Eddy-induced cross-shelf export of high Chl-a coastal waters in the SE Bay of Biscay

Anna Rubio¹, Ainhoa Caballero¹, Alejandro Orfila², Ismael Hernández-Carrasco³, Luis Ferrer¹, Manuel González¹, Lohitzune Solabarrieta⁴, Julien Mader¹

¹ AZTI-Marine Research, Herrera Kaia, Portualdea z/g, 20110 Pasaia, Spain
(arubio@azti.es)

² Marine Technologies and Operational Oceanography Department, IMEDEA (CSIC-UIB), Esporles, Spain

³ SOCIB (Balearic Islands Coastal Observing System), Parc Bit, Edificio Naorte, 2nd floor, 07121 Palma de Mallorca, Spain.

⁴ King Abdullah University of Science and Technology (KAUST), Red Sea Research Center (RSRC), Biological and Environmental Sciences and Engineering Division (BESE), Thuwal, 23955-6900, Saudi Arabia

1. Abstract

Different remote sensing data were combined to characterise a winter anticyclonic eddy in the south-eastern Bay of Biscay and to infer its effects on cross-shelf exchanges, in a period when typical along shelf-slope currents depict a cyclonic pattern. While the joint analysis of available satellite data (infrared, visible and altimetry) permitted the characterisation and tracking of the anticyclone properties and path, data from a coastal HF radar system enabled a quantitative analysis of the surface cross-shelf transports associated with this anticyclone. The warm core anticyclone had a diameter of around

50 km, maximum azimuthal velocities near 50 cm s^{-1} and a relative vorticity of up to $-0.45 f$. The eddy generation occurred after the relaxation of a cyclonic wind-driven current regime over the shelf-slope; then, the eddy remained stationary for several weeks until it started to drift northwards along the shelf break. The surface signature of this eddy was observed by means of high-frequency radar data for 20 consecutive days, providing a unique opportunity to characterise and quantify, from a Lagrangian perspective, the associated transport and its effect on the Chl-a surface distribution. We observed the presence of mesoscale structures with similar characteristics in the area during different winters within the period 2011-2014. Our results suggest that the eddy-induced recurrent cross-shelf export is an effective mechanism for the expansion of coastal productive waters into the adjacent oligotrophic ocean basin.

Keywords: Ocean mesoscale eddies, cross-shelf transport, FSLE, remote sensing, High Frequency Radar, Lagrangian Coherent Structures, Lagrangian Connectivity Maps

1. Introduction

Over the past years, several studies have demonstrated the effects of eddies on the enhancement of primary production through different mechanisms like eddy (eddy-Ekman) pumping in cyclonic (mode-water) eddies (McGillicuddy *et al.*, 1999; Gaube *et al.*, 2015) or the trapping of mesotrophic water (Brzezinski and Washburn, 2011; Huntley *et al.*, 2000). Other studies have revealed enhanced productivity also near eddies and peripheries, with an associated increase of biomass at higher trophic levels (e.g. Weimerskirch *et al.*, 2004). This enhancement has been related to stronger vertical velocities, due to submesoscale dynamics at eddy margins (Capet *et al.*, 2008; Lévy *et al.*, 2012; Mahadevan *et al.*, 2016) among other processes (Peterson *et al.*, 2011). In coastal areas, several authors also highlighted the role of mesoscale eddy activity in controlling the cross-shelf exchanges (Combes *et al.*, 2013; Péliz *et al.*, 2004). Using satellite-derived observations of chlorophyll-a (hereinafter Chl-a) and eddy kinetic energy, together with model simulations, Gruber *et al.* (2011) showed that eddy-induced transport of nutrients from the nearshore environment to the open ocean reduces productivity in eastern boundary upwelling zones. The accurate observation and monitoring of these structures, as well as the effect that they induce on the cross-shelf transport, is challenging since in coastal areas eddies interact with complex ocean dynamics, partially driven by local forcing.

In the Bay of Biscay, different works based on satellite, in-situ and model data have focused on the study of seasonal eddies formed along the SE slope. The characteristic winter slope circulation in the SE Bay of Biscay (hereinafter SE BoB) related to the Iberian Poleward Current (hereinafter IPC), is the main driver of the generation of Slope Water Oceanic eDDIES (SWODDIES). The winter IPC flows over the slope in the upper 300 m of the water column, advecting warm surface waters eastwards along the Spanish coast and northwards along the French coast (Le Cann and Serpete, 2009; Charria *et al.*, 2013) (Fig. 1). In summer, the flow is reversed being three times weaker than in

winter (Solabarrieta *et al.*, 2014). Thus, the generation of SWODDIES occurs mainly in winter, when the intensified IPC interacts with the abrupt bathymetry (Pingree and Le Cann, 1992). Teles-Machado *et al.* (2016) studied the generation of SWODDIES in the NW Iberian margin, by means of a 20-year high-resolution numerical simulation, and found a relationship between the formation of eddies, topographic features and the wind variability. A sudden decrease in southerly winds resulted in the development of instabilities in the IPC and generation of eddies, being the anticyclones (cyclones) formed mainly on the equatorward (poleward) side of the canyons and on the poleward (equatorward) side of promontories or capes (Teles-Machado *et al.*, 2016). In the SE BoB, overlaid to the density-driven slope circulation, wind-induced currents are the main drivers of the surface circulation (e.g. Lazure, 1997; Solabarrieta *et al.*, 2015; Fontán and Cornuelle, 2015; Kersalé *et al.*, 2016). During autumn and winter, SW winds dominate and generate northward and eastward drifts over the shelf. The rest of the year the winds are much weaker and less persistent, which makes wind-driven currents more variable (González *et al.*, 2004; Lazure, 1997; Solabarrieta *et al.*, 2015). The high-frequency variability is dominated by inertial oscillations and semi-diurnal and diurnal tides.

The effect of SWODDIES on the primary production has been previously investigated by several authors (Rodríguez *et al.*, 2003; Fernández *et al.*, 2004; Garcia-Soto *et al.*, 2002; Caballero *et al.*, 2014 and 2016). In several studies, the trapping of mesotrophic water from coastal areas by SWODDIES has been observed using satellite data, but not quantified (e.g., Caballero *et al.*, 2014). In-situ measurements showed that the depth-integrated Chl-a concentration was higher in the cores of anticyclonic eddies than in their periphery, influencing the plankton composition (Rodríguez *et al.*, 2003; Fernández *et al.*, 2004; Caballero *et al.* (2014). In contrast, lower Chl-a concentrations have been observed in the cores of cyclones (Garcia-Soto *et al.*, 2002; Caballero *et al.*, 2016). These studies have focused on eddies west of 3.5°W. Nevertheless, to our knowledge little has been investigated about eddies generated east of 3.5°W.

Fig. 1. Study area and schematic view of the winter shelf-slope current (solid blue arrows). The mesoscale regime is schematically represented by the hollow blue arrows (although only anticyclonic arrows are represented, eddies of anticyclonic and cyclonic polarity are observed in different locations along the slope). The high-frequency radar footprint area is delimited by the bold black lines. Black crosses show the positions of the Sea Level Anomaly data along altimeter tracks 213 and 248. Red crosses and red points show the positions where radar data were interpolated to obtain time evolution plots in Fig. 4. Stars provide the location of the high-frequency radar antennas at Matxitxako and Higer Capes. The asterisk shows the location of the model wind data series used in Fig. 4. Isobaths are depicted using a grey colourbar (in meters).

Since the installation in 2009 of a high-frequency radar (hereinafter HFR) system in the SE BoB, several mesoscale coherent structures have been reported within the HFR footprint area (Rubio *et al.* 2013; Solabarrieta *et al.*, 2014). However, their characteristics and effects on cross-shelf transport remained unstudied. In summer 2013, a cyclonic eddy was observed during a glider mission in front of Cape Matxitxako (see Fig. 1), within the HFR footprint area (Caballero *et al.*, 2016). The vertical structure of this cyclone was characteristic of cyclonic thinnies (see McGillicuddy *et al.*, 1999) with isopycnals down-

lifted (up-lifted) from surface (300 m) to at least 100 m (750 m) depth. In satellite-derived Sea Surface Temperature (hereinafter SST) maps, a colder signal was observed around its centre. Although the effect of this cyclonic structure on the vertical distribution of Chl-a was demonstrated, the lack of HFR data in that period did not permit analysing the effect of this eddy on the surface Chl-a transport.

In the present work, our main aim is to characterise mesoscale coastal dynamics in the SE BoB by means of a 4-year historical data set of HFR-derived surface currents in combination with other remote sensing platforms (AVHRR SST, MODIS Chl-a and altimetry). Particularly, we focus on the characterisation and quantification of eddy-induced cross-shelf transports. Since HFR provides continuous monitoring of surface coastal transport at high spatial and temporal resolution, it offers the possibility to study the transport properties of the flow from the Lagrangian point of view. In the last decades, new Lagrangian techniques have been developed to improve the identification of Lagrangian Coherent Structures (hereinafter LCS; see Haller and Yuan, 2000; Haller, 2015) using Finite-Size Lyapunov Exponents (hereinafter FSLE, d'Ovidio et al., 2004; Hernández-Carrasco et al., 2011). The FSLE technique has also been applied to HFR velocities in previous works, showing that it is a convenient tool to analyse transport in coastal flows (Haza et al., 2010; Berta et al., 2014). Here, we use different Lagrangian techniques, including FSLE applied to HFR data, to study the transport associated to SE BoB coastal eddies.

2. Data and methods

2.1. Coastal HFR data

Surface currents were obtained by means of two long-range HFR antennas, owned by the Directorate of Emergency Attention and Meteorology of the Basque Security Department. HFRs are capable to measure ocean surface currents over wide areas

(reaching distances from the coast over 100 km) with high spatial (1-5 km) and temporal (≤ 1 h) resolution. Recent studies have demonstrated the potential of this land-based remote sensing technology for different applications in the field of coastal oceanography (Paduan and Washburn, 2013; Rubio et al., 2017). The SE BoB radar antennas emit at a central frequency of 4.5 MHz and a 40-kHz bandwidth. They are located at Matxitxako and Higer Capes (see Fig. 1), and provide operational data since 2009. The received signal, an averaged Doppler backscatter spectrum, is processed to obtain hourly radial currents using the MUSIC algorithm (Schmidt, 1986). The coverage of radial data is of up to 150 km with a 5-km range cell resolution and a 5° angular resolution. For a more detailed description of the system, and HFR data validation exercises in the study area, the reader is referred to Solabarrieta *et al.* (2014, 2015 and 2016) and Rubio *et al.* (2011).

For this work, radial currents were processed using the Open Mode Analysis (OMA) to obtain spatially gap-filled total currents (Kaplan and Lekien, 2007). The OMA was applied by using the HFR_Progs Matlab package (<https://cencalarchive.org/~cocmpmb/COCMPwiki/>), based on Gurgel (1994) and Lipa and Barrick (1983). 85 OMA modes, built setting a minimum spatial scale of 20 km, were used to generate hourly total fields. Radial data were quality controlled using advanced procedures based on velocity and variance thresholds, noise to signal ratios and radial total coverage. Since the deployment of the HFR in 2009, the receipt antenna pattern of the two HFR sites has been calibrated at least biannually. The use of an accurate measured antenna pattern is crucial when evaluating mesoscale structures that otherwise could appear shifted from their real locations. The correctness of the calibration for the analysed period was proven by the good agreement between the different remote sensing observations shown here.

Two periods of HFR data were used in this study: (i) 2011-2014 for eddy tracking following the approach described in Section 2.4, and (ii) November 2014-January 2015 for the study of the characteristics and evolution of a particular anticyclonic eddy. During

this period, the quality of the HFR data was very good. This good quality permitted the tracking of the anticyclonic eddy in a continuous way for more than 20 days, with some interruptions of several days or hours around 20 November and the beginning of December (see Fig. 4). Unfortunately, the radar antennas started to present technical problems at the end of this period associated with hardware malfunction and no HFR data could be collected from 28 December 2014 to 21 January 2015. Thus, this period is studied using the rest of available remote sensing data.

2.2. Satellite data

To complement HFR data, measurements from different remote sensing techniques were processed and analysed. Table 1 summarizes the selected databases and their main technical characteristics. In the SE BoB, satellite images based on infrared or visible ranges are limited by the relatively high cloud coverage. For this reason, we selected one by one the images with enough cloud-free pixels and without noise before processing SST and Chl-a maps for the study period. Daily Level 2 SST images were derived from the AVHRR sensor series (1 km resolution). In the case of ocean colour satellite information, Chl-a images with two different processing levels were obtained: first, Level 2 images from MODIS-AQUA satellite (daily and 1 km resolution), and second, Level 4 images merged from different sensors and paths (weekly and 1 km resolution).

Since the area covered by the HFR was close to the coast, we used along-track coastal altimetry data. The altimetry product used in this study was the 1Hz X-TRACK Sea Level Anomaly (SLA) (<http://ctoh.legos.obs-mip.fr/products/coastal-products>), consisting of 7-km along-track filtered data from Jason-2 altimeter mission. The spatial coverage of the studied tracks, 213 and 248, is shown in Fig. 1. In addition, we analysed absolute geostrophic current fields provided in a regular cartesian grid with $1/4^\circ$ resolution (Table 1).

Table 1. Main characteristics of the different observing systems used in this work. *SLA 7-km along-track resolution product, which is filtered using a 40-km length scale.

	HFR	AVHRR	MODIS	Altimetry	
Target variable	Surface currents	SST	Chl-a	SLA	Absolute geostrophic currents
Frequency	Hourly	Daily	Daily (L2) / Weekly (L4)	10 days	Daily
Spatial resolution of the gridded product (km)	5	1	1	7 *	Cartesian 1/4° resolution
Cloud-free	Yes	No	No	Yes	Yes
Vertical integration	1 m	Surface	Surface	Vertically integrated	Vertically integrated
Study period	2011-2015	1 November 2014 – 31 January 2015	1 November 2014 – 31 January 2015	1 November 2014 – 31 January 2015	20 November 2014

2.3. Wind data

Hourly wind outputs from the Weather Research and Forecasting model (WRF) were provided by the meteorological agency of Galicia (MeteoGalicia). A detailed description of this model can be found in Skamarock *et al.* (2005). A comparison of the WRF MeteoGalicia configuration against observations from six ocean-meteorological stations in the BoB showed that WRF was able to reproduce the time evolution of the offshore wind fields with a reasonable accuracy (Ferrer *et al.*, 2010). In this study, the WRF grid nodes, with a native resolution of 12 km, were interpolated to a point located within the HFR coverage (see Fig. 1), from 1 November 2014 to 31 January 2015.

2.4. Eddy tracking methodology

Although there are several algorithms for automated eddy detection (e.g. Nencioli *et al.*, 2010; Mason *et al.*, 2014; Conti *et al.*, 2016), the presence of highly variable currents in the SE BoB made difficult their implementation. Thus, the identification of the periods when coherent mesoscale structures were present was done by visual inspection of the available current fields. Only those periods when eddies were observed for more than 5 days were considered. During these periods, eddies were tracked by an algorithm that identified at each hourly map the eddy centres by a relative maximum of the stream

function. Before applying the eddy-tracking algorithm, data were low-pass filtered (filtering out $T < 48$ -hour signals, to isolate low frequency signals) by a tenth-order digital Butterworth filter (Emery and Thomson, 2001). Then, the velocity fields were integrated to compute the velocity potential and the stream function, using Simpson's rule summation (<http://pordlabs.ucsd.edu/matlab/stream.htm>). The position of the eddy centre and the relative vorticity of the total surface fields at that position were automatically recorded at each time step.

Finally we focused on anticyclonic eddies even if cyclones were also observed by the HFR. The reason was that cyclones were, in general, smaller, less persistent and consequently difficult to monitor in SST, SLA or Chl-a maps.

2.5. Lagrangian methodology

The transport properties of the flow can be investigated by means of different diagnosis, from the Lagrangian point of view. To this end, a new version (adapted to 2D fields) of the Lagrangian Particle-Tracking Model (LPTM), previously used by Ferrer *et al.* (2009), was implemented to simulate particle trajectories using HFR velocities. The LPTM solves the path of the particles, i.e.,

$$\begin{aligned} \frac{d\vec{r}(x,y,t)}{dt} &= \vec{v}(x,y,t) \\ \vec{r} &= \vec{r}(\vec{r}_0, t) \end{aligned} \quad (1)$$

with a fourth-order Runge–Kutta scheme (Benson, 1992) permitting the computation of multiple trajectories with a low computational cost. A comparison of virtual trajectories obtained from this model using HFR velocities and real trajectories from drifters deployed in the study area (Solabarrieta *et al.*, 2016), demonstrates the skills of the LPTM applied to different HFR products (including OMA fields).

LCS can be computed from ridges in the FSLE field, which are arranged in filamental structures (d'Ovidio *et al.*, 2004; Hernández-Carrasco *et al.*, 2011). Here, the role of the eddy and frontal dynamics in organizing the coastal flow was analysed by means of the

LCS derived from the hourly HFR velocities, following the works by Shadden *et al.*, (2005), Haller and Yuan (2000), and Haller (2015). LCS are obtained computing the maximum values of the FSLE field that are located in a line-like shape (Joseph and Legras, 2002; d'Ovidio et al, 2004; Hernández-Carrasco et al, 2011).

FSLE are the adaptation of the classical definition of the asymptotic Lyapunov exponents to finite time and spatial scales (Aurell et al 1997; Boffetta et al 2001). FSLEs from the HFR velocity fields, denoted as λ , were obtained at each instant t , by computing the time T employed by pairs of particles, initially separated a distance δ_0 , to reach a final distance δ_f , i.e.,

$$\lambda(x,y,t) = \frac{1}{T} \ln \frac{\delta_f}{\delta_0} \quad (2)$$

This Lagrangian approach assumes that any particle at the ocean surface is advected by the flow with a trajectory that can be recovered from the HFR velocity following Eq. 1.

In our computations, we used an integration time step of 10 min with a bi-linear interpolation and a total period of integration of 30 days (in December 2014). Particles escaping the area before reaching the final separation δ_f were not considered in the analysis. Due to the small size of the HFR coverage area, the computation of the FSLE was calibrated, choosing a δ_0 and δ_f such that the FSLE provide robust and relevant LCS. The optimal values chosen for the two parameters were: $\delta_0 = 500$ m and $\delta_f = 15$ km.

Using the LPTM outputs, we studied the characteristic time-scales for transport processes in the HFR footprint area by means of the escape rate (Lai and Tel, 2011; Hernández-Carrasco *et al.*, 2013). The main objective of this analysis was to investigate if in addition to favour cross-shelf transport, eddies favoured the local retention of shelf particles in the study area. In our case, the escape rate was obtained by analysing how the particles initially located on the continental shelf escaped the HFR footprint area (see

Fig. 1). Assuming that the number of particles remaining in the area (N_t) decay exponentially with time (t) we can estimate the escape rate (κ) from

$$N_t \approx N_0 e^{-\kappa t} \quad (3)$$

where N_0 is the initial number of particles. Then, the escape time (τ) can be estimated as the inverse of the escape rate ($\tau = \frac{1}{\kappa}$). This quantity provides information on how quickly the particles leave the area. In addition, the number of particles remaining offshore (i.e. in areas of maximum depth > 200 m) was also recorded at each time step. The estimation of the escape times and offshore export of shelf particles was performed for two different periods in 2014: (i) 5–25 November, which was characterised by a typical winter current regime without the presence of mesoscale structures, and SW wind conditions; and (ii) 5–25 December, when an anticyclone was well developed in the study area. For both periods, 7123 particles were launched at the sea surface over the shelf within the HFR footprint area (depths between 0 m and 200 m), and advected for 20 days.

3. Characteristics of SE BoB anticyclones

3.1. Anticyclone population in the SE BoB

Five persistent anticyclonic structures, all of them with similar diameters (~40-60 km) and lifetimes (~1-5 weeks), were detected during 2011-2014. Figure 2 shows the spatial distribution of the centre of the detected eddies, together with their absolute drift (i.e. the line connecting the initial and final positions of the eddy centres). The main characteristics of the eddies are summarized in Table 2.

Table 2. Main characteristics of the anticyclones detected during 2011-2014. The eddies were named in accordance with their polarity and the month and year of their generation (A denoting that they are anticyclones, MM the month and YY the year). From left to right: eddy identifier, start and end dates, tracking duration in days, start and end positions, maximum value (during eddy

lifetimes) of the relative vorticity at the eddy centres and mean diameters (estimated as the average of the zonal and meridional diameters of the eddy, i.e. the segments connecting the points of maximum velocities at the edges and passing through the eddy centre). The anticyclones marked with an asterisk were those forming a dipole with a cyclone.

Eddy id	Start date	End date	Tracking (days)	Start lon, lat	End lon, lat	RV max	ø (km)
A1211*	23/12/2011	12/01/2012	19.9	-2.32, 43.81	-2.80, 43.63	-0.35 f	43.12
A0312	02/03/2012	17/03/2012	15.5	-2.92, 43.99	-3.04, 43.77	-0.21 f	39.51
A0912	16/09/2012	22/09/2012	6.7	-1.96, 43.90	-2.02, 43.99	-0.17 f	58.72
A0314*	14/03/2014	22/03/2014	7.8	-2.68, 43.90	-2.98, 43.72	-0.24 f	46.71
A1214	01/12/2014	26/12/2014	25.5	-2.62, 43.72	-2.50, 43.72	-0.48 f	44.92

All the eddies, excluding A0912 (observed over the French shelf), were concentrated around 2°30'W and 43°48'N over the Capbreton canyon, the deepest part of the study area. They were generated during winter (December and March), except A0912 that was generated in September. Two of them (A0314 and A1211) were observed to be part of dipolar structures, with a cyclone located at the east of the anticyclones (not shown). Four of these five anticyclones were also visible in satellite SST and/or Chl-a images, although only for A1214 a significant number of cloud-free satellite images were available.

Fig. 2. Spatial distribution of the number of anticyclone cores detected in the period 2011-2014, by $0.05^\circ \times 0.05^\circ$ bins (colourbar). The names of the different eddies are superimposed as well as the vector connecting the initial and final points of their trajectories. Eddy lifetimes (in days) are provided in brackets after eddy names. Isobaths (m): 200, 1000, 2000.

In general, weak slope currents and weak wind conditions prevailed during the periods of persistent anticyclonic eddies. It is worth noting that eddies A0314, A1214 and A1211 were detected several days after strong poleward (cyclonic) current conditions at the shelf-slope. A0314 and A1211 were observed for 8 and 20 days before they started to drift westwards, leaving the HFR footprint area. Eddy A1214 was the unique that remained quasi-stationary during all the period, presenting the largest persistence and the weakest translational velocity. This anticyclone had a clear surface signature being especially well captured by the HFR and the other platforms during almost two months. The availability of remote data from different platforms, measuring independent variables, and the agreement between them during the A1214 lifetime provided a

valuable opportunity to investigate this anticyclone and to explore its impacts on the water transport over the area.

3.2. Eddy A1214 generation and evolution

The generation of A1214 occurred on 20-23 November 2014, after the relaxation of an intense poleward shelf-slope current pulse observed by the HFR from the beginning of November. The mean flow measured by the HFR during 16-19 November, showed intense currents in the southern shelf-slope (Fig. 3a). The intensification of the current had also a signal in along-track SLA data. SLA for tracks 213 and 248, corresponding to 16-18 November, respectively, are shown in Fig. 3a overlapped to the HFR velocities. The SLA (positive in the study area) increased from the beginning of November to early December, showing a coast-offshore gradient with higher SLA values near the coast. The strong SLA gradient observed in this period was associated to an intensification of the mean poleward slope flow. As shown in previous works (e.g. Herbert et al., 2011; Xu et al., 2015), the intensification of the IPC current is observed as an intensification of the eastward geostrophic current from the altimetric signal, together with a warm water tongue observed in the SST images. An SST image, corresponding to 20 November, with absolute geostrophic currents from altimetry overlapped indicated warmer SST along the shelf-slope and a cyclonic geostrophic circulation (Fig. 3b).

On 23 November, the current relaxed (and so did the coast-offshore SLA gradient) and the signature of an anticyclonic structure started to be visible in the HFR fields (Fig. 3c). The first observations of a weak closed anticyclonic circulation were found over the shelf between both radar antennas (2°9'W and 43°30'N). The eddy drifted north-westward until its centre was located at 2°15'W and 43°40'N (Fig. 3d). Then, according to its surface signal in the HFR maps, it remained stationary for 20 days. Unfortunately, during the period 23-29 November we did not find any Chl-a or SST images with enough quality for observing the generation of this structure.

In order to investigate the drivers that could induce the generation of eddy A1214, we analysed the time evolution of the wind and currents during the days before the eddy generated (Fig. 4). Prevailing S–SW wind conditions were observed from the beginning to the end of November, along with high SLA values over the slope (Fig 4a, b). During this period, the intensification of along-shelf currents was also evident in the two sections of the HFR data displayed in Fig. 4c, d. At the end of November, the wind relaxed and the dominant wind direction changed to N-NE.

Fig. 3. (a) Mean HFR currents for the period 16 - 19 November 2014 and SLA (colourbar) along altimetry tracks 213 and 248 for the same period, showing an intensification of the poleward current before the eddy was observed. (b) SST and altimetry-derived absolute geostrophic currents on 20 November 2014. (c) HFR currents snapshot on 23 November 2014 23:00, showing the presence of an anticyclonic structure around 2°9'W and 43°30'N. (d) HFR currents snapshot on 29 November 2014 02:00, showing the presence of this anticyclonic structure around 2°15'W and 43°40'N. Isobaths (m): 200, 1000, 2000.

In early December, SLA values decreased along track 248, especially over the shelf-slope (Fig. 4b). The zonal component of the HFR surface current changed from eastwards to westwards near the coast. These changes, both in SLA and HFR currents, indicate a relaxation of the poleward current. In addition, the currents were weak around 43°45'N, and intensified again to become eastward north of this latitude. This pattern, consistent with the anticyclonic circulation shown in Fig. 3c, was observed from the end of November to the end of December, presenting similar intensity through all this period.

The anticyclone had a diameter of ~50 km, maximum azimuthal velocities of 50 cm s⁻¹ and a maximum relative vorticity of -0.45 f, according to the HFR observations during this period (Fig. 3d, 4d, e). From the end of November to the end of December, the HFR surface current fields showed a well-formed anticyclone almost stationary in position until one of the HFR antennas failed on 28 December 2014. From this date on, the tracking of the eddy with HFR data was no longer possible. However, as suggested by the values of the relative vorticity obtained from the last available HFR fields, the eddy was not at the end of its lifetime. Indeed, from the end of December 2014 to mid-January 2015, the along-track altimetry data showed a relatively high SLA signal centred around 2°12'W and 44°12'N (Fig. 4b).

Fig. 4. Time evolution from November 2014 to the end of January 2015 of: (a) Winds at 2°30'W, 44°N; (b) CTOH SLA along the track 248 (shown in Fig. 1); (c) HFR-derived surface eastward component of the current velocity in cm s⁻¹ extracted along the track 248; (d) HFR-derived surface eastward component of the current velocity in cm s⁻¹ extracted along the meridional section that crossed the eddy centre and (e) relative vorticity (expressed as a ratio of f) at the A1214 eddy centre during the tracking period. In (b) the vertical lines show the dates of available SLA data.

As already stated, the eddy was also inferred from other remote sensing data. SST images showed a warm core eddy centred around 2°30'W and 43°40'N, from 21 December 2014 to 12 January 2015 (Fig. 5 and Fig. 7); confirming that the eddy was not at the end of its lifetime at the end of the period covered by the HFR data. The agreement between the HFR current fields and the SST anomaly from 21-23 December is noteworthy (Fig. 5). The eddy core was characterised by a warm SST anomaly with a temperature around 15.8°C, the offshore waters being around 14°C.

Fig. 5. AVHRR-derived SST ($^{\circ}\text{C}$) images of (a) 21, (b) 22 and (c) 23 December 2014. The corresponding snapshots of the HFR surface current vectors on the day of the images are superimposed. Dates and times of the HFR current snapshots are: (a) 21 December 14:00, (b) 22 December 14:00, (c) 23 December 02:00. Isobaths (m): 200, 1000, 2000, 3000.

During the same period, two Chl-a images also provided the signature of an anticyclonic circulation over the area occupied by the eddy (Fig. 6). An offshore transport of coastal waters during the stationary phase of the eddy was subtracted from the two sequential images. Again, there was a good agreement between the HFR pattern and satellite Chl-a, showing the distribution of oligotrophic waters at the eddy centre and rich waters at the eddy periphery.

Fig. 6. MODIS-Aqua derived Chl-a (mg m^{-3}) of (a) 21 and (b) 22 December 2014. The corresponding snapshots of the HFR hourly surface current vectors on the day of the images are superimposed. Dates and times of the HFR current snapshots are: (a) 21 December 13:00, (b) 22 December 13:00. Isobaths (m): 200, 1000, 2000, 3000.

The warm eddy remained stationary in the same area until 29 December 2014 (Fig. 7a) when it started to drift north-eastwards along the French shelf break, according to the sequence of the SST images (Fig. 7b, c). The eddy migration started when the wind regime veered from northerlies to south-westerlies (Fig. 4a). The last day that this structure was observed in the SST images was 12 January 2015 (Fig. 7c), when the eddy was located around $2^{\circ}25'W$ and $44^{\circ}10'N$. The eddy was also observed around this

position by the along-track SLA data, corresponding to 5 January 2015 (Fig. 7d). The highest SLA values along track 248 were centred around 2°10'W and 44°N, suggesting the presence of the anticyclone.

FIG. 7. AVHRR-derived SST (°C) images on (a) 29 December 2014; (b) 31 December 2014 and (c) 12 January 2015. SLA from Jason-2 tracks 213 and 248 corresponding to 5 and 6 January, respectively, are shown in (d). Isobaths (m): 200, 1000, 2000, 3000.

4. Eddy-induced cross-shelf transports

4.1. Quantitative estimation of the A1214 cross-shelf transport

The LCS derived from HFR velocities during the A1214 lifetime provided a synoptic view of the complexity of the transport associated with this anticyclone. Here the LCS computed advecting particles in the HFR flow are used to identify the dynamical structure that separate waters from different origin, i.e. from the coast and from the offshore waters and how the periphery of the eddy (unveiled by the LCS) acted as a barrier transporting

the coastal waters offshore. Snapshots of high values of FSLE for 10-20 December, two weeks after the generation of the eddy, are shown in Fig. 8 (in grey scale). During this period, the maximum values of LCS (FSLE ridges), located between 2-3°W and 43°30' - 44°N, clearly identified the eddy periphery. Besides, high FSLE values distributed along the French shelf showed an additional frontal zone where the LCS identified an additional transport barrier avoiding coastal and offshore water exchange. In addition, the high FSLE values associated to the eddy periphery estimated for 16 December (Fig. 8e), showed a similar shape to the observed Chl-a front (Fig. 6). In order to illustrate the effect of the eddy on the exchanges between the shelf and the surrounding waters of the eddy (offshore waters), two sets of virtual particles were advected using the HFR velocity fields. The particles were launched at the same time and at two different locations; 10,000 particles were deployed in the eddy core (blue dots) and 20,000 particles at the southern part of the continental shelf in a strip of 0.15°, from 3°6'W to 2°W (red dots, see Fig. 8a). The simulation corresponded to prevailing north-westerly winds, except for the period between 12 and 14 December, when southerlies dominated (Fig. 4a). During the first days of the simulation (Fig. 8b, c), the particles initially deployed at the eddy centre (blue rectangle in Fig. 8a) were confined near the core, while the particles deployed over the shelf between 2°25'W and 3°W were advected offshore stretched along the eddy periphery. The particles deployed east of 2°25'W remained over the shelf advected north-eastwards by north-eastward shelf currents, induced by southerly winds, during 12-14 December (Fig. 8c, d). The wind also affected the distribution of particles within and around the eddy. In fact, from 14 to 16 December southerly winds forced northward currents, which constrained the flow induced by the anticyclone and prevented the particles at the periphery (shelf origin) to progress southwards at the eastern side of the eddy (Fig. 8e). Once the wind-induced current relaxed, the particles at the periphery, which had been pushed towards the north-west, blended with those of the eddy core (Fig. 8f).

Fig. 8. Evolution of the FSLE field (grey colourbar) for the simulation period 10-20 December 2014. Particles in red illustrate the evolution of shelf waters, while those in blue illustrate the behaviour of particles initially located within the eddy core. Dates and times of the snapshots are: (a) 10 December 12:00, (b) 11 December 16:00, (c) 13 December 08:00, (d) 14 December 08:00, (e) 16 December 08:00, (f) 20 December 08:00.

LCS is a valuable tool to explain the observed Chl-a structures shown in Fig. 6. Our results suggest that the eddy was driving the exchange of the shelf-slope water masses

in the area between 3°30'W and 2°25'W. The mean FSLE and Chl-a concentration for an 8-day period centred around 19 December are displayed in Fig. 9 (a and b, respectively). Again, an oligotrophic zone, with low Chl-a concentration, similar to those found in the open-sea, was measured in the eddy core, a region characterised by low FSLE values. The highest FSLE values coincided with high Chl-a concentrations in the offshore part of the area. The eddy-like structure given by the FLSE lines constrained and stirred the Chl-a concentration, indicating that the eddy acted as a key driver in the local horizontal advection between the rich coastal waters and the oligotrophic open ocean.

Fig. 9. (a) Mean simulated FSLE and (b) satellite derived Chl-a (mg m^{-3}), for the period 14-22 December 2014.

In order to provide a quantitative estimation of the transport associated to A1214 and to study the effects of the eddy on the retention of shelf particles in the study area, another

two 20-day simulations were performed with virtual Lagrangian particles. The main focus of this exercise was to compare an eddy situation with a typical winter circulation scenario, in terms of both shelf-slope transports and residence times. The two chosen periods corresponded to: November 2014, characterised by intense poleward shelf-slope currents during a typical winter regime (see Fig. 3.a), and to December 2014, characterised by an anticyclone dominating the shelf-slope transport. The initial position of the particles are shown in Fig 10 (a,c). The evolution of the number of particles being exported from the shelf to offshore waters is depicted in Fig. 10b, d. The particles exported in the area marked by the black box in Fig. 10c, due to the influence of the eddy, are also provided for December 2014 (Fig. 10d). The results in terms of escape rates and escape times obtained following Equation (3) are shown in Table 3.

Fig. 10. Behaviour of particles released at the sea surface over the shelf and quantification of cross-shelf transports and escape rates in two periods during winter 2014: (a, b) 5-25 November and (c, d) 5-25 December 2014. Positions of the particles over the shelf at the beginning of the simulation are shown by the black dots in (a) and (c). The red crosses mark in (a) and (c) the positions over the 500 m isobath where particles that were initially located over the shelf (launched at surface, over depths between 0 and 200 m) crossed to the open-sea. The evolution of the number of particles (N_i) inside the HFR footprint area (black line) and the percentage of those

being exported out of the shelf (red line) is provided in (b) and (d). The percentage of particles being exported out of the shelf in the area of influence of A1214 (black box in c) is provided by the dashed red line in d. Isobaths (m): 200, 500, 1000, 2000.

The analysis revealed a remarkable difference between the two periods in the number of particles exported offshore by the surface flow. During November, the highest percentage of particles in open waters was found around 7 November, with a maximum of 10% of shelf particles in the offshore area, decreasing after this date to remain close to zero until the end of the simulation (Fig 10c). The situation in December was significantly different, with 15-20% of particles located offshore from 7 December to the end of the simulation (Fig 10d). Regarding the percentage of particles being exported from the shelf within the area of influence of eddy A1214, we can observe that almost all the particles that remained offshore after 13 December were advected out of the shelf by the eddy. Red crosses in Fig. 10a and b provide an indication of the preferred paths for the cross-shelf export in both periods. In November (Fig. 10a), almost no particles crossed the Spanish shelf break and only a small group of particles were advected offshore at the north of the study area, crossing the French shelf break in the area between 44°7.2' and 44°18'N. Between 5 and 7 December there was an export of shelf particles around Capbreton canyon and the French shelf break (see Fig. 1), which coincided with dominant winds from N-NE in the period when the eddy was generated. From 7 December the particles initially located over the Spanish shelf were advected offshore by the anticyclone crossing the shelf break in the area east of 2°40'W (Fig. 10d). Between the 7 and 13 December the eddy induced a clear net transport of shelf particles, increasing one order of magnitude the number of particles exported from the shelf to offshore in less than one week. Note that in both simulations a significant percentage of the particles crossed the head of the Capbreton canyon (Figs. 10a b, see Figure 1 for location). These shelf particles, that were advected along the shelf, reintegrated the shelf

quickly after crossing the head of the canyon and did not contribute to the population of particles that remained offshore.

In addition to enhance the cross-shelf export, the eddy contributed to the retention of shelf particles in the study area. As suggested by Fig. 10, the escape times of the particles deployed at the sea surface over the shelf during both simulations, were significantly different (Table 3). For the November experiment (Fig. 10b), almost all the particles left the domain from the northern limit of the area covered by the HFR, with an escape rate of $\kappa = 0.16$ (Table 3). While for the December experiment, around half of the initial particles remained within the domain as the result of the eddy trapping effect (Fig. 10d), showing an escape rate three times smaller and thus, an escape time much higher.

Table 3. Parameters obtained from the exponential curve fit of equation (3) to the observed evolution of the number of particles shown in Fig. 10. The estimated initial number of particles (N_0^{fit}), escape rates (κ) and escape times (τ) are shown for the two scenarios analysed: 5-25 November and 5-25 December 2014. R is the regression coefficient between the exponential curve in equation (3) and the time evolution of the number of particles obtained during both simulations. $R = \sum_t (N_t^{fit} - \bar{N}_t)^2 / \sum_t (N_t - \bar{N}_t)^2$, where N_t^{fit} is the curve fitted to N_t .

	R	N_0^{fit}	κ	τ
5-25 November	0.89	7068.7	0.16	6.25 days
5-25 December	0.88	7441	0.05	20 days

4.2. Additional evidences of eddy-induced offshore high Chl-a concentrations

As explained in Section 3.1, the only anticyclonic observed by continuous HFR data during a period of several weeks was A1214. However, evidences of high off-shelf Chl-a concentration were also found for three of the other four persistent anticyclonic structures observed in the period 2011-2014. Examples of these evidences can be observed in Fig. 11, where the HFR current fields for eddies A1211, A0312 and A0314

545 are superimposed to the corresponding MODIS-Aqua derived Chl-a images. For these
546 three eddies, Chl-a fields similar to those for A1214 are observed, with maximum Chl-a
547 values in waters close to the coastal area and maximum offshore values confined to the
548 eddy peripheries. The absolute values of Chl-a concentration varied among the eddies,
549 depending on the Chl-a concentration of the coastal waters (which in this area is
550 maximum around spring and varies interannually). Again, the correspondence between
551 the HFR fields and the Chl-a fronts in MODIS-Aqua images was significantly high.
552 Finally, it is worth noting that eddy A0912 was not related to a clear off-shore transport
553 (not shown).

Fig. 11. MODIS-Aqua derived Chl-a (mg m^{-3}) of (a) 26 December 2011, (b) 14 March 2012 and (c) 16 March 2014, showing the off-shore Chl-a export linked to eddies A1211, A0312 and A0314, respectively. The corresponding snapshots of the HFR surface current on the day of the images are superimposed. Dates and times of the snapshots are: (a) 26 December 2011 13:00, (b) 14 March 2012 17:00 and (c) 16 March 2014. Isobaths (m): 200, 1000, 2000, 3000.

5. Summary and discussion

Coastal waters are enriched in nutrients from river outflows, sediment re-suspension and coastal upwelling. The physical mechanisms that contribute to the offshore transport of these mesotrophic coastal waters to the oligotrophic offshore areas are critically important for boosting oceanic primary production and sustaining the trophic chain. In this paper, we study and quantify the contribution of the SE BoB winter mesoscale anticyclonic SWODDIES to the advection of rich coastal waters towards the open ocean, by means of the local surface cross-shelf transport.

For the quantification of the cross-shelf advection of coastal waters we focused on the case of eddy A1214, generated around 23 November 2014, which could be monitored using data from HFR for 20 days. During this period, the eddy presented maximum azimuthal velocities of 50 cm s^{-1} and a maximum relative vorticity of -0.45 f and remained almost stationary in a location close to its generation area and inside the HFR footprint. The signature of the eddy in altimetry data was observed some days later, when the eddy started to drift to the NE and crossed one of the altimeter tracks. High SLA values were observed near the position of the eddy detected in the SST images during the first half of January 2015. Then, it was lost, presumably due to the northwards drift of the eddy. The last cloud-free SST images of the eddy were obtained in this period, and the location and dimensions of the structure agreed with altimetry observations.

The good agreement between the different satellite data and the signature of the eddy in the surface current fields, measured by the HFR, validated the use of these data for the quantitative analysis of eddy-induced surface transports. In December, the shelf-slope transports were clearly dominated by the mesoscale geostrophic currents associated to the anticyclone, although the effect of local winds was also observed. The ridges of FSLE fields identified the eddy periphery, matching regions with the highest Chl-a concentrations in the offshore area. The results obtained using the LCS, derived from the HFR velocities during the A1214 lifetime, provided a synoptic view of the

complexity of the transport associated with this anticyclone. As already demonstrated by several authors (Shadden et al., 2005; Lekien et al., 2005), LCS proved to be very helpful for identifying material lines, which act as barriers organizing the transport in the flow. As in the works of Lehahn et al. (2007) and Calil and Richards (2010), who applied this technique to altimetry data, Chl-a clearly spread along the dynamical fronts identified by the LCS. In our study, LCS helped to explain the high Chl-a concentration found at the eddy A1214 periphery. The Lagrangian simulation showed how the eddy periphery was composed by particles coming from the coastal region, demonstrating the eddy-induced offshore transport of coastal waters by lateral stirring. In order to offer further evidence on the origin of the particles that were transported by eddy A1214 backward Lagrangian connectivity maps were computed on the same dates than the images plotted in Fig. 8 (from 10 to 21 December, 2014). The maps were obtained integrating the trajectories of particles backward in time and then colouring each one depending on the boundary they crossed (Fig. 12). We used four boundaries: East, North, West and Coast, the last one corresponding to particles coming from the coastal region (marked in red in Fig. 8a). In these maps, it can be clearly observed that the eddy periphery was mostly composed by particles coming from the coastal region (in green) during the total integration time (15 days), demonstrating that the spatial distribution of Chl-a in the offshore area was largely produced by eddy-induced lateral stirring, transporting horizontally coastal waters to offshore regions.

Fig. 12 Snapshots of the backward connectivity Lagrangian maps corresponding to the same dates than the images plotted in Figure 8 (from 10 to 21 December, 2014). Green colour patches show regions where particles were coming from the coastal region. Particles coming from East, North, West boundaries are plotted in magenta, blue and brown, respectively. Particles remaining inside the area of study after the total time of integration (15 days) are coloured in cyan.

Although vertical processes like frontal upwelling of nutrients, and the consequent enhancement of the production at the eddy periphery, could also contribute to the observed offshore maximums of Chl-a, our results suggest that horizontal transport played an important role in the patchiness of Chl-a in the study area. The effect of lateral

stirring and mixing processes associated to slow-evolving dynamical structures at spatial scales larger than 50 km on the primary production has been widely studied (e.g. Rossi et al., 2008; Hernández-Carrasco et al., 2014). However, the effect of smaller spatial and temporal scale processes in coastal seas, not well resolved by altimetry, is still poorly understood. Our results in the SE BoB, using different Lagrangian techniques on HFR velocities, provide additional demonstration of the effects of lateral stirring in coastal eddies and evidences of the role of a SWODDY in the cross-shore transport of coastal enriched waters.

From 7 to 13 December the rate of particles being exported by the eddy to the offshore area was maximum, increasing in one order of magnitude the number of particles exported from the shelf to offshore in less than one week. The eddy also contributed to the retention of shelf particles in the study area. In the period when the eddy was observed by the HFR, in comparison to the values observed under the typical winter current regime, when no eddies are present, the escape times were three times larger and the offshore export of shelf particles was significantly intensified. Although no quantitative estimations of the transports related to this eddy after December 2014 were available, our results suggest that the eddy-induced offshore transport of shelf waters continued as the eddy drifted north-westwards (Fig. 7), along the shelf break off the coast of France.

The observation of similar anticyclonic eddies between November and March suggests that this is a recurrent feature in the SE BoB linked to the intensification and relaxation of poleward current events. In the case of eddy A1214, the current intensification seemed to be locally wind-driven, similarly to that described in Teles-Machado *et al.*, 2016. S–SW prevailing wind conditions were observed, from the beginning to the end of November, to contribute to the intensification of along-shelf currents at the end of November; a change in the dominant wind direction to N-NE, coincided with the relaxation of the along-shelf currents preceding the eddy generation. Since NE winds are

upwelling favourable in the study area, we hypothesise that the presence of rich coastal waters in offshore locations can be explained by a two-step mechanism: first, N-NE winds drove the increase of Chl-a in coastal waters enhancing coastal upwelling, and then, the subsequent formation of eddy A1214 helped the offshore export and retention of the upwelling enriched waters. In the area of eddy generation, HFR-derived surface velocities have large uncertainties due to the reduced angle formed by the radials of the two radar antennas, used to reconstruct total current. Although the reliability of the resulting fields is highly dependent on the quality of the OMA reconstruction and the generation process was not observable due to the lack of cloud-free images, the good agreement and complementarity between the different observing platforms regarding eddy location, dimensions and evolution after the eddy generation supported this hypothesis. Moreover, the area of generation, equatorward of Capbreton canyon, is consistent with the findings of Teles-Machado et al. (2016) concerning the generation of anticyclonic SWODDIES in the NW Iberian margin.

Eddy-induced transport was quantitatively studied only for A1214. However, evidences of high Chl-a concentration were also found for three of the other four persistent anticyclonic structures observed in the period 2011-2014. In all the cases maximum Chl-a values were observed in waters close to the coastal area while maximum offshore values of Chl-a confined to the eddies' periphery. These observations suggest that these recurrent eddies constitute an effective mechanism for the off-shore export of rich coastal waters during the winter period. In the case of eddy A0912 it was not observed a clear off-shore transport. We relate this to the fact that it is the only eddy observed over the French shelf at the end of summer and thus the generation conditions seemed to be different from the rest of observed anticyclones. Moreover, eddy A0912 showed also the shortest lifetime and the weakest relative vorticity signature. Cyclonic eddies were also observed in the HFR footprint area. However, we did not find evidences of their effects on the surface advection of SST or Chl-a in the available satellite images and they were

not investigated further. In addition to the offshore advection of temperature, salt and coastal-enriched waters, eddy-induced transport of ichthyoplankton from coastal to offshore areas could also affect the recruitment of key pelagic fish species in the SE BoB. A study focused on *Engraulis encrasicolus* (Irigoien et al., 2008) concluded that the coincidence in time and location of spawning and SWODDY-generation could favour its recruitment, by means of the advection of eggs and larvae to areas with lower predation risk (Irigoien et al., 2007), but productive enough. The retention of eggs and larvae in these low predation risk and productive areas would also be favourable to the recruitment.

The observation and monitoring of this type of fast-evolving coastal eddies, which are small, relatively weak and short-lived (if compared with persistent open ocean eddies or eddies generated in more energetic areas), is not straightforward. In this study, the combination of multiplatform data has proven to be an effective approach to overcome the limitation that the different remote sensing systems have in coastal areas. While visible and infrared images permitted the qualitative description of eddies in terms of SST gradients as well as in the advection of Chl-a, the altimetry and HFR provided quantitative estimations of their associated SLA, relative vorticity of their surface signature, and eddy-induced surface transports. The synergies between HFR and other observing systems have been used in numerous studies of coastal processes (e.g. Uttieri et al. 2011; Chavanne et al., 2010), and different methodologies have been developed to expand the surface information of HFRs to deeper levels (e.g. Shrira and Forget, 2015; Zervakis et al., 2017) and to use it for numerical model validation and data assimilation (e.g., Lorente et al., 2016; Vandenbulcke et al. 2017). The development of integrated strategies for the measurement and monitoring of surface coastal ocean processes is key to progress towards accurate estimation and forecast of 4D ocean transports and their impact in the marine ecosystem.

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