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Changes in rivers inputs during the last decades significantly impacted the biogeochemistry of the eastern Mediterranean basin: a modelling study

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Abstract

The Mediterranean Sea (MS) is a semi-enclosed sea characterized by a zonal west-east gradient of oligotrophy, where microbial growth is controlled by phosphate availability in most situations. External inputs of nutrients including Gibraltar inputs, river inputs and atmospheric deposition are therefore of major importance for the biogeochemistry of the MS. This has long been considered to be driven mainly by nutrient exchanges at Gibraltar. However, recent studies indicate that river inputs significantly affect nutrients concentrations in the Mediterranean Sea, although their resulting impact on its biogeochemistry remains poorly understood.

In this study, our aim was to make good this lack by addressing the large-scale and long-term impact of variations in river inputs on the biogeochemistry of the Mediterranean Sea over the last decades, using a coupled physical-biogeochemical 3D model (NEMO-MED12/Eco3M-Med).

As a first result, it has been shown by the model that the strong diminu-

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tion (60 %) of phosphate (PO_4) in river inputs into the Mediterranean Sea since the end of the 1980s induced a significant lowering of PO_4 availability in the sub-surface layer of the Eastern Mediterranean Basin (EMB). One of the main consequences of PO_4 diminution is the rise, never previously documented, of dissolved organic carbon (DOC) concentrations in the surface layer (by 20% on average over the EMB). Another main result concerns the gradual deepening of the top of the phosphocline during the period studied, thus generating a shift between the top of the nitracline and the top of the phosphocline in the EMB. This shift has already been observed *in situ* and documented in literature, but we propose here a new explanation for its occurrence in the EMB. The last main result is the evidence of the decline in abundance and the reduction of size of copepods calculated by the model over the years 1985-2010, that could partially explain the reduction in size of anchovy and sardine recently recorded in the MS.

In this study, it is shown for the first time that the variations in river inputs that occurred in the last decades may have significantly altered the biogeochemical cycles of two key elements (P and C), in particular in the EMB. To conclude, the magnitude of the biogeochemical changes induced by river inputs and runoff alone over the last thirty years clearly calls for the use of realistic scenarios of river inputs along with climate scenarios for coupled physical-biogeochemical forecasts in the MS.

Keywords: Mediterranean Sea, River inputs, Coupled physical-biogeochemical model, Flexible stoichiometry model, Biogeochemistry, Nutrient

1. Introduction

The Mediterranean Sea (MS) is a Low-Phosphate Low-Chlorophyll oligotrophic area characterized by a zonal west-east oligotrophic gradient [1]. The two basins, the Western Mediterranean Basin (WMB) and the Eastern Mediterranean Basin (EMB) are characterized by different biogeochemical properties: deep water phosphate (P) and nitrate (N) concentrations as well as primary production are higher in the WMB than in the EMB [2, 3, 4, 5]. Many studies have addressed the issue of nutrient limitation in the MS, and most of them have pointed out the major role of P availability in the control of phytoplankton growth [6, 7, 4, 8, 5] and bacterial production [9, 10], although N [4, 10, 11] and silicate availability [12] could also be limiting factors

12 in some areas.

13 At global scale, it is considered that nutrient availability (and especially that
14 of PO_4) in the surface layer of the ocean is mainly controlled by the exchanges
15 between the deep and the upper layers, with a limited influence of river in-
16 puts [13, 14]. Nevertheless, as an inland sea, the MS is strongly connected
17 with the Mediterranean continental region. Four main sources of external
18 inputs of nutrients to the upper layer of the MS can be distinguished : the
19 Gibraltar strait connecting the MS to the Atlantic Ocean, the Dardanelle
20 strait connecting the MS to the Black Sea (BS), rivers and runoff and atmo-
21 sphere (dry and wet deposition). In the WMB, the major external sources
22 of nutrients for the upper layer originate from the Gibraltar strait and from
23 the Rhône and Ebro Rivers. For the EMB, the major sources of nutrients
24 are the Po and Nile Rivers and the Dardanelle strait [15].

25
26 Nutrient inputs in the MS have been estimated using *in situ* data and
27 numerical models (see Béthoux et al. [16], Huertas et al. [17] for the Gibralt-
28 ar strait and Ludwig et al. [15] for rivers and the and Kopasakis et al. [18]
29 for Dardanelle strait (Black Sea)). N and P input from the rivers and the
30 Dardanelle strait have undergone significant changes since the early 1960s
31 [15, 19]: due to human activity, they increased by a factor 5 between the
32 1960s and the 1980s. After this period of strong increase, N input remained
33 high until 2000, while P rapidly dropped to reach its 1960s value.

34 Nutrient inputs from Gibraltar have long been considered as the major source
35 of nutrients for the upper layer of the MS compared to river inputs [20, 21, 22],
36 but recent studies have shown that N and P concentrations in the MS are
37 also sensitive to river [23] and atmospheric [24, 25] inputs.

38
39 Coupled physical/biogeochemical modeling is particularly suitable for as-
40 sessing the relative influence of the different nutrient inputs on the biogeo-
41 chemical cycles of biogenic elements, and on the structure of the planktonic
42 food web in the MS. Several modeling studies at basin or sub-basin scale have
43 already investigated the biogeochemistry of the MS during the last decades
44 [26, 27, 28], but without specific focus on the relative impact of nutrient
45 sources. One exception is [22], who have shown that the atmospheric inputs
46 could be a major source of nutrient in some areas of the MS. However, at-
47 mospheric nutrient inputs remain difficult to quantify and their estimation
48 suffers from considerable uncertainty, particularly regarding the bioavailable
49 fraction of these inputs [22, and references herein].

50 To the best of our knowledge, only two modeling studies have so far high-
51 lighted the large-scale influence of river inputs in the MS. [29] show that
52 primary production over the last decades could be impacted by river inputs,
53 but they mostly focus on the link between biogeochemistry and fisheries data.
54 [30] show that in the EMB primary production is sensitive to river inputs,
55 with an increase of 16 % from 1950 to 2000. They also show that the EMB
56 became more P-limited with the reduction of phosphate in anthropogenic
57 nutrient inputs.

58
59 In this study, our aim was to address the large-scale and long-term influ-
60 ence of river inputs on the biogeochemistry of the MS over the last decades
61 using an improved version of the coupled physical-biogeochemical 3D model
62 NEMO-MED12/Eco3M-MED [31, 32, 33, 26]. In order to highlight the effect
63 of river inputs alone, two near-identical simulations were run over 25 years
64 (1985-2010 period), the only difference being that one uses the estimated,
65 interannual river inputs provided by Ludwig et al. [15], while in the second,
66 river inputs are fixed to their 1985s level, i.e. before the decline in phosphate
67 discharge.

69 2. Material and methods

70 2.1. The biogeochemical model: *Eco3M-MED*

71 The biogeochemical model used in this study is embedded in the Eco3M
72 biogeochemical modeling platform, [34] which has been developed with the
73 priority given to (i) mechanistic (i.e. based on underlying processes) descrip-
74 tions of biogeochemical fluxes [33, 35, 36, 26], and (ii) modularity, with the
75 aim of easy adaptation of the model to different scientific questions (sev-
76 eral configurations already exist, some of them dedicated to studies on the
77 Mediterranean Sea [36, 26], others including diazotrophs [37] for studies in
78 the South Pacific, or *Mnemiopsis leidyi* [38] for a theoretical study on the
79 conditions favoring this comb jelly).

80
81 The Eco3M-Med configuration has been designed to represent the main
82 characteristics of the Mediterranean Sea. It includes 42 state variables grouped
83 in six different plankton functional types (PFTs), namely two phytoplank-
84 ton compartments (Large and Small), three zooplankton compartments and a
85 compartment of heterotrophic bacteria. The large phytoplankton (PHYL)(>

86 $10\mu m$) represents the micro- and the largest nanophytoplankton and is as-
87 sumed to be mainly composed of diatoms while the small phytoplankton
88 (PHYS) ($< 10\mu m$) includes picophytoplankton and the smallest nanophy-
89 toplankton cells. The three PFT of zooplankton correspond to three size
90 classes, namely nano-, micro- and mesozooplankton, which are respectively
91 associated with heterotrophic nanoflagellate (HNF), ciliate (CIL), and cope-
92 pods (COP). Each PFT, except that for copepods, is described by four state
93 variables, namely Carbon (C), Nitrogen (N) and Phosphorus (P) concentra-
94 tions, and an abundance (in cell or individuals per liter). Phytoplankton is
95 described by an additional variable (Chlorophyll-a concentration (Chl)), and
96 mesozooplankton is only described through two variables: carbon concentra-
97 tion and abundance. Three pools of inorganic matter are also represented,
98 namely nitrate (NO_3), ammonium (NH_4) and, phosphate (PO_4) as well as a
99 pool of dissolved organic matter (DOM) and two compartments of detrital
100 particulate matter, one including small particles (DETS) and the other large
101 particles (DETL).

102 The conceptual model (Fig. 1) is the same as that used in Guyennon et al.
103 [26], except that the compartment of detrital particulate matter has been
104 splitted into large and fast-sinking particles (DETL) and small particles
105 (DETS) with low sinking rate. DETL is fueled by the fecal pellets pro-
106 duced by mesozooplankton, and by the mortality of mesozooplankton and
107 large phytoplankton. The hydrolysis of large detrital material, as well as the
108 mortality of CIL, fuel the DETS compartment and the mortality of HNF
109 fuels the DOM compartment. The sinking rates of DETL and DETS are
110 respectively 50 m.d^{-1} and 2 m.d^{-1} .

111

112 Let X and Y be two biogenic elements among C , N , and P . As in previ-
113 ous versions of the Eco3M-Med model [36, 26], the intracellular ratios ($Q_{X/Y}$)
114 in organisms, as well as their intracellular quotas Q_X (intracellular quantity
115 of X per cell) are flexible and dynamically calculated by the model. These
116 intracellular ratios and quotas are extensively used to regulate the different
117 biogeochemical fluxes represented by the model, and the corresponding equa-
118 tions are given in the previously cited papers.

119

120 Only the new features of the model as compared to Guyennon et al. [26]
121 and Gimenez et al. [39] are presented in the appendix.

122

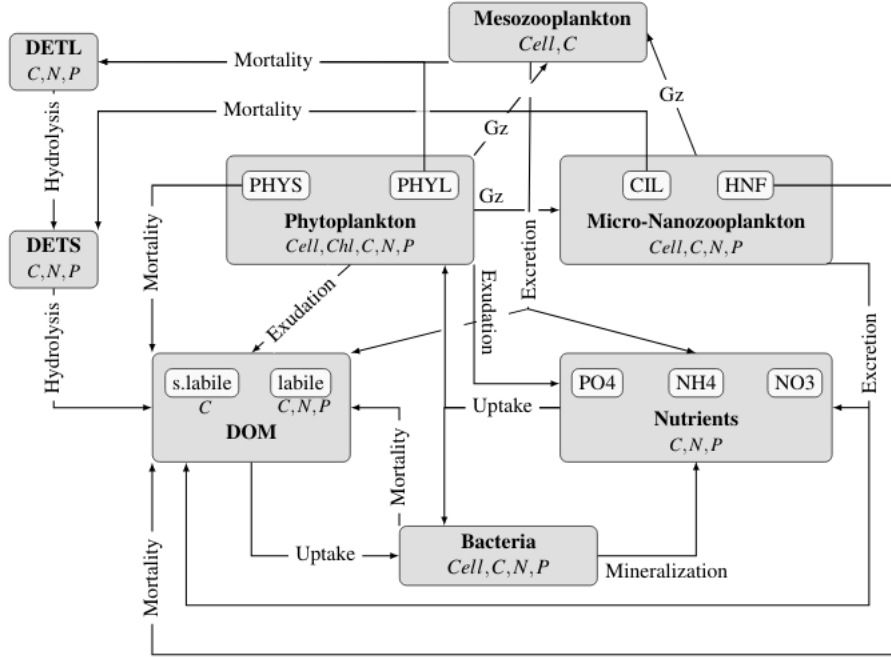


Figure 1: Conceptual model Eco3M-Med.

123 *2.2. The hydrodynamic model : NEMO-MED12*

124 In this study, we use an off-line coupling between the hydrodynamic
 125 NEMO (Nucleus for European Modelling of the Ocean) model [31] and
 126 Eco3M-MED.

127 The NEMO-MED12 configuration of NEMO which covers the entire Mediter-
 128 ranean Sea [40] is used. It includes a buffer zone from the Gibraltar strait to
 129 11 degrees east, where the open boundary conditions are gradually applied
 130 to avoid numerical instability. The horizontal resolution is 1/12 degree (6.5
 131 to 8 km cells), the vertical resolution has 75 z levels of 1 m width at the
 132 surface to 135 m at the seabed.

133

134 The hindcast hydrodynamic simulation used in this work is referred to
 135 as the NM12-FREE (no reanalysis no data assimilation) which started in
 136 October 1979 and ended in June 2013 [32].

137 In this simulation, the initial conditions for the MS were based on monthly
 138 means for temperature and salinity from MEDAR/MEDATLAS [41] and
 139 from ORAS4 for the Atlantic part. The runoff and river inputs in the NM12

140 domain came from the interannual data of [15]. The Black Sea is not included
141 in the NM12 configuration but a fresh water flux from the Dardanelles strait
142 is taken into account [42]. Atmospheric forcing is based on the dynamical
143 downscaling (ALDERA). It has a 12 km spatial resolution and a 3h tem-
144 poral resolution. For detailed information, the NM12-FREE simulation is
145 extensively described in [32].

146 *2.3. Characteristics of the hindcast simulation*

147 *2.3.1. Biogeochemical forcing*

148 **River inputs**

149

150 Monthly values of NO_3 and PO_4 inputs are provided for the 29 main
151 rivers all around the MS by the study of [15]. The contributions of the other
152 rivers were distributed in their respective sub-basins as runoffs. These nutri-
153 ent inputs are available until year 2000. Between 2001 and 2010, nutrients
154 river inputs of the year 2000 are repeatedly used as already done in [26] and
155 [22]. For dissolved organic carbon (*DOC*) concentration, an annual mean
156 over every watershed calculated by [43] has been used. In the current config-
157 uration, the river discharge is distributed over the six first vertical grid cells.
158 Figure 2 shows the phosphate (PO_4) and nitrate (NO_3) inputs to the MS
159 through river and runoff. It can be seen firstly that nutrient inputs are much
160 higher in the EMB than in the WMB. Moreover, since the end of the 1980s,
161 PO_4 input dropped down from more than 120 to less than 40 kt.a^{-1} in the
162 EMB and from 60 to less than 20 kt.a^{-1} in the WMB. The significant decrease
163 of PO_4 flux reflects the adoption of new legislation by the surrounding coun-
164 tries, such as the prohibition of phosphorus detergents, and the improvement
165 of wastewater treatment plants, as well as other features detailed in Ludwig
166 et al. [15]. By contrast, NO_3 input remains relatively stable over the period.

167

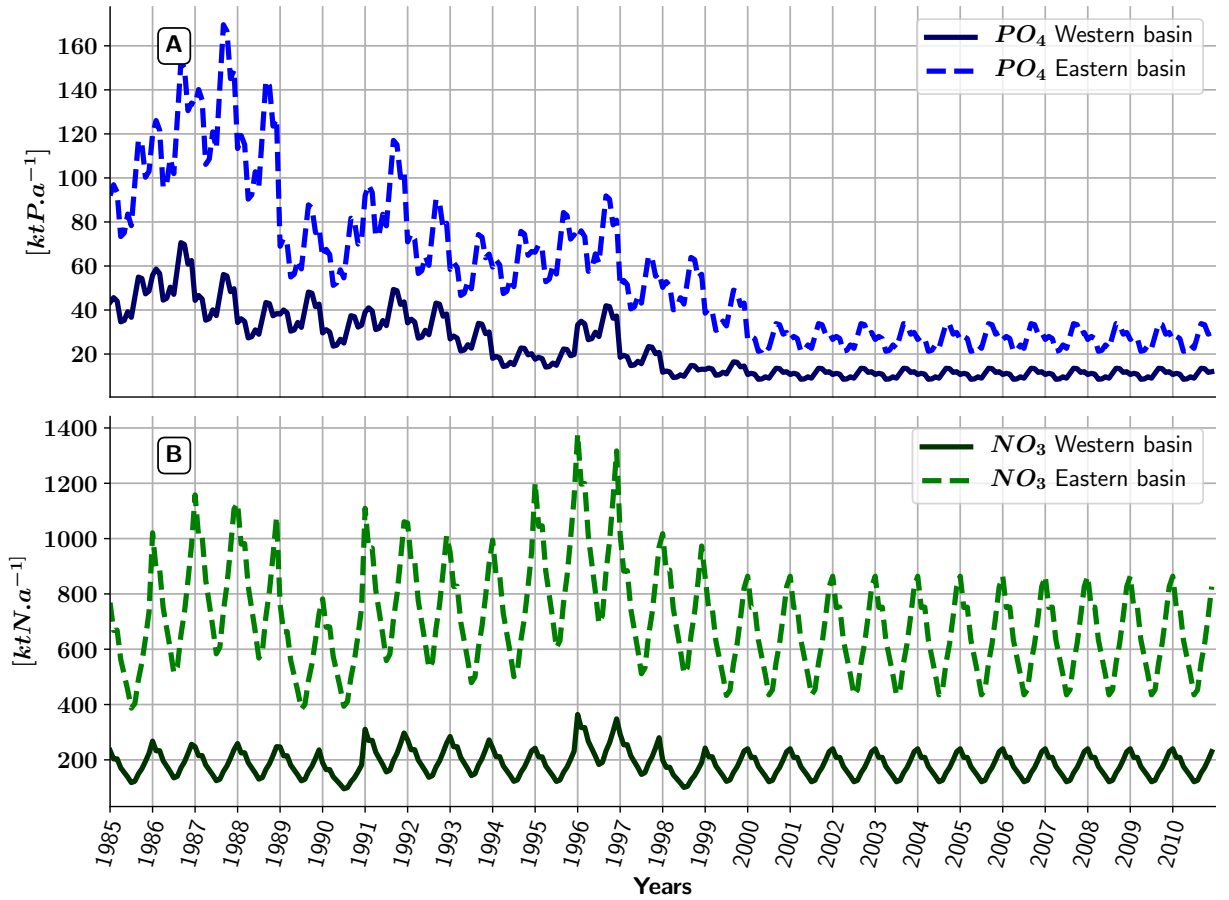


Figure 2: Nutrients inputs from rivers and runoff in $kt.a^{-1}$ [15] used in the model for the eastern basin (dotted line) and for the western basin (plain line). A) PO_4 inputs; B) NO_3 inputs.

Boundary and initial conditions

168

169 Nutrient input at Gibraltar is conditioned by the nutrient concentrations in

170 the buffer zone. Annual climatology data (monthly vertical profiles) are used
 171 in the buffer zone for each state variable of the biogeochemical model. For
 172 PO_4 , NO_3 , NH_4 and OXY , these annual climatology data are extracted from
 173 the World Ocean Atlas database. The other variables have been computed
 174 through a mean chlorophyll profile in order to reproduce seasonal variability.
 175 They are derived from the profiles using conversion factors derived from

176 published works [36]. For the initial conditions, the same procedure has
177 been applied. More details on this preliminary work can be found in [44]
178 where it has already been extensively described.

179 *2.3.2. Spin-up and Simulation plans*

180 Using the initial conditions as described before, a first 20-years spin-
181 up was run, consisting in a 5-years simulation (1982-1987) repeatedly run,
182 allowing most of the variables to reach an equilibrium state. Starting from
183 this equilibrium state, the hindcast simulation was run.

184 In this study, two simulations were run. The first is the hindcast simulation,
185 starting in 1985 and ending in 2010, described in the previous sections. This
186 simulation will be referred to hereafter as the Riv-ref simulation. The second
187 simulation is identical in all respects to the Riv-ref simulation, except that
188 the monthly river inputs of the year 1985 are used throughout the simulation
189 in order to deconvolute the impact of river inputs from other forcing. This
190 simulation is referred to hereafter as the Riv-85.

191 **3. Results**

192 *3.1. Model skill assessment*

193 Figure 3 shows the modelled (mCHL) for the Riv-ref simulation and ob-
194 served (oCHL), i.e. satellite-derived, mean surface chlorophyll *a* concentra-
195 tion over the 1997-2010 period. High chlorophyll clusters can be observed for
196 both oCHL and mCHL in the vicinity of river mouths, but only for oCHL
197 near the Nile, along the western coast of the Adriatic Sea and in the Gulf of
198 Gabes. The well-known east-west gradient of CHL (see oCHL) is also clearly
199 visible in the mCHL pattern. Excluding the coastal areas (i.e. depth < 200
200 m) which are more impacted by river inputs, the mean chlorophyll concen-
201 trations, oCHL and mCHL, are equal to 0.047 and 0.04 $\mu g.l^{-1}$, and to 0.032
202 and 0.034 $\mu g.l^{-1}$, in the WMB and in the EMB, respectively.

203 Several similar structures can also be observed in both oCHL and mCHL in
204 the WMB, such as i) a well-defined Liguro-Provencal current, ii) an intense
205 Liguro-Provencal bloom, though slightly more expanded for mCHL than for
206 oCHL, iii) a high-chlorophyll gyre to the south-east of Corsica. For the east-
207 ern basin, very low chlorophyll concentrations are observed and modelled,
208 except in the Rhodes gyre where higher concentrations can be seen in both
209 oCHL and mCHL patterns.

210

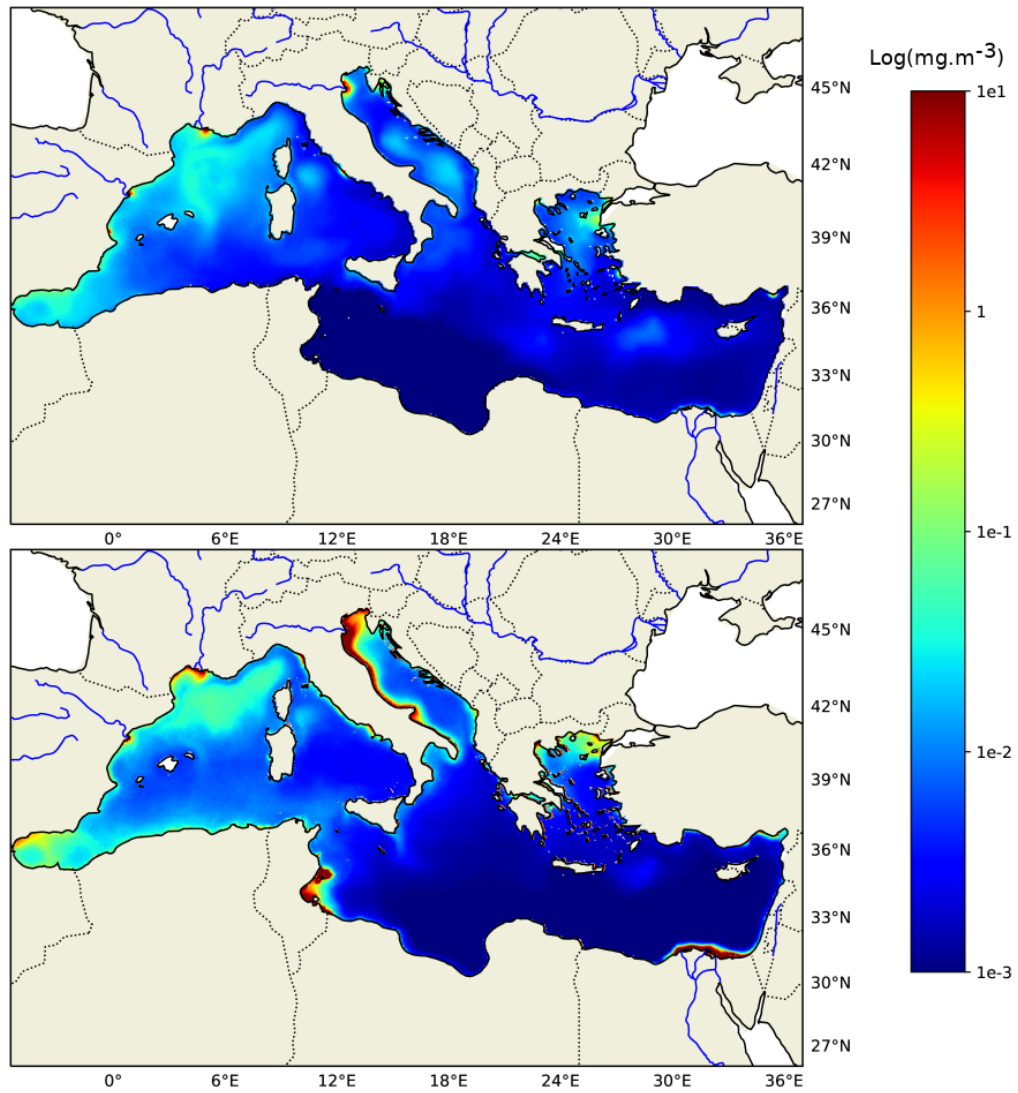


Figure 3: Average surface chlorophyll *a* concentration between 1997 and 2010, (top) calculated by the model and (bottom) observed by satellite.

212 Overall, the model shows a good ability to reproduce the main structures
213 of surface chlorophyll in the MS, and especially all the main productive areas
214 are detected by the satellite. However, in some areas, Chl structures are not
215 well represented by the model, such as i) the Rhodes gyre where mCHL is
216 too high ($+ 0.05 \mu g.l^{-1}$ than oCHL), which can be partially ascribed to the
217 too intense convection estimated by the hydrodynamic model in this area
218 [32], ii) the center part of the Adriatic Sea, which is more productive in the
219 model ($+ 0.08 \mu g.l^{-1}$ than oCHL), iii) the coastal Italian side of the Adriatic
220 Sea, which is less productive in the model than in data. This could be due
221 to insufficient PO_4 inputs from the Po river in the model leading to a too
222 strong PO_4 limitation of phytoplankton growth, combined with chlorophyll
223 data which are less reliable in case II waters [45], iv) the gulf of Gabes which is
224 less productive in the model ($- 0.5 \mu g.l^{-1}$ than oCHL), where high phosphate
225 supply from the land and the seabed are not taken into account in the model,
226 v) the Nile mouth which is less productive in the model ($- 1.06 \mu g.l^{-1}$ than
227 oCHL) where nutrient input is probably poorly represented because of the
228 lack of data [15].

229

230 A quantitative comparison between *in situ* data and model outputs has
231 also been undertaken using a Taylor diagram [47] that shows the standard
232 deviation, the correlation between the data and the model and the root
233 mean square error (Fig. 4). Mean vertical profiles of four biogeochemical
234 variables, dissolved organic carbon (DOC), CHL, NO_3 and PO_4 measured
235 at the Dyfamed station [46] over the 1990-2002 period, are compared with
236 the model outputs averaged over the same period. For CHL, NO_3 and PO_4 ,
237 correlations are higher than 0.95, with relative standard deviations ranging
238 between 0.78 and 1.2, and an error close to 0.2, showing that the model can
239 predict relatively well those variables at Dyfamed station. For DOC, the
240 comparison with data is less favorable. This could be partly ascribed to the
241 number of available DOC data, which is well below the number of data for
242 the other variables, and to the fact that the comparison is partly biased since
243 Dyfamed data concern the whole DOC pool while the modelled DOC only
244 includes the labile and semi-labile pool. The refractory part of the modelled
245 DOC is therefore arbitrarily set to a constant value for the comparison with
246 *in situ* data, thereby introducing a systematic error. These comparisons and
247 others not shown led us to conclude that the model was able to reproduce

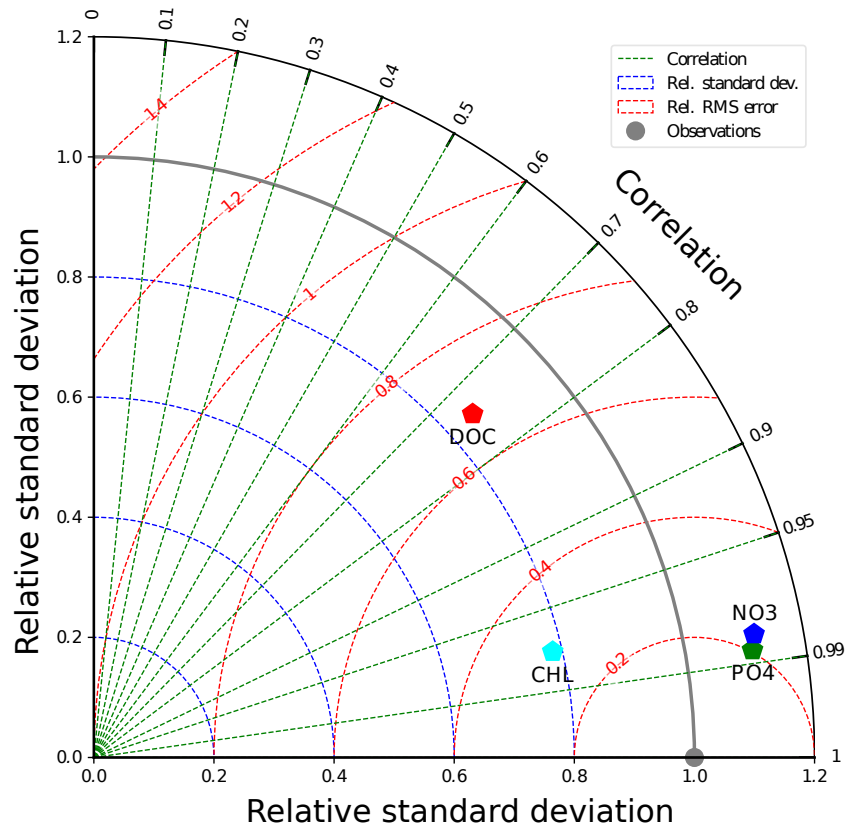


Figure 4: Taylor diagram showing the standard deviation of the normalized model outputs, the correlation between *in situ* data and model outputs, and the root mean square error between *in situ* data and model outputs. Data consist in vertical profiles of NO₃, PO₄, DOC and CHL obtained at Dyfamed [46] station during the period 1990-2002. Model outputs are vertical profiles averaged over the same period. In red: dissolved organic carbon (DOC), in light: blue chlorophyll *a*; in green: PO₄ and in blue: NO₃.

248 most of the major biogeochemical features of the MS and could be used to
 249 investigate the effects of the variations in nutrient concentration in the river
 250 inputs.

251 *3.2. River input and the biogeochemistry of the MS*

252 *3.2.1. Nutriclines*

253 According to the model, over time, the evolution of continental nutrient
254 inputs has various effects on the biogeochemistry of the MS.

255 One of them concerns nutriclines, and more specifically the top of nutriclines.
256 Let us first define how the top of the nitracline (Ncline) and phosphacline
257 (Pcline) are determined. The top of the Ncline is located at the first depth,
258 starting from the sea surface, at which NO_3 reaches $0.05 \mu\text{mol.l}^{-1}$. This
259 threshold corresponds to the classical quantification limit of nitrate mea-
260 surement using an autoanalyser [48]. Such determination of the top Ncline
261 has already been used by Pujó-Pay et al. [2] and Bahamón et al. [49].

262 The depth of the top of the Pcline is based on a threshold value of 3
263 nmol.l^{-1} . The latter value corresponds to the nitrate threshold (i.e. 0.05
264 μM) divided by 16, that is, by the Redfield proportion between N and P.
265 Figure 5 shows the patterns of change over time of the top of the Pcline
266 for the WMB (A) and the EMB (B) over the period 1985-2010. There is
267 no clear trend over this period in the WMB (Fig. 5 A). The top of the
268 Pclines seasonally reaches the surface in winter and deepens to around 60 m
269 in Summer (Fig. 5 A). In the EMB (Fig. 5 B), the top of the Pcline never
270 reaches the surface, not even during winter convection. Moreover, there is
271 a clear trend towards a deepening of the Pcline between the 1980s and the
272 year 2000s. This deepening can be better quantified in figure 5 D where
273 the difference between the depths of Pcline for the Riv-ref simulation (using
274 realistic changes in river input) and the Riv-85 simulation is reported for the
275 EMB. It can be seen there that the the top of the Pcline can deepen as far as
276 40m. A similar result (not shown) is obtained for the 0-150 m integrated PO_4
277 concentration (referred to as I - PO_4 hereafter). In the WMB, this deepening
278 is far less marked, that is less than 10 m (Fig. 5 C). Concerning the top of
279 the nitracline (not shown), it exhibits the same seasonal variations as the
280 Pcline, but no clear trend could be evidenced, either in the WMB, or in the
281 EMB.

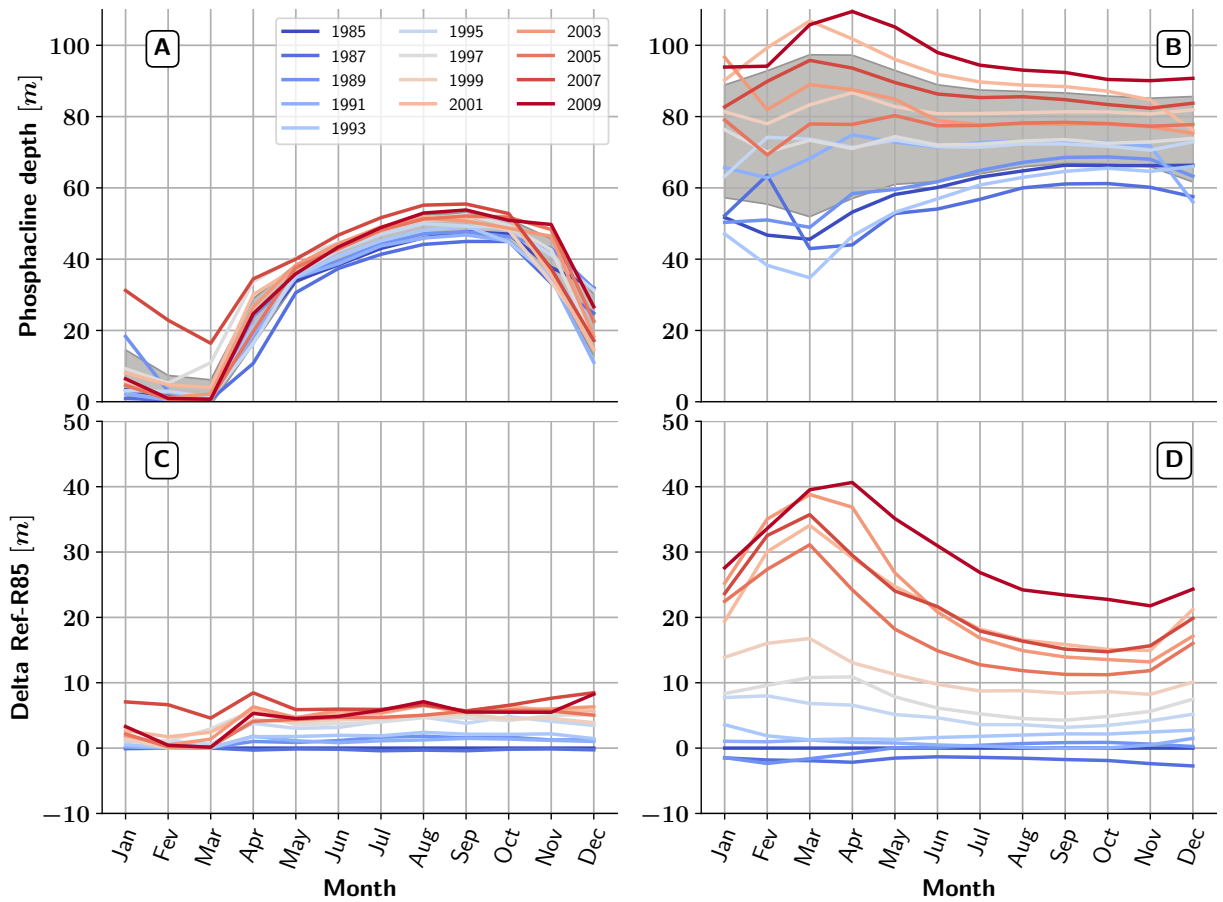


Figure 5: Patterns of change in the depth of the top of the phosphocline (see the definition in the text) for (A) the western basin and (B) the eastern basin and difference between the top of the phosphocline for the Riv-ref and the Riv-85 simulations for the (C) western basin and (D) the eastern basin over the period 1985-2010. Each line corresponds to a two-year average. The line colors progressively change from blue (1985) to red (2010) in order to highlight the temporal changes during that period. The grey area delimits the maximum standard deviation of the 1985-2010 averaged depth of Pcline (throughout period 1985-2010).

282 In the model, the biogeochemical processes controlling the depth of the
 283 Pcline are the different production and consumption fluxes: uptake of PHYS
 284 (Fig. 6 A); uptake of PHYL (Fig. 6 B); uptake of BAC (Fig. 6 C); excretion
 285 of CIL and HNF (Fig. 6 D) and mineralization by BAC (Fig. 6 C). The mean
 286 depth at which production and consumption fluxes of PO_4 are balanced is

287 also represented (Fig. 6 F). PO_4 uptake by PHYS in the upper surface (0-50
288 m) decreases from $0.6 \pm 0.1 \times 10^{-15} \text{ mol.l}^{-1}.\text{s}^{-1}$ in 1985 to $0.89 \pm 0.1 \times 10^{-16}$
289 in 2010 (Fig. 6 A). The maximum uptake rate, corresponding to the maxi-
290 mum abundance (not shown), is a little bit weaker and deeper in 2010. For
291 PHYL, the maximum uptake decreases from $3.3 \pm 0.1 \times 10^{-16}$ in the 1980s to
292 $5.14 \pm 0.1 \times 10^{-17} \text{ mol.l}^{-1}.\text{s}^{-1}$ in the years 2000s (Fig. 6 B). PO_4 uptake by
293 bacteria (Fig. 6 C) decreases only at the surface and becomes deeper over
294 the years. The maximum uptake deepens slightly between 1985 and 2010,
295 but its intensity remains stable around $4 \times 10^{-14} \text{ mol.l}^{-1}.\text{s}^{-1}$.
296 The excretion by microzooplankton (CIL) and nanozooplankton (HNF) de-
297 creases progressively over the period (Fig. 6 D) and the maximum excretion
298 deepens (though this is barely visible in this figure). The maximum reminer-
299 alization by heterotrophic bacteria also deepens from less than 200 m in the
300 1980s to almost 300 m in the years 2000's and is also less intense (Fig. 6 E).
301 The depth where a balance between production and consumption fluxes is
302 reached also deepens from 200 m in 1985 to almost 300 m in 2010 (Fig. 6 F).

303

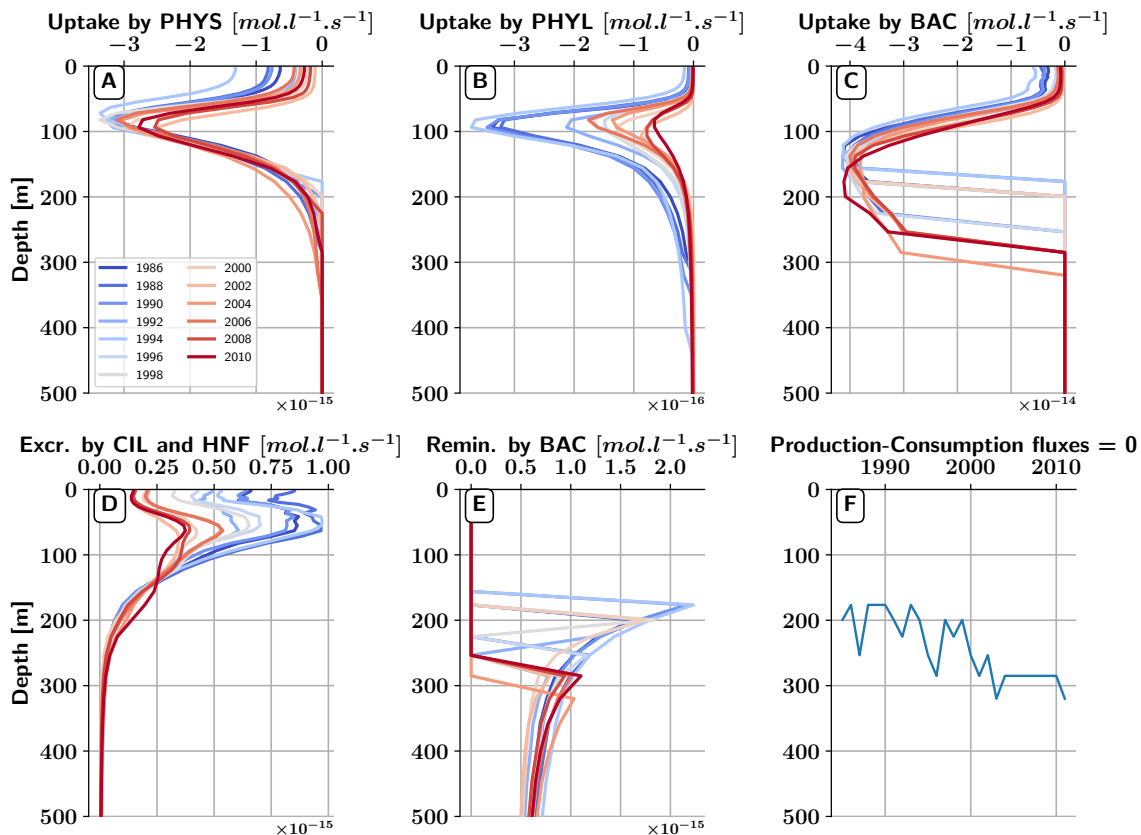


Figure 6: Patterns of change in the different production and consumption fluxes of PO_4 playing a role in the position of the phosphacline in the eastern basin; A) Uptake by small phytoplankton; B) Uptake by large phytoplankton; C) Uptake by bacteria; D) Excretion by micro and nanozooplankton; E) Remineralization by bacteria; F) Depth where a balance between production and consumption fluxes is reached. The line colors progressively change from blue (1985) to red (2010) in order to highlight the temporal changes during that period. Negative values refer to fluxes from water towards organisms and positive ones from organisms towards water.

304 3.2.2. Surface Dissolved Organic Carbon

305 Surface DOC concentration exhibits a clear seasonal pattern, not only for
 306 the WMB (Fig. 7 A) but also for the EMB (Fig. 7 B). To highlight a potential
 307 trend in surface DOC concentrations over the 1985-2010 period, the difference
 308 between DOC concentration for the Riv-ref and the Riv-85 simulations is
 309 plotted for the two basins. The trend is tenuous in the WMB (Fig. 7 C),
 310 while there is a regular and significant DOC concentration increase of nearly

311 20% in the EMB over the same period (Fig. 7 D).

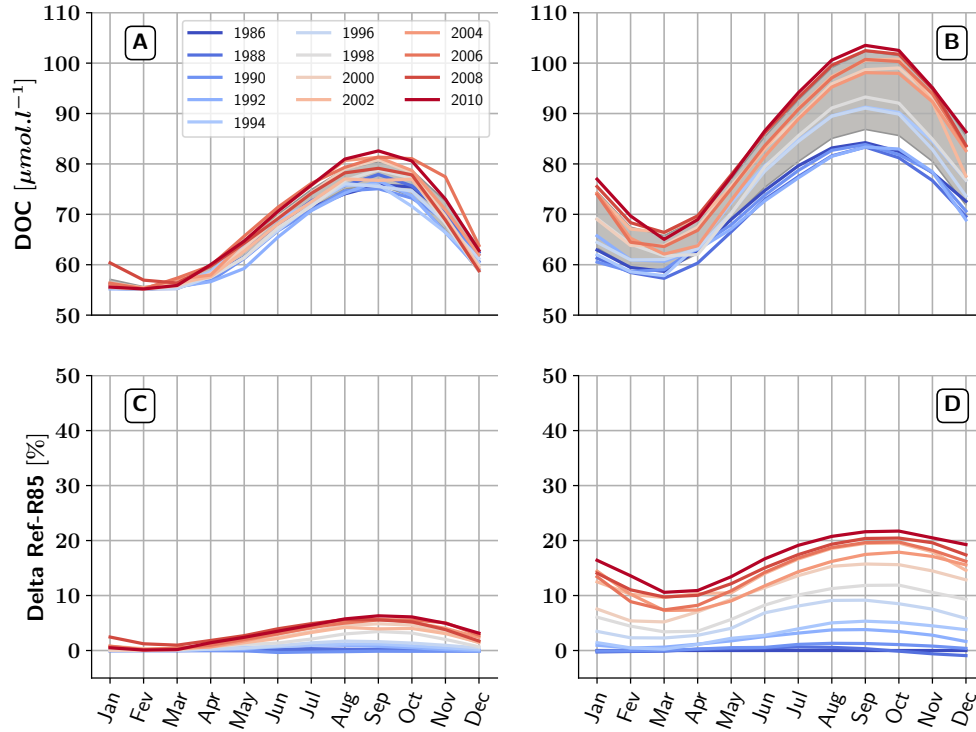


Figure 7: Patterns of change in surface DOC concentration in $\mu\text{mol.l}^{-1}$ for (A) the western basin and (B) the eastern basin and difference between the top of the phosphacline for the Riv-ref and the Riv-85 simulations for the (C) western basin and (D) the eastern basin over the 1985-2010 period, as calculated by the model. The line colors progressively change from blue (1985) to red (2010) in order to highlight the temporal changes during that period.

312

313 *3.2.3. Time and spatial distribution of certain biogeochemical variables at*
314 *basin scale*

315 Figure 8 shows that during the simulated period, I-PO₄ drops everywhere
316 in the EMB (Fig. 8), except near the Sicilian strait and to the south of
317 Rhodes due to very strong and deep vertical mixing. This decrease in I-PO₄
318 can be as high as 40 % (Fig. 8). In the WMB, the spatial variability of the
319 difference in I-PO₄ between 1985 and 2010 is slightly more noticeable but
320 remains weak. The difference in I-PO₄ remains close to 0 % except near the
321 coastal areas where the decrease in I-PO₄ over the period can reach up to
322 30 %, and offshore of the Gulf of Lions where I-PO₄ is higher in 2010 than
323 1985. It can also be seen that DOC concentration at the surface progressively
324 increases between 1985 and 2010 in the EMB (Fig. 8) and reaches more than
325 40 % in some areas, while DOC concentration remains nearly constant in the
326 WMB.

327 The patterns of change over with time of the 0-150 m integrated carbon
328 biomass of copepod (I-COP-C) is also reported in the same figure, showing
329 that I-COP-C decreases mostly in the EMB between 1985 and 2010 (Fig. 8).
330 In the same period, we observe a decrease in COP abundance (not shown).
331 Furthermore, I-COP-C exhibits wide mesoscale variability over the MS (Fig
332 8) with a decrease in the EMB in coastal areas and an increase in the gulf of
333 Gabes and near the Algerian coast. This result highlights the importance of
334 mesoscale activity with regard to the biogeochemistry of the Mediterranean
335 sea.

336

337 **4. Discussion**

338 *4.1. The decrease in PO₄ input by rivers strongly impacts the biogeochemistry*
339 *of the eastern basin*

340 The hindcast simulation over the period (1985-2010) using the coupled
341 model NEMO-MED12/Eco3M-Med shows a significant decrease in the 0-150
342 m integrated PO₄ concentration (I-PO₄), especially in the EMB (Fig. 8).
343 At first glance, several factors could explain this decrease, namely (i) a drift
344 of the model, (ii) changes in PO₄ surface inputs at Gibraltar strait, (iii)
345 changes in the vertical exchanges between the upper and the deep layers, or
346 (iv) changes in river input and runoff, or possibly a combination of all these
347 factors. The three former causes have been ruled out: it has been verified

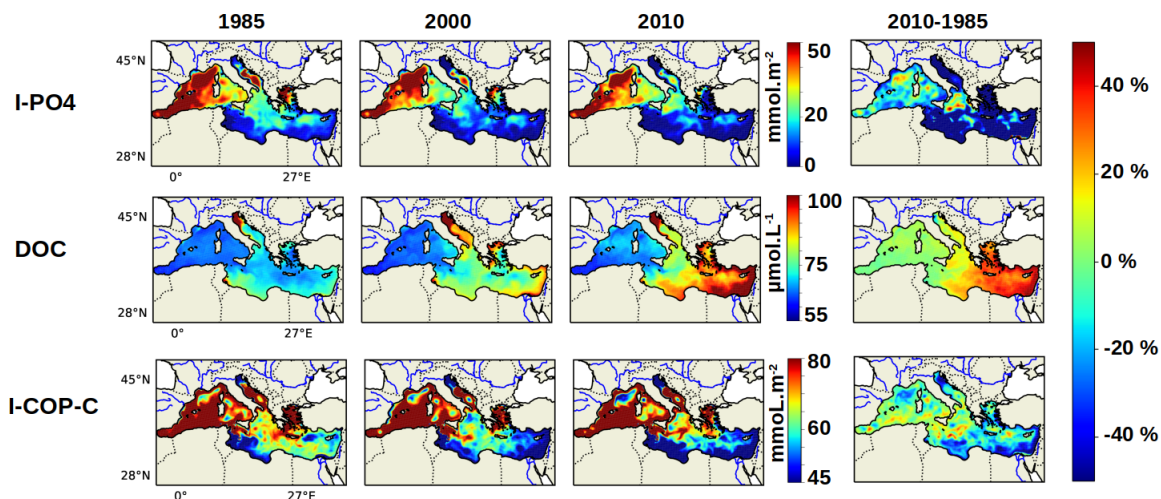


Figure 8: Patterns of change at basin scale between 1985 and 2010 of: (top) the 0-150 m integrated PO_4 concentration (I- PO_4), (middle) the surface DOC concentration, (bottom) the carbon biomass of copepods (I-COP-C) integrated between 0 and 150 m. The first three columns refer to the years 1985, 2000 and 2010, respectively, and the last column shows the difference between 1985 and 2010 (i.e 2010 value - 1985 value)

348 first that the model drift was negligible after having run the spin-up, and that
 349 PO_4 surface inputs at Gibraltar strait were approximately constant during
 350 the simulated period. Concerning vertical mixing, it has been confirmed that
 351 the mean position of the mixed layer depth (MLD) did not significantly vary
 352 over this period, that the seasonal and annual standard deviation of the ML
 353 did not show any trend, and that vertical velocities as well as the vertical
 354 eddy diffusivity at the bottom of the ML did not exhibit any trend either.
 355 As a result, changes in river input and runoff is the only factor in the model
 356 able to explain the decrease in integrated PO_4 concentration in the EMB. In
 357 order to confirm this assumption, a twin simulation only differing by nutrient
 358 input from rivers and runoffs has been run. In the second simulation, PO_4
 359 input remains at the 1985s level.

360

361 The comparison between the two simulations confirms the major influence
 362 of changes in PO_4 river input and runoff on the integrated PO_4 concentra-
 363 tions and beyond on the MS biogeochemistry, especially in the EMB. The
 364 decrease in I- PO_4 probably results from the combination of a direct and an
 365 indirect effect. The direct effect is a consequence of the decrease in PO_4 input

366 by Mediterranean rivers between 1985 and 2000 [15]. PO_4 input from rivers
367 and runoff strongly decreased during this period in the WMB and in the
368 EMB (see Fig. 2), while NO_3 input remained roughly unchanged. Moreover,
369 this decrease is stronger in the EMB: PO_4 inputs indeed decreased from 140
370 kt.a^{-1} to less than 40 kt.a^{-1} between the 1980s and the 2000s in the EMB,
371 and from 50 kt.a^{-1} to less than 20 kt.a^{-1} in the WMB during the same pe-
372 riod.

373 Overall, the model shows, on time scales of a few decades, a strong relation-
374 ship between nutrient input via rivers and nutrient availability in the surface
375 layer, as already pointed out by Powley et al. [30], as well as the link be-
376 tween the decrease in PO_4 input by rivers and the increase of P depletion in
377 the EMB. It is nevertheless in contradiction with the study of [14] showing
378 similar annual PO_4 input by the Rhône River and annual PO_4 storage in the
379 upper sediment of the Gulf of Lions, indicating no strong influence only close
380 to the river mouth of one of the major rivers in the MS.

381 Furthermore, a decrease in surface PO_4 has been recently reported in the
382 Levantine basin [50]. This decrease is however rather a shift in phosphate
383 concentrations than a progressive decrease over years, which may be caused
384 by decadal reversals in the North Ionian Gyre, i.e. Bimodal Oscillation Sys-
385 tem (BiOS). Such alterations of the MS circulation, as well as many other
386 factors that are not necessarily included or well represented in our model may
387 indeed contribute to an impact on the biogeochemistry of the MS. However,
388 considering that our results rely on two identical simulations only differing by
389 river inputs and runoff, the unavoidable inaccuracies in the aforementioned
390 model do not call into question the unexpected conclusions they lead to on
391 the major influence of river inputs on the biogeochemistry of the MS.

392
393 The indirect effect of changes in PO_4 river input and runoff is the deepen-
394 ing of the top of the phosphocline (i.e. Pcline as defined in section 3.3) which
395 occurs only in the EMB (from 60 m in 1985 to 90 m in 2010). This deepening
396 exacerbates the decrease in PO_4 in the surface layer by restricting the PO_4
397 flux brought to the surface through winter mixing. Investigating the reasons
398 for this deepening requires to describing in detail all PO_4 fluxes shaping the
399 Pcline. The position of the Pcline within the water column (during stratified
400 conditions) results from an equilibrium between PO_4 production and con-
401 sumption fluxes [3, 2, 51].

402
403 The consumption of PO_4 in the model is driven by PHYS, PHYL and

404 BAC uptake. Phytoplankton and bacteria need nutrients (NO_3 , PO_4) to
405 grow, as well as carbon. Carbon essentially comes from DIC uptake (photo-
406 synthesis) by phytoplankton and from DOC uptake by heterotrophic bacteria
407 [52]. This uptake progressively decreased over time in surface waters because
408 of the gradual depletion of PO_4 (Fig. 6). The maximum PO_4 uptake rates at
409 depth (around 100 m) for PHYS and PHYL also decrease with time, mostly
410 for PHYL (Fig. 6) because sufficient nutrient concentrations to sustain the
411 growth of organisms are only found at greater depth. However, the efficiency
412 of photosynthesis decreases with depth since light energy decreases as well,
413 leading to an increase in carbon limitation for phytoplankton and to lower
414 cell abundance, and in turn to a decrease in nutrient uptake rates.

415 PHYL is more sensitive to nutrient variations in the model. Because
416 of the scaling relationship between nutrient uptake and organism size [53],
417 PHYL is characterized by a higher half-saturation constant than PHYS [33],
418 making it less adapted to ultra-oligotrophic conditions. The uptake of BAC
419 is deepening over the period (Fig. 6 c) but it does not strongly decrease at
420 depth since, unlike phytoplankton, bacteria use DOC as carbon source and
421 are therefore not limited by light. Bacteria follow the deepening of the Pcline
422 as long as labile DOC is available.

423 PO_4 is produced by zooplankton excretion and bacteria remineralization.
424 Excretion of CIL and HNF is regulated by Q_P , their intracellular P quota
425 (i.e. excretion non-linearly increases with Q_P). Since the abundance and
426 the Q_P of CIL and HNF's preys (namely PHYS and BAC for HNF, and
427 PHYS, BAC and HNF for CIL) decline over the period (not shown), the Q_P
428 of CIL and HNF decrease as well. As a result, PO_4 excretion by HNF and
429 CIL decreases. The deepening of PO_4 production by BAC remineralization
430 could also be explained by the P quota of BAC. BAC reach their maximum P
431 quota (i.e. the value allowing remineralization of organic P) deeper because
432 of the increasing P depletion in the surface layer. Moreover, the decrease in
433 remineralization intensity with depth is also due to the diminution of BAC
434 abundance associated with the lower concentration of labile DOC at depth.

435
436 To sum up, PO_4 consumption fluxes show a clear decreasing trend in the
437 surface layer while the maximum of consumption deepens and its intensity
438 remains almost unchanged. PO_4 production fluxes also show a clear decreasing
439 trend in the surface layer, as well as in depth. As a result, the equilibrium
440 between all those processes occurs deeper in the water column, resulting in a
441 Pcline that deepens over the years. Furthermore, the amount of PO_4 brought

442 to the surface layer annually during winter mixing also decreases, thereby re-
443 enforcing the lower availability of PO_4 in the surface layer.

444 To the best of our knowledge, no deepening of the top of the phosphacline
445 in the EMB during the last decades has yet been reported in the literature.
446 The lack of data and the quantification limit issue associated with PO_4 mea-
447 surement probably explains why this question has not been addressed so far.
448 We gathered the few available NO_3 and PO_4 data recorded in the center of
449 the Levantine Sea and collected during five cruises over our simulation pe-
450 riod, namely POEM 05 (1987), LBD01 (1989), MINOS (1996), PROSOPE
451 (1999) and BOUM (2008). The vertical PO_4 and NO_3 profiles measured dur-
452 ing these cruises have been reported in figure 9 in order to test the hypothesis
453 of the deepening of the Pcline using *in situ* data. According to the POEM
454 and BOUM cruises data, PO_4 concentration between 100 and 200 m seems to
455 decrease between 1987 and 2008 while NO_3 concentration remains constant
456 during the same period. Given the limited set of data available in the open
457 EMB, and taking into account the issue of the relatively high quantification
458 limit for PO_4 measurements, those data are obviously not a sufficient basis
459 for any definite conclusions, but they do however seem to confirm the deep-
460 ening with time of the top phosphacline simulated by the model, as well as
461 the roughly constant position of the top nitracline.

462

463 In the model, the fact that only the top Pcline deepened in the EMB be-
464 tween 1985 and 2010 results in the appearance of a shift between Pcline and
465 Ncline which increases with time. During the BOUM cruise in 2008, [2] mea-
466 sured a maximum shift between nutriclines of 130 m in the Levantine basin,
467 and a mean shift of around 60 m if we exclude the eastern stations sampled
468 in the center of an anticyclonic eddy characterized by specific hydrodynamic
469 conditions [1]. To calculate the position of the top of the nitracline [2] use,
470 as we do (see section 3.3), the threshold of $0.05 \mu\text{mol.l}^{-1}$, leading to a mean
471 nitracline top located at approximately 75 m, which is consistent with the
472 top of the nitracline depth calculated by our model (between 70 m and 75
473 m). For the determination of the depth of top of the phosphacline, [2] use the
474 threshold value of $0.02 \mu\text{mol.l}^{-1}$, resulting in a mean top phosphacline depth
475 at around 130 m if we exclude the eastern stations for the reason previously
476 mentioned. In the model, we find a phosphacline top depth at around 90 m
477 in the EMB with the more restrictive threshold of $0.003 \mu\text{mol.l}^{-1}$. However,

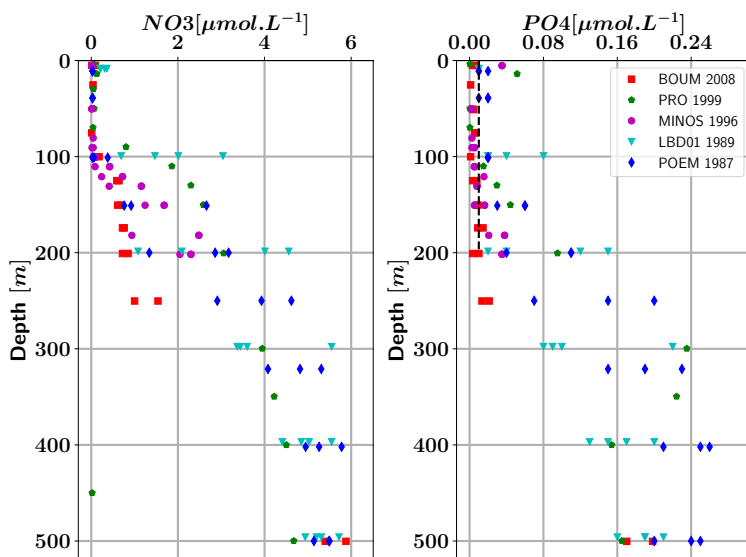


Figure 9: NO_3 (left) and PO_4 (right) data from five cruises in an area located in the center of the Levantine sub-basin, namely : i) POEM 05 (June 1987) in blue; ii) LBD01 (April 1989) in cyan; iii) MINOS (June 1996) in pink; iv) PROSOPE (September 1999) in green; v) BOUM (July 2008) in red. The black dotted line shows the quantification limit, except for the BOUM cruise during which sensitive methods of analysis were used.

478 if we apply the same threshold value as [2], the model calculates a phospho-
 479 cline top depth between 110 and 125 m in the EMB, which is consistent with
 480 *in situ* data.

481 The shift between the top of nutricline depths in the EMB has been
 482 previously reported in literature [4, 54, 2] and explained by several processes
 483 but changes in river input were never suspected of playing a significant role
 484 in this shift. So far, the most common explanation for this shift (and for
 485 the associated high subsurface $\text{NO}_3:\text{PO}_4$ ratio) was related to the high deep
 486 $\text{NO}_3:\text{PO}_4$ ratio, i.e. higher than the Redfield value, as a result of nutrient
 487 budgets regulated by nutrient exchanges at straits, and especially at the
 488 Gibraltar strait [55]. Upward diffusion of deep nutrients taken up biologically
 489 at a constant molar N:P ratio of 16:1 may theoretically lead to subsurface
 490 ratios as high as those observed at depth [7, 4]. External atmospheric inputs
 491 were also recently suggested to play a role in the high surface and subsurface
 492 $\text{NO}_3:\text{PO}_4$ ratio [25, 24].

493 This study suggests that the N:P ratio in nutrient input by rivers, and its

494 deviation from the Redfield ratio, may partly explain the shift between the
495 top of the nitracline and phosphacline in the MS as a result of a deepening
496 of the Pcline (due to the strong decrease in PO_4 inputs from rivers), without
497 a similar deepening in the Ncline.

498 *4.2. Patterns of change in DOC concentration between 1985 and 2010 and*
499 *consequences for the biological carbon pump*

500 DOC surface concentration increases strongly over the simulated period,
501 especially in the EMB (Fig. 7 and 8). At the scale of the EMB, this increase
502 reaches 20 % (Fig. 8) but it is far higher in the Levantine sub-basin, reaching
503 there more than 40 %. An inverse trend for PO_4 concentrations was observed
504 (Fig. 8) reinforcing the west to east oligotrophy gradient in the EMB.

505 This increase in DOC is driven by the same mechanisms as those in-
506 volved in the surface DOC accumulation observed every summer in the MS
507 [8, 9]. The latter, namely an increase in DOC exudation by P-limited phyto-
508 plankton exceeding bacterial DOC demand, since bacteria are also strongly
509 P-limited, have already been extensively described in Guyennon et al. [26].
510 Over the simulated period, the EMB upper waters become more and more P-
511 depleted (Fig. 8) which induces a rise in DOC exudation by phytoplankton
512 (Fig. 8). Furthermore, because of the strong P-limitation of both phyto-
513 plankton and heterotrophic bacteria, the abundance of bacteria decreases in
514 the surface layer, as has been evidenced *in situ* [9]. The decrease in bacte-
515 rial abundance probably also leads to a decrease in DOC consumption by
516 bacteria and reinforces DOC accumulation.

517 A DOC concentration increase between 1985 and 2010 cannot be validated
518 with any certainty since very few DOC measurements in the EMB before the
519 years 2000 are available, and most of them were carried out in coastal areas.
520 Moreover, as already mentioned, the comparison is not easy since DOC *in*
521 *situ* data refer to total DOC, while the modelled DOC does not include
522 the refractory part, making necessary an approximation for refractory DOC.
523 Overall, the model seems to provide realistic DOC values as suggested by
524 comparison with *in situ* data from the DyFaMed station over the 1992-2002
525 period (see Fig. 4) or from the BOUM cruise (not shown). The modelled
526 increase in dissolved organic carbon is not observed in the detrital particulate
527 carbon, which even slightly decreases. However the total organic carbon
528 increases, indicating that the pool of organic carbon available for export has
529 increased during the period. Since, as already shown by [26], the export
530 of DOC in the eastern basin is the main component of the exported organic

531 carbon, the strong DOC increase in the EMB has significantly increased DOC
532 export during this period.

533 *4.3. A simulated decrease in mesozooplankton abundance and biomass with*
534 *expected consequences for higher trophic levels*

535 Despite the wide variability associated with mesoscale activity (Fig. 8),
536 a strong decrease in biomass (I-COP-C) and abundance of copepods was
537 modelled in the EMB, as well as in the offshore part of the WMB, between
538 1985 and 2010. The carbon intracellular quota (Q_C) of COP decreases as
539 well in the same regions. In the model, COP are the top predators. Their
540 intracellular carbon is directly related to the abundance and the carbon con-
541 tent of their prey, namely PHYL, CIL and HNF, with a preference for PHYL
542 over the two others. Because of strong phosphate limitation, abundance of
543 PHYL decreases (not shown), thereby limiting the number of prey available
544 for COP. The abundance of HNF and CIL also decreases, because of the
545 decrease in prey abundance. Such depletion of COP preys explains the de-
546 crease in COP biomass and abundance. A similar decreasing trend in COP
547 abundance due to increasing land-based N:P nutrient load has already been
548 observed in the San Francisco Estuary Bay Delta [56].

549 The decrease in COP abundance could have a significant effect on small
550 pelagic fishes such as sardine and anchovy. Copepods are indeed an impor-
551 tant link in marine food webs as prey for larger pelagic predators [57]. As
552 an example for the MS, [58] highlighted changes in biomass and fish mean
553 weight of sardine and anchovy in the Gulf of Lions around 2008. They showed
554 that the bottom-up control exerted by the plankton community played an
555 important role in those changes through a decrease in fish energy income.
556 They also showed that copepod abundance was directly linked to fish char-
557 acteristics (size and weight). Those results are difficult to reproduce with
558 our model since the Gulf of Lions is too small and too coastal an area with
559 regard to the size of the horizontal grid used, but they nevertheless seem to
560 confirm the general trend predicted by the model at larger scale. In the same
561 way, [59] showed a decrease in the mean length of sardines between 1996 and
562 2000 in the EMB. They pointed out that, among other factors, the quality
563 of their preys (among which copepods) could have decreased, leading to a
564 diminution of the size of sardine. This could be linked to the decrease in
565 COP abundance and Q_C predicted by the model (Q_C can indeed be seen as
566 a proxy of the nutritional quality of copepods and of their size) during the
567 same period and at least partially explained by the changes in river outputs

568 during the last decades. Furthermore, this suggests that COP abundance
569 and Q_C , as calculated by the model, could be used as one indicator among
570 others of the stocks and size of small pelagic fish in the MS in future modeling
571 scenarios.

572 5. Conclusion

573 This study provides new insight into the possible effects of changes in
574 nutrients provided by river inputs on the biogeochemistry of the MS over
575 the last decades. The strong reduction of PO_4 input by river and runoffs,
576 that occurred over the last decades in the EMB, induces a lowering of PO_4
577 availability in the sub-surface layer of this basin. An indirect consequence of
578 these strong variations in river inputs lies in the deepening of the top of the
579 phosphacline, as an adjustment of organisms and biogeochemical cycles to
580 the sub-surface PO_4 decrease. Since the position of the top of the nitracline
581 remains unchanged during that period, a shift between the two nutriclines
582 gradually emerges. This provides a new explanation for the shift between
583 the top of the nutriclines already mentioned in literature.

584 Another result provided by this modelling study concerns the rise of the
585 DOC concentration in the surface layer between 1985 and 2010, as evidenced
586 by the model in the EMB. The increasing P limitation in this basin results
587 in higher DOC accumulation in the surface layer, and therefore in increas-
588 ing DOC export fluxes over the last decades (not shown). This is of major
589 importance since DOC export represents the major part of the total (dis-
590 solved and particulate) carbon export in the MS, as has been evidenced in
591 Guyennon et al. [26].

592 Finally, we have highlighted the decline over the years 1985-2010 in cope-
593 pod abundance and intracellular content, the latter being a proxy of copepod
594 size. Those decreases could have had an important impact on the higher
595 trophic levels, and potentially provide an explanation to the smaller size of
596 sardine or anchovy recently observed in the MS. Broadly speaking, the model
597 underlines a trend towards the decline of large organisms in favour of small
598 organisms.

599 Overall, this study emphasizes the fact that the biogeochemistry of the
600 two basins of the MS did not exhibit the same response to the variation
601 of rivers inputs. Significant biogeochemical trends were simulated over the
602 period 1985-2010 in the eastern basin. By contrast, the WMB seems to be less
603 sensitive to changes in river inputs, but it is difficult within the scope of this
604 study, to determine whether this is due to the difference in the characteristics
605 of the two basins, or whether it is due to the lower variations observed in
606 river inputs in the WMB as compared to those in the EMB. It is probably
607 a combination of these two factors. It has also been evidenced that these
608 variations in river inputs and runoff may affect not only the coastal areas

609 and the direct vicinity of river mouths, but also offshore areas. Finally, the
610 magnitude of the biogeochemical changes induced by river inputs and runoff
611 alone over the last thirty years clearly calls for the use of realistic scenarios of
612 river inputs along with climate scenarios for coupled physical-biogeochemical
613 forecasts in the MS.

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622 Appendix A. New features of the biogeochemical model

623 Since the Alekseenko et al. [36] first version of the Eco3M-Med model,
624 some features of the original model were improved and some new features
625 were introduced to correct the model major flaws or to add some realism
626 to the model. In [26], it has been shown that the position of the nitracline
627 and the phosphacline were not well represented by the model (Figures S3
628 and S4 in the Supplement). A deep work has then been undertaken on the
629 remineralization process which was up to now function of the N:C and P:C
630 ratios in bacteria. In the present version of the model, the outflow of N
631 and P associated with the uptake of dissolved organic matter (DOM) is still
632 function of the N:C and P:C intracellular ratios (i.e. it is maximum when the
633 N:C or the P:C ratio takes its maximum value), but the intracellular carbon
634 quota Q_C will redirect this outflow either towards the DOM pool when Q_C
635 is high or towards the mineral pool otherwise. Concerning parameters, in
636 [39], the half-saturation constants (Ks) for the DOP uptake were divided by
637 1 order of magnitude in order to better match in situ data. However, Ks
638 values in the original model were all calculated using a similar method and
639 mechanistic considerations based on the shape of cells and the control of the
640 uptake rate by molecular diffusion at low nutrient concentrations. Here, we
641 consider a more realistic cells shape to derive new values of the Ks for NO_3 ,
642 NH_4 , PO_4 , LDON and LDOP involved in the model in a similar way. Using
643 the diffusion flux established by Kiorboe [60] for cigare-shaped (ellipsoid)
644 cells, we derive the following relationship between the maximum uptake rate
645 (V^{max}) of a given nutrient and the associated half-saturation constant as
646 done in Mauriac et al. [35]:

$$K_s = \frac{V^{max} \text{Ln}(\frac{2a}{b})}{4\pi \mathcal{D} a} \quad (\text{A.1})$$

647 where a and b stand for the semiaxes of the cigare-shaped ellipsoid ($a^2 \gg b^2$)
648 and \mathcal{D} for the molecular diffusion coefficient (see Tab. Appendix A).

Variable	Value
\mathcal{D}_{NO_3} diffusion coefficients [$m^2.s^{-1}$]	$1.7 \cdot 10^{-9}$
\mathcal{D}_{PO_4} diffusion coefficients [$m^2.s^{-1}$]	$7.5 \cdot 10^{-10}$
\mathcal{D}_{NH_4} diffusion coefficients [$m^2.s^{-1}$]	$1.9 \cdot 10^{-9}$
\mathcal{D}_{DON} diffusion coefficients [$m^2.s^{-1}$]	$3.0 \cdot 10^{-10}$
\mathcal{D}_{DOP} diffusion coefficients [$m^2.s^{-1}$]	$3.0 \cdot 10^{-10}$

649 Table Appendix A gives the values for a associated with each functional
650 group. The ratio a/b has been set to 10. Finally, the K_s values derived from
651 Eq. A.1 provide a consistent set of K_s values and they were all multiplied
by the same number (50) to match the range given by literature.

Variable	PHYL	PHYS	BAC
a Semi major axis of the ellipsoid [μm]	$2 \cdot 10^{-5}$	$2.5 \cdot 10^{-6}$	$4 \cdot 10^{-7}$

652

653 Other parameter values were modified (see table A.3), either to improve
654 the consistency between the model parameters (for photosynthetic param-
655 eters), or to better integrate the knowledge from literature (hydrolysis rates),
656 or to improve the model outputs (costs of DOC uptake, sinking rates).

Table A.3: Other parameters

Variable name	Value
PHYL PSII cross section [$\text{m}^2.\text{J}^{-1}$]	2.5
PHYS PSII cross section [$\text{m}^2.\text{J}^{-1}$]	2.0
MOPL specific hydrolysis rate [d^{-1}]	15
MOPS specific hydrolysis rate [d^{-1}]	7.5
Sinking rate of MOPL [$m.d^{-1}$]	50
Sinking rate of MOPS [$m.d^{-1}$]	2.0
Cost of DOC uptake	0.15
Cost of SLDOC uptake	0.25

657 **References**

- 658 [1] T. Moutin, F. Van Wambeke, L. Prieur, Introduction to the Biogeo-
659 chemistry from the Oligotrophic to the Ultraoligotrophic Mediterranean
660 (BOUM) experiment, *Biogeosciences* 9 (2012) 3817–3825.
- 661 [2] M. Pujó-Pay, P. Conan, L. Oriol, V. Cornet-Barthaux, C. Falco, J. F.
662 Ghiglione, C. Goyet, T. Moutin, L. Prieur, Integrated survey of elemental
663 stoichiometry (C, N, P) from the western to eastern Mediterranean
664 Sea, *Biogeosciences* 8 (2011) 883–899.
- 665 [3] G. Crispi, R. Mosetti, C. Solidoro, A. Crise, Nutrients cycling in
666 Mediterranean basins: the role of the biological pump in the trophic
667 regime, *Ecological Modelling* 138 (2001) 101–114.
- 668 [4] T. Moutin, P. Raimbault, Primary production, carbon export and nu-
669 trients availability in western and eastern Mediterranean Sea in early
670 summer 1996 (MINOS cruise), *Journal of Marine Systems* 34 (2002)
671 273–288.
- 672 [5] I. Siokou-Frangou, U. Christaki, M. G. Mazzocchi, M. Montresor,
673 M. Ribera D’Alcala, D. Vaque, A. Zingone, Plankton in the open
674 mediterranean Sea: A review, *Biogeosciences* 7 (2010) 1543–1586.
- 675 [6] M. D. Krom, S. Brenner, L. I. Gordon, Phosphorus limitation of pri-
676 mary productivity in the eastern Mediterranean Sea, *Limnology and*
677 *Oceanography* 36 (1991).
- 678 [7] F. Diaz, P. Raimbault, B. Boudjellal, N. Garcia, T. Moutin, Early spring
679 phosphorus limitation of primary productivity in a NW Mediterranean
680 coastal zone (Gulf of Lions), *Marine Ecology Progress Series* 211 (2001)
681 51–62.
- 682 [8] T. F. Thingstad, M. D. Krom, R. F. Mantoura, G. A. F. Flaten,
683 S. Groom, B. Herut, N. Kress, C. S. Law, A. Pasternak, P. Pitta,
684 S. Psarra, F. Rassoulzadegan, T. Tanaka, A. Tselepides, P. Wassmann,
685 E. M. S. Woodward, C. W. Riser, G. Zodiatis, T. Zohary, Nature of P
686 limitation in the ultraoligotrophic Eastern Mediterranean. Supporting
687 Material, *Water* (2002) 1–10.

- 688 [9] F. Van Wambeke, U. Christaki, A. Giannakourou, T. Moutin, K. Sou-
689 vemerzoglou, Longitudinal and vertical trends of bacterial limitation by
690 phosphorus and carbon in the Mediterranean Sea, *Microbial Ecology* 43
691 (2002) 119–133.
- 692 [10] T. F. Thingstad, M. D. Krom, R. F. C. Mantoura, Nature of P limitation
693 in the ultraoligotrophic Eastern Mediterranean, *SCIENCE* (2005).
- 694 [11] T. Tanaka, T. F. Thingstad, U. Christaki, J. Colombet, V. Cornet-
695 Barthaux, C. Courties, J. D. Grattepanche, A. Lagaria, J. Nedoma,
696 L. Oriol, S. Psarra, M. Pujo-Pay, F. Van Wambeke, Lack of P-limitation
697 of phytoplankton and heterotrophic prokaryotes in surface waters of
698 three anticyclonic eddies in the stratified Mediterranean Sea, *Biogeo-*
699 *sciences* 8 (2011) 525–538.
- 700 [12] K. Leblanc, J. Arístegui, L. Armand, P. Assmy, B. Beker, A. Bode,
701 E. Breton, V. Cornet, J. Gibson, M.-P. Gosselin, E. Kopczynska,
702 H. Marshall, J. Peloquin, S. Piontkovski, A. J. Poulton, B. Quéguiner,
703 R. Schiebel, R. Shipe, J. Stefels, M. A. van Leeuwe, M. Varela, C. Wid-
704 dicombe, M. Yallop, A global diatom database – abundance, biovolume
705 and biomass in the world ocean, *Earth System Science Data* 4 (2012)
706 149–165.
- 707 [13] W. Broecker, T. Peng, *Tracers in the Sea*. (1982) 1–690.
- 708 [14] N. V. D. Broeck, T. Moutin, Phosphate in the sediments of the Gulf of
709 Lions (NW Mediterranean Sea), relationship with input by the river
710 Rhone, *Hydrobiologia* (2004) 85–94.
- 711 [15] W. Ludwig, E. Dumont, M. Meybeck, S. Heussner, River discharges of
712 water and nutrients to the Mediterranean and Black Sea: Major drivers
713 for ecosystem changes during past and future decades?, *Progress in*
714 *Oceanography* 80 (2009) 199–217.
- 715 [16] J. P. Béthoux, P. Morin, D. P. Ruiz-Pino, Temporal trends in nu-
716 trient ratios: Chemical evidence of Mediterranean ecosystem changes
717 driven by human activity, *Deep-Sea Research Part II: Topical Studies*
718 *in Oceanography* 49 (2002) 2007–2016.
- 719 [17] I. E. Huertas, A. F. Ríos, J. García-Lafuente, G. Navarro, A. Makaoui,
720 A. Snchez-Romn, S. Rodriguez-Galvez, A. Orbi, J. Ruíz, F. F. Pérez,

- 721 Atlantic forcing of the Mediterranean oligotrophy, *Global Biogeochem-*
722 *ical Cycles* 26 (2012) 1–9.
- 723 [18] K. I. Kopasakis, A. N. Georgoulas, P. B. Angelidis, N. E. Kotsovinos,
724 Simulation of the long term fate of water and pollutants, transported
725 from the Dardanelles plume into the North Aegean Sea, *Applied Ocean*
726 *Research* 37 (2012) 145–161.
- 727 [19] W. Ludwig, A. F. Bouwman, E. Dumont, F. Lespinas, Water and nu-
728 trient fluxes from major Mediterranean and Black Sea rivers: Past and
729 future trends and their implications for the basin-scale budgets, *Global*
730 *Biogeochemical Cycles* 24 (2010) 1–14.
- 731 [20] D. Macías, A. P. Martín, J. García-Lafuente, C. M. García, A. Yool,
732 M. Bruno, A. Vázquez-Escobar, A. Izquierdo, D. V. Sein, F. Echevarría,
733 Analysis of mixing and biogeochemical effects induced by tides on
734 the Atlantic-Mediterranean flow in the Strait of Gibraltar through a
735 physical-biological coupled model, *Progress in Oceanography* 74 (2007)
736 252–272.
- 737 [21] H. R. Powley, M. D. Krom, P. Van Cappellen, Understanding the unique
738 biogeochemistry of the Mediterranean Sea: Insights from a coupled phos-
739 phorus and nitrogen model, *Global Biogeochemical Cycles* 31 (2017)
740 1010–1031.
- 741 [22] C. Richon, J. C. Dutay, F. Dulac, R. Wang, Y. Balkanski, P. Nabat,
742 O. Aumont, K. Desboeufs, B. Laurent, C. Guieu, P. Raimbault, J. Beu-
743 vier, Modeling the impacts of atmospheric deposition of nitrogen and
744 desert dust-derived phosphorus on nutrients and biological budgets of
745 the Mediterranean Sea, *Progress in Oceanography* 163 (2018) 21–39.
- 746 [23] J.-Y. Moon, K. Lee, T. Tanhua, N. Kress, I.-N. Kim, Temporal nutrient
747 dynamics in the Mediterranean Sea in response to anthropogenic inputs,
748 *Geophysical Research Letters* (2016) 5243–5251.
- 749 [24] M. D. Krom, K.-c. Emeis, P. V. Cappellen, Why is the Eastern Mediter-
750 ranean phosphorus limited?, *Progress in Oceanography* 85 (2010) 236–
751 244.

- 752 [25] Z. Markaki, M. D. Loÿe-Pilot, K. Violaki, L. Benyahya, N. Mihalopoulos,
753 Variability of atmospheric deposition of dissolved nitrogen and phospho-
754 rus in the Mediterranean and possible link to the anomalous seawater
755 N/P ratio, *Marine Chemistry* 120 (2010) 187–194.
- 756 [26] A. Guyennon, M. Baklouti, F. Diaz, J. Palmieri, J. Beuvier,
757 C. Lebaupin-Brossier, T. Arsouze, K. Beranger, J. C. Dutay, T. Moutin,
758 New insights into the organic carbon export in the Mediterranean Sea
759 from 3-D modeling, *Biogeosciences* 12 (2015) 7025–7046.
- 760 [27] C. Ulses, P.-A. Auger, K. Soetaert, P. Marsaleix, F. Diaz, L. Coppola,
761 M. M.J., F. Kessouri, C. Estournel, Budget of organic carbon in the
762 North-Western Mediterranean open sea over the period 2004-2008 using
763 3-D coupled physical-biogeochemical modeling, *Journal of Geophysical*
764 *Research: Oceans* (2016) 1–14.
- 765 [28] P. Lazzari, C. Solidoro, S. Salon, G. Bolzon, Spatial variability of phos-
766 phate and nitrate in the Mediterranean Sea: A modeling approach,
767 *Deep-Sea Research Part I: Oceanographic Research Papers* 108 (2016)
768 39–52.
- 769 [29] D. Macias, E. Garcia-gorrioz, C. Piroddi, A. Stips, Biogeochemical con-
770 trol of marine productivity in the Mediterranean Sea during the last 50
771 years, *Global Biogeochemical Cycles* (2014) 897–907.
- 772 [30] H. R. Powley, M. D. Krom, K. C. Emeis, P. Van Cappellen, A bio-
773 geochemical model for phosphorus and nitrogen cycling in the Eastern
774 Mediterranean Sea: Part 2: Response of nutrient cycles and primary
775 production to anthropogenic forcing: 1950-2000., *Journal of Marine*
776 *Systems* 139 (2014) 420–432.
- 777 [31] G. team Madec, NEMO, NEMO ocean engine (2016).
- 778 [32] M. Hamon, J. Beuvier, S. Somot, J.-m. Lellouche, E. Greiner, G. Jordà,
779 M.-n. Bouin, T. Arsouze, F. Sevault, M. Hamon, J. Beuvier, S. Somot,
780 J.-m. Lellouche, E. Greiner, M. Hamon, J. Beuvier, S. Somot, J.-m.
781 Lellouche, E. Greiner, G. Jordà, Design and validation of MEDRYS
782 , a Mediterranean Sea reanalysis over the period 1992 – 2013, *Ocean*
783 *Science* (2016).

- 784 [33] M. Baklouti, V. Faure, L. Pawlowski, A. Sciandra, Investigation and
785 sensitivity analysis of a mechanistic phytoplankton model implemented
786 in a new modular numerical tool (Eco3M) dedicated to biogeochemical
787 modelling, *Progress in Oceanography* 71 (2006) 34–58.
- 788 [34] M. Baklouti, F. Diaz, C. Pinazo, V. Faure, B. Quéguiner, Investiga-
789 tion of mechanistic formulations depicting phytoplankton dynamics for
790 models of marine pelagic ecosystems and description of a new model,
791 *Progress in Oceanography* 71 (2006) 1–33.
- 792 [35] R. Mauriac, T. Moutin, M. Baklouti, Accumulation of DOC in Low
793 Phosphate Low Chlorophyll (LPLC) area : is it related to higher
794 production under high N : P ratio ?, *Biogeosciences* (2011).
- 795 [36] E. Alekseenko, V. Raybaud, B. Espinasse, F. Carlotti, B. Queguiner,
796 B. Thouvenin, P. Garreau, M. Baklouti, Seasonal dynamics and stoi-
797 chiometry of the planktonic community in the NW Mediterranean Sea:
798 A 3D modeling approach, *Ocean Dynamics* 64 (2014) 179–207.
- 799 [37] A. Gimenez, M. Baklouti, S. Bonnet, T. Moutin, N. Caledonia, Bio-
800 geochemical fluxes and fate of diazotroph-derived nitrogen in the food
801 web after a phosphate enrichment: modeling of the VAHINE mesocosms
802 experiment (2016) 5103–5120.
- 803 [38] E. Alekseenko, M. Baklouti, F. Carlotti, Main factors favoring *Mne-*
804 *miopsis leidyi* individuals growth and population outbreaks : a mod-
805 elling approach, *Journal of Marine Systems* (2019).
- 806 [39] A. Gimenez, M. Baklouti, T. Wagener, T. Moutin, Diazotrophy as the
807 main driver of the oligotrophy gradient in the western tropical South
808 Pacific Ocean: Results from a one-dimensional biogeochemical-physical
809 coupled model, *Biogeosciences* 15 (2018).
- 810 [40] J. Beuvier, C. L. Brossier, K. Béranger, R. Bourdallé-badie, C. Deltel,
811 Y. Drillet, N. Ferry, F. Lyard, J. Beuvier, C. L. Brossier, K. Béranger,
812 T. Arsouze, R. Bourdallé, MED12, oceanic component for the modeling
813 of the regional Mediterranean earth system. (2012).
- 814 [41] M. Fichaut, G. Maria-jesus, G. Alessandra, I. Athanasia, K. Alexander,
815 Achimer MEDAR / MEDATLAS 2002 : A Mediterranean and Black Sea

- 816 database for operational oceanography Elsevier Oceanography Series 69
817 (2003).
- 818 [42] E. V. Stanev, J. A. Simeonov, E. L. Peneva, Ventilation of Black Sea
819 pycnocline by the Mediterranean plume, *Journal of Marine Systems* 31
820 (2001) 77–97.
- 821 [43] J. Palmiéri, J. C. Orr, J.-C. Dutay, K. Béranger, A. Schneider, J. Beu-
822 vier, S. Somot, Simulated anthropogenic CO₂ storage and acidification
823 of the, *Biogeosciences* (2015) 781–802.
- 824 [44] A. Guyennon, Etude de l’exportation de carbone organique à
825 l’échelle de la mer Méditerranée à l’aide de la modélisation couplée
826 physique/biogéochimie, Ph.D. thesis, Aix Marseille, 2015.
- 827 [45] G. Volpe, R. Santoleri, V. Vellucci, M. Ribera d’Alcalà, S. Marullo,
828 F. D’Ortenzio, The colour of the Mediterranean Sea: Global versus
829 regional bio-optical algorithms evaluation and implication for satellite
830 chlorophyll estimates, *Remote Sensing of Environment* 107 (2007) 625–
831 638.
- 832 [46] L. Coppola, The DYFAMED time series have been provided by the
833 Oceanological Observatory of Villefranche-sur-Mer (L.Coppola). This
834 project is funded by CNRS-INSU and ALLENVI through the MOOSE
835 observing network, 1991.
- 836 [47] K. E. Taylor, Summarizing multiple aspects of model performance in a
837 single diagram, *Journal of Geophysical Research* 106 (2001) 7183–7192.
- 838 [48] A. Aminot, R. Kérouel, Dosage automatique des nutriments dans les
839 eaux marines : méthodes en flux continu., Ifremer, 2007.
- 840 [49] N. Bahamón, Z. Velásquez, A. Cruzado, Chlorophyll a and nitrogen
841 flux in the tropical North Atlantic Ocean, *Deep-Sea Research Part I:
842 Oceanographic Research Papers* 50 (2003) 1189–1203.
- 843 [50] T. Ozer, I. Gertman, N. Kress, J. Silverman, B. Herut, Interannual
844 thermohaline (1979 – 2014) and nutrient (2002 – 2014) dynamics in
845 the Levantine surface and intermediate water masses , SE Mediterranean
846 Sea, *Global and Planetary Change* 151 (2017) 60–67.

- 847 [51] T. R. Anderson, D. O. Hessen, J. J. Elser, J. Urabe, T. R. Anderson,
848 D. O. Hessen, J. J. Elser, J. Urabe, Metabolic Stoichiometry and the
849 Fate of Excess Carbon and Nutrients in Consumers, American society
850 of naturalists 165 (2005) 1–15.
- 851 [52] D. L. Kirchman, Microbial Ecology of the Oceans, Second Edition, 2008.
- 852 [53] E. Litchman, Klausmeier, A. Christopher, Trait-Based Community
853 Ecology of Phytoplankton Trait-Based Community Ecology of Phyto-
854 plankton, Annual Review of Ecology Evolution and Systematics (2008).
- 855 [54] B. Klein, W. Roether, N. Kress, B. B. Manca, M. Ribera, E. Souverme-
856 zoglou, A. Theocharis, G. Civitarese, A. Luchetta, Accelerated oxygen
857 consumption in eastern Mediterranean deep waters following the recent
858 changes in thermohaline circulation, Journal of Geophysical Research
859 108 (2003).
- 860 [55] B. Coste, P. L. Corre, H. J. Minas, Re-evaluation of the nutrient ex-
861 changes in the strait of gibraltar, Deep Sea Research Part A, Oceanog-
862 raphic Research Papers 35 (1988) 767–775.
- 863 [56] R. C. Dugdale, F. P. Wilkerson, V. E. Hogue, A. Marchi, The role of
864 ammonium and nitrate in spring bloom development in San Francisco
865 Bay 73 (2007) 17–29.
- 866 [57] J. T. Turner, The importance of small planktonic copepods and their
867 roles in pelagic marine food webs, Zoological Studies 43 (2004) 255–266.
- 868 [58] C. Saraux, E. Van Beveren, P. Brosset, Q. Queiros, J. H. Bourdeix,
869 G. Dutto, E. Gasset, C. Jac, S. Bonhommeau, J. M. Fromentin, Small
870 pelagic fish dynamics: A review of mechanisms in the Gulf of Lions,
871 Deep-Sea Research Part II: Topical Studies in Oceanography (2018).
- 872 [59] P. Voulgaridou, K. I. Stergiou, Trends in various biological parameters
873 of the European sardine , *Sardina pilchardus* (Walbaum , 1792), in the
874 Eastern Mediterranean Sea, Scientia Marina 67 (2003) 269–280.
- 875 [60] T. Kiorboe, A Mechanistic Approach to Plankton Ecology, Princeton
876 University Press, 2008.