Seasonal cycle of plankton production in the Iberian margin based on a high resolution ocean model

Rosa Reboveda^{a,*}
rosa.reboveda@ua.pt

Rita Nolasco^a
rita.nolasco@ua.pt

Carmen G. Castro^b
cgcastro@iim.csic.es

Xosé A. Álvarez-Salgado^b
xsalgado@iim.csic.es

Nuno G.F. Cordeiro^a
ngfc@ua.pt

Henrique Queiroga^c
henrique.queiroga@ua.pt

Jesus Dubert^a
jdubert@ua.pt

^aCESAM and Departamento de Física, Universidade de Aveiro, Campus de Santiago, 3810-194, Aveiro, Portugal

^bIIM-CSIC, Instituto de Investigaci3n Mariñas, Eduardo Cabello 6, 36208 Vigo, Spain

^cCESAM and Departamento de Biologia, Universidade de Aveiro, Campus de Santiago, 3810-194, Aveiro, Portugal

*Corresponding author.

Abstract

The seasonal variability of plankton in the entire Iberian margin and the adjacent oceanic region was simulated by applying a *NPZD*-type biogeochemical model coupled to a physical high resolution configuration of the 3D Regional Ocean Modeling System (ROMS). The *NPZD* model simulated the time and space evolution of nitrate, phytoplankton/chlorophyll, zooplankton and detritus. Model results were compared to remotely sensed sea surface temperature from AVHRR, mixed layer depth from ARGO floats, and sea surface chlorophyll-a from a monthly SeaWiFS climatology. The model was able to reasonably reproduce the seasonal cycle of phytoplankton biomass in the Iberian Atlantic margin and the adjacent oceanic region. It allowed [us](#) to make a general characterization of the spatio-temporal patterns of phytoplankton and zooplankton biomass, as well as detritus and nitrate distribution. However, some limitations in the model were revealed by the Taylor Diagrams analysis. The model seemed to overestimate the offshore spring phytoplankton bloom and the upwelling-related coastal maxima of chlorophyll-a in the shelf. On the other hand, winter chlorophyll-a decrease simulated by the model over the shelf agreed with in situ samplings reported in the literature, contrasting with the high chlorophyll-a estimations of satellite data. This evidenced that care should be taken when validating model results in the Iberian coastal region using satellite chlorophyll-a products, particularly in winter.

Keywords: Chlorophyll; Biogeochemical modeling; ROMS; Upwelling; East Atlantic; Iberian Margin; Portugal; Spain

1 Introduction

Phytoplankton biomass in the Iberian shelf reaches maxima in summer because of the fertilizing effect of the wind-driven coastal upwelling (Barton et al., 1998; Fiuza et al., 1982; Wooster et al., 1976) (Fig. 1). This physical biological

interaction makes the Iberian margin a very productive ecosystem, characterized by a rich marine biodiversity and important fishing and shellfish resources (Figueiras et al., 2002; Santos et al., 2005; Tenore et al., 1995).

Fig. 1 Region of study and model domains: the first domain (FD), comprising the Iberian Peninsula, the north of Africa (Morocco) and the Azores Islands; and the second domain (SD), comprising the Iberian margin. Main bathymetrics and topographic features are shown: Strait of Gibraltar (SG), Cape St Vicente (CSV), Gorrington Bank (GoB), Estremadura Promontory (EP), Iberian Abyssal Plain (IAP), Galicia Bank (GB), Cape Finisterre (CF) and Cape Ortegal (CO).

The upwelling season is driven by dominant northerly winds from April to September (Wooster et al., 1976), which cause an offshore Ekman transport of surface sea water and the upwelling of cold and nutrient rich subsurface Eastern North Atlantic Central Water (ENACW) (Fraga, 1981; Peliz et al., 2002; Relvas et al., 2007). Although nutrient levels of subsurface ENACW are 1/2–1/3 of those in other upwelling systems, the gross primary production for the upwelling season ($\sim 2.5 \text{ g C m}^{-2} \text{ day}^{-1}$) is similar to other coastal upwelling regions (Álvarez-Salgado et al., 2010; Aristegui et al., 2006). This fact is usually attributed to an efficient recycling (mineralization) of organic matter under periodic (1–3 weeks) wind stress–relaxation cycles (Álvarez-Salgado et al., 1993; Aristegui et al., 2009). The autumn (October–November) brings a shift to southerly winds, which favors downwelling conditions over the shelf (Álvarez-Salgado et al., 2003), coinciding with the onset of a warm and saline poleward current over the slope, the Iberian Poleward Current (IPC) (Haynes and Barton, 1990). This shift is usually coincident with a phytoplankton autumn bloom in the coast (Álvarez-Salgado et al., 2003; Bode et al., 1996; Casas et al., 1997; Castro et al., 1997). Upwelling pulses are still observed during winter which, along with water column haline stratification and nutrient supply from continental runoff, may keep chlorophyll-a concentration high (Ribeiro et al., 2005). In the adjacent oceanic region (Fig. 1) the seasonal cycle is characterized by low offshore phytoplankton biomass in summer (June–September), when nutrient depletion by strong thermal stratification occurs, and by a conspicuous spring bloom, as part of the North Atlantic spring bloom (Longhurst, 1998).

In the western Iberian margin, the event-scale variability associated to mesoscale phenomena such as fronts, eddies, filaments, and river buoyant plumes are a major factor influencing the variability of the ecosystem through a tight morphological–physical–biological coupling (e.g. Castro et al., 2000; Cravo et al., 2010; Queiroga et al., 2007; Santos et al., 2007). For example, the shelf–ocean exchange of biogenic materials is thought to be strongly influenced by such mesoscale events, the off-shelf export being favored through filaments developed during the spring–summer upwelling (Álvarez-Salgado et al., 2001, 2007; Cravo et al., 2010) in opposition to in situ mineralization favored by autumn–winter termohaline fronts developed under downwelling conditions/slope poleward flow (Álvarez-Salgado et al., 2003). Differences in the shelf width and the presence of topographical structures, such as capes, promontories and submarine canyons are

related to spatial differences in the mesoscale activity (Relvas et al., 2007), which is thought to have effects on the spatial differences in the ecosystem along the Iberian margin (Cunha, 2002).

The temporal and spatial variability of biological production in the Iberian margin has been monitored over the last decades, with field studies (e.g. Bode et al., 1996; Casas et al., 1997; Castro et al., 2006; Moita, 2001; Silva et al., 2009); satellite ocean color images (Álvarez et al., 2012a; Oliveira et al., 1994; Peliz and Fiuza, 1999; Sousa and Bricaud, 1992) or frequently a combination of both (e.g. Álvarez-Salgado et al., 2002, 2003; Joint et al., 2002; Ribeiro et al., 2005). These studies have contributed to our understanding of the planktonic ecosystem and biogeochemical functioning and variability in the Iberian margin. However, most of them are local or subregional studies and/or present a limited time coverage, due to the inherent ~~diffulties~~~~difficulties~~ of oceanographic sampling. Also, a division between the studies focusing on the NW Iberian margin and on the Portuguese margin is evident from a literature review, despite the common regional oceanography, so a joint view of the Iberian plankton ecosystem functioning and variability is usually lacking. In this respect ocean modeling can contribute to improve the current knowledge of the Iberian plankton ecosystem, complementing the spatial and temporal constraints of observations. Coupled physical~~–~~biogeochemical ocean models are useful to study the physical~~–~~biological interactions and help to understand their influence on the seasonal evolution and the variability and distribution of biogeochemical properties, as seen for other coastal upwelling systems such as California (Gruber et al., 2006; Moisan and Hofmann, 1996; Powell et al., 2006), Humboldt (Echevin et al., 2008), and Benguela (Koné et al., 2005; Machu et al., 2005). For the Iberian margin, an interannual simulation of the period 2001~~–~~2010 was carried out in Reboreda et al. (in press) for the analysis of the interannual variability of chlorophyll-a over the region, which is a companion work to the climatological analysis presented in the current work.

The aim of this work was to study the spatio-temporal patterns of the plankton ecosystem of the Iberian margin, namely the seasonal evolution over the shelf and the adjacent oceanic region. To this end, we performed climatological simulations of a high resolution regional configuration of the three-dimensional (3D) Regional Ocean Modeling System (ROMS) coupled to a NPZD (Nitrate~~–~~Phytoplankton~~–~~Zooplankton~~–~~Detritus) biogeochemical model. Special attention is given to phytoplankton pigment (chlorophyll-a) distribution, as a proxy of phytoplankton biomass and primary production. The regional configuration of the coupled hydrodynamical~~–~~biogeochemical model was forced with climatological conditions over 9 years. The following sections describe the model setup, data sets used for model validation, present the validation of model results, and show a general characterization of the spatio-temporal patterns of the plankton ecosystem in western Iberia by integrating model results and existing observations which so far were dispersed in the literature.

2 Model setup

2.1 Hydrodynamic model

A climatological simulation was run for a high resolution regional configuration of the Regional Ocean Modeling System (ROMS) (Haidvogel et al., 2008; Penven et al., 2006; Shchepetkin and McWilliams, 2005) for the Iberian margin. ROMS is a three dimensional (3D) ocean circulation model with free-surface, vertical terrain-following coordinates (sigma-coordinates), and horizontal orthogonal curvilinear coordinates. ROMS is based in the Boussinesq and hydrostatic approximations to solve the ~~inmeopressible~~~~incompressible~~ primitive equations, and it is coupled with advection/~~diffussion~~~~diffusion~~ schemes for potential temperature, salinity and biological tracers, as well as a non linear equation of state. The advection scheme is the same ~~as that~~ described in Marchesiello et al. (2009), which involves the split of advection and diffusion as a biharmonic operator, i.e., no explicit diffusion was implemented. Vertical mixing consists in the K-profile parameterization scheme (Large et al., 1994). The range of scales to be solved, from the large-scale to the mesoscale, was handled using a two-domain approach, as shown in Fig. 1. A large-scale first domain (FD) was run independently (offline) in order to provide initial and boundary conditions to our second domain (SD). The first domain (FD) included the northeast Atlantic region between 30° N~~–~~48° N and 0.8° E~~–~~32° W, and had 1/10° (~ 9 km) horizontal resolution and 30 vertical s-levels, in order to resolve the large-scale circulation features. The high-resolution domain, or second domain (SD), included the western Iberian region from the Gulf of Cádiz to northwest Iberia (Galicia) (34.5° N~~–~~45.5° N and 5.5° W~~–~~12.5° W; ~ 1200 ~~×~~ 600 km) (Fig. 1) and had ~~a~~ horizontal resolution of 1/27°~~–~~(~ 3 km) and 60 vertical s-levels in order to properly resolve the Mediterranean undercurrent, ~~which the~~ circulation ~~of which~~ is known to influence the surface transport of chemical and biological properties (Serra et al., 2010). A more detailed description of this climatological regional configuration of ROMS can be found in Nolasco et al. (2013).

The FD was initialized with temperature and salinity climatologies from Conkright et al. (2002), which also provided the open boundary conditions. The surface was forced with monthly climatological wind stress and fluxes of heat and freshwater from the Comprehensive Ocean~~–~~Atmosphere dataset (COADS; da Silva et al., 1994), computed over 1945~~–~~1989. COADS spatial resolution is 0.5° for all variables except for sea surface salinity, which is 1°. Surface fluxes were interpolated to the model grid. Initial velocities were zero and monthly geostrophic velocities (referenced to 1200 m) and Ekman velocities were calculated from the climatology and applied along the lateral boundaries. The Mediterranean outflow was introduced as a nudging condition as described in Peliz et al. (2007). The forcing for the high-resolution (SD) configuration was the same ~~as that~~ used for the FD, i.e., COADS climatology. The initialization (1st January) and the open boundary conditions of the physical boundaries were obtained using year 5 from FD. The open boundary conditions were applied following the methodology of Marchesiello et al. (2001), using the same nudging sponge layer as described in Nolasco et al. (2013). The exchange of Atlantic and Mediterranean waters at the Strait of Gibraltar was explicitly represented in the SD domain by the imposition of vertical profiles of temperature, salinity and zonal velocity at the 5 grid points at the Strait, similarly to Peliz et al. (2007).

The freshwater continental runoff from the main rivers of the region (identified in Fig. 1) was included with monthly climatological discharge values: For the Portuguese rivers, climatological values were provided by Instituto Nacional da Água (INAG); the climatological discharge of the Galician rivers was obtained from (Río-Barja and Rodríguez-Lestegás, 1992).

The SD domain was run for 6 years, having reached a stable equilibrium solution in the 3rd year, until the Mediterranean water was in equilibrium and adjusted along the western and northern Iberian margin (Nolasco et al., 2013). The month of January of the

7th year run was chosen to initialize the biogeochemical model.

2.2 Biogeochemical model

A biogeochemical *NPZD* model was run coupled to the hydrodynamic model to simulate the base trophic levels and biogeochemical components of the system. The biogeochemical model consisted of a 4-component nitrogen based ecosystem model, computing 5 state variables: nitrate (NO₃), phytoplankton (*Phyt*), zooplankton (*Zoo*) and detritus (*Det*), all expressed in mmol N m⁻³ (Fig. 2). Additionally, chlorophyll-a (mg m⁻³) is derived from phytoplankton concentration using a variable chlorophyll:carbon ratio, θ (mg chlorophyll-a (mg C)⁻¹), that is a function of light and ~~nutrients~~~~nutrient~~ availability, and a C:N ratio of 6.625 (mmol C (mmol N)⁻¹), i.e., a Redfield ratio. The variable θ describes the proportion of photosynthetically fixed carbon that is used for chlorophyll-a biosynthesis considering the model of Geider et al. (1997). Its implementation in the ocean model is described in Gruber et al. (2006). The configuration of the *NPZD* model used here is the same ~~as that~~ applied in Marta-Almeida et al. (2012), which described its operational implementation and made a first model skill assessment for a trial period.

Fig. 2 Diagram of the *NPZD* model. Model state variables (nitrate, phytoplankton, zooplankton and detritus) are represented in terms of nitrogen concentration.

The 3D time evolution of the concentration of any of the biogeochemical variables (B_i) is influenced by diffusion, horizontal advection, vertical mixing and the biogeochemical processes that act as sink or source for the variable:

$$\frac{\partial B_i}{\partial t} = \nabla \cdot K \nabla B_i - u \cdot \nabla_h B_i - (w + w_{sink}) \frac{\partial B_i}{\partial z} + SMS(B_i) \tag{1}$$

where K is the eddy kinematic diffusivity tensor, u is the horizontal velocity, w and w_{sink} are the vertical velocity and the vertical sinking rate of the biogeochemical variable (all particulated variables, except ~~zooplankton~~~~zooplankton~~), respectively. The biogeochemical processes included in the source minus sink (SMS) term are specific for each variable.

The set of *SMS* equations for each of the biogeochemical variables is:

$$SMS(N) = -\mu(PAR, T) \cdot \mu(N) \cdot Phyt + t_{D_{remin}} Det + t_{Z_{remin}} Zoo \tag{2}$$

$$SMS(Phyt) = \mu(PAR, T) \cdot \mu(N) \cdot Phyt - m_{PD} Phyt - g_{max} Zoo \frac{Phyt}{K_p + Phyt} \tag{3}$$

$$SMS(Zoo) = \beta g_{max} Zoo \frac{Phyt}{K_p + Phyt} - m_{ZD} Zoo - t_{Z_{remin}} Zoo \tag{4}$$

$$SMS(Det) = m_{PD} Phyt + m_{ZD} Zoo + (1 - \beta) g_{max} Zoo \frac{Phyt}{K_p + Phyt} - t_{D_{remin}} Det \tag{5}$$

$$SMS(\theta) = \mu(PAR, T) \cdot \mu(N) \cdot \left(\frac{\mu(T) \cdot \mu(N) \cdot \theta_{max}}{\sqrt{\mu(T)^2 + (\alpha PAR \theta)^2}} - \theta \right). \tag{6}$$

The biogeochemical processes included in the *SMS* terms represent the conceptual description that follows. Phytoplankton uptakes nitrate (NO₃) at a rate that is dependent on the instantaneous nitrate concentration and light intensity (PAR: photosynthetically available radiation), and further constrained by temperature (*T*). The nutrient (NO₃) limitation of the growth rate, $\mu(\text{NO}_3)$, is calculated by a Michaelis-Menten function

$$\mu(\text{NO}_3) = \frac{\text{NO}_3}{K_{\text{NO}_3} + \text{NO}_3} \tag{7}$$

where K_{NO_3} is the half-saturation constant for nitrate uptake by phytoplankton. *T* and *PAR* limitation of the phytoplankton growth rate, $\mu(\text{PAR}, T)$, follows the equations of Smith (1936) (Eq. (8)) and Eppley (1972) (Eq. (9)) modified to include θ .

$$\mu(\text{PAR}, T) = \frac{\mu(T) \cdot \alpha \cdot \text{PAR} \cdot \theta}{\sqrt{\mu(T)^2 + (\alpha \cdot \text{PAR} \cdot \theta)^2}} \tag{8}$$

$$\mu(T) = \ln 2 \cdot 0.851 \cdot (1.066)^T \tag{9}$$

The inclusion of θ tried to represent the expected increase in photosynthesis when phytoplankton cells allocate a higher percentage of their structure to the photosynthetic apparatus (higher θ), which seems to occur in nearly nutrient-replete regions such as the upwelling zone or in the proximity of the sub-surface chlorophyll maximum (Gruber et al., 2006). *PAR* refers to in situ PAR, and α is the initial slope of the growth versus light relationship. PAR at the surface, PAR_0 , is calculated as 43% of the incident radiation and attenuated with depth as it is absorbed by water and chlorophyll,

$$\text{PAR} = \text{PAR}_0 \cdot \exp (k_w + k_{\text{chl}a} \text{Chl}) \Delta z \tag{10}$$

where k_w and $k_{\text{chl}a}$ are attenuation coefficients for pure water and chlorophyll and Δz is the depth step. *PAR* is given in W m⁻². The total phytoplankton growth rate is written as

$$\mu = \mu(\text{PAR}, T) \cdot \mu(\text{NO}_3). \tag{11}$$

Phytoplankton dies at a constant linear rate (m_{PD}), which has been dead phytoplankton being automatically incorporated to the detritus pool. Zooplankton growth relies on its grazing on phytoplankton, which the rate of which depends on prey (phytoplankton) concentration, through a Michaelis-Menten function,

$$g = g_{\text{max}} \frac{\text{Phyt}}{K_p + \text{Phyt}} \tag{12}$$

and on zooplankton assimilation efficiency (β). A constant excretion rate ($\text{f}_{\text{excretion}}$) is attributed to zooplankton, providing a source of nutrients to the nitrate pool. Zooplankton incorporates to the detritus pool at a constant linear mortality rate (m_{ZD}). Mineralization of detritus is formulated as direct transformation to nitrate at a constant nitrification rate ($\text{f}_{\text{denitrification}}$). Model parameters values for the sink/source terms selected to represent our region of study are listed in Table 1. These parameters aimed at representing the eutrophic coastal ecosystem dominated by diatoms, what which necessarily implied reducing the ability of the model to represent correctly the oligotrophic offshore environment, as only one phytoplankton functional group was included.

Table 1 Parameter values of the *NPZD* model.

Parameter		Value	Unit
K_w	Light attenuation in seawater	0.04	m ⁻¹
$K_{\text{chl}a}$	Light attenuation by chlorophyll	0.024	(m ² mg Chla) ⁻¹
α	Initial slope of the P-I curve	1	mg C (mg ChlaW m ⁻² d) ⁻¹
θ	Maximum cellular chlorophyll:C ratio	0.03	mg Chla (mg C) ⁻¹
K_{NO_3}	Half-saturation for phytoplankton NO ₃ uptake	1.5	mmol N m ⁻³
K_p	Zooplankton half-saturation constant for ingestion	1	mmol N m ⁻³
g_{max}	Maximum zooplankton growth rate	0.9	d ⁻¹
β	Zooplankton assimilation coefficient	0.75	n.d.
m_{PD}	Phytoplankton mortality rate	0.03	d ⁻¹

m_{ZD}	Zooplankton mortality rate	0.1	d^{-1}
t_{Zmetab}	Zooplankton specific excretion rate	0.1	d^{-1}
t_{Dremin}	Detrital mineralization to NO_3 rate	0.05	d^{-1}
w_p	Sinking velocity for phytoplankton	0.5	$m\ d^{-1}$
w_D	Sinking velocity for detritus	5	$m\ d^{-1}$

The ~~concentration~~ concentrations of nitrate and chlorophyll-a for the model initial and boundary conditions were supplied by the climatological data sets World Ocean Atlas 2009 (Garcia et al., 2010) and SeaWiFS, respectively. For nitrate, seasonal (for depths down to 500 m) and annual (depths below 500 m) climatologies were used. For chlorophyll-a, the seasonal climatology of surface concentrations from SeaWiFs data was used. Seasonal vertical profiles were created from these surface concentrations using the algorithm of Morel and Berthon (1989). The initial and boundary values of phytoplankton and zooplankton were derived from chlorophyll-a ($Phyt = 0.5 \cdot Chl$; $Zoo = 0.2 \cdot Chl$), as in Gruber et al. (2006). Detritus was not available from climatological datasets, so it was introduced constant (initial and boundary conditions) with the value $0.02\text{ mmol N m}^{-3}$, as in Gruber et al. (2006). The initial and boundary conditions were built using ROMSTOOLS package (Penven et al., 2007). Boundary conditions were supplied seasonally, applying the same nudging boundary layer as for the physical variables. At the Strait of Gibraltar a constant vertical profile of nitrate (annual mean) was additionally imposed, at the same 5 grid points mentioned in Section 2.1 for the physical variables. The aim was to better characterize the nutrient characteristics of Mediterranean water and avoid numerical errors found in previous simulations. This nitrate profile was obtained from the Mediterranean nitrate climatology made available by the University of Liège (<http://gher-diva.phys.ulg.ac.be>). The riverine inputs of nitrate and chlorophyll were ~~used~~ constant ~~constantly~~ along the year (Table 2 Marta-Almeida et al., 2012).

The coupled biogeochemical-physical model ~~was~~ run for 9 more years. After just one year of spinup the model reached a stable annual cycle for all the biogeochemical variables, since it started from an already stable hydrodynamic simulation. The small year to year variations that were detected were only attributable to the internal variability of the model, since the atmospheric forcings used were climatological (i.e., without interannual variability). Model results presented were averaged over 6 years (4th to 9th climatological years) in order to smooth this internal variability.

2.3 Data sets for model evaluation

Model results were evaluated by comparison with climatological databases. Sea surface temperature (SST) was compared with data from the Advanced Very High Resolution Radiometer (AVHRR) of the National Oceanic and Atmospheric Administration (NOAA). The data were extracted from the EUMETSAT Ocean & Sea Ice Satellite Application Facility (OSI-SAF) (www.osi-saf.org) and were made available by CERSAT (IFREMER, France). The product has a horizontal resolution of about 2 km, and corresponds to the SST average over the years 2002 to 2008 of the night satellite sweep. Annual and monthly surface chlorophyll-a was compared with the correspondent SeaWiFS climatology. The climatology, averaged over the period 1997-2004, was generated by the NASA Goddard Space Flight Center (<http://oceancolor.gsfc.nasa.gov>). The horizontal resolution is 9 km.

Additionally, modeled mixed layer depth (MLD) was compared to a monthly climatology (2002-2010) constructed using ARGO ~~floats~~ float profiles within the region (Holte et al., 2010). Modeled MLD was calculated from model temperature profiles, following Lorbacher et al. ~~s~~ (2006) criteria, and averaged over the model domain along one climatological year.

3 Results

The reliability of the model to reproduce the physical and biogeochemical characteristics of the Iberian system was assessed. Firstly, a general assessment of the hydrodynamic model is presented, by comparing the SST annual average of model results with satellite (AVHRR) observations (Section 3.1). The modeled seasonal evolution of the MLD over the domain was next compared to a MLD climatology from Argo floats in the region. A detailed validation of the hydrography, seasonal circulation, vertical structure of the flow and meridional transport of this ROMS climatological configuration for the Iberian margin has been carried out by Nolasco et al. (2013). A general evaluation of the biogeochemical model to reproduce the spatio-temporal distribution of phytoplankton biomass was carried out by comparing the modeled annual and monthly means of surface chlorophyll-a concentration ([Chl]) with the correspondent means from the SeaWiFS climatology (Section 3.2). A quantitative analysis of the MLD and chlorophyll-a comparisons was performed by plotting Taylor diagrams.

In order to make a general characterization of the spatial patterns of the biomass and ~~and~~ nutrient pools in the Iberian margin, surface annual means of zooplankton, detritus and nitrate were presented and discussed (Section 3.3). Finally, the seasonal vertical distribution of chlorophyll, nitrate and detritus along the Iberian margin was analyzed through cross-shelf monthly means at three selected zonal sections (Section 3.4).

3.1 Hydrodynamic model evaluation

The conspicuous meridional gradient of SST in the region was well represented in the model (Fig. 3). The SST annual mean of model and AVHRR climatological values agreed reasonably well, presenting a bias lower than 1 °C for most ~~part~~ parts of the domain (white regions in Fig. 3(c)). However, there was a band of coastal water noticeably colder in the model than in the AVHRR climatology (typical bias of ~~-~~ 1 to ~~-~~ 2 °C). This band was restricted to the inner shelf in the NW coast ~~an~~ and the central Estremadura

promontory, whereas to the north and south of this promontory the band occupied the entire shelf (Fig. 3(c)). This bias resulted from an overestimation of the upwelling intensity during the summer (not shown; for a seasonal analysis see Nolasco et al., 2013). A colder region in the model was also observed in the SW, close to the boundary of the domain (Fig. 3(c)). On the contrary, in the NW region around cape Finisterre the modeled SST was overestimated. It seems that ~~the~~~~the~~ strong upwelling center usually found there, was not entirely reproduced by the model.

Fig. 3 Annual mean SST from ROMS model (a), from AVHRR climatology (b) and difference between them (model-AVHRR) (c). The 200 m isobath is shown.

The modeled seasonal evolution of MLD over the domain could satisfactorily reproduce the climatological seasonal evolution obtained from ARGO ~~floats~~~~float~~ profiles (Figs. 4 and 7(a)). The mixed layer depth was maximum in February (domain average ~ 150 m), corresponding to the winter vertical mixing in the region, and shoaling in the subsequent spring months to less than 50 m. The summer was characterized by a remarkable stratification of the water column from May to September and then the MLD started deepening again in autumn. Fig. 7(a) shows a correlation of 0.99 between the ~~modelled~~~~modeled~~ and ARGO MLD over the entire domain. A similar correlation was shown for the separately analyzed areas, except for the southern domain and the southern shelf, which showed a slightly lower correlation of about 0.95. The model was able to reproduce the observed variability, as shown by the similar standard deviations. The low rms indicated an overall good performance of the model, ~~been~~~~being~~ slightly higher (around 0.5) for the southern areas (Fig. 7(a)).

Fig. 4 Mixed layer depth (m) annual cycle in the Iberian margin (SD model domain) obtained from ROMS temperature profiles for the 6th climatological year (3 days averages; mean ± sd).

3.2 Evaluation of annual and seasonal [Chl] at the sea surface

The modeled annual [Chl] in the offshore region of the domain showed similar values to the SeaWiFS climatology, i.e., generally lower than 0.5 mg m^{-3} (Fig. 5). Nevertheless, in the southern part of the domain, modeled annual [Chl] was slightly higher than the [Chl] from SeaWiFS. The SeaWiFS climatology suggested that to the south of about 37° N [Chl] tended to be lower than ~~that~~ in the rest of the region, whereas this was not evident in model results, except for the southernmost limit of the domain. [Chl] was highest

over the western shelf, where model values ($\sim 1 \text{ mg m}^{-3}$) were lower than satellite-derived values ($\sim 2 \text{ mg m}^{-3}$). Higher [Chl] occurred in the northwestern shelf than in the southwestern shelf, south of the Estremadura promontory, for the SeaWiFS data, whereas this difference was not evident in the model. Over the northern and southern ~~shells~~~~shelves~~ (east of Cape Finisterre and Gulf of Cadiz, respectively), modeled [Chl] was noticeably low, contrasting with satellite values. These low values were unexpected for the shelf, suggesting an underestimation of modeled [Chl] in these areas.

Fig. 5 Annual mean of modeled surface [Chl] (mg m^{-3}) (left) compared with SeaWiFS annual mean climatology (right). Model result corresponded to ~~an average of~~ 6 years ~~average~~, and the SeaWiFS annual climatology was averaged over the period 1997–2004. Note different spatial ~~resolution-resolutions~~ in model and satellite fields.

Fig. 6 presents a comparison of monthly means of modeled surface [Chl] with the corresponding monthly means for the SeaWiFS climatology, for selected months that aim to represent the seasonal evolution of [Chl]: January (winter), April (spring), July (summer), and October (autumn). The modeled [Chl] in January was similar to that of the SeaWiFS climatology, with moderate offshore values ($\sim 0.5 \text{ mg m}^{-3}$), but as pointed out for the annual mean, modeled [Chl] over the shelf was noticeably lower than in the satellite data. The high surface [Chl] of April, corresponding to the spring phytoplankton bloom over the North Atlantic, was reproduced by the model (Fig. 6). The bloom was characterized by a marked latitudinal gradient, with [Chl] decreasing from N-~~to~~ S. [Chl] in the northern part of the domain (north of ~~42–43°~~ N) generally exceeded 2 mg m^{-3} in the SeaWiFS climatology, whereas this value was higher in model results for this area. On the contrary, modeled [Chl] seemed to be lower than in the satellite ~~climatlogy~~~~climatology~~ between ~ 40 -~~and~~ 42° N. Also for April, modeled [Chl] over the shelf was lower than in the SeaWiFS climatology. In July the surface [Chl] distribution was characterized by high values ($> 2 \text{ mg m}^{-3}$) over the shelf, as a result of the summer dominant upwelling conditions, and low offshore values resulting from thermal stratification of the water column (Fig. 6). These patterns were captured by the model, although the offshore [Chl] was considerably lower than ~~that~~ observed in the satellite climatology, except in the vicinities of the shelf, where the cross-shelf exchange was probably the reason for the increased [Chl]. As for the shelf, the modeled [Chl] was similar to that observed in the SeaWiFS climatology ($> 2 \text{ mg m}^{-3}$), showing that the model could appropriately reproduce the increase in phytoplankton biomass due to the upwelling of cold and nitrate rich subsurface ENACW driven by the prevailing northerly winds and the associated offshore Ekman transport (Fraga, 1981; Peliz et al., 2002; Relvas et al., 2007). The [Chl] over the shelf seemed to be higher in the North, off the Galician Rias Baixas and the northwestern Portuguese shelf, than in the southwestern Portuguese shelf, both in the model and SeaWiFS images. In October, low [Chl] over the shelf was obtained from model outputs, whereas SeaWiFS [Chl] over the shelf was about the same ~~as that~~ found in July. October–~~November~~ represent a transition in the ecosystem from the summer dominant upwelling situation to the autumn dominant downwelling situation (Álvarez-Salgado et al., 2003; Castro et al., 1997), driven by a shift in the wind regime from northerlies to southerlies. It also coincides with the onset of the relatively warm and saline IPC over the slope (Haynes and Barton, 1990). This shift is usually coincident with a phytoplankton autumn bloom in the coast (Álvarez-Salgado et al., 2003; Bode et al., 1996; Casas et al., 1997; Castro et al., 1997). However this coastal bloom was not evident from model outputs. The offshore [Chl] in the model remained low, contrasting with the higher values in the SeaWiFS climatology, which showed a slight increase in [Chl] in the NW offshore region. Also in October, there was an anomalous entry of high [Chl] from the southern boundary of the model domain, caused by a local intensification of the nitrate concentration through that boundary (not shown) as a result of the local circulation.

Fig. 6 Monthly mean (January [winter]; April [spring]; July [summer]; October [Autumn]) of modeled surface [Chl] (mg m^{-3}) compared with SeaWiFS monthly mean climatology. Model results corresponded to an average of 6 years averages, and the SeaWiFS monthly climatology was averaged over the period 1997–2004. Lines of 1 mg m^{-3} and 2 mg m^{-3} are shown. Note different spatial resolution-resolutions in model and satellite fields.

A quantitative comparison between monthly averages of modeled and SeaWiFS [Chl] is presented in Fig. 7(b). The correlation between the model and SeaWiFS was nearly 0.95 for the entire domain, been-which is even higher in the southern region and around 0.9 for the northern region. On the other hand, the correlation was poor for the shelf region. The variability for model results was generally higher than that for SeaWiFS. The A better rms (< 1) was obtained for the entire domain and for both the northern and southern regions, been-the rms being > 1 for the shelf region.

Fig. 7 Taylor diagrams of: (a) monthly modelled-modeled MLD (domain averaged) compared to monthly climatology (2002–2010) from Argo floats selecting profiles available for the same area; and (b) monthly modelled-modeled surface chlorophyll compared to monthly SeaWiFS climatology (1997–2004). Each diagram shows comparisons for the entire model domain (DOMAIN), for the area north and south of 39.5°N (North and South), for the western shelf area (Near Shore) and for the western shelf north and south of 39.5°N (Near North and Near South). The root mean square (rms) between the model result and the observed climatology is given by the distance between the model point and the climatology-climatology point indicated on the abscissa.

3.3 Mean Zoo, Det and NO₃ standing stocks at the sea surface

The surface annual mean of zooplankton, detritus, and nitrate obtained from model outputs for the western Iberia ecosystem are presented in Fig. 8. As expected, the zooplankton distribution resembled that of chlorophyll, as a consequence of zooplankton concentrating in the areas of highest phytoplankton biomass for grazing. Higher zooplankton biomass was reproduced over the western shelf, and progressively decreased offshore. The northwestern shelf, north of Cape Roca, showed higher zooplankton biomass than the southwestern shelf, as described also for chlorophyll (Fig. 5). This model result was in agreement with the findings of Cunha (2002) from the CICLOS cruises, who concluded that conditions for primary and secondary marine production in the western Iberian shelf were better off the northern coast than off the southern coast. In the northwestern shelf off the vicinity of the river Douro estuary, the model climatology showed higher zooplankton biomass in the outer shelf than in the inner shelf (Fig. 8). This was consistent with observations in this area showing that thermohaline fronts are preferential areas for zooplankton concentration, also separating different zooplankton communities (Queiroga et al., 2005). The southern (Gulf of Cadiz) and particularly the northern (Cantabrian) shelves presented low zooplankton biomass.

Fig. 8 Modeled sea surface annual mean of zooplankton (a), detritus (b), and nitrate (c) in the western Iberia ecosystem. All variables in mmol N m⁻³.

The detritus distribution was similar to that of chlorophyll as well (Fig. 8b), although with a more pronounced onshore-offshore decrease than phytoplankton or zooplankton biomass. This was due to the different sinking velocities (Table 1), as the detritus sinking velocity was one order of magnitude higher than the phytoplankton sinking velocity (no sinking velocity attributed to zooplankton). As a result, the detritus was less susceptible to surface offshore transport. The sinking velocities used here for phytoplankton and detritus are commonly used in other modeling studies (e.g. Gruber et al., 2006; Koné et al., 2005). As described for phytoplankton and zooplankton biomass, surface detritus concentration was higher over the northwestern shelf than over the southwestern shelf.

The nitrate distribution (Fig. 8b) was characterized by a latitudinal and onshore-offshore gradient. In addition, the model reproduced a marked onshore-offshore gradient of nitrate as a consequence of the upwelling of subsurface ENACW along the shelf mainly during the spring-summer upwelling favorable wind conditions.

3.4 Seasonal vertical distribution of Chl, NO₃ and Det along the western Iberian shelf

Differences in the vertical seasonal distribution of chlorophyll-a, nitrate and detritus along the western Iberian shelf were explored plotting three cross-shelf monthly averages from model results at 42° N, 40° N, and 38° N (Figs. 9, 10, and 11). Monthly averages of the thermohaline properties were also plotted with chlorophyll (Fig. 9). Each of the four months plotted aimed to represent a particular season (January-Winter, April-Spring, July-Summer, October-Autumn). The latitudes for the cross-shelf sections were selected to represent the spatial differences in the shelf characteristics along the western Iberian margin. The 42° N section represented the northern shelf off the Galician coast, with an irregular coastline due to the presence of four coastal embayments, the Rias Baixas, and medium shelf width. The wide shelf between the river Minho mouth and Cape Roca (Fig. 1) was represented in the section at 40° N, whereas the southern narrow shelf between Cape Roca and Cape São Vicente was represented in the 38° N section. Both areas present a regular coastline with meridional orientation. In addition, a main difference between them was the higher continental runoff to the northern shelf than to the southern shelf.

Fig. 9 Cross-shelf vertical sections of modeled chlorophyll (mg m⁻³, color scale), temperature (solid line, depicted every 2°), and salinity (dashed line, depicted every 0.1 psu) monthly means (January: Winter; April: Spring; July: Summer; October: Autumn) across 3 locations in the western Iberian margin: 42° N, 40° N, and 38° N.

Fig. 10 Cross-shelf vertical sections of modeled nitrate (mmol N m^{-3} , color scale and solid contour line) across 3 locations in the western Iberian margin: 42° N, 40° N, and 38° N.

Fig. 11 Cross-shelf vertical sections of modeled detritus (mmol N m^{-3} , color scale and solid contour line) across 3 locations in the western Iberian margin: 42° N, 40° N, and 38° N.

In the three sections the evolution of [Chl] along the year was similar to that described in Section 3.2, i.e., a progressive increase from winter (January) to spring (April), when the maximum of the spring bloom occurred, and a summer (July) coastal maximum associated to the prevailing upwelling conditions, as evidenced by the upward blending of the isotherms near the coast (Fig. 9). Offshore, surface [Chl] was low during summer and autumn (October) due to surface nitrate depletion caused by strong thermal stratification (Figs. 9 and 10). Nevertheless, a subsurface [Chl] maximum developed at about the base of the thermocline, at ~ 50 m. The [Chl] at the subsurface maximum and particularly at the surface coastal maximum noticeably decreased from North to South, supporting the idea that conditions for primary production are more favorable in the wide northwestern shelf than in the narrow southwestern shelf (Cunha, 2002). Subsurface upwelled water was colder, less saline and showed a higher nitrate concentration in the northwestern shelf than in the southwestern shelf (Figs. 9 and 10). This illustrated the prevalence of ENACWp in the northern shelf, and of ENACWt in the southern shelf. Also, as the residence time of upwelled water in the narrow southern shelf was lower, i.e., the nitrate rich water was more rapidly washed-out, it was less available for in situ phytoplankton growth. Nonetheless, [Chl] was higher in the 42° N section than in the 40° N section, in spite of the narrower shelf width, which suggested a higher influence of the characteristics of the upwelled water than of the shelf width.

The detritus distribution was similar to the chlorophyll distribution, with the highest concentrations offshore during the spring bloom and a coastal and subsurface maximum during the summer upwelling (Fig. 11). The low salinity over the shelf at 42° N and 40° N (< 35.8) in January showed the influence of the rivers discharge, with the presence of the WIBP (Peliz et al., 2002) delimiting an area of higher [Chl] over the shelf ($\sim 0.5 \text{ mg m}^{-3}$) where stratification favored phytoplankton growth (Ribeiro et al., 2005). Maximum salinity cores showed the presence of the IPC in October and January in the vicinities of the shelf, although no evident effect on [Chl] could be detected from model results.

4 Discussion

4.1 Model evaluation

The overestimation of the summer upwelling intensity by the model, revealed by the lower modelled-modeled SST, has also been detected and described in Nolasco et al. (2013). Note that climatological winds do not account for the drop-off of the wind stress in the neighborhood of the coast (Veitch et al., 2010, and references therein), and thus the upwelling is overestimated. Also, climatological wind data lack the synoptic variability that characterizes the Iberian upwelling, with typical intermittent upwelling/relaxation events of 1–3 weeks (Álvarez-Salgado et al., 1993; Aristegui et al., 2009). On the other hand, Dufois et al. (2012) have alerted for a warm bias in satellite observations nearshore in eastern boundary upwelling systems. The overestimation of modelled-modeled SST detected around Cape Finisterre is most likely a consequence of the particularities of the real wind field around this area. According to Torres et al. (2003) the wind field in this area is very heterogeneous and has a number of dominant patterns that are responsible for

the typical distributions of upwelling/downwelling off the Galician coast, namely the formation of filaments. For their analysis they used Quikscat real winds (0.25° resolution) and in situ wind observations over two years (1999–2001). Thus, due to the particular structure of the observed wind field, the climatological winds cannot properly reproduce the offshore extension of upwelling observed off NW Galicia, given its seasonal averaged nature.

As for the low annual [Chl] model outputs over the shelf, compared to SeaWiFS annual climatology, some underestimation could occur in model results. However, an overestimation of SeaWiFS [Chl] in the Iberian coastal region is also likely, as this effect has been reported for the coastal zone when using SeaWiFS data, originated by errors in the algorithm estimations of [Chl] (Le Fouest et al., 2006). On the other hand, the underestimation of modelled-modeled [Chl] over the shelves east of Cape Finisterre and Gulf of Cadiz, respectively, were probably related to the limitations of the COADS wind forcing to reproduce the synoptic wind variability mentioned in Section 3.1. The averaged wind probably lacked the occurrence of winds with significant zonal component which induce upwelling events in the northern and southern shelf (García Lafuente and Ruiz, 2007; Ospina-Alvarez et al., 2010), in contrast to the dominant northeasterlies that induce upwelling in the N-S oriented western shelf. Nevertheless, in the case of the Galician coast, a general north to south increase in [Chl] has been reported (Álvarez et al., 2012a; Bode et al., 1996). It has been attributed to the parallel increase in nutrients-nutrient mineralization to the south, which is thought to be a consequence of coastal morphology, namely the presence of the Rias Baixas, four large coastal embayments in the southwest Galician coast which export organic matter to the adjacent shelf (Álvarez-Salgado et al., 1993, 1997; Fraga, 1981; Prego et al., 1999).

The underestimation of [Chl] over the shelf revealed by the seasonal analysis, namely in January (winter), may also be attributable to an overestimation of [Chl] in the SeaWiFS data for the coastal zone, as already discussed, specially considering the expected higher amount of suspended matter from increased continental runoff in winter, interfering with the remotely sensed [Chl] estimations. Nonetheless, it is possible that the use of climatological rivers in the model, i.e., monthly averaged discharges and constant nutrients (nitrate) concentrations, was not able to reproduce the input of nutrients and stratification conditions that is thought to contribute to some events of [Chl] increase in the Western Iberia Buoyant Plume (WIBP) (Ribeiro et al., 2005). In addition, the lack of synoptic winds already mentioned could not account for the episodic upwelling events known to occur in winter (Álvarez et al., 2012b; Ribeiro et al., 2005). These limitations of the wind forcing have been reported when modelling-modeling other upwelling regions (Gruber et al., 2006).

The differences in [Chl] over the northwestern and southwestern shelves pointed out by the model in July (summer) have also been observed in data obtained during the CICLOS cruises, that seasonally sampled the Portuguese shelf during 1985–1986 (Cunha, 2002; Moita, 2001). They were mainly attributed to the wider extension of the northwestern shelf compared to the southwestern shelf and the possible differences in the upwelling dynamics associated. Also, high mineralization rates have been found for these areas of the northwestern shelf, increasing the potential primary production (Álvarez-Salgado et al., 1997).

The seasonal evolution of [Chl] described from model results seemed to be related with the seasonal variation of the MLD described in Section 3.1 (Fig. 4). During summer, high SST induced the developement-development of a shallow MLD, which seemed to correspond to low [Chl] offshore, due to nutrients-nutrient depletion (Fig. 6, July). The autumn–winter deepening of the MLD seemed to supply new nutrient-nutrients to allow phytoplankton growth offshore (Fig. 6, January). The spring bloom coincided with the steep shoaling of the MLD (Fig. 6, April).

The contrasting seasonal evolution of [Chl] over the shelf between the SeaWiFS climatology, which showed high [Chl] for every season, and the model results, which indicated noticeable changes in [Chl] along the year, rose-give rise to the question of whether the satellite data overestimate-were-overestimating or the model results underestimate-were-underestimating [Chl] values over the shelf. Comparisons with in situ observations were limited by the scarcity of data series with enough time and space distribution along the western Iberian shelf. Still, comparisons with surface [Chl] data provided by the referred CICLOS cruises over the western and southern Portuguese shelf (CICLOS I, August 1985; CICLOS II, November 1985; CICLOS III, January 1986; CICLOS IV, March 1986) revealed a similar seasonal evolution of [Chl] to that reproduced by the model. The highest [Chl] was found in August (summer) (~ 1–3 mg m⁻³), and moderate [Chl] occurred in November and March (autumn–spring) (~ 0.5–1 mg m⁻³), whereas the lowest surface [Chl] was found in January (winter) (~ 0.5 mg m⁻³) (Moita, 2001). For the northwestern Iberian shelf off Galicia, Álvarez-Salgado et al. (2003) showed some [Chl] data from several cruises carried out in the region during the 80s–90s at different times of the year. Low surface [Chl] was observed during January 1998 (winter, CD110b cruise), comparable to model results, and they drew attention to an in situ value of 0.85 mg m⁻³ contrasting with the 2.2 mg m⁻³ SeaWiFS estimate at the same location (albeit 6 days later). On the contrary, high [Chl] was detected during late winter 1984 (February–March, GALICIA VII cruise) in the same region, but coinciding with a period of upwelling favorable winds (Álvarez-Salgado et al., 2003). High surface [Chl] (> 3 mg m⁻³) was also observed during June–July 1998 (Bg9815c cruise) under a typical summer upwelling situation, comparing well with both model and SeaWiFS data. The autumn [Chl] values of September 1991 (GALICIA XII cruise) and November–December 1993 (MORENA II cruise) were considerably high (> 1 mg m⁻³), contrasting with the low modeled [Chl] of October. The late spring cruise of May 1993 (MORENA I) found unexpected-unexpectedly low [Chl] values for this time of the year, because of the dominant downwelling conditions, and thus it did not compare well with neither the model or-nor the SeaWiFS climatology. These comparisons supported that care should be taken when evaluating the model performance over the shelf based only on SeaWiFS estimations, as previously pointed out.

4.2 Mean Zoo, Det and NO₃ standing stocks at the sea surface

The low zooplankton biomass obtained from model outputs over the Gulf of Cadiz and Cantabrian shelves was likely a consequence of what was already discussed for chlorophyll, i.e., the limitations of the climatological wind forcing for this part of the coast with a different orientation.

The latitudinal gradient of nitrate was a manifestation of the regional hydrography characterized by the presence of two subsurface branches of ENACW: a water branch of subpolar origin (ENACWp) to the North, with higher nitrate concentration, and a water branch of subtropical origin (ENACWt) and lower nitrate concentration to the South (Fiuza, 1984; Fiuza et al., 1998; Perez et al., 1993; Rios et al., 1992), which the model was able to reproduce. Another relevant feature known to cause the nitrate latitudinal gradient was the shallower winter vertical mixing in the south (~ 100 m) compared to that in the north (~ 300 m), resulting in a general northward increase in the nitrate concentration (Perez et al., 2005).

4.3 Seasonal vertical distribution of Chl, NO₃ and *Det* along the western Iberian shelf

The shelf width differences seemed to strongly influence the detritus concentration and fate, as the highest detritus concentration occurred over the wider shelf, at 40° N, and the lowest detritus concentration was that over the narrower shelf at 38° N. In the narrow southwestern shelf the subsurface maximum of detritus reached farther offshore, indicating that organic matter export was favored in opposition to accumulation. Cunha (2002) proposed that over the western Iberian shelf phytogetic material is advected from the north into the south under northern winds and that part of this material sinks in the south increasing benthic production due to higher bottom detritus concentration, contrasting with the higher pelagic production in the north. However, model results did not show higher detritus concentration reaching the shelf bottom in the south that would support this hypothesis. The northern shelves receive a higher freshwater input (average/climatological river outflow was used in the model), which seemed to have an effect on the winter chlorophyll cross-shelf distribution (Fig. 9).

5 Summary and conclusions

The coupled hydrodynamic-biogeochemical model was able to reasonably reproduce the climatological seasonal cycle of phytoplankton biomass in the Iberian Atlantic margin and the adjacent oceanic region. It allowed to make a general characterization of the spatio-temporal patterns of phytoplankton biomass (chlorophyll-a), as well as a general characterization of zooplankton, detritus and nitrate distributions. These model results were discussed together with remotely sensed data and in situ observational data from the literature, giving for the first time a joint picture of the plankton ecosystem variability in western Iberia, limited so far for the difficulties of long time and space oceanographic samplings. The implementation of the ocean-biogeochemical model to the Iberian margin is also an important contribution for potential research applications and forecast of ocean biogeochemical properties. Still, during the evaluation process some differences with the remotely sensed climatologies were detected, which should be taken into account. Namely, the anticipation and overestimation of the offshore spring phytoplankton bloom, and the overestimation of upwelling-related coastal maxima in the northwestern shelf, apparently due to the intensified upwelling in the model. On the other hand, the rather constant [Chl] over the shelf retrieved from satellite estimations contrasted not only with the marked seasonality of modeled [Chl], which showed a considerable decrease in winter, but also with in situ samplings reported in the literature showing a similar seasonal evolution. This evidenced that care should be taken when validating model results in the Iberian coastal region using satellite [Chl] products, as there seemed to be an overestimation in remotely sensed [Chl] values, particularly in winter.

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Highlights

- A NChIPZD biogeochemical model was implemented to the Iberian margin.
- Model results were discussed together with remotely sensed data and in situ observations.
- A characterization of the seasonal cycle of the plankton ecosystem is presented.
- Over the shelf, a general north-to-south decrease in plankton biomass was detected.
- Differences in the shelf width influenced the offshore export of detritus.

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