



The relevance of deep chlorophyll maximum in the open Mediterranean Sea evaluated through 3D hydrodynamic-biogeochemical coupled simulations



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ABSTRACT

Decades of oceanographic observations on the Mediterranean Sea have consistently indicated that its open-sea region presents oligotrophic characteristics during long periods of the year (from late spring to autumn) with very low and uniform surface chlorophyll values interrupted by the presence of several productivity hot-spots associated to mesoscale features. Another commonly observed phenomenon in the basin is the widespread and consistent presence of subsurface or deep phytoplankton biomass accumulations. However, given the difficulty of observing those deep structures with the adequate spatial and temporal resolution, a comprehensive description of their spatial and temporal variability is yet to be done. Here we use a 3D hydrodynamic-biogeochemical coupled model of the entire Mediterranean Sea to explore the contribution of the deep chlorophyll maximum (DCM) to total plankton biomass and primary productivity in the open-sea regions of the basin. We found that, on annual average, DCM are present in 73.5% of total open-sea regions with a clear annual cycle, being more frequent (up to 98% of the area) in summer months and less common (~9%) during winter. Our model also indicates that, on average, nearly 53% of total phytoplankton biomass and ~62% of total primary production in open-sea regions of the Mediterranean takes place within such structures. They must, then, be duly considered for a correct assessment of the biological productivity in the open sea regions of the Mediterranean basin.

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1. Introduction

The Mediterranean Sea is generally considered as an oligotrophic basin (e.g., Antoine et al., 1995) with some local regions with enhanced productivity (see an extensive review in Siokou-Frangou et al., 2010). The general oligotrophy of the basin is interrupted by production hotspots in some coastal areas (e.g., Alboran Sea, García-Gorriz and Carr, 2001), in the vicinity of river mouths (Meybeck et al., 2007), in highly dynamic regions with strong frontal activity (e.g., the Balearic Sea, La Violette, 1990) and in the Adriatic Sea (Revelante and Gilmartin, 1976; Polimene et al., 2006). The image of a 'biologically poor' sea has been recently reinforced by remote sensing information on the surface chlorophyll (Chl_a) distribution in the basin (e.g., D'Ortenzio, 2009) as open-sea regions are typically characterized by low (~0.3 mg m⁻³, western basin) to very low (~0.09 mg m⁻³, eastern basin) mean surface Chl_a concentrations.

However, subsurface phytoplankton accumulations (i.e., deep chlorophyll maximum, DCM) are a common and persistent feature in the open Mediterranean Sea except during the winter mixing period (Siokou-Frangou et al., 2010; Oguz et al., 2013). Phytoplankton biomass concentration at the DCM within the Mediterranean Sea could be as large as 23 mg Chl_a m⁻³ (Gould and Wiesenburg, 1990) but a more usual concentration is around 1.0 mg Chl_a m⁻³ (Siokou-Frangou et al., 2010). Primary production rates at the DCM represent a significant contribution to the total productivity of the water column, being over 30% in some cases (Estrada et al., 1985).

The appearance of the DCM is one of the most common and discussed features of the oceanic water column (Longhurst and Harrison, 1989), appearing in most marine ecosystems, from coastal regions to the open sea and from equatorial to polar areas (Cullen, 1982) and accounting for a substantial fraction of the world's primary production (Takahashi and Hori, 1984; Field et al., 1998). The genesis of the DCM has been explained in terms of biological processes, such as preferential production on thermoclines, phytoplankton behavioral aspects or adaptive changes in the chlorophyll to carbon ratio and physical processes, such as horizontal and/or vertical intrusions, changes in plankton cells sinking

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speed, etc. . . (for a detailed review see Cullen, 1982). In short, the existence of a DCM may be explained, as a first approach, by the presence of two vertically opposing gradients of resources (Cullen, 1982) that control the vertical distribution of planktonic biomass: light availability from the surface and high nutrient concentration in deep waters (Longhurst and Harrison, 1989). The biomass of photosynthetic plankton organisms is, thus, accumulated in a narrow region where there is sufficient light for photosynthetic activity and adequate inorganic nutrients to allow net positive growth.

DCMs in the Mediterranean typically occur far deeper than the *first optical depth* (i.e., where incident light reduces to 63%), usually between 30 and 120 m depth depending on location (Boldrin et al., 2002; Christaki et al., 2001; Dolan et al., 2002), so they could not be directly observed using remote sensors. As, satellites only can 'see' a very small fraction of the water column, a vertical integration using bio-optical models is needed to assess the total plankton biomass present in the water column. One of the most used vertical integration models is the one proposed by Morel and Berthon (1989) combined with surface satellite-derived Chl_a data as described by Morel and André (1991). Total water column Chl_a content is, then, derived assuming a predefined vertical distribution and using surface values as input data to this bio-optical model. Stratification of the water column is one of the key factors to determine the vertical plankton distribution, which is assumed to be homogeneous during non-stratified periods and presenting a DCM during stratified epochs (Morel and Berthon, 1989). This bio-optical model is, thus, relying on a number of regionally adjusted parameters (stratification structure, light field, etc. . .) that need to be provided by hydrodynamic models or derived from field observations. Such models could not be considered, then, as mechanistic descriptors of the vertical plankton distribution but, rather, as a statistical approach.

Thus, as DCMs could not be observed with adequate spatial and temporal resolution, relatively little is known so far about its spatial and temporal variability in the Mediterranean Sea (e.g., Saiz et al., 2007). 3D high-resolution hydrodynamic-biogeochemical numerical models could be a promising tool to study the persistence of subsurface features and to numerically compute their contribution to total basin production and biomass. In spite of being a rough representation of the real system, this type of model allows a comprehensive description of the 3D structures (e.g., Lazzari et al., 2012) given that careful calibration and validation against available field data are performed.

In this work we set-up a coupled hydrodynamic-biogeochemical model of the entire Mediterranean basin and focus on the study of the importance of subsurface phytoplankton biomass accumulations on the biogeochemical characteristic of its open-sea region. Details of model configuration and on the remote sensing information used to calibrate and validate the model are given in Section 2. Validation of surface patterns provided by the model simulation against available remote sensing data is performed in Section 3.1. Section 3.2 describes the vertical structure found in different regions of the basin and evaluates the importance of subsurface biomass accumulations. Finally, the results obtained are discussed in Section 4.

2. Methods

A fully coupled 3D hydrodynamic-biogeochemical model of the entire Mediterranean basin (Fig. 1) was run covering the period from 1995 to 2012. The first three years of the model run (1995, 1996 and 1997) were not used in the analysis to avoid any influence of the initial conditions (spin-off period). Coupling of hydrodynamic and biogeochemical models was performed by using the Framework for Aquatic Biogeochemical Model (FABM, Burchard

et al., 2006) which is a general framework that provides the linkage between an arbitrary physical 'host' model and any number of arbitrary biogeochemical models (<http://fabm.sourceforge.net/>). This is a two-way coupled model system where hydrodynamics modifies biogeochemistry by water movement, substance transport, light availability and temperature dependence of process rates while biogeochemistry influences water column properties through light attenuation modifications by phytoplankton self-shading (Burchard et al., 2006).

Model integration time-step was 27 second and monthly mean values of all hydrodynamics and biogeochemical variables were stored throughout the entire simulation time-span. Details of the two models used are provided in the next Sections 2.1 and 2.2.

2.1. Hydrodynamic model

The 3D general estuarine transport model (GETM) was used to simulate the hydrodynamics in the Mediterranean Sea. GETM solves the three-dimensional hydrostatic equations of motion applying the Boussinesq approximation and the eddy viscosity assumption (Burchard and Bolding, 2002). A detailed description of the GETM equations could be found in Stips et al. (2004) and at <http://www.getm.eu>. The configuration of the Mediterranean Sea (Fig. 1) has a horizontal resolution of 5' × 5' and includes 25 vertical layers. ETOPO1 (<http://www.ngdc.noaa.gov/mgg/global/>) was used to build the bathymetric grid by averaging depth levels to the corresponding horizontal resolution of the model grid (color scale in Fig. 1).

2.2. Biogeochemical model

The ecological regional ocean model (ERGOM, Neumann, 2000) was selected as the initial framework to represent the biogeochemical characteristics of the Mediterranean Sea. This model originally incorporates three macronutrients (nitrate, ammonium and phosphate), three phytoplankton types (diatoms, flagellates and cyanobacteria), one zooplankton variable (representing model closure), detritus, dissolved oxygen and a sediment compartment (coupled to the pelagic one through sedimentation and resuspension processes) (Neumann et al., 2002) (see scheme in Fig. 2). ERGOM uses nitrogen as internal currency, and the balance of phosphorus and oxygen is based on nitrogen using stoichiometric Redfield ratios.

This model is, initially, adequate to represent the two main pathways for food and energy transfer in the Mediterranean, the classical herbivores–carnivores food path usually present in eutrophic regions and the small-sized microbial community more usual in the open-sea regions (Siokou-Frangou et al., 2010). Also, this model is able to take into account the limitation by different macronutrients such as nitrate, ammonia and phosphate as the maximum growth rate of phytoplankton groups are modulated by the relative concentration of each nutrient (Neumann, 2000). This is especially important for representing the Mediterranean basin as nitrate is usually limiting planktonic production in the western Mediterranean (e.g., Macías et al., 2009) whereas phosphate becomes limiting eastwards (e.g., Siokou-Frangou et al., 2010).

However, and in spite of being a potentially suitable candidate to represent the Mediterranean ecosystem, ERGOM was initially created and further developed to simulate the Baltic Sea, which has some obvious differences with the Mediterranean. Henceforth, and besides changing the values of several parameters (see Table 1), we needed also to modify and tailor the ERGOM code to our study site. As this model has been extensively described in several references in the literature (e.g., Burchard et al., 2006; Neumann, 2000; Neumann et al., 2002) we will focus here on the specific modifications made on its original implementation to adapt this model

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