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Surface temperature, chlorophyll and advection patterns during a summer upwelling event off central Portugal

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ABSTRACT

Satellite-derived sea surface temperature (SST) and chlorophyll ([Chl]) concentration maps are used together with numerical models to study the advection patterns observed during a summer upwelling event off central Portugal, a region characterized by a complex coastline and bathymetry. It is shown that the model solutions realistically reproduce the main patterns of spatial and temporal SST variability, namely the 2−2.5 °C decrease in the active upwelling areas during the wind intensification phase, the 1-day lag between the peak of the northerlies and minimum SST, and the small SST variability in the sheltered embayments. The expected circulation features are reproduced in the model solutions: the strong along-slope flows, the development of filaments and separated jets, shadow areas downstream of main capes, frontal-scale instabilities and the rapid onset of coastal counter currents along the inshore zone during relaxation. The evolution of the oceanographic conditions, specifically the mixed layer depth and horizontal velocity, and the advection patterns obtained from a Lagrangian model are compared with the observed SST and [Chl] variability. The results imply that the potential phytoplankton accumulation/growth (PPAG) areas are characterized by surface temperatures lower than 16.5 °C, mixed layer depth and horizontal velocity less than 30 m and 0.3 m/s, respectively. It is shown that remotely-sensed [Chl] concentration patterns, namely its asymmetric distribution relative to SST during the intense wind phase, is primarily related to the mixed layer depth and secondly to the horizontal velocity. The trajectories obtained with the Lagrangian model confirmed earlier suggestions of the presence of recirculation cells, downstream of the capes where the coastal jet separates from the coast, and revealed that significant vertical displacements occur in these cells.

1. Introduction

The summer oceanographic conditions along the west Portuguese coast are dominated by the coastal upwelling driven by persistent equatorward winds. Previous works based on satellite-data (Fiúza, 1983; Haynes et al., 1993; Sousa and Bricaud, 1992; Peliz and Fiúza, 1999) have shown that the summer sea surface temperature (SST) and chlorophyll ([Chl]) patterns are similar to those observed in other coastal upwelling regions, characterized by the recurrence of cold pigment-rich filament structures extending offshore.

Among the various locations where filament structures recurrently appear, the area off central Portugal as attracted the attention of recent works, suggesting that the local conditions could favor the development of harmful algal blooms (Moita et al., 2003; Amorim et al., 2004). This area, extending roughly from 38°N to 40°N, is characterized by major changes in coastline orientation, irregular bottom topography and the presence of large estuary (Tagus), leading to complex flow patterns with active upwelling centres and shadow areas (Moita et al., 2003).

Recent results have highlighted the importance of the temporal and spatial structure of upwelling to understand the high levels of productivity of coastal upwelling systems. Temporal fluctuations, provided by alternating pulses of upwelling and relaxation, and spatial structuring provided by alternating upwelling at headlands and retention in bays, allow strong upwelling that favors nutrient delivery to be juxtaposed with less energetic conditions that favor stratification and plankton blooms (Largier et al., 2006). On the other hand, it has been proposed that geographical variability in eddy activity and mixing of offshore and nearshore waters is a key factor for explaining the observed variability in primary production of different upwelling regions (Marchesiello and Estrade, 2007). These results and the growing evidence of a large primary production variability at scales ranging from 2 to 100 km has

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prompted the need to better understand the mechanisms by which the physical dynamics are reflected by the biological processes at such scales (Levy, 2008).

In this work we use satellite images and numerical model results to build up a framework under which relevant oceanographic features during an upwelling event off central Portugal (July 2005) are interpreted and discussed. Contrasting satellite data against the model solutions we show the model's ability to realistically reproduce the observed SST variability and describe the time evolution of the SST and [Chl] patterns. The results of a Lagrangian model are used to determine the impact of the shelf circulation on actual water displacements, to provide insight on potential origins and destinations of upwelled water and related them to the evolving SST and [Chl] patterns.

2. Data, models and methods

2.1. Satellite data

The satellite image sequences were constructed from various instruments with different space and time sampling capabilities. The SST maps were derived from SEVIRI (spinning enhanced visible and infra red imager, on board Meteosat), AVHRR (advanced very high resolution radiometer, NOAA satellite) and MODIS (moderate resolution imaging spectrometer, Aqua satellite) data, with nominal spatial resolutions respectively of 5, 2 and 1 km. SEVIRI and AVHRR SST products (CMS, 2005) were obtained from EUMETSAT's Ocean and Sea Ice Satellite Application Facility. The SST and [Chl] concentration maps derived from MODIS data (Feldman and McClain, 2006) were obtained from the Goddard's Space Flight Centre ocean colour data archive.

For the comparison between the satellite-derived and the model SST, the 3-hourly model temperatures of the top level of the model were linearly interpolated to the same spatial and temporal grid of the satellite images (~2 km). Moreover, only the valid (cloud-free) grid points (pixels) of the satellite images were considered for the model averages. Each model distribution interpolated for the time of the satellite pass was masked to retain only the same grid points of satellite image. SST time series were constructed for one offshore (area 0, Fig. 1) and three coastal areas with different responses to the wind forcing: the meridionally aligned coastal segment north of Cape Roca (area 1), the embayment between Capes Roca and Espichel herein referred to as Lisbon Bay (area 2) and the area between Capes Espichel and Sines herein Setúbal Bay (area 3).

2.2. Ocean model

The ocean simulations were performed using the Regional Ocean Modeling System (ROMS) described in Shchepetkin and McWilliams (2003, 2005), Wilkin et al. (2005), with embedded nesting capabilities, ROMS-AGRIF (Adaptive Grid Refinement In Fortran; Penven et al., 2006). ROMS is a 3D free-surface, sigma-coordinate, split-explicit primitive equation model with Boussinesq and hydrostatic approximations. ROMS-AGRIF enables the use of online and offline nesting thus permitting the regional applications to be built based on basin and local-scale configurations, and to cover a wide range of time and space scales. The present modeling experiments are a follow up of the Peliz et al. (2007a) numerical study, which the reader is referred to for a more thorough description of the model and of the approach used in the configurations. Herein we present a general overview.

The ocean model experiments are conducted using three domains; large, medium and small (LD, MD, SD) shown in Fig. 1. The initial and boundary conditions for the first domain (LD) are obtained from Peliz et al. (2007a) experiments from a first level of offline nesting. This domain of about 9 km resolution is intended to act like a buffer to downscale the basin scale variability (see Peliz et al., 2007a) into the Coastal Transition Zone. However, at this resolution the mesoscale is still poorly resolved. An additional grid of 3 km resolution (MD) is used to resolve the mesoscale, and in particular the Mediterranean outflow, its associated features like meddies, and its interaction with surface circulation. Finally, to solve frontal scale processes and coastal processes like river runoff and innershelf circulation features a third smaller domain (SD) with resolution in the order of 1 km is used (see in Fig. 1). The model bathymetry is based on National Geophysical Data Centre 2 min topography (ETOPO2) (Smith and Sandwell, 1997). The bathymetry depth data (h) is interpolated into model grids and smoothed several times until the factor $r = \delta h/2h$ (Haidvogel and Beckmann, 1999) is below 0.2. Sixty sigma levels are used with sigma resolution increasing near the surface ($\theta_s = 4$ and $\theta_b = 0$). Tidal elevation along the boundaries is included in LD (e.g. Marta-Almeida and Dubert, 2006), and point sources of mass (100 m^3/s), temperature (15 °C), and salinity (15) to simulate the Tagus river are imposed in SD grid. A realistic Mediterranean Undercurrent was imposed by a boundary inflow/outflow condition at the Strait of Gibraltar (see Peliz et al., 2007a for details). All grids communicate in 1-way nesting as described in Penven et al. (2006).

The experiments were conducted in two phases: a spin-up phase (May and June, 2005) with only LD and MD active and forced with low resolution atmospheric fluxes obtained from NCEP reanalysis (heat fluxes and solar shortwave radiation), and from QuickScat data (momentum fluxes). The second phase corresponds to the target simulation with all three domains, to approximate the June–August 2005. In this phase, high resolution atmospheric fields from WRF simulations (described below) are used. The results analysed in this paper correspond to this period and to the small domain (SD).

2.3. Atmospheric model

The Weather Research and Forecast atmospheric model (WRF V2.0) was used to dynamically downscale atmospheric reanalysis for the study period. WRF is a widely used research and forecast system (Skamarock, 2005) and an application of WRF simulations with ROMS is reported in Teles-Machado et al. (2007, e.g.). A regional configuration of WRF is set-up for the study period from June to August, 2005. The WRF simulations are initialised and forced along the open boundaries with the National Centre for Environment and Prediction (NCEP) reanalysis data (Kalnay et al., 1996). A grid of 15 km and 60 vertical levels is used. Surface winds, humidity, pressure, temperature and radiative data are calculated and passed to the ocean model for the air-sea fluxes calculation through a bulk formulation.

2.4. Lagrangian analysis

A Lagrangian submodel (floats for brevity) coupled to ROMS (Capet et al., 2004; Peliz et al., 2007b) is used for analysis of water parcel displacement. The floats use the 3D model velocity field for advection with a fifth-order scheme based on Adams-Bashforth/Adams-Moulton predictor–corrector time step algorithm. AGRIF has been adapted to manage the communication of floats through the different model domains (Capet et al., 2004).

A set of floats was initialized to obtain a Lagrangian description of the flow during the onset and relaxation of the upwelling event at time scales of interest for phytoplankton development.