Biophysical 3D modeling approach of the Canary Current System: a ROMS-PISCES coupling study

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Abstract

Eastern Boundary Currents host complex ecosystems due to the large variability induced by oceanic processes at the mesoscale (10-100 km) and sub-mesoscale (1-10 km) levels. Biophysical models are increasingly useful tools to reproduce and understand this variability. Although physical-biological models have been developed for the California Current and the Humboldt Current upwelling ecosystems, there is at present little information about the Canary Current Ecosystem (CCE). Here we provide for the first time results of a ROMS (Regional Oceanic Modeling System) circulation model coupled to a PISCES (Pelagic Interaction Scheme for Carbon and Ecosystem Studies) biogeochemical model in the CCE. PISCES simulates marine biological productivity and give insights to the spatial-temporal variability of the carbon and inorganic nutrient (P, N, Si, Fe) cycles. As a first step we have used the inferred modeled chlorophyll as a proxy for the model performance. We observe that the modeled temporal patterns of chlorophyll distribution closely agree with surface chlorophyll observations derived from remote sensing, although concentrations in the open ocean seem to be underestimated. Chlorophyll distribution is also compared with in situ data, observing good agreement. We also provide guidelines to improve the model at forward steps.

Las denominadas Corrientes de Frontera Este comprenden ecosistemas complejos debido a la presencia de procesos a mesoscala y submesoscala que aumentan la variabilidad del sistema. Los modelos de acoplamiento físico-biológico son herramientas bastante interesantes para ayudar a entender dicha variabilidad. Aunque se han desarrollado modelos para los sistemas de afloramiento de las Corrientes de California y de Humboldt, el Ecosistema de la Corriente de Canarias sigue sin ser ampliamente estudiado bajo este enfoque. En este trabajo mostramos los primeros resultados de un modelo acoplado ROMS (Sistema de Modelización de Oceanografía Regional)-PISCES (Esquema de Interacción Pelágica para Estudios de Carbono y de Ecosistemas) para el Ecosistema de la Corriente de Canarias. PISCES simula la productividad oceánica y la variabilidad espacio-temporal de los ciclos de carbono y de nutrientes (P, N, Si, Fe). Como un primer paso, hemos usado la distribución de clorofila como proxy para determinar el funcionamiento del modelo. Se ha observado que los patrones de la distribución de clorofila concuerdan bastante bien con las observaciones realizadas por imágenes de satélite, aunque también se observa que el modelo subestima los valores de las concentraciones. También se compara la distribución de clorofila en la columna de agua con datos reales observándose una buena relación con la clorofila modelada. Además, se incluyen directrices a seguir para mejorar el modelo.

Key words: ROMS, PISCES, modeling, bio-physical coupling, chlorophyll distribution

1 Introduction

In general, the so-called Eastern Boundary Currents (EBC) such as California, Canary, Humboldt and Benguela Currents account for the most productive coastal environments (Carr, 2001), hosting upwelling marine ecosystems of big complexity due to the incidence of different scale processes. The Canary Current Ecosystem (CCE, hereafter), first described by Barton (Barton et al., 1998), has strong geographical diversity along its range (Arístegui et al., 2009) . Former studies on the 70's and 80's (e.g. Braun, 1980) described the CCE as oligotrophic by the fact of the low availability of nutrients. However, more recent studies have changed this view, partly because the observation, by satellite images and in situ measurements, of recurrent mesoscale variability in the region (see Arístegui et al., 1994). Indeed, the zonally-distributed Canarian *archipelago* at around 28$^{\text{o}}$N of latitude act as a barrier both to the weak equator-ward flow of the Canary Current and the Trade winds from north, inducing the development of meso- (and submeso-) scale eddies that can have a profound impact in the productivity of the area (Arístegui et al., 1994 ; Arístegui et al., 1997). Likewise, filaments from the nearby upwelling region may contribute to the export of organic matter offshore enhancing productivity as well (Arístegui et al., 2009). Besides short-scale processes, the inter-annual variability of the upwelling modulates productivity distribution on the CCE. Based on Barton et al. (1998), the productivity cycle in the Canaries waters spans three periods: (1), The late-winter bloom, when the seasonal thermocline erodes and mixing allows the input of nutrients into the photic layer; (2) Summer, when the trade winds are stronger and, hence, coastal upwelling more intense, although productivity is lower than during the late-winter bloom; (3), Autumn when stratification is at its most, due to the surface warming and the decrease in wind intensity, and productivy drops down. Such a complex system leads to a narrow coupling between physical and biological processes that would need not only of satellite and in situ studies, but also other techniques like biophysical coupled modeling, because the selective sampling cannot cover all variability displayed by this system.

Oceanographic modeling has helped the understanding of the different EBC systems. All of these systems share a high biological productivity as consequence of the nutrients supply from upwelling, due to the equator-ward winds that push surface waters offshore through Ekman transport, and allow deeper and richer waters to upwell. Nevertheless, a strong variability along the upwelling range and the presence of meso- and submeso-scale features are characteristics of EBC systems (Gruber et al., 2006). In general, the California Current System is the most studied EBC and has been object of physical-biological coupled model studies, but very little has been made in terms of modeling in the other 3 large upwelling ecosystems.

The very first coupled models were based on a Fasham-kind nitrogen-based biogeochemical simulation (Fasham et al., 1990). Indeed, Fasham et al. (1993) applied its own nitrogen-based approach to a physical model of the North Atlantic showing a good agreement with the chlorophyll distribution simulated. Since then, a big effort has been made to develop more complete and better resolution simulations. Recently, Echevin et al. (2008) solved the lack of studies out of California Current by coupling a biogeochemical model with a physical one for the Peruvian Upwelling system (part of the Humboldt system). In this study a Regional Oceanographic Modeling System (ROMS; Shchepetkin and McWilliams, 2005) configuration was coupled with a more complex nitrogen-based biogeochemical module called PISCES (Pelagic Interaction Scheme for Carbon and Ecological Studies; Aumont and Bopp, 2006). The simulation outputs were compared with satellite and in situ data showing that simulation agreed pretty well with real data. Taking that into account, the coupled model was used to investigate the mechanisms controlling chlorophyll distribution as a proxy of the productivity in the area. Keeping the good agreement between simulation and reality in EBC systems in mind, Lachkar and Gruber (2011) has recently compared the California and Canary Current systems using a coupled model with a slightly simpler nitrogen-based biological model than PISCES. They aimed to demonstrate that physical conditions control the biological productivity in both upwelling systems. They found that, though nutrient concentrations were higher in California, production was almost half than in the Canary counterpart. The authors explained this paradox, by a longer residence time of the upwelled waters in the CCE due to a lower influence of mesoscales processes –although several studies indicate a high occurrence of these features along the CCE (Arístegui et al., 1997 ; Sangrá et al., 2009)-. More modeling studies, with a higher temporal and spatial resolution, are therefore necessary to address this question properly.

In this paper we present a first approach of a physical-biogeochemical coupled model for the CCE using a combined ROMS and PISCES biophysical model. The main goal of the study is to present preliminary results of the model performance and its capacity to reproduce key processes in the area. To look at correlations with real data we have used satellite imagery, data from the World Ocean Atlas (WOA) and other published in situ studies. Chlorophyll distribution has been used extendedly as a proxy of the primary production of a region; especially since color satellite images were first used (Gower et al., 1980). Even though we are aware that the use of chlorophyll as a proxy has some problems (it can be just the excess of zooplankton grazing; Arístegui, 1990) we chose chlorophyll distribution as an indicator of the degree of agreement between simulation and reality, due to the availability of data from remote sensing studies. In general, the model reproduces qualitatively well the chlorophyll distribution patterns, although underestimates quantitatively the chlorophyll concentrations. Possible biases sources will be discuss in order to arrange solutions for latter attempts. Additionally, we also looked at organic matter distribution and physical parameters relationships with the simulation to evaluate the model performance.

2 Methods

For our simulation we have coupled an IRD (Institut de Recerche pour le Dèveloppement) version of ROMS (Penven et al., 2006) with a biological module based on the biogeochemical model PISCES. The simulation was run for ten years and the outputs averaged monthly in order to look for seasonality on the results. In general, the information goes into the model grid by a forcing coming through the boundaries. There can be problems on the initial states due to differences between the resolution of the forcing and the model. We do not consider the first year of simulation, even though it is based on an already steady state solution, to avoid any boundary undesirable effect.

2.1 The physical model

We have used ROMS to simulate the physical dynamic of the area. ROMS is a free surface, sigma vertical coordinate -designed to enhance resolution near the sea surface-, primitive equation of flow model system, which employs a mode-splitting algorithm to separate the natural time-scale between barotropic and baroclinic processes, by solving the vertically-integrated barotropic momentum equations (Shchepetkin and McWilliams, 2009). The prognostic variables are surface elevation, barotropic and baroclinic horizontal velocity components, temperature and salinity, besides density which is derived from the state equation of Jackett and Mcdougall (1995) . For the biological purposes it is relevant to notice that the open boundary conditions are formulated as a combination of outward radiation and flow-adaptive nudging toward prescribed external conditions (Gruber et al., 2006).

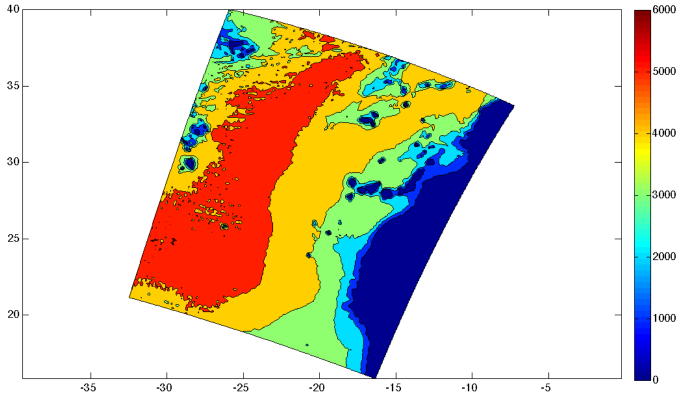


Figure 1: Model domain bathymetry. The grid has been rotated 20.75º clockwise.

In this study, we have used a method of grid nesting that consists on modifying boundary conditions by using an outer grid (called the parent). This would be matched with the interior grid (the child) optimizing the final solution thanks to the use of a checked stable less resolution simulation to force the final higher-resolution simulation. This method is called roms2roms and it was formulated by E. Mason and J. Molemaker (Mason et al., 2010). The child grid has 296x242 grid points being its horizontal resolution 7.5 km and having 32 sigma-levels in the vertical, with an increase of resolution near the surface, being the stretching factors of surface and bottom respectively 6 and 2. The use of sigma coordinates makes the vertical resolution to depend on depth, meaning that the different levels do not have the same depths along its amplitude (Echevin et al., 2008). All depths shallower than 10m were reset to 10m.

Fig. 1 shows the child grid topography, which includes the Canary Islands *archipelago* and a large portion of the Canary upwelling region from Cape Blanc (20.08º North) to Cape Ghir (30.06º North). Furthermore, due that the domain is rotated clockwise (20.75º), in order to close the eastern boundary with the African coast, keeping opened the southern, western and northern boundaries, the grid reaches 40ºNorth and 15º South in its limits. The model is forced by COADS ocean surface monthly climatology (da Silva et al., 1994) and uses grid nesting to force the three lateral open boundaries. The model applied to force the open boundaries corresponds to the widely validated eddy-resolving physical model developed by Mason (2009) and Mason et al. (2011) . It is expected that the general flow follows the characteristics of the subtropical gyre (Machín et al., 2006). ROMSTOOL QuikSCAT wind climatology is used as it has a resolution of 0.5 degrees (Penven et al., 2008) that is suitable for our simulation.

2.2 The biogeochemical model

For this simulation we have coupled PISCES to our physical solution. PISCES is a biogeochemical model derived from HAMOCC5 (Hamburg Model of Carbon Cycle (Aumont et al., 2003) which, in turn, has derived from HAMOCC3.1 (Six and Maier-Reimer, 1996). PISCES simulates the marine biological productivity and describes the biogeochemical cycles of carbon and the main nutrients (P, N, Si, Fe). It assumes, as describes by Monod (1958) , that phytoplankton growth is directly limited by the external availability in nutrients (Aumont and Bopp, 2006). This assumption makes PISCES to be simpler than other similar models but, in turn, allow PISCES to be suited for a wide range of scales. It is a Redfield-like model because it assumes constant Redfield ratios for C, N and P on all the living compartments. The internal concentrations of Fe and Si are simulated as a function of the external concentration of nutrients and of the light level (Aumont and Bopp, 2006).

PISCES has twenty-four compartments divided as follows:

- Five modeled limiting nutrients for phytoplankton growth: Nitrate, Ammonium, Phosphate, Silicate and Iron. Due to the use of Redfield ratios, phosphate and nitrogen (Nitrate+Ammonium) pools, are not really independent.

- Four living compartments including two phytoplankton size-classes and two zooplankton size-classes. Phytoplankton is divided into nanophytoplankton and diatoms, while zooplankton comprises microzooplankton and mesozooplankton. Phytoplankton prognostic variables are iron, chlorophyll and silicon contents, and so, as a consequence, the phytoplankton ratios of Fe/C, Chl/C and Si/C are fully predicted by the model. Diatoms differentiate from nanophytoplankton by their dependence on Si and Fe and by higher half-saturation constants.

  Regarding zooplankton, only total biomass is modeled. Microzooplankton grazing depends on temperature and grazes over nanophytoplankton. Observations have shown that diatom biomass increases by the addition of larger cells that escape grazing by microzoplankton. Thus, PISCES assumes that above a certain concentration of diatoms, the excess is unavailable to microzooplankton. Mesozooplankton grazing is parametrized as they grazes always over the preferred-prey. This avoid the maintenance of great amount of mesozooplankton when small cells dominate the system. Moreover, a flux-feeding grazing is added for mesozooplankton grazing as it has been shown to be very important for the fate of particles below the euphotic zone (Stemmann et al., 2004).

- Three non-living compartments of organic carbon are considered: semi-labile dissolved organic carbon (DOC), and two sizes of particulate organic carbon (POC). Again, Redfield ratios are used for all nutrients except iron, silicon and carbonate which are modeled. The sedimentation rate, dependent on the "ballast effect" (i.e. the particles content in calcite and biogenic silicate; Armstrong et al., 2001) is not taken into account in this formulation. Aggregation of particles are due to turbulent shear and differential settling, transferring carbon from the semi-labile DOC pool to the two size of particulate material (Gehlen et al., 2006). The sedimentation of particulate material is a function of the mortality and aggregation (depending on the proportion of calcifying organisms in nanophytoplankton and on biogenic silica density in diatoms).

In the outputs of the model we can also find dissolved inorganic carbon, total alkalinity and dissolved oxygen with C/O2 ratios proposed by Takahashi et al. (1985). Chlorophyll is prognostically predicted based on the external concentrations of the limiting nutrients and parameterized using the photo-adaptive model of Geider et al. (1998). Its concentration depends on the chlorophyll-to-carbon ratio, which has been recognized as a major source of errors in phytoplankton growth studies.

2.3 Observational data

The model outputs were compared to satellite imagery. Particularly, monthly averaged SeaWiFS (Sea-viewing Wide Field-of-view Sensor) chlorophyll images were resized to fit the model child grid and used to compare with model data. SeaWiFS is a multispectral radiometer sensor that has been in orbit since 1997 (Franz et al., 2005) covering a wavelength range of 400-900nm. It uses algorithms to estimate Chlorophyll a concentration at surface (O'Reilly et al., 1998) with a spatial resolution of about 9km at the equator (Signorini et al., 1999), slightly larger than our model. In general, ocean color remote sensing has several sources of bias like cloud effects, ice, phytoplankton diversity, etc. SeaWiFS has been used for a high number of studies including modeling, algal bloom studies, inter-annual variability studies, etc.

Additionally, we have used in situ chlorophyll data collected in several oceanographic surveys in the past years to compare with our model results. The project COCA (Coastal-Ocean Carbon Exchange in the Canary Region) consisted in two surveys carried out on board the BIO Hespérides at the end of summer 2002 (COCA1) and beginning of summer 2003 (COCA2). Two zonal sections north and south the Canary Islands were sampled for many biogeochemical parameters, including phytoplankton pigments in the water column.

Several studies carried out in the vicinity of the Canary Islands have been used to make comparisons to reality as well. Barton et al. (1998) is an overview of the dynamic of the CCS. They used data from three oceanographic cruises on three different periods to cover interannual variability: (1) the end of the winter period, when a bloom takes place; (2) the strongest Trade wind period, when coastal upwelling is most developed; and (3) early autumn, when winds are weakest and stratification is strongest. They differentiates 4 areas depending of being affected by coastal upwelling and/or by the islands-perturbation of the Canary Current flow. It was also consulted a work carried out around Gran Canaria island by Arístegui and Montero (2005). This work was aimed on the effects of the mesoscale features over respiration and biomass. It includes measurements of chlorophyll on mesoscale features that can help to elucidate the performance of the simulation in representing the enhancement of productivity induced by eddies.

To compare the distribution of the modeled organic matter we have used mainly the study carried out recently by Alonso-González. Alonso-González et al. (2009) studies the lateral advection of POC from margins to the open ocean at the islands' latitude with a box-model approach. It includes 2D profiles of POC distribution across the water column from 0 to 3000 derived from an oceanographic survey carried out west of the Canary Islands.

3 Results

3.1 Surface chlorophyll distribution

PISCES splits chlorophyll into two compartments; NCHL (chlorophyll due to nanophytoplankton) and DCHL (diatoms' chlorophyll). For the purpose of this study, chlorophyll compartments were added and used as one output. However, it is interesting to note that nanophytoplankton chlorophyll dominates on every season over diatoms chlorophyll on these waters as it was expected (Fig. 2). Previous studies have pointed out the dominance of nanophytoplankton over diatoms in waters of this area (Bode et al., 2001). In general, diatoms and other large phytoplankton are abundant when the enrichment of surface waters with newly upwelled nutrients supports relatively high productivity in coastal upwelling areas (Baltar et al., 2009). However, in waters of the CCS, the production is thought to be dominated by smaller cells, like in other oligotrophic regions (Quevedo and Anadón, 2001). NCHL represents around 70% of the total chlorophyll concentration near the coast, except in the summer when nanophytoplankton largely dominates, representing about 90% of the total chlorophyll. Offshore, NCHL ranges from 90 to almost 99% of the total chlorophyll but this percentage decreases in summer when diatoms account for almost 25%.

Chlorophyll (all sizes) surface distribution maps from satellite imagery for the Canary Current area display the typical pattern of upwelling regions with higher concentration near coast and decreasing offshore (e.g. Small and Menzies, 1981). Since SeaWiFS chlorophyll product does not represent surface data alone but penetrates some meters on the water column (depending on the light penetration), the two nearest surface layers of modeled chlorophyll data were combined. Because depth levels in the model are based on sigma-coordinates, this exercise will improve the chlorophyll comparison especially on coastal area where the differences on depth of the layers are small. Upwelling is present all year round, being more intense roughly between 15 and 20ºN, in the area of Cape Blanc (Nykjaer and Van Camp, 1994 ; Pastor et al., 2008). This trend can be seen both on SeaWiFS and the model. The convective mixing that takes place in winter on temperate seas, may explain the presence of high chlorophyll concentrations in the northern part of our region of study. Mesoscale variability assciated both with the Azores Front and the Madeira eddy corridors (see Sangrá et al., 2009) may contribute as well to the high chlorophyll concentrations in the northern region.

Modeled chlorophyll is compared with SeaWiFS satellite imagery (Figure 3) seasonally averaged to show inter-annual variability over a period of years (ten in the case of the model). In general, the model reproduces qualitatively well the observed patterns. In particular, the model clearly shows the increment of chlorophyll concentration off Cape Blanco induced by the coastal upwelling and the westward offshore transport of this chlorophyll. Furthermore, higher concentrations of chlorophyll located along the African coast are well reproduced by ROMS-PISCES simulation, stressing the importance of the enhancement on nutrients supplied by the upwelled waters. Nevertheless, there is an underestimation of the chlorophyll concentrations from the model output. The maximum concentration modeled that is found at surface level is about 0.7 mgChl/m3, being more than double the highest values from the sensor imagery. In general, the resolution of this simulation, although able to simulate mesoscale processes, may underestimates the submesoscale presence. Moreover, eddy/wind interactions that occur in the area are not taking into account by the model, and may contribute also to this underestimation.

A glimpse on the seasonality of the surface chlorophyll reflects the behavior of the CCS. The presence of a quasi-permanent thermocline on the surface waters around the Canary Islands restricts the productivity and, hence, phytoplankton accumulation (Arístegui et al., 2001). The vertical flux of nutrients from deep waters are mainly due to diffusive mixing, being strong convective mixing very limited. During winter, the surface cooling weakens the thermocline and the mixed layer deepens in the water column. This event has its maximum about March (Barton et al., 1998) when the so-called “Late-winter Bloom” takes place and chlorophyll concentration reaches its maximum values (up to 1.5 mg Chl/m3), mainly due to the presence of large phytoplankton. However, the bloom is short-lived because zooplankton grazing controls it, giving rise to ups and downs in the dominance of different small phytoplankton groups and microzooplankton grazers (Schmoker, 2010). During summer, the thermocline reforms, and productivity drops down limited by the lack of nutrients. The stratification has its maxima on October, when surface waters are

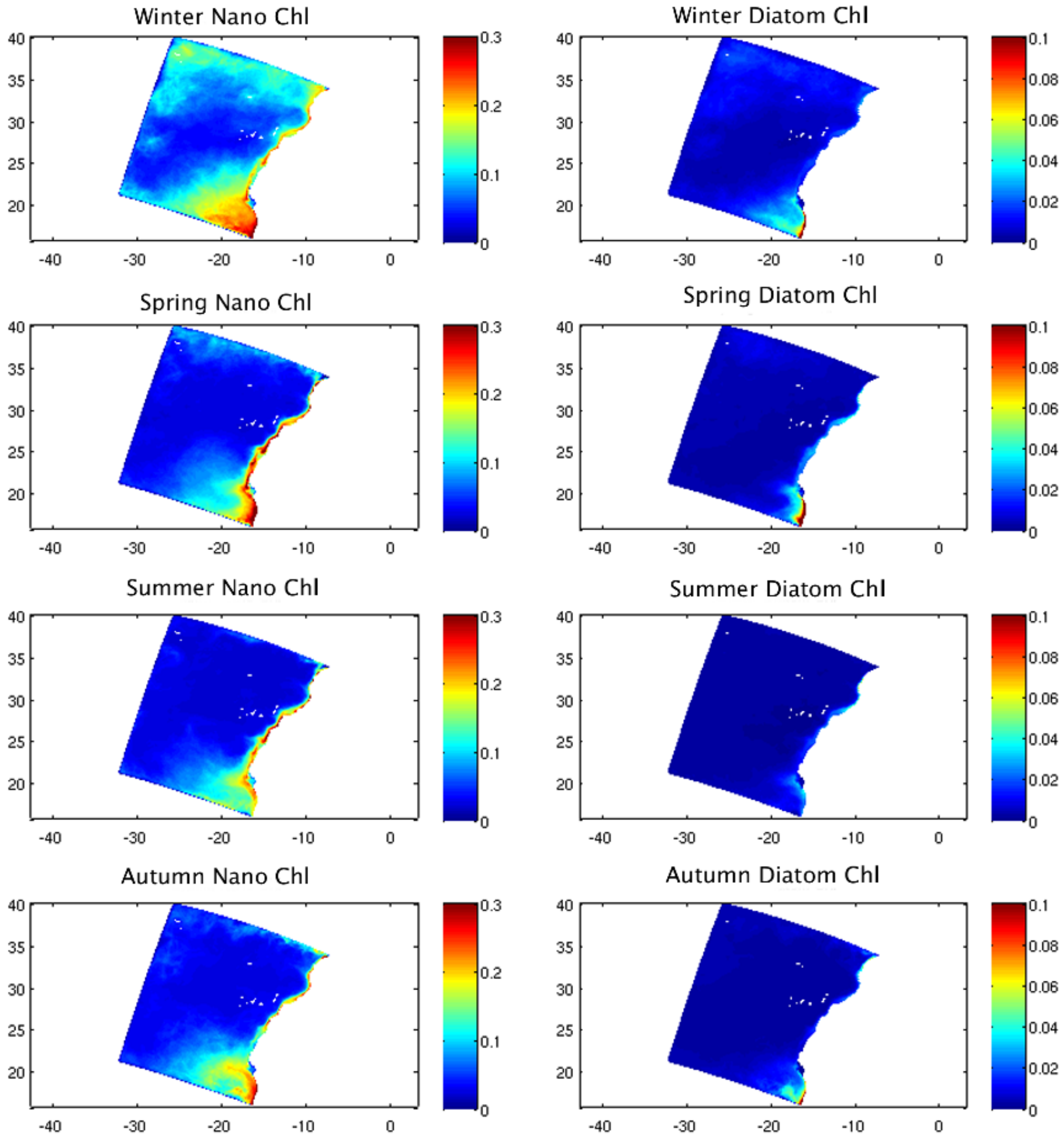


Figure 2: Surface maps of nanophytoplankton chlorophyll (left side maps) and diatoms chlorophyll (right side maps). Nanophytoplankton chlorophyll scales from 0 to 0.3 mg/m3, Diatoms chlorophyll scales from 0 to 0.1 mg/m3. Chlorophyll concentrations are on mg/m3.

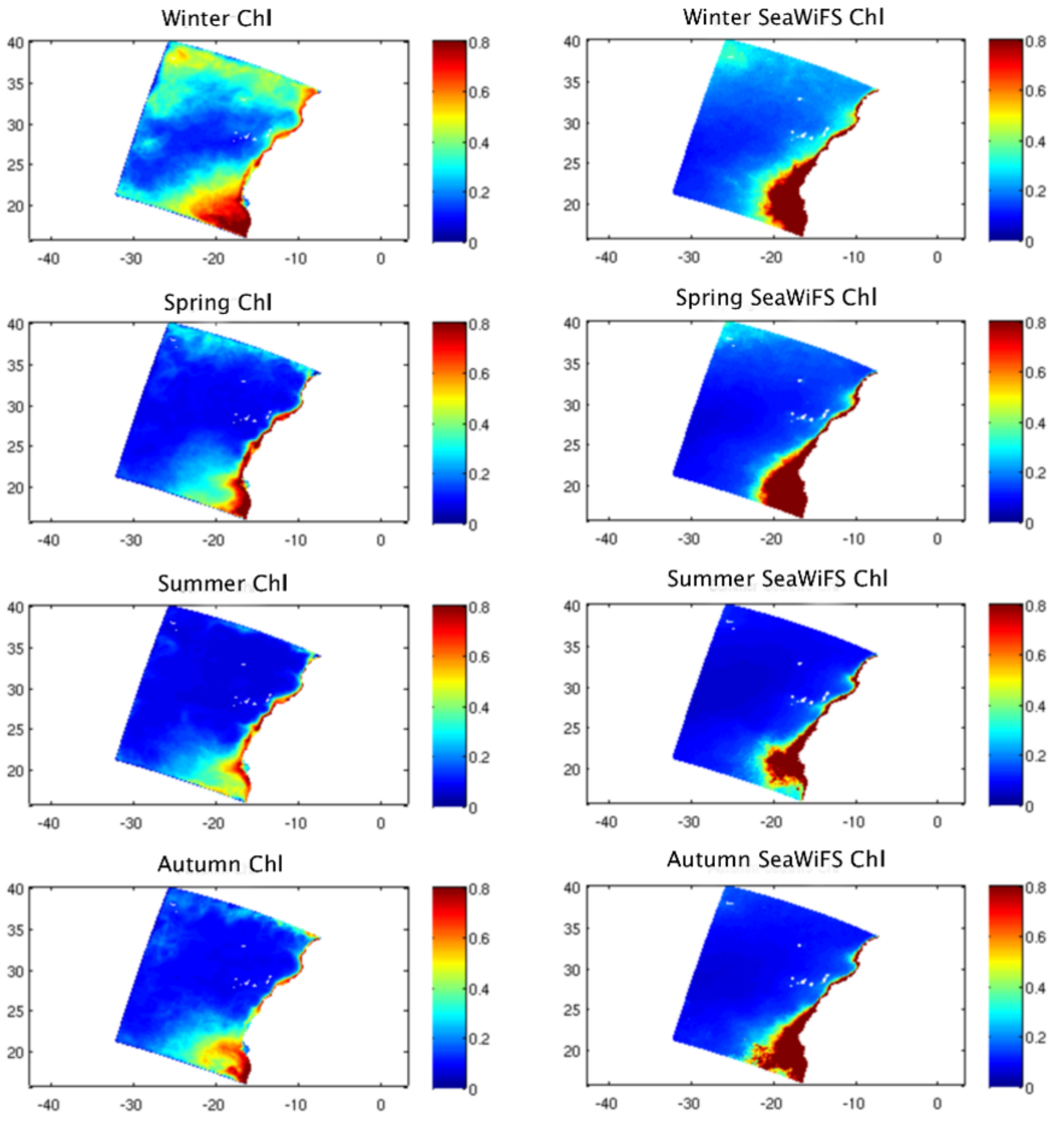
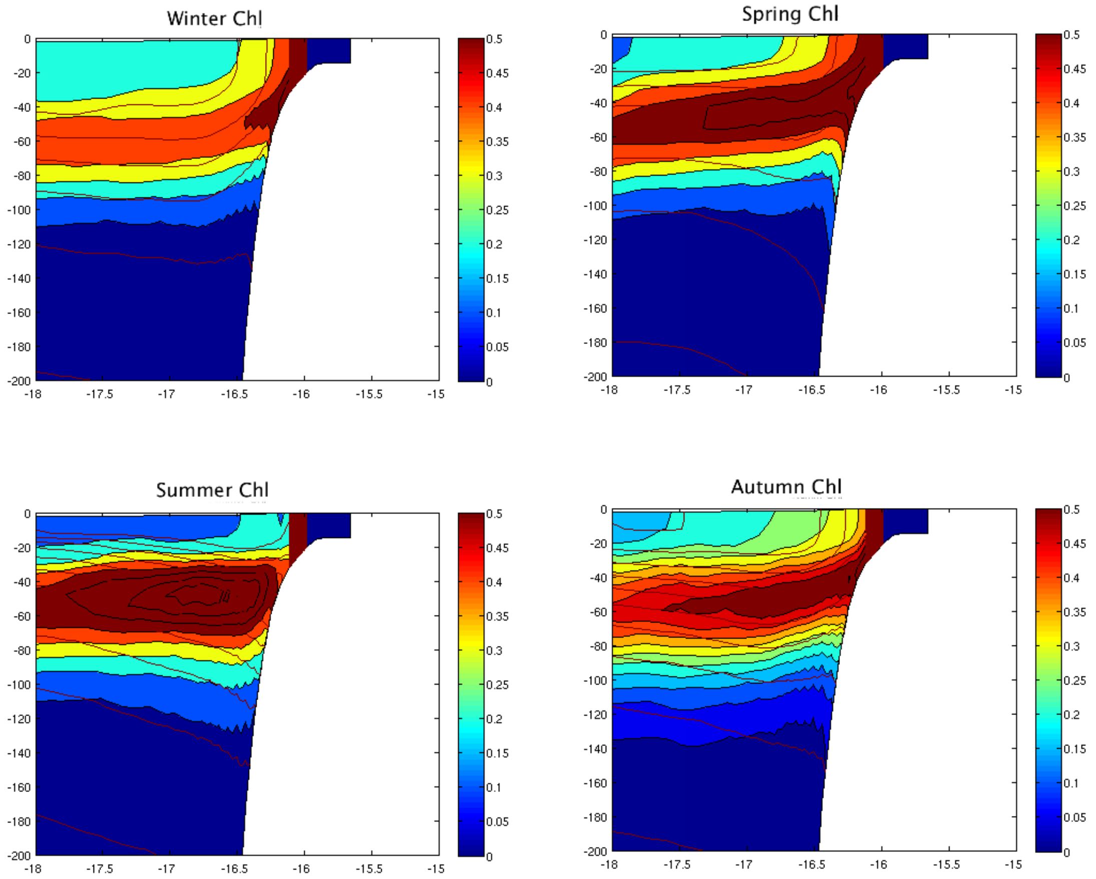


Figure 3: Surface maps of chlorophyll. Model outputs (left side maps) are compared to SeaWiFS remote sensing data (right side maps). Chlorophyll is expressed on mg/m3


Winter Chl

Spring Chl

Summer Chl

Autumn Chl

Figure 4: 2D Profile of modeled chlorophyll distribution. It corresponds to a 27-29º latitude averaged band. The first 200m are represented, showing the stratification state of the water column by including isopycnals. Chlorophyll is on mg/m3.

warmest (about 23ºC). As soon as surface waters cools the thermocline begin to weaken, starting over the cycle.

3.2 Deep Chlorophyll Maximum

Chlorophyll distribution in depth (fig 4) is compared with in situ data from the COCA project surveys. Fig. 4 shows modeled chlorophyll from 0 to 200 m depth averaged for a band of 27º to 29º latitude, just north of Canary Islands. Potential density (Jackett and Mcdougall, 1985) is included in the figure to see their relationship. Highest values of about 0.5-0.6 mg/m3 follows DCM (Deep Chlorophyll Maximum) near coast for the whole year. As can be seen in the in situ data, DCM increases its depth reaching almost 150 meters on open ocean although the values at this depth never exceed 0.2 mg/m3. Below this, the chlorophyll concentration is very low.

2D profiles from model point out the great abundance of chlorophyll on summer on the upwelling areas when wind-forcing is high. Although in winter the chlorophyll concentration is higher, the water column is well mixed making chlorophyll to spread over a wider band of depth. In summer however, the stratified waters make this band to be narrower permitting chlorophyll to accumulate.

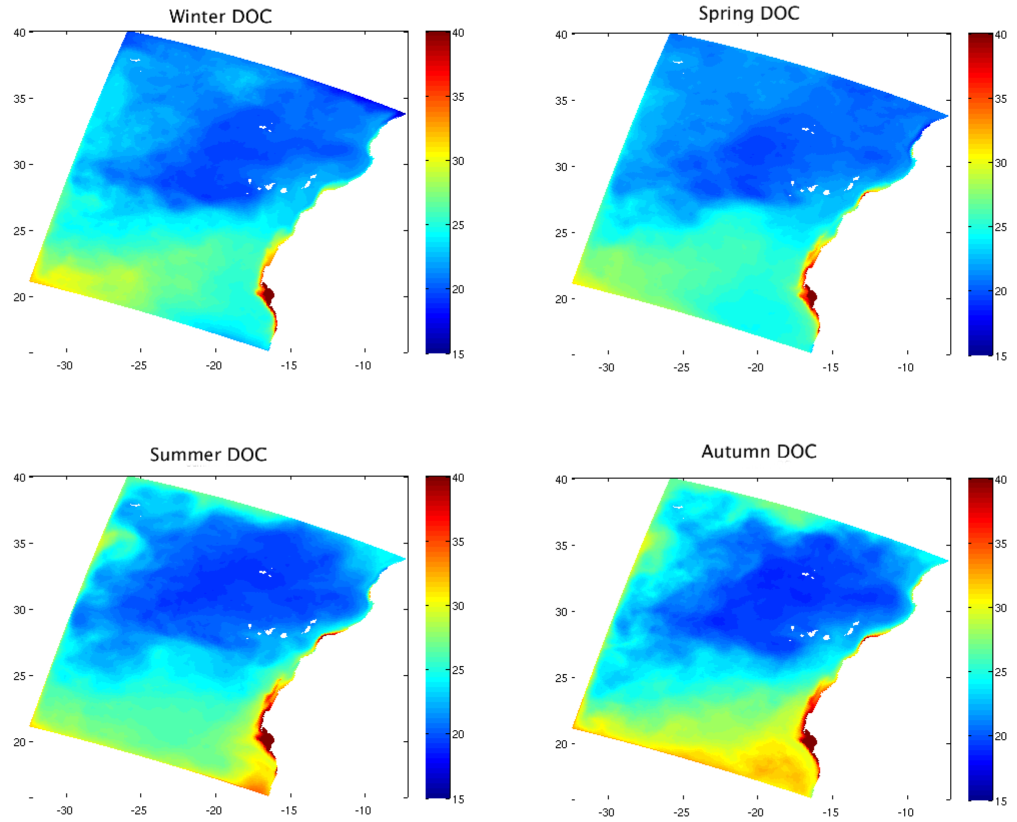


Figure 5: Modeled semi-labile DOC surface distribution. DOC is expressed on µmol C.

3.3 Organic matter

PISCES also allows to model organic matter distribution. Figures 5 and 6 show seasonal surface maps of semi-labile dissolved organic carbon (DOC) and particulate organic carbon (including both low-sinking and fast-sinking particles) respectively. The pattern is very similar in both images. DOC reaches values of 40µmol/l, and POC rarely exceed 1 µmol/l at surface. Their surface concentrations seem to follow the same pattern observed in the chlorophyll distribution; with maximum values along the coast, especially south of the islands, and a marked reduction towards the ocean. Offshore transport of organic matter is particularly intense along EBCs, as observed in several studies (Ávarez-Salgado et al., 2007 ; Pelegrí et al., 2005). Alonso-González et al. (2009) studied the transport of POC assuming that when water is collected with oceanographic bottles the particles are suspended or having very low sedimentation rates. Although this process is not computed specifically on the model, in the figures it can be seen that the POC concentration scale down until reach the open ocean. Lateral transport of POC is a consequence of the flow strength and particle weight, and particles are transported through neutral density layers. These factors will be modeled adequately in following versions of the model to accurately simulate this process.

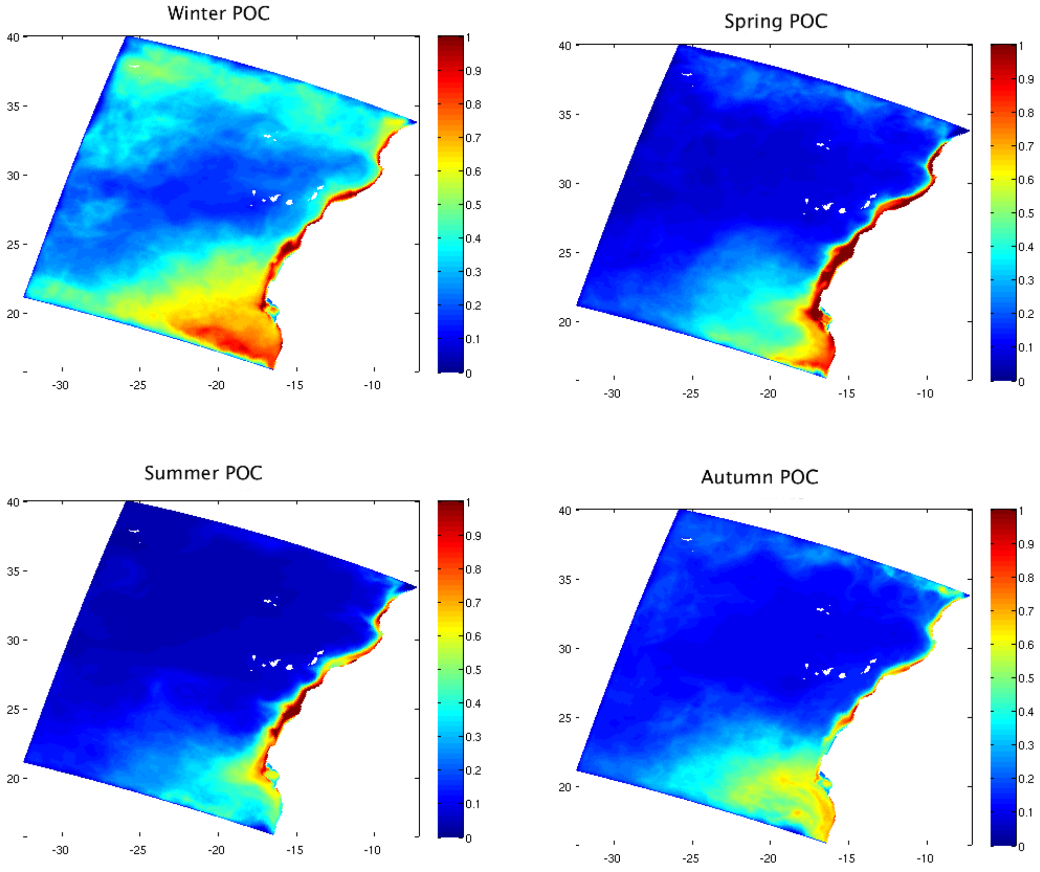


Figure 6: Modeled POC surface distribution. POC includes two size particles; slow-sinking particles and fast-sinking particles, represented as one pool.DOC is expressed on µmol C.

4 Discussion

4.1 Surface Chlorophyll underestimation

The error range suitable for SeaWiFS dataset was fixed on 35% RMS (root mean square log error). Several studies have checked that the dataset is under this maximum. One of the most complete studies about the reliability of SeaWiFS chlorophyll data can be found in Gregg and Casey (2004). In this work, the authors compare SeaWiFS 9km-resolution chlorophyll distribution (Level-3) to a wide dataset of more than 35000 real measurements. Basically, they found an acceptable 31% RMS error globally but they also distinguished between different areas to see where the remote sensor needs for a review. They found that the presence of the Saharan Desert compromises the atmospheric correction accuracy of the algorithm due to the excess of aerosol in the atmosphere. Since the North Atlantic is optically a very complex environment, the study divides the basin in 5 regions. The Northeast Central Atlantic host part of the Iberian coast and the CCS, reaching south of Cape Verde. In this region, even though the RMS is very low (29.1%) they found that the dust plumes spreading from the Saharan Desert represent about 15.3% of positive bias, hence SeaWiFS overestimates chlorophyll in the region. Additionally, they analyzed the areas where high biases were found resulting that the south of the Canary Islands is one of the most overestimated areas (especially in autumn). Thus, SeaWiFS data have to be used with caution because, depending on the presence of aerosols, the estimates may include significant errors. Indeed, Davenport et al. (2002) found very good agreements between the sensor values and in situ data north of Canary Islands when no evidence of atmospheric aerosols were found, although using only three stations. The simulation carried out here shows smaller values of surface chlorophyll distribution for all seasons and for the whole domain than SeaWiFS. Part of this could be explained by the fact that SeaWiFS climatology slightly overestimates real values.

SeaWiFS overestimates chlorophyll in the region, but we do not think that our simulation agrees completely with real data. The resolution of the simulation (7.5 km horizontally) makes it unsuitable to reproduce most of the small-scale processes taking place in the region. The average Rossby radius of deformation for the CCS area is about 25 km (Chelton et al., 1998); hence, our simulation is able to represent mesoscale features, but no submesoscale, which are considered to be from 1 to 10 km (Thomas, 2007). Aumont and Bopp (2006) observed that PISCES underestimates chlorophyll in the subtropical oligotrophic gyres and suggested that, in the case of the North Atlantic area, the coarse resolution of their model, 2^{o} by 2^{o}cosø (where ø is latitude) is unable to reproduce all the dynamic processes of the system. Mesoscale features have been seen to have important implications in upwelling areas (Lévy et al., 1998 ; Lévy et al., 2001). Indeed, some studies have suggested its importance on the primary production of the CCS region (Arístegui et al., 1994 ; Arístegui et al., 1997), although there is a lack of information about smaller-scale processes that may increase primary production as well. Oceanographic modeling can help to elucidate this question (see Lévy et al., 2001) but very few studies have been done yet because of the computing costs and the implicit difficulty of modeling such complex processes.

Productivity and the strength of the biological pump are typically limited by light and the availability of nutrients at surface. Several studies such as Lévy et al. (2001) showed that an increment on the model resolution increases the upward flux of nutrients into the euphotic layer indicating that submeso-scale processes are at play. Although it is still difficult to figure out their explicit impact, studies carried out in oligotrophic conditions (Oschlies and Garzón, 1998 ; Mahadevan and Archer, 2000 ; Lévy et al., 2001) have revealed an increase of 10 to 30% in primary production when mesoscale processes are accounted for, and till a twofold increase when the impact of submeso-scale is included. Nonetheless, some studies (e.g. Oschlies, 2002) discuss the possibility of an overestimating of the effects of mesoscale processes by the model, although there is no agreement in their implications due to the scarcity of in situ studies. Anyway, both meso- and submeso-scale features have a paramount role in supplying nutrients to euphotic layer, and hence in the enhancement of primary production (Oschlies, 2008) and should be included in modeling studies.

There are some other processes that our physical solution does not include. In general, most oceanographic models do not include the impact of eddy/wind interaction on vertical velocities and eddy characteristics (Anderson et al., 2011). According to McGillicuddy et al. (2007), eddy/wind interaction is directly related to the increment of diatom biomass and primary productivity within the eddy. In this respect, our simulation needs to include this forcing mechanism to account for eddy/wind driven productivity. Furthermore, Anderson et al. (2011) observed that by including this process the distribution of eddies change significantly, improving the agreement between modeled and observed eddy phytoplankton relationships.

On the other hand, modeled phytoplankton growth (and hence chlorophyll distribution) depends on the availability of nutrients (Aumont and Bopp, 2006). In that respect, our simulation needs to be closely adapted to reproduce the specific elemental ratios characteristic of the CCS. As it was indicated, PISCES bears problems when representing complex hydrographic regions. Indeed, very few studies have been carried out using ROMS and PISCES combined. In Echevin et al. (2008) the modeled chlorophyll is compared with in situ and SeaWiFS data. They concluded that the simulation reproduced fairly well (both qualitatively and quantitatively) the surface chlorophyll distribution for almost the whole domain, although SeaWiFS data were slightly higher than the model output (particularly north of 11ºS). PISCES was adapted to include the behavior of the Humboldt Current improving the solution. We feel that the ratios chlorophyll-to-carbon and energy assimilated-to-energy absorbed that define chlorophyll on PISCES have to be revised in future simulations to bring the simulation to reality.

4.2 Chlorophyll on the water column

Figures 7a and 7b illustrate in situ chlorophyll data from two COCA surveys. COCA 1 (fig 7a), was carried out at the end of the summer, when the Canary Current flows stronger due to an intensification of the Trade winds (Knoll et al., 2002). COCA 2 represents the end of spring/beginning of summer when the Canary Current is located further from coast. The two figures are from the northern section of the cruise, located south of the islands. This area is influenced year round by the eddy field generated from the perturbation of the main flow by the islands (Sangrá et al., 2007). Recently Piedeleu et al. (2009) observed, using a 2 years mooring and remote sensing data, that eddies are more frequently generated in spring and summer. Indeed, the figure from the end of summer (COCA1) can be interpreted as affected by mesoscale variability, because the water column is not homogeneously stratified, as it would be expected. On the other hand, the structure at the beginning of summer (COCA2) presents a more typical distribution of the chlorophyll across the water column. Near-coast the DCM is very shallow and the maximum concentration reaches the surface. This maximum deepens towards the open ocean, decreasing in intensity from about 0.4 to less than 0.2, just 1km offshore. In the simulation figure it can be seen that the distribution on depth of modeled chlorophyll follows a very similar pattern to the COCA2 distribution over the year: high values located at surface near coast, decreasing offshore. The highest values are around 0.5 mg Chl/m3, representing about 20% more than COCA 2 maximum values.

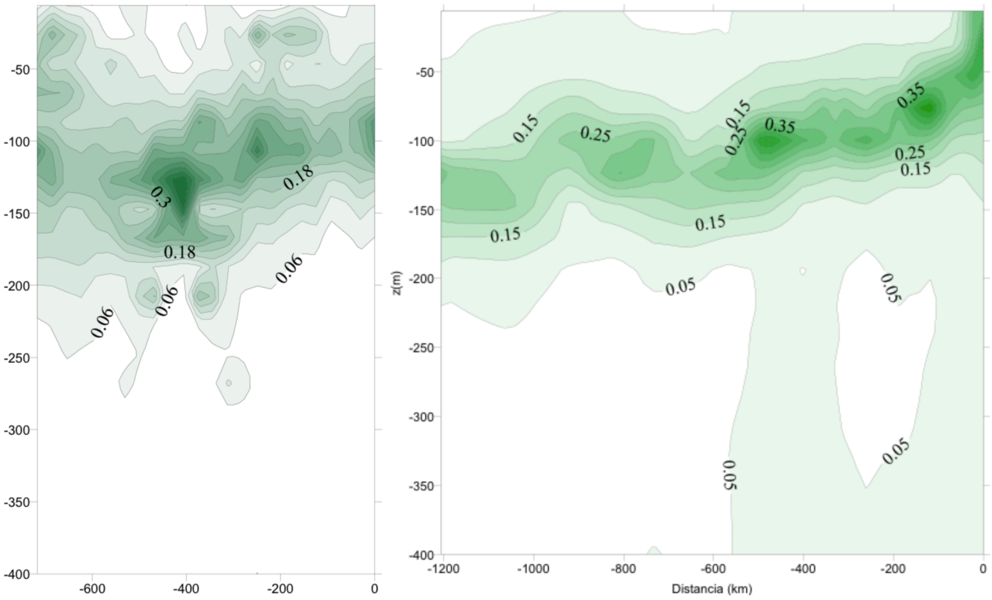


Figure 7: In situ fluorescence distribution from COCA surveys. 7a represents COCA1 survey data at the end of the summer. 7b corresponds to COCA2 survey data at the end of spring. Chlorophyll concentrations are on mg/m3.

The underestimation we have seen at surface comparing with SeaWiFS is not clearly seen on the water column. Maximum values of 0.3-0.5 seems to be well reproduced by the model. The depth of the DCM is into the depth range found by real observations. Arístegui and Montero (2005) estimated an average of 0.5 mg/m3 of chlorophyll on the DCM layer for waters surrounding Gran Canaria. These estimates agree well with our simulation results although, as it was pointed out, our values are somewat smaller. It can be argued that waters near the island are affected by local processes that could increase the chlorophyll concentrations. Since our simulation is unable to reproduce this dynamic it would need for an increase of resolution at later stages.

On the other hand, Barton et al. (1998) found consistent smaller values for chlorophyll at the DCM in October 1992, when surface waters were extremely warm and the water column heavily stratified. North of the islands the chlorophyll concentration was exceptionally low (around 0.1 mg/m3); being slightly higher (0.3 to 0.4 mg/m3) south of the island, presumably enhanced by the eddy field influence. Fig 4 represents a section close to the north transect sampled by Barton et al. and shows average values slightly higher for the whole year. Chlorophyll concentrations diminish rapidly from coast to the open ocean, especially in autumn. The DCM from the field data is located about 15 m deeper than in the model; although Neuer et al. (2007) observed a shallower DCM than in our simulation for the same period at the ESTOC station (north of Gran Canaria). Figure 8 shows chlorophyll concentrations at the ESTOC station from 1994 to 2000. Annual chlorophyll concentrations at the ESTOC rarely exceed 0.3 and maximum values reach shallower depths only during winter time. Overall, compared with the simulation, the in situ chlorophyll concentrations are somewhat higher, contrasting with surface modelled chlorophyll that is lower compared to remote sensor data.

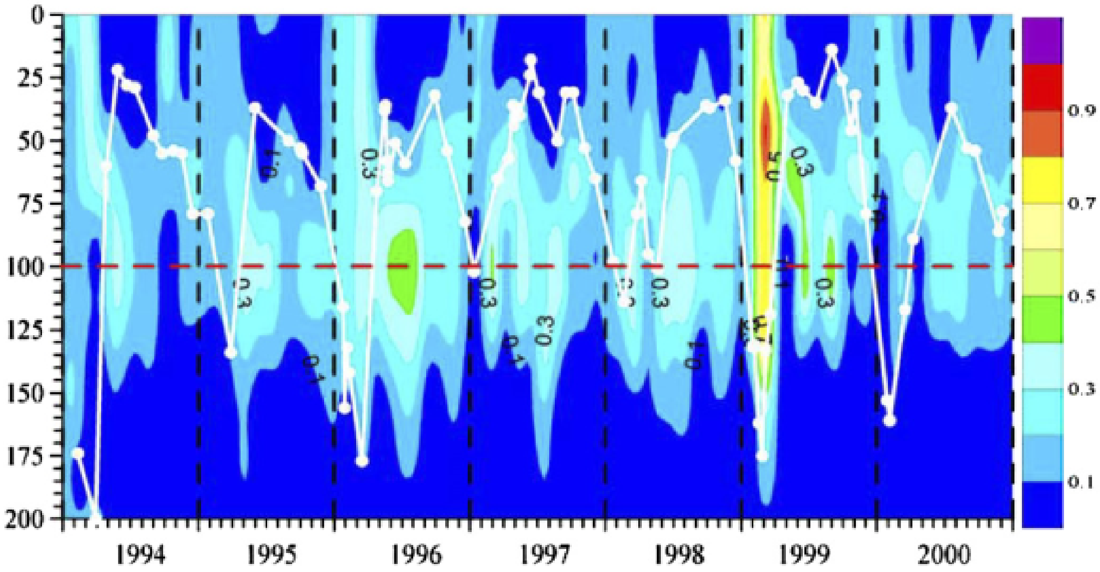


Figure 8: ESTOC chlorophyll temporal series from 1994 to 2000. Extracted from Neuer et al. (2007). Red dot-line indicates the euphotic zone depth, white dot-line denotes the mixed layer depth. Chlorophyll concentrations are on mg/m3.

4.3 Organic matter

Organic matter is modeled by PISCES in three pools. One corresponds to the semi-labile dissolve matter, and two to the particulate matter. These latter compartments share, essentially, the same origin: plankton mortality, aggregation and organic matter degradation. What differentiates the two pools of POC is the sedimentation rate with depth, as described in Berelson (2001): low-sinking POC (3 m/d) and fast-sinking POC (50 to 200 m/d) (Aumont and Bopp, 2006). Some parameters, however, are not considered in this size partition, like ballast effect (Armstrong et al., 2001), lateral advection (Alonso-González et al., 2009), or sloppy-feeding by zooplankton. In order to improve these compartments mork work has to be done in the future to include other processes that may influence the dynamic of organic matter.

Our results give a higher amount of slow-sinking particles over fast-sinking ones (not included). Alonso-González et al. (2010) studied the contribution of the fast and slow settling velocity particles on the flux of POC south of the islands for three periods. They found that the relative contribution of fast-sinking particles was higher in winter and spring (the season when the water column is less stratified), but low-sinking particles dominated the rest of the year. In the model, large POC tends to be close to the shelf except in winter when it reaches offshore areas. In the model it seems impossible to see a seasonal variability of dominance as can be seen on sediment trap data used by Alonso-González. However, new mechanisms have to be added to the particulate organic matter way of modeling. Besides, Redfield ratios imposed for C/N/P would be revised and changed by more realistic approaches. Smaller POC profiles (not included) show a higher time of residence in surface waters and open the question of the lateral advection of the so-called suspended POC (Bauer and Druffel (1998)). In winter and spring the values of POC have their maxima between 200 m and surface, very well defined over the rest of the water column. They seem to be consumed in the mix-depth layer and no particles of this size range reach deeper areas. In the stratified period (summer and autumn), the particles appear to be more distributed and reach about 450-500 m of depth, as well as more oceanic areas. This could support the idea suggested by Alonso-González et al. (2009) that a lateral advection (although not being modeled specifically) along the neutral density isopycnals is taking place.

5 Conclusions

We have developed the first 3dimensional ROMS-PISCES eddy-resolving bio-physical model for the CCS. A first approach has given acceptable results when compared with in situ and remote sensing chlorophyll data, even though key questions need for a revision at future stages. Both SeaWiFS chlorophyll satellite imagery and our simulation show the typical pattern of upwelling areas, with chlorophyll concentrations near coast decreasing gradually offshore. Our model confirms the importance of having a good physical representation of the area, since modeled chlorophyll distribution reproduces pretty well (at least qualitatively) remote sensing data. However, an underestimation of the surface chlorophyll concentrations has been observed. Apparently, satellite imagery has problems to represent with good reliability chlorophyll in the area due to interference with aerosol from the Saharan Desert (see section 4.1). Furthermore, the effects of submesoscale processes on the area, not simulated by the model, must affect the final chlorophyll concentrations. Indeed, recent simulations of ocean dynamics highlight the impact of the small scales variability on primary production (Capet el al., 2008 ; Klein et al., 2008). Non-accounting for small-scale processes may understimate primary production by at least 30% (Lévy et al., 2001 ; McGillicuddy et al., 2003). Besides, ratios of conversion chlorophyll-to-carbon must be adapted specifically to CCS realm before proceeding with downscaling in future approaches.

5.1 Future work

Roms2roms interpolates physical variables with a frequency higher than a month. This means that every data is "refreshing" very little time improving the final results. Meanwhile, biological variables, that are not feeding on the parent solution, have a climatological forcing with a monthly frequency. Hence, physical and biological variables are not in phase. To solve this and advance to a higher resolution at a meso- and submeso-scale eddy-resolving model, we pretend to improve the solution presented in this work to use it as a parent solution. In this way, we will be able to increase not only the spatial resolution but also, and most important, the temporal resolution.

It is important to note that the role of mesoscale on enhancing primary production is not completely clear. The upward transport of tracers that may occur on the eddies is still not quantified nor well understood. Are submesoscale processes responsible of the ascend of nutrients and the enhancement of primary production? (Mahadevan et al., 2008). Are mesoscale eddies the cause of this ascend? (Lehahn et al., 2007). These questions have to be adressed in the future. As can be seen on Klein and Lapeyre (2009), some studies suggest that when the spatial resolution is high enough, much larger vertical exhanges of tracers are obtained and this significant increase is principally due to the small scales. In this regard, a submesoscale-resolving model could help to understand the processes behind eddies in terms of vertical injection of tracers. Furthermore, Mason (2009) pointed out using a simple modeling experiment that having a higher resolution wind stress impacts over the creation of island-induced eddies south of the islands. Higher resolution wind-product are planned to be included in forward stages to improve eddies representation, hence, giving a better view of the eddy field south of the island.

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