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Characterisation of coastal counter-currents on the inner shelf of the Gulf of Cadiz

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ABSTRACT

At the Gulf of Cadiz (GoC), poleward currents leaning along the coast alternate with coastal upwelling jets of opposite direction. Here the patterns of these coastal countercurrents (CCCs) are derived from ADCP data collected during 7 deployments at a single location on the inner shelf. The multiyear (2008–2014) time-series, constituting ~18 months of hourly records, are further analysed together with wind data from several sources representing local and basin-scale conditions. During one deployment, temperature sensors were also installed near the mooring site to examine the vertical thermal stratification associated with periods of poleward flow. These observations indicate that the coastal circulation is mainly alongshore and barotropic. However, a baroclinic flow is often observed shortly at the time of flow inversion to poleward. CCCs develop all year-round and exclusively control the occurrence of warm coastal water during the upwelling season. On average, one poleward flow lasting 3 days was observed every week, corresponding to CCCs during ~40% of the time without seasonal variability. Thus, the studied region is distinct from typical upwelling systems where equatorward coastal upwelling jets largely predominate. CCCs often start to develop near the bed and are frequently associated with 2-layer cross-shore flows characteristic of downwelling conditions (offshore near the bed). In general, the action of alongshore wind stress alone does not justify the development of CCCs. The coastal circulation is best correlated and shows the highest coherence with south-eastward wind in the basin that proceeds from the rotation of southward wind at the West coast of Portugal, hence suggesting a dominant control of large-scale wind conditions. In agreement, wavelet analyses indicate that CCCs are best correlated with alongshore wind occurring in a band period characteristic of the upwelling system (8–32 days). Furthermore, in the absence of wind coastal currents tend to be poleward during summer. This set of observations supports that CCCs develop in response to the unbalance of an alongshore pressure gradient during the relaxation of (system-scale) upwelling-favourable winds, oriented south-eastward in the basin. The relaxation periods defined based on this wind direction show a good correspondence with the periods of poleward flow.

1. Introduction

Poleward currents leaning along the coast are characteristic features of Eastern Boundary Upwelling Systems (EBUS). These flows alternate with the predominant coastal upwelling jets of opposite equatorward direction, and are as such commonly referred to as "coastal countercurrents" (CCCs). The occurrence of CCCs has been reported in major coastal upwelling systems, in particular along the Gulf of Cadiz (GoC, Southern Iberia) in the Portuguese–Canary Current Upwelling System (Mittelstaedt, 1991; Pelegrí et al., 2005a; Pelegrí et al., 2005b; Relvas and Barton, 2002), over the Namaqua shelf (South Africa) in the Benguela Current upwelling system (Fawcett et al., 2008), and in the northern (Kosro, 2005; Largier et al., 1993; Lentz and Chapman, 1989; Send et al., 1987; Winant et al., 1987), central (Harms and Winant, 1998; Melton et al., 2009; Washburn et al., 2011; Woodson et al., 2009) and southern (Dever, 2004; Winant et al., 1999; Winant et al., 2003) portions of the California Current upwelling system. Typically, 10 to 30 km-wide CCCs advect warm water previously retained in the lee of capes or embayments during active upwelling and temporarily displace the previously upwelled colder water offshore (Send et al., 1987). This process causes rapid temperature changes over the inner shelf (Melton et al., 2009; Relvas and Barton, 2002). In addition, CCCs may affect ecosystems with the transport of water-borne material such as pollutant and larvae into nearshore areas, where many subtidal

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and intertidal species settle (e.g., Dudas et al., 2008; Mace and Morgan, 2006; Wilson et al., 2008; Wing et al., 1995).

Most of the studies about the characteristics and forcing mechanisms of CCCs have been conducted at the California Current upwelling system, based on very extensive sets of hydrographic observations across and along the inner shelf, completed with wind data from buoys and coastal stations. Examples include the CODE experiments and the multiyear Santa Barbara Coastal Long-Term Ecological Research (SBCLTER) project (Melton et al., 2009; Washburn et al., 2011). A major result from these observations was the establishment that CCCs are driven by poleward alongshore pressure gradients (APGs) that result from differences in sea level along the coast. Large scale alongshore sea surface slopes are produced between coastal headlands by the persistence of equatorward (upwelling favourable) winds (Largier et al., 1993; Winant et al., 1987; Winant et al., 2003). Numerical studies have further indicated that interactions between coastal upwelling jets and alongshore variations in the coastline and shelf bathymetry promote the development of smaller scale poleward APGs in the lee (i.e., equatorward) of capes and promontories (Gan and Allen, 2002). CCCs are triggered when these large- or small-scale APGs become unbalanced during wind relaxation events; these are defined as the weakening or even reversal of usually strong upwelling favourable winds (Huyer and Kosro, 1987).

In contrast with the Californian inner shelf, few studies have been devoted to the coastal circulation in the GoC. Until now, most of these works dealt with remotely sensed sea-surface temperature (SST) or climatological data (Fiúza, 1983; Fiúza et al., 1982; Folkard et al., 1997; Sánchez and Relvas, 2003; Vargas et al., 2003). The few hydrodynamic observations performed on the inner shelf with fixed stations (Lobo et al., 2004; Sánchez et al., 2006) or shipboard surveys (García-Lafuente et al., 2006) were of short duration (less than 1 month), with the exception of a multiyear (2002, 2004, 2005) current time-series used to examine the surface circulation at the seasonal and interannual time-scales (Criado-Aldeanueva et al., 2009). However, there is so far no detailed study based on long-term observations dealing with current inversions at an "event scale" for the definition of the patterns of poleward flows (e.g., duration and frequency) and their relation with wind conditions. Consequently, the CCC patterns in this region and their driving processes are not clear yet. Based on SST satellite imagery, coastal wind and tidal gauge data, Relvas and Barton (2002) proposed that CCCs are driven by a background APG, similar to the situation along the Californian coast. Other processes that have been proposed for the production of an APG in southern Iberia include exchanges through the Strait of Gibraltar (Mauritzen et al., 2001), the effects of large-scale atmospheric pressure systems (Sánchez et al., 2006), and tidal advection of warmer (hence lighter) coastal water from the numerous shallow inland areas located in the eastern GoC (García-Lafuente et al., 2006). Numerical studies also suggest that CCCs are produced in response to the action of wind stress alone, rather than to the relaxation of upwelling favourable wind (Teles-Machado et al., 2007). This latter hypothesis does not require a background APG for the development of CCCs.

The present research compiles 7 Acoustic Doppler Current Meter (ADCP) deployments of about 1 to 3 months duration at a single location on the inner shelf of the GoC. This dataset is used to characterise the dynamics of CCCs from an Eulerian perspective, with the aim of contributing to untangle the mechanisms that drive these currents in the region, including their connection with the offshore circulation. In particular, it is verified whether the action of wind stress alone is able to account for the observed periods of poleward flows.

2. Region of study

The GoC is the wide embayment of the Atlantic Ocean that constitutes the equatorward extremity of the Iberian upwelling system. The northern margin of the GoC stretches along the south-western Iberian Peninsula from Cape St Vicente (CSV, southwest Portugal) to the western side of the Strait of Gibraltar (Fig. 1). Cape Santa Maria (CSM) divides the continental shelf (approximately bounded by the 150 m isobath) into two halves with distinct morphological settings. West of CSM the shelf is narrow (<15 km) and incised with various canyons; to the East, it is steep and narrow (<5 km) near CSM, but quickly widens (>40 km) eastward with a gentle slope. These characteristics may create a distinct and independent water circulation over the eastern and western regions (Criado-Aldeanueva et al., 2009; García-Lafuente et al., 2006).

The upwelling season of the Iberian upwelling system is well-defined between April and October (Fiúza et al., 1982; Haynes et al., 1993; Peliz and Fiuza, 1999; Wooster et al., 1976), based on highly contrasted seasonal wind regimes associated with the zonal displacement of the Azores high- and Icelandic low-pressure systems. During the upwelling season, strong northerly winds blow along the West coast, while westerlies and southwesterlies prevail in winter. Northerlies rotate counter clockwise around CSV and blow south-eastward off southern Portugal, due to the establishment of a low pressure centre over the Iberian Peninsula in summer, together with orographic constraints (Relvas and Barton, 2002).

Although included in the Canary Current Upwelling System (CCUS), the eastern boundary discontinuity imposed by the entrance to the Mediterranean Sea modifies the Canary Current upwelling regime prevailing at the GoC. Typically, the Iberian upwelling system is associated with equatorward coastal flows (i.e., southward and eastward along the West and South coasts, respectively) of cool water forced by geostrophic adjustment. East of CSV, however, the coastal jet proceeds from the one affecting the West coast, and its propagation along the South coast depends on the local wind conditions, with westerlies and easterlies promoting and hampering its poleward extension, respectively (Fiúza, 1983; Fiúza et al., 1982; Folkard et al., 1997; Sánchez and Relvas, 2003). Westerlies also tend to produce a secondary upwelling core immediately east of CSM that may merge with the more permanent core off CSV. Overall, while the upwelling regime is quasi-permanent in summer at the West coast, the intensity and occurrence of upwelling events at the South coast are significantly reduced, in particular towards the eastern GoC, as reported by Relvas and Barton (2002) based on the analysis of a multiyear dataset of SST images. These data further show that the coastal circulation during summer along the South coast is rather dominated by the alternation of equatorward (i.e., eastward) upwelled water and a poleward (i.e., westward) warm flow (CCC) propagating from the eastern GoC. In their detailed study based on cloud-free satellite images available mostly during the summer months, Relvas and Barton (2002) have noted the presence of warm CCC during 45% of the time at the South coast. These flows were associated with temperature increases, reaching more than 5 °C in some cases. The coastal tongue of warm water is typically about 10–15 km wide, with an estimated velocity around 0.2 m s^{-1} that has been confirmed by direct measurements in summer (García-Lafuente et al., 2006) and winter (Sánchez et al., 2006). Based on cross-shore ship measurements, García-Lafuente et al. (2006) have suggested that the CCC is a stable feature in summer, being the northern boundary of a cyclonic cell located on the eastern shelf between CSM and the mouth of the Gualdalquivir Estuary (for location, see Fig. 1). In any case, the propagation of poleward currents depends on local wind conditions (Fiúza, 1983; Folkard et al., 1997; Relvas and Barton, 2002). García-Lafuente et al. (2006) have further proposed that westward blowing wind is required for the coastal current to pass over CSM. In extreme cases, CCCs may reach CSV and extend more than 100 km northwards along the West coast (Relvas and Barton, 2002). SST images in winter also show the occurrence of CCCs associated with a cold water signature along the coast. The presence of a pool of cold water on the eastern GoC in winter has been attributed to freshwater advection from the large rivers of this coastal sector (Peliz et al., 2004).