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Poleward along-shore current pulses on the inner shelf of the Bay of Biscay

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ABSTRACT

We analyzed strong events of coastal poleward along-shore currents above 10 cm s^{-1} and up to more than 50 cm s^{-1} on the inner shelf (50–80 m depth) of the Bay of Biscay (BoB) from the Spanish coast to the Brittany coast. We used data from four acoustic Doppler current profilers (ADCPs) deployed from July 2009 to August 2011. The goal of this study was to analyze current variability at meso- and subinertial scales and its generation mechanism. These currents occurred all year long and were classified into three types. Events occurring principally in the southern part of the BoB were classified as *southern events*. *Bay-scale events* were defined when strong poleward currents were detected over all the shelf, typically stronger on the Spanish and the southern Brittany shelves. *Strong events* were characterized by depth averaged current velocities over 40 cm s^{-1} in the southern part of the BoB. At short time lags, the along-shore currents were clearly related to along-shore wind stress at upstream locations. An explanation is provided for longer time lags in terms of coastal trapped wave (CTW) dynamics. The first CTW mode phase speeds were in agreement with the propagation speeds of the fastest events (> 5 m s^{-1}), while inner shelf modes could explain the slowest events (~ 1–3 m s^{-1}). The cross-shelf density gradient and the extension of the IPC were also associated with strong coastal poleward along-shore currents. The duration of the events, the vertical structure of the currents and the associated coastal trapped waves were studied in relation with the stratification.

1. Introduction

Eastern boundary current systems are characterized by the generation of strong and intermittent poleward currents (Brink and Robinson, 1998). In many cases, these poleward flows are surface intensified and encompass the shelf. Several mechanisms have been suggested for their generation. A number of local forcings can be identified such as buoyancy, wind and rectification of coastal trapped waves (CTWs). Considering the frequent occurrence of such poleward currents flowing against prevailing equatorward winds, larger-scale, non-local forcing mechanisms, that may be mediated by CTWs, have been proposed and classified by Hill et al. (1998). These authors show that an along-shore surface slope or an offshore pressure gradient can also generate these flows. The establishment of these pressure gradients can be due to regional wind stress and meridional density gradients, known as the joint effect of baroclinicity and relief [JEBAR, Huthnance (1984)], and can be modified by along-slope topography.

Studies of those dynamical processes which govern continental shelves have been reported along the U.S. west coast [*e.g.* recently in Kim et al. (2013), Washburn et al. (2011), Melton et al. (2009), Noble et al. (2002)] and along the Mexican west coast (Flores-Vidal et al., 2014). The continental shelf north of San Francisco [Coastal Ocean Dynamics Experiment - CODE, Beardsley and Lentz (1987)], the Western Florida shelf (Maksimova and Clarke, 2013) and the central west coast of India (Amol et al., 2012) have been also proposed as typical regions of poleward flows. The most recent studies, described above, were based on experimental results from high-

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frequency (HF) radar systems or multi-year Acoustic Doppler current profilers (ADCPs) measurements. The Australian Coastal Experiment [ACE, Freeland et al. (1986)], conducted in the coastal waters of New South Wales (east coast of Australia) with a three main lines array of current meters, was the most ambitious early observational study aimed specifically at coastally trapped waves. The data obtained allowed a detailed examination of the dynamics of flow on the continental shelf and slope and in particular a description of coastal trapped wave modes propagating within the coastal waveguide.

Despite its complex topography, the Bay of Biscay (BoB - Fig. 1), located at mid-latitudes in the north-eastern Atlantic, off western Europe, exhibits the classical current system found in eastern boundary regions, with poleward flow on the shelf and slope (Pingree and Le Cann, 1989; Koutsikopoulos and Le Cann, 1996; Lavin et al., 2006). The BoB, area of interest in this study, is characterized by three main parts (Fig. 1): an abyssal plain, a continental slope and a northward widening continental shelf (~ 20 km at 3°W - Spanish shelf, ~ 60 km at 44°N - Aquitaine shelf, ~ 150 km at 47°N - Armorican shelf).

The North Atlantic circulation over the abyssal plain has been relatively well studied in several works (Pingree, 1993; Van Aken, 2002; Colas, 2003; Charria et al., 2013). The averaged, anticyclonic, circulation is characterized by weak values (1–2 cm s^{-1}) but larger velocities due to mesoscale dynamics (Paillet, 1999) are observed, such as anticyclonic eddies (Pingree and Le Cann, 1992).

Along the slope, the currents are characterized by a cyclonic circulation with higher mean velocities, 5–10 cm s^{-1} (Pingree and Le Cann, 1989; Pingree and Le Cann, 1990). These currents exhibit a strong seasonality. The along-slope circulation is marked by the occurrence of an intensified poleward surface flow (Iberian Poleward Current - IPC) in autumn and winter north of the Iberian Peninsula. Stronger over the upper part of the slope, the signature of the IPC, a warm and saline current, has been described in different studies (Frouin et al., 1990; Pingree and Le Cann, 1992; Relvas et al., 2007; Solabarrieta et al., 2014). This eastward current can reach velocities over 70 cm s^{-1} and can extend to the Aquitaine and Armorican upper slopes (Le Cann and Serpette, 2009; Garcia-Soto and Pingree, 2012).

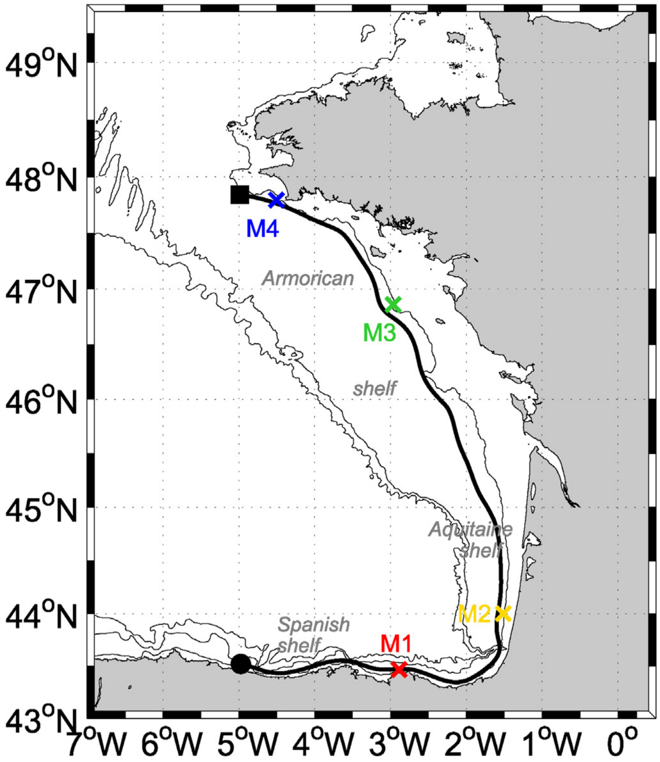

Fig. 1. Study area and moorings position. The thick black line denotes the positions along the 100 m isobath section where the component of the wind stress is calculated and projected. The black dot (black square) represent the beginning (end) of the 100 m isobath section used for wind stress plots. Thin black lines indicate the 60, 130 and 450 isobaths.

The general features of the circulation on the shelf have been described. Charria et al. (2013) suggest a link between the northern Spanish shelf circulation and the one of the Aquitaine shelf similar to the continuity of the slope current from Spanish to Celtic slopes (Pingree and Le Cann, 1990). Several studies have been undertaken to describe the main ocean processes affecting the Spanish shelf and slope circulation (Gonzalez-Pola et al., 2005; Torres and Barton, 2006; Fontán et al., 2009; Rubio et al., 2013; Alvarez et al., 2014). A detailed description of the dominant surface current patterns observed by HF radars in the southeast corner of the BoB has been proposed by Solabarrieta et al. (2014, 2015) in relation to seasonal, mesoscale and high-frequency variability. Over the French shelves, weak values with residual sub-tidal currents of about 3 cm s^{-1} have been measured (Pingree and Le Cann, 1989; Le Boyer et al., 2013). Charria et al. (2013) have shown a strong seasonality of the surface current direction: equatorward in spring and summer, and poleward in winter and autumn. These changes are driven by the seasonal variation of wind (Pingree and Le Cann, 1989, 1990). At smaller spatial scales, the freshwater discharges induce also a significant circulation over the inner shelf, especially in the Gironde and Loire plumes (Lazure and Jégou, 1998; Lazure et al., 2006; Ferrer et al., 2009). On the northern Armorican shelf, a cold pool of water (11–12 °C) centered between 60 m and 120 m depths is present from spring to autumn. This pool of dense water, called "bourrelet froid" [for "cold pool", Vincent and Kurc (1969)], is associated with surface cyclonic circulation (Charria et al., 2013).

Influenced by large-scale oceanic basin circulation and by local forcings, such as seasonal wind regimes and important river discharges, the BoB shelf circulation is frequently affected by the occurrence of poleward flows. These poleward flows appear as intermittent and locally variable currents, defined as pulses, and have been reported during different seasons in the BoB. On a weekly scale, the shelf is associated with strong surface currents near the coast in the northern part of the domain in winter and strong currents affecting the whole water column in the southern part of the domain in autumn (Le Boyer et al., 2013). Indeed, poleward flows on the shelf exist all year long, with stronger intensity in autumn-winter than in spring-summer (Charria et al., 2013). From October to March, marked weekly poleward currents (up to 15 cm s^{-1}) are observed over the Aquitaine shelf.

A summer poleward coastal event of up to 32 cm s^{-1} during 22 days along the Aquitaine shelf was investigated using ADCP and drifting buoys measurements by Batifoulier et al. (2012). One possible mechanism of this event was reported and linked to westerlies, along-shore wind events inducing downwelling conditions along the Spanish coast. This downwelling induces an along-shore pressure gradient and can generate CTW and Kelvin waves (Batifoulier et al., 2012). Lazure et al. (2008) described an autumn poleward current over the Armorican shelf up to 20 cm s^{-1}. The mechanism of this event was linked by the authors to the breakdown of stratification at this season, inducing strong cross-shore density gradients. In both cases (summer and autumn events), a bottom front is generated and, following the thermal wind balance, a surface intensified poleward density driven current is generated.

Due to intense fishing activity, long-term moorings have rarely been deployed over the shelf, even if an understanding of the shelf dynamics and its seasonality is crucial for many studies, *e.g.* on vertical distribution of phytoplankton (Farrell et al., 2014),