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

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ABSTRACT

Different remote sensing data were combined to characterise a winter anticyclonic eddy in the southeastern 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 high-frequency 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 $-0.45f$. 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.

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, 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; Peliz 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 southeastern (hereinafter 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 Serpette, 2009; Charria et al., 2013) (Fig. 1). In summer, the flow is reversed being

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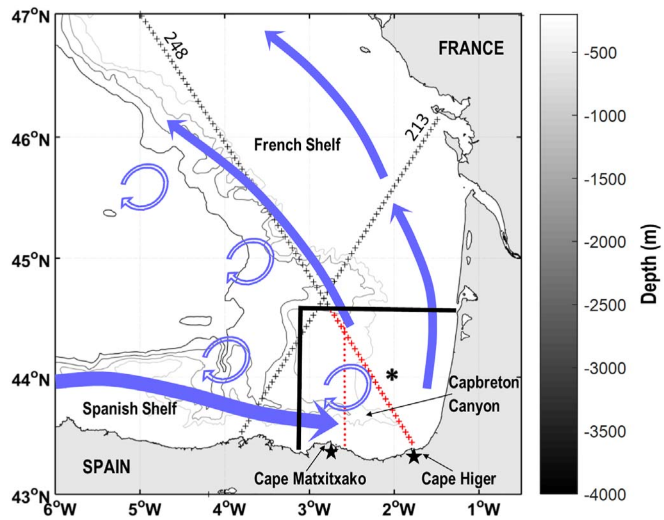

Fig. 1. Study area and schematic view of the winter shelf-slope current (solid blue arrows). The mesoscale regime is schematically represented by the hollow blue arrows (although only anticyclonic arrows are represented, eddies of anticyclonic and cyclonic polarity are observed in different locations 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 high-frequency 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). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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, southwesterly 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 Caballero et al., 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 at 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.

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), Solabarrieta et al. (2015), Solabarrieta et al. (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). Eighty-five 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