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# Nutrient and chlorophyll *a* transports during an upwelling event in the NW margin of the Gulf of Cadiz

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ABSTRACT

The present study describes the fluxes and transports of nutrients and chlorophyll *a* inferred from direct observations carried out off south Portugal, during a research cruise in early October 2006. The covered area corresponds to the western part of the northern margin of the Gulf of Cadiz, from Cape São Vicente (9.0°W) till the Guadiana River mouth (7.4°W). Unlike in the western Iberian margin, the upwelling in this region is rather intermittent during the summer season. It is interleaved by periods when warm waters coming from the eastern part of the Gulf of Cadiz occupy the coastal region. However, our observations were taken during an intense upwelling event that took place at the end of the upwelling season. Ten meridional transects were sampled in a total of 90 CTD casts. Current velocity profiles were acquired along the ship's track with a hull-mounted acoustic Doppler current profiler (ADCP). The analysis of the circulation field and water masses characteristics led to the quantification of the fluxes and transports of chlorophyll *a* and nutrients in 5 meridional transects along the coast. Results show the prevalence of the alongshore eastward flow over the offshore Ekman transport in the coastal circulation without formation of upwelling filaments. Transport of chlorophyll *a* showed a near surface maximum (<30 dbar), while transport of nutrients were generally higher in the layer below (30–100 dbar). The estimates show net eastward alongshore transports of chlorophyll *a* and nutrients into the Gulf of Cadiz and weak cross-shore exchanges. At the deepest levels, the estimates of the transports by the shallow vein of the Mediterranean Water show an important input of nutrients to the Atlantic. However, waters in the top 100 dbar, impoverished in nutrients by biological utilisation due to upwelling, show that nitrate and phosphate transports provided into the Gulf of Cadiz exceed those carried westward by the shallow vein of the Mediterranean Water.



## 1. Introduction

The coastal region off southwest Iberia (Fig. 1) fits into the North Atlantic eastern boundary and is part of the northern branch of the Canary Current Upwelling System (CCUS). It encompasses the southern edge of the western Iberia coast and the western part of the Gulf of Cadiz northern margin that intercept at a right angle in the culminating point of the Cape São Vicente.

In coastal regions, the main dynamic control of biological processes at the seasonal scale derive from the alternation between a seasonal vertical mixing of the water column during winter and a progressive stratification in spring/summer, due to the solar radiation heating of the upper layers. In the northern section of the CCUS, this stratification period coincides with the upwelling season, which spans from March/April to September/October. However, off southwest Iberia two contrasting oceanographic regimes alternate during the upwelling season (Relvas and Barton, 2002): 1) an upwelling pattern related to local upwelling of subsurface cold water, driven by northerly/westerly winds on the west/south coast, together with the development of an associated geostrophic flow that turns cyclonically around Cape São Vicente into the Gulf of Cadiz, and 2) a non-upwelling pattern during wind relaxation that corresponds to the westward progression of a warm and saline coastal countercurrent progressing from the Gulf of Cadiz that turns northward around the Cape São Vicente at times, driven by an alongshore pressure gradient.

Similar episodes of northward advection of surface warm and saline waters over the inner shelf during the upwelling season have been observed along the NW Iberian Peninsula (Sordo et al., 2001), and in others eastern boundary upwelling systems (EBUS) at the shadow of prominent capes (Fawcett et al., 2008; Melton et al., 2009). However, the southwest Iberia constitutes a singular case, because it configures a right angle discontinuity in the CCUS and the alternation of the two above mentioned regimes is not episodic. The warm inshore countercurrent is recurrent and stands for periods that can reach more than two weeks during the upwelling season, because the advection of the cold upwelled water into the Gulf of Cadiz has to balance the pre-existing alongshore pressure gradient (Relvas and Barton, 2002). The interaction of the

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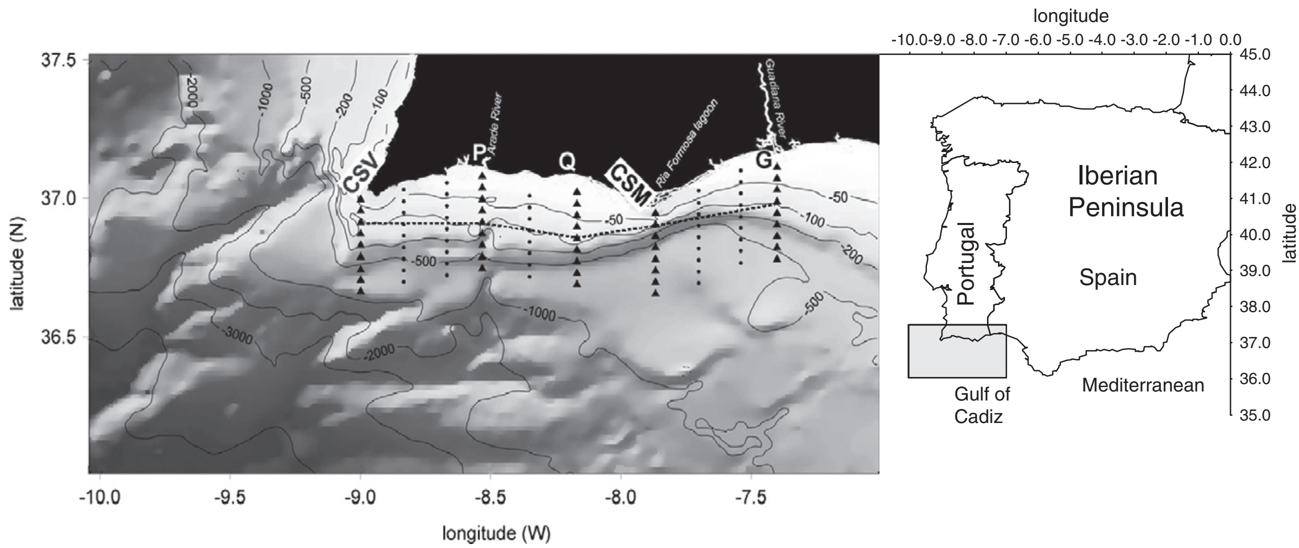


**Fig. 1.** Location of the study area and sampling stations. Dots represent the CTD stations and triangles the stations where chemical and biological characterisation was also conducted. The 5 transects with chemical and biological sampling are identified as Guadiana (G), Cape Santa Maria (CSM), Quarteira (Q), Portimão (P) and Cape São Vicente (CSV). Bottom topography and bathymetric contours are represented. The dashed line over the outer continental shelf represents the alongshore section referred to in the text.

coastal countercurrent with the upwelling jet results in conspicuous mesoscale phenomena in the surroundings of the Cape São Vicente and off the south Portuguese coast.

During the occurrence of coastal upwelling, cold nutrient-rich water ascends into the photic layer along the nearshore region, forced by favourable winds, following the Ekman mechanism. At the initial stage, upwelled waters are characterised by low temperature, low chlorophyll *a* and high nutrient concentrations (Alvarez-Salgado et al., 2001). Afterwards, if water stratification conditions occur, a fast growth of the phytoplankton can take place, promoting a quick consumption of the available nutrients in the water, sometimes almost reaching their exhaustion (Joint et al., 2001). The offshore Ekman transport in the upper layers promotes the exchange of chlorophyll *a* and nutrients with offshore waters, enhancing the biological productivity, even in waters that are considered oligotrophic. The irregular bottom topography of the studied region, along with the coastline configuration, which shows a succession of headlands and bays, strongly modulate the spatial development of the upwelling. Retention in bays takes place, leading to water stratification and nutrient supply in less energetic conditions that favour the development of the phytoplankton (Largier et al., 2006; Oliveira et al., 2009).

Another singularity of the studied region is the presence of Mediterranean water (MW) at levels as shallow as 400 dbar or less, along the continental slope off SW Iberia (Ambar, 1983). The presence of MW at these levels and its effects upon the nutrient concentration distribution was first observed in the early 30s and documented in the pioneering work of Boto (1945). Subsequent works confirmed the existence of a shallow core of MW in the region and analysed some of its chemical characteristics (Ambar et al., 2002; Cabeçadas et al., 2002). Despite not being the main goal of our study, the MW was identified during the observations and its influence on the nutrient dynamics will be reported here.

Studies devoted to the chemical characterisation of the water masses in the Gulf of Cadiz mainly describe either the upper layers down to 200 dbar, centred in the biological processes (Anfuso et al., 2010; García et al., 2002; Huertas et al., 2005, 2006; Navarro et al., 2006; Prieto et al., 1999, 2009; Ruiz et al., 2006), or the deep waters, such as the MW, where the surface layer is marginally considered (Ambar et al., 1976, 2002; Brogueira et al., 2004; Cabeçadas et al., 2002). Few recent studies describe the chemical characteristics from surface down to 2000 dbar (Flecha et al., 2012; Huertas et al., 2012). In this study we explore the *in situ* data to describe the water column from surface down to 500–800 dbar and it extends a previous investigation about the chemical signatures in the region during an upwelling event (Cardeira et al., 2013). Although it was late in the upwelling season, the environmental data show that an intense upwelling event was occurring at the time. Thus, the present study aims to analyse the water mass characteristics and quantify the fluxes and transports of chlorophyll *a* and nutrients associated with the upwelling regime along SW Iberia. In the absence of upwelling favourable wind stress, the westward progression of the warm and saline coastal countercurrent should transport to the region waters originating from the Gulf of Cadiz that are poor in nutrients and chlorophyll *a*. These oligotrophic waters are mainly observed during summer (Navarro and Ruiz, 2006), reducing the biological productivity of the continental shelf. However, a thorough characterization of this non-upwelling regime would be necessary in order to have a full picture of this interleaved regime.

## 2. Data acquisition and methods

### 2.1. Sampling strategy and data

The sampled area was the coastal ocean off southern Portugal, extending from near the coast to about 40 km offshore, and from the Cape São Vicente (9.0°W) to the Guadiana River mouth (7.4°W) (Fig. 1). Ten meridional transects were sampled between 1st and 5th October 2006 on board the research vessel *NRP D. Carlos I*, from the Portuguese Navy. Nine CTD stations were executed at each transect with an *Idronaut* OS 316 CTD coupled with a Rosette sampler till a maximum depth of 900 dbar. A total of 90 CDT casts were performed. The CTD sampling rate was 20 Hz and the lowering speed was 1 m $s^{-1}$. Water samples for nutrients and chlorophyll *a* (chl *a*) quantification were acquired only at 5 selected transects along the coast (Fig. 1). The selected depth levels were: 5, 10, 20, 30, 50, 75, 100, 125, 200, 250, 300, 500, 700, and 800 dbar. Spectrophotometric methods based on calibration curves were used for the nutrient determination as described by Grasshoff et al. (1983). For the chl *a* quantification, a spectrofluorometric method was chosen as described in Yentsch and Menzel (1963). Further details are given in Cardeira et al., 2013.