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Cross-shore transport in a daily varying upwelling regime: A case study of barnacle larvae on the southwestern Iberian coast

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ABSTRACT

With favored offshore and downstream advection, the question of which physical mechanism may promote onshore transport of larvae in upwelling systems is of central interest. We have conducted a semi-realistic high resolution (0.25 km) numerical study of Lagrangian transports across the inner-shelf under upwelling-favorable wind forcing conditions, focusing on the shelf area of the Southwestern Portuguese coast, in the lee of Cape Sines. We add our findings to several years of biological observations of *C. montagui*, a planktonic species with higher recruitment during the upwelling peak timely with the daylight flood. Simulations cover a fifteen days period during the summer of 2006. We focused on Spring and Neap tide periods and observed upfront differences between simulations and the in situ observations. However, the model is capable of representing the main dynamics of the region, namely the repetitive character of the inner-shelf currents. We find that the cross-shore flow varies significantly in the daily cycle, and locally within a scale of a few kilometers in association with local topography and the presence of the cape. We consider the region immediately in the lee of the cape to be an upwelling shadow where the larvae became retained, and found that tidally tied migration proves beneficial for successful recruitment during the spring tides period. Our work suggested that the wind is not the only mechanism responsible for the daily variability of the cross-shore exchange. However, its sharp reversal at midday is critical for the advection of larvae towards the coast.

1. Introduction

The inner-shelf dynamical processes of plankton cross-shore transport and dispersion, are critical in several aspects of marine ecology and have motivated many different studies in recent years (Fewings et al., 2008; Lentz et al., 2008; Paris et al., 2013).

Many coastal species have a planktonic phase and larvae must be transported back onshore for settlement. This process is particularly interesting for species inhabiting coastal zones dominated by upwelling regime where average wind conditions favor offshore transport of surface material and onshore transport of the intermediate and bottom waters (dos Santos et al., 2008). This average circulation pattern may require complex adaptive responses in terms of the larval behavior and vertical distribution (Shanks and Brink, 2005; Marta-Almeida et al., 2006), for larvae to overcome the mean advective tendency, and enable recruit on inshore areas. At the inner shelf, however, the double layer cross-shore circulation may shut down (Lentz et al., 2008) with a blocking of the cross-shore transport. Very close to shore, processes other than wind (e.g., tides and waves) need to be accounted for to explain onshore transport.

In this paper, we contribute to the knowledge of the cross-shore transport processes in upwelling systems. The southwestern Iberian coast is dominated by quasi-steady upwelling winds in summer (May–September) (Lemos and Pires, 2004). This coast is characterized by rocky shores that provide habitat for many benthic species with a planktonic phase. In particular, the case of *Chthamalus montagui* that is the most abundant intertidal barnacle of the Portuguese continental coast (Cruz et al., 2005). From the point of view of cross-shore transport, *C. montagui* has two interesting characteristics. First, its recruitment has been observed to occur from March to October, being highest during summer (O'Riordan et al., 2004) timely with the peak of upwelling activity.

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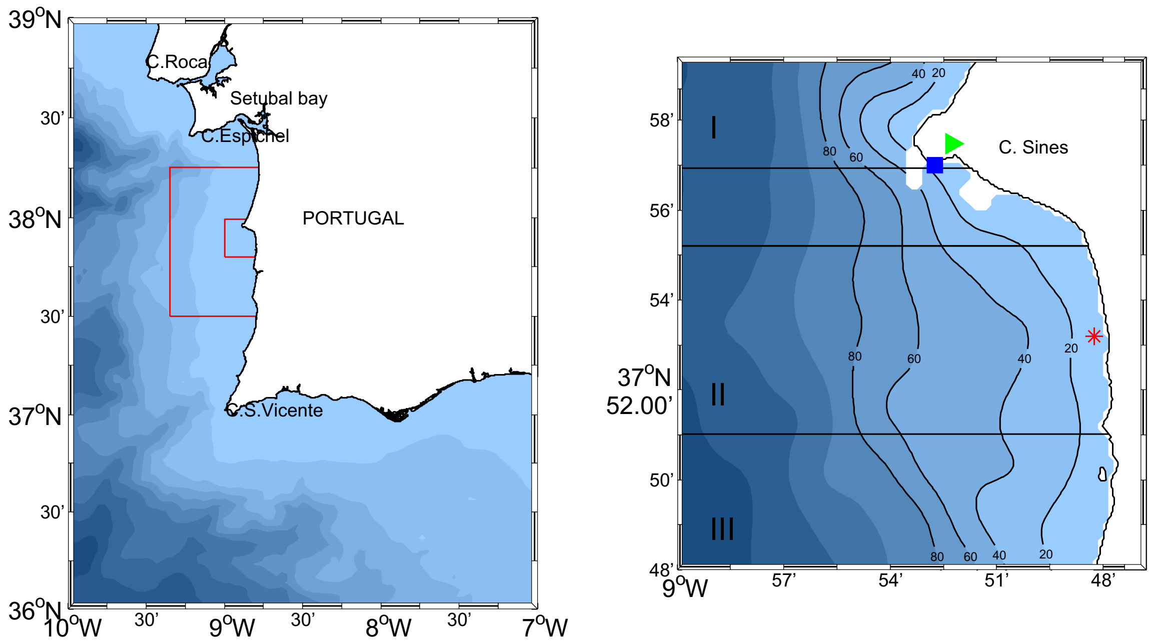

Fig. 1. Map and topography of the study area. The red boxes show the model domain and the study area. The right side figure shows the Port of Sines (P. Sines), the model topography in the study area, the location of the moored ADCP (*), the Meteorological Station (▶) and the Tide Gauge (■). Markers I, II and III represent regions of recruitment assessment. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

On the other hand, variability of tidal recruitment (recruitment within the tidal cycle) of this species has been observed (Cruz, 1999; Cruz et al., 2005; Jacinto and Cruz, 2008). Recently it has been observed that settlement of this species occurs mostly during the day and during the flood (Cruz et al., 2005, 2009) and suggested that cyprids (last larval stage) of this species are mostly neustonic during daylight flood (Cruz et al., 2009).

In this study, we use numerical modeling to simulate the shelf circulation and the cross-shore transport patterns during a typical period of upwelling on the southwestern coast of Portugal (around Cape Sines (Fig. 1)) where the recruitment of *C. montagui* has been studied for several years now (e.g., O'Riordan et al., 2004). The processes of plankton dispersal on larger spatial and time scales, which determine the availability of larvae for settlement, are not addressed here. We assume that larvae are available near the coast, and our central objective is to understand the near shore circulation and the physical mechanisms that promote onshore transport during typical upwelling conditions, as well as explore its relation with the observed larval preference for settling during the daylight flood (Cruz et al., 2009).

Despite the localized nature and species-specific assumptions our conclusions may be applicable to other upwelling areas and to other planktonic species.

In the next sections we describe all the observations and models that were used. After, we make a detailed description of an upwelling event in the selected period with the existing data. We described all the numerical simulations of the shelf circulation and compared them to observations with a focus on the cross-shore circulation. The Lagrangian model results are presented, summarized and discussed with emphasis on the most relevant patterns of the daily cycle.

2. Data and models

2.1. Data

Atmospheric data (air temperature, incoming solar radiation and wind) were collected at the meteorological station of the Port of Sines authority. Tides were measured by a tide gauge located inside the port (Fig. 1 (right)). The above data were collected for three summers (2006–2008). Velocity and temperature profiles of the inner-shelf zone in the lee of Cape Sines (see Fig. 1), were measured with an Acoustic Doppler Current Profiler (ADCP) and a 5 thermistors chain deployed at a nominal depth of about 12 m. Thermistors measured temperature data at 2, 3, and 5 m above the sea floor, at the surface and 2 m depth. ADCP data were also collected for the above mentioned summer periods while thermistors data were only available for the summers of 2006 and 2007. All the data were hourly averaged. We used the observation period between July 20th and August 4th of 2006 to produce the ocean model initialization and forcing, and also to compare with the ocean model simulation outputs.

Satellite derived SST daily maps (~2 km resolution) are used to illustrate the larger scale context during the study period, for the 20th and 30th of July and the 4th August of 2006. The satellite data were obtained from the Ifremer Cersat website (Medspiration Project).

2.2. Ocean model

Simulations were carried out with the Regional Oceanic Modeling System (ROMS), described in Shchepetkin and McWilliams (2005) and Haidvogel et al. (2008), on a high resolution 0.22×0.22 km grid for a fifteen day period. In the vertical, 32 σ levels are used with significant surface stretching ($\theta_s = 7$), a critical depth ($Hc = 5$ m) and no bottom stretching ($\theta_b = 0$) resulting in enhanced vertical resolution at surface levels. Topography data compiled in Peliz et al. (2013) was used. A low level of topographic smoothing is required because of the high resolution. To avoid large differences of topography around the domain (in particular the canyons on the north), a cutoff depth of 800 m is imposed. The minimum depth is 5 m (see model topography in Fig. 1 right).

Bottom drag quadratic parametrization is used with a variable coefficient $Cd = (k/\log(z_b/z_0)^2)$ with $z_0 = 0.005$, where k is the von Kármáan's constant and z_b is the height of the deepest level (Marta-Almeida and Dubert, 2006) (a test with constant