Continental Shelf Research 143 (2017) 67–77

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Diurnal variability of inner-shelf circulation in the lee of a cape under upwelling conditions

L. Lamas[a,b,*], A. Peliz[b], J. Dias[a], P.B. Oliveira[c], M.M. Angélico[c], J.J. Castro[d], J.N. Fernandes[d], A. Trindade[e], T. Cruz[d]

[a] MARE – Marine and Environmental Sciences Centre, Faculdade de Ciências da Universidade de Lisboa, Campo Grande 1749-016, Lisboa, Portugal
[b] Instituto Dom Luiz, Faculdade de Ciências da Universidade de Lisboa, Campo Grande 1749-016, Lisboa, Portugal
[c] Instituto Português do Mar e Atmosfera, 1449-006 Lisboa, Portugal
[d] MARE – Marine and Environmental Sciences Centre, Laboratório de Ciências do Mar, Universidade de Évora, 7520-903 Sines, Portugal
[e] Institut de Ciències del Mar, Departament Oceanografia Física i Tecnològica, 37-4908003 Barcelona, Spain

ARTICLE INFO

Keywords:
Coastal oceanography
Wind-driven circulation
Upwelling
Diurnal variability
Topography
Inner-shelf circulation

ABSTRACT

The nearshore circulation in the lee of a cape under upwelling conditions was studied using in-situ data from 3 consecutive summers (2006–2008). Focus was given to a period between 20 July and 04 August 2006 to study the diurnal variability of the cross-shelf circulation. This period was chosen because it had a steady upwelling-favourable wind condition modulated by a diurnal cycle much similar to sea breeze.

The daily variability of the observed cross-shelf circulation consisted of three distinct periods: a morning period with a 3-layer vertical structure with onshore velocities at mid-depth, a mid-day period where the flow is reversed and has a 2-layer structure with onshore velocities at the surface and offshore flow below, and, lastly, in the evening, a 2-layer period with intensified offshore velocities at the surface and onshore flow at the bottom. The observed cross-shelf circulation showed a peculiar vertical shape and diurnal variability different from several other systems described in literature. We hypothesize that the flow reversal of the cross-shelf circulation results as a response to the rapid change of the wind magnitude and direction at mid-day with the presence of the cape north of the mooring site influencing this response.

A numerical modelling experiment exclusively forced by winds simulated successfully most of the circulation at the ADCP site, especially the mid-day reversal and the evening's upwelling-type structure. This supports the hypothesis that the cross-shelf circulation at diurnal timescales is mostly wind-driven. By analysing the 3D circulation in the vicinity of Cape Sines we came to the conclusion that the diurnal variability of the wind and the flow interaction with topography are responsible for the circulation variability at the ADCP site, though only a small region in the south of the cape showed a similar diurnal variability.

The fact that the wind diurnally undergoes relaxation and intensification strongly affects the circulation, promoting superficial onshore flows in the leeside of Cape Sines. Despite the small-scale nature of the observed cross-shelf circulation, onshore flows as the ones described in this study can be particularly helpful to understand the transport and settlement of larvae in this region and in other regions with similar topography and wind characteristics.

1. Introduction

The cross-shelf circulation over the nearshore region plays a key role on the distribution of plankton, nutrients, heat, salt and sediments, and has been the subject of many recent studies (Fewings et al., 2008; Lentz et al., 2008; Hendrickson and MacMahan, 2009; Marchesiello and Estrade, 2010; Ganju et al., 2011; Lentz and Fewings, 2012; Liu and Gan, 2014). Wind-driven upwelling and downwelling systems are particularly important because of the cross-shelf exchange that is forced in these wind conditions, which promotes transport of material across the shelf, especially over stratified shelves (Austin and Lentz, 2002). In the region onshore of the upwelling front, stratification is often weaker and the surface and bottom turbulent layers overlap, causing the reduction or shut-down of the cross-shelf transport (Estrade et al., 2008). This region is normally referred to as inner-shelf (Lentz, 2001; Austin and Lentz, 2002; Fewings et al., 2008). In

* Corresponding author at: MARE – Marine and Environmental Sciences Centre, Faculdade de Ciências da Universidade de Lisboa, Campo Grande 1749-016, Lisboa, Portugal.
E-mail addresses: lalamas@fc.ul.pt (L. Lamas), ajpeliz@fc.ul.pt (A. Peliz), jdias@fc.ul.pt (J. Dias), pboliveira@ipma.pt (P.B. Oliveira), mmangelico@ipma.pt (M.M. Angélico), jjc@uevora.pt (J.J. Castro), jfer@uevora.pt (J.N. Fernandes), atrindade@icm.csic.es (A. Trindade), tcruz@uevora.pt (T. Cruz).

http://dx.doi.org/10.1016/j.csr.2017.06.006
Received 2 May 2016; Received in revised form 5 June 2017; Accepted 11 June 2017
Available online 13 June 2017
0278-4343/

spite of weaker cross-shelf transport conditions, this shallow part of the shelf is an attractive habitat for many coastal species. For example, inter-tidal species, having their planktonic larval phase over the shelf, must cross the nearshore zone for settlement. Cross-shelf transport processes over the shelf are thus critical for the larvae supply to the shore, which then determines recruitment (Pineda et al., 2009). Understanding the physical processes behind the cross-shelf exchange over the inner-shelf is of particular interest for this type of studies.

The wind-driven shelf response over a straight coastline has been extensively studied. Upwelling-favourable winds drive cross-shelf exchange with an offshore flow at the surface boundary layer and a compensating onshore flow near the bottom. This occurs for depths typically greater than 50 m, when the surface and bottom boundary layers are relatively thin when compared with total water depth (a region often called mid-shelf (Lentz and Fewings, 2012)). With strongly stratified waters, this region moves inshore as the turbulent layers thin due to stronger stratification, extending the cross-shelf circulation farther inshore when compared with unstratified conditions (Austin and Lentz, 2002; Horwitz and Lentz, 2014). Less is known for systems with complex topography variations. Divergences in the along-shelf and cross-shelf flows may occur with the presence of complex coastline topography and subtle bathymetric features, that can drive substantial cross-shelf exchange (Barth et al., 2000; Gan and Allen, 2002; Kirincich et al., 2005; Sanay et al., 2008; Ganju et al., 2011). As seen in several studies (Gan and Allen, 2002; Gutierrez et al., 2006; Kuebel Cervantes and Allen, 2006; Maza et al., 2006), strong along-shore pressure gradients can form in the presence of a cape, when the upwelling wind regime relaxes. These pressure gradients are accompanied by geostrophically balanced cross-shelf flows over the inner-shelf, resulting in the intensification of the upwelling in the lee of the cape. A cyclonic recirculation that may form in the presence of a cape, can also be relevant since it enhances the onshore transport in the leeside of the cape (Barth et al., 2000; Doglioli et al., 2004; Meunier et al., 2010; Liu and Gan, 2014).

here we conduct a study of the shelf circulation at a site with sharp along-shelf topography changes, and with a marked diurnal variability. the strong diurnal cycle of the wind motivated the focus on the daily variability of the circulation, since sea breeze events are found to be particularly important in promoting onshore transport across the inner-shelf, through its influence on both winds and waves (Woodson et al., 2007; Hendrickson and MacMahan, 2009; Lucas et al., 2013).

The study area lies within the meridional coast of Portugal around Cape Sines (Fig. 1). The shelf is relatively narrow (around 30 km) with the shelf break at approximately 150 m depth. South of the Cape, the shore is mostly rocky and crucial for many inter-tidal species including barnacles (Cruz et al., 2005). The processes of barnacle recruitment at this site have been under investigation for many years now, in the frame of various projects (Cruz, 1999; Cruz et al., 2005; Jacinto and Cruz, 2008; Cruz et al., 2009; Trindade et al., 2016). We used Eulerian velocity measurements collected at 12-m water depth in the lee of Cape Sines, over 3 consecutive summers (2006–2008). Summertime is the period when the larvae recruitment of several barnacle species is higher for the study region (Cruz, 1999; Cruz et al., 2005; Jacinto and Cruz, 2008), which can be particularly interesting since, during summer, the western Iberian coast is typically under upwelling-favourable winds (Relvas et al., 2007), which intensify the along-shelf currents and promote the shut-down of cross-shelf transport in the region inshore of the upwelling front (Estrade et al., 2008). However, in the presence of a cape, diurnal relaxation periods may induce retention-favourable conditions, which can be beneficial to larvae recruitment in the leeside of the cape (Roughan et al., 2005a, 2005b; Peliz et al., 2007; Woodson et al., 2007; Oliveira et al., 2009; Lucas et al., 2013).

We chose a period between 20 July and 04 August 2006 when the wind showed a steady upwelling-favourable condition modulated by a diurnal cycle of the wind. The use of a period with such stable wind forcing enabled us to minimize other forcing effects and to focus on the wind-driven part of the circulation. A numerical model simulation was also conducted to study the wind-driven circulation in the vicinity of Cape Sines during this period. This study adds new insights about the spatial patterns of the circulation at diurnal timescales in the leeside of Cape Sines and how transport across the shelf may be promoted.

2. Data and methods

2.1. In-situ data

Wind data for the summers of 2006, 2007 and 2008 were collected at the Meteorological station of the Port of Sines authority, at 37° 57′ 25″ N; 8° 52′ 74″W which is about 10 km North of the ADCP location (Fig. 1). Wave and tidal data for the same period were collected at 37° 55′ 14″ N; 8° 55′ 47″W, and 37° 56′ 89″ N; 8° 53′ 27″W respectively (Fig. 1).

Four thermistors (Stowaway TidBit, Onset Computer Corp.) were deployed from July 19, 2006 to September 15, 2006 and from 1 to 14 of August 2007, on a mooring next to the ADCP location. Temperature was measured at 4 different depths: 1 m, 3 m and 5 m above the sea floor, and at the surface. A fifth thermistor was deployed in 2006 at 2 m from the surface.

Velocity profiles were measured with a bottom-mounted upward looking Acoustic Doppler Current Profiler (WorkHorse Sentinel 1200 kHz), with a bin size of 0.5 m, and a ping frequency between 0.83 and 1.67 Hz, deployed in approximately 12-m water depth at 37° 53′ 11.52″N, 8° 48′ 15.42″W, and about 600 m offshore (Fig. 1). The data was collected in 2006, between July 19 and August 29; in 2007, between July 31 and August 14; and in 2008, between July 22 and September 9 (with a gap between August 05 and August 19). As bottom-mounted ADCPs do not sample the entire water column, the deepest bin corresponds to approximately 1.5 m above sea bed.

The upper bins of the ADCP correspond either to emersed or submersed depth cells depending on the height of the free surface, mainly due to tidal movements. Therefore it was first necessary to find the sea surface, and disregard all bins above that surface. To find the contaminated bins, and since the data was collected at a shallow location where the tidal amplitude ranges from 14% to 30% of the total depth, the 'tide-following method' was used (Kirincich et al., 2005). For each profile, the depth of maximum backscatter intensity was marked as the water surface and all bins above this surface were discarded, plus three bins immediately below it.

2.2. Time-averaging and vertical coordinate transformation

The fact that the sea surface undergoes significant changes in shallow waters rises the question of how to compute the daily time averages of data along the same depth. If a bottom or surface reference coordinate system is used (Kirincich et al., 2005; Fewings et al., 2008; Lentz et al., 2008), an average along the same z-level will include data that are at very different relative distances to the surface (especially in spring tides and shallow waters) and this will produce an aliased mean. To overcome this problem, a dynamical (tide-following) vertical coordinate $z' = z/h$, where h is the total water column depth (changing with tides), was used. The total depth (or the sea surface height) was computed by adjusting the surface detected with the maximum of total backscatter intensity to the sea surface using the tidal height measured at the port of Sines (near the ADCP location, see Fig. 1). Each ADCP profile was then interpolated into this new coordinate system. Time-averaging was then performed along each of the dynamical-surfaces, ensuring that the time-averaging of velocity values is done along levels that are at equal relative distances to the bottom and sea surface. The dynamical vertical coordinate conserves information of both bottom and surface bins and it was, therefore, the one chosen for this study.

The coordinate system was rotated based on the principal axis direction of the subtidal depth-averaged velocity. For most deploy-