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Modeling the biogeochemical seasonal cycle in the Strait of Gibraltar

E. Ramírez-Romero [a,1,*], M. Vichi [b], M. Castro [c], J. Macías [c], D. Macías [d], C.M. García [a], M. Bruno [e]

[a] Departamento de Biología, Área de Ecología, Facultad de Ciencias del Mar y Ambientales, Universidad de Cádiz, Cádiz, Spain
[b] Centro Euro-Mediterraneo sui Cambiamenti Climatici, Bologna, Italy
[c] Departamento de Análisis Matemático, Universidad de Málaga, Málaga, Spain
[d] European Commission, Joint Research Center, Institute for Environment and Sustainability, Via E. Fermi 2749, 21027, Ispra, Italy
[e] Departamento de Física Aplicada, Facultad de Ciencias del Mar y Ambientales, Universidad de Cádiz, Cádiz, Spain

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ABSTRACT

A physical-biological coupled model was used to estimate the effect of the physical processes at the Strait of Gibraltar over the biogeochemical features of the Atlantic Inflow (AI) towards the Mediterranean Sea. This work was focused on the seasonal variation of the biogeochemical patterns in the AI and the role of the Strait; including primary production and phytoplankton features. As the physical model is 1D (horizontal) and two-layer, different integration methods for the primary production in the Biogeochemical Fluxes Model (BFM) have been evaluated. An approach based on the integration of a production-irradiance function was the chosen method. Using this Plankton Functional Type model (BFM), a simplified phytoplankton seasonal cycle in the AI was simulated. Main results included a principal bloom in spring dominated by nanoflagellates, whereas minimum biomass (mostly picophytoplankton) was simulated during summer. Physical processes occurring in the Strait could trigger primary production and raise phytoplankton biomass (during spring and autumn), mainly due to two combined effects. First, in the Strait a strong interfacial mixing (causing nutrient supply to the upper layer) is produced, and, second, a shoaling of the surface Atlantic layer occurs eastward. Our results show that these phenomena caused an integrated production of 105 g C m^{-2} year^{-1} in the eastern side of the Strait, and would also modify the proportion of the different phytoplankton groups. Nanoflagellates were favored during spring/autumn while picophytoplankton is more abundant in summer. Finally, AI could represent a relevant source of nutrients and biomass to Alboran Sea, fertilizing the upper layer of this area with 4.95 megatons nitrate year^{-1} (79.83 gigamol year^{-1}) and 0.44 megatons C year^{-1}. A main advantage of this coupled model is the capability of solving relevant high-resolution processes as the tidal forcing without expensive computing requirements, allowing to assess the effect of these phenomena on the biogeochemical patterns at longer time scales.

1. Introduction

The Strait of Gibraltar is the only connection between the Mediterranean Sea and the Atlantic Ocean. The water exchange between these two basins occurs following a two-layer, inverse-estuarine circulation scheme, with a mixture of Surface Atlantic Water (SAW) and North Atlantic Central Water (NACW) entering the Mediterranean Sea at surface and denser deep Mediterranean water outflowing towards the Atlantic (MOW). The intense hydrodynamics of the Strait can be considered the most important forcing agent explaining the distribution and behavior of biogeochemical variables in the Atlantic Jet (AJ) (e.g. Macías et al., 2007). The hydrological processes in the Strait, as in other coastal regions, cover a wide range of temporal scales including interannual, seasonal, sub-inertial and tidal (Lacombe and Richez, 1982). Thus, biological features in the Strait, heavily dependent on the physical processes, should follow these temporal scales too. In spite of the wide scales associated to the physical-biological coupling in the area, most of the studies have been focused on the tidal scale and particularly on internal waves generation and effects; e.g. biogeochemical effects of the undulatory processes currents have been widely studied (e.g. Macías et al., 2006; Vázquez et al., 2009). These relevant undulatory processes are forced by the interactions of sharp topography (Camarinal Sill) with tidal currents (e.g. Bruno et al., 2002).

The Atlantic Inflow (AI) through the Strait consists mainly of open ocean waters coming from the Gulf of Cádiz (Criado-Aldeanueva et al., 2006) with oligotrophic features (Macías et al., 2008; Navarro et al., 2006; Ramírez-Romero et al., 2012). Previous works showed that the pelagic ecosystem in the Gulf of Cadiz and near the open Atlantic

* Corresponding author at: Facultad de CC de Mar y Ambientales, Avda, República Saharaui sn, 11510 Puerto Real, Cádiz, Spain. Tel.: +34 956016024, +49 431 600 4411; fax: +34 956016019.
E-mail addresses: Eduardo.ramirez@uca.es, eramirez-romero@geomar.de (E. Ramírez-Romero).
[1] Present address: GEOMAR Helmholtz Centre for Oceanography, Düsternbrooker Weg 20, D-24105 Kiel, Germany.

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presents an annual cycle (Longhurst, 1995; Navarro and Ruiz, 2006; Navarro et al., 2012; Teira et al., 2005). The original seasonal cycle of biological features in the AI could, however, suffer important changes crossing the Strait. This modification is especially obvious during spring tides and includes interfacial mixing associated to internal waves or intrusions of high chlorophyll patches (Macías et al., 2006; Ramírez-Romero et al., 2012; Vázquez et al., 2009).

Assessment of phytoplankton productivity in the ocean is a key goal of Biological Oceanography, as assimilation of Carbon by marine phytoplankton via primary production is the basis of the ocean's food web and of the biological carbon pump. Hence, the determination of primary production rates is a relevant aim; however the complexity of the interactions of hydrodynamics with primary producers in the Strait constitutes a limitation but also an extra-motivation in this field laboratory. Classical incubation methods as oxygen evolution or C^{14} uptake (Macías et al., 2009) have already been used to estimate primary production in this area. Fluorescence-based measurements of photosynthesis have also been used in the area (Fast Repetition Rate Fluorometry, FRRF) (Bartual et al., 2011). Recent works have shown that biological probes (as FRRF) can be a useful tool to obtain high spatial and temporal resolution primary production estimations, particularly in highly dynamic systems (Bartual et al., 2011). Nevertheless, the non-synoptic and scattered nature of the sampling process implies limited spatial and temporal estimations of primary production, especially at larger scales as seasonal or interannual.

Coupled physical-biological models can cover these larger scales, including long-time processes and regional (e.g. Franks and Chen, 2001; Lazzari et al., 2012) or global scale simulations (Vichi et al., 2007a). In addition, due to its high spatio-temporal resolution, coupled models could cover a wide range of processes, as very local or short-scale could be simulated too. Nevertheless in the Strait, most of the modeling efforts focused on hydrodynamic processes (e.g. Izquierdo et al., 2001; Sánchez-Garrido et al., 2011; Sannino et al., 2007). Some studies included coupled physical-biological models (Macías et al., 2007; Skliris and Beckers, 2009). However, nitrogen-based, single compartments models, as used in previous works, did not provide direct estimations of C-based primary production nor of plankton's structure. In order to fulfill these aims, in the present work the Biogeochemical Flux Model (BFM) was used. This model distinguishes three different functional groups of phytoplankton (diatoms, nanoflagellates and picophytoplankton; see details in Vichi et al., 2007b). Furthermore, this model can simulate separately the dynamics for the C, N, P, Si and chlorophyll content; reproducing in a coarse way the physiological features of the different phytoplankton species. Therefore, BFM allows to infer the effect of the physical forcing on the different components of the model both under the taxonomic-biological and biogeochemical point of view.

The main purpose of this work was the development of a coupled model focusing in local phenomena at the central channel of the Strait of Gibraltar. As explained above, this is a very particular and extreme ecosystem forced by tidal dynamics. A proper inclusion of these local phenomena is needed to simulate correctly the processes in the Mediterranean basin (Malanotte-Rizzoli et al., 2013; Oguz et al., 2013; Sannino et al., 2009). To fulfill this aim, we propose a phytoplankton seasonal cycle, which could be used as an input or boundary condition for coupled models of the Mediterranean Basin. Our first aim was to simulate primary production and phytoplankton's biomass and structure in the incoming Atlantic waters (open ocean waters of the Gulf of Cadiz and nearby areas). Afterwards we assessed the effect of the hydrological processes (tidal forcing) at the Strait and their modulation of the biological features of the AI.

2. Methodology

2.1. Hydrodynamical model

The hydrodynamical component of the physical-biological coupled model was a 1-D two-layer shallow water model for channels with irregular geometry, in both width and depth. In this model sea-water density was uniform and prescribed in each layer. The first layer represented the surface Atlantic water entering the Alboran Sea, where biological processes take place. The second layer represented the denser Mediterranean water flowing deeper. A simple scheme of the model geometry is presented in Fig. 1, where A_1 and A_2 were the upper and lower layer wet area (depending on the position along the Strait axis and time)(Fig. 1a). h_1 and h_2 were the upper and lower layer thickness, respectively (Fig. 1b). A complete model description, including governing equations and parameter values used can be found in Castro et al. (2004a, b, 2009) and Bruno et al. (2010).

Model equations were discretized using a second order extension of the finite volume scheme presented in Castro et al. (2004a) by means of a flux limiter function as described in Toro (1989).

The biological model was a subset of the BFM (Vichi et al., 2007b) formulated in conservative form. The temporal changes in the concentration of the constituents were given by the general equation:

$$\frac{\partial(A_1\ C)}{\partial t}+\frac{\partial(u_1\ A_1\ C)}{\partial x}=\text{Biological terms;} \tag{1}$$

where C was the concentration of a biogeochemical variable and u_1 was the upper layer averaged velocity.

2.1.1. Interfacial mixing between layers

Besides advection, interfacial mixing in the Strait of Gibraltar is a crucial phenomenon for understanding the biogeochemical patterns in this area (e.g. Macías et al., 2007). The value of the stability Froude number was used to determine interfacial mixing in order to avoid complex parameterizations strongly dependent on poorly constrained coefficients:

$${F_I}^2=\frac{(u_1-u_2)^2}{g'\ (h_1+h_2)}; \tag{2}$$

In this expression, u_1 and u_2 were the upper and lower layer averaged velocities, respectively. $g' = g\ (1 - r)$ was the reduced gravity with $r = \frac{\rho_1}{\rho_2} = \frac{1027}{1029} = 0.99805$ the ratio of densities, and g gravity.

When $F_I^2 > 1$, Kelvin-Helmholtz instabilities appear. In this situation, interfacial mixing has an important role (Cushman-Roisin, 1994). Then in a more complete form, biological flux equations were finally computed as:

$$\frac{\partial(A_1\ C)}{\partial t}+\frac{\partial(u_1\ A_1\ C)}{\partial x}=\text{Biological terms}\ +\ C_m; \tag{3}$$

where C_m was the mixing term, parameterized as:

$$C_m=k_{mix}*\left(C_{ref}-C\right); \tag{4}$$

$$k_{mix}=\alpha*F_I^2*A_1/h_1; \tag{5}$$

where k_{mix} was a function of the mixing between layers that parameterized as a function of the Froude stability number. C_{ref} was the constant concentration in the deep Mediterranean layer and C was the computed concentration of a variable for the upper Atlantic layer. α was a coefficient found calibrating this term with *in situ* data as explained below (here α = 0.002). Therefore using this parameterization, mixing is proportional to ${F_I}^2$. Eq. (4) was valid for the physical variables (salinity, temperature) and biogeochemical variables with non-null concentration in the deep layer (Mediterranean layer) as nutrients. For the rest of the variables, mixing term was computed as: $C_m = -k_{mix} * C$. The values for the variables in deeper layer have been collected in Table 1.