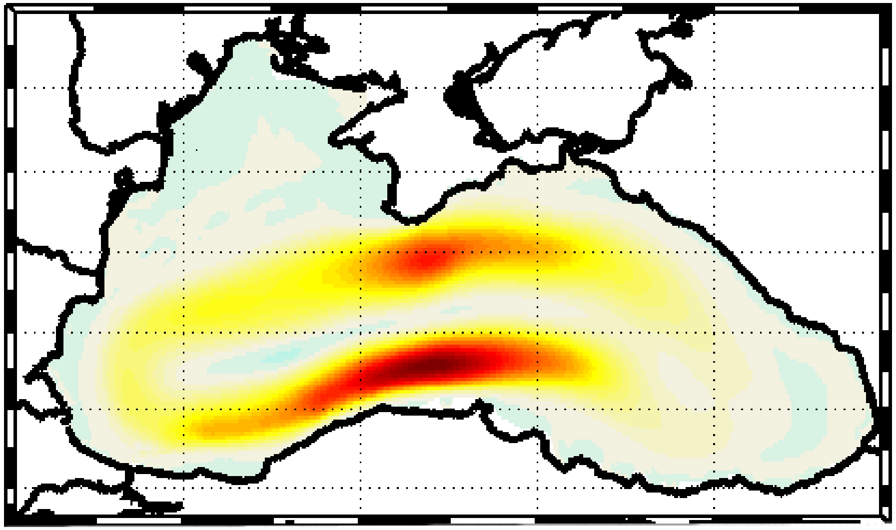
(Capet et al. 2012, Deep-Sea Research II)

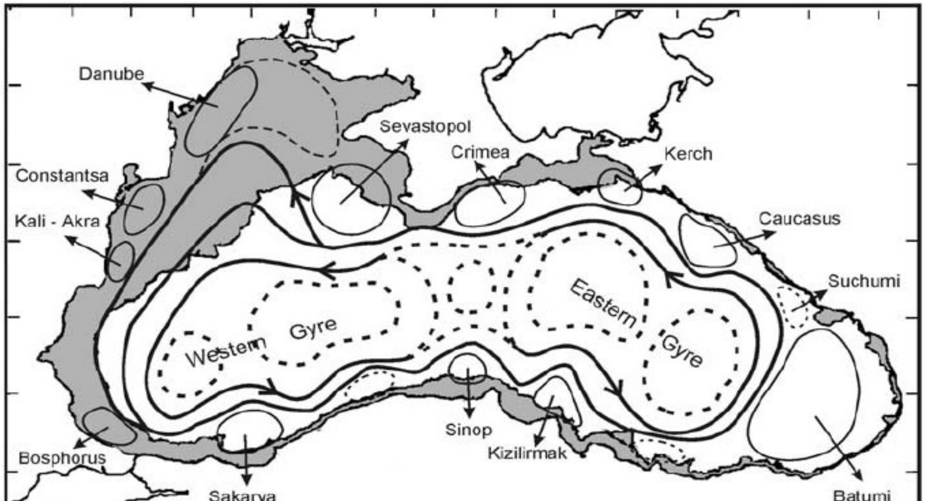
Rim Current intensity

Kinetic energy







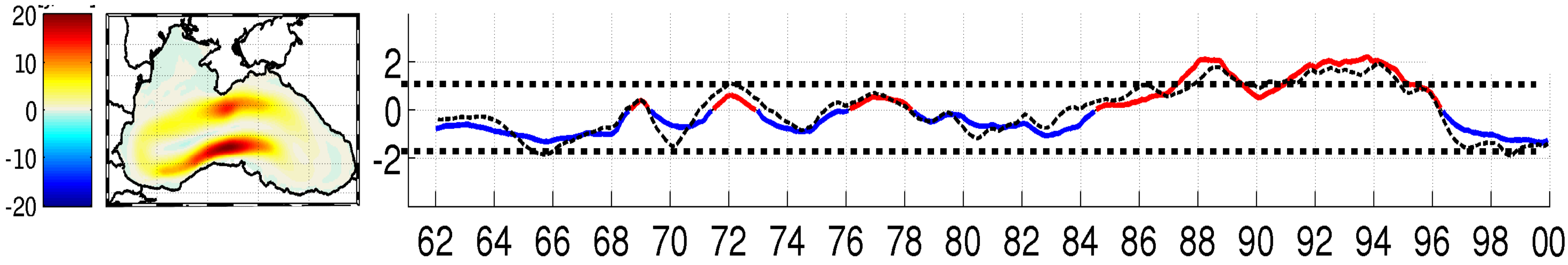


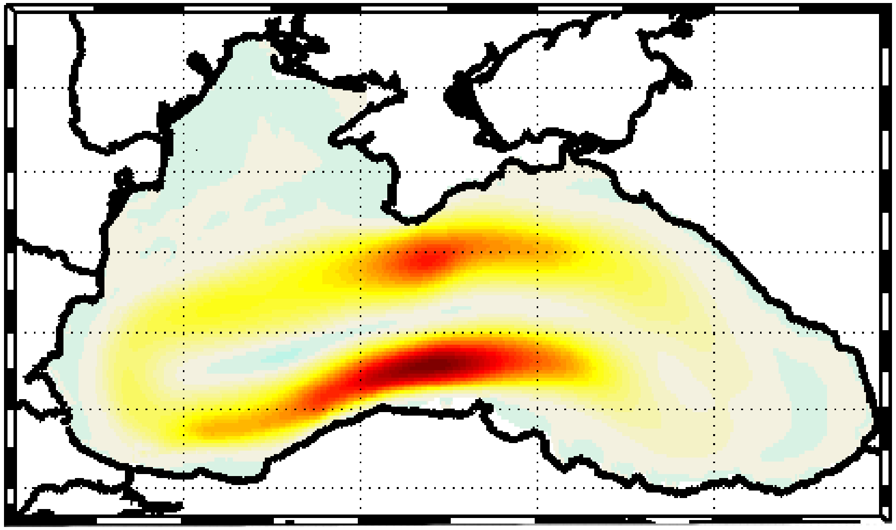
Korotaev, 2003

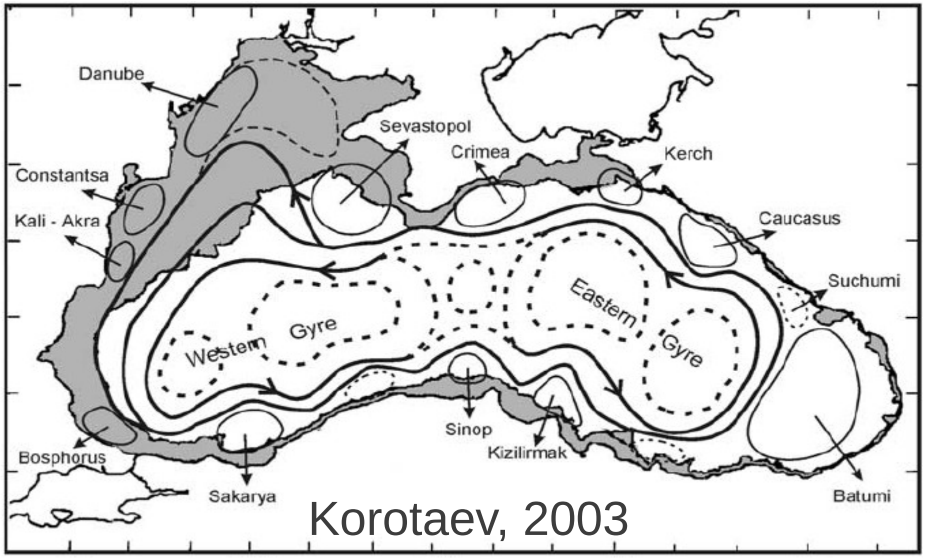
(Capet et al. 2012, Deep-Sea Research II)

Rim Current intensity

Kinetic energy



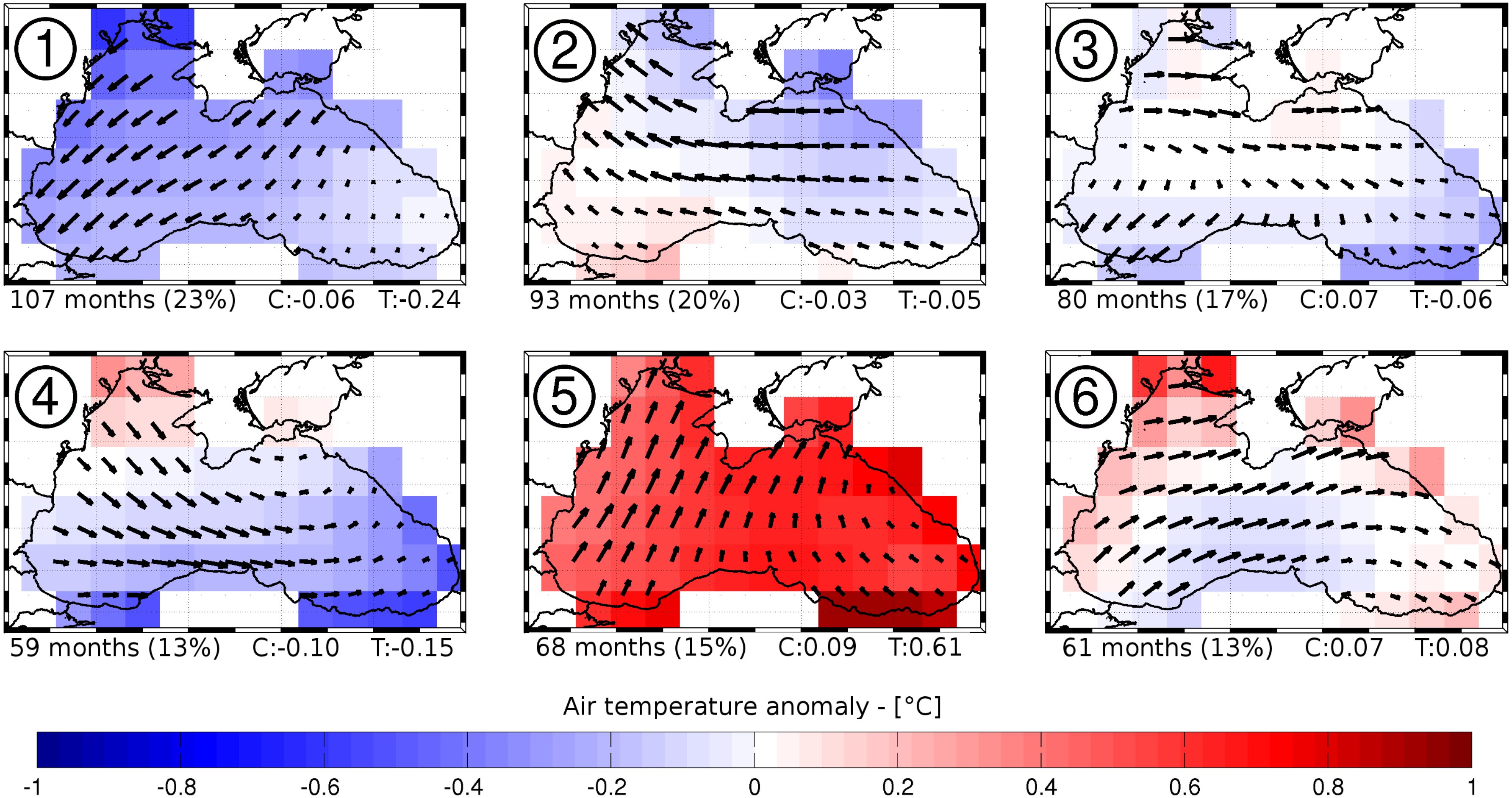




(Capet et al. 2012, Deep-Sea Research II)

Atmospheric regimes

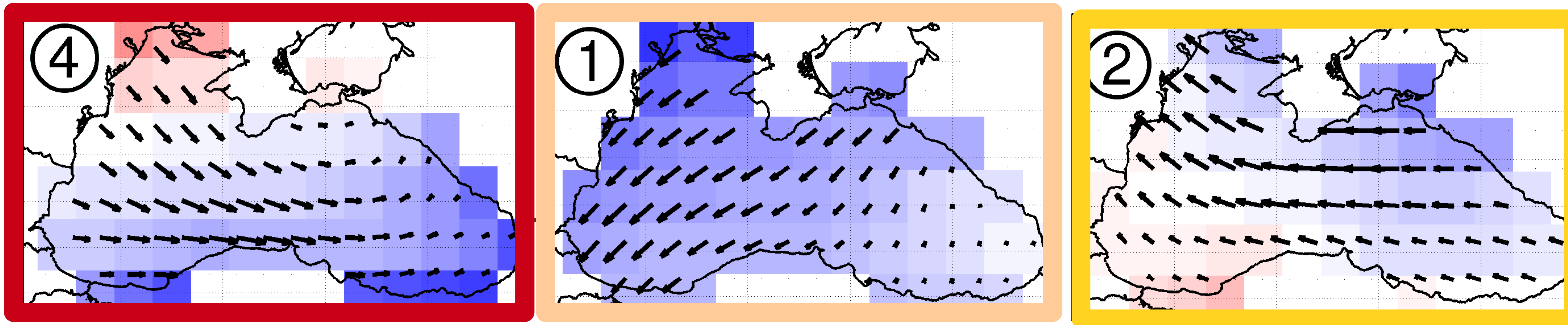
38 years = 468 monthly anomalies classified in 6 patterns (Self Organizing Maps analysis)



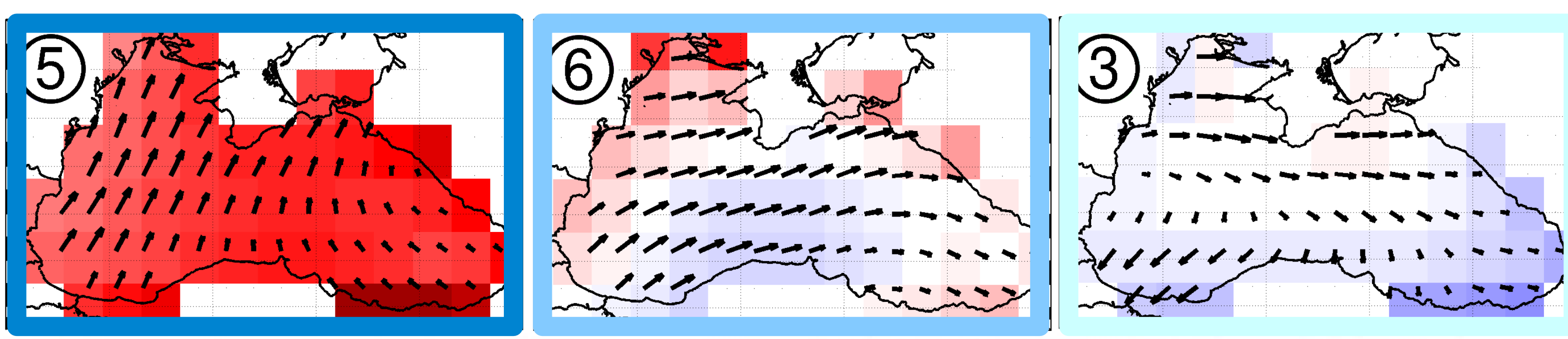
(Capet et al. 2012, Deep-Sea Research II)

Rim current & winds regime

Cyclonic patterns

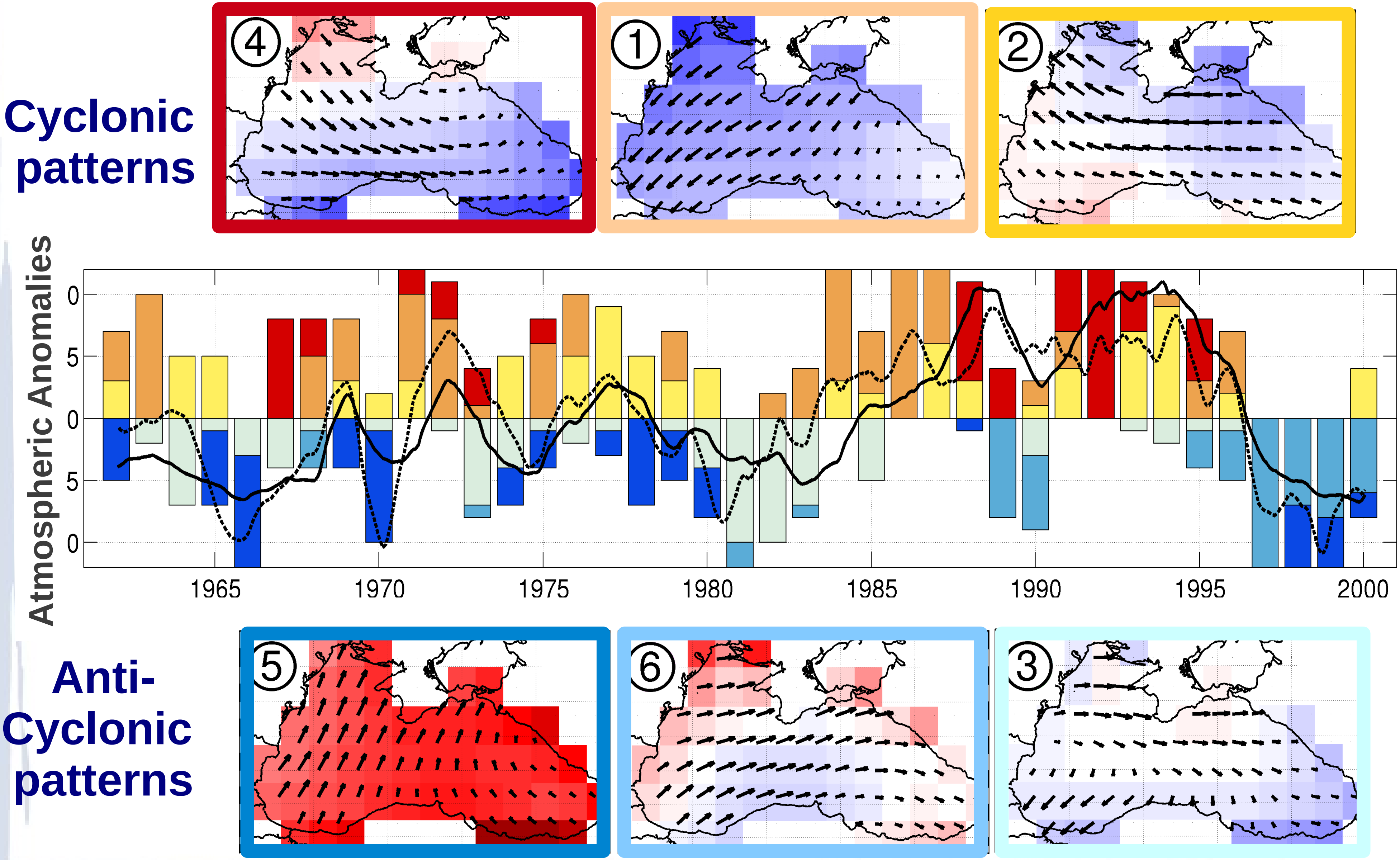


Anti-Cyclonic patterns



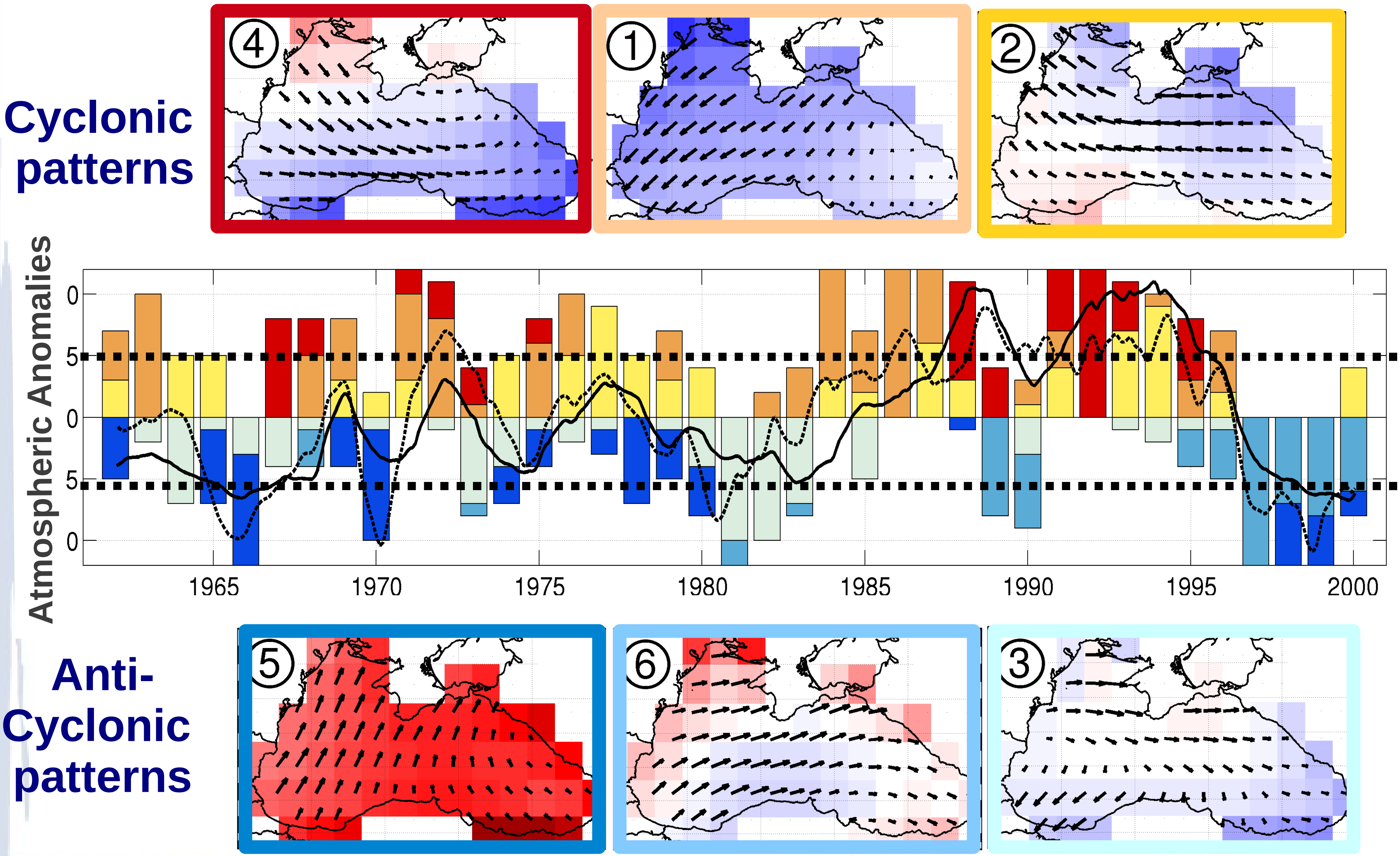
(Capet et al. 2012, Deep-Sea Research II)

Rim current & winds regime



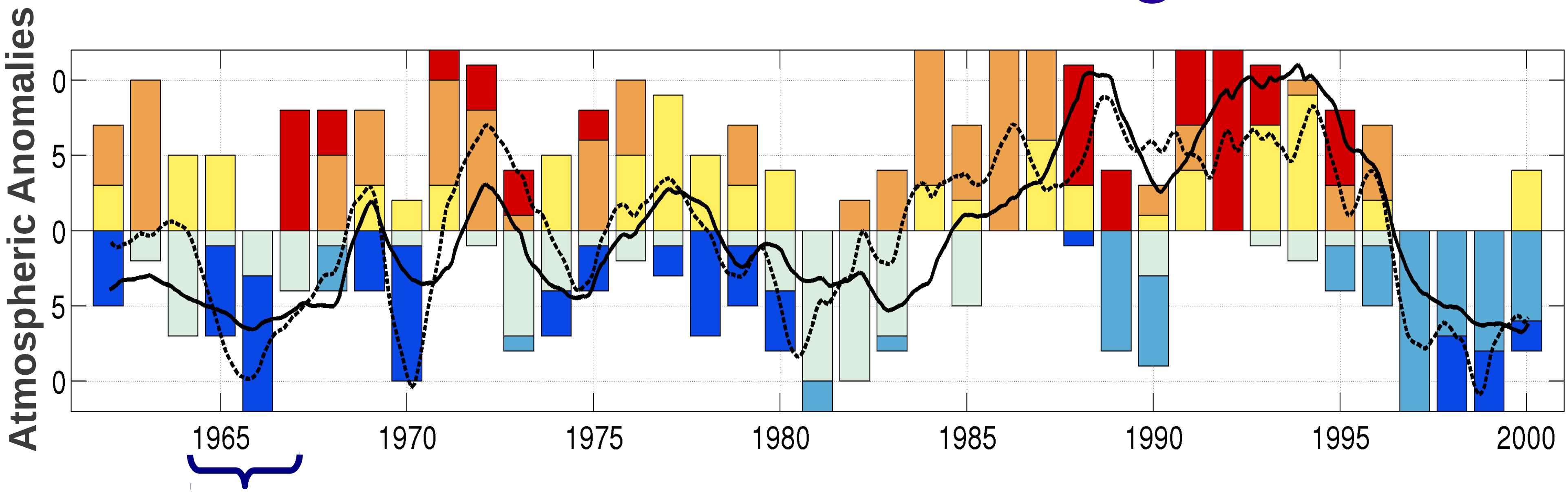
(Capet et al. 2012, Deep-Sea Research II)

Rim current & winds regime

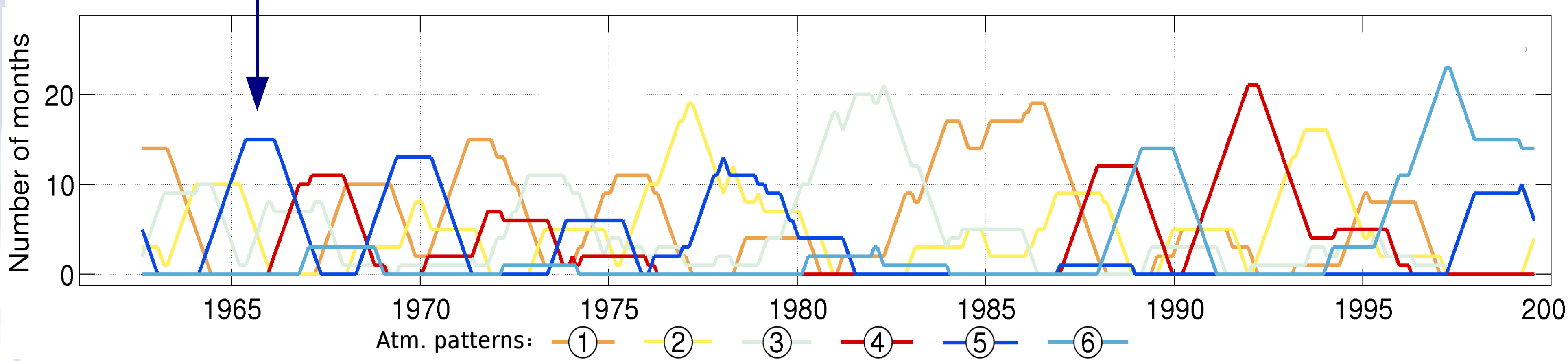


(Capet et al. 2012, Deep-Sea Research II)

Rim current & winds regime



How times the patterns appears in a two year ?



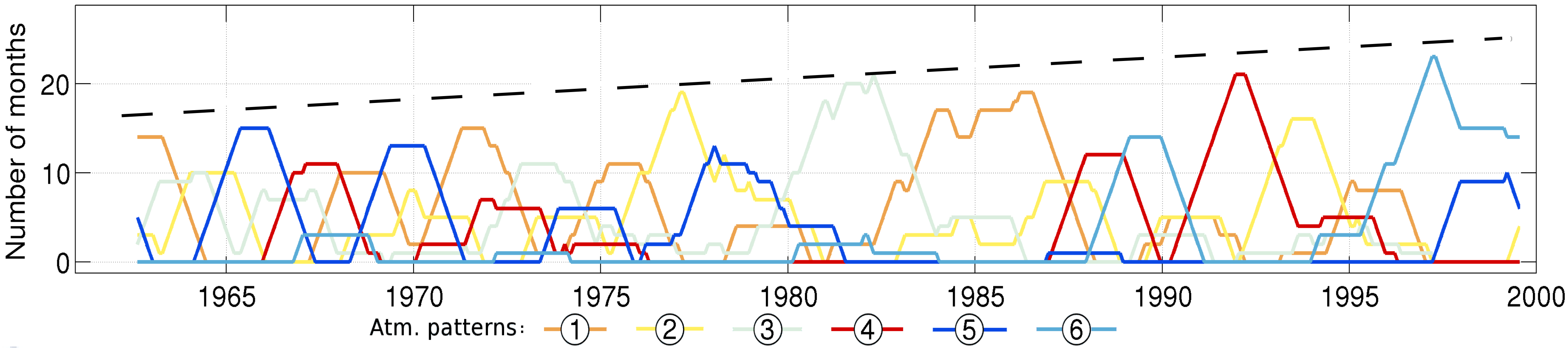
(Capet et al. 2012, Deep-Sea Research II)

Rim current & winds regime

Longer persistence of anomalous patterns

↓

Black Sea system further from equilibrium.

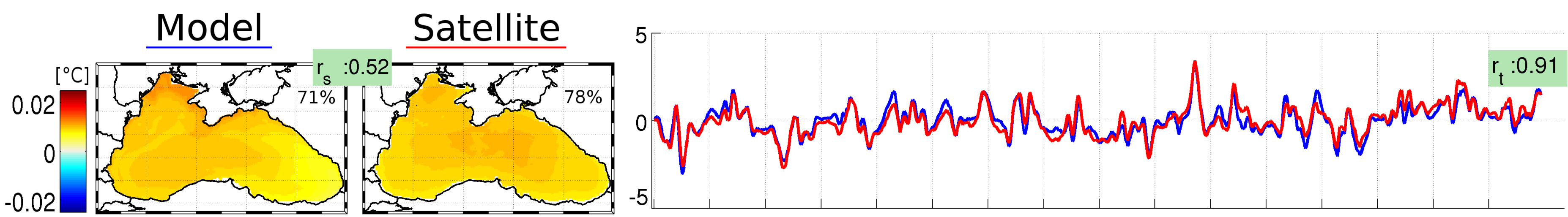


(Capet et al. 2012, Deep-Sea Research II)

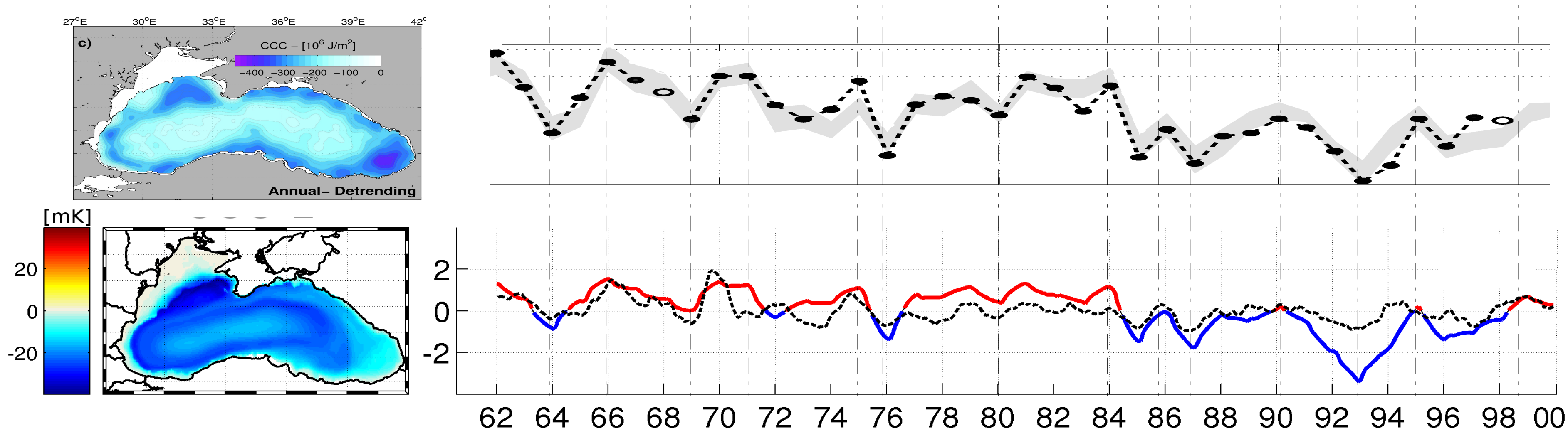
Conclusions (Hydrodynamics)

Conclusions (Hydrodynamics) -1/3

- The 3D model reproduces the variability of hydrodynamics with accuracy.
  - Surface variability validated with satellite data.

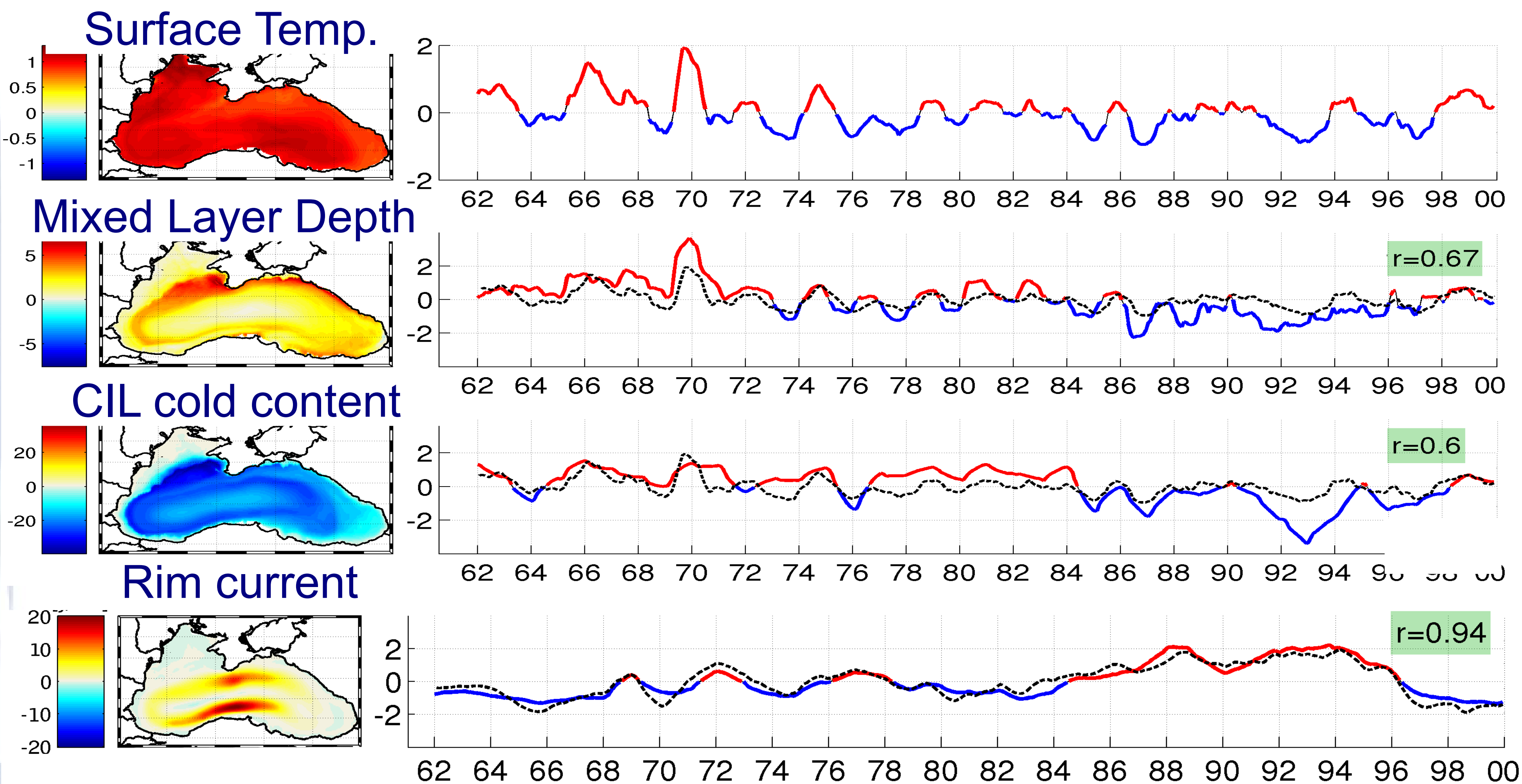


  - Internal variability validated vith vertical profiles.



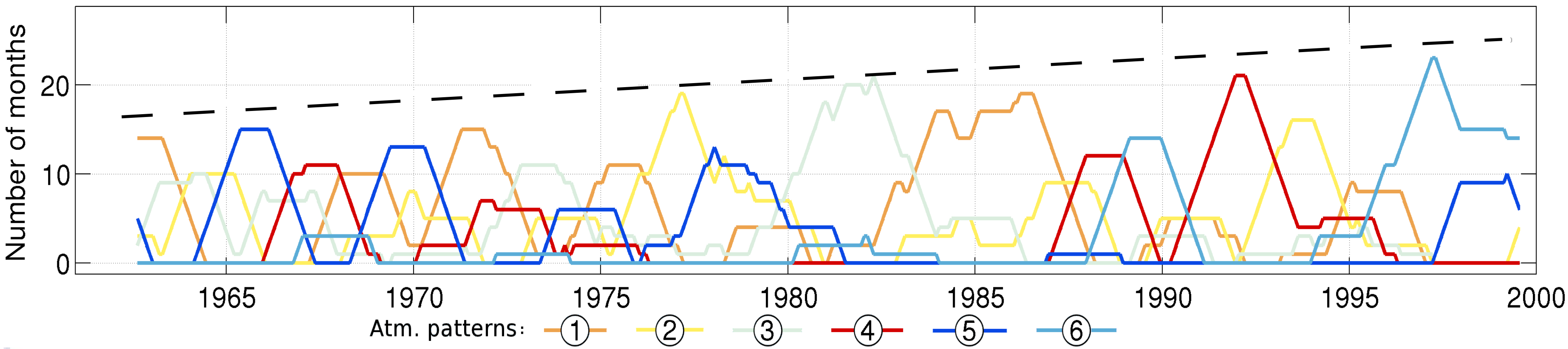
Conclusions (Hydrodynamics) - 2/3

- The Rim current intensity regulates the sensitivity of the Black Sea structure to air temperature.



Conclusions (Hydrodynamics) - 3/3

- The longer persistence of atmospheric anomalies brought the System further from its average state



Outline

Hydrodynamics

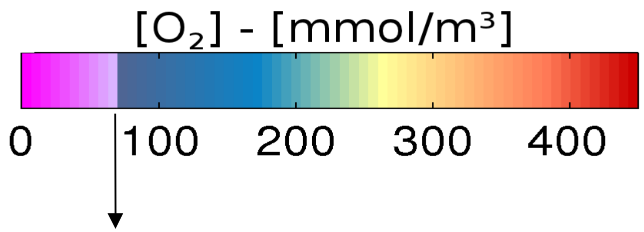
- Introduction: The Black Sea structure
  - Variability from observations: describe
  - Variability from model: resolve and explain

Biogeochemistry

- Introduction: Hypoxia in the Northwestern shelf
  - Model requirements
  - Dynamics of hypoxia

(Capet et al. 2013, Biogeosciences)

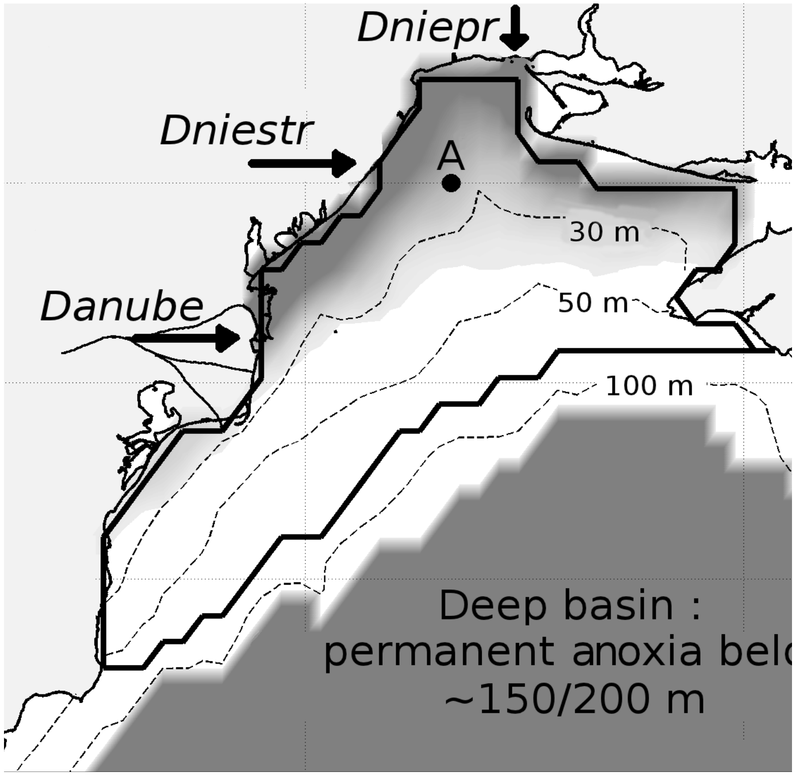
What is hypoxia ?



Hypoxic thresold : $[O_2]$ < **62 mmol/m^3 (2 mg/l)**

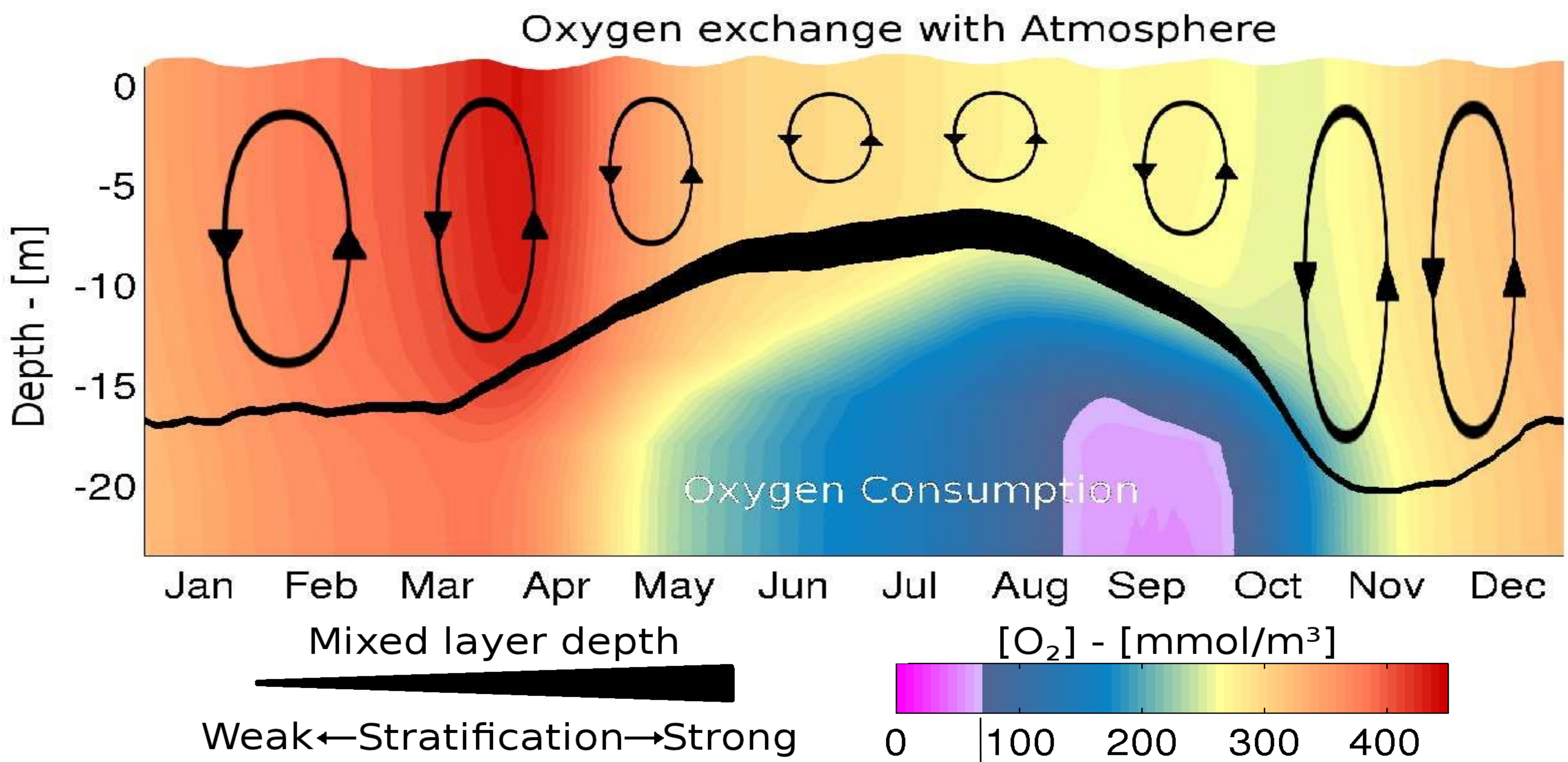
Why does hypoxia occurs ?

(Capet et al. 2013, Biogeosciences)



(Capet et al. 2013, Biogeosciences)

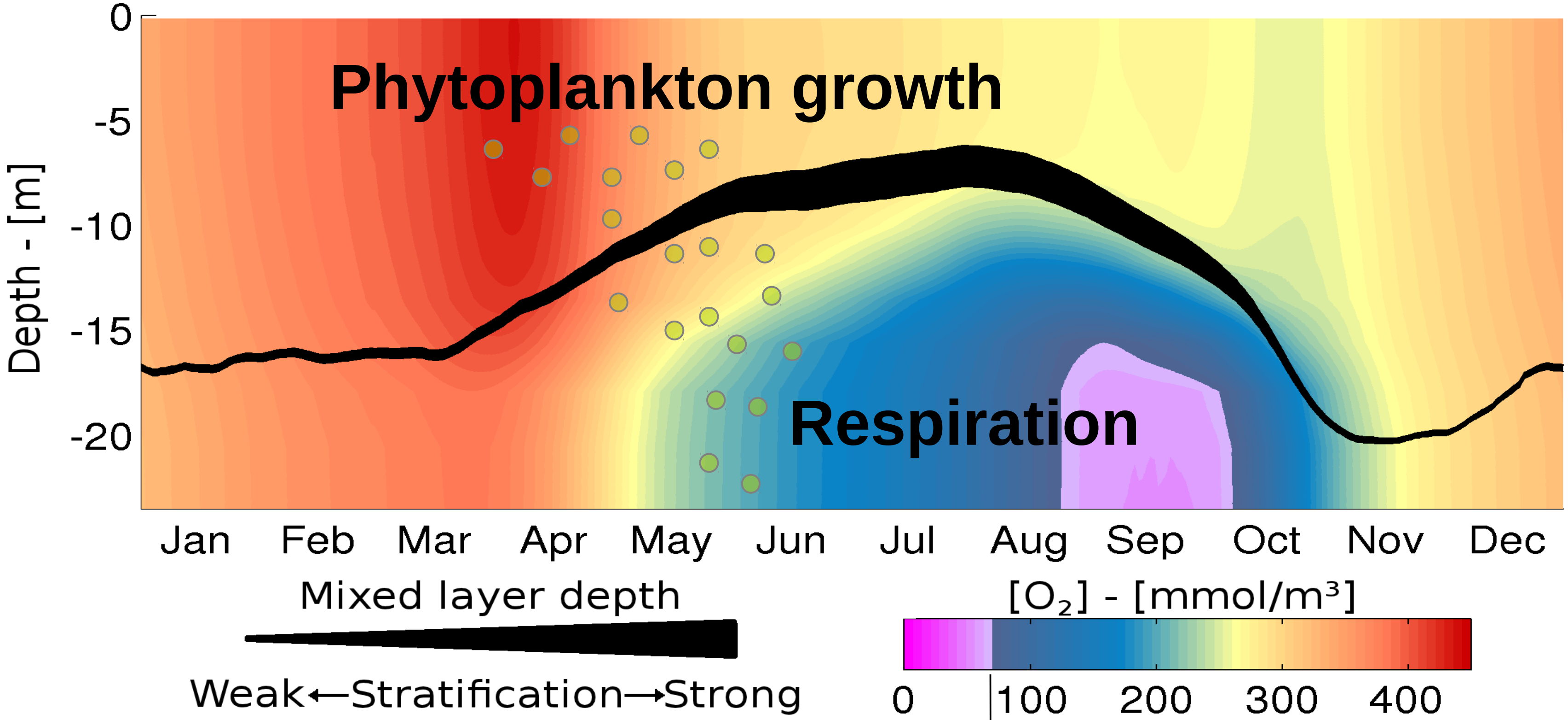
Seasonal Hypoxia



Hypoxic thresold : $[O_2]$ < **62 mmol/m³ (2 mg/l)**

(Capet et al. 2013, Biogeosciences)

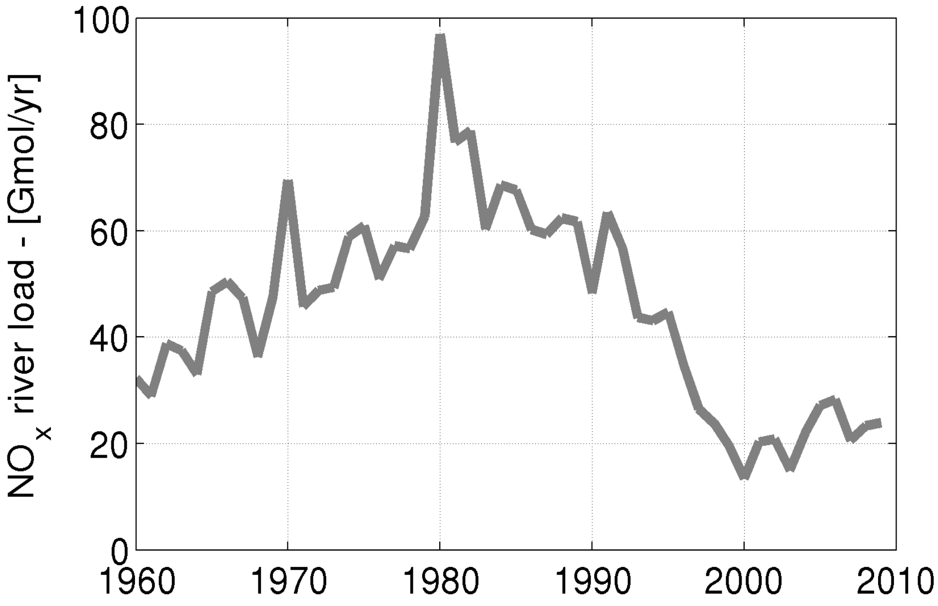
Seasonal Hypoxia

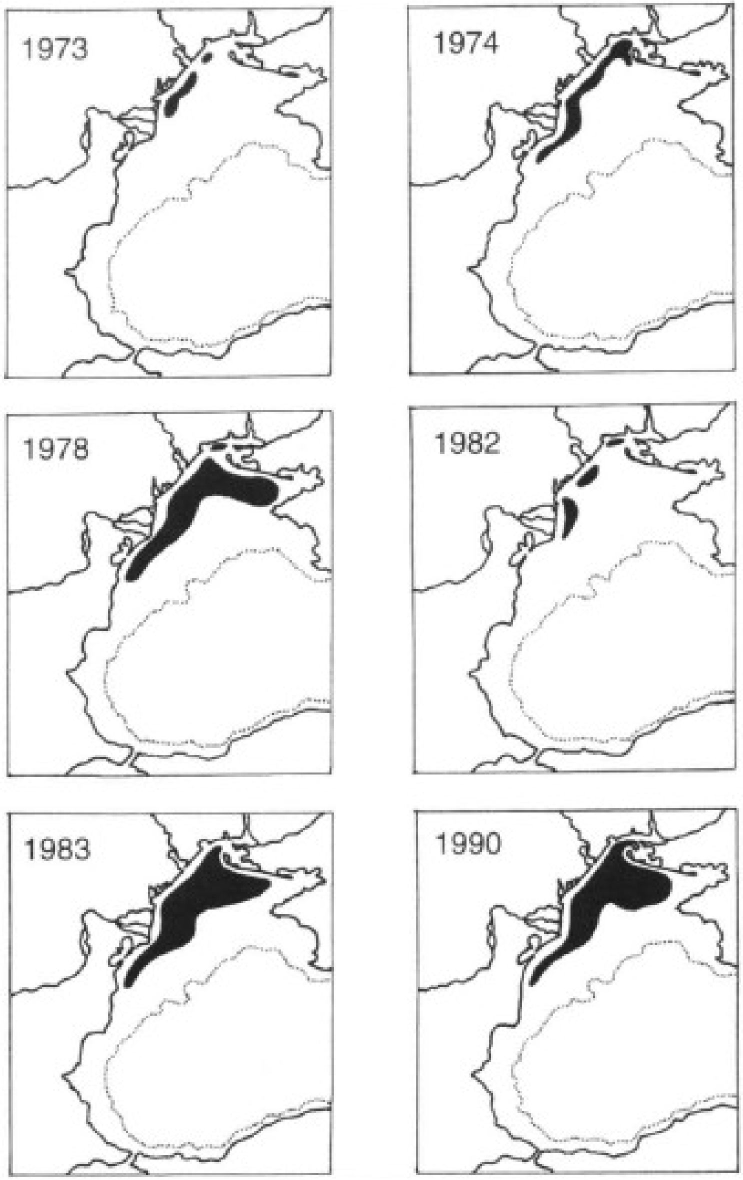


Hypoxic thresold : $[O_2]$ < **62 mmol/m³ (2 mg/l)**

(Capet et al. 2013, Biogeosciences)

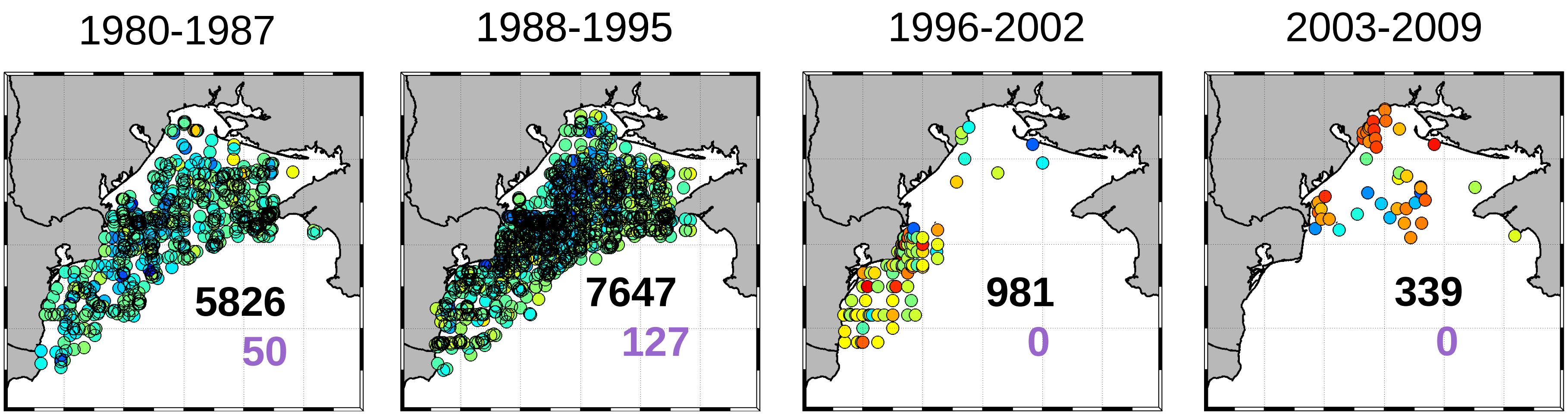
Seasonal Hypoxia in the BS-NWS





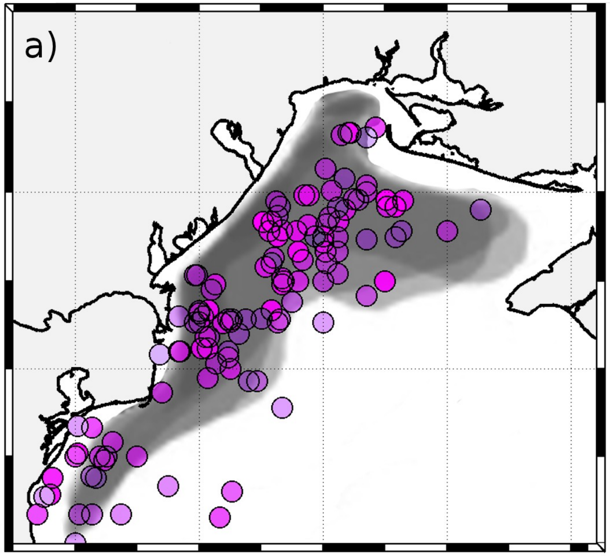
(Capet et al. 2013, Biogeosciences)

Recovery ?



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

Hypoxic records
(<62 mmol O/m³)



(Capet et al. 2013, Biogeosciences)

Studying Hypoxia with a 3D model

(Capet et al. 2013, Biogeosciences)

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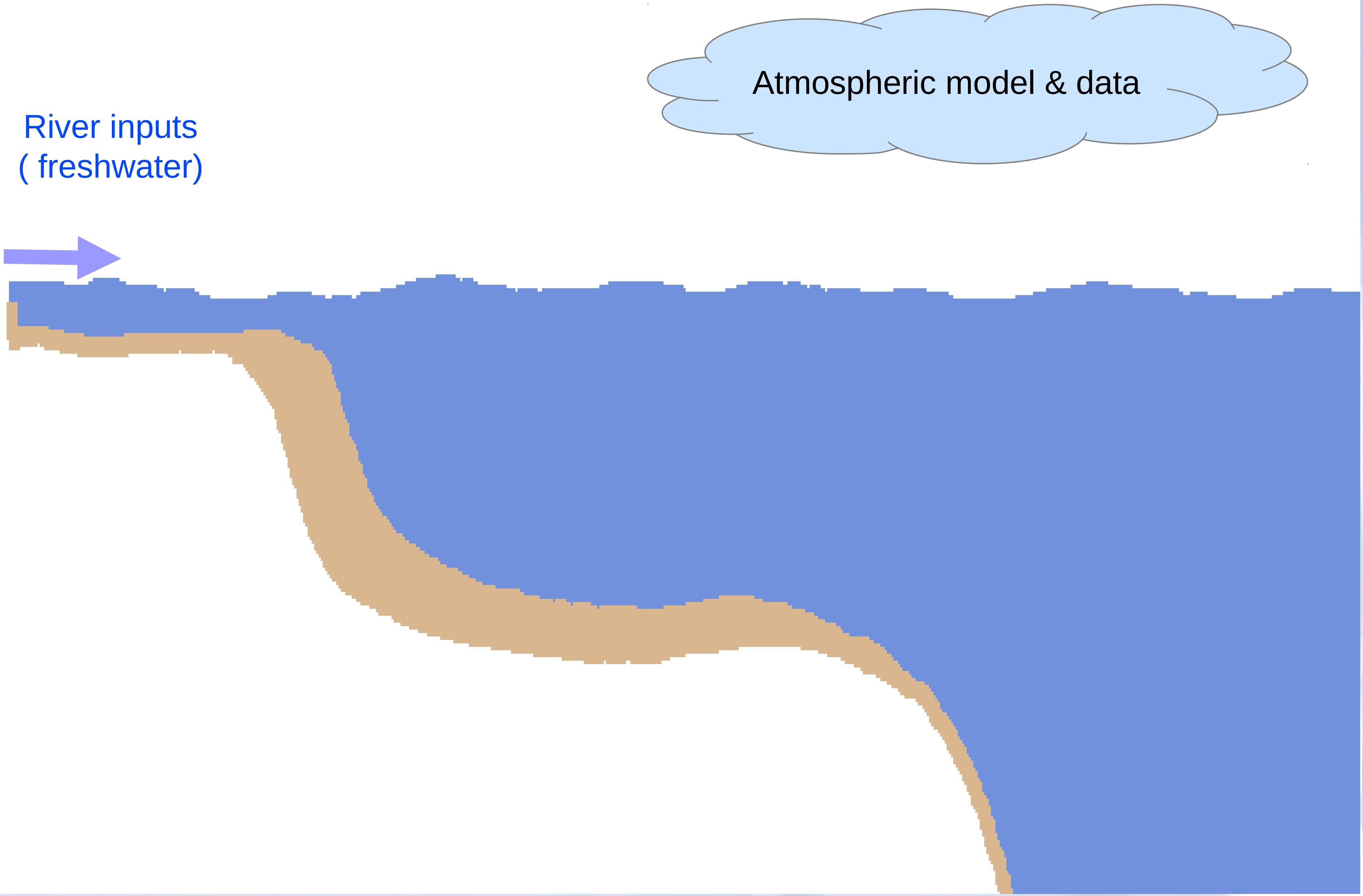
(Capet et al. 2013, Biogeosciences)

To build a biogeochemical model you need...



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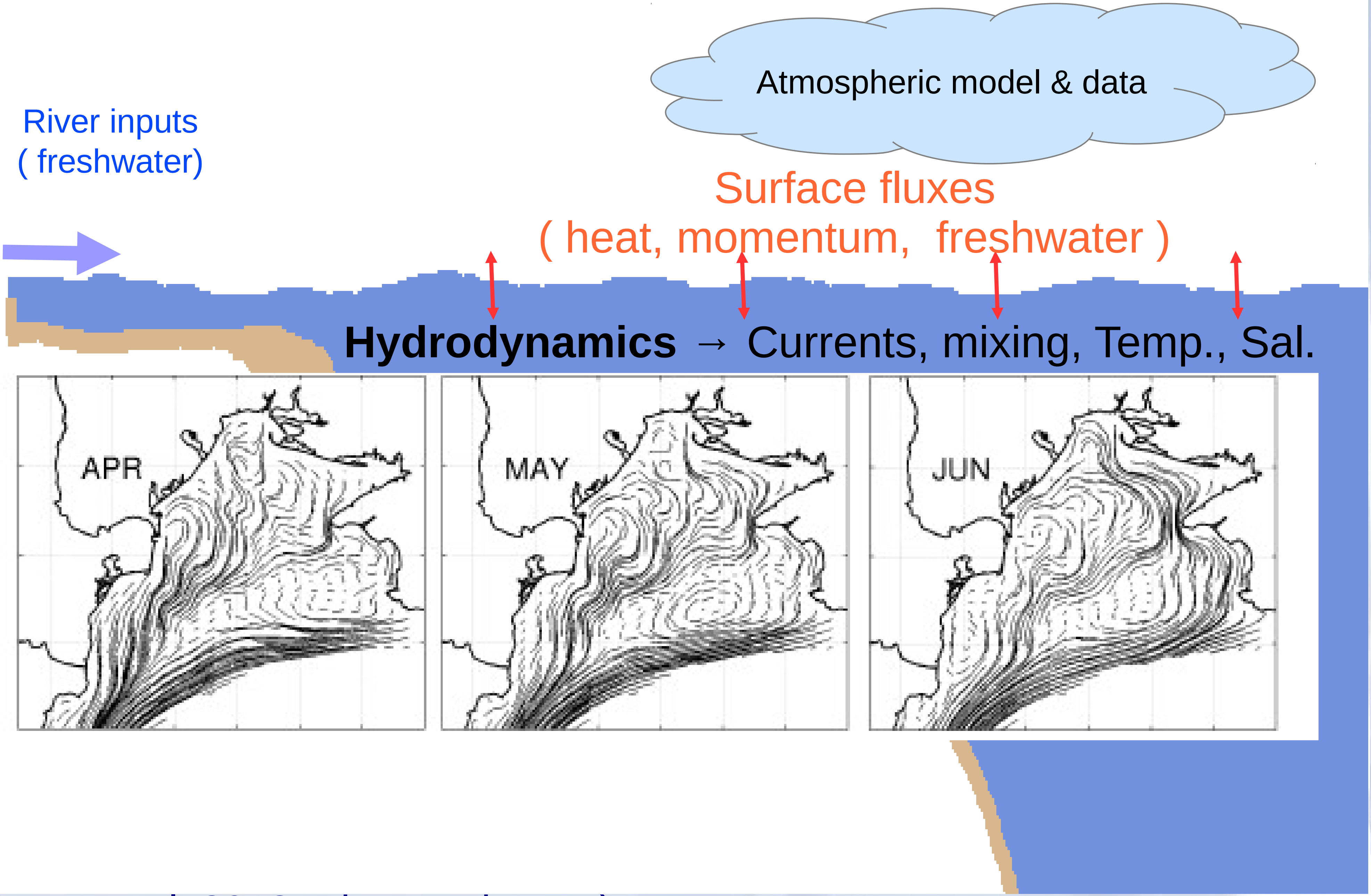

(Capet et al. 2013, Biogeosciences)

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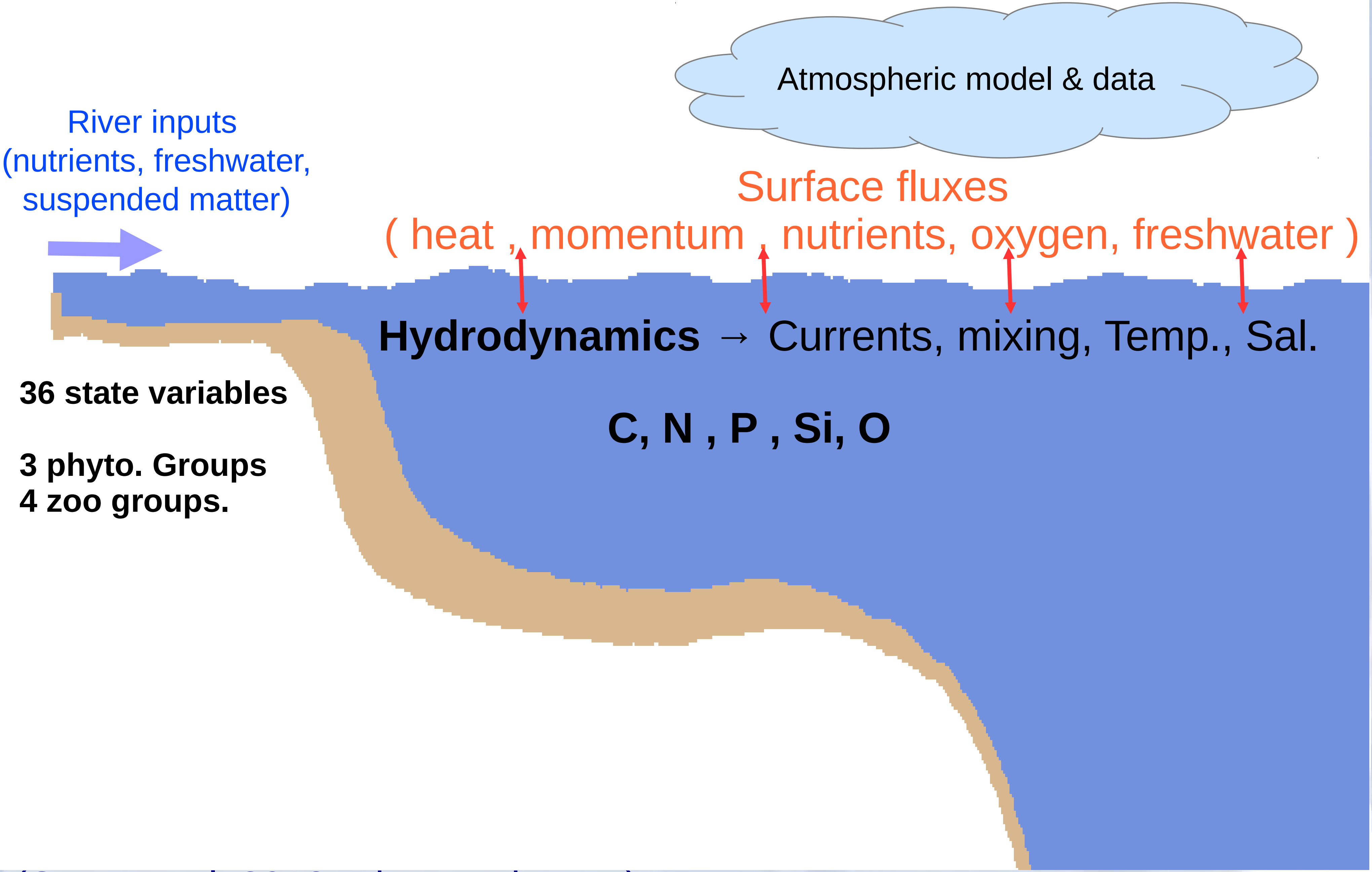

(Capet et al. 2013, Biogeosciences)

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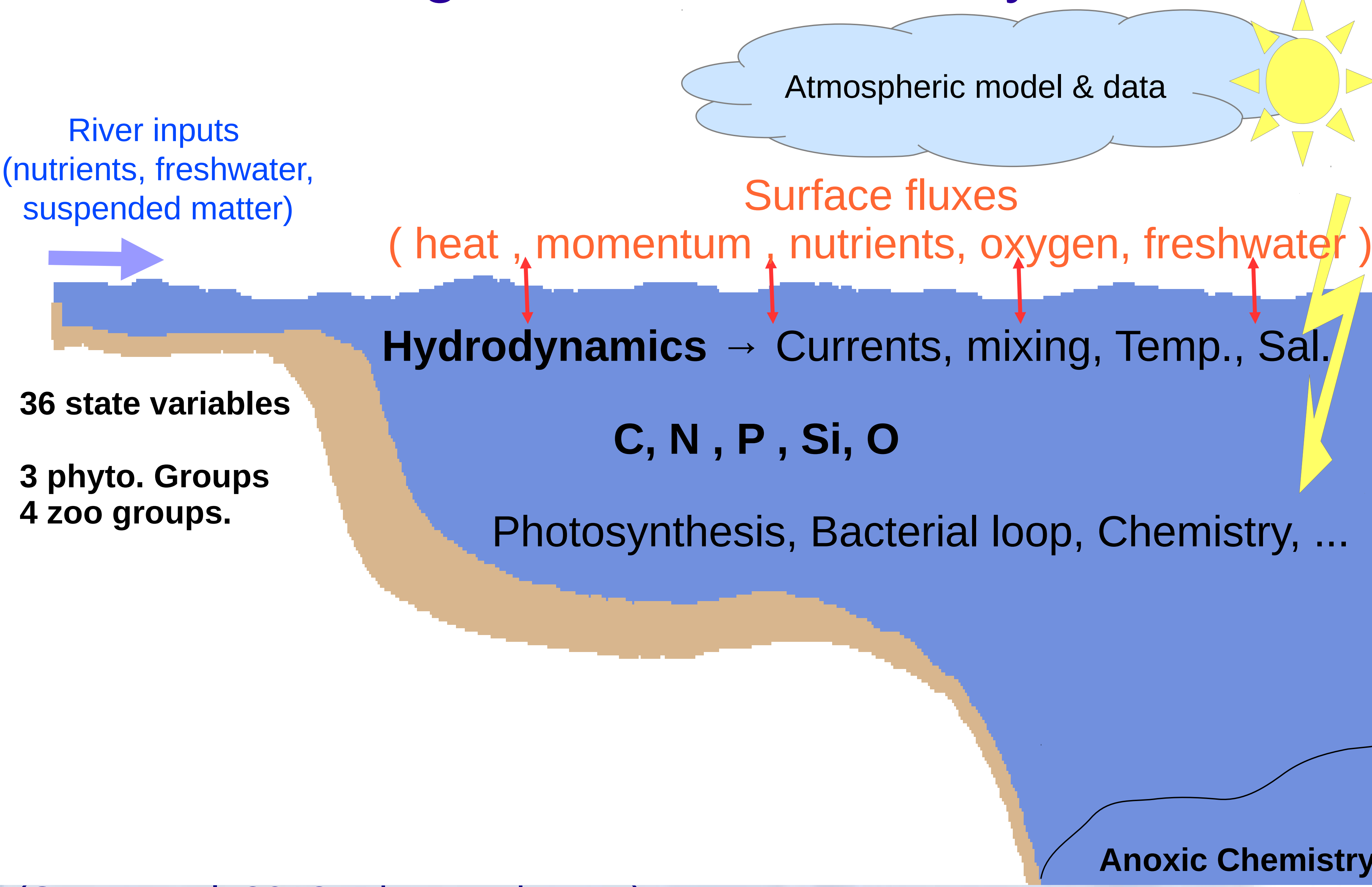
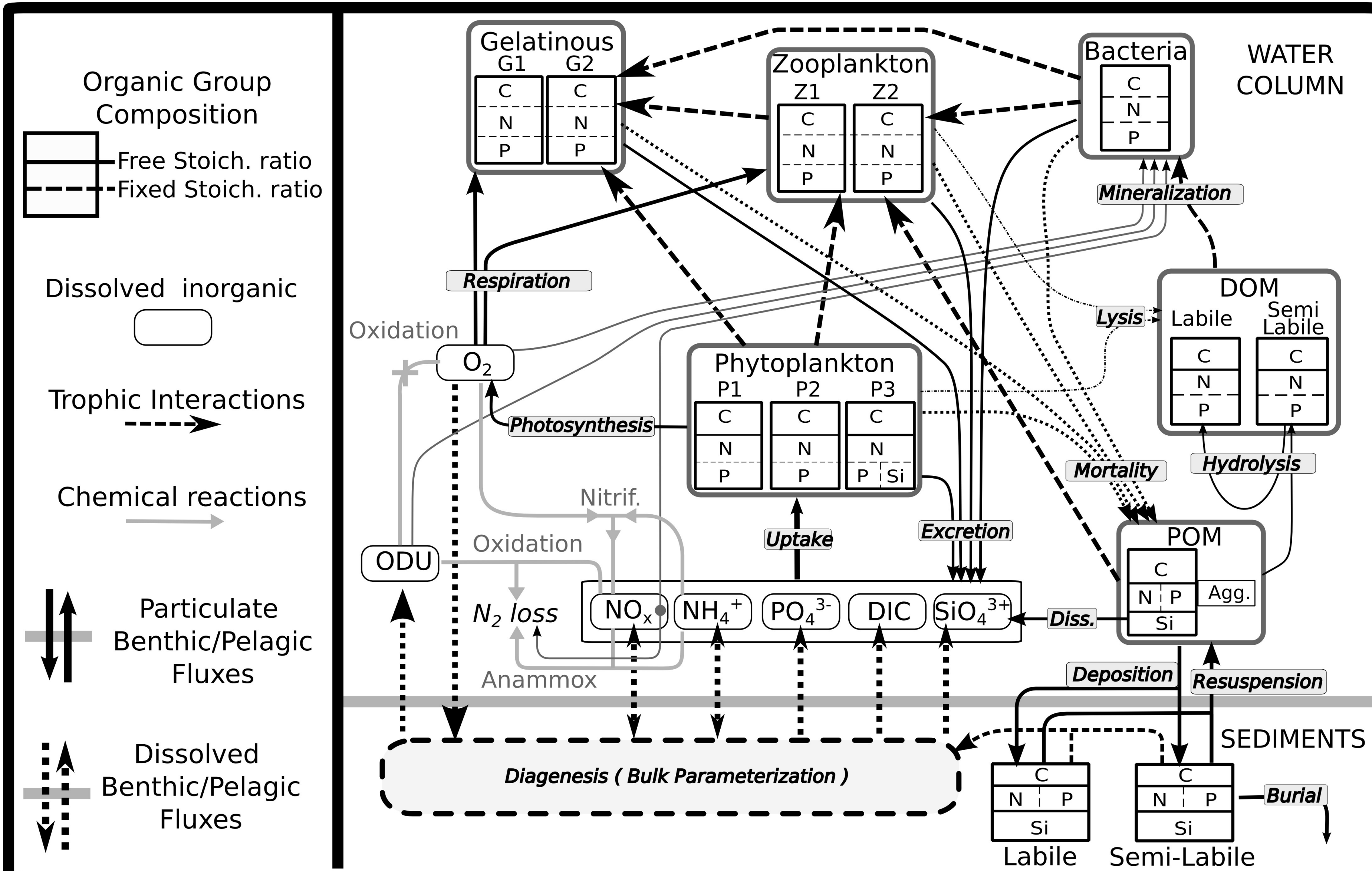


(Capet et al. 2013, Biogeosciences)

36 State variables



(Capet et al. 2013, Biogeosciences)

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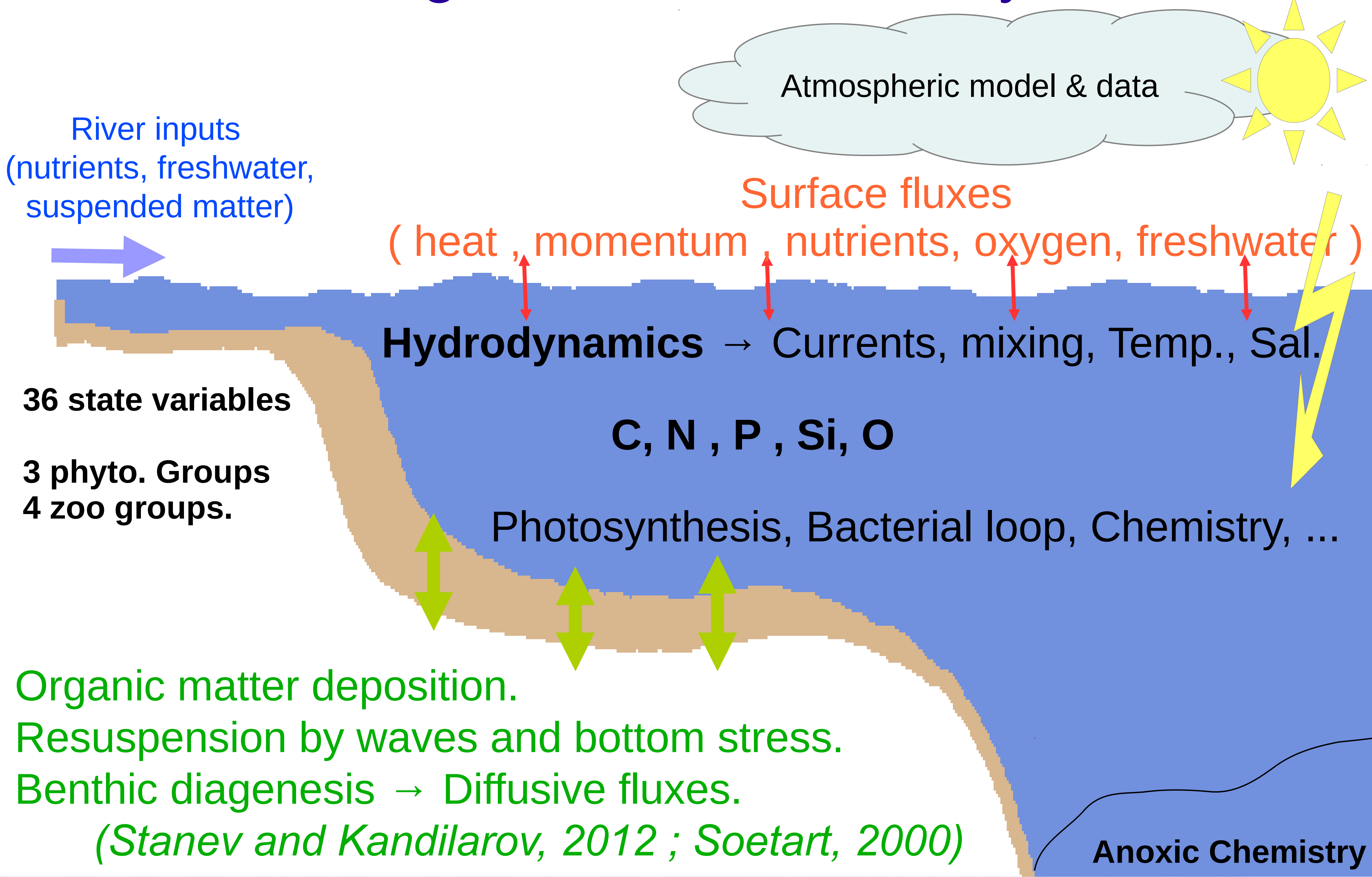
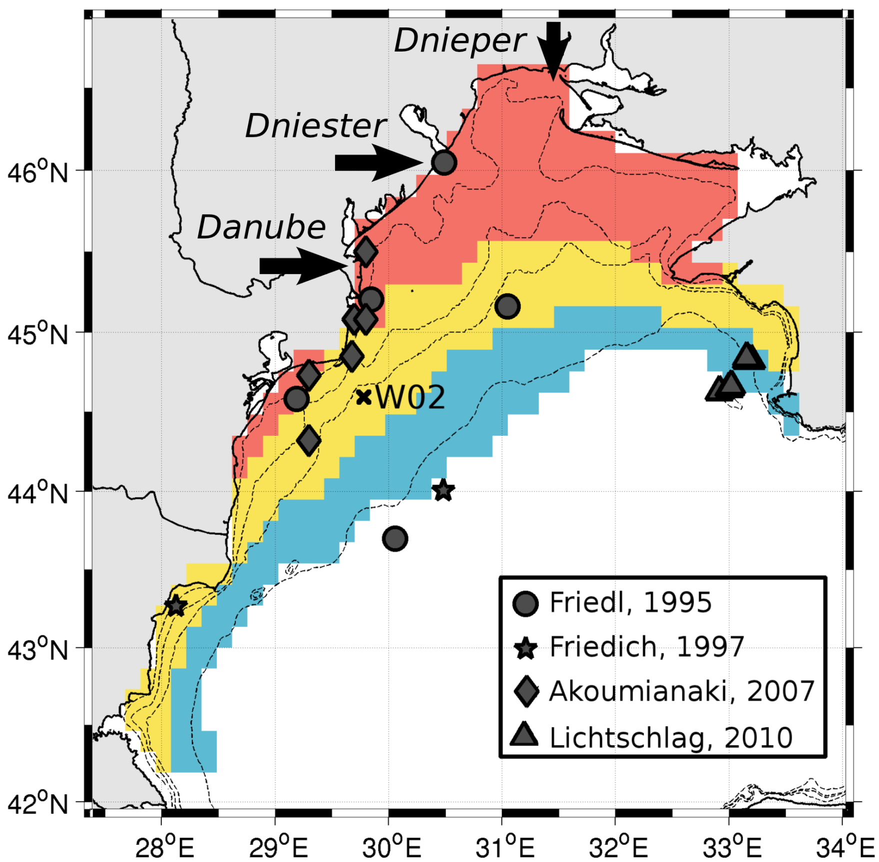
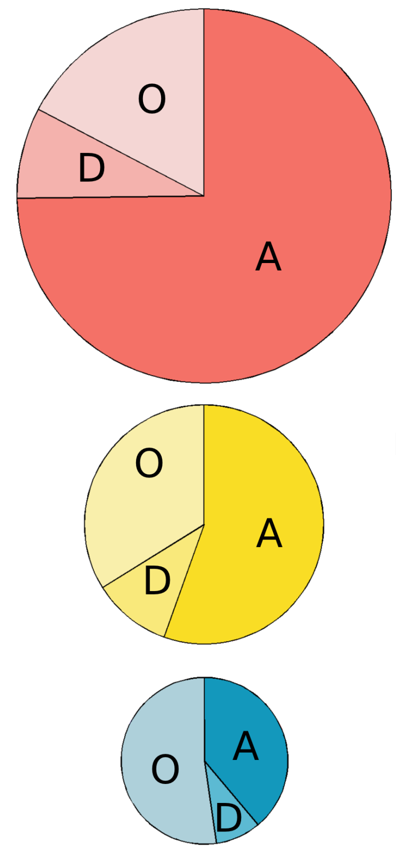


(Capet et al. 2013, Biogeosciences)

Biogeochemical role of the sediment layer



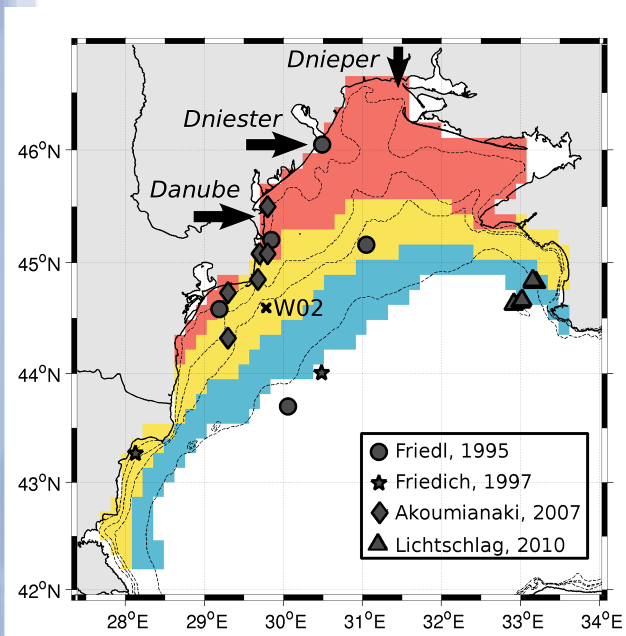


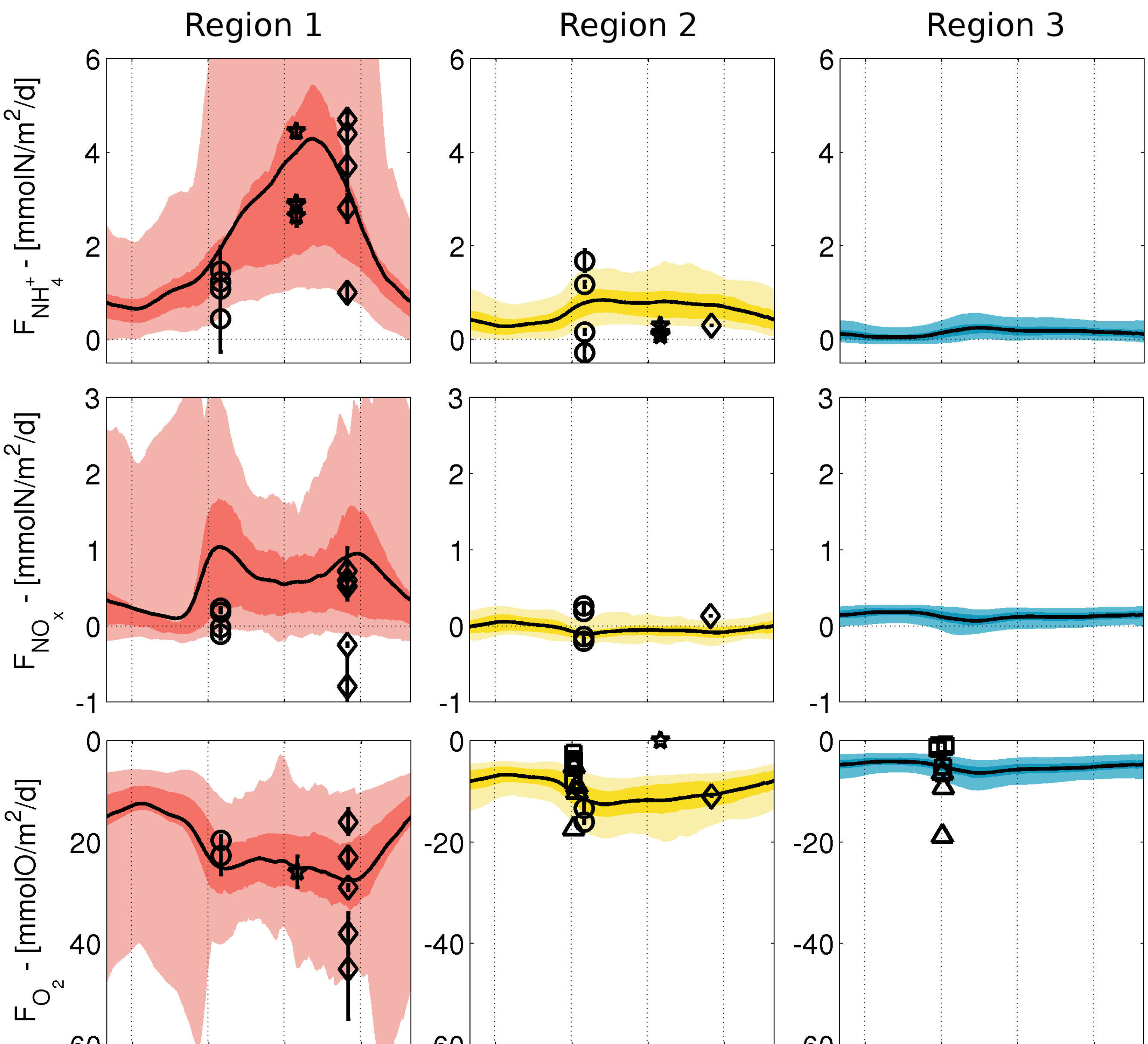
Region 1 (25 km² / 15-57 m)
Avg. D_C: 9 molC/m²/yr
Oxic : 17%
Denit.: 8%
Anox.: 75 %

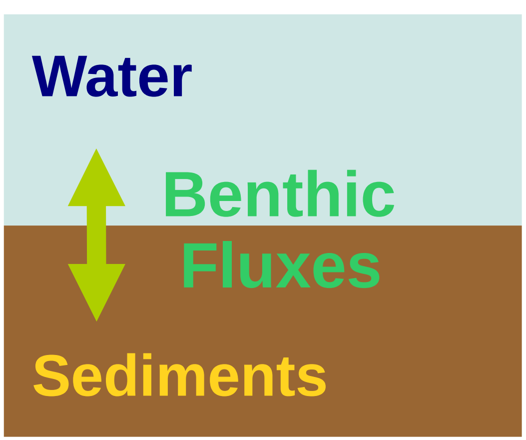
Region 2 (30.2 km² / 23-95 m)
Avg. D_C: 4 molC/m²/yr
Oxic : 34%
Denit.: 11%
Anox.: 55 %

Region 3 (23.2 km² / 46-120 m)
Avg. D_C: 2 molC/m²/yr
Oxic : 52%
Denit.: 9%
Anox.: 39 %

Biogeochemical role of the sediment layer







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(Capet et al. 2013, Biogeosciences)

Model validation

Does the model adequatly resolves ...

the horizontal distribution

the seasonal distribution

the interannual distribution

the vertical distribution

the specific occurrence of hypoxia

... reflected by in situ observations ?

(Capet et al. 2013, Biogeosciences)

Model validation

Does the model adequatly resolves ...

the horizontal distribution

the seasonal distribution

the interannual distribution

the vertical distribution

the specific occurrence of hypoxia

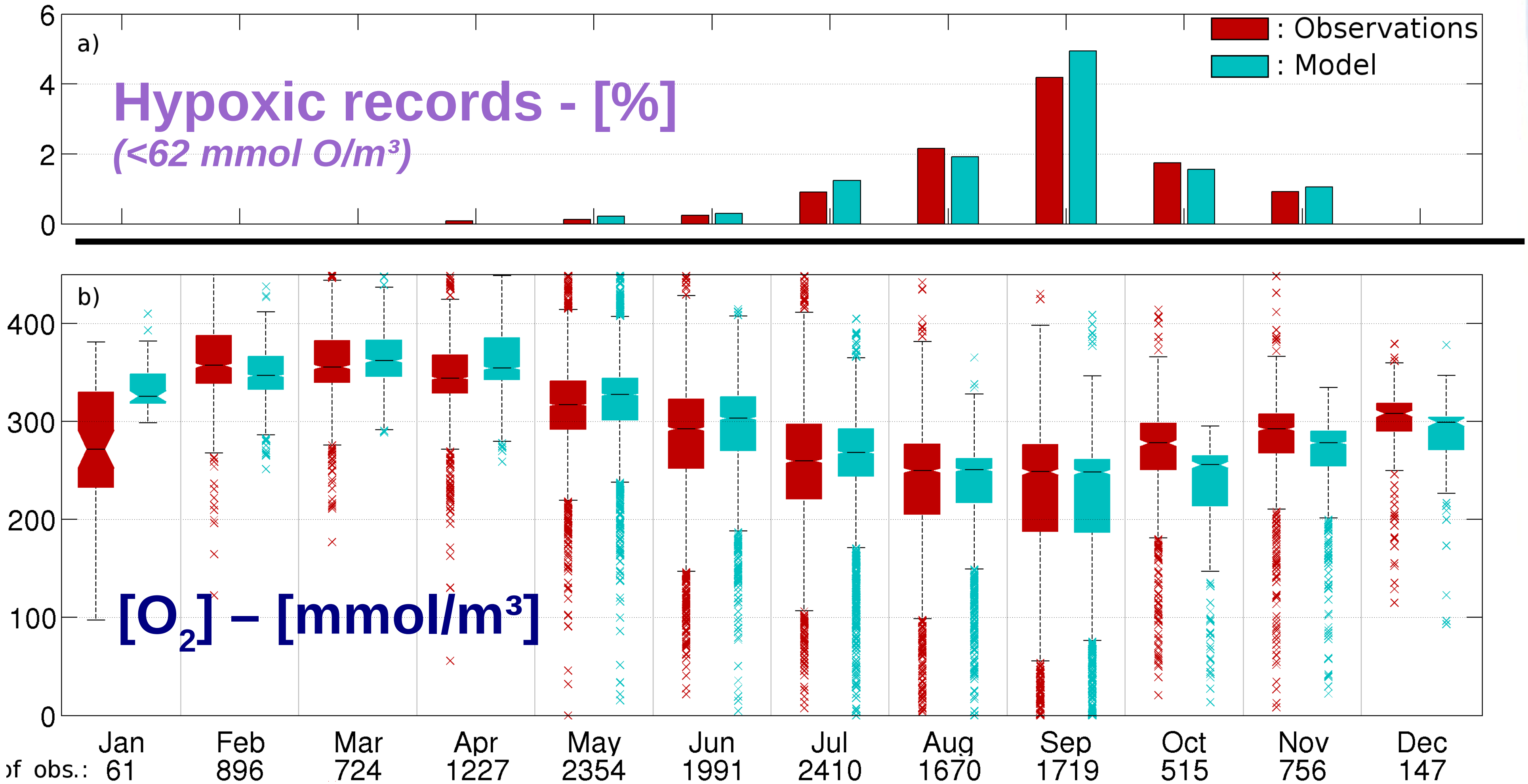
... reflected by in situ observations ?

Yes , yes , yes, yes and yes

(Capet et al. 2013, Biogeosciences)

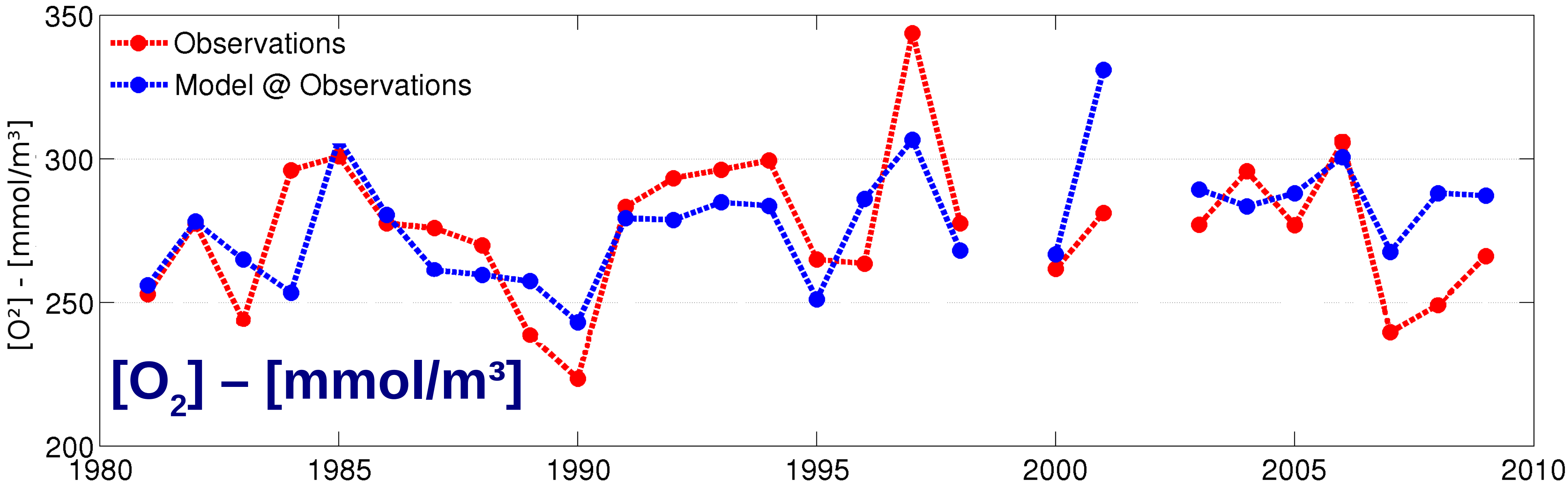
Model Validation : Point-to-point

Merged by months → validation of the seasonal cycle



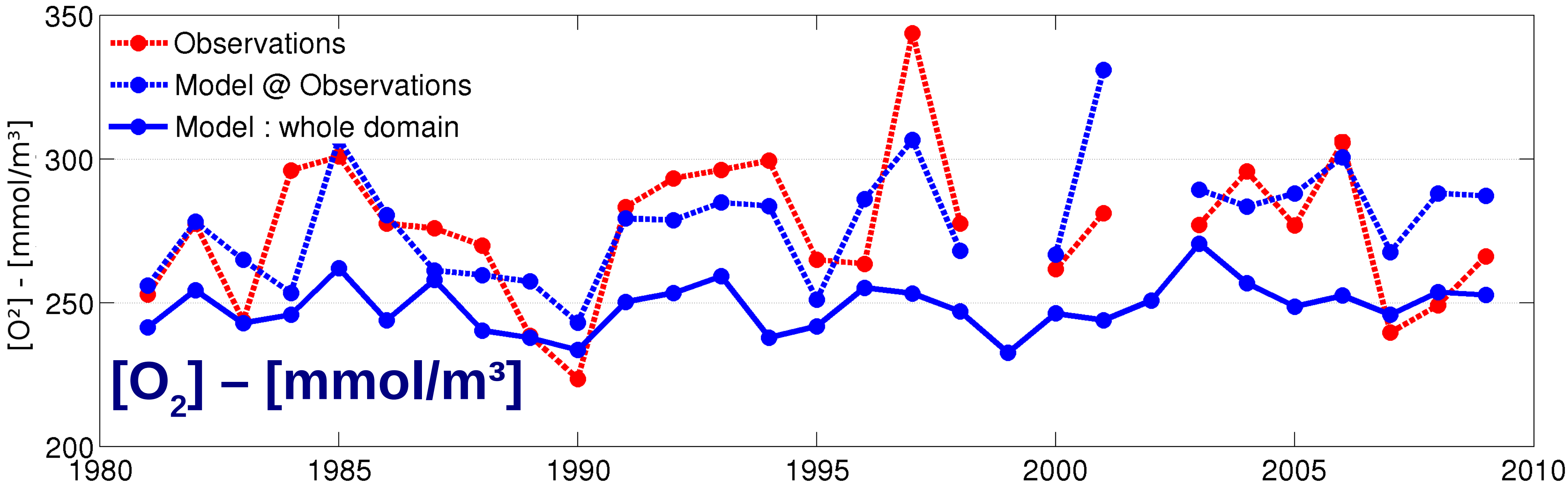
(Capet et al. 2013, Biogeosciences)

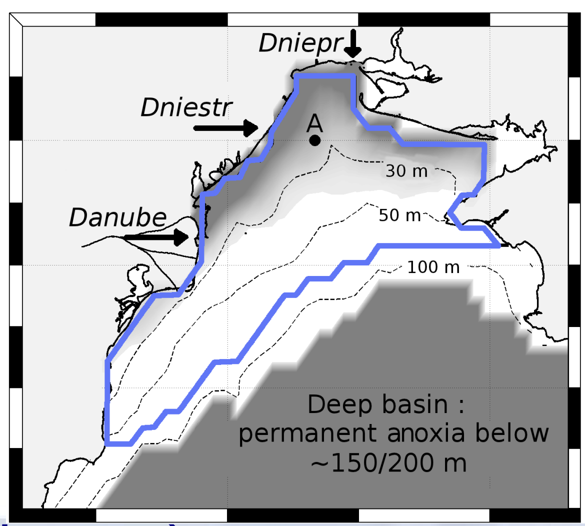
Interannual Model-Data comparison



(Capet et al. 2013, Biogeosciences)

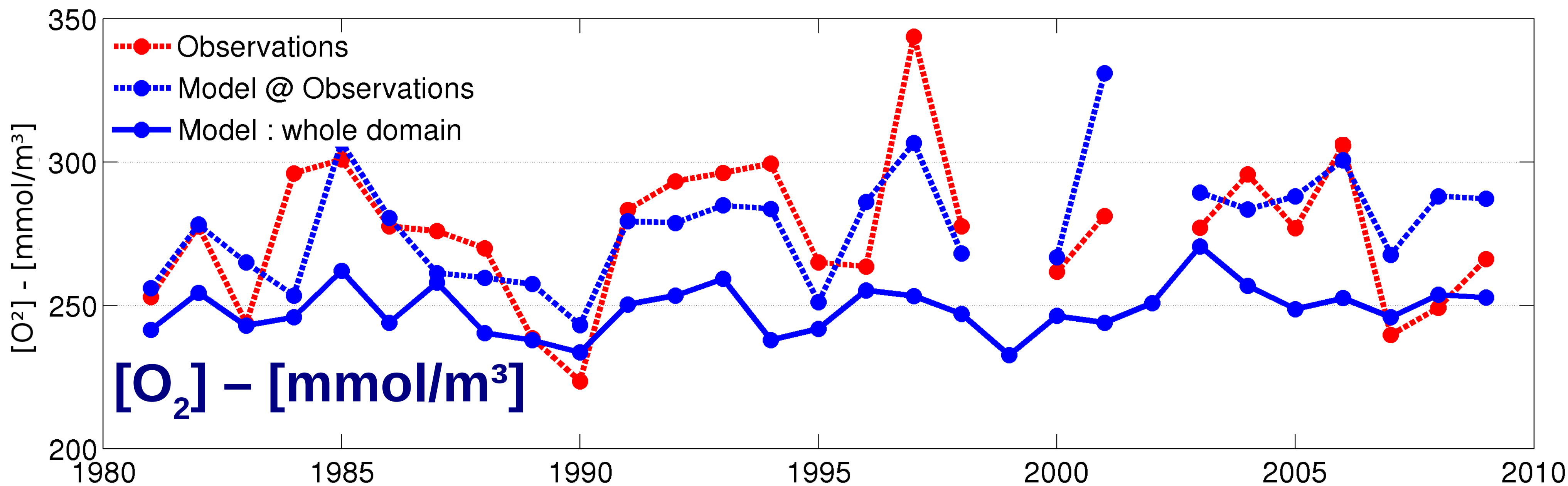
Interannual Model-Data comparison

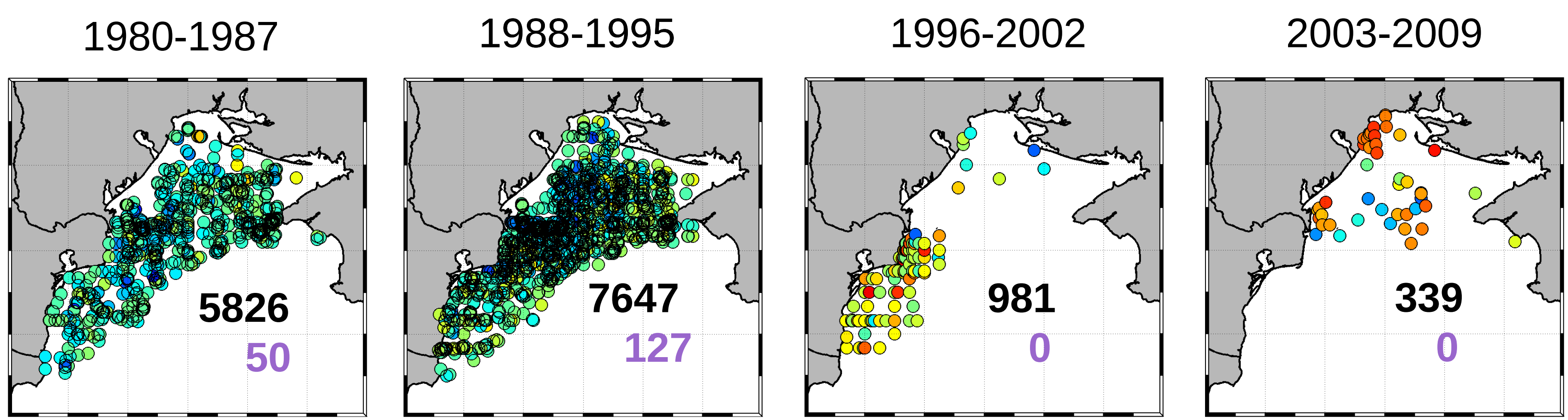




(Capet et al. 2013, Biogeosciences)

Interannual Model-Data comparison





(Capet et al. 2013, Biogeosciences)

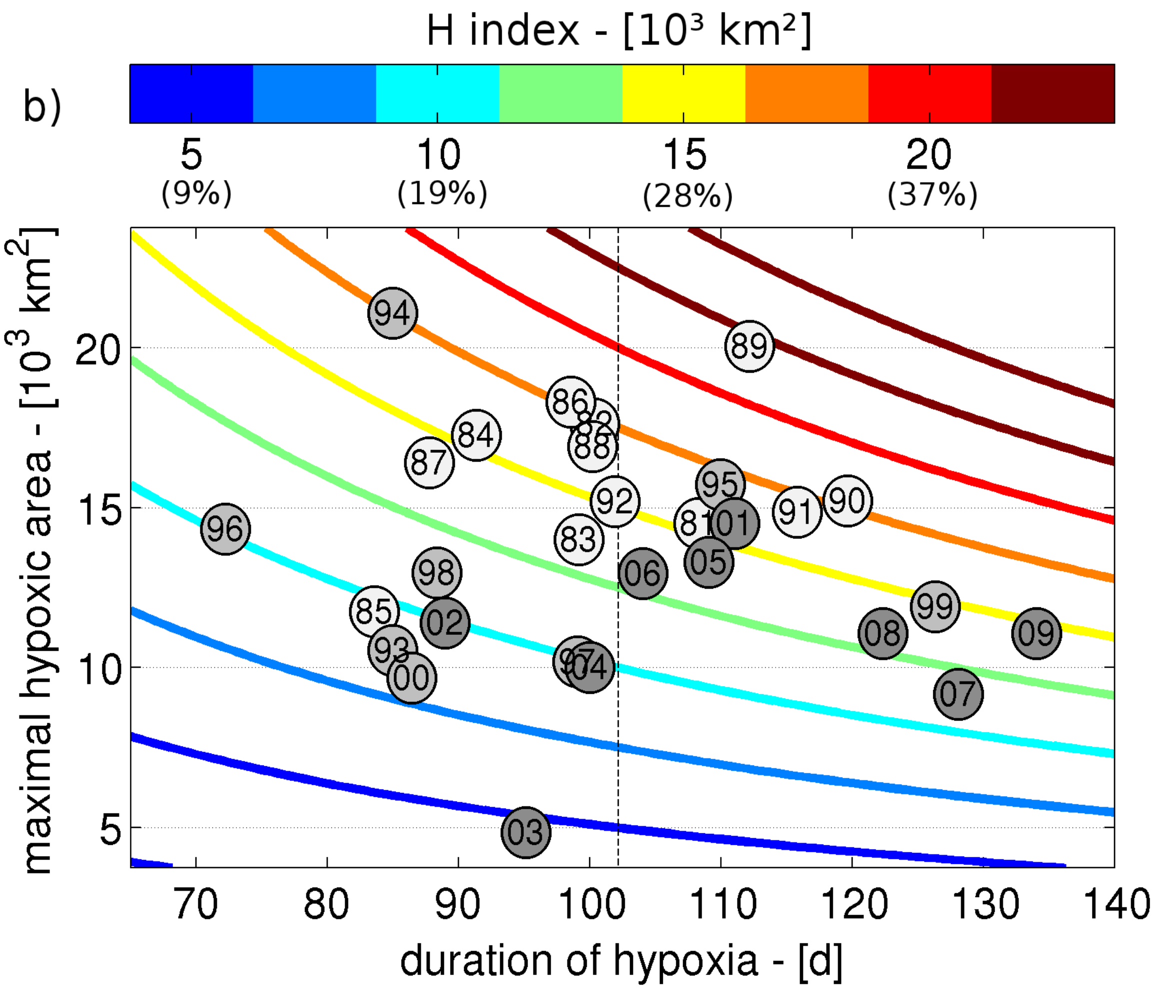
Interannual variability

The H-index

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

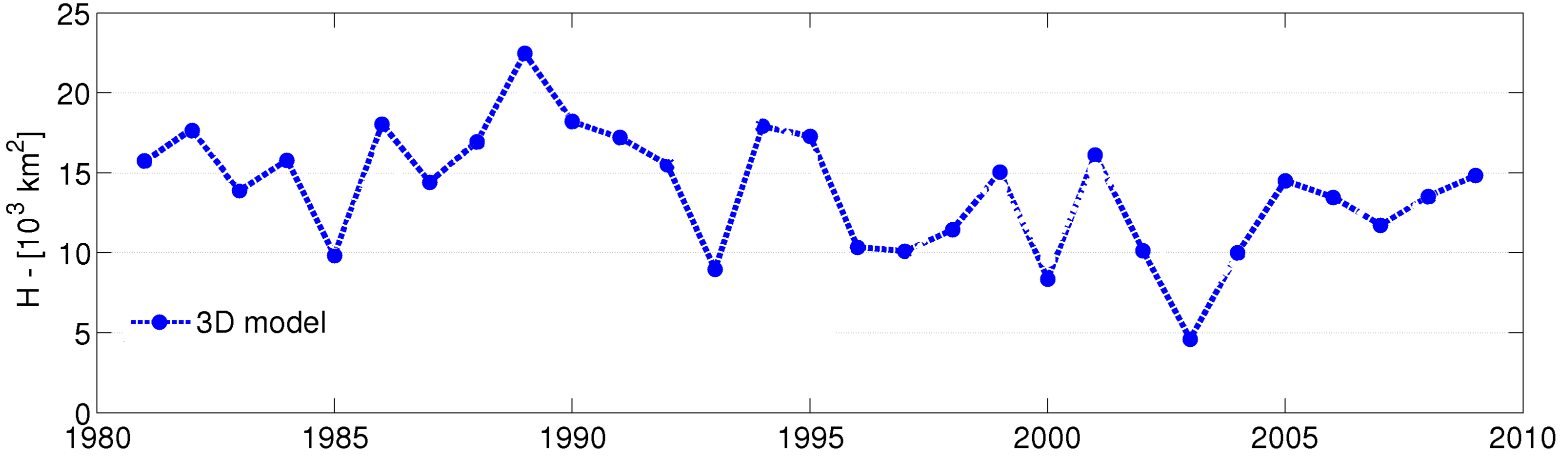
The H-index express
the spatial extension
of hypoxia..

.. modulated by the
duration of hypoxia



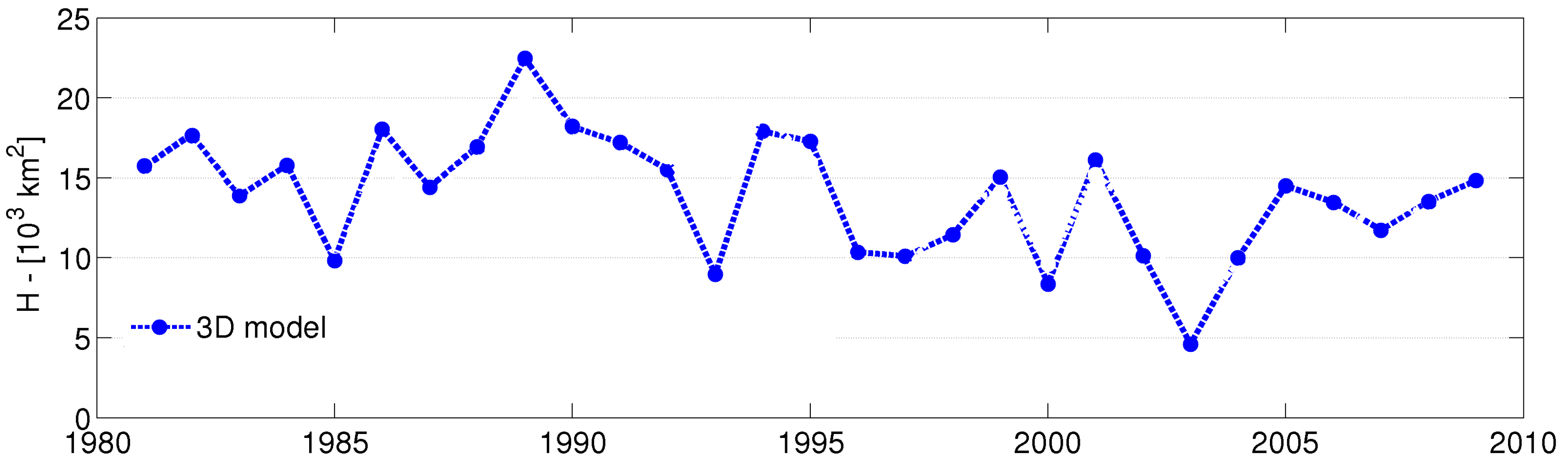
(Capet et al. 2013, Biogeosciences)

Interannual variability of Hypoxia



(Capet et al. 2013, Biogeosciences)

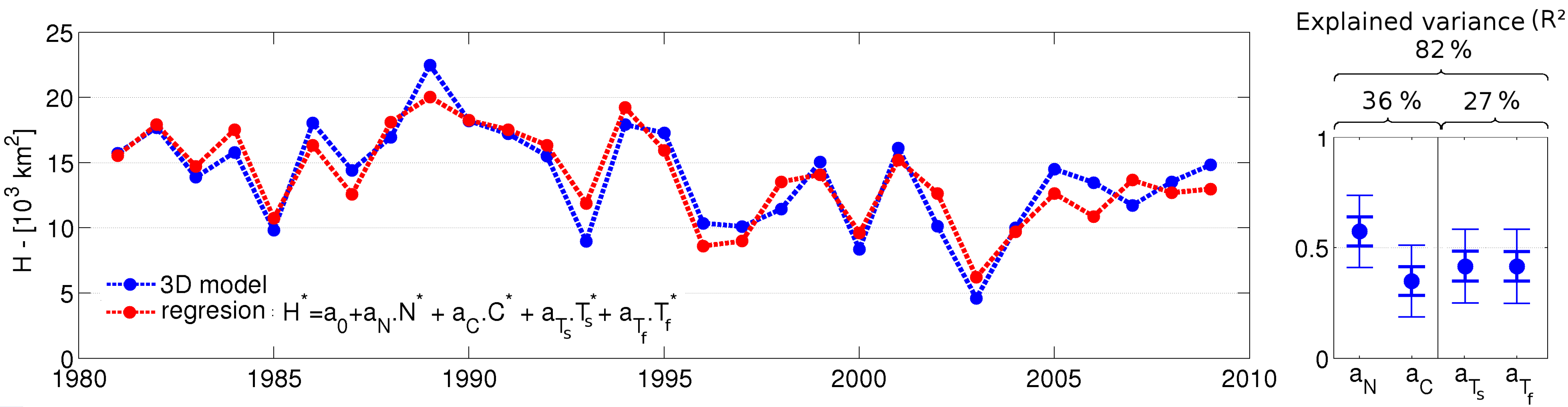
Interannual variability of Hypoxia



What are the drivers of this interannual variability ?

(Capet et al. 2013, Biogeosciences)

Interannual variability of Hypoxia



Eutrophication **and** **climate**

(1) High nitrogen riverine discharge.

(2) High sedimentary organic carbon content.

36 %

(3) Warm springs.

(4) Warm summers.

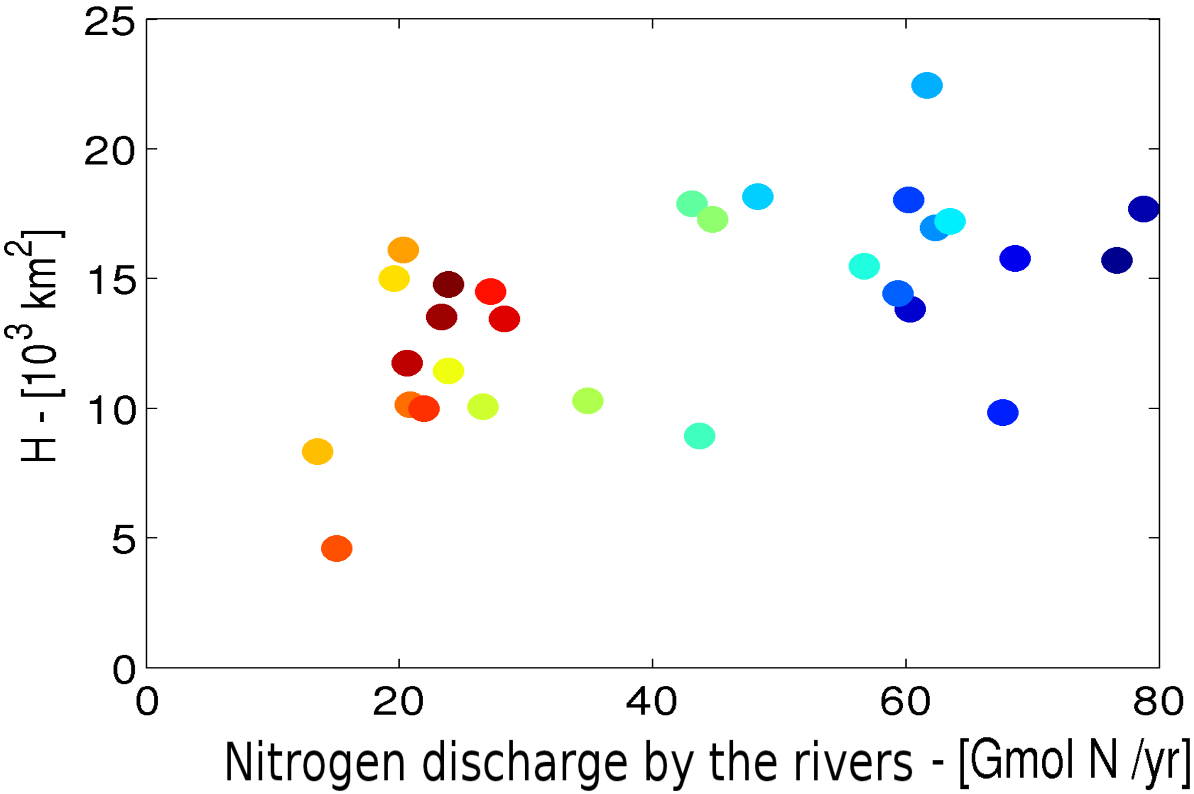
27 %

82 %

(Capet et al. 2013, Biogeosciences)

Can we exploit this knowledge for management purposes ?

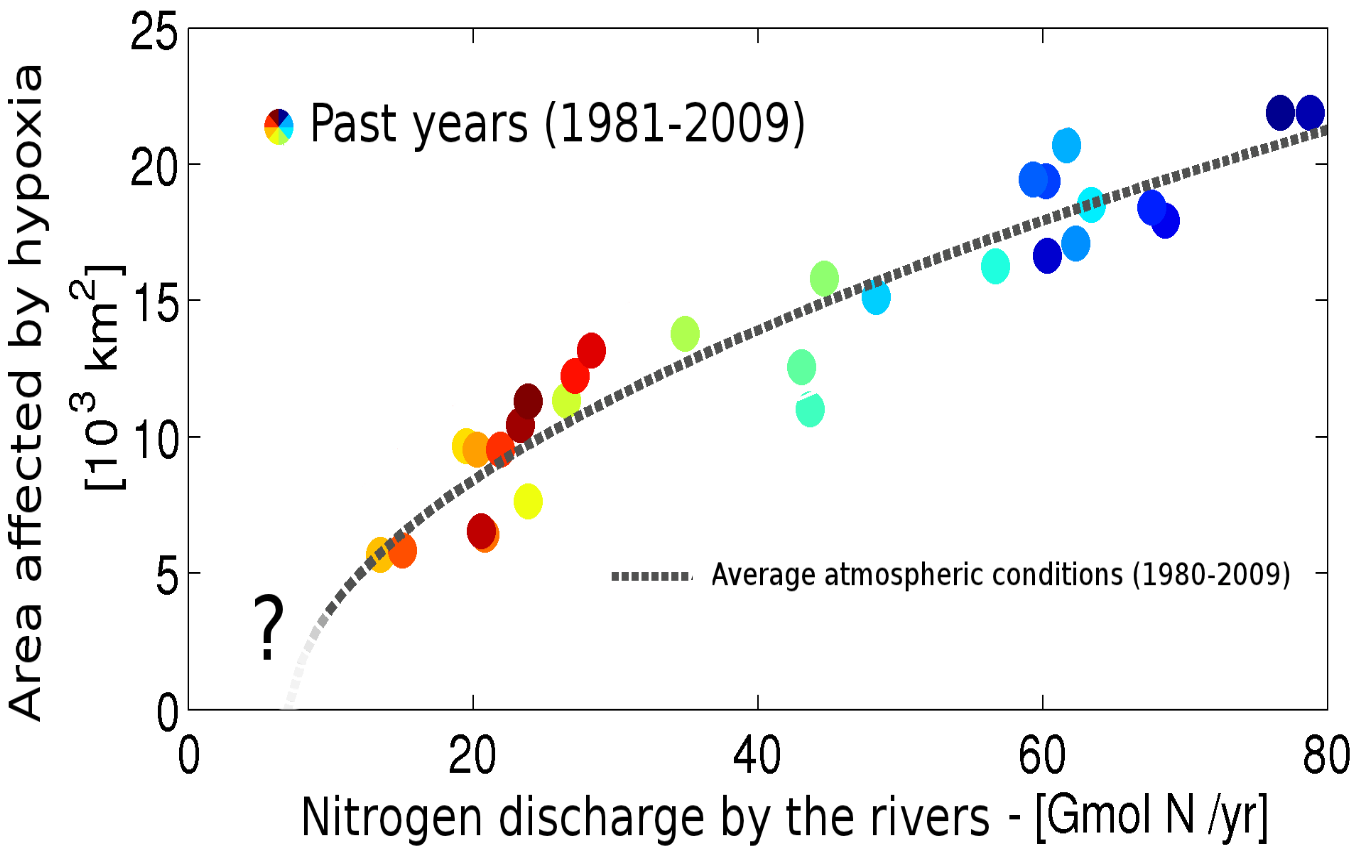
Hypoxia response to N discharge



Includes the year specific influences of climatic and sediments drivers

(Capet et al. 2013, Biogeosciences)

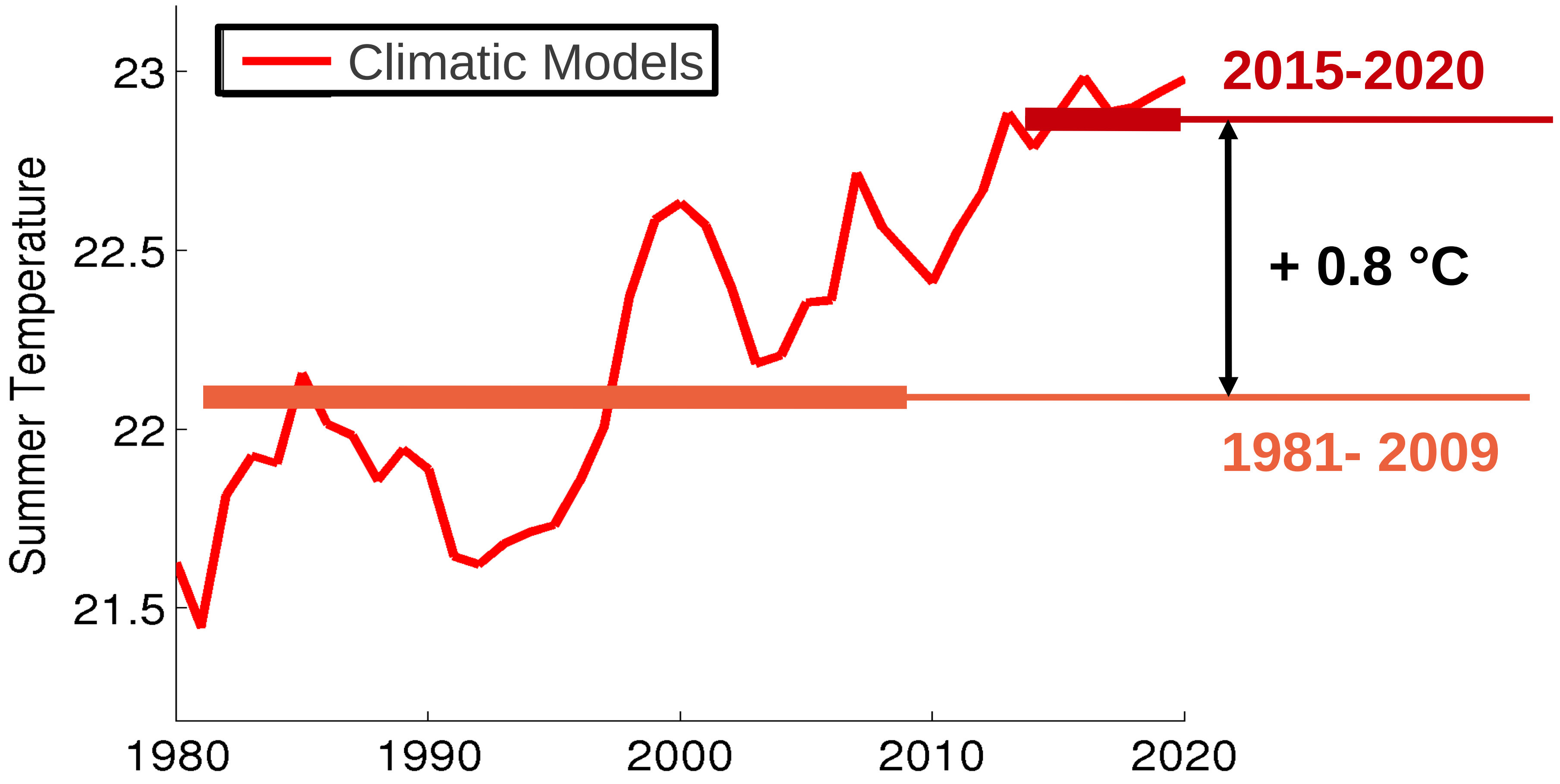
Hypoxia response to N discharge



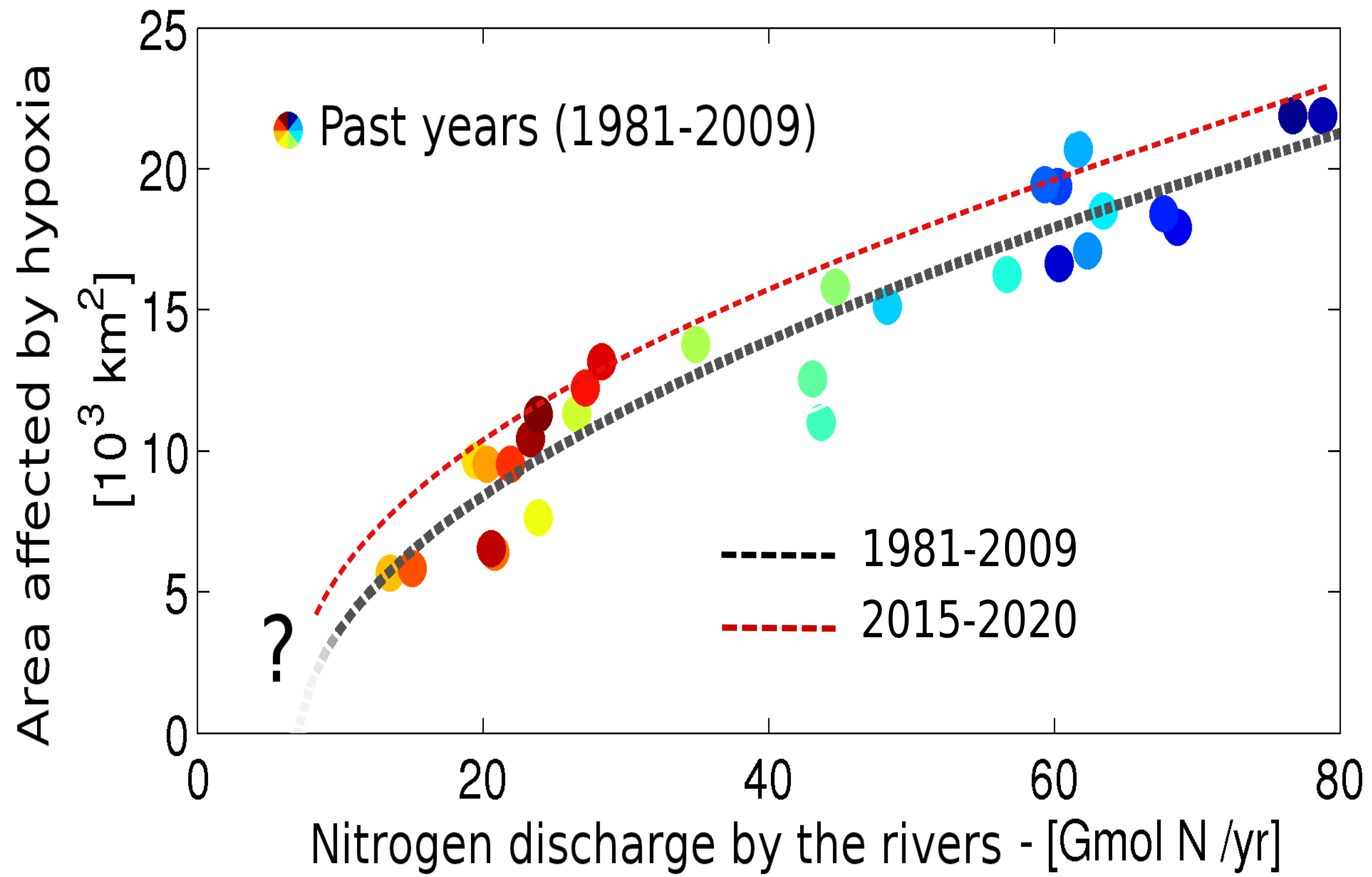
Response curve for average atmsopheric conditions (1980-2009)

(Capet et al. 2013, Biogeosciences)

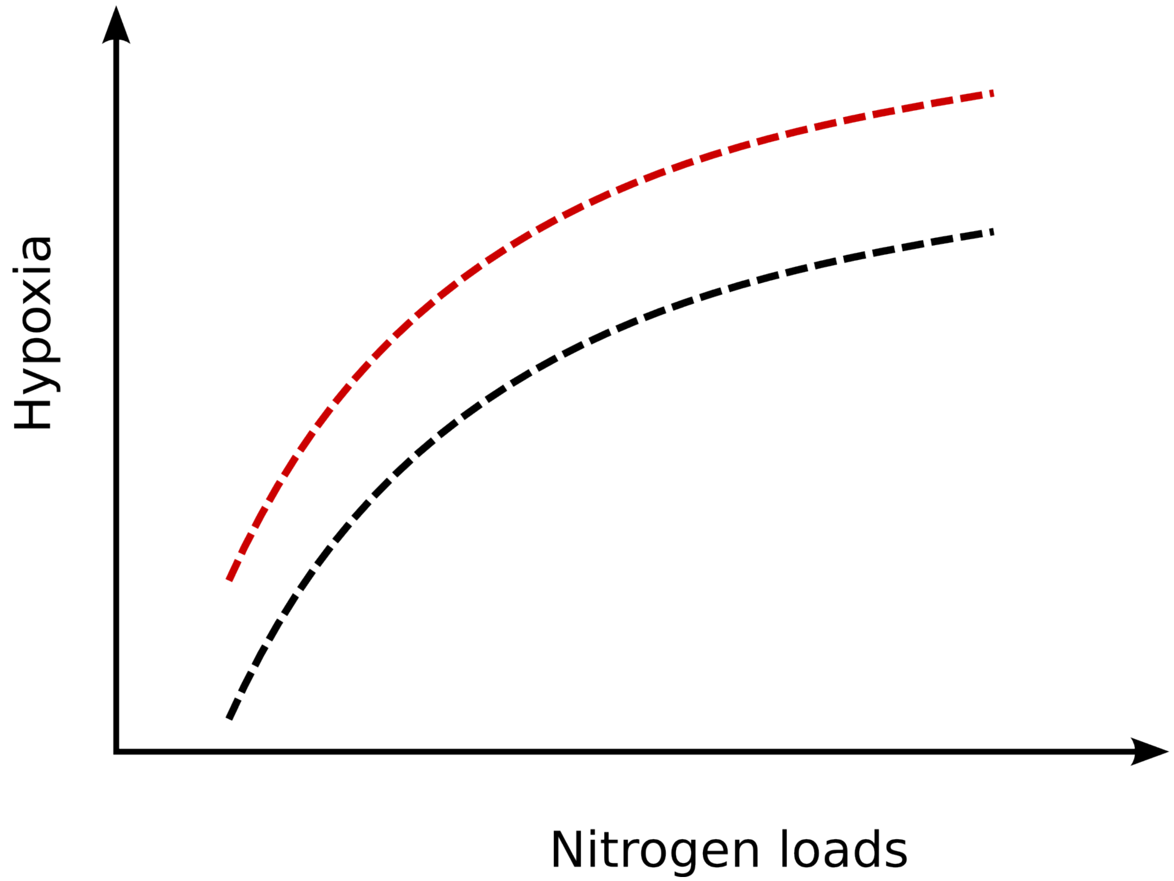
These average atmospheric conditions are not valid anymore



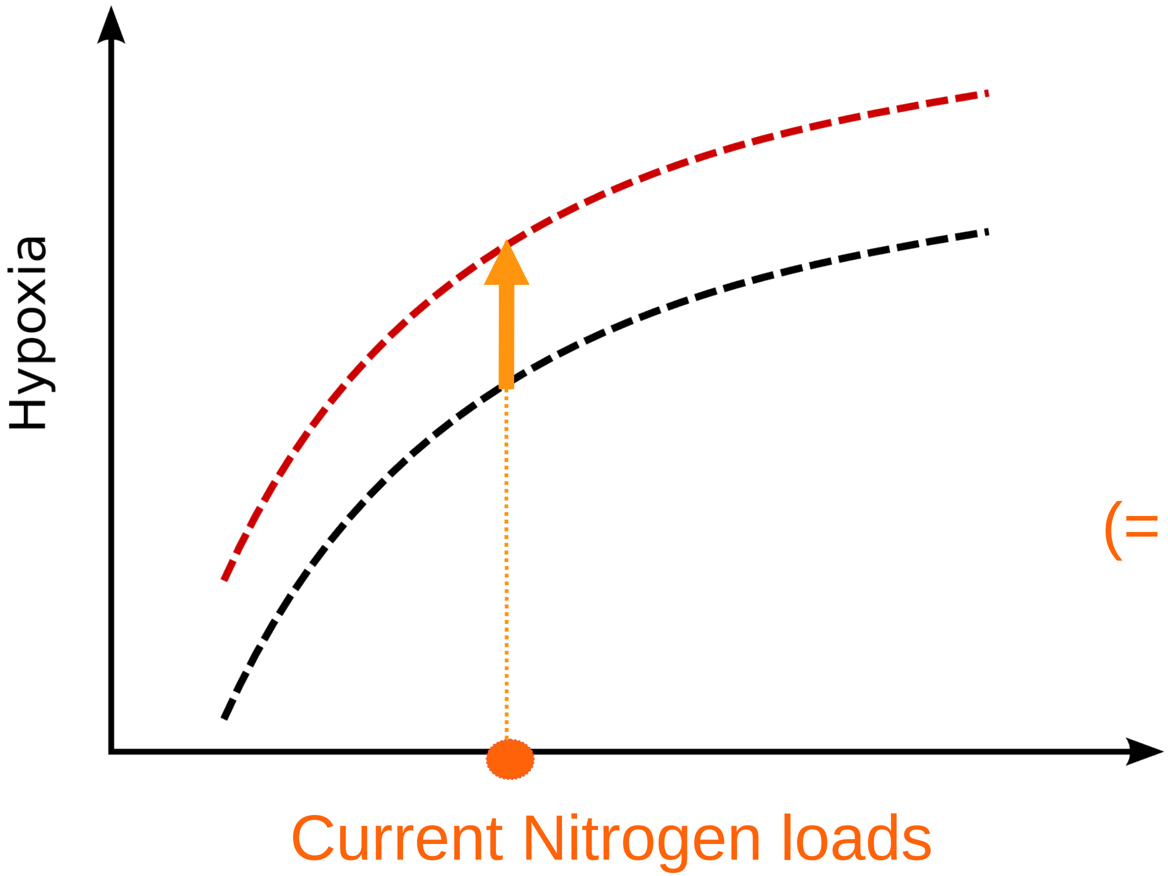
Hypoxia response to N discharge



The cost of warming



The cost of warming



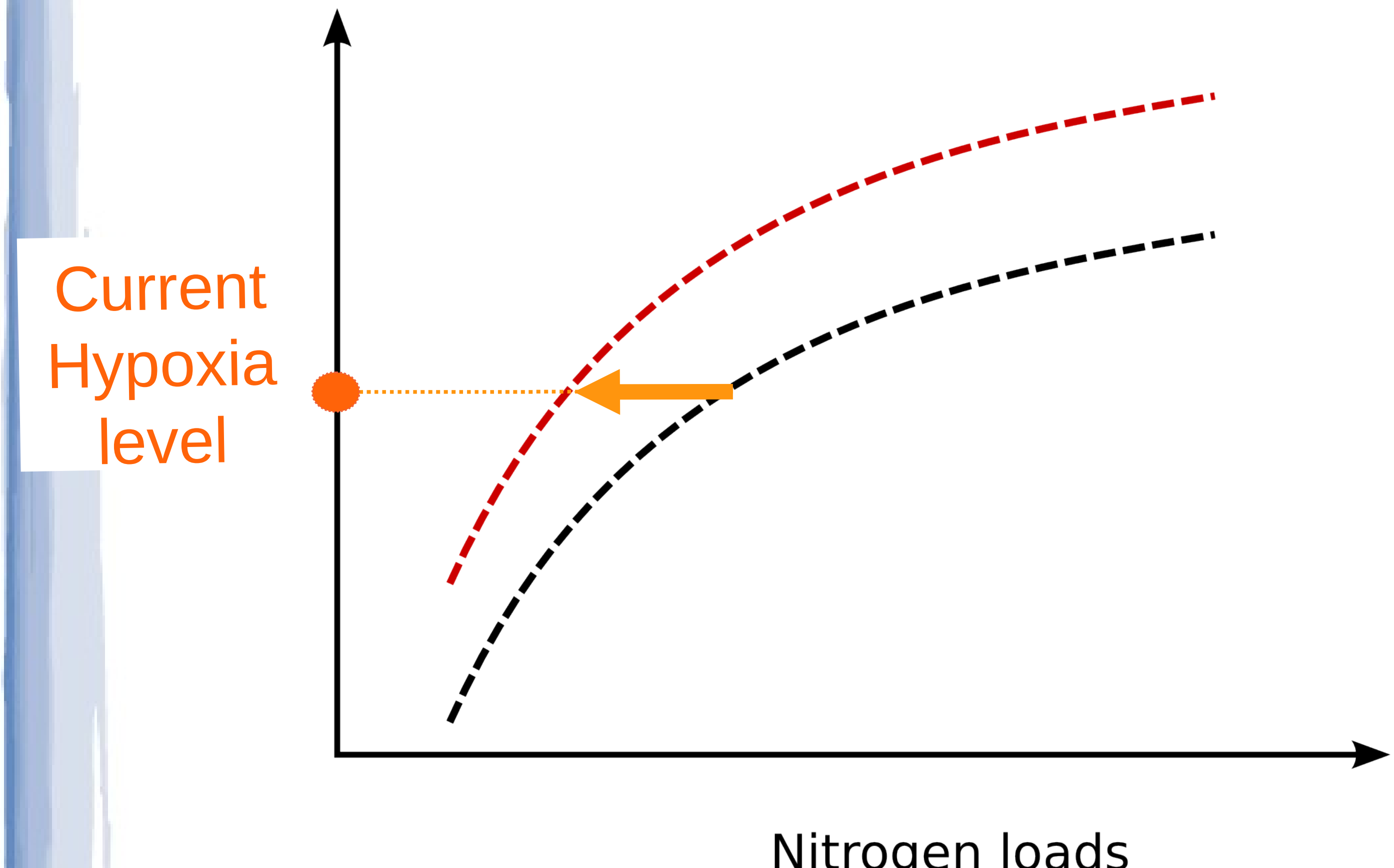
Environmental cost

20 % increase

of Hypoxia

(= +3% of the shelf area)

The cost of warming



<u>Economical cost</u>

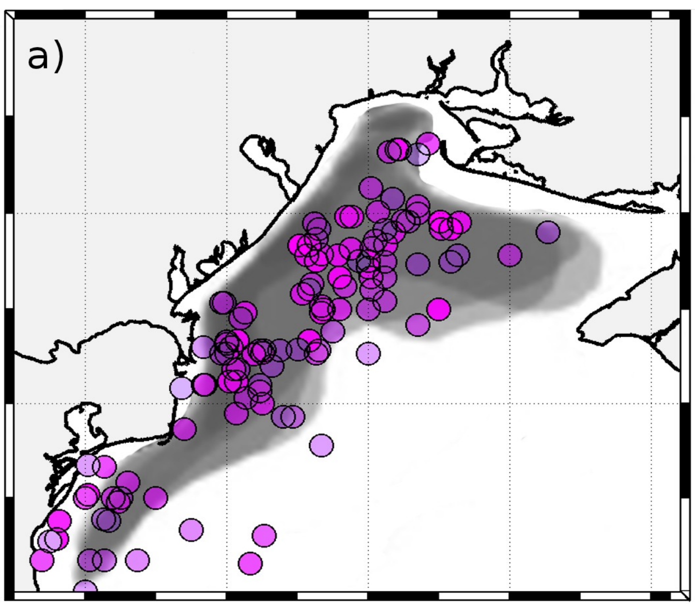
24 % reduction of nutrient loads

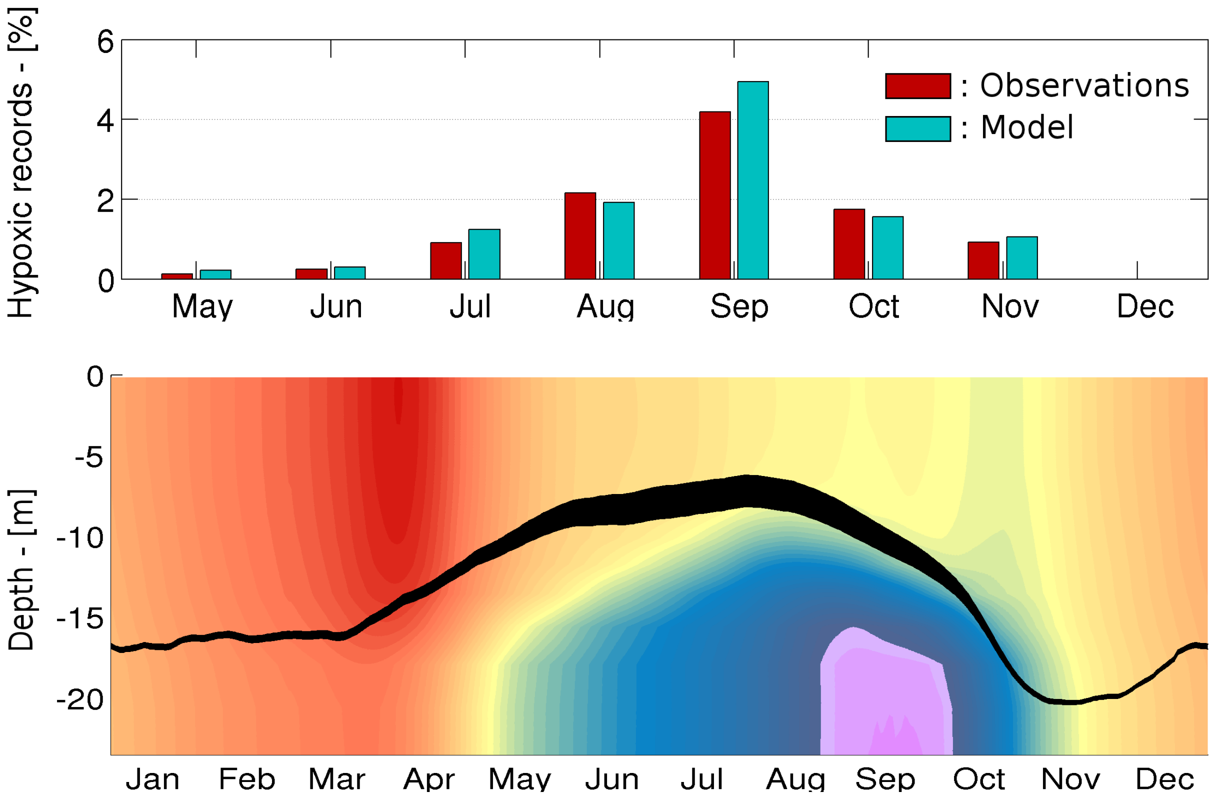
Conclusion (Hypoxia)

Conclusion (Hypoxia) – 1/3

Hypoxia is still ongoing in the Black Sea NWS

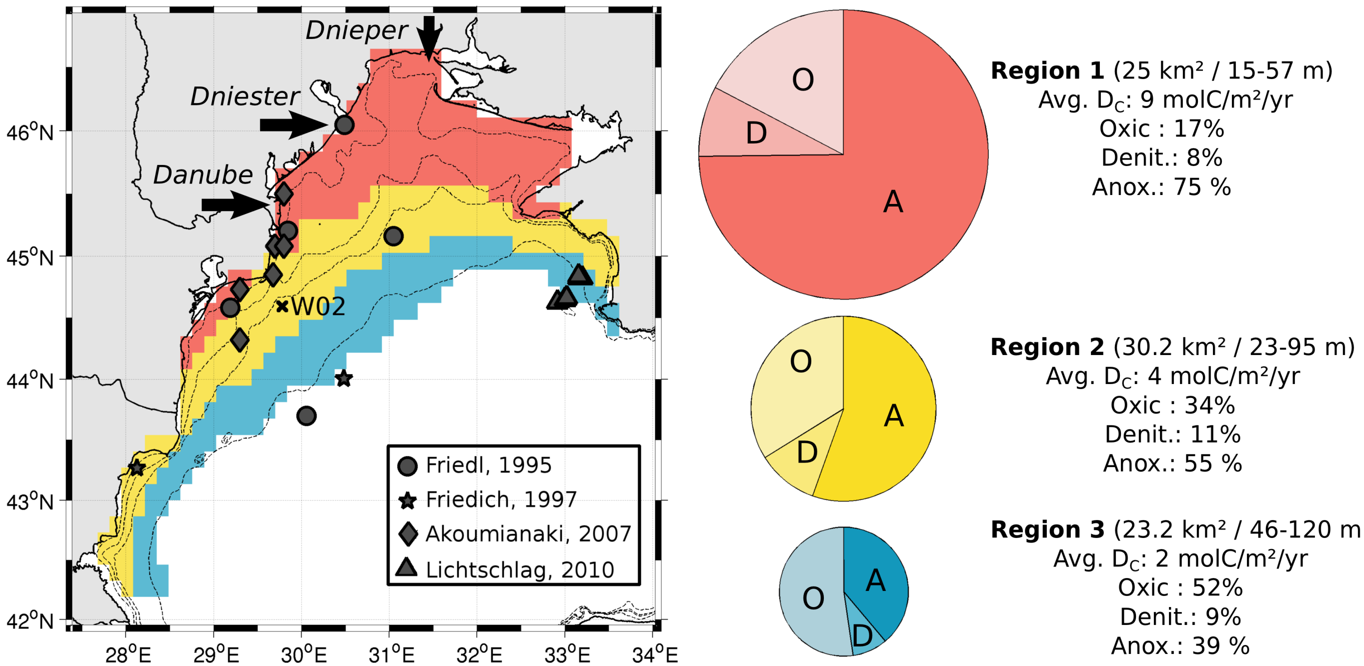
Monitoring should be focused on the area, months and depth of known hypoxia occurence





Conclusions (Hypoxia) – 2/3

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

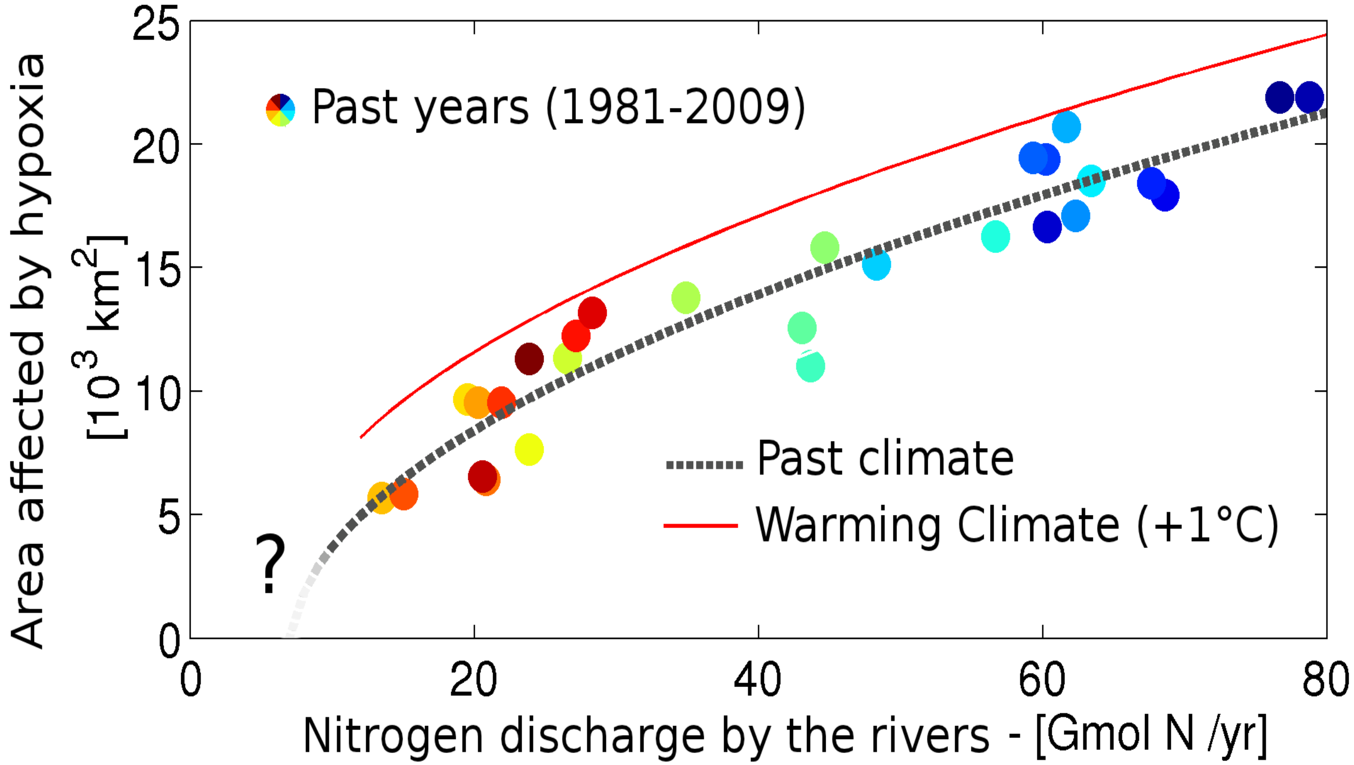


Systems with decreasing N → Inertia in the recovery process

Systems with increasing N → Increase of the H/N ratio

Conclusion (Hypoxia) – 3/3

Climate impacts almost as much as eutrophication.



Nutrient reduction policies must account for realistic climatic scenarios

.

General Conclusions

- The physical model reproduces the **variability of the Black Sea internal structure** and allows to investigate its **sensitivity to atmospheric conditions**
- The biogeochemical model allowed us to untangle the **complex dynamics of hypoxia** and to evidence the **specific impact of its main drivers**

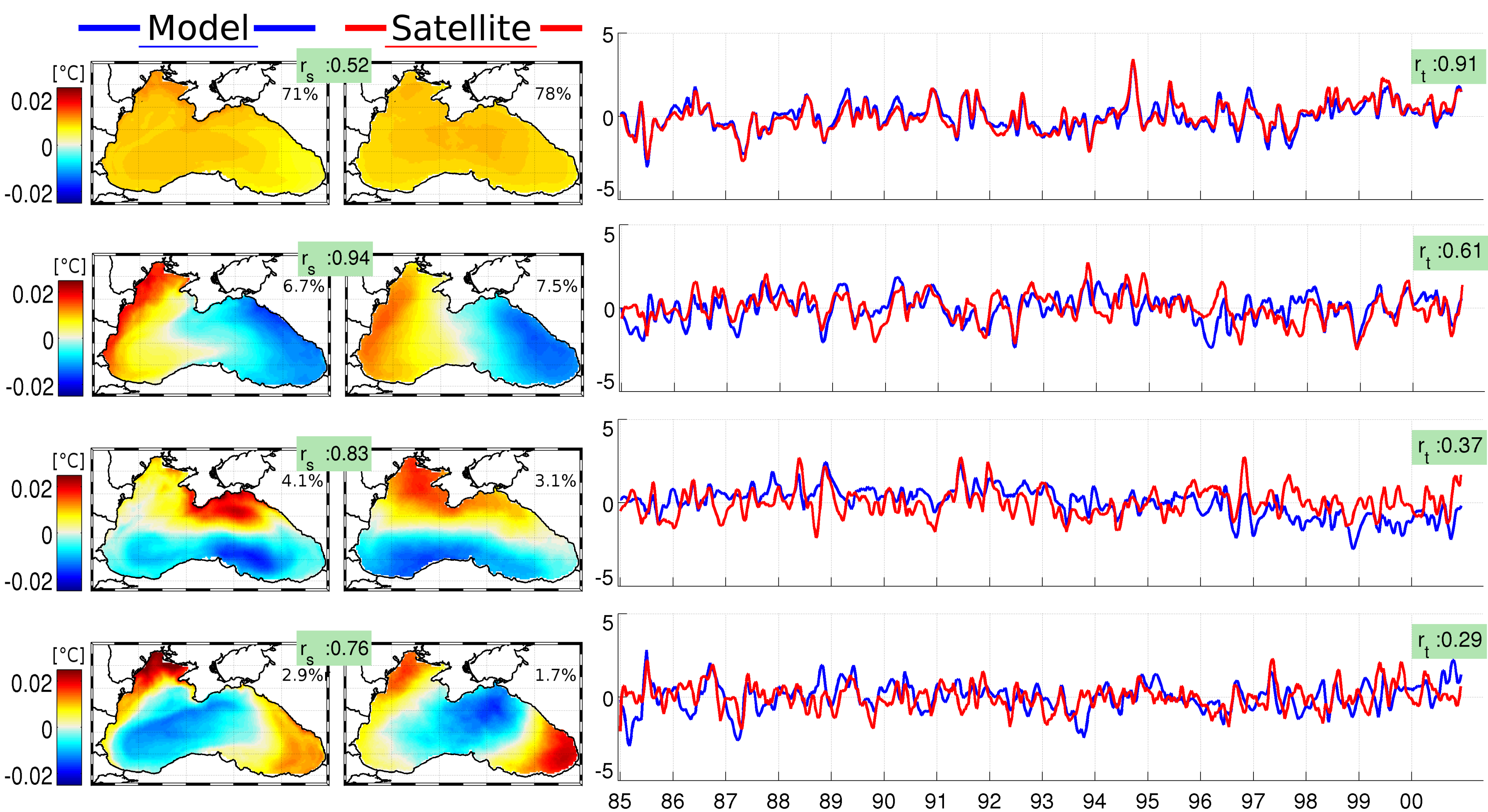
General Conclusions

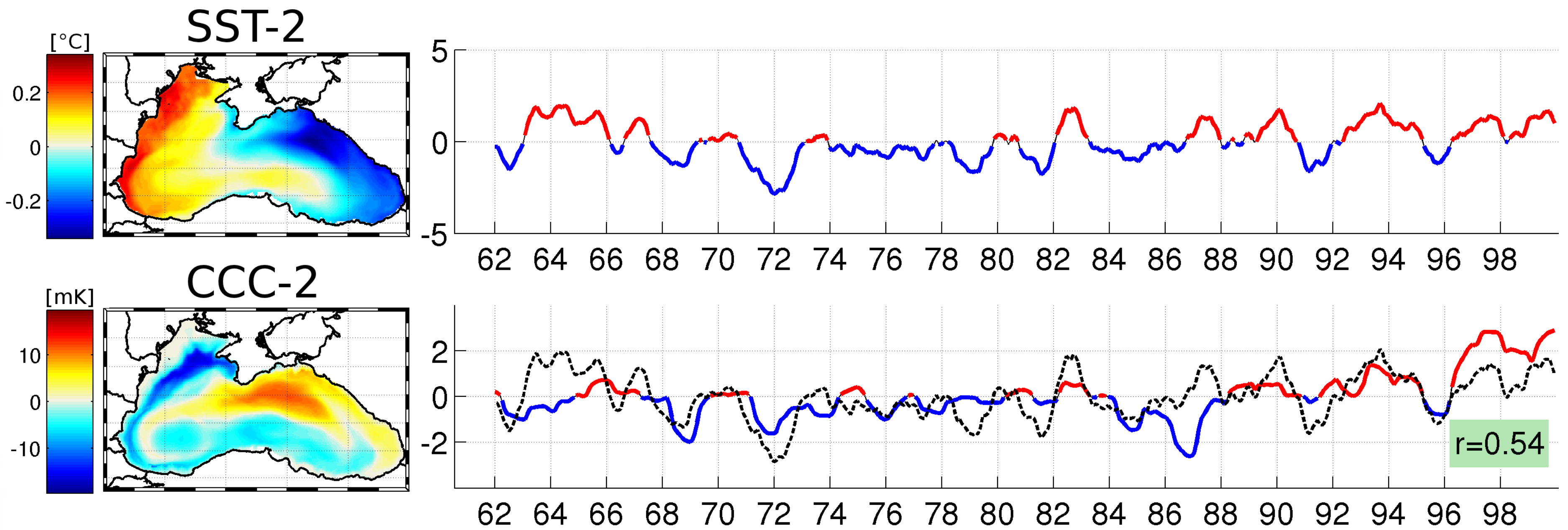
- 3D biogeochemical models are essential to understand to **complex dynamics of marine ecosystems**, in which physical, chemical and biological processes are intimately interconnected
- As such these models are indispensable to allows a **sustainable management of the goods and services** provided by marine ecosystems and to assess to which extent these are endangered by the **synergestic impacts of environmental pressures**.


Thank you for your attention
… and questions !

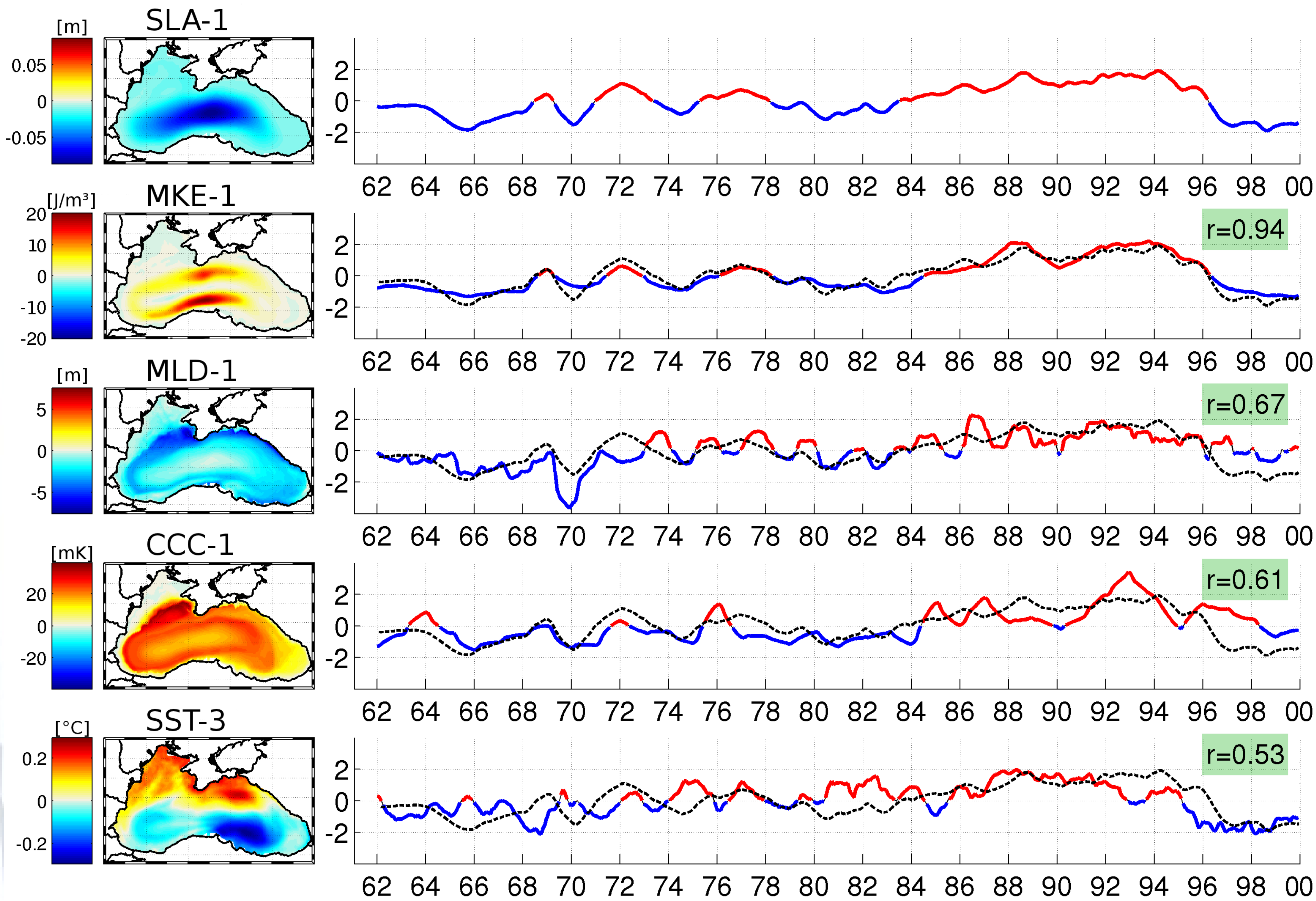
SST anomalies

Model VS Satellite (1985-2000)

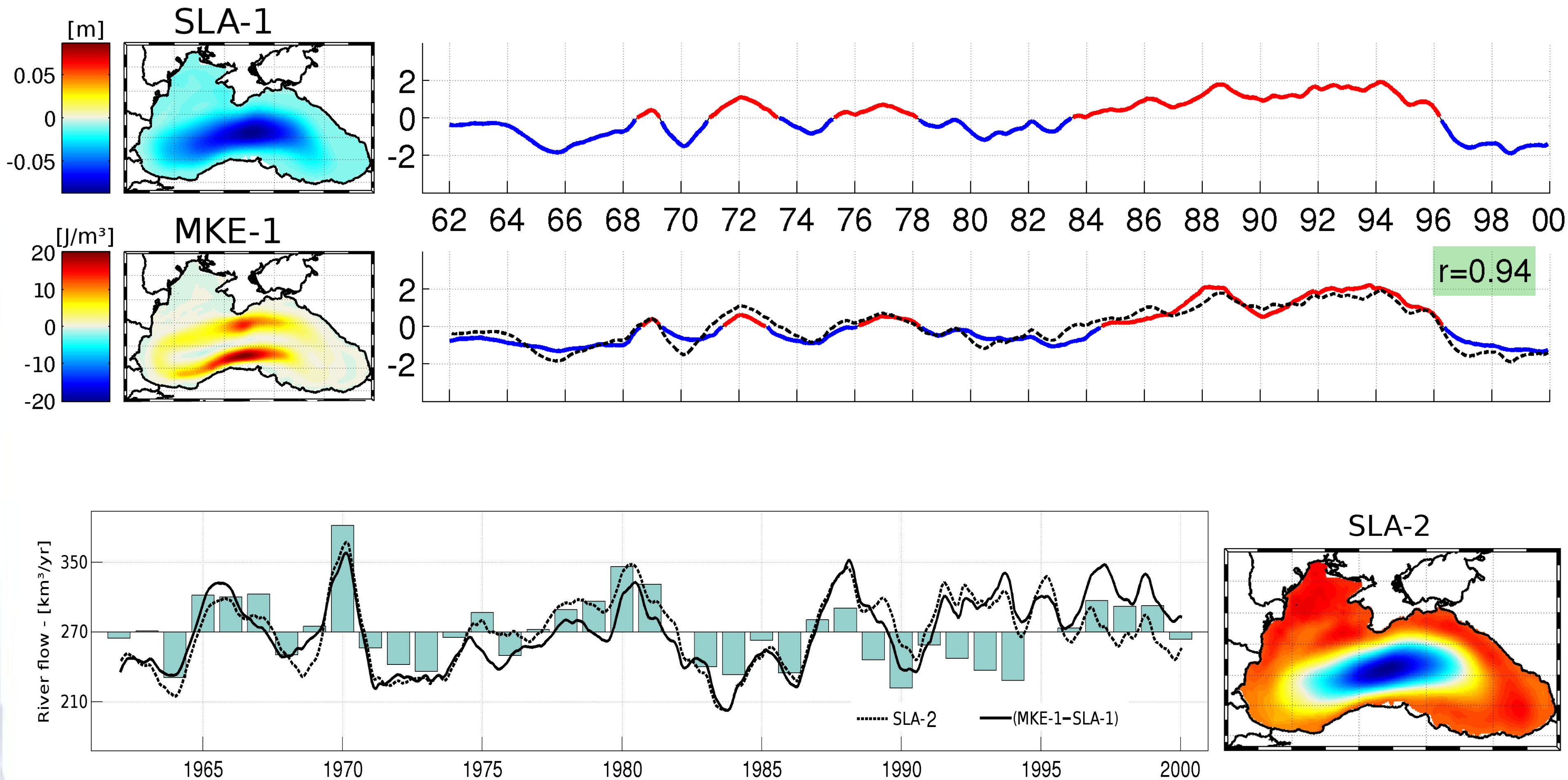




SST-2
[°C]
0.2
0
-0.2
5
0
-5
62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98
CCC-2
[mK]
10
0
-10
2
0
-2
r=0.54
62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98

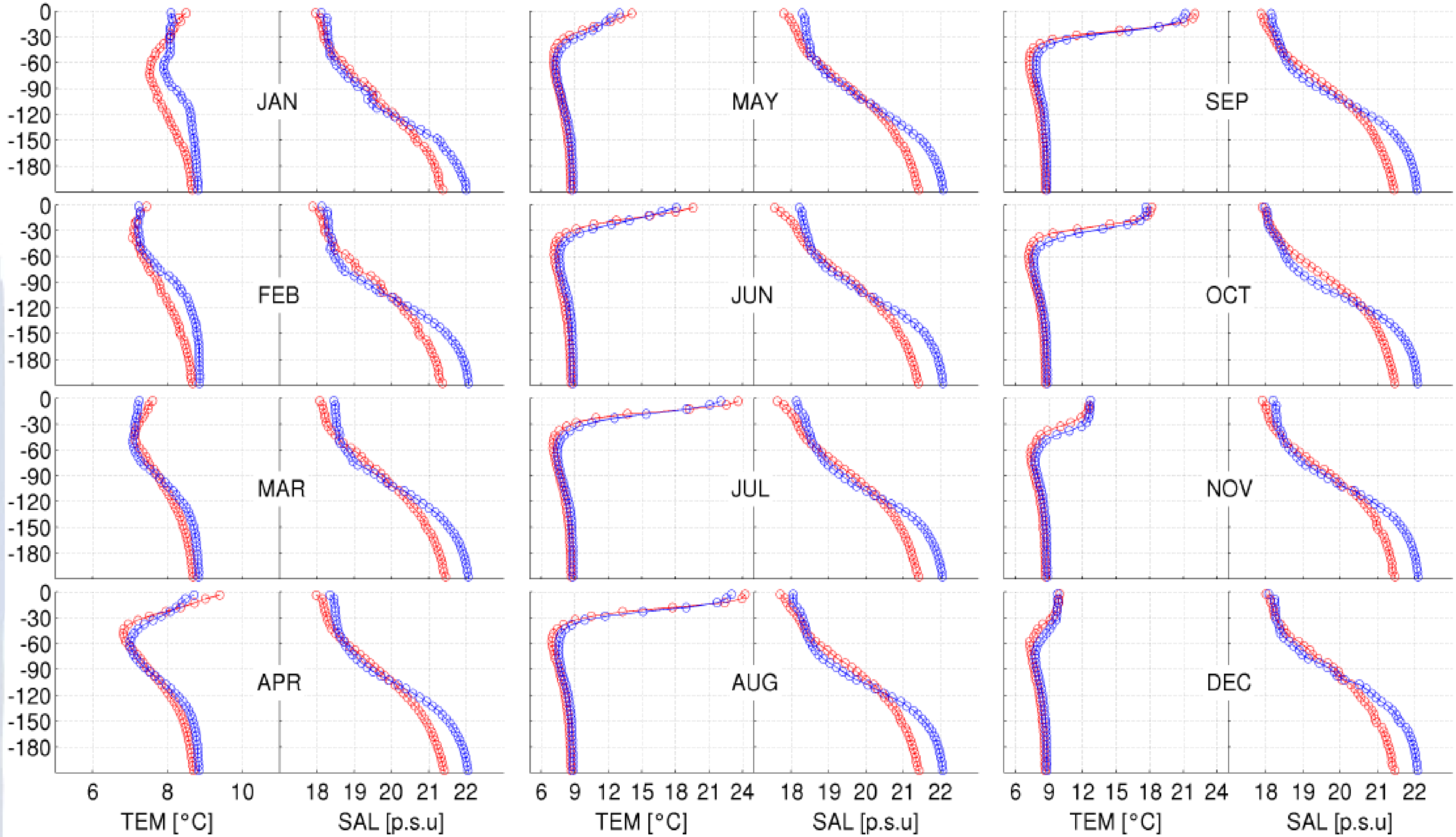


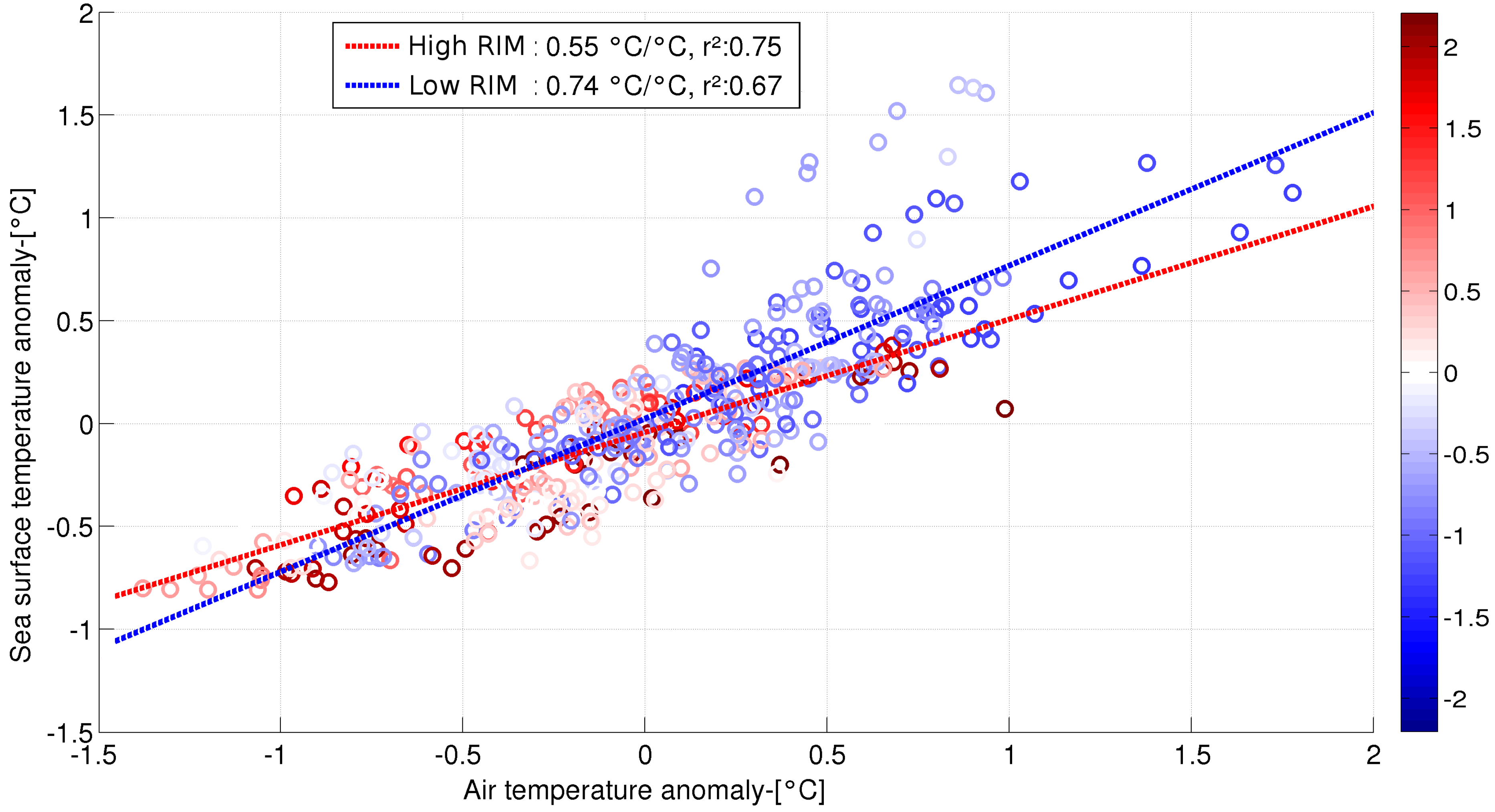
SLA-1
[m]
0.05
0
-0.05
MKE-1
[J/m³]
20
10
0
-10
-20
r=0.94
MLD-1
[m]
5
0
-5
r=0.67
CCC-1
[mK]
20
0
-20
r=0.61
SST-3
[°C]
0.2
0
-0.2
r=0.53
2
0
-2
62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 00



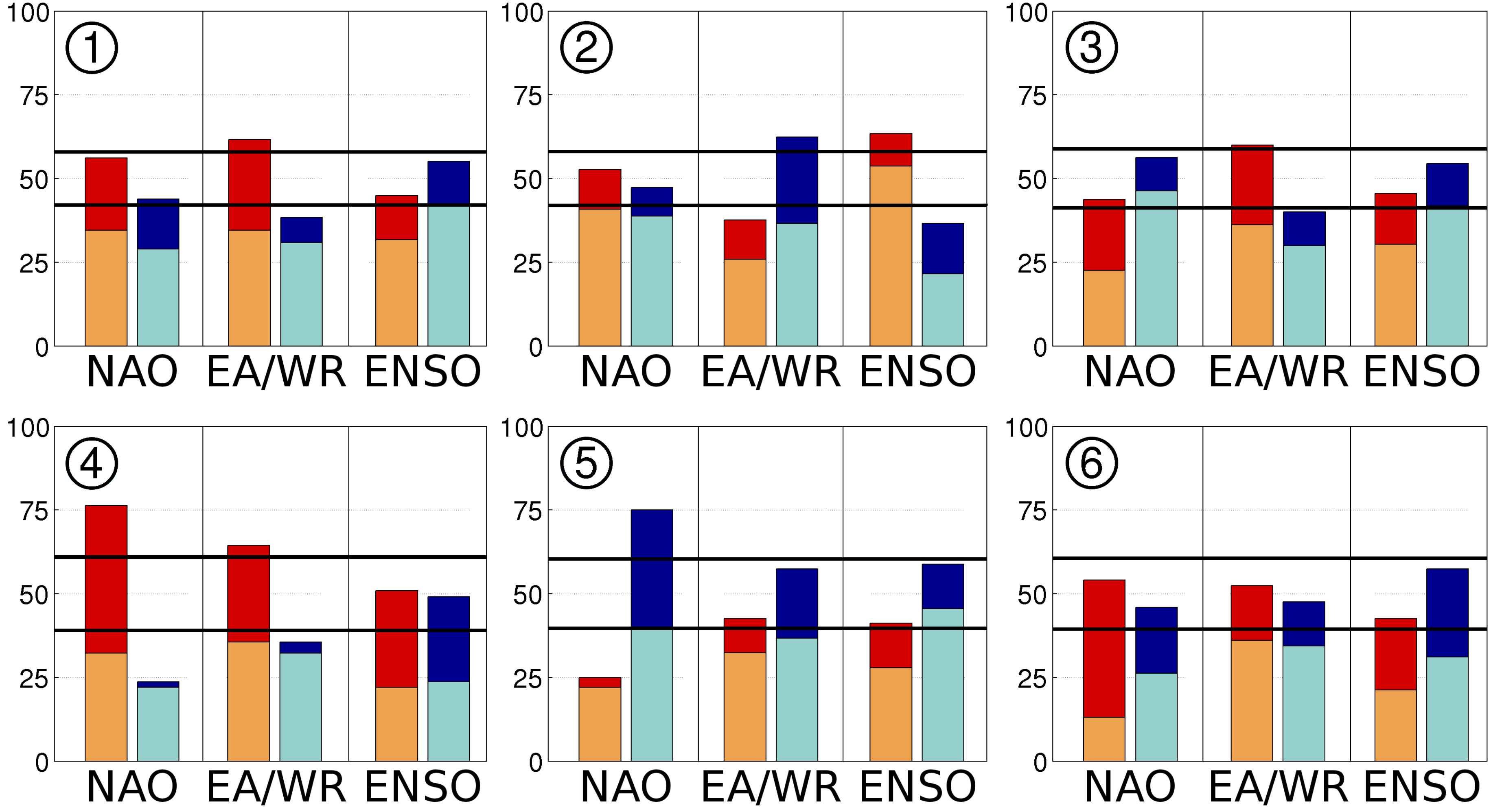
SLA-1
[m]
0.05
0
-0.05
62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 00
MKE-1
[J/m³]
20
10
0
-10
-20
r=0.94
River flow - [km³/yr]
350
270
210
1965
1970
1975
1980
1985
1990
1995
2000
SLA-2
(MKE-1–SLA-1)
SLA-2

T and S profiles: Central Basin



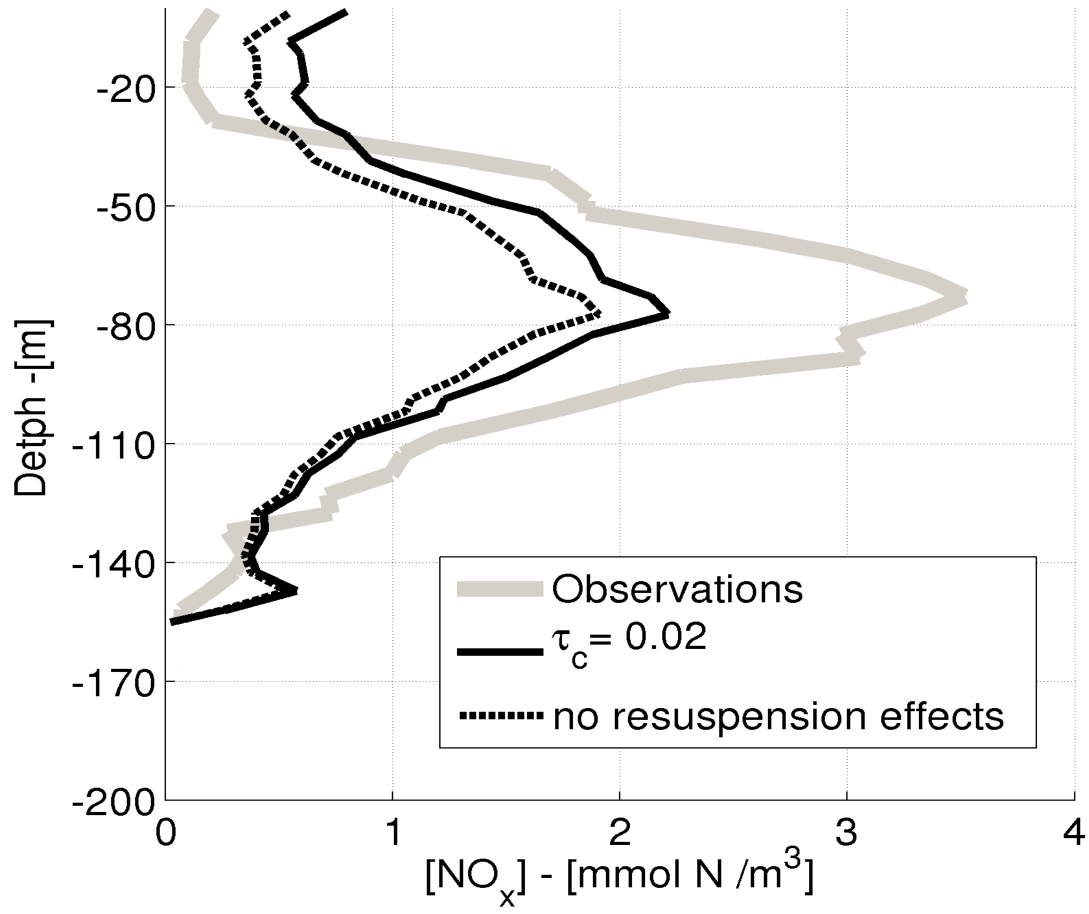


High RIM : 0.55 °C/°C, r²:0.75
Low RIM : 0.74 °C/°C, r²:0.67
Sea surface temperature anomaly-[°C]
Air temperature anomaly-[°C]
2
1.5
1
0.5
0
-0.5
-1
-1.5
-1.5
-1
-0.5
0
0.5
1
1.5
2
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2

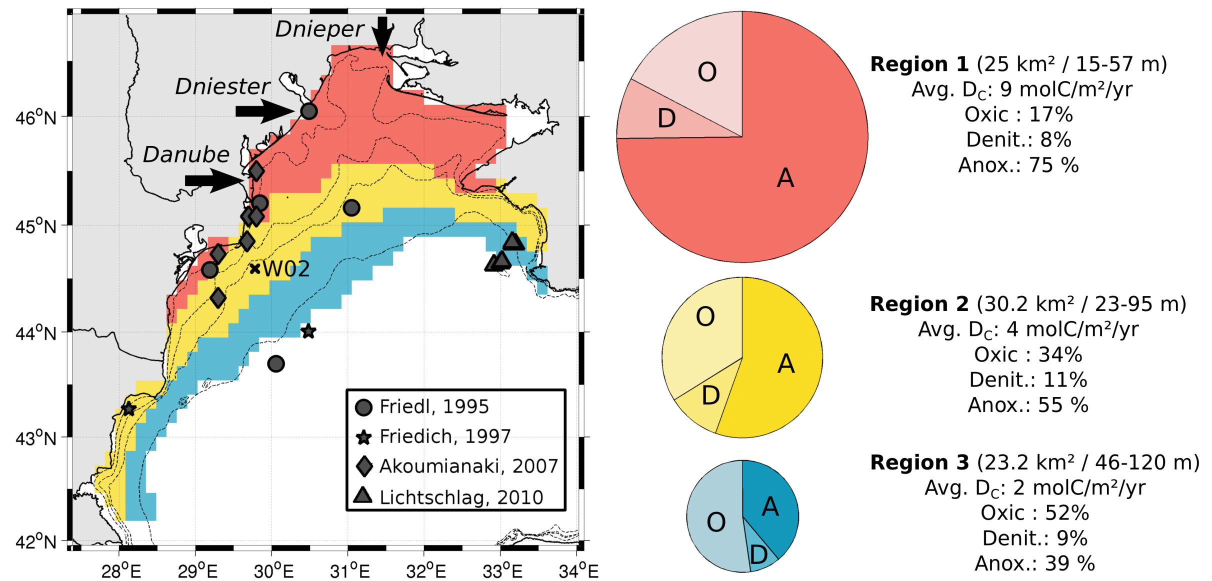


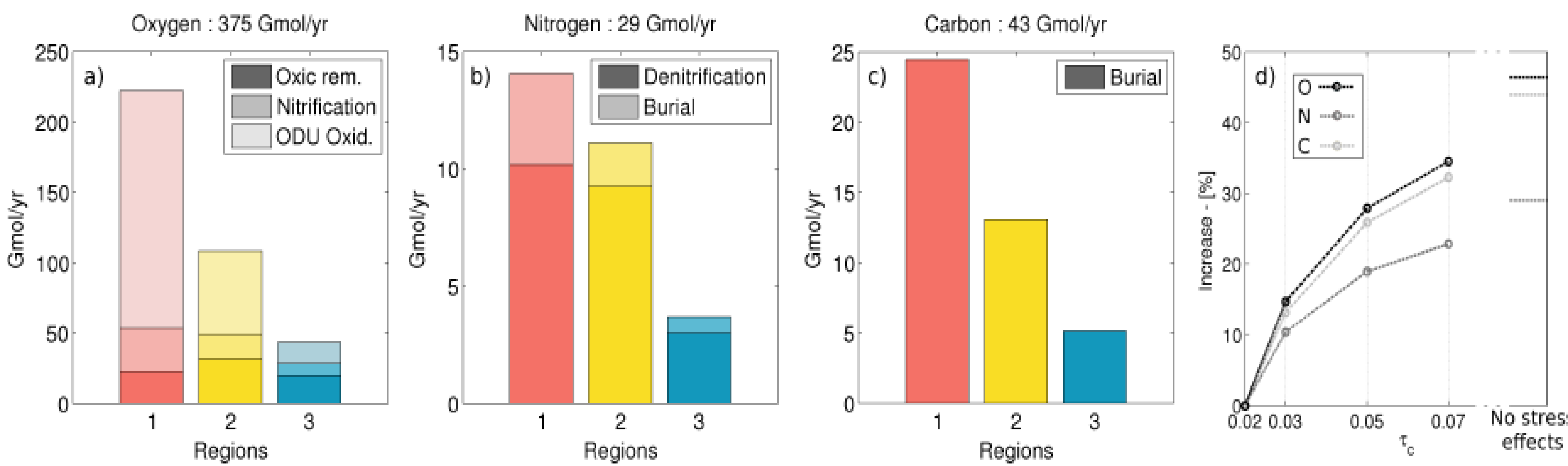
100
75
50
25
0
①
②
③
④
⑤
⑥
NAO
EA/WR
ENSO

Nitracline in the open basin



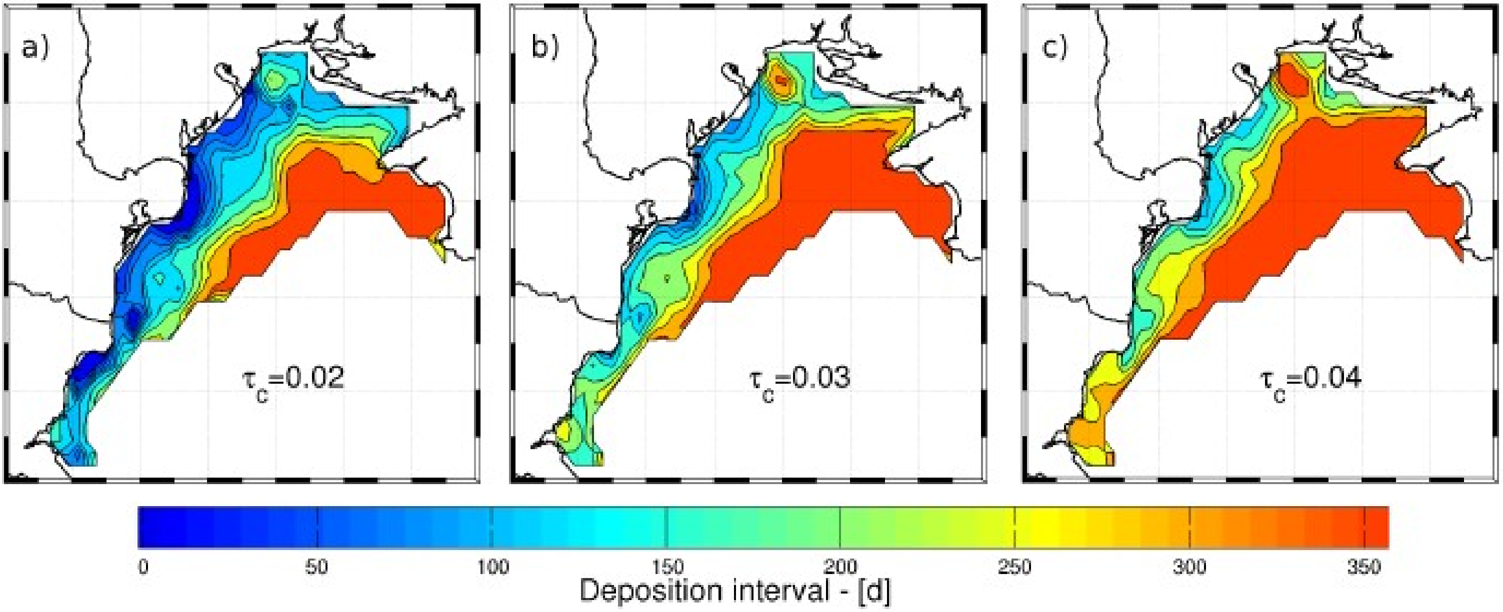
Role of the sediments layer in biogeochemical budgets on the shelf



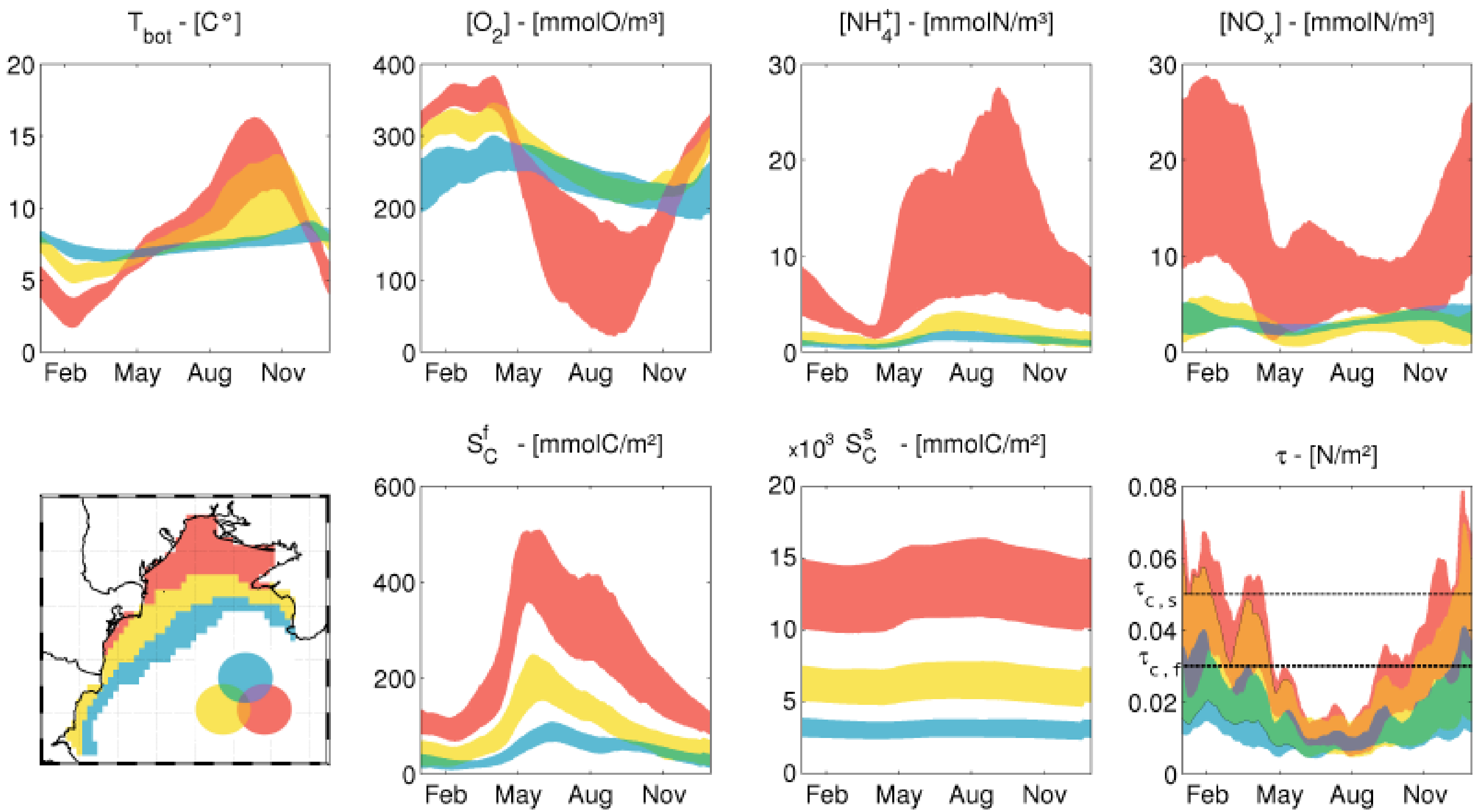


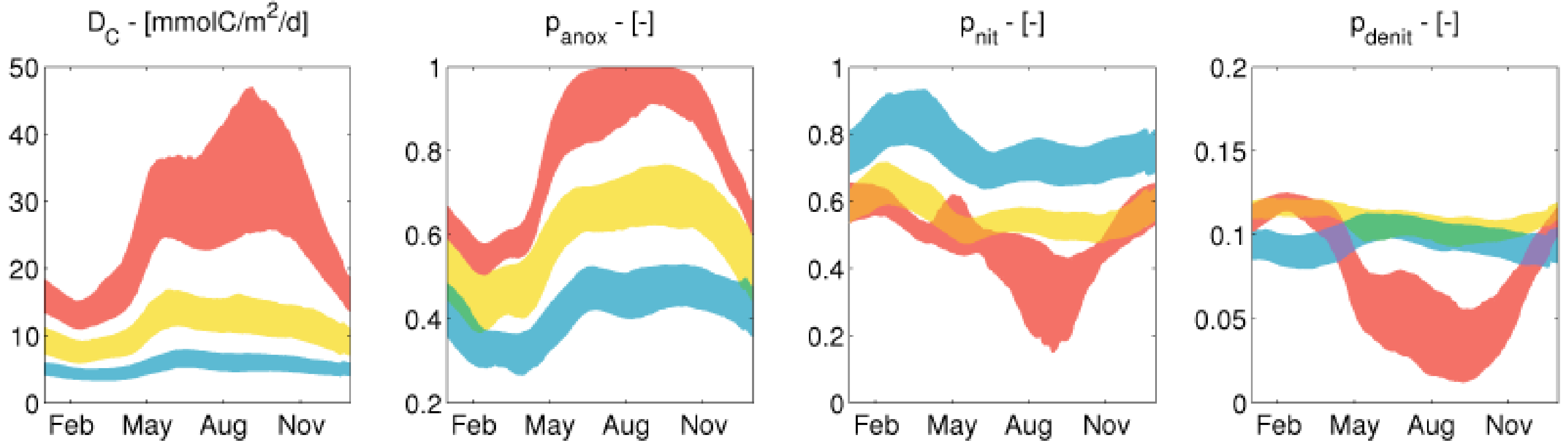
Deposition Interval

Time during wich bottom stress is generally lower than the resupsension thresold

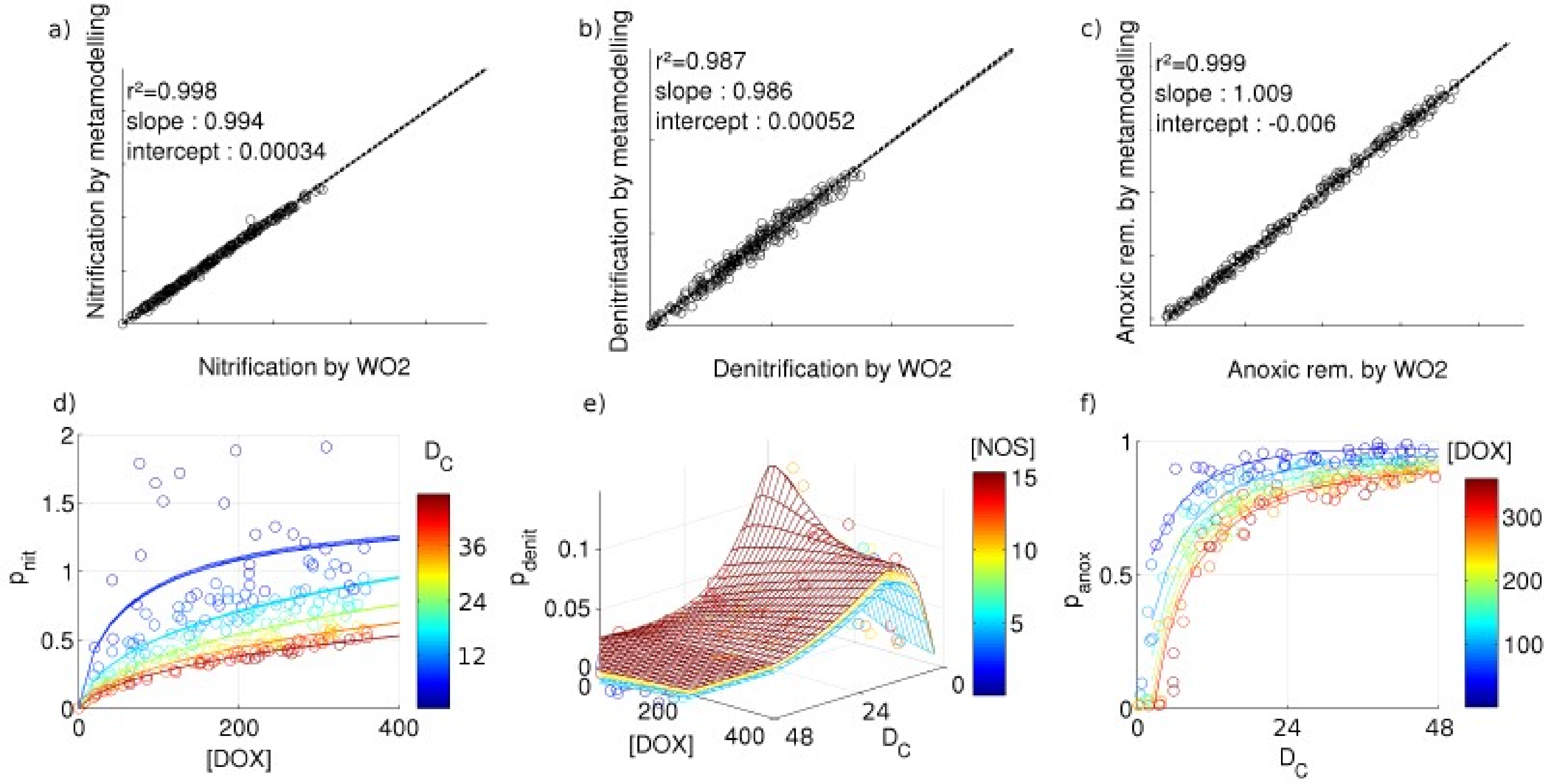


Benthic environmental conditions



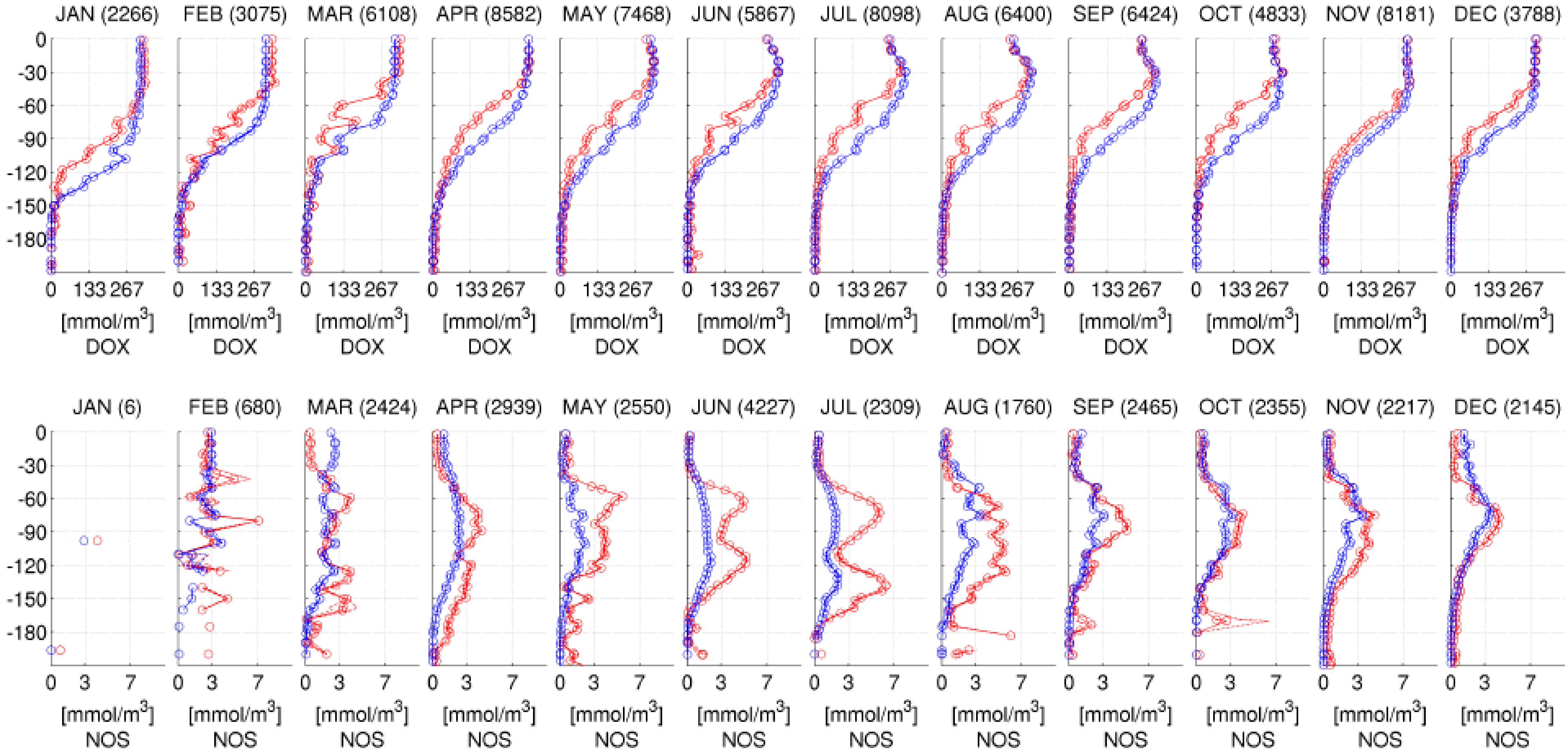


D_C - [mmolC/m^2/d]
50
40
30
20
10
0
p_{anox} - [-]
1
0.8
0.6
0.4
0.2
p_{nit} - [-]
1
0.8
0.6
0.4
0.2
0
p_{denit} - [-]
0.2
0.15
0.1
0.05
0
Feb
May
Aug
Nov

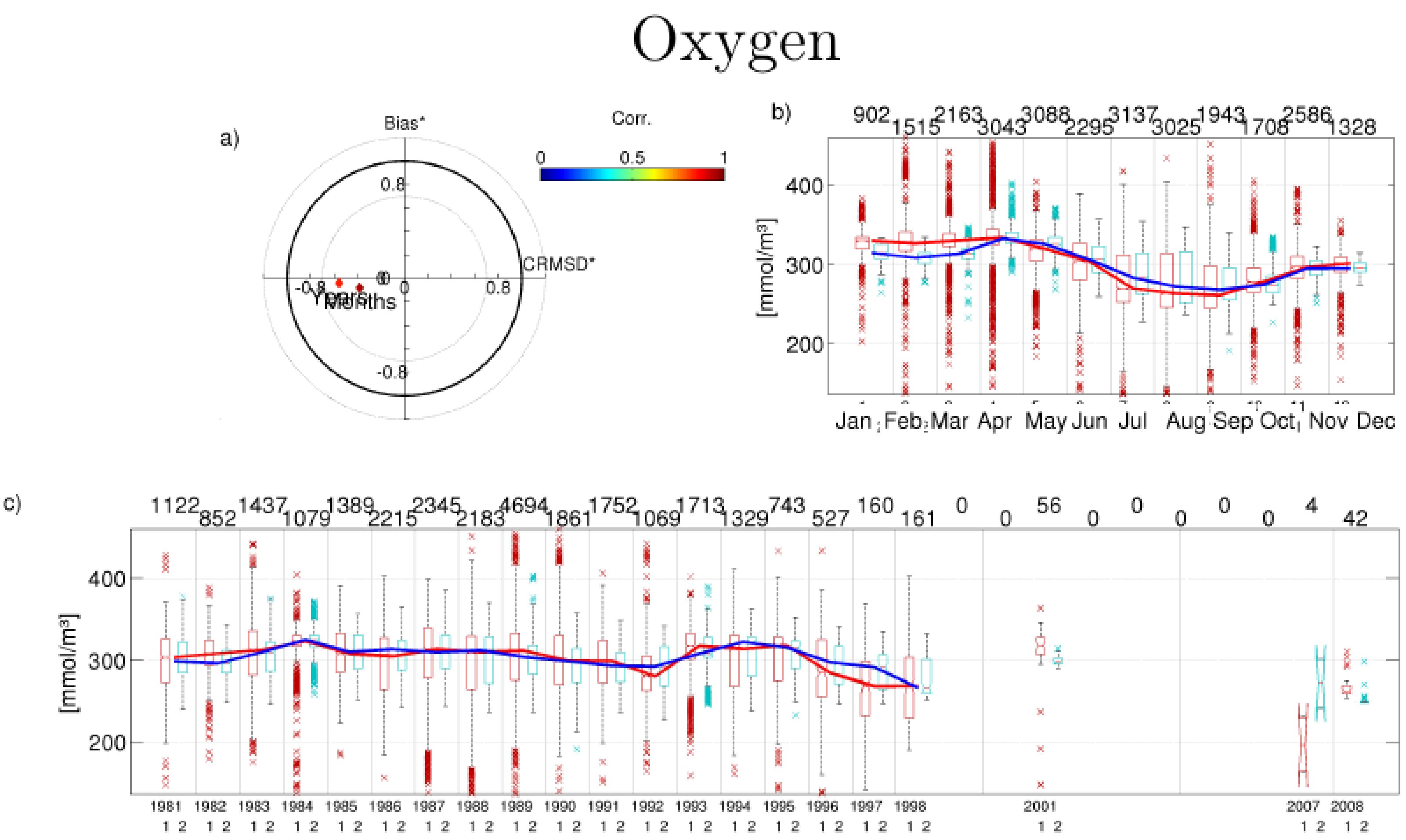


a)
r²=0.998
slope : 0.994
intercept : 0.00034
Nitrification by metamodelling
Nitrification by WO2
b)
r²=0.987
slope : 0.986
intercept : 0.00052
Denitrification by metamodelling
Denitrification by WO2
c)
r²=0.999
slope : 1.009
intercept : -0.006
Anoxic rem. by metamodelling
Anoxic rem. by WO2
d)
p_nit
[DOX]
D_C
e)
p_denit
[DOX]
D_C
[NOS]
f)
p_anox
D_C
[DOX]

Validation in the Open basin : Oxygen, Nitrate



Validation in the Open basin : Oxygen Temporal



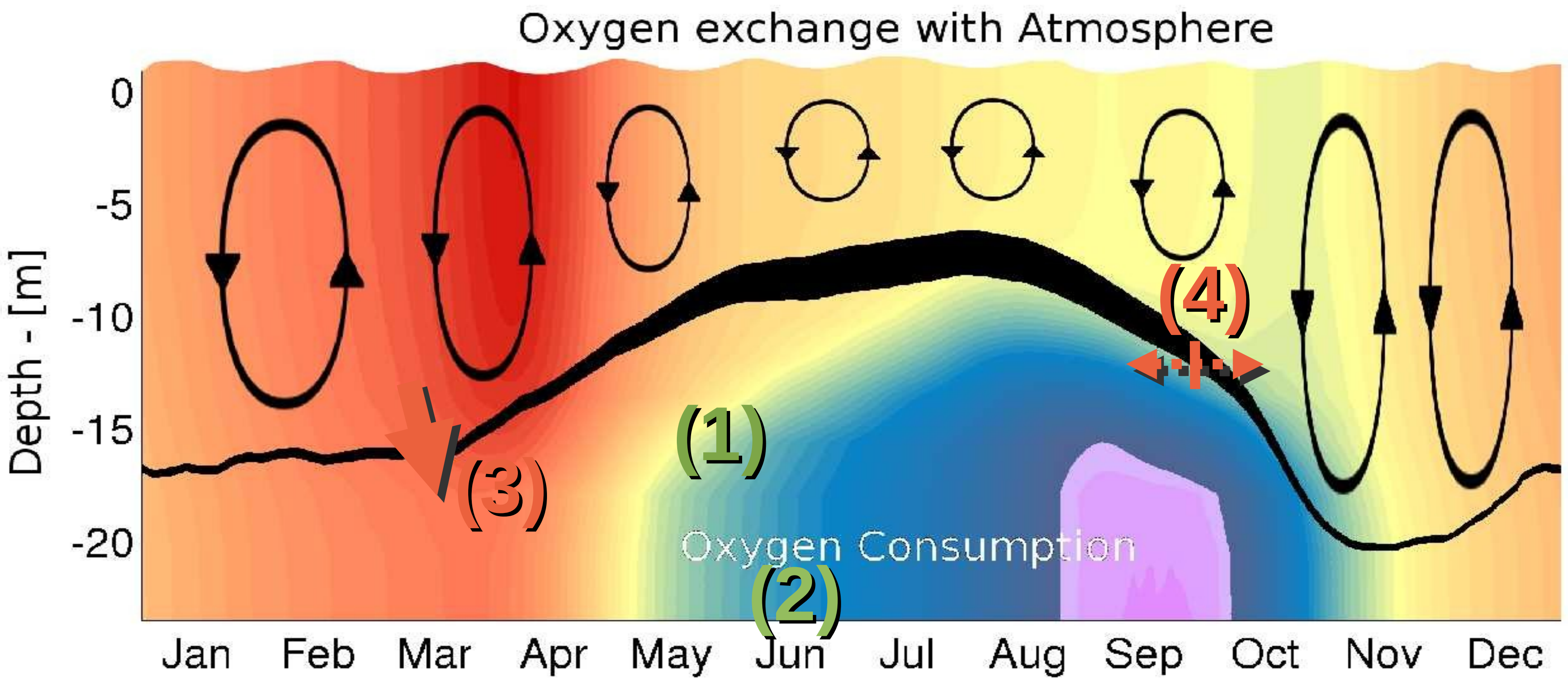
Interannual variability of Hypoxia

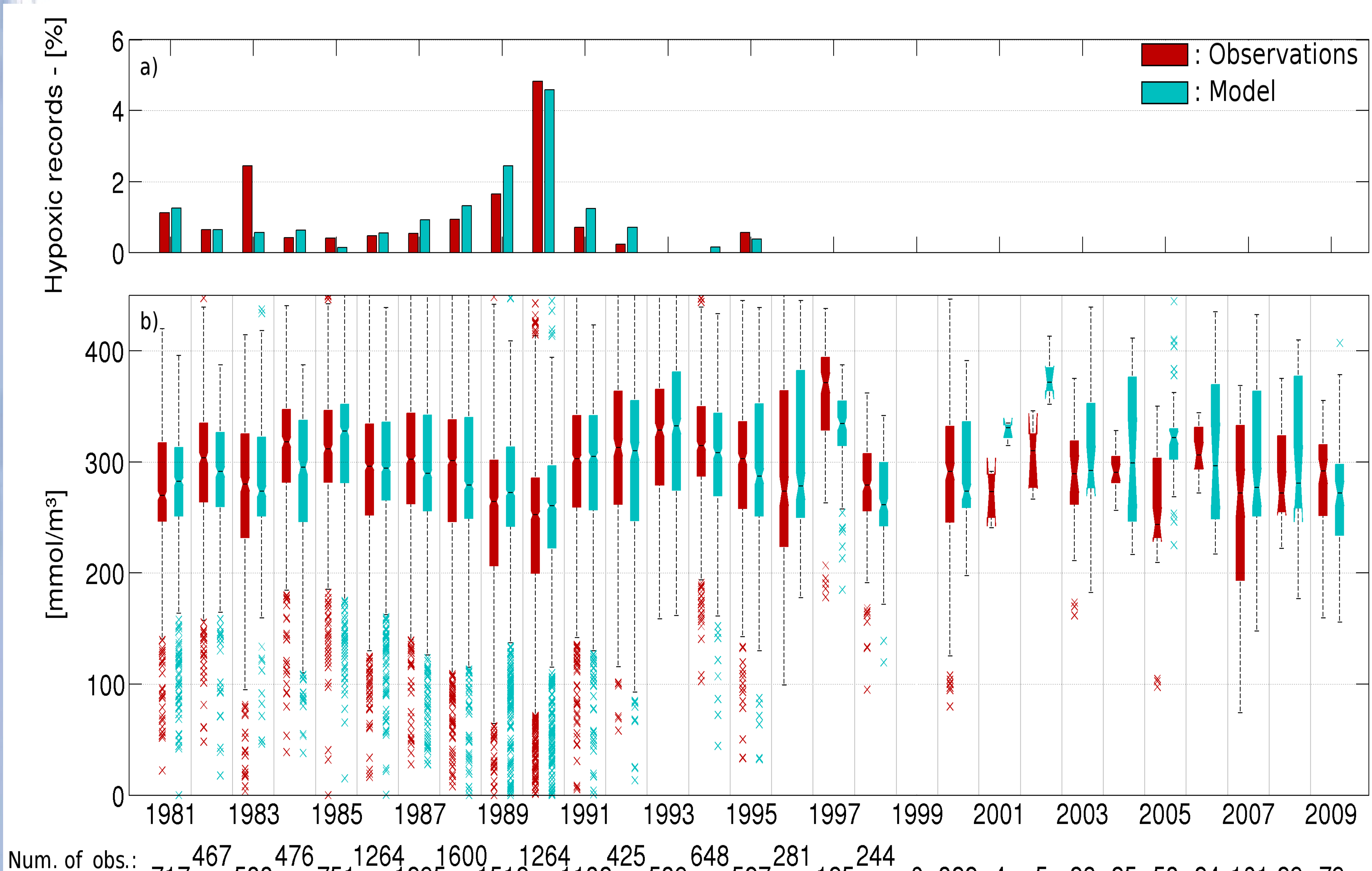
(1) High nitrogen riverine discharge enhance the influx of organic matter to bottom waters

(2) High sedimentary organic carbon content enhances the benthic oxygen consumption.

(3) Warm springs reduce the ventilation and **set summer bottom temperature.**

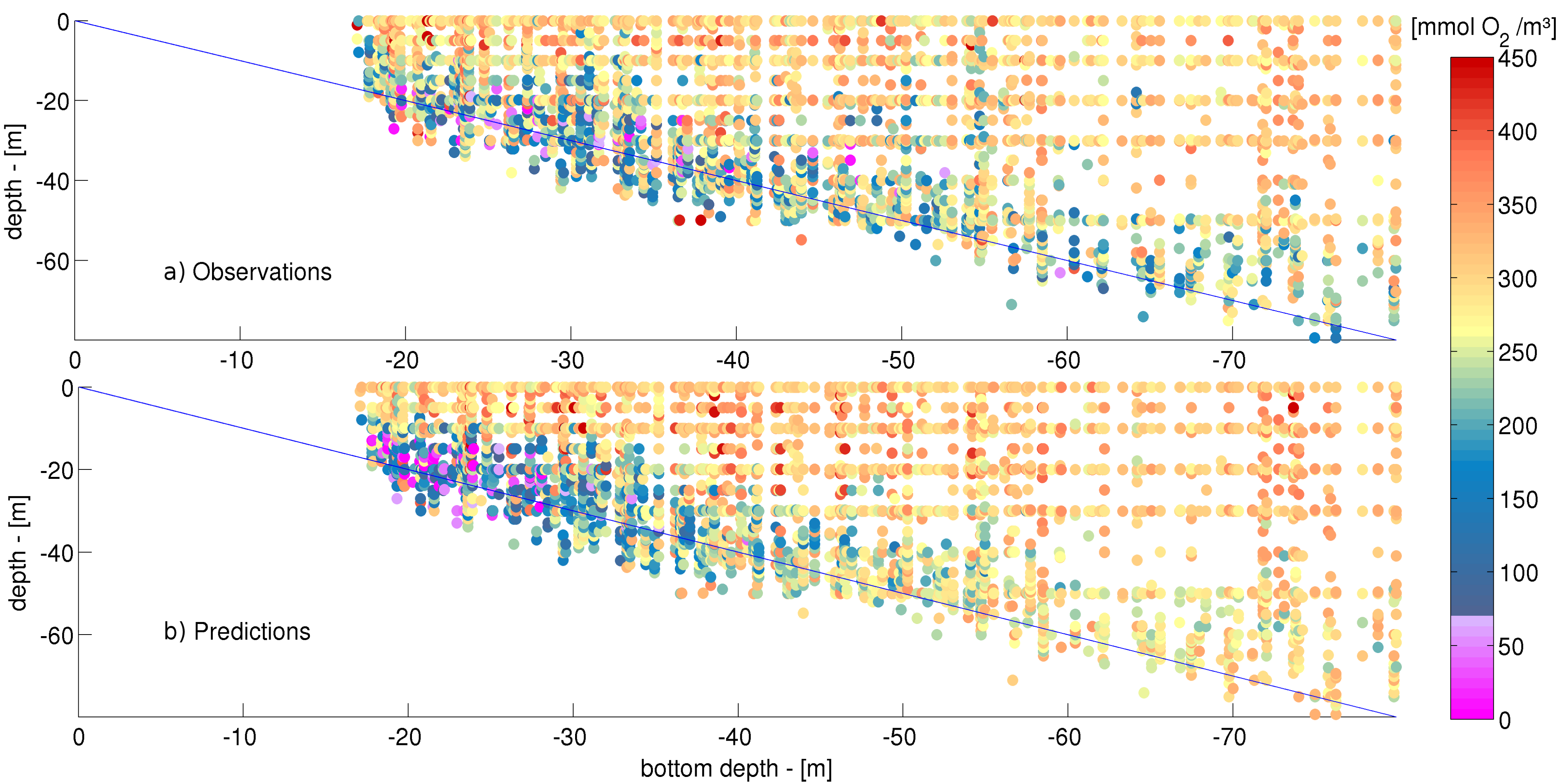
(4) Warm summers extend the duration of the stratified period.





a)
b)
Hypoxic records - [%]
[mmol/m³]
: Observations
: Model
0
2
4
6
100
200
300
400
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
Num. of obs.:
467 476 1264 1600 1264 425 648 281 244

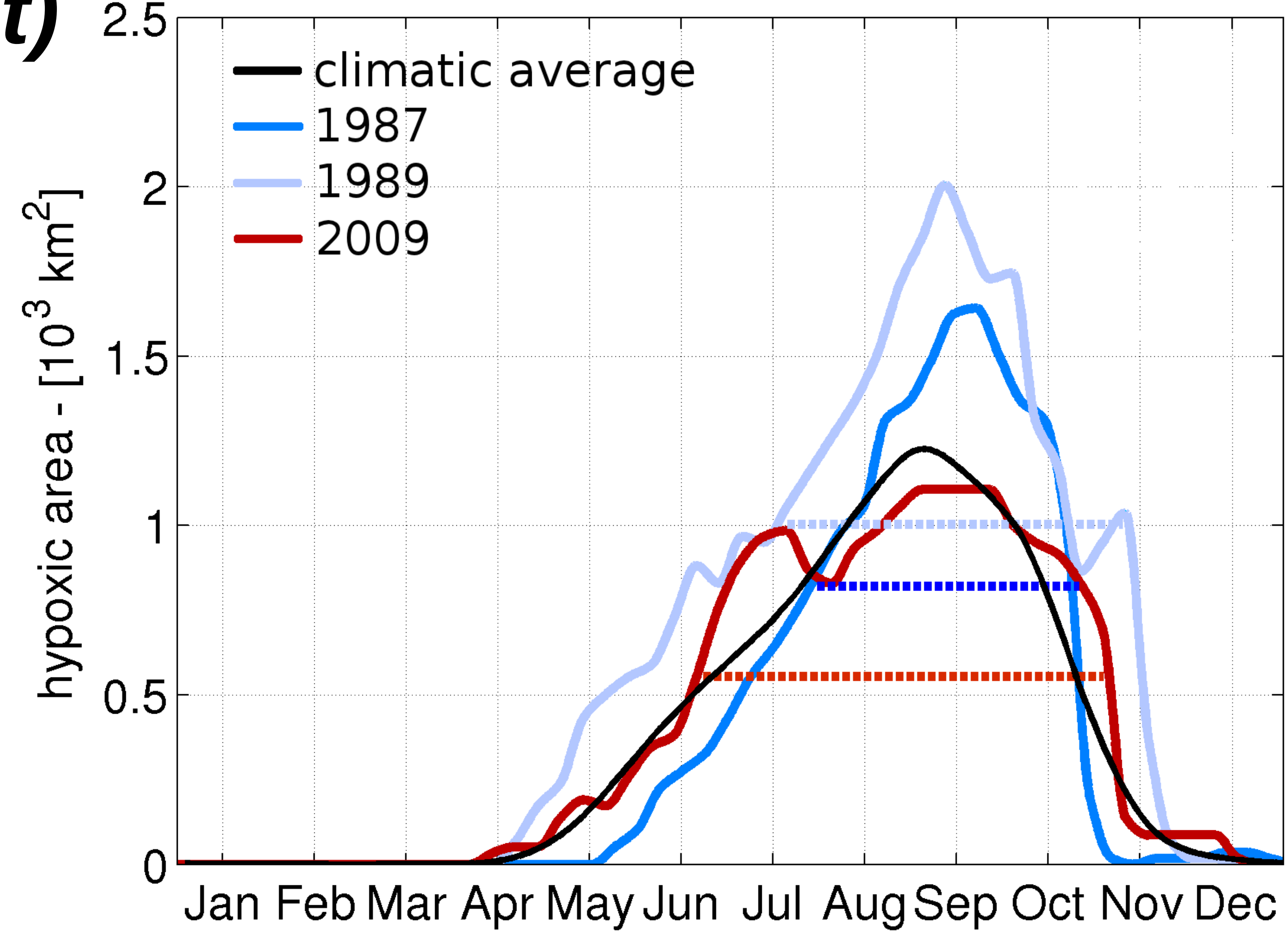
Model Validation : Point-to-point



$$D = \frac{1}{\max A(t)} \int_{year} A(t)dt,$$

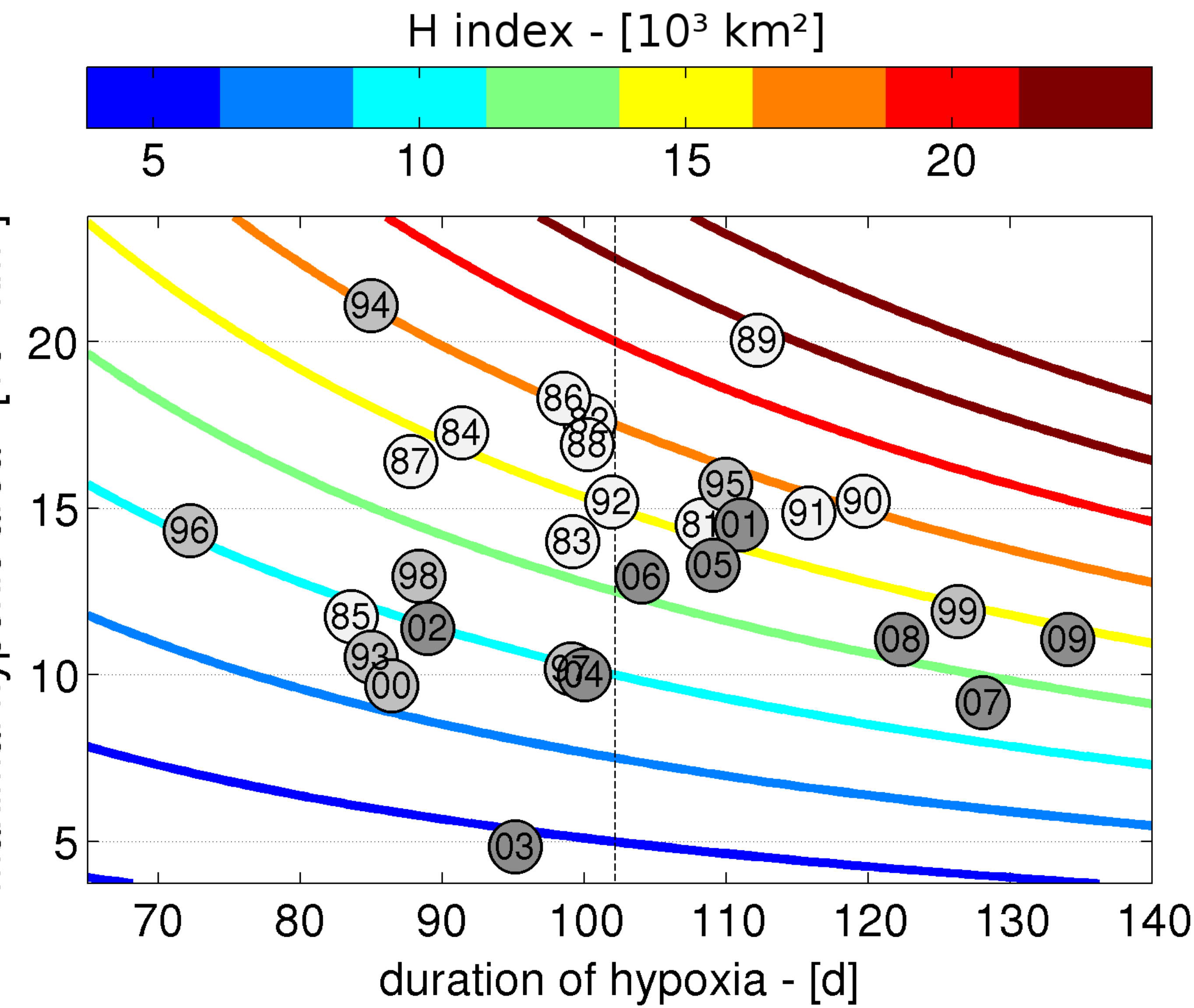
$$H = \frac{1}{\overline{D}} \int_{year} A(t)dt,$$

A(t)

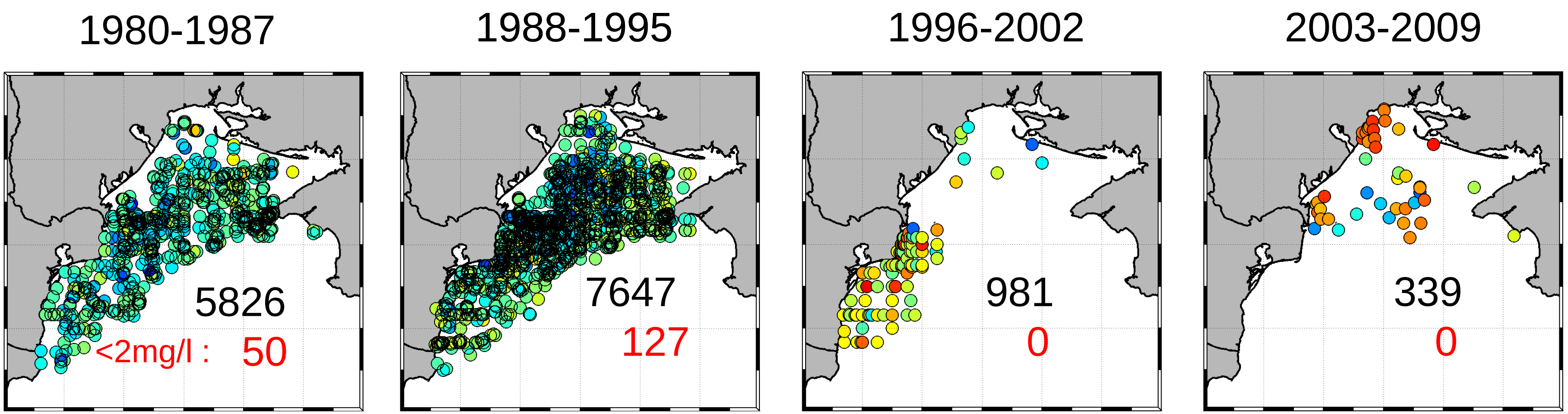


$$D = \frac{1}{\max A(t)} \int_{year} A(t)dt, \qquad H = \frac{1}{\overline{\overline{D}}} \int_{year} A(t)dt,$$

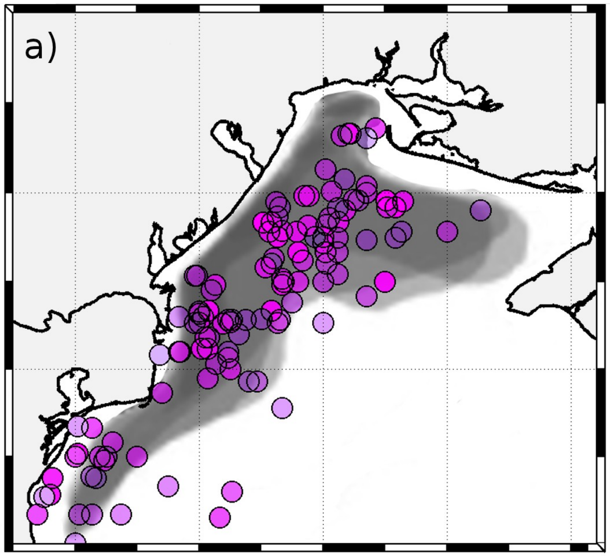
b)



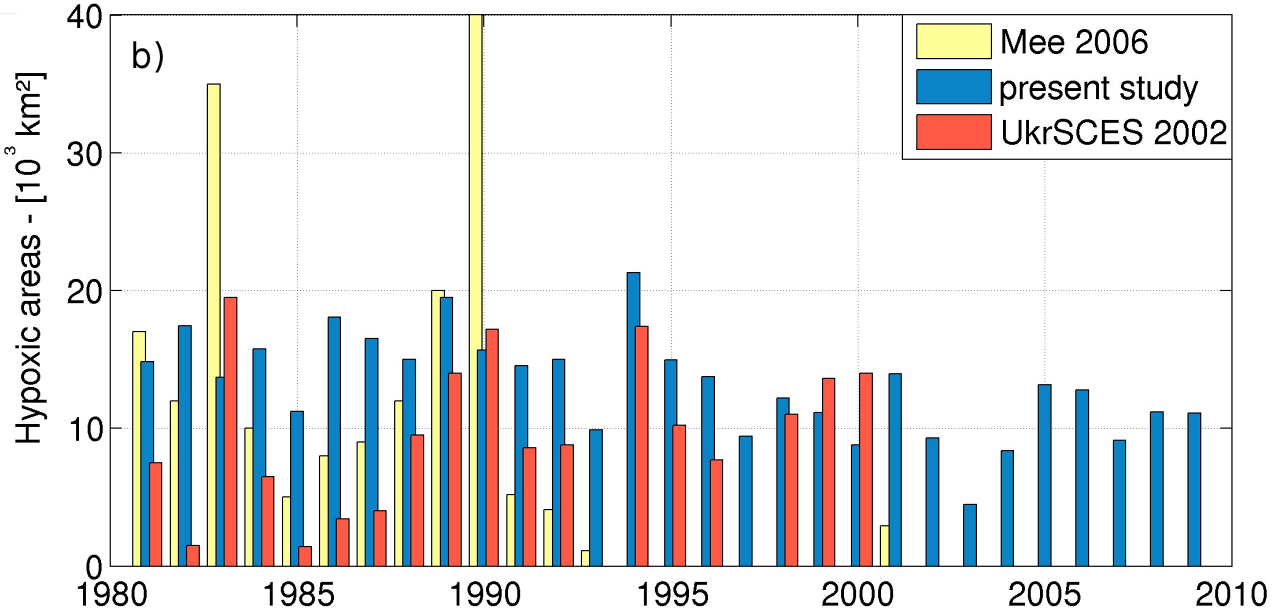
Recovery ?



1980-1987
1988-1995
1996-2002
2003-2009
5826
<2mg/l :
50
7647
127
981
0
339
0

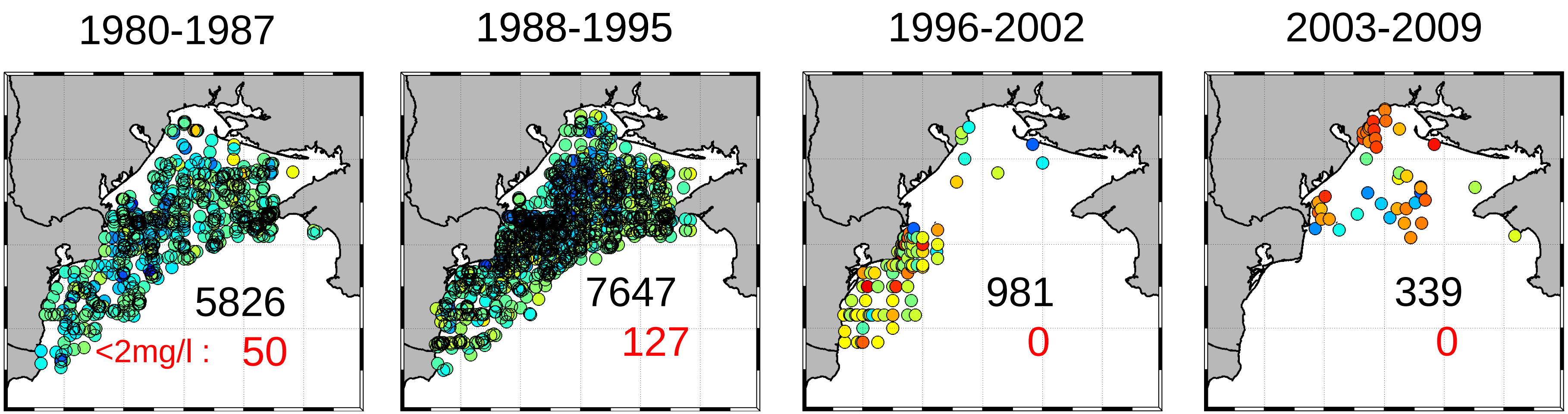


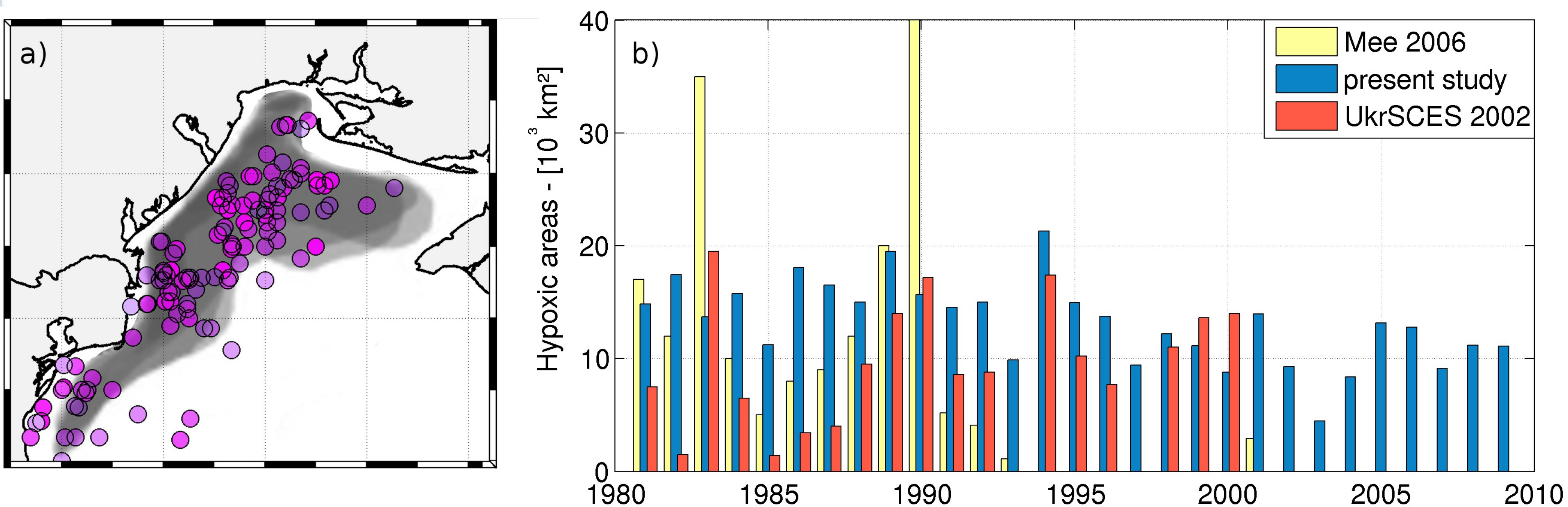
a)



b)
Mee 2006
present study
UkrSCES 2002
Hypoxic areas - [10³ km²]
0
10
20
30
40
1980
1985
1990
1995
2000
2005
2010

Recovery ?


1980-1987
5826
<2mg/l : 50
1988-1995
7647
127
1996-2002
981
0
2003-2009
339
0


a)
b)
Hypoxic areas - [10^3 km²]
Mee 2006
present study
UkrSCES 2002
0
10
20
30
40
1980
1985
1990
1995
2000
2005
2010

Benthic Model

sedimenting variables
(POM, Diatoms)

W_{POC} is given by aggregation model

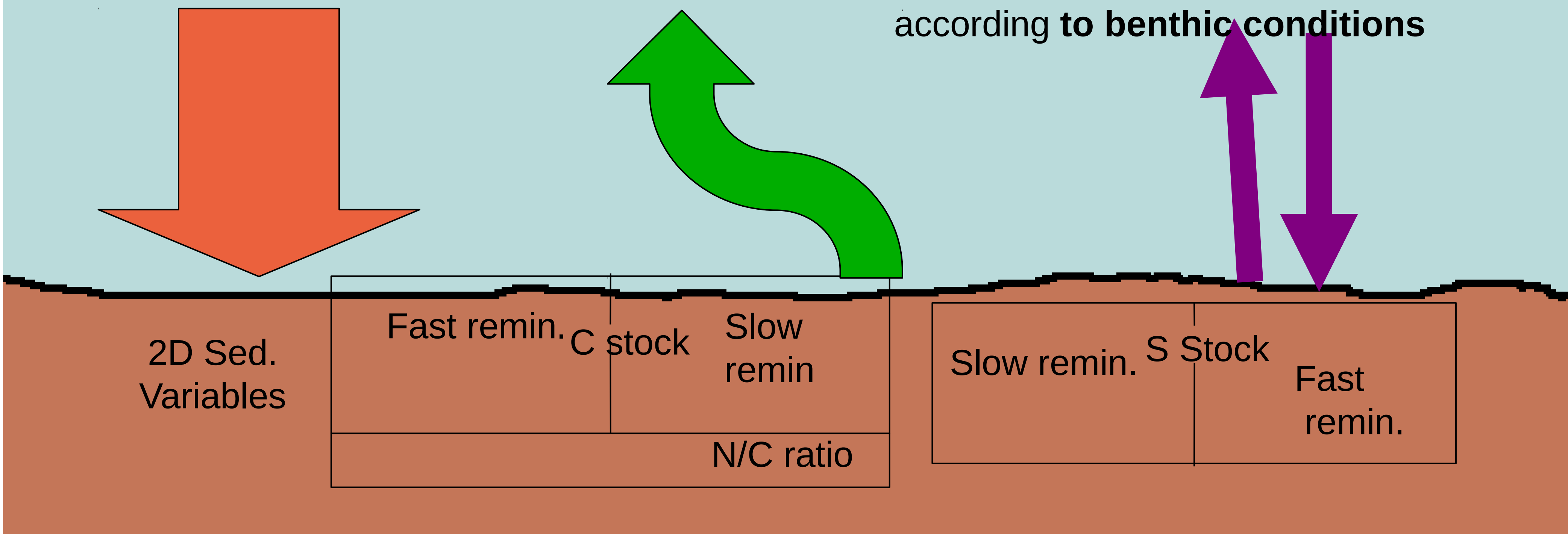
Resuspension
in particulate form

due to bottom stress from **currents** and (mainly) **waves**.

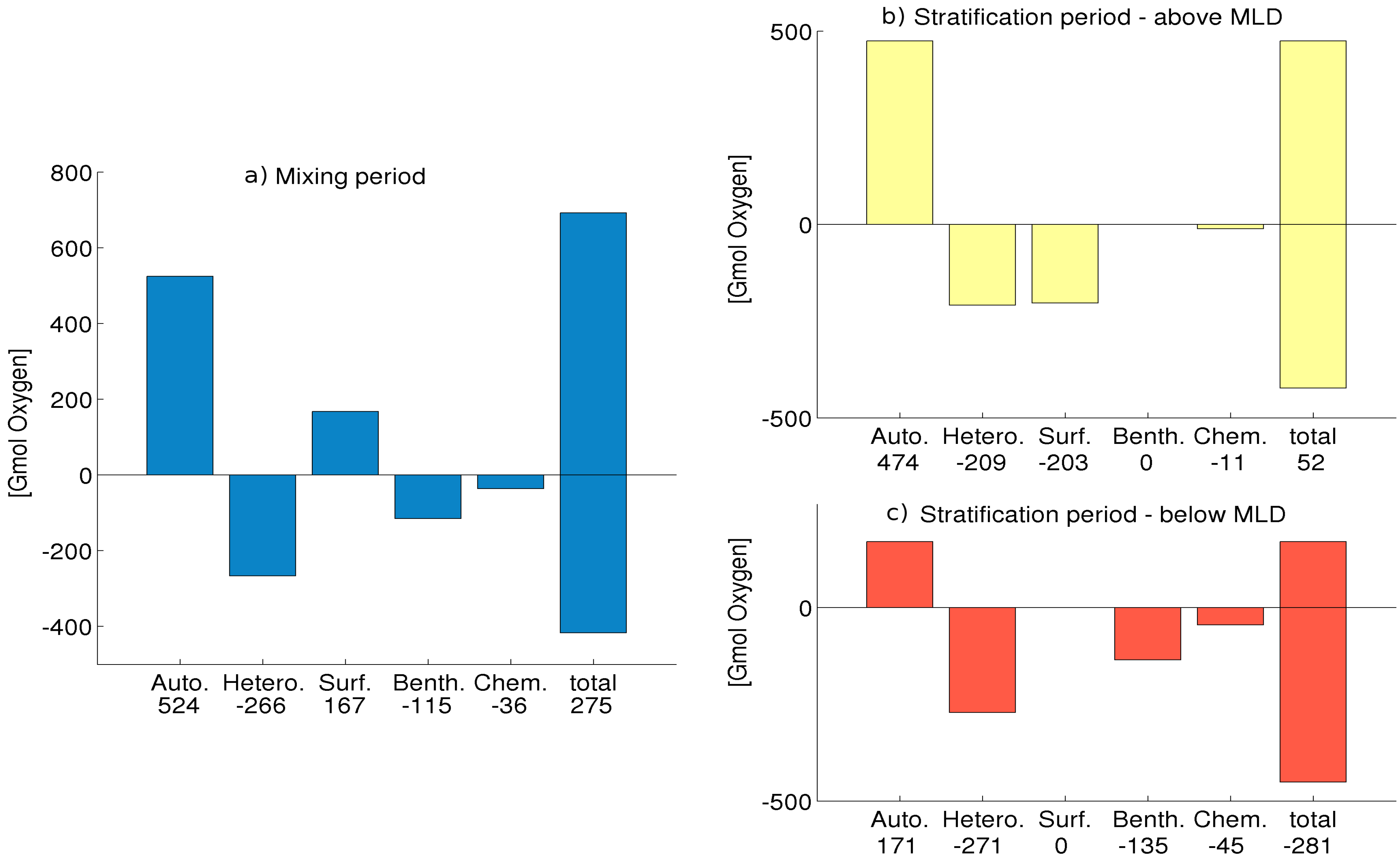
Benthic remineralisation

Remineralised content (in mmolC/m²/s)
= [fast C stock] . K_{fC} . f(T°)
+ [slow C stock] . K_{sC} . f(T°)

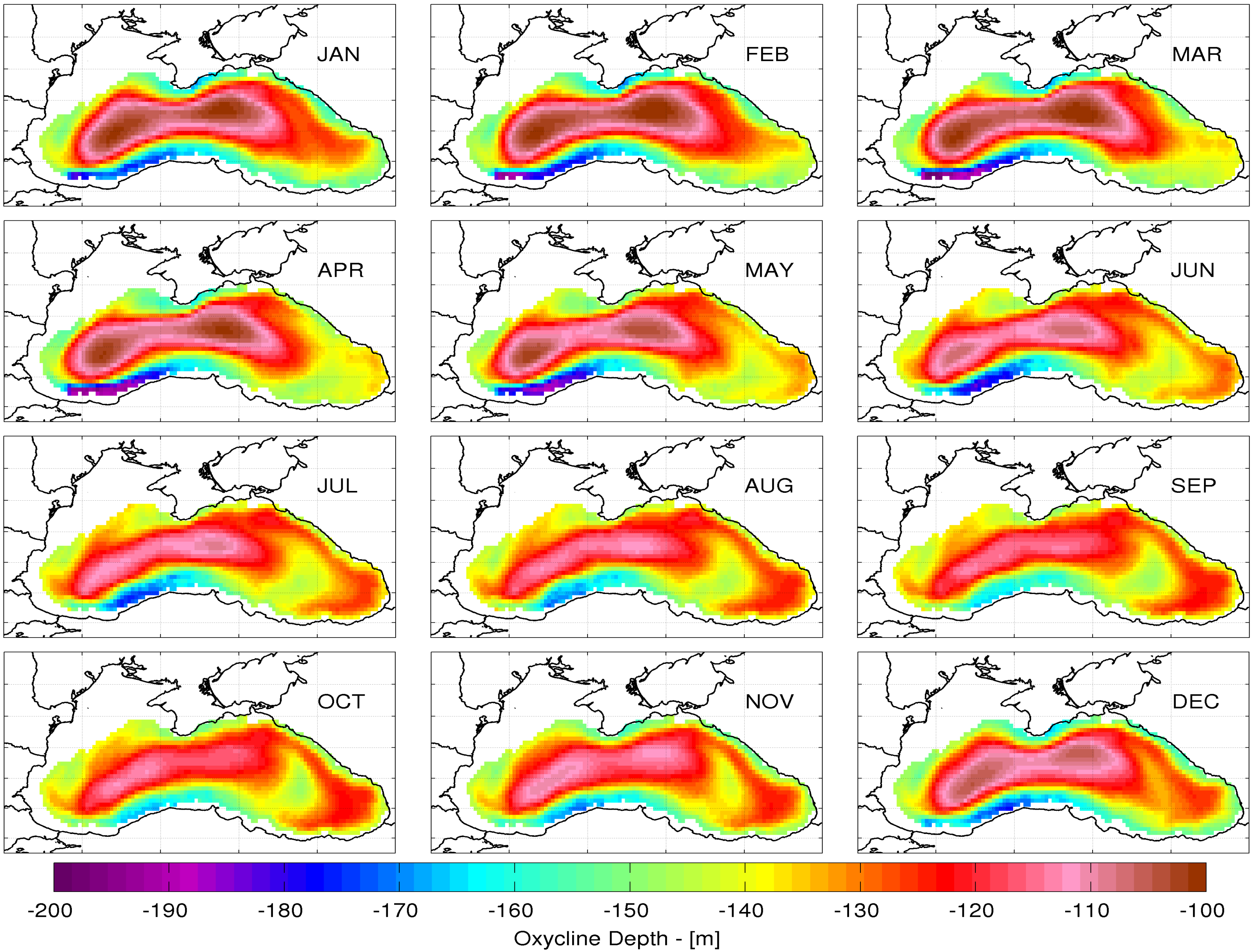
Calibrated functions compute from Cmin and Nmin, the fluxes of **Oxygen**, **ODU, DIC, Ammonium**, **Nitrate, Silicate,** according **to benthic conditions**



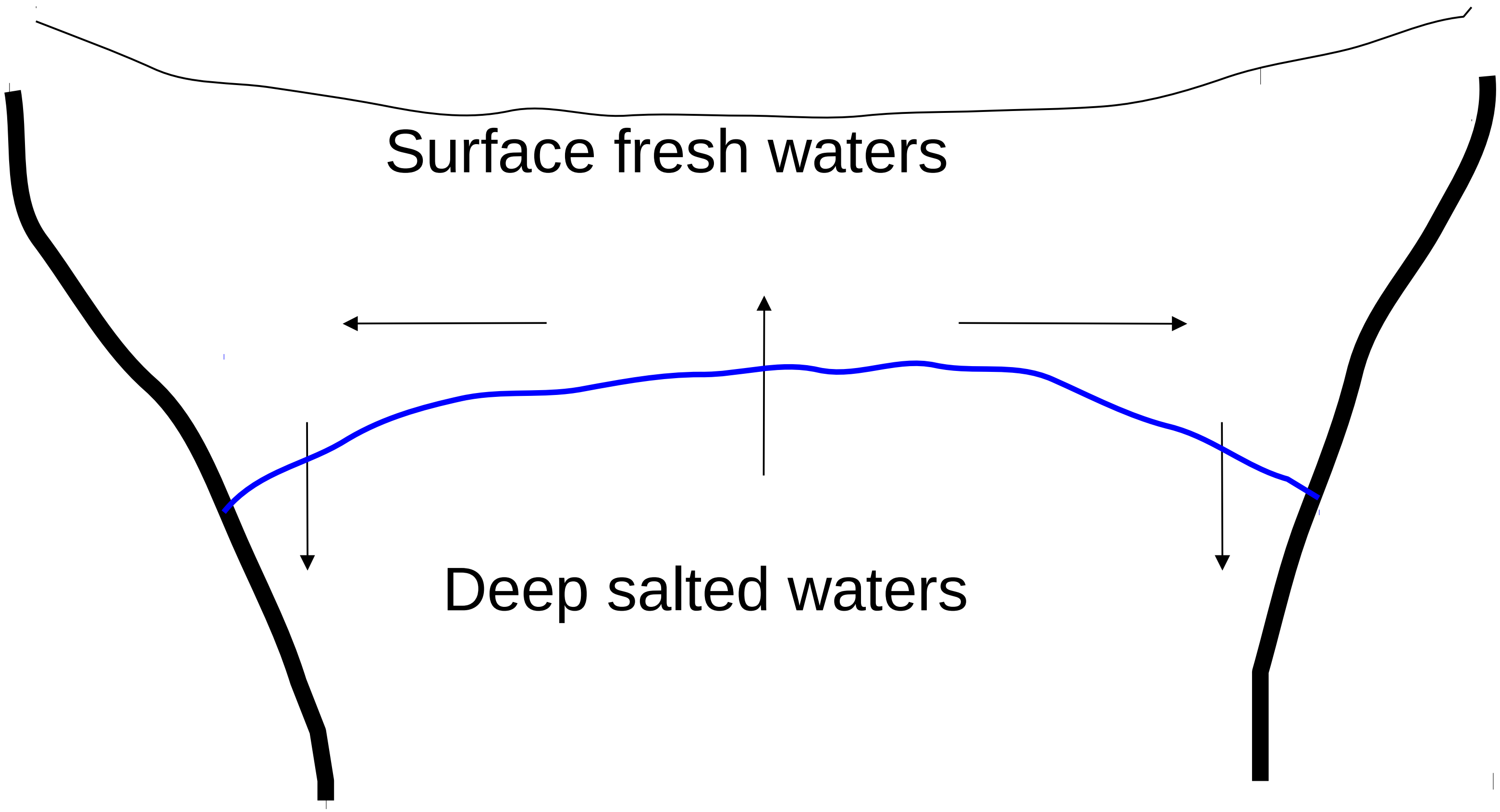
Application : dynamique de l'hypoxie sur le plateau continental Nord Ouest



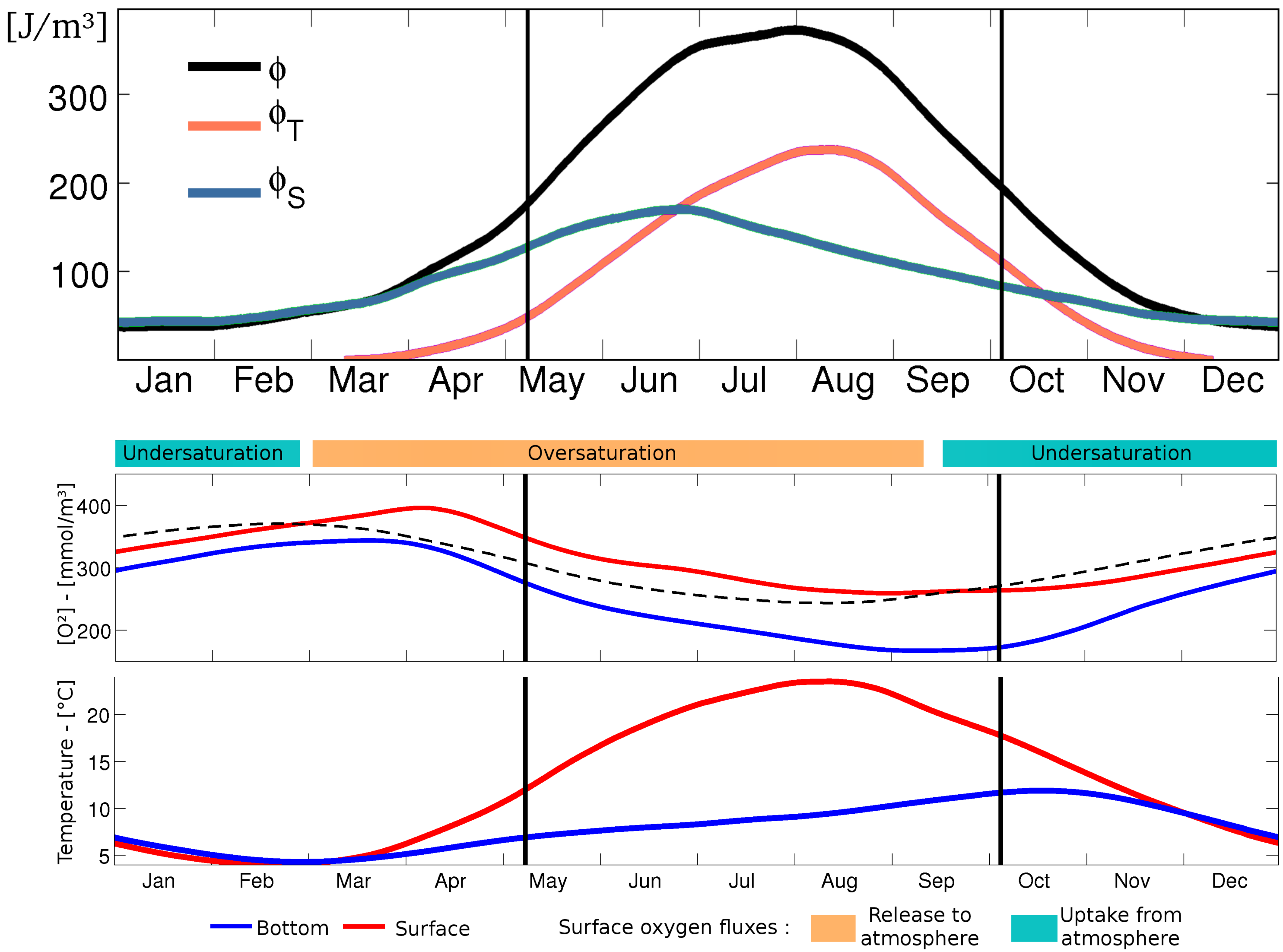
Circulation: impact sur la structure verticale

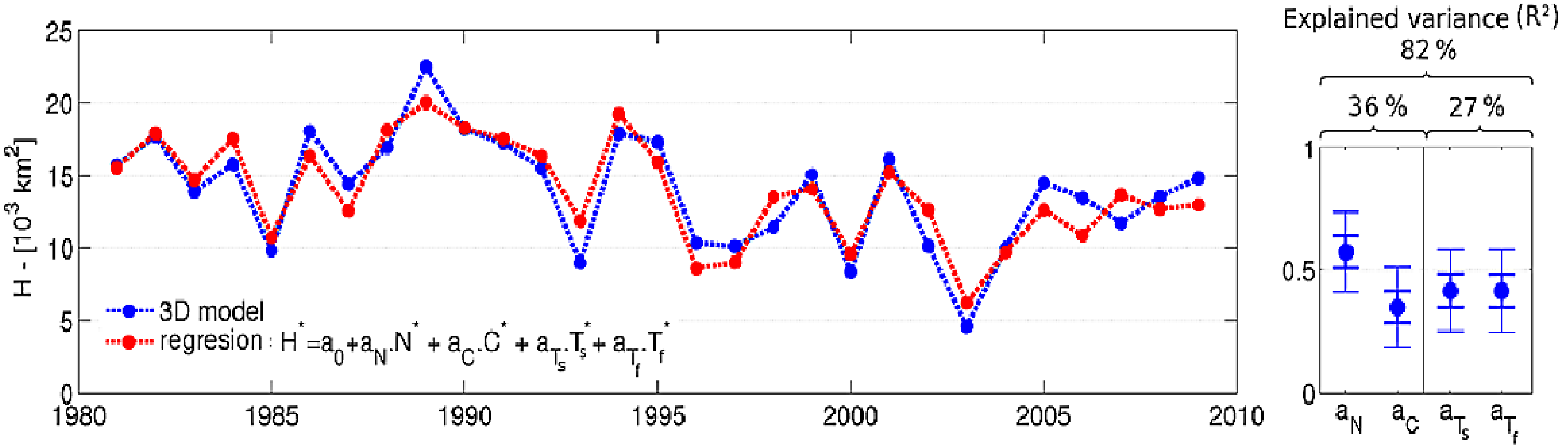


Circulation



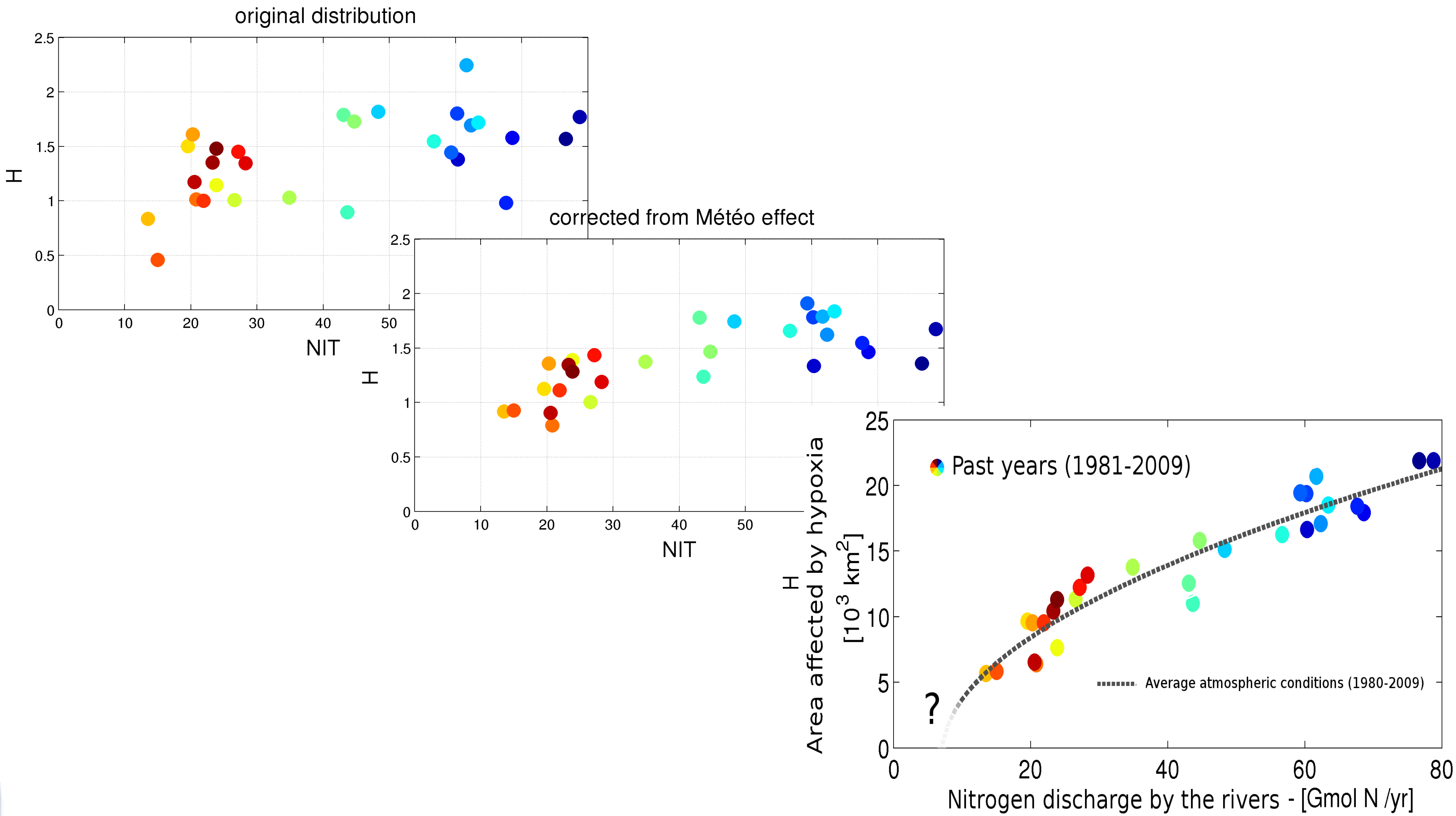
Oxygen solubility





Explained variance (R^2)
82 %
36 %
27 %
H - [10^3 km^2]
3D model
regresion : $H^* = a_0 + a_N.N^* + a_C.C^* + a_{T_s}.T_s^* + a_{T_f}.T_f^*$
a_N
a_C
a_{T_s}
a_{T_f}

The case of Hypoxia

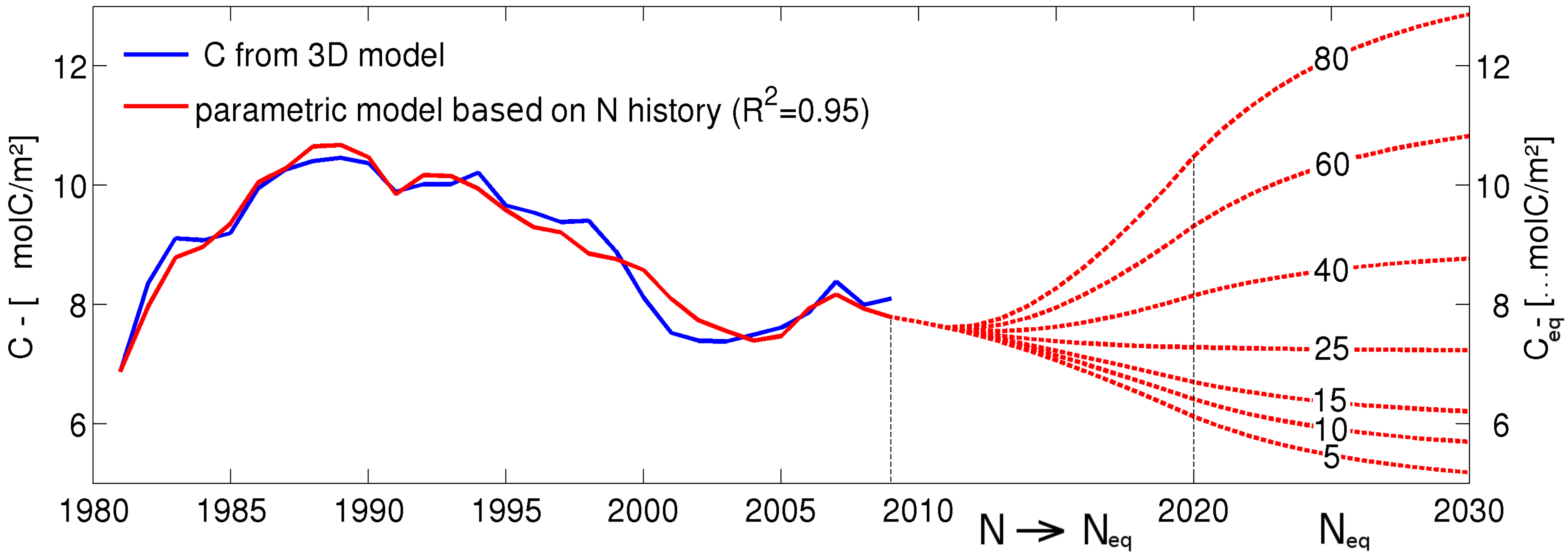


Organic matter accumulates in the sediments

$$C(y+1) = C(y)(1-\beta(y)) + \alpha(y) \cdot N(y) \quad (8)$$

$$\beta(y) = \beta_0 \cdot Q^{T_s^*(y)} \quad (9)$$

$$\alpha(y) = \alpha_0 + \alpha_{\mathrm{Si:N}} \cdot (\mathrm{Si}(y) \ : \ \mathrm{N}(y)) \quad (10)$$



Next ? : End-to-end modeling !