

Nutrients cycling in Mediterranean basins: the role of the biological pump in the trophic regime

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Abstract

The Mediterranean Sea is generally characterized by the presence of oligotrophic conditions, which are more pronounced in its eastern part. The effects of physical and biological fluxes on the nitrogen and phosphorus distributions are here addressed by means of a box model. Numerical simulations obtained with realistic fluxes, as well as the analysis of the asymptotic behavior of the model support the hypothesis that inverse estuarine circulation is not sufficient to explain the oligotrophic regime. Conversely, it appears that the downward fluxes of organic matter play a major role in sustaining and stabilizing the oligotrophy as found in the observations. Indeed the trophic gradients between the western and the eastern Mediterranean arise as a consequence of the unbalance of the loads emitted in the basins, with greater inputs into the western, but, in any case, they are maintained in the long run by the biological pump. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Nitrogen; Phosphorus; Mediterranean Sea; Box model; Biological pump

1. Introduction

The Mediterranean, an elongated, virtually land-locked, semi-enclosed sea, is one of the largest nutrient-depleted area in the world (Thomsen, 1931; McGill, 1961). Coastal areas directly interact with the pelagic environment, since the coastal shelves are relatively narrow, with some but important exceptions such as the Catalan Sea and the Tunisine shelf. A well developed shelf is present also in the regional seas, Adriatic and Aegean, which differ from the rest

of the basin also because they present mesotrophic or eutrophic conditions, as a consequence of the input of macronutrient received by the Po river, in the case of the former, and by the Black Sea, in the case of the latter.

The Mediterranean has relevant exchanges only at the Gibraltar Strait and is splitted in two basins by the Sicily Strait, a shallow sill that substantially decouples its eastern and western parts. On the interannual, or longer, scale there is a large variability both in the dynamics (Röther et al., 1996) and in the biochemical budgets (Béthoux et al., 1992). The Mediterranean response is relatively fast compared to the ocean and this suggests that physical/ecological interactions at basin scale have a profound

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influence in determining the evolution of the ecosystem.

The exchanges at Gibraltar Strait compensate the slightly deficient water and heat budgets, which drive the thermohaline cell controlling the upper circulation in Mediterranean (Gilman and Garrett, 1994). Thus the surface layers are affected by the modification and redistribution of the Atlantic Water (AW) inflow into the western

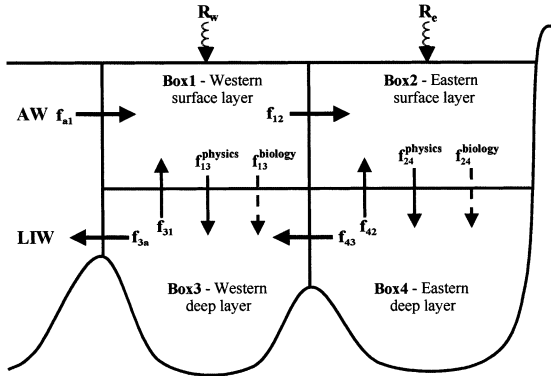


Fig. 1. Schematic diagram of the boxes and fluxes in the model: BOX 1 is the western Mediterranean surface layer, BOX 2 eastern Mediterranean surface layer, BOX 3 western Mediterranean deep layer, BOX 4 eastern Mediterranean deep layer. Bold arrows represent water fluxes inside the basin, or between the basin and the Atlantic Ocean. Bent arrows represent nitrogen and phosphorus inputs from western, R_w , and eastern Mediterranean rivers, R_e . The fluxes $f_{13}^{physics}$, $f_{24}^{physics}$ and $f_{13}^{biology}$, $f_{24}^{biology}$ are referred to in the text respectively as f_{13}^p , f_{24}^p and f_{13}^b , f_{24}^b .

Table 1
Biogeochemical parameters

Parameter	Definition	Unit	Value
d	Phytoplankton mortality	s^{-1}	5.55×10^{-7}
β_N	Organic fraction of total nitrogen		0.2
β_P	Organic fraction of total phosphorus		0.33
r_N	Regeneration rate of nitrogen	s^{-1}	1.18×10^{-6}
r_P	Regeneration rate of phosphorus	s^{-1}	2.36×10^{-6}
w_D	Detritus sinking velocity	cm/s	0.0058

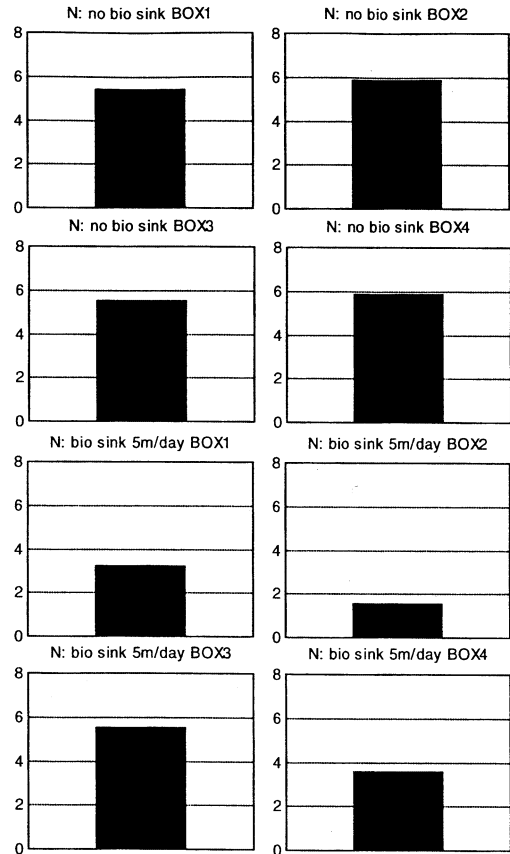


Fig. 2. Total nitrogen equilibrium concentrations, in $\mu\text{M/l}$, without (high plate) and with biogenic fluxes (low plate) as obtained in the four boxes, upper layers and deeper layers, in the western and eastern boxes.

and the eastern basins, while the deeper layers are connected through an opposite flux of the outflowing Levantine Intermediate Water (LIW). This mechanism, known as the inverse estuarine circulation, is thought to be the reason of the nutrient-depleted Mediterranean (Redfield et al., 1963). In fact, the amount of nutrients flowing in the surface layer from the Atlantic Ocean is smaller than the one flowing out in the bottom layer. This loss is dynamically compensated by anthropic and natural sources. Analogous reasons are also used to explain the permanence of the westerly increasing trophic gradient, which is present both in upper and in deeper layers.

The role played by the biotic component, through the so-called biological pump, should also be taken into account. The detritus, fed by planktonic biota is subject to sinking phenomena, potentially able to alter the mass distribution along the basin. Indeed, yearly simulations (Crise et al., 1999) showed that by increasing the downward flow of matter related to sinking velocity, the magnitude of the trophic gradient increased as well.

In this article the influences of the inverse estuarine circulation, of the nutrients river inputs and of the biological pump on the oligotrophy and on the trophic gradients in the Mediterranean Sea are investigated by means of a box model, designed

along the Eppley and Peterson (1979) guidelines on the balance of the vertical fluxes inside the basin. The aim is to give a basis to an explanation of the trophic gradients origin and persistence. In fact, the resulting simplification in the parameterization of the transport processes permits us to analyze the long-term evolution, by performing a study of the asymptotic behavior of the system with respect to the variation of the parameters of the model.

The biological cycle is described by three-state variables, nutrient–plankton–detritus, an aggregation already used for the three-dimensional modeling of the nitrogen cycles in Mediterranean (Crise et al., 1998). This structure will be applied

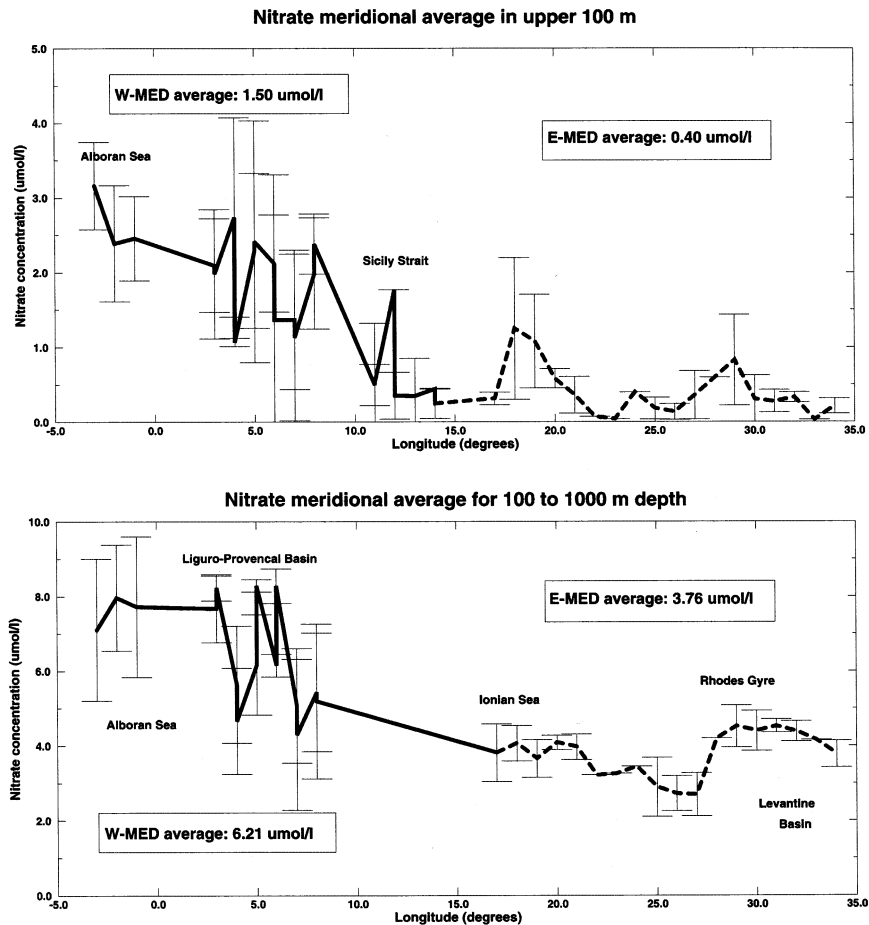


Fig. 3. Nitrates data meridional averages, in $\mu\text{M/l}$, in the western and eastern Mediterranean Sea for the upper, 100 m, layer (high plate) and for the deeper, 100–1000 m, layer (low plate).

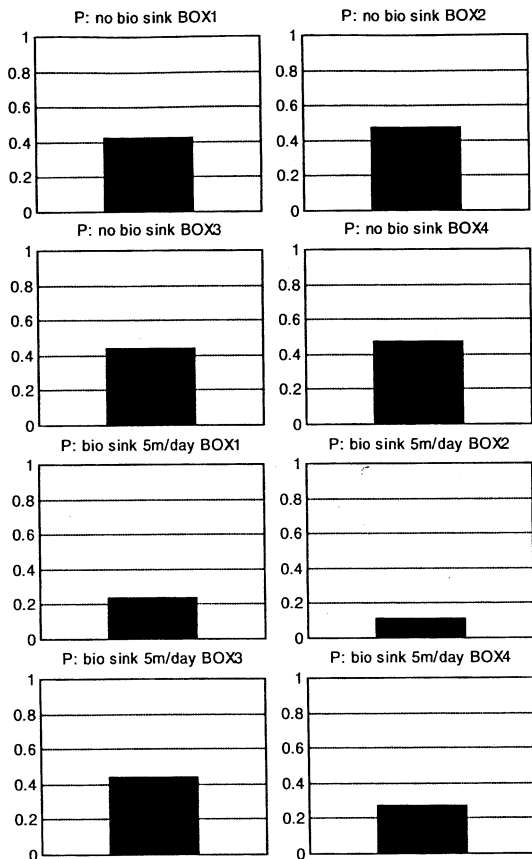


Fig. 4. Total phosphorus equilibrium concentrations, in $\mu\text{M/l}$, without (high plate) and with biogenic fluxes (low plate) as obtained in the four boxes, upper layers and deeper layers, in the western and eastern ones.

in this article also to describe the phosphorus cycle.

The coupling of nitrogen and phosphorus cycles, and the effects of multi-nutrient limitation are not addressed in the present work since that would have required a parameterization too complex to permit an analytical discussion of the long term evolution of the system, such as that considered here. On one hand, interaction studies (Crispi et al., 1998) of these biotic processes in Mediterranean are in progress; on the other, the choice of disregarding these processes is commonly adopted in ocean ecosystem model-

ing when applied to biogeochemical scales (Najjar et al., 1992).

The advective, diffusive and convective mass fluxes are imposed at the interfaces of four boxes, namely an upper and a bottom box for each of the two basins, describing the averaged biogeochemical processes in the western and eastern Mediterranean. The adoption of a box model approach may seem a rather strong approximation, but the analysis of the non-linearities coming from the interaction in ocean among physical dynamics and biogeochemical processes in a three-dimensional quasi-geostrophic framework (Smith et al., 1996), shows that, from a biogeochemical point of view, the averaged effects of basin dynamics can be successfully modeled by a properly one-dimensional averaged representation of the processes.

In Section 2 the biological model is described and its forcing through the fluxes across the boxes is defined. In Section 3 the forcing functions are discussed, the parameterization used is introduced and the comparison data are detailed. Section 4 follows, regarding comparison with data acquired in the Mediterranean. Section 5 summarizes the consequences in terms of biogeochemistry of the Mediterranean and its possible applications.

2. Definition of the box model

The basin is divided into four boxes, two boxes for the euphotic layers of the western and the eastern Mediterranean, and two boxes for the aphotic ones. Water fluxes are prescribed in order to simulate the inverse estuarine circulation and the transport phenomena occurring along the vertical.

The schematic diagram of the box model and of the fluxes used is shown in Fig. 1. The equations of the model for the total tracer concentrations inside each box therefore read as

$$V \frac{d}{dt} \Sigma = F \Sigma + L, \quad (1)$$

where

$$\Sigma(t) = \begin{bmatrix} \Sigma_1 \\ \Sigma_2 \\ \Sigma_3 \\ \Sigma_4 \end{bmatrix},$$

are the total concentrations in each box,

$$L = \begin{bmatrix} L_1 = f_{a1}\Sigma_a + R_w \\ L_2 = R_e \\ 0 \\ 0 \end{bmatrix},$$

are the loads, the matrix F of the water fluxes is

$$F = \begin{bmatrix} -(f_{12} + f_{13}) & 0 & f_{31} & 0 \\ f_{12} & -f_{24} & 0 & f_{42} \\ f_{13} & 0 & -(f_{31} + f_{3a}) & f_{43} \\ 0 & f_{24} & 0 & -(f_{42} + f_{43}) \end{bmatrix},$$

and the matrix V of the volumes is is

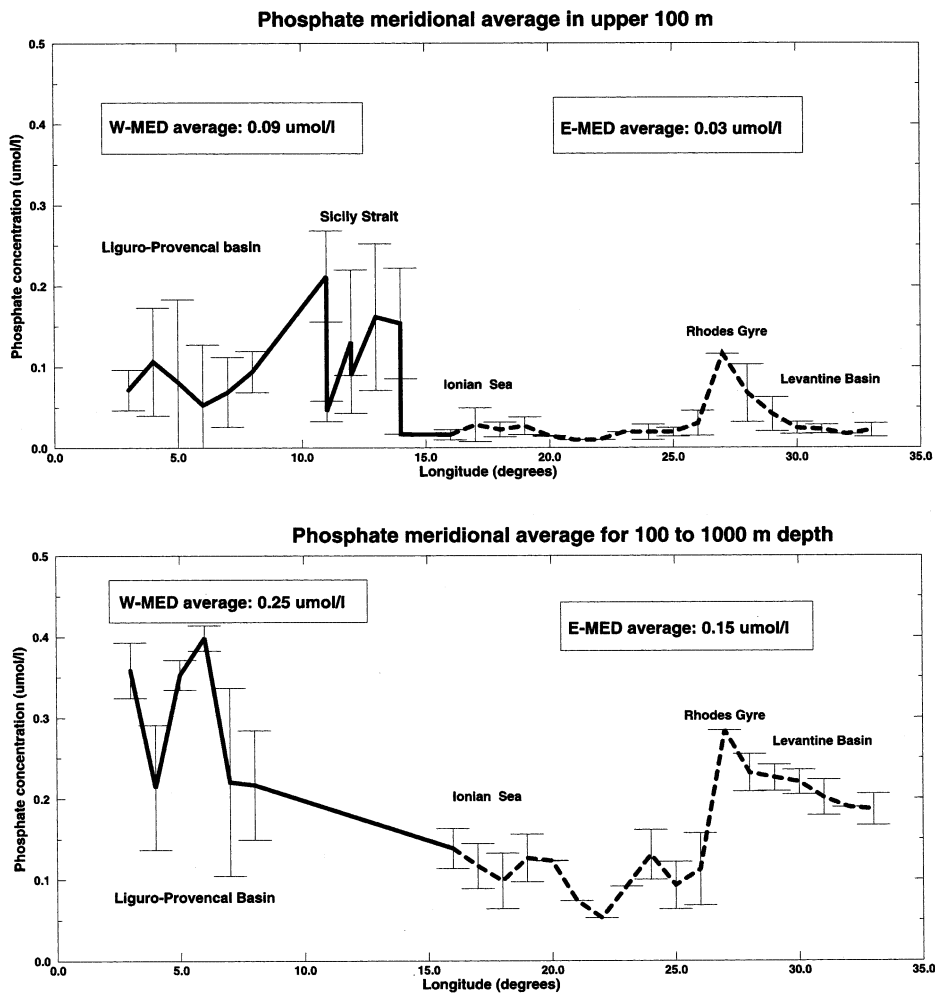


Fig. 5. Phosphates data meridional averages, in $\mu\text{M/l}$, in the western and eastern Mediterranean Sea for the upper, 100 m, layer (high plate) and for the deeper, 100–1000 m, layer (low plate).

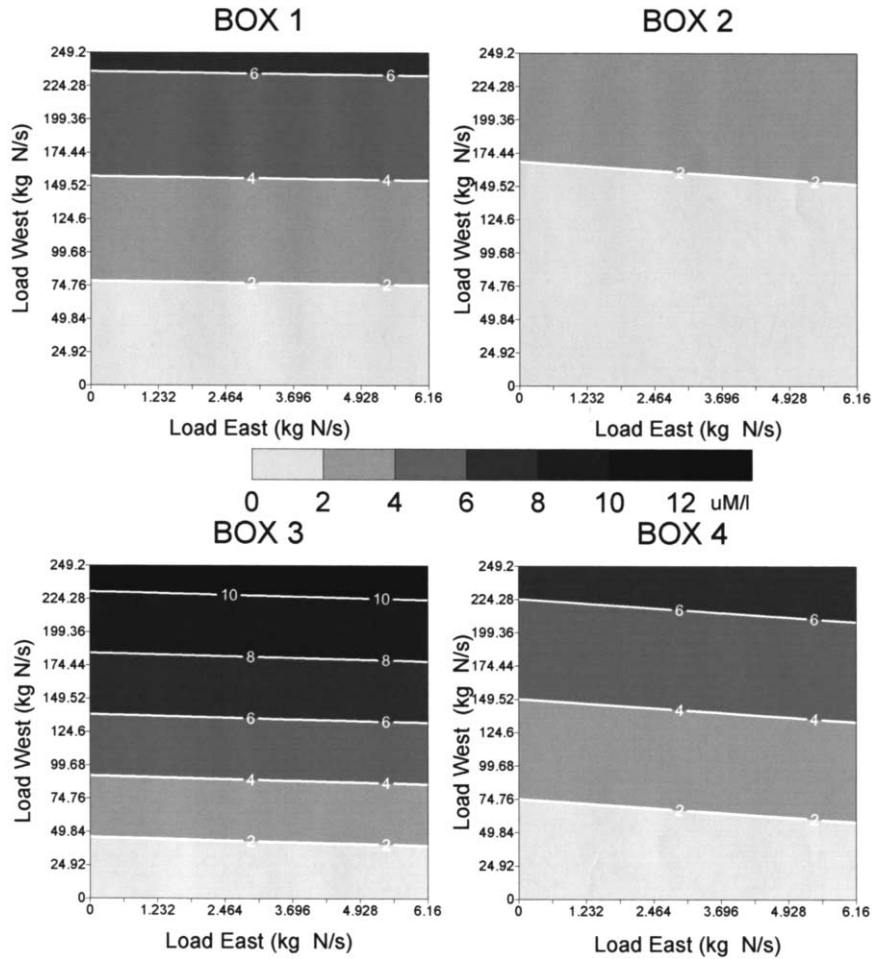


Fig. 6. Total nitrogen equilibrium concentrations, in $\mu\text{M/l}$, in the four boxes changing the loads, kg N/s, in the eastern basin (abscissa) and in the western basin (ordinates) from 0% to 200% of the reference values.

$$V = \begin{bmatrix} V_1 & 0 & 0 & 0 \\ 0 & V_2 & 0 & 0 \\ 0 & 0 & V_3 & 0 \\ 0 & 0 & 0 & V_4 \end{bmatrix}.$$

Here f_{ij} indicates the water flux between the i th box and the j th box, R_w and R_e the total nitrogen and phosphorus inputs in the system from the rivers in the western and eastern Mediterranean, f_{a1} is the water flux flowing into the basin across the Gibraltar Strait, Σ_a is the concentration of such a water, f_{3a} is the outflow from the Mediterranean into the Atlantic Ocean, and V_i is the volume of the i th box.

The downward fluxes f_{13} and f_{24} are sums of two different contributions. In fact, besides the flux due to physical processes, such as advection and convection, an additional flux due to the sinking of particulate matter is present. This flux can be thought of as a measure of the biological activity.

These fluxes therefore are

$$f_{13} = f_{13}^p + f_{13}^b,$$

for the western basin and

$$f_{24} = f_{24}^p + f_{24}^b,$$

for the eastern basin, where f_{13}^p and f_{24}^p are the physical fluxes and f_{13}^b and f_{24}^b are the biological ones.

The assessment of the biological fluxes requires the parameterization of the detritus compartment, D , whose general equation is

$$\frac{\partial D}{\partial t} = -(\vec{u} \cdot \nabla)D - w_D \frac{\partial D}{\partial z} + K_H \nabla_h^2 D + \frac{\partial}{\partial z} \left(K_V \frac{\partial D}{\partial z} \right) - rD + dP, \quad (2)$$

where P is the phytoplankton, \vec{u} is the water velocity, ∇_h^2 is the horizontal Laplace operator. K_H and K_V are the horizontal and vertical turbulent diffusion coefficients, r is the regeneration rate, d is the phytoplankton mortality, and w_D is the detritus sinking velocity.

In the solution of this equation the following assumptions are introduced:

1. the system (1) is quasi-stationary on average when considering decadal evolution, such that the fluxes are well represented by the average multiannual fluxes and equation (2) is quasi-stationary as well;
2. there is large scale spatial homogeneity, such that the loads give an averaged effect upon the concentrations of both basins;
3. the residence times are longer than the seasonal cycles inside the basins, such that an annual average of biomass and production is taken into account;

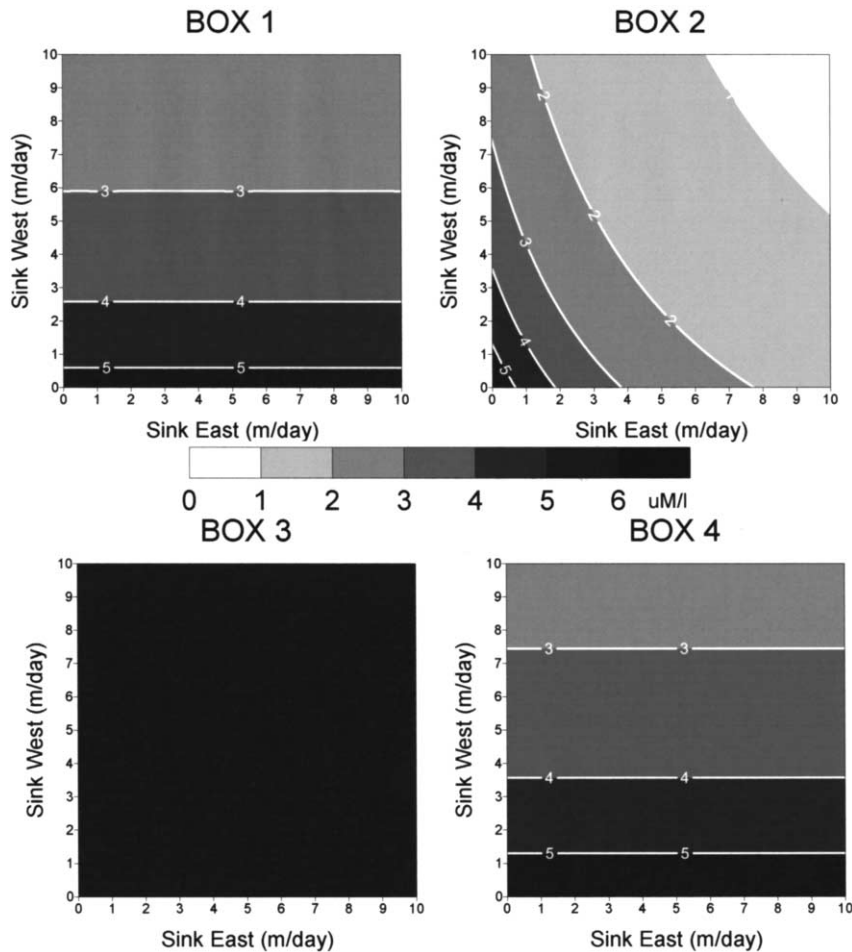


Fig. 7. Total nitrogen equilibrium concentrations, in $\mu\text{M/l}$, in the four boxes changing detritus sinking velocity, m/day, in the eastern basin (abscissa) and in the western basin (ordinates) from 0% to 200% of the reference value.

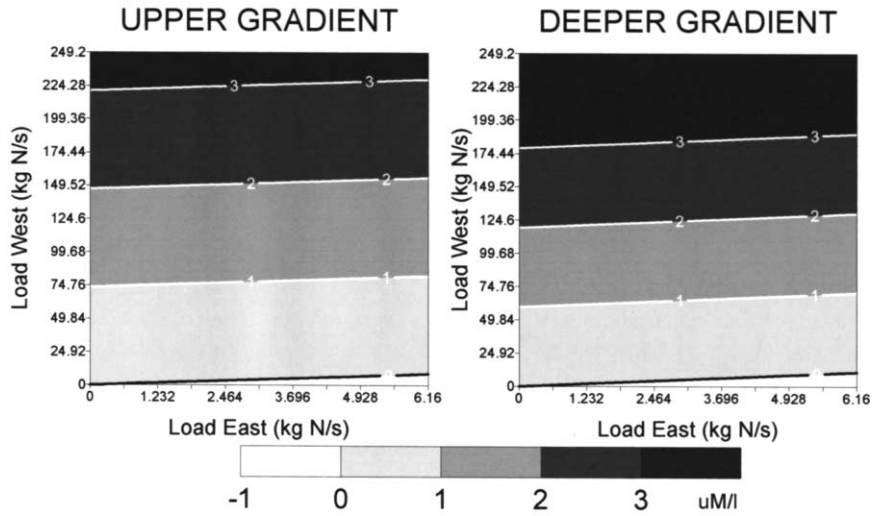


Fig. 8. Nitrogen gradients, in $\mu\text{M/l}$, between the upper layers (high plate) and between the deeper layers (low plate) changing the loads, kg N/s, in the eastern basin (abscissa) and in the western basin (ordinates) from 0% to 200% of the reference values. The black contour line indicates where the gradient is null.

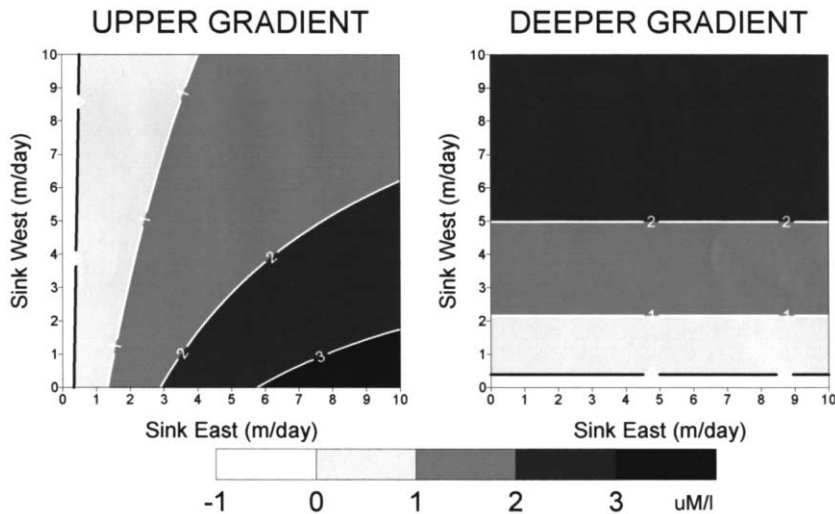


Fig. 9. Nitrogen gradients, in $\mu\text{M/l}$, between the upper layers (high plate) and between the deeper layers (low plate) changing detritus sinking velocity (m/day) in the eastern basin (abscissa) and in the western basin (ordinates) from 0% to 200% of the reference value. The black contour line indicates where the gradient is null.

4. The sinking term is assumed to be much larger than the vertical turbulent diffusivity term.

Under these conditions Eq. (2) can be written as:

$$\frac{\partial D}{\partial z} = -\frac{r}{w_D} D + \frac{d}{w_D} P. \quad (3)$$

In the above equation the mortality term dP accounts for the difference between phytoplankton time rate of change and the net primary production. At the steady state mortality is dynamically balanced by net primary production ($dP = \mu P - \text{resp}P$).

It is worth noting that the positive contribution to detritus concentration is connected only to the difference between the gross primary production μP and the respiration $\text{resp}P$, and does not depend directly upon the primary production itself.

The solution of the equation 3, with uniform distribution of the phytoplankton, \bar{P} , from 0 to z_0 , depth of the euphotic layer depth, is

$$D(z) = \frac{\bar{P}d}{r} \left(1 - e^{-\frac{rz}{w_D}} \right). \quad (4)$$

The detritus average inside the upper layer is evaluated in terms of the average phytoplankton by

$$\bar{D} = \frac{\bar{P}d}{r} \alpha, \quad (5)$$

with

$$\alpha = 1 + \frac{w_D}{rz_0} e^{-\frac{rz_0}{w_D}} - \frac{w_D}{rz_0}.$$

In the following the total concentration, Σ , is defined

$$\Sigma = \Sigma_{\text{dis}} + \Sigma_{\text{par}}, \quad (6)$$

as the sum of the dissolved fraction, Σ_{dis} , and of the particulate fraction, Σ_{par} ,

$$\Sigma_{\text{par}} = \bar{P} + \bar{D}. \quad (7)$$

The latter is assumed as a constant fraction of the total concentration

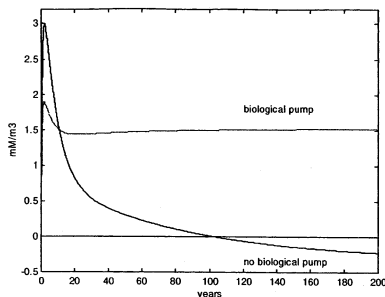


Fig. 10. Evolution of nitrogen upper gradient, in $\mu\text{M}/\text{l}$, with time, in years, in case of no biological pump and in case of biological pump with reference detritus sinking velocity in all basins. The initial conditions are $1 \mu\text{M}/\text{l}$ in both upper layer boxes, 7 and $5 \mu\text{M}/\text{l}$, respectively, in the western and eastern deeper layers. The null line is also shown.

$$\Sigma_{\text{par}} = \beta \Sigma, \quad (8)$$

where the generic parameter, β , has different values for the nitrogen cycle, β_{N} , and for the phosphorus cycle, β_{P} .

Eliminating Σ_{par} from Eq. (7) and Eq. (8) and solving for \bar{D} , it is possible to write the downward fluxes related to the biological pump, hereafter referred to as the biogenic fluxes:

$$f_{13}^{\text{b}} = A_w \frac{\alpha}{\alpha + r/d} \beta w_D,$$

for the western layer and

$$f_{24}^{\text{b}} = A_e \frac{\alpha}{\alpha + r/d} \beta w_D,$$

for the eastern layer, where A_w and A_e are respectively the western and the eastern area.

3. Forcings, parameterization and comparison data

The parameterization of the box model is performed following the principle of the analogy of treatment of nitrogen and phosphorus cycles, taking into account the specific Gibraltar and river inputs, and the different remineralization rates and organic fractions.

The euphotic layers' depth, z_0 , is assumed 100 m thick. In these layers, Box 1 and Box 2, all compartments coexist, while in the deeper layers the phytoplankton is absent, and the detritus sinking into the deeper layers, Box 3 and Box 4, is considered as immediately remineralized.

The assessment of the water exchanges at Gibraltar Strait is still an open question. There are a number of estimations of these fluxes, f_{a1} and f_{3a} , starting both from currentometer data (Bryden and Kinder, 1988; Bryden et al., 1994) and from two-layer models, mass budgets and salinity fluxes (Béthoux, 1980; Bryden and Stommel, 1984; Sarmiento et al., 1988; Garrett et al., 1990; Bryden and Kinder, 1991; Harzallah et al., 1993). The multiannual averages obtained from the recent observations converge to that obtained from two layer models. Anyway a reanalysis based on barotropic influence of sea level can introduce a correction up to 50% (Hopkins, 1999).

A similar two layer dynamics is present also at Sicily Strait. The Modified Atlantic water inflows the eastern Mediterranean Sea (f_{12}), while the countercurrent of the Levantine intermediate water flows westerly in the bottom layer (f_{43}). Also in this case estimates are known both as analysis of data after Astraldi et al. (1996) and as evaluation from salinity and water budget (Béthoux, 1980; Sarmiento et al., 1988; Harzallah et al., 1993). These estimates of the two fluxes are closer than in the Gibraltar case. Moreover convection, upwelling and downwelling, and vertical mixing are the processes to be parameterized to obtain the total vertical fluxes.

For the simulations shown in the next sections the fluxes after Béthoux (1980) for the horizontal exchanges at the straits and after Béthoux (1989) for the vertical ones are used in the box model.

The terrestrial inputs by UNEP (1977) are here used as the nitrogen and the phosphorus external sources. The estimates are summarized in western total contributions and in eastern contributions, without contributions of the Bosphorus inflow and of all the Adriatic inputs. This choice is motivated from recent evaluations of fluxes at the Cretan Arc (Balopoulos et al., 1997) and at the Otranto Strait (Civitaresi et al., 1998).

The inputs from Atlantic are taken into account considering the measures by Coste et al. (1988) at Gibraltar Strait. Starting from this data the ratio of particulate organic nitrogen with respect to the total nitrogen results at Gibraltar is 0.11 in the surface layer. This is a lower boundary because in the western Mediterranean values of 0.16–0.19 are reached being the particulate about 0.4–0.5 $\mu\text{M/l}$ along all the surface layer as measured by Puyo-Pay et al. (1995) while the inorganic nitrogen average is 2.1 $\mu\text{M/l}$. In the eastern Mediterranean values of 0.18 for winter and of 0.22 for summer are obtained considering the Ionian surface water (Socal et al., 1999). In the present work a value of 0.20 is chosen for the nitrogen organic fraction in both basins.

The evaluation for phosphorus organic fraction is about 0.15 at Gibraltar (Coste et al., 1988) for the inflowing water. Inside the basin the phosphate concentration is almost depleted in the upper layer and consequently phosphorus organic

fraction is given a value of 0.33 in the present work as characteristic of the entire Mediterranean. This is an average of the estimates reported by Ediger et al. (1999) for the open sea sites. The parameters used in the model for nitrogen and phosphorus cycles are shown in Table 1.

These values, except the two organic fractions estimates for nitrogen and phosphorus discussed in this section, are chosen as in the Mediterranean three-dimensional models cited in Section 1 and are used here as averaged informations about the processes as schematized in the box model.

Recent data acquired during cruises in different areas are used in this article for obtaining nitrate and phosphate average concentrations. In particular MEDIPROD I (Coste et al., 1972) and DISCOVERY (Cruzado, 1995) in the western Mediterranean Sea, and POEM (Rabitti et al., 1994) in the eastern Mediterranean Sea are selected.

4. Results and discussion

Firstly a general solution of the system (1) is computed. After this the parameterization given in the Section 3 is specified.

In matrix notation the solution of the system, $\Sigma(t)$, is:

$$\Sigma(t) = e^{V^{-1}Ft}C - F^{-1}L,$$

where the constant vector C is given by

$$C = \Sigma_0 + F^{-1}L,$$

with the initial conditions

$$\Sigma_0 = \Sigma(t = t_0)$$

In terms of eigenvalues, λ_i , right eigenvectors, v_i , and left eigenvectors μ_i^T of the matrix $V^{-1}F$, the solution becomes:

$$\Sigma(t) = \sum_{i=1}^4 e^{\lambda_i t} v_i \mu_i^T C - \sum_{i=1}^4 \lambda_i^{-1} v_i \mu_i^T V^{-1}L. \quad (9)$$

Therefore the equilibrium concentrations are obtained in the following closed form:

$$\Sigma = \frac{f_{31}(L_1 + L_2) + f_{3a}L_1}{f_{3a}(f_{12} + f_{13})}, \quad (10)$$

$$\Sigma_2 = \frac{f_{42} + f_{43}}{(f_{12} + f_{13})f_{24}f_{3a}f_{43}} [f_{12}(f_{31} + f_{3a})L_1 + (f_{12}f_{13} + f_{12}f_{3a} + f_{13}f_{3a})L_2], \quad (11)$$

$$\Sigma_3 = \frac{L_1 + L_2}{f_{3a}}, \quad (12)$$

$$\Sigma_4 = \frac{1}{(f_{12} + f_{13})f_{3a}f_{43}} [f_{12}(f_{31} + f_{3a})L_1 + (f_{12}f_{13} + f_{12}f_{3a} + f_{13}f_{3a})L_2]. \quad (13)$$

The unicity and the stability of the equilibria is guaranteed by the fact that the determinant of the matrix F is positive, being $|F| = (f_{12} + f_{13})f_{24}f_{3a}f_{43}$.

The gradient, western total concentration less eastern concentration, is for surface layers

$$\overline{\text{grad}} = \frac{(f_{13} + f_{3a})L_1 + f_{31}L_2}{f_{3a}(f_{12} + f_{13})} - \frac{[f_{12}(f_{13} + f_{3a})L_1 + (f_{31}f_{12} + f_{12}f_{3a} + f_{13}f_{3a})L_2](f_{43} + f_{42})}{(f_{12} + f_{13})f_{24}f_{3a}f_{43}},$$

while for the deeper layers

$$\overline{\text{grad}} = \frac{L_1 + L_2}{f_{3a}} - \frac{f_{12}(f_{31} + f_{3a})L_1 + (f_{31}f_{12} + f_{12}f_{3a} + f_{13}f_{3a})L_2}{(f_{12} + f_{13})f_{3a}f_{43}}.$$

From Eqs. (10)–(13) it results that Σ_3 , the concentration of the deep layer in the western Mediterranean, does not depend on the fluxes within that basin, but only on the outflow exchange with Gibraltar Strait and on the loads in both basins.

Analogously Σ_4 , the eastern Mediterranean aphotic concentration, does not depend on the vertical fluxes inside that basin, f_{24} and f_{42} , but only on the western vertical ones, and on the Gibraltar and Sicily Straits inflows and outflows.

Σ_1 is instead affected by the western vertical fluxes, but not by the eastern ones, while Σ_2 is a function of the vertical fluxes in both basins. The bottom gradient does not depend on the vertical fluxes of the eastern basin, whereas the surface gradient is affected by all the parameters of the model.

As a matter of fact, the equilibria and the gradients are linear functions of loads on both

basins, L_1 and L_2 . Using the parameterization previously described, the following numerical results are obtained. Fig. 2 (high plate) shows total nitrogen equilibrium concentration values in absence of biogenic fluxes. Values about 6 $\mu\text{M/l}$ are found in all the boxes. Both the eastern boxes exhibit values slightly larger than western ones.

The introduction of the biogenic fluxes modifies substantially the scenario, Fig. 2 (low plate). In both the upper and deeper layers the gradients change sign and become positive; moreover the lower layers are twice richer than the surface layers and the whole basin becomes more nutrient-depleted. These results are comparable with the average values measured in the Mediterranean for the upper 100 m, Fig. 3 high plate, and for the deeper layer, Fig. 3 (low plate). The agreement between model results and data is better for the deeper layers, while the upper layers estimates are about 0.9 $\mu\text{M/l}$ higher compared to the data.

The inorganic upper gradient in the box model results in 1.33 $\mu\text{M/l}$ (1.1 $\mu\text{M/l}$ in the data) and the deeper gradient gives 2 $\mu\text{M/l}$ (2.5 $\mu\text{M/l}$ in the data). Thus the box model is capable to reproduce the concentration gradients.

Analogous considerations can be derived by analyzing the parameterization referring to the phosphorus cycle. The total phosphorus equilibrium concentrations reached in absence of biogenic fluxes are about 0.4 $\mu\text{M/l}$ in all boxes, with greater values in the eastern boxes (Fig. 4, high plate). The levels decrease significantly in the four boxes when the biogenic fluxes are considered, and the gradients change their sign (Fig. 4, low plate). The comparison with phosphate average data measured in the Mediterranean for the upper 100 m is good for upper layers (Fig. 5, high plate). The model predicts a concentration about 0.06 $\mu\text{M/l}$ in excess with respect to the data. Also for deeper layers the qualitative situation is confirmed by the average values measured in the Mediterranean from 100–1000 m (Fig. 5, low plate). Anyway there is more distance in this case with the experimental data, about 0.18 $\mu\text{M/l}$ in the western deeper layer and 0.12 $\mu\text{M/l}$ in the eastern one. The comparison for the upper layers' estimation gives about 0.06 $\mu\text{M/l}$ in excess of concentration with respect to the data.

The inorganic phosphorus upper gradient in the box model gives $0.08 \mu\text{M/l}$ ($0.06 \mu\text{M/l}$ in the data) and the deeper gradient is $0.06 \mu\text{M/l}$ ($0.10 \mu\text{M/l}$ in the data), confirming a good reproduction of the gradients also for phosphorus cycle.

Fig. 6 shows the linear dependence of total nitrogen equilibrium concentrations, in $\mu\text{M/l}$, on the loads. The figure focuses on the nitrogen cycle, but similar results are obtainable for phosphorus. In the example the loads (kg N/s) are varied continuously between 0% and 200% of the reference value. The concentration of Σ_3 increases with both western and eastern loads, while Σ_1 is more sensitive to the eastern river inputs. In the eastern part of the basin an increasing influence of the western river inputs is recognized, also in this case with a higher sensitivity in the deeper layer than in the upper one. It can be noted also the null loads situation, which gives a completely nutrient-depleted basin.

The resulting nitrogen gradients, in $\mu\text{M/l}$, are shown in Fig. 7, for the upper layers (high plate) and for the bottom ones (low plate). It can be seen as both gradients increase by increasing the western loads and decrease by increasing the eastern loads. However the concentration is higher for deeper layers at the same load conditions.

The total nitrogen equilibrium concentrations, in $\mu\text{M/l}$, obtained for values of f_{13}^b and f_{24}^b , which vary from 0% to 200% of the detritus sinking velocity reference value are plotted in Fig. 8. As expected western deeper layer concentration is not influenced by these parameters, western upper layer and eastern deeper layer are affected only by the western flux, f_{13}^b , while upper eastern layer is sensitive to both sinking velocities, more to the eastern than to the western one. In any case, an increment of the biogenic fluxes, i.e., of the biological activity, results in a higher degree of oligotrophy.

In Fig. 9 this situation is shown and summarized by the nitrogen gradient, in $\mu\text{M/l}$, for the upper and for the deeper layers. In the first case, high plate, the gradient is negative for low values of detritus sinking, in particular for the situation without biogenic fluxes. It is necessary to reach a minimum flux value in the eastern basin to obtain a positive gradient. After this sill the two vertical

fluxes control the gradient, with values nearly constant along the diagonal. The deeper layers' gradient, low plate, has a simpler behavior, and it increases only with the western sinking velocity. This is due to the fact that neither the western concentration nor the eastern one depends on the eastern value of the biogenic fluxes.

In Fig. 10 the evolution of nitrogen upper gradients, in $\mu\text{M/l}$, is shown. Here the cases with biogenic fluxes (full line) and those without them (dotted line) are compared. The initial conditions are in both simulations $1 \mu\text{M/l}$ in both upper layer boxes, 7 and $5 \mu\text{M/l}$, in the western and eastern deeper layers, respectively. In the second case, the transient lasts for quite a long time: the gradient initially null, increases as a result of Gibraltar inflow for 10 years, decreases after that, it is zero around 100 years and reaches its negative equilibrium condition after approximately 250 years. On the other hand, if the biological pump is active the evolution time required to dampen the transient is much shorter, about 20 years. In fact the gradient, while increasing the result of Gibraltar input, get closer to its equilibrium point and then stabilizes around a positive value.

5. Conclusions

The inverse estuarine circulation and the river inputs unbalance, with minor total inputs in the eastern basin both for nitrogen and for phosphorus, are able to explain the nutrient-depleted content of the deeper layers of the Mediterranean Sea with respect to the ocean. On the other hand, if downward fluxes of matter related to sinking velocity is not considered, then non-oligotrophic concentrations in the upper layers and negative westerly trophic gradients are present. Conversely, if the biogenic fluxes are taken into account, oligotrophy of the upper layers and positive westerly trophic gradients are obtained.

Thus we can conclude that the gradients are induced by the asymmetry of the loads, namely of the Gibraltar input and the river inputs. These loads are then distributed along the Mediterranean by the inverse estuarine circulation. Nevertheless our numerical results show that the

circulation alone is not sufficient to drive a redistribution of the matter such as to maintain these gradients. Actually after an initial increment a negative value must be reached, even if in the long run. The positive value for the gradients is instead maintained if the biological pump is active. Simulations indicate also that an increment of the downward fluxes related to biological activity results in a higher degree of the oligotrophy in both basins.

The long and medium term evolution in Mediterranean outlined in this work relies on hypotheses, which characterize the main biogeochemical features. These hypotheses should not be disregarded, also when dealing with processes at multi-annual scales. Other biological and geochemical processes (e.g., microbial food web, nitrogen fixation, atmospheric inputs) should also effect the general oligotrophy of the basin and can be introduced in this framework to give a finer representation and a more precise evolution.

There are three causes of variability in the results of the model, as presented here, such as biogenic fluxes, nitrogen and phosphorus loads, and initial conditions. Indeed, the sensitivity analysis shows the changes of the box model results under different biogeochemical parameters and inputs. The initial conditions are essential in fact after a change in the terrestrial inputs, due to anthropogenic or natural activity, the system may be in a non-stationary situation. An example of this fact can be seen in the results obtained for the deeper layers' phosphorus. Reaching stability takes about 100 years and the final equilibrium is far from the initial conditions. Such a thing becomes clear if river inputs before and after Nile damming are compared. The higher loading of about six times of phosphate in the rivers, as evidenced in UNEP (1977) with respect to McGill (1969), can induce a phosphate increase of about 0.14 $\mu\text{M/l}$ for the western deeper layer, while for the eastern deeper layer can give 0.09 $\mu\text{M/l}$ as excess of concentration. At the moment the ecosystem should be intermediate between its final state and its initial conditions, with an increase of about one half of the total expected variation. This would result in reasonable accord with present experimental data.

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