

Physical oceanography of the western Iberia ecosystem: Latest views and challenges

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Abstract

The present review is focused on the mesoscale physical processes recognized in the Western Iberia Ecosystem, complementing earlier reviews dedicated to larger scales. Recent studies support the idea that the mesoscale processes, superimposed on the larger scale variability, are the major factor controlling the ecosystem functioning in the region. A complex structure of interleaved alongshore slope, shelf and coastal currents that interact with eddies, buoyant plumes, upwelling filaments and fronts, surface layer expressions of the subsurface circulation and internal waves is revealed by the latest research. All of these contribute in different ways to have an effect on the ecosystem. The supposedly less variable winter circulation also exhibits significant mesoscale activity, in the form of eddy shedding from the poleward slope current, intermittent upwelling events and transient nearshore poleward flows. The present incomplete knowledge of this complex system presents a number of challenges and questions that must be addressed if we are to arrive at a satisfactory understanding and predictive capability for the system as a whole.

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1. Introduction

The North Atlantic Upwelling Region extends from the northern Iberian Peninsula at 43°N to the south of Senegal at approximately 10°N. The major characteristics of this large current system are comparable to the other large Eastern Boundary Currents (Benguela, Humbolt and California). They are characterized offshore by slow broad equatorward gyre recirculation, a meridional alignment of coastlines and a predominant

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equatorward wind direction during a substantial part of the year (in some places permanently). These equatorward winds force an offshore Ekman transport in the upper layer and the consequent decline of the sea level towards the coast. As a result of the geostrophic adjustment of the coastal ocean, an alongshore equatorward jet is formed, transporting cold and nutrient rich upwelled water. Poleward flows typically below 150 m over the slope compensate the along-coast mass transport and long filaments promote the exchange with offshore waters. The ecosystem functioning is similar in all these major world upwelling systems, bringing about initiatives for comparative research strategies (e.g. GLOBEC, 1999; GEOHAB, 2005; EUROCEANS, 2005).

In the case of the North Eastern Atlantic system (Fig. 1), the Canary and Iberian regions form two distinct subsystems (e.g. Barton, 1998). The separation is not simply geographical, but is a consequence of a distinctive

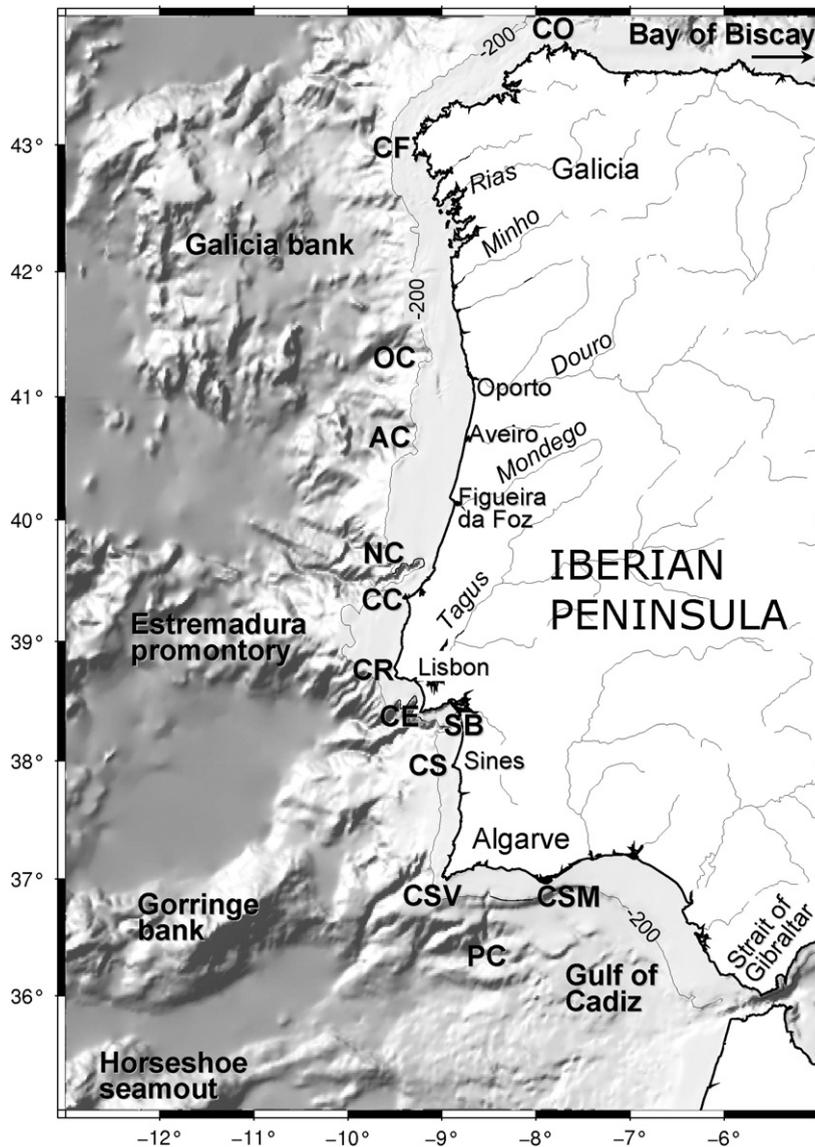


Fig. 1. Geography of the Western Iberian Ecosystem, showing the main features referred to in the text. The 200 m bathymetric contour, that roughly delimits the continental shelf, is represented. From north to south: CO, Cape Ortegal; CF, Cape Finisterre; OC, Oporto Canyon; AC, Aveiro Canyon; NC, Nazaré Canyon; CC, Cape Carvoeiro; CR, Cape Roca; CE, Cape Espichel; SB, Setúbal Bay; CS, Cape Sines; CSV, Cape São Vicente; PC, Portimão Canyon; CSM, Cape Santa Maria.

characteristic of this Northeastern Atlantic region, the discontinuity imposed by the entrance to the Mediterranean Sea. Although the sill is shallow (~ 300 m), it allows the exchange between two different water masses with a profound impact not only in the slope dynamics but also in the regional circulation. Seaward of this point, the Azores Current extension eastward clearly separates the oceanic gyre circulation regime into the north (Portugal Current) and the South (Canary Current) (e.g. Saunders, 1982; Pollard and Pu, 1985; Pingree, 1997). Modelling studies suggest that the Mediterranean outflow has a dynamic impact in the ocean upper layer and may constitute a complementary mechanism for the formation of the Azores current (Jia, 2000). The separation of these subsystems is also associated with the sharp seasonality of the western Iberia system mainly due to the annual cycle of the atmospheric systems. The seasonal interplay of the large scale climatology between the Azores high pressure cell, strengthened and displaced northward during the summer, and the Iceland low, weakened at that time, governs the set up of upwelling favourable winds (northerlies) off western Iberia between April and October (Wooster et al., 1976; Fiúza et al., 1982). During the peak summer months the upwelling winds are strengthened by the development of a thermal low over central Iberia.

During the winter the dominant wind direction changes and poleward flow becomes a conspicuous feature at all levels between the surface and the Mediterranean water at ~ 1500 m, along the Iberian shelf edge and slope. The surface poleward flow carries relatively warm and saline water, clearly identifiable in sea surface temperature satellite imagery (Frouin et al., 1990; Haynes and Barton, 1990; Peliz et al., 2005) that propagates into locations as far north as the Cantabrian coast (Pingree and Le Cann, 1990) and the Goban Spur (Pingree, 1993). The generation of this poleward flow has been attributed to the interaction of the meridional density gradient with the continental slope and shelf (Huthnance, 1984; Peliz et al., 2003b) and the reversal of the wind regime, which has a southerly component during this time of the year (Frouin et al., 1990). Whether the surface signal of the poleward flow is maintained during the summertime, simultaneous with the coastal upwelling jet, is the subject of debate (Coelho et al., 2002; Peliz et al., 2005; Colas, 2003). The connection of the poleward flow with a northward recirculation of the Azores Current cannot be excluded either (Peliz et al., 2005). The poleward flow shows a turbulent character, with eddies and smaller scale instabilities typically being generated in the shear regions (Peliz et al., 2003b). Recently, occasional winter upwelling events (Vitorino et al., 2002), with significant biological impacts, have been documented (Santos et al., 2004; Ribeiro et al., 2005), but the extent of the dynamical implications is still unknown.

Recent work suggests that the large scale climatological patterns in the ecosystem are partly obscured by the mesoscale activity. The oceanography of the region is largely dominated by medium size structures that represent the “weather” variability of the ocean. Time scales of a few tens of days explain more than 70% of the variability of the coastal alongshore wind stress, a major factor governing the coastal circulation (Álvarez-Salgado et al., 2003). The continental shelf, ≤ 10 km wide south of Lisbon, 30–40 km wide off central Portugal and somewhat narrower again off northern Portugal and Galicia, is populated by topographical structures, such as prominent capes, promontories and submarine canyons, whose spatial scales are tens to hundreds of kilometers. The observed oceanographic patterns in the Iberian system reveal a conspicuous succession of mesoscale structures such as jets, meanders, ubiquitous eddies, upwelling filaments and counter-currents, superimposed on the more stable variations at seasonal timescales (Haynes et al., 1993; Peliz et al., 2002, 2005; Serra and Ambar, 2002; Torres et al., 2003; Relvas and Barton, 2005). Internal waves have also been studied at sites along the Iberian shelf (Jeans and Sherwin, 2001; Sherwin et al., 2002).

The mesoscale features constitute the ocean response to sub-seasonal temporal scales and sub-basin spatial scales and largely dominate the ecosystem behaviour. Thus, the observed summer pattern is much more complicated than a simple contorted band of cold, upwelled water along the coast. Moreover, even in winter, supposedly less variable, significant mesoscale activity, including upwelling events, have been reported (Oliveira et al., 2004; Peliz et al., 2005) and it is clear that buoyant low salinity plumes play a major role in the ecosystem behavior (Peliz et al., 2004; Santos et al., 2004). For individual eggs and larvae, scales on the order of 100–1000 m and 1–10 days are usually important (Okubo, 1994). On the other hand, mesoscale dynamics with spatial scale of about 10–100 km become more important at the community level for the transport of larval stages and their retention in or dispersal from favorable nursery areas. Thus, the spatial and temporal scales of importance for marine plankton communities are mainly related to mesoscale features, including fronts, buoyant plumes, eddies, stratification, coastal upwelling and related features (e.g. Bakun, 1996; Queiroga and Blanton, 2005; Santos et al., 2007).

Several reviews have been already published on the eastern boundary of the North Atlantic (Canary Current/Iberia) with their main focus in the temporal and spatial variability of the large-scale circulation, upwelling, and fisheries (e.g. Barton, 1998, 2001; Arístegui et al., 2006). Thus, this paper is mainly focused on those phenomena and features that occur at smaller spatial and temporal scales along the Iberian margin, as well as those processes though not classified as upwelling patterns modify the Iberian system response to upwelling winds. It is intended to complement the earlier reviews by examining these particular processes and pointing to some implications for the ecosystem.

2. Winter circulation patterns

The winter ocean circulation system of the Iberian Basin is the result of different mechanisms of forcing and interactions with the open ocean circulation. In this section, an overview of these mechanisms, their importance and their consequences for the ocean circulation in the neighbourhood of the shelf/slope system is made.

2.1. Iberian poleward current system: description, forcing and main features

The poleward flow observed along the west coast of the Iberian Peninsula is characterized by a transport of warm and salty water (typical surface anomalies, 1–1.5 °C and 0.1–0.3 in salinity) with velocities up to some 0.2–0.3 m s⁻¹ reported by Haynes and Barton (1990) and Frouin et al. (1990). From the point of view of hydrological fields, this current, recently reviewed by Peliz et al. (2005), is characterized by a coastal downwelling of the isopycnal field of up to 200 m in an across-shore distance of about 40 km. Associated with the flow, there is a subsurface salinity maximum (with typical values 35.8–36.0) centred typically about 100 m depth, which has been often used as tracer of slope poleward flow. This salinity maximum is usually close to the slope, although it has been observed located from 36 to 55 km off the shelf edge (Torres and Barton, 2006). The maximum of the current appears to be located in the upper layers near the shelf break (at the levels of the ENACW). It transports a few Sverdrups (1 Sv = 10⁶ m³ s⁻¹), and has a strong seasonal character. Another estimate of the mean current associated with the poleward flow is given by Huthnance et al. (2002), who cite a mean value of ~0.1 m s⁻¹ based on two months of current observations integrated vertically between the surface and 600 m. Lagrangian estimates by Martins et al. (2002), indicate a mean value of 0.15 m s⁻¹.

This current is observed on the western coast of the Iberian Peninsula during the winter season, beginning in September–October at the end of the upwelling season, until the spring transition in April–May, when the northerly winds begin to dominate. During this period the prevailing winds are mainly westerly and southerly (Isemer and Hasse, 1987). The poleward flow is seen to extend downstream along the northern Biscay coast and is relatively well characterized north of Cabo Carvoeiro. Its southern extension across the Strait of Gibraltar or any connection with the Azores Current is only hypothetical, in the absence of direct observation.

One of the forcing mechanisms of the poleward flow observed along the west coast of the Iberian Peninsula (and indeed in other eastern boundary current systems like the Leeuwin Current, for instance) is the interaction of a meridional density gradient with the shelf and slope off the N–S oriented coast, in this case between Cape São Vicente and Cape Finisterre (Fig. 1). This “JEBAR” (Joint Effect of Baroclinicity And Relief) mechanism was studied theoretically by Huthnance (1984), and applied to the conditions of the Iberian poleward current system by Peliz et al. (2003a,b). Off NW Spain, Torres and Barton (2006) found good agreement between the JEBAR and a least square fit of the normalised depth-averaged velocities from a series of ADCP cross-sections of the poleward current between the shelf-edge and mid-slope 40 km further offshore.

The meridional distribution of density at the latitudes of the west coast of Iberian Peninsula shows the coexistence of a large scale gradient and the presence of several narrow frontal regions. The large scale structure of the meridional density gradient has been studied, among others, by Mazé et al. (1997) (see their Fig. 6) and van Aken (2001) (his Fig. 7), and their results show that from the latitudes 37°N to 43°N, south to north the typical rise of the isopycnal field for $\sigma_\theta = 27.0$ is 150 m approximately. This large scale meridional gradient supports a weak eastward velocity, with a maximum value of about 0.02 m s⁻¹. The coastward flow integrated between the latitudes of Cape São Vicente and Cape Finisterre provides an onshore transport of about 1.95 Sv (Mazé et al., 1997), part of which may represent the forcing of the poleward flow observed at the slope.

Simultaneously with the large scale meridional density gradient, short scale (on the order of 100 km) frontal regions are recurrently observed. Vitorino (1995) reports one example of this frontal region, separating stratified waters to the south of about 39.5°N, from homogeneous waters north of that latitude, at a longitude of 12°W, giving rise to typical onshore velocities of 0.05–0.1 m s⁻¹. Similarly, frontal zones are reported in Pollard and Pu (1985), at latitudes centred at about 41.5°N, with the outcropping of the isopycnal field. Recurrent frontal zones near Cape São Vicente, Cape Carvoeiro and Cape Finisterre were also analysed by Peliz et al. (2005), based on sea surface temperature satellite imagery. These regions of stronger meridional density gradient are associated with enhanced onshore flow, which has been shown to be one of the forcing mechanisms of poleward flow observed at the west coast of the Iberian Peninsula (Peliz et al., 2003a,b).

The poleward current system is rich in mesoscale features, like instabilities of the flow, eddy interactions, eddy shedding, and separation from the slope. We can consider four different stages of the development of the poleward current system:

- (i) The adjustment phase, which corresponds to the generation of a tongue of lighter water propagating in the poleward direction along the bathymetry, which is clearly seen, for example, in the satellite images presented in Pingree and Le Cann (1990).
- (ii) The eddy development phase, which starts with a decoupling between the tongue's path and the bathymetry. The offshore front, separating the tongue water from the surrounding water starts to develop into instabilities, in the form of anticyclonic and cyclonic surface meanders. These instabilities are first discernible downstream of the main bathymetric features, like the Estremadura promontory, and the Aveiro canyon. The analysis of satellite observed sea surface level anomalies (Fig. 15 of Peliz et al., 2005) shows that positive sea surface anomalies predominate for the winter period, that the anticyclonic features have their main axes aligned NW–SE, and that they are larger than the cyclonic features, mainly associated with filaments of cold water with axes in the SE direction.
- (iii) The eddy interaction phase, involving both meanders and eddies described earlier, develops new structures. Due to the predominance of anticyclonic structures, with a dominant wavelength of ~150 km, the flow between Cape Carvoeiro and Cape Finisterre organizes into three or four large anticyclonic structures, and the expulsion of two or three dipoles that migrate offshore, by a self-advection mechanism.
- (iv) The decay phase is characterized by the offshore migration of the structures described above, due to the dipolar interaction and beta effect, which promotes westward advection of anticyclonic anomalies and westward radiation of Rossby waves.

Anticyclonic eddy generation and separation near Cape Finisterre, where the bathymetry turns abruptly by 90°, is a clear evidence of flow separation. This was reported by Pingree and Le Cann (1992b), Pingree and Le Cann (1992a), who named the resulting structures SWODDIES (Slope Water Oceanic eDDIES). As in the case of the west coast, the separation occurs due to the interaction of dipolar (and even tripolar) structures, with predominance of anticyclonic vorticity.

Another different separation process consists in the detachment of the poleward flow to the north of Aveiro canyon, where it turns offshore and probably contours Galicia Bank to the north. This process was originally suggested by Mazé et al. (1997). Peliz et al. (2005) provided some observational support based on a cross-shore section of hydrology that shows evidence of warmer and salty water, characteristic of the poleward slope flow, 200 km offshore at 41.5°N, suggesting poleward flow separation.

The fate of the poleward flow during summer is subject of debate. The thermal signature of the light water tongue no longer exists, because the surface layer is strongly modified by heat fluxes, and the upwelling frontal zone at the shelf/slope region, and its associated features like filaments and squirts, tend to mask the thermal contrast typical of winter poleward flow. However there are observations that show the tendency for a poleward flow offshore during summer (Peliz et al., 2002). Furthermore, Jorge da Silva (1992) showed that the summertime flow at three moorings at 41°N tended to be poleward once the upwelling favourable wind ceased. Peliz et al. (2005) hypothesize that the poleward current does not reverse completely but that the core of the flow is moved offshore and that the slope zone is occupied by dominantly equatorward current.

Le Cann et al. (2001) calculated an annual cycle of the along-slope current based on long currentmeter records for the depths 150, 400, 700 in two moorings near 9.5°W 42°N over 1200 and 2000 m isobaths (see

also Colas, 2003). The obtained annual cycle shows maximum poleward flow in September–October at all depths. A secondary peak of poleward flow is seen in December–January, but only at the uppermost current meter. Interestingly, the maximum equatorward flow corresponds to the months of February–April. Equatorward flow at 400 m is very weak and weaker than the values calculated for the 700 m current meters. These annual cycles of intensification of poleward flow are similar to the ones described in Pingree et al. (1999) for the Goban Spur slope zone.

Poleward flows, ubiquitous and sometimes dominant features of eastern boundary upwelling systems, are important in that they are strongly implicated in the onset of harmful algal blooms with significant economic repercussions for local fisheries and aquaculture. In the Benguela Current, the occurrence of poleward flow in the extensive St Helena Bay has been related to harmful algal blooms and anoxic events (Probyn et al., 2000) leading to fish mortality and mass ‘walk outs’ of lobster populations. Indeed, the autumn spin-up of the Iberian poleward current is linked with the development of toxic blooms in the Rías Baixas detrimental to the mussel culture there. The poleward flow may also be instrumental in forming convergence zones over the shelf-break off the NW Iberia, which are of ecological importance for the retention and/or poleward transport of the phytoplankton (Ribeiro et al., 2005) and sardine larvae (Santos et al., 2004). Castro et al. (1997) and Álvarez-Salgado et al. (2003) also describe a shelf-ocean blocking effect due to the poleward current and its consequences for biogeochemical processes. It has been suggested that frontal dynamics associated with the Iberian poleward flow helped limit the arrival of contaminants from the Prestige oil spill at the coast (Álvarez-Salgado et al., 2006).

Other eastern boundary regions show poleward regimes, as off Oregon, where a regime similar to Iberia with the seasonal alternation between upwelling and downwelling is described (Huyer, 1983). The Leeuwin Current represents perhaps an extreme example. There, the effect of the wind forcing is obscured by the along-shore density gradient, except in confined regions off the west Australian coast (Woo et al., 2006). Poleward flow regimes have been observed in the California Current region (Hickey, 1998), extending south till central Mexico (Lavin et al., 2006). For the western Iberia system, it is clear that both density and atmospheric forcing drive the along-slope current system, the seasonality of which is modulated by the poorly understood interplay of these two factors.

2.2. Wind forced currents over the shelf

It is well recognised that the slope circulation off west Iberia during wintertime is mainly dominated by the presence of the poleward current discussed above. However, the poleward current does not penetrate onto the shelf because of the mechanisms of isolation (Csanady and Shaw, 1983), except in episodic events associated with instabilities on its inner side. Taking this into account, the most important mechanism of forcing of the shelf circulation is the wind stress. The prevailing winds in the west coast of Iberian Peninsula during winter are mainly south-westerlies (Isemer and Hasse, 1987), and the atmospheric circulation is dominated by the eastward displacement of cyclonic perturbations and their associated frontal systems. However, in some years the presence of episodic atmospheric anticyclonic circulation (the Azores High) could give rise to northerly wind events during winter (Borges et al., 2003). As stated by Vitorino et al. (2002), few studies are devoted to the winter circulation over the shelf. These authors analysed data from a current meter mooring located near the head of Oporto canyon, on the 85 m isobath during November 1996–January 1997 and January 1998–May 1998. Several winter upwelling events were observed, namely in December 1996 and in 1998, generating equatorward currents of $\sim 0.40 \text{ m s}^{-1}$. Despite this, the currents were predominantly poleward with intensities of $0.10\text{--}0.15 \text{ m s}^{-1}$ but in some cases (as in 1996) could exceed 0.2 m s^{-1} . Most of this variability was related to wind forcing. A strong correlation, with a lag of 6 h, between the surface and bottom currents over the mid-shelf and the wind, was documented by Vitorino et al. (2002) at 41.3°N . Off Galicia, the early development of the poleward current in autumn is directly related to downwelling favourable winds (Torres and Barton, 2006). Consistent northward velocities of $0.2\text{--}0.3 \text{ m s}^{-1}$ are reported by Haynes and Barton (1990), Vitorino et al. (2002), Torres and Barton (2006) on the northern part of the western Iberian shelf outside the upwelling season.

Recently, Marta-Almeida et al. (2006) also showed that there is a good correspondence of wind stress and shelf currents in a study that compares numerical modeling simulations, current meter data in the mid shelf

and winds from NCEP re-analysis. Peliz et al. (2003b) show a decoupling between the the shelf circulation forced by the wind and the poleward flow forced by the large scale meridional density gradient. Over the shelf, wind forced currents dominate whereas over the slope the poleward flow is not strongly affected by wind circulation.

3. Coastal upwelling and associated phenomena

The predominantly equatorward winds observed in summer off West Iberia, drive an offshore Ekman transport and force the upwelling of colder, nutrient-rich, subsurface waters along coast. Satellite-derived sea surface temperature (SST) maps, like the one shown in Fig. 2, have been used in the past decades to describe the upwelling patterns in the region, owing to the clear thermal contrast between the cold, vertically mixed, upwelled waters, typically found over the shelf, and the thermally stratified oceanic waters.

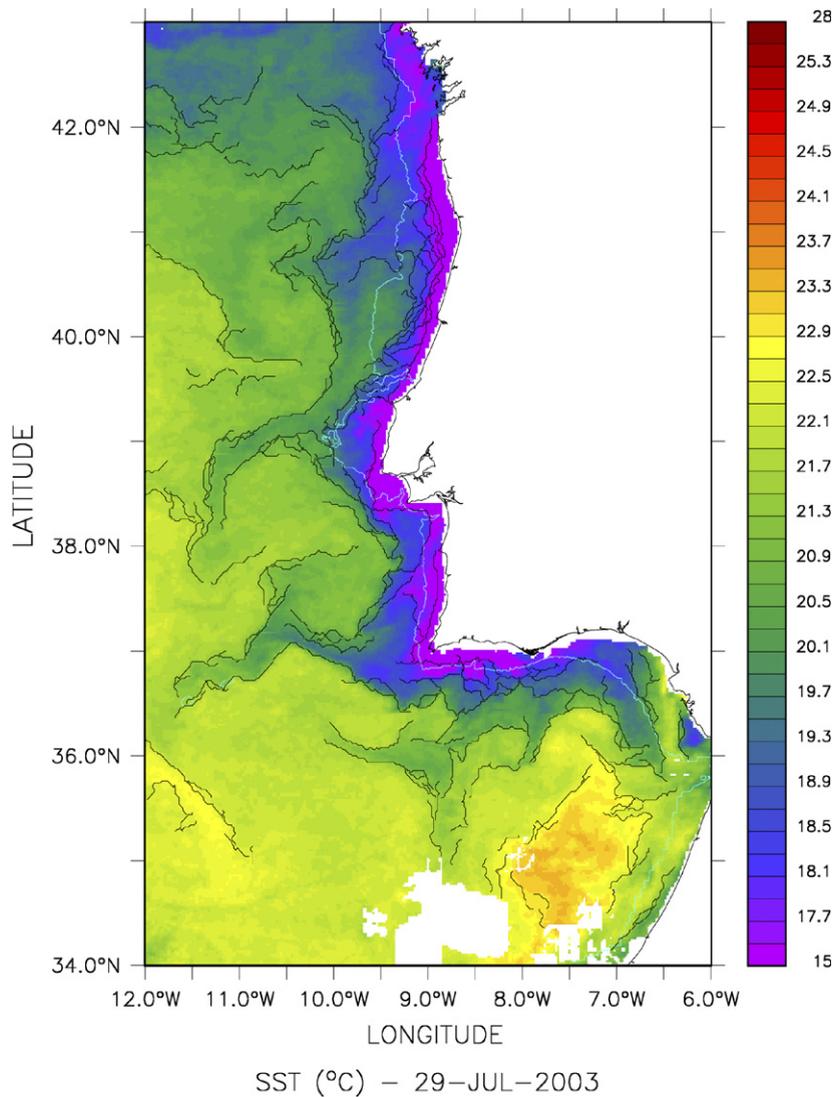


Fig. 2. Satellite-derived SST map for 29-JUL-2003. Solid contours indicate the location of thermal fronts computed using a single image edge detection algorithm developed by Cayula and Cornillon (1992). Blue line represents the 200 m bathymetric contour. Land and cloud areas are masked in white. Data from Eumetsat's Ocean & Sea Ice Facility.

It has been recognized that the main summer upwelling features off Western Iberia resemble those observed in other upwelling regions (e.g. NW Africa, California) with comparable wind forcing and morphological features (e.g. Fiúza, 1983; Haynes et al., 1993), which may be summarised as follows. When equatorward winds start to prevail (late spring/early summer), a narrow band of cold water of relatively uniform width is observed along the coast, and small scale (20–30 km) perturbations are usually seen along the thermal front. Approximately one month after the beginning of upwelling favourable winds, major filament structures start to develop, associated with offshore currents reaching 0.5 m s^{-1} , leading to the classical picture of what is usually called “fully developed upwelling” where several cold water filaments are seen to extend more than 200 km offshore (cf. Fig. 2).

Filaments export a much larger mass along their principal axis than expected by the purely wind-driven Ekman circulation, being an important mechanism of exchange between coastal and open ocean waters, with obvious implications in the ecosystem functioning. The new production of an entire upwelling season could be entirely exported to the open ocean by upwelling filaments (Aristegui et al., 2006) and organic matter sedimentation could take place far away from the upwelling source. However, the results of observations made by Barton et al. (2001) showed that a portion of the water transported off shelf recirculated back to the shelf on time scales of about 1 month, and this could have implications for the retention of biological material on the shelf (e.g. fish larvae).

Strub et al. (1991) summarized the theories for the development of filament formation off the west coast of North America, which include instabilities of the long-shore upwelling jet and its interaction with the offshore vorticity field. Off western Iberia, most of the filaments occur associated with prominent capes, but with exceptions (Haynes et al., 1993). Numerical model studies by Roed and Shi (1999) suggest that they are independent of the presence of irregularities in the shelf-slope topography or coastline geometry, and Batteen et al. (1992) attribute the filament formation to wind stress curl. Relvas and Barton (2002) report the westward growth of a filament off Cape São Vicente, interpreted as the result of the meandering of the equatorward jet. This mechanism was also proposed by Haynes et al. (1993) as instrumental in the formation of the filament recurrently observed off Aveiro. These studies point to the conclusion that filament formation off western Iberia cannot be explained by a single mechanism.

Direct *in situ* observations of the upwelling structures off Western Iberia, with high spatial resolution, have been achieved only more recently, off NW Iberia (Barton et al., 2001; Peliz et al., 2002) and off Cape São Vicente, SW Iberia (Sanchez, 2005). The studies dedicated to the structure of the filaments in the region show that there are more similarities between the filaments occurring in the northern and southern extremes of W. Iberia than with filaments sampled off the west coast of North America (e.g. Ramp et al., 1991) or off NW Africa (Barton et al., 2004). Off W. Iberia they show relatively weak dynamical structure with the offshore flow restricted to the near surface layer above $\sim 100 \text{ m}$, as a result of surface-trapped horizontal density gradients. Using data from a cruise conducted off the NW coast of Portugal in September 1998, Peliz et al. (2002) called attention to the presence of a low salinity layer ($S < 35.7$), responsible for the maintenance of a strong stratification over the shelf that reduces the thickness of the Ekman layer and corresponding offshore Ekman transport, and in the creation of an inner shelf front with associated northward baroclinic transport. The observation of a poleward flow at the ocean side of the upwelling front, interacting with the topography and the upwelling jet, led these authors to consider flow interaction as an important contribution to filament development. This mechanism is perennial only if the poleward flow is maintained along with the summer upwelling jet. Thus, the definition of the seasonal behaviour of the poleward flow represents a critical point for the understanding of the functioning of the western Iberia ecosystem.

To illustrate the average effect of the upwelling structures described above and to discuss their variability, maps of average SST anomaly and frontal probability are presented in Fig. 3. The maps were constructed using all summer images ($n = 1940$) available at the Eumetsat's Ocean & Sea Ice Facility (Brisson et al., 2001), for June to September of the years 2001–2005. The SST anomaly is defined here as the difference relative to the zonal mean values for the range $11\text{--}12^\circ\text{W}$. The methodology used to compute the frontal probability was the same as described by Mavor and Bisagni (2001), using a single-image edge-detection algorithm (Cayula and Cornillon, 1992) counting only the pixels identified as fronts where the local SST gradient was above $0.1 \text{ }^\circ\text{C}/\text{km}$.

The SST anomaly map shows three main locations where the SST difference between the onshore and offshore regions exceeds 3 °C: between Capes São Vicente and Sines (37–38°N), between Capes Espichel and Carvoeiro (38.5–39.5°N) and between the mouth of Douro and Minho rivers (41–42°N) (cf. white contour in Fig. 3 top). These may be regarded as the source areas for the filaments that are recurrently observed along the coast south of 42°N (Fiúza, 1983; Sousa and Bricaud, 1992; Haynes et al., 1993; Relvas and Barton, 2002). The different bottom topography and coastal morphology of the areas adjacent to these main upwelling centres suggest that different processes are responsible for the smaller SST differences observed in these areas. The areas south of Cape Espichel and Cape São Vicente are characterized by major changes in coastline orientation, in clear contrast with the straight coast off Aveiro.

The cold water band along the 200 m bathymetric contour, south of Cape São Vicente is in close agreement with Relvas and Barton (2002) observation that the preferred direction for the spreading of the cold water upwelled north of Cape São Vicente is eastward along the southern shelf break and slope. These authors suggest that this flow would result from the topographic steering of coastal water along the depth contours around the Cape. The same process can be invoked to explain the prevalence of a cyclonic circulation south

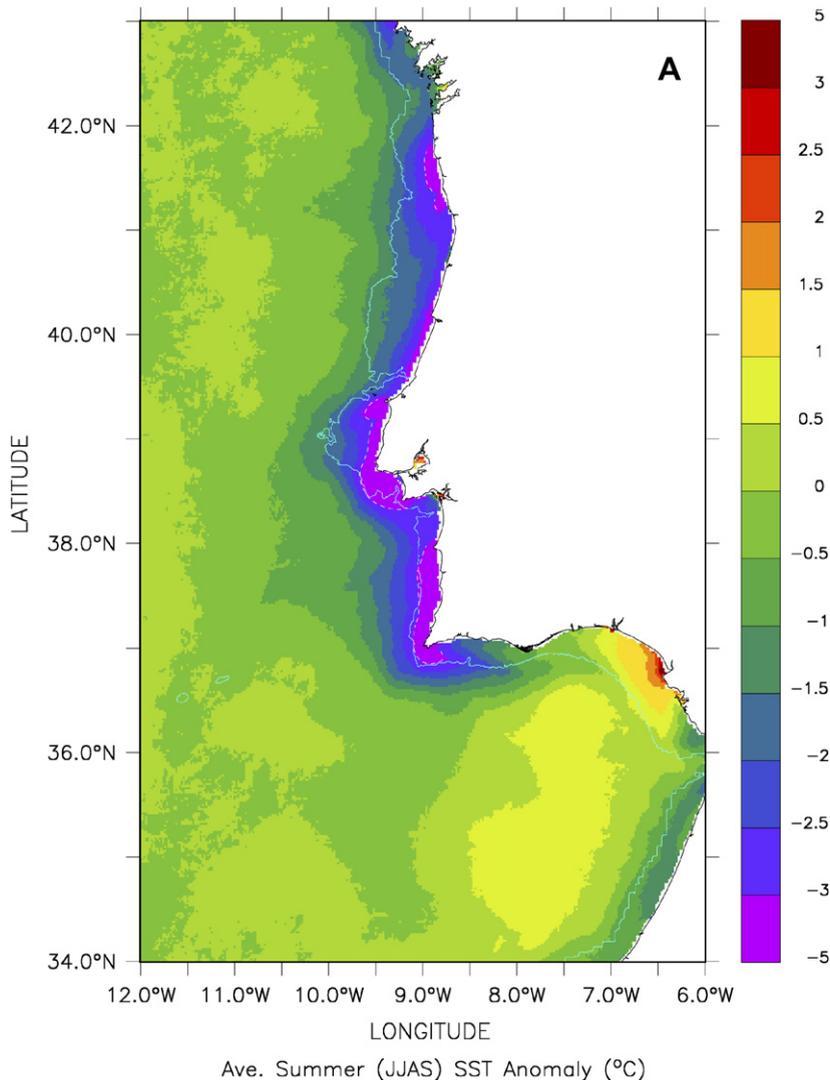


Fig. 3. Average summer SST anomaly (June–September 2001–2005) (A) and frontal probability for the SW Iberia (B–next page). Blue line (A) and dashed line (B) represents the 200 m bathymetric contour.

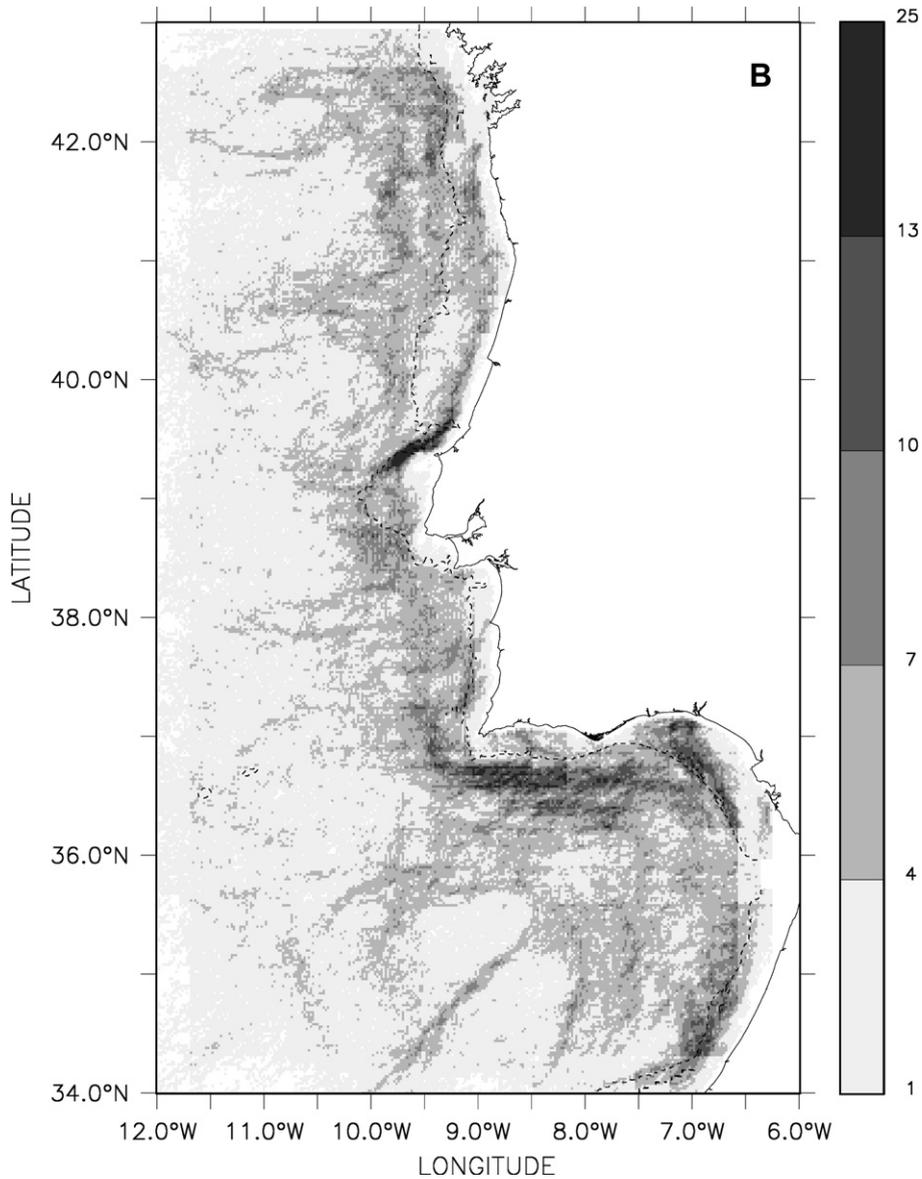


Fig. 3 (continued)

of Cape Espichel that would be responsible for the advection of warmer offshore waters into Setúbal Bay. Off Aveiro it is likely that the relatively warmer SST results from the onshore return flow located to the south of the filament jet, a characteristic feature of the filament structures (Strub et al., 1991; Ramp et al., 1991), coupled to the dynamics of the poleward slope current in the vicinities of the Aveiro canyon, and the entrainment of low salinity water in the shelf. The relatively weak upwelling signal on the outer shelf between Cape Carv-oeiro and Aveiro, and the low frontal probability, indicate that the pattern observed in Fig. 2 is recurrent, suggesting that this area, together with the areas south of Capes Espichel and São Vicente, is retentive for bio-genic material with small offshore advection.

Other prominent features that emerge from the frontal map (Fig. 3B) are the much higher probability along the slope in the south coast of Algarve and the southern edge of Nazaré Canyon, in the vicinities of Cape Carv-oeiro. The maximum probability values are found off this Cape, suggesting a strong topographical control of the flow, constrained to the canyon axis. In this region it is probable that other processes apart from the coastal

upwelling play an important role in locking the thermal fronts to the shelf edge, particularly the tides, which are strongly affected by topography (Marta-Almeida and Dubert, 2006). The frontal band extending along all the Algarve coast indicates that the eastward advection of the cold water around Cape São Vicente may be linked to a larger water inflow into the Gulf of Cadiz, i.e., the eastern branch of the Azores Current. On the other hand, the signature of a nearshore warm water wedge in the 5-year average SST anomaly (Fig. 3A), indicates a prevalence of the coastal (westward) counterflow, described by Relvas and Barton (2005), relative to the upwelling events in the Algarve coast as illustrated in the synoptic image presented in Fig. 2.

The open ocean frontal probability is about half of the probability in some nearshore regions, such as Cape Carvoeiro and Cape São Vicente. This reveals a greater variability in the positions of the offshore fronts associated with the upwelling filaments, specially south of Cape Carvoeiro, suggesting that filament development is influenced by the off-shelf mesoscale eddy field.

4. Inner shelf circulation

During the last decade the inner shelf has received much more attention from oceanographers than before. An example is the PISCO (Partnership for Interdisciplinary Studies of Coastal Oceans) project, without parallel in Europe, that focuses on the understanding of the nearshore ecosystems of the US West Coast, a region with oceanographic similarities with western Iberia. Continental shelves assume an exceptional importance in ocean processes because they represent the interface between the populated coastline and open oceans. Most of the human-induced influence on the coastal ecosystems behaviour occurs via the inner part of the shelf. Fresh water draining from inland regions also impact these regions.

There is an increasing perception that the inner shelf dynamics is somewhat independent from the outer shelf dynamics. Traditionally physical processes over the continental shelf are defined in terms of Ekman dynamics that predicts cross-shelf transport proportional to the wind stress and associated alongshore currents due to geostrophic adjustment. As we move onshore into reduced water depth, surface and bottom boundary layer tend to overlap, reducing the cross-shelf transport. This has ecological consequences by preventing the transport between the inner shelf and the outer shelf, so that alongshore dispersion and consequent retention of larvae stages, phytoplankton and detritus prevail over the inner shelf. The definition of inner shelf depends on the width and depth of the platform, surface wind stress, bottom stress and stratification, but it includes those water parcels that lie inshore of the upwelling or downwelling front (Austin and Lentz, 2002). In the absence of strong Ekman dynamics, nearshore regions are exposed to forcing factors other than the wind stress.

4.1. Inshore countercurrents

Multiple examples of the distinctive behaviour of the inner shelf circulation, contrasting with the seasonal regime, have been observed in the western Iberia ecosystem. Off SW Iberia, satellite sea surface temperature imagery show the recurrent development during the upwelling season of a warm countercurrent over the inner shelf, progressing from the Gulf of Cadiz, often turning poleward around Cape São Vicente (Fig. 4, top sequence). This feature, 15–25 km wide, is associated with periods of weakening or relaxation of upwelling favourable winds. Estimates of the mean speed of the warm counterflow progression based on satellite imagery gives about 0.17 m s^{-1} along the southern coast and double that (about 0.35 m s^{-1}) along the western coast (Relvas and Barton, 2002). Direct observation of the inshore counterflow in June 1994 revealed velocities up to 0.4 m s^{-1} when turning Cape São Vicente (Relvas and Barton, 2005), consistent with the previous estimates. Beyond the Cape, the counterflow progressed poleward inshore of an equatorward jet-like flow of cold waters upwelled further north. Analysis of tide gauge data reveal the existence of a negative alongshore sea surface slope (pressure gradient), stronger during the upwelling season, forcing the poleward coastal flow against the alongshore circulation associated with the upwelling mechanism (Relvas and Barton, 2002).

A remarkably similar situation occurs off Galicia, as reported by Sordo et al. (2001) based on observations from several upwelling seasons. There, on the inner shelf and after the cessation of upwelling, a relatively narrow poleward warm flow progresses inshore of a southward moving tongue of cold water previously upwelled (Fig. 4, bottom left). Poleward inshore velocities up to 0.31 m s^{-1} were inferred from the drifter data of

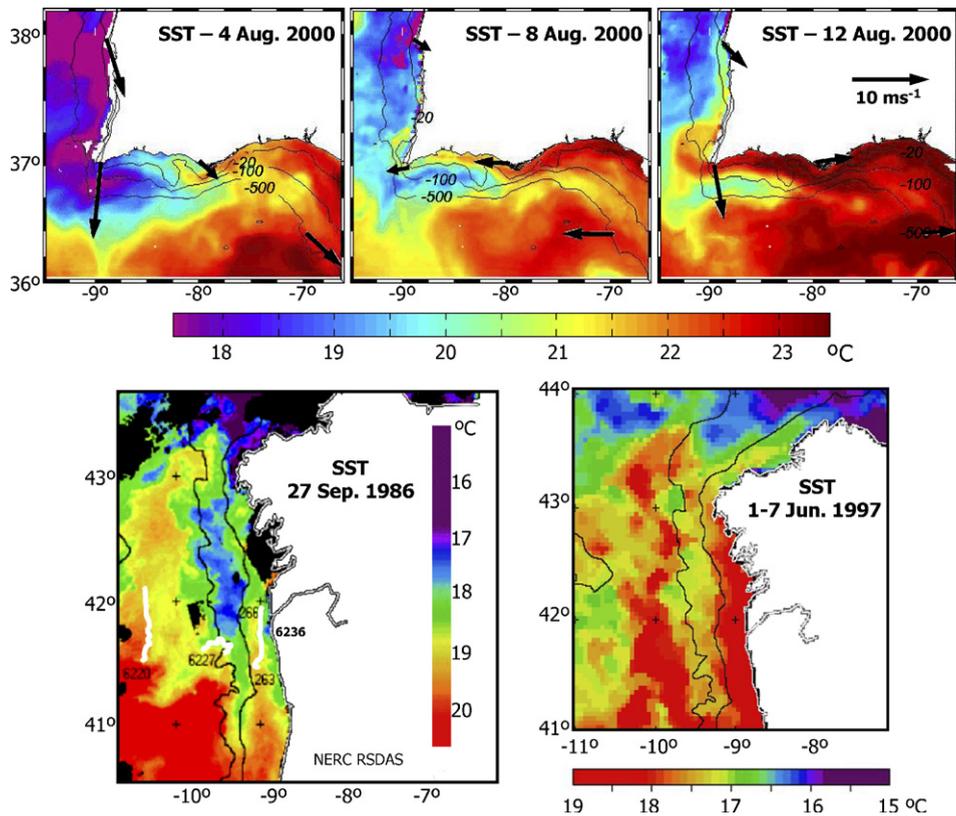


Fig. 4. Satellite SST images showing inshore warm countercurrents observed along western Iberia during the upwelling season. Top sequence – progression along southwest Iberia, turning the Cape São Vicente following a wind relaxation event. Arrows represent the wind averaged over the 24 h prior to the image capture in coastal stations and Gulf of Cádiz buoy (adapted from Sanchez, 2005). Bottom left – image from 27 September 1986 off Galicia, with drifter tracks overlaid (thick white lines), showing poleward flow in the offshore and nearshore warm tongues and near-zero flow at the southern end of the cold feature (adapted from Sordo et al., 2001). Bottom right – composite over a week in the beginning of June 1997 at 4 km resolution, showing a pattern similar to that of September 1986 (adapted from Torres and Barton, 2007).

Haynes and Barton (1990). The set up of the inshore flow seems to presage the northward transport of toxic dinoflagellates to the entrance of the Galician Rias, that then spread inside under favourable conditions. Further south, off Aveiro (between 40.5°N and 41.0°N), based on geostrophic calculations, Peliz et al. (2002) describe a warm northward along-coast current flowing over the inner-shelf, separating colder upwelled waters from the coast. This survey took place at the end of the upwelling season, during the decay of a fully developed upwelling event too.

In the cases described above, a double frontal system was present, with the equatorward flowing upwelling waters forming the conventional upwelling front in the oceanic side, with the warmer offshore waters flowing poleward, and a second front in the inner side with the inner-shelf countercurrent, also advecting warmer waters poleward (Fig. 4). The occurrence of inner-shelf countercurrents in the Iberian margin seems to be well established, although a number of forcing mechanisms appear to be responsible. The evaluation of their ecological consequences, namely in the alongshore dispersion of coastal species, is only just beginning. In a recent modelling study, Peliz et al. (2007) showed that the inner-shelf dynamics could be a mechanism for the interchange between invertebrate populations that live in the estuaries of NW Iberia, but much research and direct observations remain to be done.

Inshore poleward countercurrents are not exclusive of the western Iberia system and have been observed to recur during the upwelling season in the California system, whenever upwelling favourable winds relax (Huyer and Kosro, 1987; Send et al., 1987; Winant et al., 1987). Evanescent nearshore poleward flows may be set up

locally equatorward of capes following wind relaxations (Kosro, 1987). On a regional scale, embayments provide topographic situations conducive to re-circulations with poleward slope flows, such as the Southern California Bight (Harms and Winant, 1998) in a way similar to that described here for the Gulf of Cadiz (Relvas and Barton, 2005). Alongshore pressure gradients have been acknowledged as a major forcing for the poleward flow on the inner shelf too. Recent studies have stressed the contrasting circulation in the outer and mid shelf with the inner shelf circulation, on relatively short temporal scales (less than a month) off the Pacific coast of the US (Cudaback et al., 2005; Kirincich et al., 2005; Kaplan et al., 2005).

During winter, under non-upwelling conditions, direct observations taken from two upward looking 600 kHz ADCP's moored near 30 m depth in the Gulf of Cádiz between 25 November and 7 December 2001 reveal the alternating nature of the coastal flow along the SW Iberian Peninsula, featuring a sharp current inversion on time scales of less than 2 days. The subinertial flow drastically changed from $\sim 0.25 \text{ m s}^{-1}$ westward to $\sim 0.17 \text{ m s}^{-1}$ eastward, parallel to the bathymetric contours, uncorrelated with the local wind stress (Sánchez et al., 2006). Such observations show the dominant alongshore flow on the inner shelf off the northern margin of the Gulf of Cádiz, with implications to the ecosystem behaviour and particularly in harmful algae blooms in the region (Amorim et al., 2004). Sharp inner shelf flow reversals have been observed in other regions, but associated with upwelling regimes (Chant et al., 2004; Cudaback et al., 2005). Remotely forced disturbances propagating along the coast in the form of coastal trapped waves have been hypothesised to explain the variability of the nearshore velocity field off California (Hickey et al., 2003).

4.2. Influence of the terrestrial runoff

Lenses of low salinity water, with their source in river runoff into the coastal ocean, can result in buoyant plumes that develop into inshore currents. Most of the river outflow of the Iberian Peninsula occurs in the northern segment of the western Iberia. Several rivers drain between the latitudes of Lisbon and Cape Finis-terre, namely the Tagus, Mondego, Douro and Minho, and the Galician Rias rivers. There, a recurrent buoyant plume is observed, characterized by salinity values < 35.8 . This feature has been named the Western Iberian Buoyant Plume (WIBP) (Peliz et al., 2002). The WIBP in the neighbourhood of the rivers is identified in winter sea surface temperature satellite imagery from its low temperature signature compared to the shelf waters. On the other hand, during summer the plume waters are warmer than surrounding waters (Torres and Barton, 2007). The typical thickness of the low salinity lenses is about 20–30 m, and the offshore extension is variable. Both characteristics depend strongly on the shelf/slope circulation and surface forcing, mainly wind stress through Ekman dynamics and mixing. The dynamics of these buoyant plumes have been studied with theoretical and numerical models (see for instance Yankovsky and Chapman (1997)). Their interaction with wind forcing was studied for idealised cases by Fong and Geyer (2001) and detailed diagnostic studies of mixing in idealised plumes were done by Hetland (2005). During typical winter conditions, the prevailing south-westerly winds generate an onshore Ekman component of transport, convergent at the coast, and hence a saline front. The plume develops into a narrow (5–10 km) coastal current with strong poleward velocities. An extreme example of this behaviour on 4–6 March 2001 (Marta-Almeida et al., 2002) occurred when a discharge from the river Douro of up to $10,000 \text{ m}^3 \text{ s}^{-1}$ combined with strong southwesterly winds to generate poleward currents faster than 1 m s^{-1} .

In the case of upwelling conditions, which occur several times every winter, the Ekman surface transport advects the plume equatorward and offshore as part of the upwelling induced current, to more than 100 km offshore in a few days (one upwelling event). One example of this behaviour is detailed by Ribeiro et al. (2005) who relates the influence of a winter upwelling pulse on the distribution of chlorophyll-a. They estimate offshore velocities up to 29 km/day. Recently, Santos et al. (2004), studied a mechanism that allows the retention of the biological material contained in the low salinity plume in the presence of upwelling favourable winds during winter. The stratification induced by the plume provides the vertical retention mechanism, while the presence of the Iberian poleward flow at the slope acts like a barrier to hinder the offshore advection of the plume. Therefore, at the shelf break, the offshore Ekman transport forced by the winds generates a convergence region where the plume thickens and retains the biological material.

The buoyant plume can persist through the spring transition to summer upwelling conditions. Torres and Barton (2007) reported a complex circulation off Galicia in early summer following the onset of upwelling-

favourable winds, where poleward flow over the slope co-exists with coastal upwelling and strong outflow from the Rias. A coastally trapped branch of the poleward flow advects low salinity waters of the WIBP (Fig. 4, bottom right). Because of vernal warming, the buoyant plume was warmer than adjacent oceanic waters, in contrast to the winter situation when it is colder. The pattern observed here is similar to that observed by Sordo et al. (2001) for the end of the upwelling season (Fig. 4, bottom left). Even for the southern Iberian coast, Garcia-Lafuente et al. (2006) attribute the development of the summer inshore warm counter-current described by Relvas and Barton (2002) (Fig. 4, top) to the strong warming of coastal waters during the intertidal inland displacement in flat marshes in the Gulf of Cadiz. Whether or not the source of the inner-shelf counterflows is inland is an issue that needs further investigation.

5. Tides and internal waves

The oceanic tide interacts with the shelf/slope geometry and gives rise to intensification of tidal ellipses at the shelf and slope, which are characteristic features of the barotropic tide. On the other hand, the interaction of the barotropic tide with the stratification induces the so called internal tides, which are the origin of short-period internal waves, including strongly non-linear internal “solitary” waves (ISWs), frequently observed at the west coast of the Iberian Peninsula. In this section, an overview of these phenomena is described, divided for convenience in barotropic tides, internal tides and short-period internal waves.

5.1. Barotropic tides

Most of the modern studies on oceanic tides are performed with numerical modelling techniques, which are validated by comparison with tide gauge data, and current meters in a series of coastal and oceanic stations and moorings. With this methodology, the amplitudes and the phases for the main components of the tidal wave are well known (Fanjul et al., 1997).

The tidal wave propagation along the shelf/slope of the west coast of the Iberian Peninsula is dominated by the interaction of the oceanic Kelvin wave type tidal wave with bathymetric features, like canyons (Aveiro and Porto canyons, for instance) and Estremadura Promontory.

Recently, the detailed structure of the barotropic tides, with special emphasis on the tidal ellipses, and their horizontal and vertical structure, was discussed by Marta-Almeida and Dubert (2006). Tidal currents in the western Iberian coast are dominated by the semi-diurnal tidal components M_2 and S_2 , which give rise to clear spring-neap cycles modulated by other constituents. In some parts of the shelf like the Estremadura Promontory, diurnal harmonics, especially K_1 , assume a large importance, and significantly modify the tidal currents pattern in that region (Fig. 5). The topography of the shelf/slope of the western coast of the Iberian Peninsula is responsible for a large modification of the tidal ellipses in that region, namely an amplification, inversion of the sense of rotation, and polarization of the major axis of the ellipses, in the neighborhood of canyons, as visible in Fig. 5. Indeed, while the offshore oceanic tidal ellipses are primarily orientated parallel to the coast, along the S–N direction, in the neighborhood of the main canyon systems, the tidal ellipses are polarized with the major axis, almost perpendicular to the bathymetry.

For the diurnal ellipses this polarization effect is no longer visible, and the tidal ellipses are almost tidal circles, with significant values at the Estremadura Promontory, and between Aveiro and Porto canyons, due to the effect of diurnal amplification in presence of promontories.

5.2. Internal tides

Internal tides (also referred as Internal Tidal Waves, ITWs) are large-scale internal waves with tidal periods that are found in many shelf edge regions, in particular on the Iberian shelf (Jeans and Sherwin, 2001). They produce a distinct signature both in radar satellite images (Ermakov et al., 1998) and in ocean colour remotely-sensed images (da Silva et al., 2002). Bands of enhanced levels of near-surface chlorophyll (width of 30–50 km) in the central region of the Bay of Biscay (near 46°N, 7°W, where strong internal tides had been observed before) are associated with the crests of internal tidal waves travelling away from the shelf break. These signatures have been explained as likely to result from the uplifting of a subsurface chlorophyll

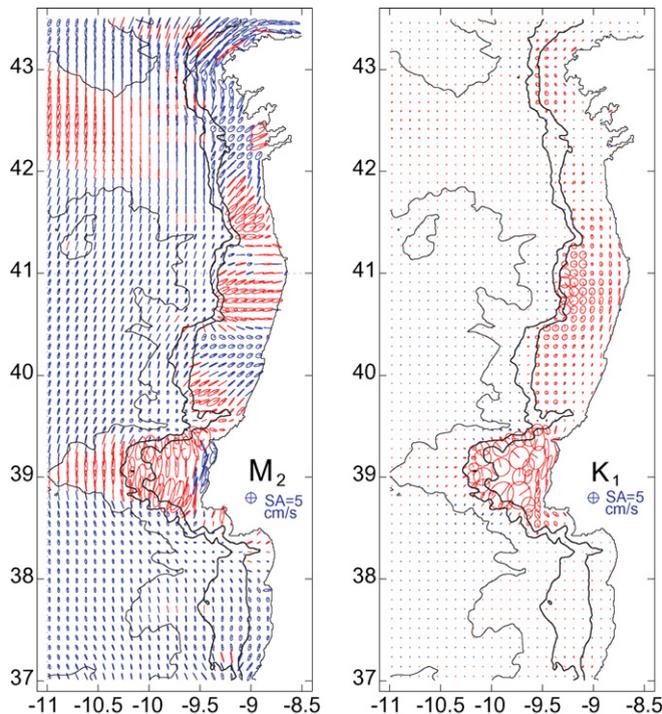


Fig. 5. Barotropic tidal ellipses of the tidal components: M_2 , and K_1 . Blue (red) ellipses means counterclockwise (clockwise) rotation. The radial line inside the ellipses gives the Greenwich phase (adapted from Marta-Almeida and Dubert, 2006).

maximum by the passing internal tides, to such a level that they may be “seen” by the satellite sensor. da Silva et al. (2002) have investigated SeaWiFS ocean colour images for those times when there were also near-coincident high resolution radar imagery. While the SeaWiFS sensor (with a 1 km resolution) is unable to detect the presence of short-period ISWs, the SAR (with a 25 m resolution) is able to image them. More recently, da Silva (unpublished data) found also examples of exact synergy between overlapping swaths of MERIS and ASAR ENVISAT data revealing similar patterns to those presented in da Silva et al. (2002). The vertical structure of the internal tide is characterized by pronounced isothermal depressions to about 110 m deep from a mean depth of about 50 m. These are the internal tidal troughs, whereas in between the thermocline rises to about 30 m deep in the internal tidal crests (these are typical depths for the Bay of Biscay). In the Bay of Biscay as well as in the Western Iberia, the ISWs propagate with approximately the same phase speed as the internal tide, and they may be considered as phase-locked to the internal tidal troughs, and correlated with quasi-coincident ocean colour data, revealing that bands of enhanced chlorophyll correspond to the internal tidal crests. The simple model used by da Silva et al. (2002) to explain their ocean colour observations is based on the assumption that the phytoplankton is passive to the internal wave motions and that a Deep Chlorophyll Maximum (DCM) often occurs in the summer when levels of surface nutrients, phytoplankton and chlorophyll have become depleted following the spring bloom, leaving behind a subsurface maximum near the thermocline. Recent *in situ* observations revealed that both assumptions are reasonable for the case of the Western Iberian Peninsula, suggesting that internal tides may have a significant role for biological processes, such as primary production.

A mechanism by which internal tidal waves may increase primary production in the upper pycnocline is by increasing the average light intensity experienced by phytoplankton near the pycnocline. Light intensity decreases exponentially with depth, and thus a passive phytoplankton cell undergoing vertical displacements by internal waves is exposed to an average light intensity that is greater than the light intensity at its average depth if there were no internal waves. Since near the thermocline the photosynthesis should be proportional to the total daily irradiance, resulting from the linear response to the dim light conditions near the euphotic zone,

the vertical motion introduced by internal waves may significantly enhance primary production. In fact, Lande and Yentsch (1988) derived a simple model to estimate the increase in average light intensity on phytoplankton cells that are passively displaced by a random field of internal waves in the upper pycnocline, the lower portion of the euphotic zone. For eutrophic waters such as off the Iberian Peninsula, the attenuation coefficient of PAR (Photosynthetic Active Radiation) is in the range $k = 0.10\text{--}0.20\text{ m}^{-1}$, and the factor by which internal waves increase primary production was estimated to be in the range 1.65–7.38. One of the objectives of the on-going project SPOTIWAVE-II is to explore further synergistic satellite observations of chlorophyll patchiness due to internal wave activity and verify the extent to which they result in an enhancement on primary production.

Baroclinic tides are still poorly known off western Iberia. The application of modeling techniques to the definition of their generation zones and characteristics, and the validation of the results through remote sensing with emphasis in SAR images, is a logical direction for future research.

5.3. Short-period internal waves

A SEASAT SAR image dated 20 August, 1978 (21:42 UTC), off the Portuguese coast in the region of Figueira da Foz and Aveiro, revealed surface manifestations of a large number of internal “solitary” wave trains. Within a packet the wavelength of these waves decreases with distance from the leading crest, indicating that they represent non-linear dispersive wave trains (see Fig. 6 for a typical example of internal wave patterns over the Portuguese shelf). These wave trains were initially interpreted to be generated by the action of the barotropic tide at the continental shelf break (Alpers, 1985). However, estimations performed by a two-layer nonlinear internal tide-generation-slice model, based on a numerical representation of K-dV dynamics (Gerkema, 1996), predicted an essentially linear internal tide response with an amplitude of only 1.5 m. Such internal tide could not, clearly, have generated the large non-linear features observed by satellite. Despite this single observation (SEASAT

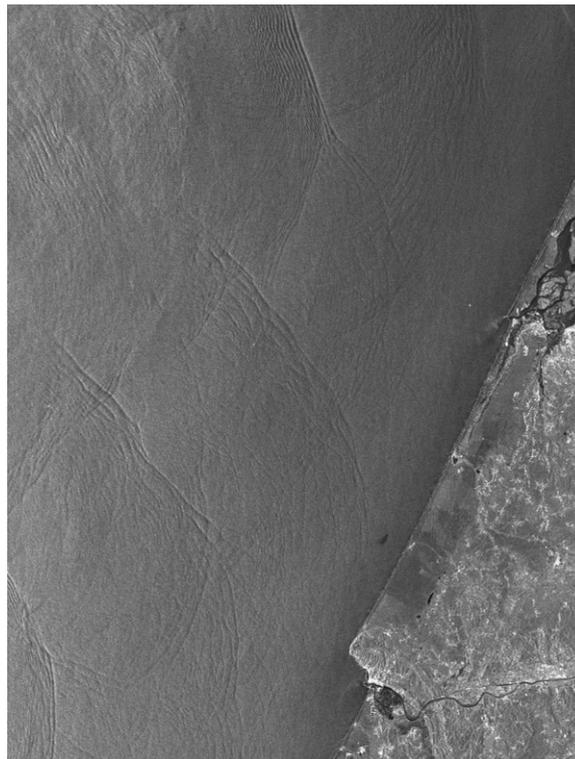


Fig. 6. ENVISAT ASAR dated 20 August 2004, acquired at 22:25 UTC off the west Portuguese coast (near Figueira da Foz), showing surface signatures of non-linear internal waves. The image width is about 100 km and internal wave inter-packet separation is approximately 25 km and crest length can exceed 55 km, for some trains.

ceased operation only three months after launch, in 1978), this was enough evidence to subsequently prompt a field campaign to make *in situ* measurements of high-frequency IWs over the shelf at 41°N. Observations were performed in August 1994, using thermistor chains, moorings and remote sensing techniques (Jeans and Sherwin, 2001; da Silva et al., 1998). Data obtained by the ship-mounted thermistor chains revealed the appearance of thermocline depressions at different points of the shelf with vertical displacements as large as 45 m. Observations from a month long thermistor chain mooring deployed in August 1994, showed that packets of large solitary-like internal waves occurred in every tidal cycle, spanning from neap to spring tides.

Sherwin et al. (2002) analysed the distribution of the barotropic tidal forcing in the studied area and demonstrated that along slope (but not across slope) interactions with bottom topography can be a major source of internal tidal energy and may explain why the signal observed at 41°N was so large. They calculated the horizontal distribution of the tidal forcing according to Baines (1982) and integrated through the water column for a full semi-diurnal tidal cycle. Their conclusion was that the short-period IWs observed propagating in the across slope direction at 41°N were actually a result of the internal tide that initially propagates into the ocean from a region of strong forcing found along the slope to the south of latitude 40.6°N, where the shelf break extends westward. These authors also showed that the internal tide undergoes refraction in the horizontal plane due to local variations in the phase speed, that were due to two factors: the buoyancy frequency $N(x, z)$ in the upper 150 m along 41°N decreased towards the shelf, and the pycnocline was wider and deeper in the ocean than it was at the shelf edge. These characteristics, which were explained by seasonal upwelling, originate a decrease in the phase speed for the first-mode internal tide between the open ocean and the shelf break, resulting in strong refraction patterns. The internal tide, which initially radiates seaward from the slope, is subsequently refracted back towards the shelf edge at about 41°N and propagates on-shore, and results in transformation into packets of non-linear internal “solitary” waves.

A similar methodology to that of Sherwin et al. (2002) was used by Azevedo et al. (2006) to study the generation of very strong internal solitary waves near Cape Finisterre that propagate into the southern Bay of Biscay. Unpublished results by da Silva (2006) also reveal that the tidal forcing is a good indicator of non-linear IW activity to the South of Estremadura Promontory. These methods, namely the depth-integrated body force of Baines (1982), and the examination of internal tidal ray paths, are now being applied to find hot-spots of internal wave generation off the Iberian Peninsula, which are also validated by satellite image data from the ERS and ENVISAT missions.

Short-period internal waves may also be important from a biological point of view, since their impact on the development and transport of plankton may be significant. Many species are dependent on some cross-shore advection transport mechanism to reach adult habitats, since they are very small and cannot control their cross-shore position by swimming long distances. Non-linear internal waves may produce a net transport of in-water particles (phytoplankton, zooplankton), which in the upper surface layer is usually in the same direction as the IW propagation (when the pycnocline displacements are of depression type, as it is the case off the west Iberian coast). Typical distances reached by such horizontal transport have been modelled by Lamb (1997) and are of the order of several km for a train of ISWs, which is particularly effective when transport by internal waves is “aided” by wind drift and/or plankton swimming in the direction of propagation of the wave (see also Shanks, 1995). Internal tidal bores have also been identified as an important mechanism of nutrient supply to the near-shore by Pineda (1991), who proposed a mechanism that produces upwelling by advecting subsurface water to the shoaling near-shore. Indeed, Pineda (1999) has found some evidence of larval accumulation at the leading edge of internal tidal bores, causing aggregation of organisms in slicks that would be effectively transported onshore, reach the adult habitat, and have an opportunity to complete their life cycle.

Zwolinski, Oliveira and Stratoudakis (IPIMAR, unpublished data) using acoustical signature of planktonic scattering layers observed during a fisheries acoustic survey over the western Portuguese shelf in Spring 2001, detect the propagation of internal waves in the echograms and characterised the wave packets in terms of wave number, amplitude and length. The coherence of the high resolution acoustic images enabled to infer the circulation within the wave packets, pointing towards the existence of trapped zooplankton cores that accumulate and are transported in the wave direction, concluding that internal waves are likely to be an important transport mechanism for planktonic organisms off Western Iberia, between spring and autumn, confirming the results obtained by other authors (Helfrich and Pineda, 2003).

6. Extra-coastal and subsurface circulation

A unique feature of the West Iberian hydrography is the presence at intermediate depths (centered at ~ 1000 m) of a relatively warm and salty water mass, resulting from the mixing between the Atlantic Intermediate Water and the Mediterranean Water (MW) flowing through the Strait of Gibraltar (e.g. Ambar and Howe, 1979). Initially interpreted to be a result of advection and/or eddy diffusion processes (Needler and Heath, 1975), the discovery of isolated vortices containing water of Mediterranean origin, named “Meddies” (McDowell and Rossby, 1978), has challenged the classical interpretation of how the MW is spread in the Atlantic (e.g. Armi and Stommel, 1983; Richardson et al., 1989; Danialt et al., 1994; Mazé et al., 1997).

The main effect of the Mediterranean Outflow is to generate a dramatic salinity-driven (in excess of 2.4 salinity units) density plume. This plume is bottom advected, and a few tens of kilometers off the strait it accelerates up to velocities in the order of 1 m s^{-1} . At this point, strong mixing occurs and the volume of the plume grows significantly from about 0.7 Sv at the exit of the strait to about 2 Sv in the eastern part of the Gulf of Cadiz (based on the estimates of Baringer and Price, 1997). West of this point, the entrainment of Atlantic Central Water continues, but at reduced rates (e.g. Serra et al., 2005).

According to modelling results this process impacts the circulation of the whole Eastern North Atlantic. Jia (2000) proposes the entrainment of the North Atlantic Central Water as an alternative or complementary mechanism beyond the generation of the Azores Current. Özgökmen et al. (2001) present a process oriented study where the connection between the Mediterranean Outflow and the Azores Current is investigated. The authors use simplified dynamics (a $1\frac{1}{2}$ layer model) and show that the process of entrainment in the Gulf of Cadiz can be approximated to a steady potential vorticity source at the upper-ocean layer. The response of the upper layer to the loss of mass that corresponds to the entrainment is the formation of a cyclonic eddy of limited meridional extent but that grows westward, until it is bounded by the western margin. This process explains the Azores Current and its associated countercurrent also frequently referred in literature (e.g. Ríos et al., 1992; Alves et al., 2002). The established horizontal circulation is about one order of magnitude greater than the transport needed to fill the entrainment process, which fits other transport estimates and studies about the recirculation inside the Gulf.

Mauritzen et al. (2001) show this recirculation to be a crucial factor for the development of the anomalous salty Central Water of the Eastern North Atlantic. Laboratory studies described in Mauritzen et al. (2001) demonstrated that the Mediterranean Outflow is prone to strong Kelvin–Helmoltz instabilities that enhance the vertical diffusion and mixing with Central Water. In laboratory conditions, this mixing induces the generation of a lighter but saltier Central Water. The authors termed this process ‘detrainment’ and speculate that in real ocean both processes (entrainment/detrainment) can coexist. The authors hypothesise that the saltier (detrained) waters in the eastern Gulf of Cadiz are advected offshore by the Azores Current recirculation and feed the high salinity anomaly of the Central Water.

This latter work supports the idea that the circulation inside the Gulf of Cadiz is associated with the entrainment and detrainment but is larger (~ 5 Sv) than the actual values needed to feed these processes (~ 2 Sv – values from Mauritzen et al., 2001) and call for a larger horizontal recirculation. Some observational evidence is presented in Mauritzen et al. (2001), which suggests a recirculation and westward flow south of Portugal. However, very few data and modelling studies address this circulation feature. On the other hand, the transport into the Mediterranean (the Atlantic Inflow) is also subject of present research. Recent estimates (e.g. Tsimplis and Bryden, 2000; Baschek et al., 2001) show that a relatively steady inflow of ~ 0.8 Sv enters the Mediterranean. The connection of this flow with the Gulf of Cadiz circulation is unknown. Recent measurements reported in Garcia-Lafuente et al. (2006) show a continuous current structure circulating anticyclonically along the northern slope of the Gulf of Cadiz suggesting a connection between the western slope of the Gulf and the Strait of Gibraltar. Recent modelling developments (Serra et al., 2005; Peliz et al., 2006) suggest that the water that feeds the inflow might originate from the north (anticyclonically along the slope) and not from the west deep ocean as some large scale studies suggest (e.g. Paillet and Mercier, 1997).

In the western part of the Gulf of Cadiz, in the vicinity of the Portimão Canyon, the Mediterranean Outflow stops its descent phase and gives rise to the Mediterranean Undercurrent stabilized at about 1200 m. Bower et al. (2002) analyse an extensive float record and describe the Mediterranean Undercurrent, the

generation of Meddies and lateral spreading of Mediterranean water by processes other than Meddies (an extensive review of Meddies is presented in Richardson et al., 2000). The authors show that the Mediterranean Undercurrent past Cape São Vicente is rather weak ($\sim 0.06 \text{ m s}^{-1}$) and broad when compared with the flow upstream ($\sim 0.2 \text{ m s}^{-1}$). The Cape São Vicente is one of the preferred locations for Meddy generation but other sites like Portimão Canyon and Gorringe Bank (Serra and Ambar, 2002) Estremadura Promontory (Bower et al., 1997), or even in the northwest part of Iberia between Cape Finisterre and Cape Ortegal (e.g. Paillet et al., 1999) also give rise to Meddies. After the generation off southwest Iberia, Meddies first propagate northwest near Gorringe Bank and then turn south–southwest, west of the Horseshoe-seamount system. This path is also apparent in non-Meddy floats. Some of the floats not caught by Meddies show circulation features that indicate a strong correlation with nearby Meddies.

Very few events of float propagation north of Estremadura promontory have been observed (Richardson et al., 2000; Colas, 2003). Sparrow et al. (2002) separate Meddy from non-Meddy floats to show that south of 36°N the background flow is weak and incoherent, whereas to the north of that latitude the background flow is significant and oriented northwestward. On the other hand, the Meddies propagate southward and no northward Meddy propagation is observed. The authors hypothesize that the Mediterranean water spreading south of 36°N is due to Meddy propagation and to background flow north of that latitude. The authors speculate that the two regimes of MW spreading are separated by the Azores Current.

The eddies may also be associated with a dipolar structure (e.g. Serra and Ambar, 2002; Serra et al., 2005; Carton et al., 2002) in which case the Meddy is accompanied by a cyclone. These dipolar eddies show a much faster evolution and can trigger Meddy propagation towards far regions or substantially increase the mixing of the Meddies with background water through stirring. All studies agree that although Meddies are intermediate water features they can have a signature at the surface. Recent analyses of Meddies south of Iberia show Meddies to have velocities up to 0.1 m s^{-1} near surface (Carton et al., 2002). Vertical coupling between floats placed at different depth in Meddy sites show that some Meddies induce rotation up to shallower levels (Serra and Ambar, 2002). They also influence the surface topography (Stammer et al., 1991; Pingree and Le Cann, 1993; Oliveira et al., 2000, 2004). It is expected that the off-shelf surface circulation is influenced by the MW flow at intermediate depths and that surface Meddy flow interacts with other along slope circulations. A possible example of this type of interaction is presented in Peliz et al. (2004).

Though a significant understanding of Meddy generation has been achieved there is still need for research in the field of intermediate-surface circulation coupling both in the sense of the background flow and of the mesoscale activity. It is also interesting to note that the expected dispersion of Mediterranean Water north of 40°N is not clear in the lagrangian measurements (Colas, 2003).

7. Conclusions and challenges

As concluding remarks, a number of challenges can be identified on the basis of the present review.

An emerging view that needs to be addressed is that the slope poleward flow is not exclusive to the winter circulation but that it persists year round off western Iberia. The presence of a poleward flow along the Iberian margin outside the upwelling season (from September–October till April–May) is a well established characteristic of the western Iberian ecosystem. There is some evidence that this surface poleward flow exists all year, shifted offshore and coexisting with the equatorward flow associated with the upwelling, but definitive observations are lacking.

While the continuity of the surface poleward flow along Iberia and into the Cantabrian Sea appears well established, its southern extent in the Gulf of Cadiz and further south remains unknown. Ample evidence of a sub-surface countercurrent has been compiled at locations along the NW African coast (Barton, 1998), but little is known of its temporal variability or alongshore continuity, and in particular it is unknown whether any linkage of the poleward flow exists across the Strait of Gibraltar.

Poleward flows over the inner shelf are also characteristic of the circulation off western Iberia. They have been identified during upwelling relaxation events by their thermal contrast with the cooler equatorward upwelling jet in infrared satellite imagery. In conjunction with the offshore poleward flow they develop a double frontal structure, with the cold upwelling jet interleaving between the inner shelf and

the offshore warmer poleward flows. Direct measurements document their occurrence during winter too, when they may be colder than surrounding waters because of their origin in terrestrial run off. Poleward flow over the slope and near-shore on the shelf are not necessarily related. The former appears to be mainly driven by large scale meridional pressure gradients, as discussed earlier, while the latter may be a result of more local forcing by freshwater outflows (Peliz et al., 2005) or by set-up in gulfs (Relvas and Barton, 2005). The nature of the inner-shelf circulation, its origin, its relation with the outer shelf waters, especially with the cold upwelled waters, and its ecological implications are important questions that need further research.

The latest results indicate that, although traditionally seen as a relatively stable season, winter is a period when significant mesoscale variability is superimposed on the climatological circulation. The transition zone between the coastal and open ocean waters is a complex area populated by interacting transient and recurrent mesoscale features and fronts. Buoyant plumes associated with terrestrial runoff seem to play an important role in the nearshore oceanography, influencing stratification, phytoplankton patterns and larval fish survival (Santos et al., 2007). Upwelling events have been reported to occur also during winter. The ecological impacts of this winter dynamics in egg and larvae distributions and survival is a promising topic (e.g. Santos et al., 2007).

Internal waves have been observed off western Iberia and their signature observed in SAR imagery. The effect on near-surface chlorophyll distributions has been identified in ocean color satellite images. The vertical displacement the cross-shore advection, and particularly the turbulence produced by short-period non-linear internal waves may have a significant role in biological processes. How much internal wave activity enhances primary production, where its hot-spots are located, and what is the relative efficiency of the “local”, as opposed to other, generation mechanisms are outstanding problems requiring resolution.

There is evidence that the subsurface circulation, closely linked to the presence of Mediterranean waters at intermediate levels, exerts significant control on the upper layer hydrography and dynamics off southwestern Iberia. Recent results show that Meddies can form a signature in the surface topography and vorticity patterns. Modelling efforts suggest that the existence of the Azores Current depends upon the Mediterranean outflow. Recent ideas point to a relation between the Mediterranean outflow and the upper layer circulation in the northern part of the Gulf of Cádiz. However, a satisfactory understanding of the coupling between subsurface and surface circulation requires further research. Future research should also bring new insights on the influence of climatic fluctuations of Mediterranean Water outflow and interannual variability of the atmospheric forcing on the poleward current and upwelling system off Iberia.

The present view of the ocean off the western Iberian Peninsula is that the ecosystem behaviour is largely governed by the mesoscale activity, superimposed on the large scale climatology (see also Santos et al., 2007; Queiroga et al., 2007). Interleaving alongshore slope, shelf and coastal currents, eddy interactions with the alongshore circulation, buoyant plumes, upwelling filaments and fronts, impacts of the subsurface circulation on the upper levels and internal waves all have their effect on the ecosystem. Although the scenario presented in this paper is based on recent work in the region, many of the hypothesised interactions need further exploration. Most of the work reviewed here is based on event-scale studies over limited spatial scales, while the long term structure and variability is poorly sampled. The available large scale remote sensing observations of sea surface temperature and ocean topography, as well as modelling studies, point to the important role of the mesoscale dynamics in the ecosystem functioning. Future research should implement regional scale experiments aimed at the acquisition of coherent data along the western Iberian margin. Comparative studies of relatively long time series would permit more definitive conclusions. Systematic *in situ* observations, a requirement for the improvement of modelling efforts, the implementation of operational oceanography and the testing of these ideas, provides an important challenge for the future.

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