Numerical modelling of the phytoplankton patterns in an upwelling event off the NW Iberian Margin

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ABSTRACT

Rocha, C., Cordeiro, N., Nolasco R., Dubert J., 2013. Numerical modelling of the phytoplankton patterns in an upwelling event off the NW Iberian Margin. *In:* Conley, D.C., Masselink, G., Russell, P.E. and O'Hare, T.J. (eds.), *Proceedings 12th International Coastal Symposium* (Plymouth, England), *Journal of Coastal Research*, Special Issue No. 65, pp. 117-122, ISSN 0749-0208.

An extreme event in September 2007, presenting a strong upwelling core detaching from the Galician NW coast and extending towards west-northwest from the Cape Finisterre - Cape Ortegal zone, with the formation of several filaments and a consequent strong response in chlorophyll concentration values is analyzed. To do so, a NPZD biogeochemical module coupled to a ROMS_Agrif configuration is used. The model response was satisfactory and an analysis of the event, including its forcing, was made. The particular wind direction and intensity along with the specific coastal orientation of the study area were identified as important characteristics for the development of the event. The analysis of the behavior and evolution of this phytoplankton bloom may give further insight in the relations between atmospheric forcing, the consequent characteristic coastal ocean processes, and their conditioning in phytoplankton distribution and patterns in the study area.

ADDITIONAL INDEX WORDS: *Biogeochemical module, upwelling, chlorophyll, SST, biophysical coupling, Iberian Peninsula, ROMS.*

INTRODUCTION

In the mid-latitudes, the phytoplankton is both light and nutrient limited (Lévy *et al*., 2005, Oliveira *et al*., 2009) with its development strongly controlled by the circulation in the upper layers of the ocean waters (Fraga, 1981). The coastal upwelling has an important role in defining the distribution of high primary production areas and, due to the importance of the high biological productivity of the world regions where this phenomenon occurs, they are profusely researched. Several of these studies include the use of numerical oceanic models with coupled biogeochemical solving capabilities, as Gruber *et al*. (2006) and Powell *et al*. (2006).

The basic framework for most marine biogeochemical models has been in use for the last decades (Fasham *et al*., 1990). These models are intrinsically highly empirical, non-linear and full of formulations based on poorly constrained parameters. They generally aggregate plankton populations into broadly defined trophic compartments (phytoplankton, zooplankton, detritus) and track the flow of a limiting element, such as the concentration of nitrogen or carbon, among the compartments. The various terms for processes such as photosynthesis by phytoplankton, zooplankton grazing or detrital remineralization are calculated using standard, though not always well agreed-upon, sets of empirical functional forms derived either from limited field data or from laboratory experiments (Doney, S., 1999).

Nevertheless, biogeochemical models can provide a valuable tool when coupled with circulation models. They can complement a limited ensemble of observations and offer the possibility to further explain biogeochemical processes and help in the understanding of the variability of its elements. One of the simplest versions of these models is usually denoted as NPZD (Nutrients-Phytoplankton-Zooplankton-Detritus) and can give information on the concentration of biological state variables over time, also having strong potentialities for analysis and prediction.

In order to allow a preliminary study of the NW Iberian Margin biogeochemical dynamics, with special focus on general chlorophyll-*a* surface concentrations and patterns, one of these modules was incorporated into an existent three-dimensional regional oceanic circulation model (ROMS_Agrif). The study focused especially in both empirical and objective model performance assessments through comparison of surface chlorophyll-*a* model outputs with an extensive satellite dataset produced by IFREMER/CERSAT and in the verification of the model ability to reproduce theoretically expected phenomena. Its performance was considered fairly satisfactory and its results were made available in a pre-operational form (Marta-Almeida *et al*., 2012).

Influenced by the work of Oliveira *et al*. (2009), which numerically studies a filament using a high resolution model, and making use of the recently available ocean-biogeochemical coupled model configuration, we focused in the study of an event occurred on September 2007 (with its maximum expression at September 11), in which upwelling favorable winds created a large upwelling core with a significant biological response. This filament is one of the strongest registered in that place, and

DOI: 10.2112/SI65-021.1 received 07 December 2012; accepted 06 March 2013.

presents negative anomalies of about 4ºC in relation to the climatological values of sea surface temperature. An associated positive anomaly of 3 mg.m^{-3} of chlorophyll-*a* in relation to the climatological values is also observed. In the present paper we discuss the physical conditions in which this abnormally strong filament developed, while also identifying the particular forcing mechanisms behind it. Although this study represents a particular event, we believe that this analysis is generally applicable to the understanding of other upwelling centers in this region, which condition the phytoplankton distribution and patterns in the study area.

METHODS

Numerical Ocean Model

A high-resolution, 1/27º (~3 km), optimized configuration of the Regional Ocean Modelling System (ROMS), Penven *et al*., 2006, is used to simulate the ocean circulation of the Iberian System. ROMS is a split-explicit, free-surface, topography following coordinate model, designed to solve regional problems (Shchepetkin and McWilliams, 2003, 2005).

A biogeochemical module to simulate the evolution of marine ecosystem components was coupled to the hydrodynamic core model. This module uses a simple nitrogen-based NPZD configuration, based in Fasham *et al*. (1990), computing 4 state variables: Nutrients (nitrate), and single groups of Phytoplankton, Zooplankton and Detritus, all expressed in mmolN.m^{-3}. Chlorophyll-*a* (mg.m^{-3}) is derived from phytoplankton concentration using a chlorophyll:C ratio of 0.02 (mg Chla/mg C) and a C:N ratio of 6.625 (mmolC/mmolN), i.e., a Redfield ratio.

The simulated processes between the biogeochemical variables include nitrate uptake by phytoplankton, zooplankton grazing, phytoplankton and zooplankton mortality (to detritus), metabolism products and mineralization (to nitrate).

The 3D time evolution of the concentration of any of the biogeochemical variables (B_i) follows the general equation:

$$\frac{\delta B_i}{\delta t} = \nabla \cdot K \nabla B_i - \vec{u} \nabla_h B_i - \left(w + w^{sink}\right)\frac{\delta B_i}{\delta z} + sms\left(B_i\right) \qquad (1)$$

where the terms in the right hand side account for diffusion, horizontal advection, vertical mixing and sink minus source (*sms*) biological processes, respectively. *K* is the eddy kinematic diffusivity tensor, ū is the horizontal velocity of the fluid, *w* and w^{sink} are the vertical velocity of the fluid and the vertical sinking rate of the biogeochemical tracer, respectively, with the exception of zooplankton and nitrate, to which no sinking rate is attributed.

Model Configuration

The strategy to manage the large range of ocean dynamics scales involved consisted in the implementation of a two-domain approach, as shown in Figure 1. A large-scale first domain (LD) is run independently in order to provide initial and boundary conditions to the target domain (denoted TD hereafter) through an off-line nesting. The Large Domain horizontal resolution is 1/10º (~10 km), and the main aim for this domain is to solve the large-scale circulation features such as the Azores current, and its interaction with the Atlantic margin of the Iberian Peninsula.

This configuration was performed with a similar methodology as that described in Peliz *et al* (2007).

For this domain, 30 sigma vertical levels were used, with θs = 7 and θb = 0. The bathymetry is based on the ETOPO1 (Smith and Sandwell, 1997), with corrections near the slope and a smoothing filter to fulfill the r = Δh / 2h criteria (Haidvogel and Beckmann, 1999), with r < 0.2.

The Levitus *et al*. (1994) climatology was used as the initial value for the temperature and salinity fields, and also to recycle these fields along the nudging bands, providing open boundary conditions. Surface fluxes are derived from the Comprehensive Ocean-Atmosphere Dataset (COADS, da Silva *et al*., 1994), interpolated to the grid with the Roms_tools (Penven *et al*., 2008) package. Initial velocities are zero, and monthly geostrophic velocities (with level of reference 1200 m) and Ekman velocities are calculated from the climatology and applied along the open boundaries.

Sponge layers were applied along the edges with a band of 120 km, with a viscosity coefficient ranging from 600 m^2.s^{-1} at the boundary to zero at the interior. Explicit diffusivity is null, and a linear drag formulation with coefficient r = 3 x 10^{-4} m.s^{-1} is applied at the bottom. This configuration was run for five years and it reached equilibrium solutions after four. After that period, realistic forcing at the surface (instead of a climatological one) was used. The forcing consisted in the NCEP2 air-sea fluxes (www.ncep.noaa.gov) and reanalyzed satellite winds from CERSAT (cersat.ifremer.fr): QuikSCAT, with a spatial resolution of 0.50º.

The climatological outputs of the LD were then used to initialize and provide boundary conditions to the climatological runs on TD grid, through offline nesting, and later, with realistic forcing, as boundary conditions for the 2007 period.

The target model domain, TD (Figure 2), has a horizontal resolution of 1/27º, (~3 km), and includes the Gulf of Cadiz, the West Iberian Margin, and part of the western Bay of Biscay, extending for 1200 km in the meridional direction, from 35.5ºN to 45.5ºN. In the zonal direction, the domain extends from the Strait of Gibraltar, located at 5.5ºW to 12.5ºW, covering a width of about 600km. Sixty sigma vertical levels with θs = 4.0 and θb = 0.0 were used to properly solve the Mediterranean undercurrent

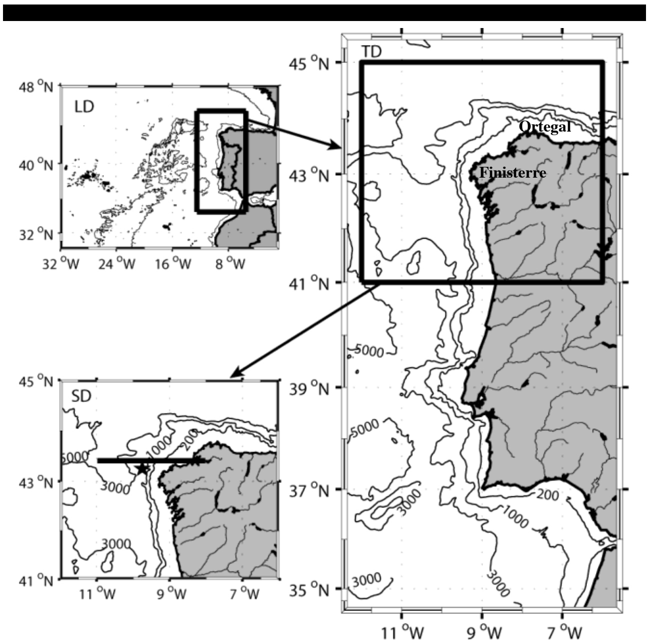

Figure 1. Illustration of the “Large Domain” (LD - on the top left), the “Target Domain” (TD - on the right), and the study domain (SD – on the bottom left) geographic localization with identification of the main bathymetric lines. The vertical profile position and the central point of the box used for wind direction and values estimation are also identified in the SD image.

with enough near-bottom resolution. In this way, the grid has 60 x 188 x 389 cells. Bathymetry was based in an (~1 km resolution) Atlantic bathymetric chart (Sibuet *et al*., 2004), with improvements at the continental shelf, which was smoothed to fulfill the same criteria (r-factor less than 0.2) of the large-scale domain.

The physical forcing for this high-resolution configuration is the same used for the large scale (LD) one, ensuring consistency of forcing for both domains and avoiding problems at the boundaries. The initialization and the boundary conditions are obtained using "year 5" from LD. Also, similarly to the large-scale simulation, a nudging sponge layer was introduced and a quadratic bottom drag coefficient of 5 x 10^{-3} was used.

The biogeochemical initial fields were supplied by Levitus climatological means as so were the biogeochemical boundary conditions, with the available seasonal fields being coupled to the LD fields which were provided eight daily.

The inflow of freshwater in the ocean originated from the main rivers of the region was included, with measured values provided by INAG (Water Institute of Portugal) for physical properties as salinity and temperature and calculated from European Environment Agency's database and from Ferreira *et al*. (2002) for biochemical concentrations of nitrates and chlorophyll-*a*.

The *spin-up* time for this domain, in which the volume averaged kinetic energy stabilizes (the *spin-up* time for the biogeochemical module is rather shorter), was five climatological years, a run which was the initial basis for the 2007 simulation period.

Satellite Data

The satellite image sequences were constructed from various instruments with different space and time sampling capabilities.

The SST maps were derived from the Advanced Very High Resolution Radiometer (AVHRR) of the National Oceanic and Atmospheric Administration (NOAA) which provides data extracted to the EUMETSAT Ocean & Sea Ice Satellite Application Facility (OSI-SAF) and is made available by CERSAT (IFREMER, France). The product has an approximate resolution of 2 km and the data from its night satellite sweep was remapped to the LD grid through a triangle-based linear interpolation.

For the chlorophyll-*a* maps, IFREMER/CERSAT datasets, having daily availability and full coverage for the study period and area, were the choice between other remote sensing products and were thus also interpolated to the model grid in order to enable comparison.

IFREMER/CERSAT processing unit merges data from three sensors available to observe the whole planet following a polar orbit around the Earth: MERIS, launched in 2002 by the ESA and SeaWiFS and Modis Aqua, launched respectively in 1997 and 2002 by the NASA. The chlorophyll-*a* maps are made available as daily means of approximately 1.1 km resolution that are generated with the best data retrieved from the sensors, making use of the OC5 algorithm. This algorithm pays a particular attention to the effect of the suspended matters, abundant on the European shelf, on the retrievals of the chlorophyll-*a* from the satellite radiances and has proven to be efficient on the 10 years data set of SeaWiFS, MODIS and MERIS data.

Spatially averaged wind was obtained from the mean of nine QuikSCAT grid points centered in the point illustrated in Figure 1, which was in turn used as the wind reference for the ensuing analysis.

RESULTS

Wind Evolution

Previous analysis of winds showed that 2007 was one of the years with strongest upwelling favorable winds during the 2000-2012 period. Embedded on the typical summer strong northerly wind regime of 2007, several complete cycles of strong intensification and short relaxation of these winds occurred in late August and September. Additionally, during the period from August 25th to September 15th, a strong easterly component of the wind, with mean values above 7 m.s^{-1}, was observed and the intensity of the northerly wind component, from August 19 to September 19, was also above 7 m.s^{-1}. The conjunction of these wind components created an anomalous strong upwelling favorable regime for the coastal segment located between Finisterre and Ortegal capes (Figure 1) from mid August to mid September 2007. These conditions were on the origin of the upwelling center addressed in this work.

Surface Temperature, Chlorophyll-*a* and Circulation Patterns

In conjunction with the described wind field, the development of an upwelling center is observed between capes Finisterre and Ortegal, associated to the SW-NE coast orientation. Although the description of the full details of this evolution is out of the scope of the present work, it is important to remark that throughout August the upwelling was mostly located along the west coast, south of Finisterre cape, and associated to the northerly wind component. This west coast core would present a significant decrease, starting around August 25, while a progressive increase on the Finisterre-Ortegal region was observed.

Illustrating this upwelling center, the sea surface temperature and surface chlorophyll-*a* concentration patterns for the SD region by day September 11th, 2007, are presented in the left and right columns of Figure 3, respectively. Upwelled cold waters are highlighted by the 15°C line, with a visible strong center located between Capes Finisterre and Ortegal. In the west coast, as remarked above, the upwelling influence is clearly less intense than in the anomalous upwelling core.

It is observed that the model sea surface temperature present a negative bias with respect to the satellite image of about 1ºC, which is generally associated to the lack of detailed structure of the forcing winds near the coast. The wind usually decreases due to the proximity of the coastline and this effect is deficient on the QuikSCAT winds.

Associated to the upwelling center visible on both satellite and model images, the estimated surface velocities show the presence of an intense equatorward flow, with values higher than 0.5 ms^{-1}, developing from the Northern coast at 6ºW and extending along the coast up to the Finisterre cape. In the surface, the effect of the Ekman layer is also visible, consisting in offshore surface flows which advect cold water in that direction, with a maximum located at 43.5ºN. This offshore transport is responsible for rapid advection of cold recently upwelled waters and contributes for the spreading of the upwelled center in the offshore direction.

Also, due to the destabilization of the coastal alongshore jet, the presence of offshore filaments aligned in the offshore direction is observed in the Finisterre cape particularly, both in the model and in the satellite SST images.

Associated to the cold water center described above, a strong chlorophyll-*a* ([Chl-a]) bloom develops in the recently upwelled waters, with concentrations above 5 mg.m^{-3}. For both model and satellite image, it is possible to observe that this higher [Chl-a]

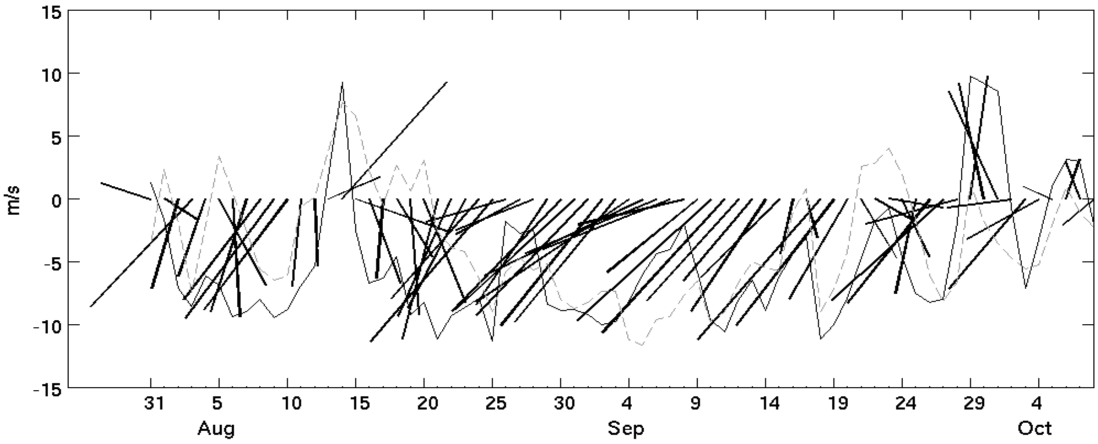

Figure 2. Spatially averaged QuikSCAT winds from a nine grid points box centered at 43.25ºN, 9.75ºW (stick diagram, *v* component in black, *u* in dashed gray).

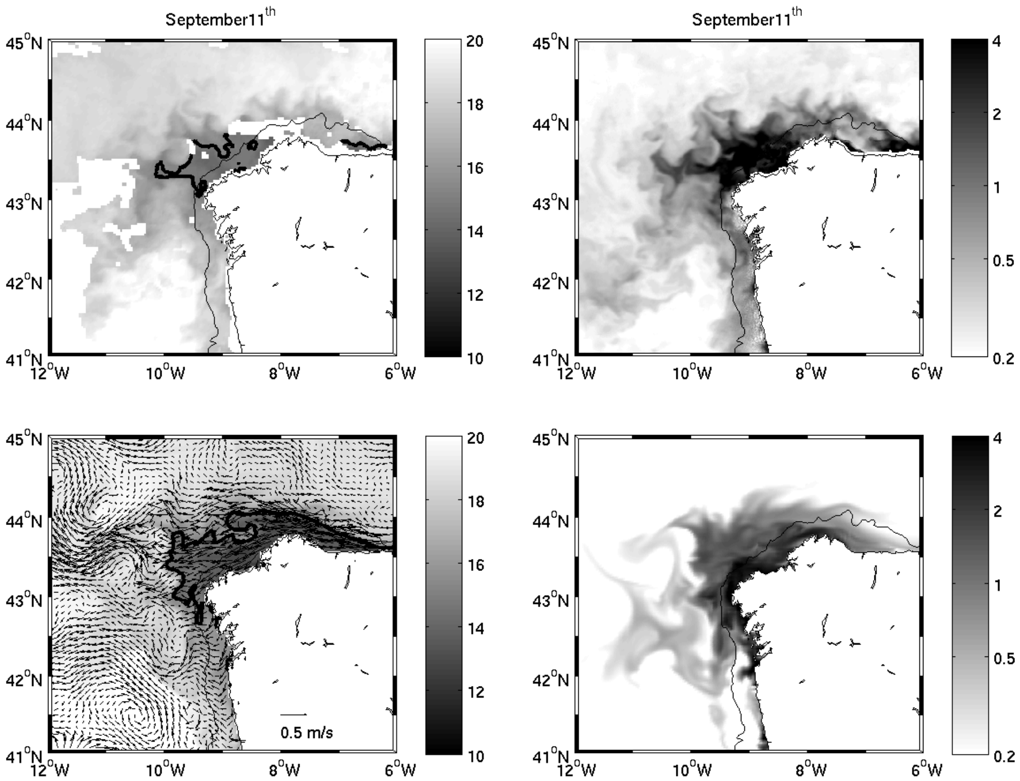

Figure 3. OSI-SAF surface sea temperature (top left), Ifremer/CERSAT chlorophyll-*a* map (top right) and daily averaged model surface temperature and velocities (bottom left) and chlorophyll-*a* (bottom right) for September 11, 2007. The solid line in the SST maps represents the 15ºC isotherm.

values are extended eastward to a narrower band in the northern coast, where filaments are not observed (and with the model not reproducing properly its extension eastward of 6.5ºW).

Still, in the western coast, south of Finisterre, lower values (less than 1 mg.m^{-3}) of [Chl-a] are observed. The shape of the filaments generated in this area seems to be related to interactions with offshore mesoscale features, illustrated in the surface velocity field (Figure 3).

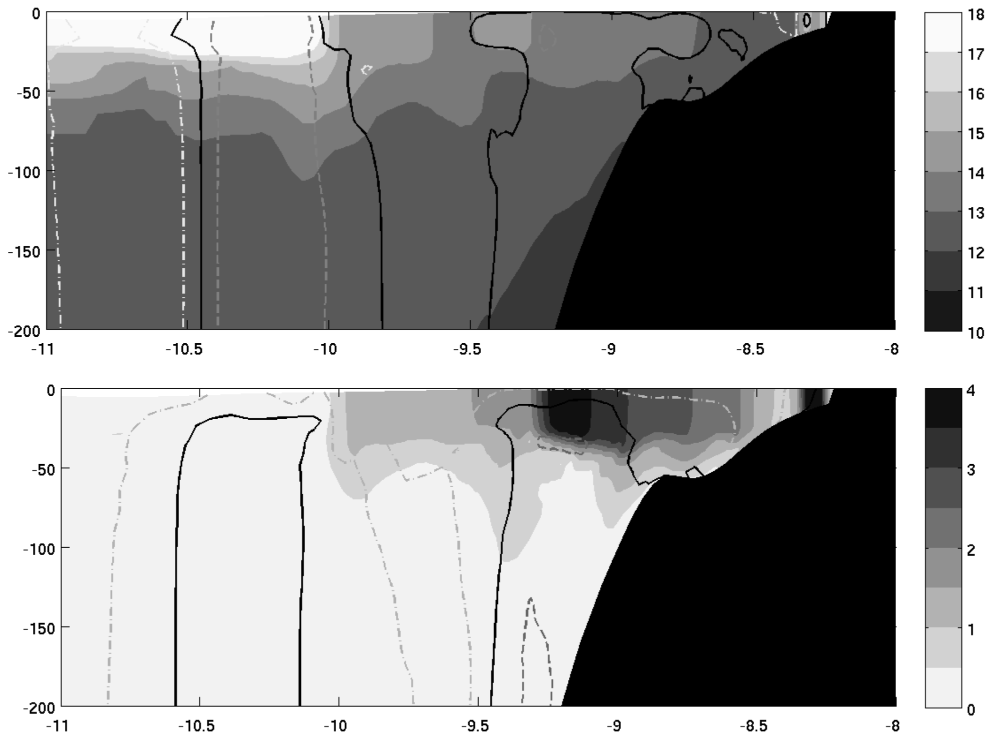

Figure 4. Vertical profiles of the model results for September 11 in the zonal line identified on the bottom left image of Figure 1. Filled contours represent temperature values in ºC (top) and chlorophyll-*a* concentrations in mg/m^3 (bottom). Contour lines represent meridional (top) and zonal (bottom) velocity fields (solid lines = 0 m/s; dashed dark gray = 0.1 m/s; dot-dashed light gray = -0.1 m/s).

Vertical Structure

In order to study of the upwelling region a zonal section was chosen at latitude 43.4ºN. The temperature profile (Figure 4, top) evidences the specific late summer situation under study. The main upwelling front is outcropping at about 10ºW, separating the oceanic waters with a mixed layer depth (MLD) of nearly 20 m thick from an upwelled region with larger values of MLD. In the cold onshore side of the upwelling front, the MLD is higher, and the thermocline is weaker than on the offshore side. This conditions the behavior of the [Chl-a], which is displayed on the bottom of Figure 4, with its modeled distribution being strongly associated to the temperature field. A concentration of less than 0.5 mg.m^{-3} of chlorophyll-*a* is observed across most of the profile associated to waters below the thermocline, and surface waters located offshore the front. Higher chlorophyll-*a* concentrations are observed in the surface mixed layer east of 10°W, with values varying between 1 to 4 mg.m^{-3}. Two surface cores of concentrations higher than 3.5 mg.m^{-3} are observed near 9°W and west of 8.5°W.

A cyclonic circulation is observed west of 10°W, a pattern which is also visible in the surface maps (Figure 3) and is being advected offshore by westward currents from the coast. The westward currents are interrupted by a northeastward moving subsurface region situated around 9°W, below the highly chlorophyll-*a* concentrated surface core.

DISCUSSION

In this work we analyze one of the strongest upwelling events observed in the NW corner of the Iberian Peninsula where the coast changes its orientation from the northern direction (at the Atlantic Margin) to the eastern direction (in the Bay of Biscay) through a coastline segment in the SW-NE direction between Finisterre and Ortegal.

During the period of analysis (mid August-mid September 2007) an intense quasi-stationary NE wind regime has established itself almost uninterruptedly in the area. This anomalous situation was originated from the unusual location of the Azores High which instead of its usual position at the longitude of the archipelago of the Azores and a latitude of 36-38ºN, was instead centered around 48ºN 20ºW, in front of French Britain, and extended in a ridge along the Bay of Biscay. It was this quasi-stationary synoptic situation from mid August to mid September 2007 which generated the observed persistent NE winds in the NW Iberian and low northerly winds along the Portuguese coast. A similar uncommon wind regime is reported by Torres et al (2003).

First of all, it is important to bear in mind that the coastal orientation plays a significant role in the observed ocean dynamics, as the local winds blew mostly parallel to the coastline between capes. In terms of [Chl-a], the values estimated by the satellite and the model represent a high anomaly in relation to the mean values for the area, consequence of the anomalous strong upwelling spot between Finisterre and Ortegal. Chlorophyll-*a* maximum concentrations of around 8 mg.m^{-3} and minimum temperature values of 13°C were observed in both model and satellite data for the 11th of September (Figure 3 and 4). This core covers an area of about 0.5º in both zonal and meridional direction, and is about 40 meters thick. A delay of about two days is observed between the maximum intensity of the wind and the maximum values of [Chl-a].

The SST signature of this event, as the correspondent biological response, gradually fade away until the end of September, roughly preserving its main structure for about two weeks.

A band of high concentration with similar location, shape and propagation as this case was also identified by Peliz and Fiúza (1999) in CZCS-derived phytoplankton pigment concentration images, but for the spring period instead. This event, for the month of September, can be considered as strongly anomalous.

CONCLUSION

The pattern of this event, which represents a strong upwelling core from the Galician NW coast and that extends itself towards northwest from the Cape Finisterre - Cape Ortegal zone, with the formation of ocean features as filaments, can be observed in both model outputs and satellite data, with a strong relation between SST and chlorophyll-*a* maps being evidenced.

The origin of the upwelling center observed during August-September 2007 is to be related to the anomalous location of the Azores anticyclone during that period.

We have made several model runs with diverse configurations and the results suggest that this kind of events, although not with this anomalous dimension, are recurring and seem greatly associated to the wind regime and coast orientation.

Furthermore, its illustration can serve to highlight the importance of the ocean circulation in the chlorophyll-*a* distribution, as there seems to be an inverse relation between surface temperature and chlorophyll concentration values in both satellite and model data, with a good response of the biogeochemical module to the simulated SSTs pattern, and an easily observable relation between satellite SSTs and chlorophyll-*a* patterns. This relation between cold upwelled waters pattern and the pattern of highly concentrated values of chlorophyll is typical but, due to the complexity of the phytoplankton innate characteristics, may not always be true.

ACKNOWLEDGEMENTS

The present work has been supported by RAIA Coastal Observatory, financed by POCTEP 2007–2013 (0313-RAIA-1-E and 0520-RAIA-CO-1-E), and ‘ISCAD - Inner shelf circulation and dispersion patterns: Interactions with estuarine systems”, PTDC/MAR/65760/2006 research project, also funded by the FCT under the European Regional Development Fund.

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