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The Gulf of Cádiz pelagic ecosystem: A review

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Abstract

The Gulf of Cádiz, strategically situated between the North Atlantic Ocean and the Mediterranean Sea, has been the focus of attention of a few oceanographic studies dealing with the deep circulation in order to understand the dynamics of the dense plume of Mediterranean water. Much less attention has been paid to the surface pelagic layer which holds important living resources of commercial and ecological interest. This overview summarizes the recent advances that have been made concerning the regional oceanography of the northern half of this important basin from an interdisciplinary point of view. Probably the most relevant oceanographic feature of the basin is its strong seasonality, which is linked to the meteorologically-induced seasonality of the eastern boundary current system of the North Atlantic. The prominent cape Santa Maria divides the continental shelf off the southern Iberian Peninsula in two shelves of different shape that hold different oceanographic processes, which in turn determine the characteristics of the pelagic ecosystem. Mass and energy inputs from land as well as tidally-driven processes makes the wider eastern shelf be more productive while the narrower western shelf, cut by a sharp submarine canyon, is under the influence of the almost-permanent upwelling spot off cape San Vicente. Under easterlies, the west-going, warm coastal countercurrent that is observed in the eastern shelf may invade the western shelf thus connecting biologically both shelves in an east-to-west direction. Westerlies induce generalised upwelling off the southern Iberia Peninsula, which adds to the almost-permanent one off cape San Vicente and generates an upwelling jet that moves eastwards. Cape Santa Maria may deflect this flow by generating a cold filament that extends southward and diverts water from the western shelf to the open ocean. This pattern of circulation hampers the biological connection between shelves in the west-to-east direction, which is therefore less effective. The eastern shelf is prone to hold a cyclonic circulation cell during summer. This cell seems to be part of the reproductive strategy of fish species like anchovy with significant commercial interest in the region. The coupling between spawning and circulation is particularly beneficial under westerlies, when productivity in the eastern shelf is enhanced and the plankton is confined within the cyclonic cell. Easterlies favour oligotrophy and the westward export of plankton, which has an adverse effect on the recruitment and correlates low anchovy catches with periods of noticeable easterly intensity.

Keywords: Seasonal variations; Upwelling; Subsurface chlorophyll maximum; Anchovy; Surface circulation; Continental shelf; Cape Santa Maria; Cape San Vicente; Guadalquivir River

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1. Geographical frame

The Gulf of Cádiz (GoC hereinafter) is the basin that connects the North Atlantic Ocean and the Mediterranean Sea. The north, east and south boundaries of the basin are the Iberian Peninsula and Northwest African coasts whereas the west boundary is not well defined. The 9°W meridian running through Cape San Vicente (CSV hereinafter, see Fig. 1) would be a good choice for delimiting the GoC to the west. CSV is a sharp topographic feature where the shoreline changes orientation from north to east at almost right angle, separating the oceanographic regime west of Portugal from the more peculiar regime of the GoC. The prominent cape Beddouzza, close to CSV longitude, could be considered a nominal southern limit.

This paper focuses on the northern GoC, roughly speaking the area north of 36°N (the latitude of the Strait of Gibraltar). In addition to CSV, this area has two other noticeable capes, Santa María (CSM hereinafter) and Trafalgar. CSM is an abrupt break off where continental shelf hardly exists. The continental shelf extends offshore to depths of around 100 m where the shelf slopes down and the continental slope begins. It is divided by CSM in two different portions with distinct characteristics. West of the cape, the continental shelf is narrow (around 15 km), it is cut by the pronounced Portimao submarine canyon (see Fig. 1) and there are hardly any inputs of continental freshwater. East of the cape, on the contrary, the shelf widens (around 50 km) and important rivers like Guadiana, Guadalquivir, Tinto and Odiel (Fig. 1) feed it with freshwater and other dissolved or suspended substances from the continent. East of Cape Trafalgar the shelf narrows again as the GoC faces its eastern limit at the strait of Gibraltar.

2. The Gulf of Cádiz and the North Atlantic circulation

The role in the global circulation and climate of the Mediterranean waters, and its connection to the Atlantic across the Strait of Gibraltar and the GoC, has been and still is controversial. Consequently, the deep circulation in the GoC has been the focus of attention of many oceanographic studies whereas surface features, more tightly connected to primary and secondary production, are less known. Because of its location, surface circulation at the GoC is linked to the northeastern part of the North Atlantic subtropical gyre formed by the Azores current, which is a zonal meandering flow that stretches across a large extent of the North Atlantic, and the equatorward, slowly-moving Canary current that represents the eastern boundary of the Sverdrup circulation. According to several authors (Jia, 2000; Johnson and Stevens, 2000), the Strait of Gibraltar is critical for the formation of the Azores current, not only because the need of feeding the inflow of Atlantic water into the Mediterranean Sea but also, and more importantly, due to the presence of the energetic plume of Mediterranean water in the GoC. The typically 1 Sv of dense, salty water overflowing the sills of Gibraltar (Lacombe and Richez, 1982; Bryden et al., 1994; Baschek et al., 2001; García Lafuente et al., 2002) increases by a factor of 3 near CSV due to the entrainment of the overlying North Atlantic Central Water (NACW) along the GoC (Ambar and Howe, 1979; Baringer and Price, 1997). The entrainment represents a sink to the upper layer in the GoC and the flow of entrained water, along with the net surface inflow into the Mediterranean Sea which is typically 1 Sv as well (Lacombe and Richez, 1982; Bryden et al., 1994; Baschek et al., 2001; García Lafuente et al., 2002), are responsible for the eastward penetration of the Azores current. The numerical experiments by Jia (2000) and Johnson and Stevens (2000) show that the eastward extent of the Azores current is strongly reduced if the Strait of Gibraltar is closed.

3. Seasonal cycles in the basin

3.1. Circulation

The surface circulation in the GoC is affected by the seasonal fluctuations of the North Atlantic subtropical gyre. The size and position of this gyre follows the displacements of the Azores atmospheric high, which extends northwards in summer and reduces its size in winter. Following these fluctuations, the eastward-flowing Azores current would flow at a latitude greater than the GoC latitude when the North Atlantic subtropical gyre is large, whereas it would be displaced to the south when the subtropical gyre diminishes the size. This seasonality is mirrored by the circulation along the eastern boundary of the mid-latitude North Atlantic. An

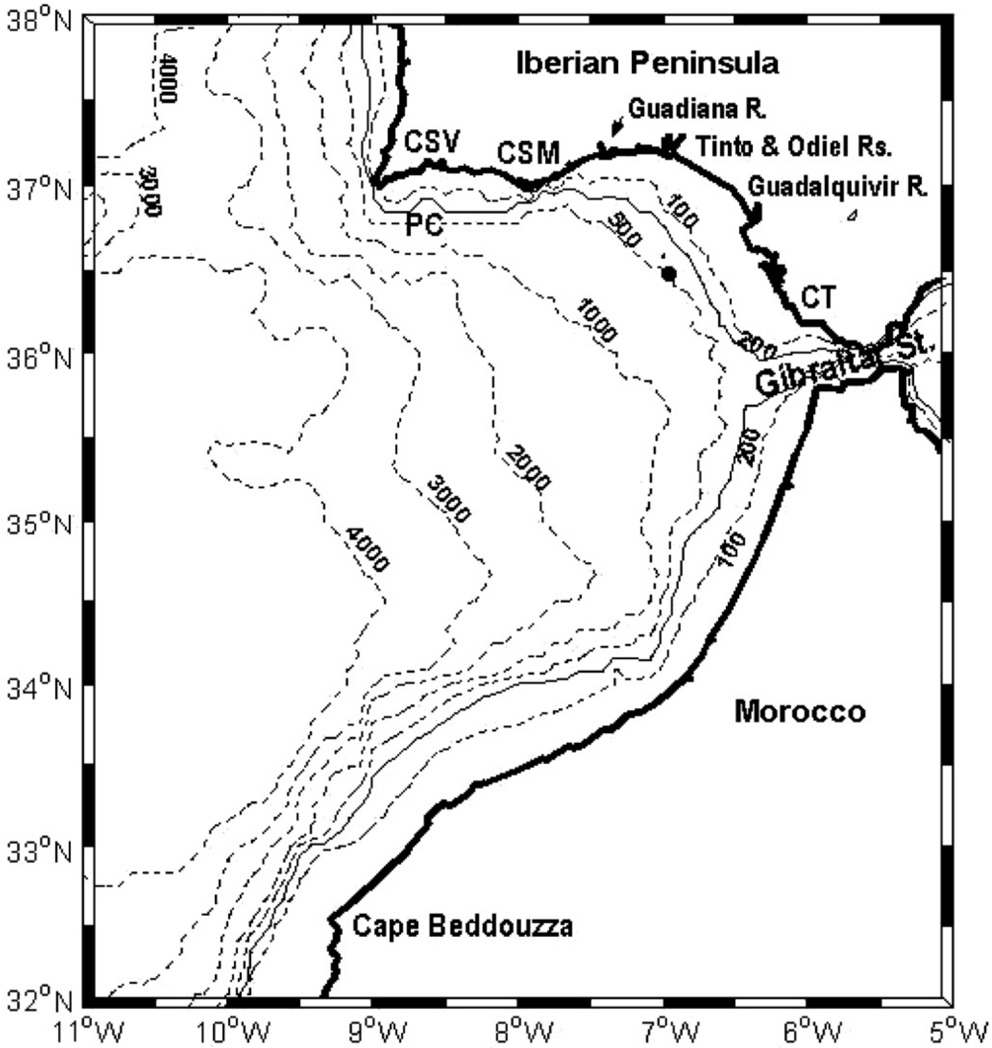

Fig. 1. Map of the Gulf of Cádiz showing the bathymetry and the most important coastline features. CSV, CSM and CT stand for cape San Vicente, cape Santa Maria and Cape Trafalgar, respectively. PC indicates the position of Portimao submarine canyon. The position of the *Red de Aguas Profundas* (*RAP*) oceanographic buoy has been marked with a solid circle.

example is the winter appearance of the Poleward Current flowing northwards at the surface along the Portuguese coast (Frouin et al., 1990; Haynes and Barton, 1990), which is replaced by the equatorward upwelling jet during the upwelling season from May to October (Wooster et al., 1976; Fiúza et al., 1982; Haynes et al., 1990; Peliz and Fiúza, 1999).

Obviously, the GoC circulation is sensitive to these large-scale variations. Relvas and Barton (2002) suggest that, when the upwelling jet formed in summer reaches CSV, it spreads preferably to the east along the shelf break and slope of the northern part of the GoC, providing a generalised anticyclonic circulation in the basin. Other less preferred directions for the spreading are southward and westwards, developing cold filaments anchored near the cape. The extensive analysis of the GoC surface circulation carried out in May 2001 (Criado Aldeanueva et al., 2006) depicts a clear pattern of anticyclonic circulation (Fig. 2) and illustrates the first situation. Part of the flow entering the GoC feeds the Atlantic surface inflow into the Mediterranean Sea and part recirculates anticyclonically to merge with the Azores and Canary currents further south (Fig. 3). Other oceanographic surveys carried out in spring–summer (Ochoa and Bray, 1991; García et al., 2002) indicate similar anticyclonic circulation as does the spring–summer climatological analysis by Sánchez and Relvas (2003).

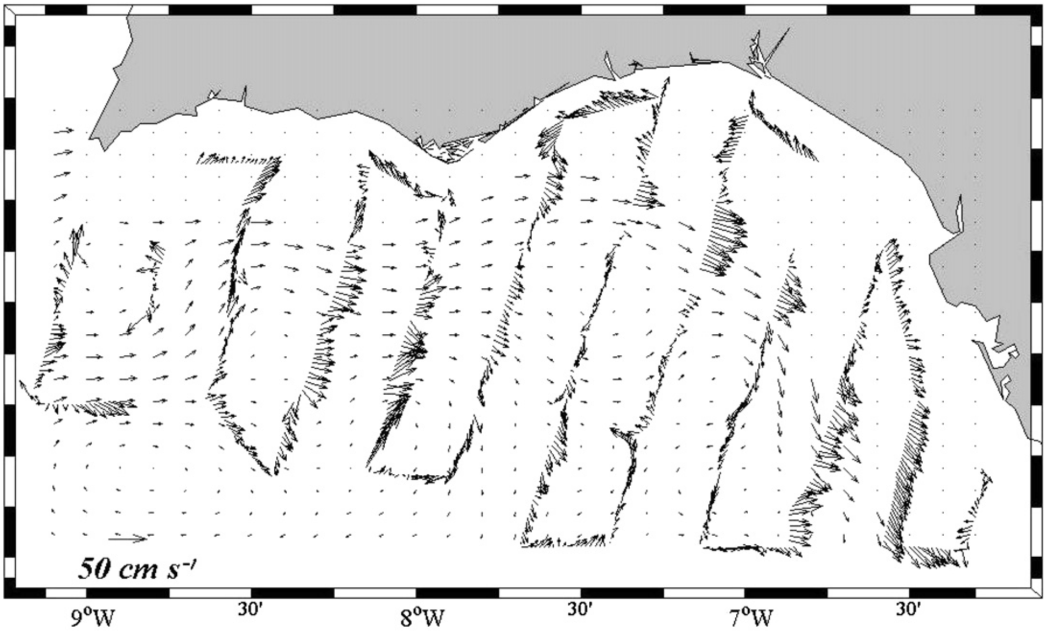

Fig. 2. Acoustic doppler current profiler (ADCP) velocities at 18 m depth during May 2001 (outcropped arrows along ship path) and geostrophic currents relative to 300 m depth (gridded arrows).

These results cannot be generalised due to the scarcity of observations in winter, even when the sea surface temperature (SST) based study by Vargas et al. (2003) suggests anticyclonic circulation throughout the year.

The SST study by Folkard et al. (1997) and the numerical model by Jia (2000) show that the surface flow into the Mediterranean through the Strait of Gibraltar comes from the interior of the GoC in winter, which is suggestive of cyclonic circulation along the northern GoC during this season. Other studies like that by Mauritzen et al. (2001) based on data collected in October 1995 also report cyclonic circulation with surface waters flowing westwards along the northern boundary. A similar circulation is suggested by the geostrophic analysis

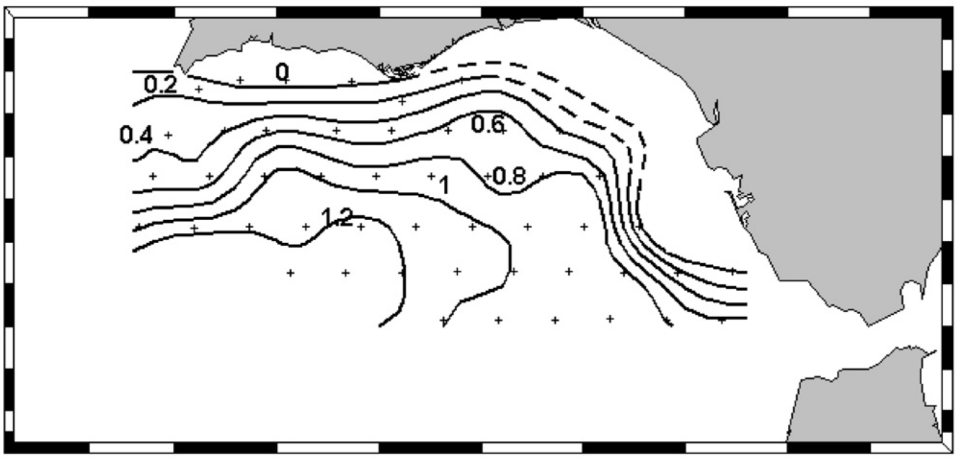

Fig. 3. Geostrophic transport in Sv (1 Sv $= 10^6\ m^3\ s^{-1}$) during May 2001 computed from geostrophic velocities relative to 300 m (figure adapted from Criado Aldeanueva et al., 2006).

of CTD data collected in September 1997 and January 1998 by Ambar et al. (2002), although this result is inconclusive since the main focus of their paper was the Mediterranean outflow and little attention was paid to the surface circulation.

Therefore, the pattern of the large scale circulation in the GoC seems to be anticyclonic in summer with probability to switch to cyclonic in winter. The model of the northern Canary Current system by Batteen et al. (2000) is suggestive of this bimodality, showing anticyclonic circulation in spring–summer and less clear but cyclonic-like circulation in winter. The simple quasi-geostrophic model of the mid-latitude eastern North Atlantic by Machín et al. (2006) shows that the bimodality follows the changes of the large-scale wind patterns, being likely related to the seasonal changes of the geographical position of the Azores current mentioned previously. Surface currents at 5 m depth observed in 36.48°N, 6.96°W (*Red de Aguas Profundas* – RAP – of Puertos del Estado, Spain; see Fig. 1 for location and http://www.puertos.es for further details) also points to seasonal alternation (Fig. 4) with nearly permanent anticyclonic circulation along the northern continental slope of the GoC only interrupted for short periods in winter.

An anticyclonic circulation provides an oceanographic connection between the continental shelf of the northern GoC (at least the eastern continental shelf) and the Alborán basin in the Mediterranean Sea. The connection is achieved by advection of biogeochemical products residing in the eastern shelf along the northern half of the anticyclonic meander that feeds the Atlantic inflow, which is in contact with, or closer to continental shelf waters. Obviously, the connection is unidirectional from the northern GoC towards the Mediterranean Sea. Because the pattern of surface circulation is subjected to a seasonal switch, the oceanographic connection between both areas is as well, spring–summer being the favourable season, while in winter

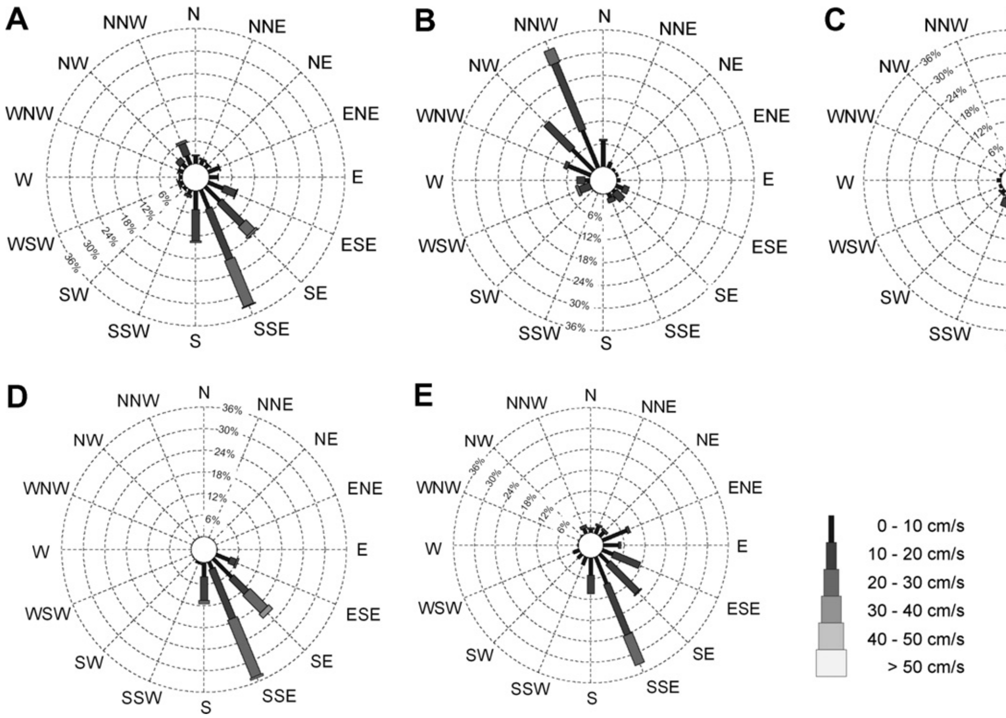

Fig. 4. Rose of the subinertial currents recorded by the RAP oceanographic station during year 2002 (tidal currents, which are very small, have been removed). Panel A: annual; Panel B: winter (December 2001–February 2002); Panel C: spring (March–May); Panel D: summer (June–August) and Panel E: autumn (September–November). The annual rose shows the clear dominance of southeastward surface current, the expected direction for anticyclonic circulation in the northern Gulf of Cádiz. The spring, summer and autumn roses indicate that southeastward is practically the only direction during these seasons, a fact that is strictly true during summer. Current directions are to the northwest in winter suggesting a reversal of the basin-scale surface circulation during this season. It must be noticed however that, although reversals are usual in winter, the winter of year 2002 seems to be somewhat of an exception, with more persistent northwestward currents than other winters.

the substances advected by the inflow would come preferably from the southern GoC (the African shelf) if the circulation changes to cyclonic.

3.2. Chlorophyll

3.2.1. Surface distribution

The likely presence of a winter pattern of cyclonic circulation in the open waters of the GoC does not result in high primary production in the basin. The low winter radiances and the strong zonal winds blowing over the basin at this time of the year (Ruiz et al., 2006) produce deep mixed layers and keep phytoplankton growth rates at very low values of about 0.01 d^{-1} because of light limitation (Navarro and Ruiz, 2006). Low growth rates prevent the existence of high chlorophyll concentrations during this period although maximum values are achieved in late winter (Fig. 5). Photoadaptation is also regarded as a potential origin of winter maxima for satellite chlorophyll in the open ocean but in regions where the seasonality of surface nutrients is less pronounced (Letelier et al., 1993; Winn et al., 1995).

The existence of an open ocean maximum in late winter is noteworthy for a basin geographically located in an eastern boundary current where upwelling favourable winds occur in summer. This seasonality is akin to the North Atlantic Gyral Province (Longhurst, 1998) and resembles the open-ocean dynamics of other eastern boundary upwellings like that off Chile, where satellite chlorophyll peaks in winter rather than in the upwelling season (Yuras et al., 2005). Summer winds off the Iberian Peninsula generate a cold and productive equatorward upwelling jet along the western Portuguese coast. Summer is also the season when the production at the Eastern (Canary) Coastal Province of the North Atlantic is at its maximum (Longhurst, 1998). The lack of a chlorophyll maximum in the GoC during the upwelling season reflects the uncoupling generated by the abrupt change in the shoreline direction at CSV. This topographic feature makes the GoC separate the Iberian upwelling from the upwelling off northwest Africa. Therefore, the GoC divides the North Atlantic Coastal Province in two sectors (European sector and African sector) separated by an intrusion of warm and oligotrophic water that interrupts the band of cold and nutrient-rich upwelled waters. The prevailing anticyclonic circulation of the GoC during summer also contributes to generate this peculiar regime by adding a downward tilting of isopycnals to the seasonal heating of the water column.

3.2.2. Chlorophyll vertical distribution

The seasonal cycle of the basin shows significant modification of the vertical distribution of chlorophyll throughout the year. During winter, the water column undergoes deep mixing during wind bursts and a chlorophyll-maximum is not manifested neatly at any depth of the water column (Navarro et al., 2006). The mixed-layer depth reaches 150 m at this time of the year (Fig. 5A) in agreement with the typical values of

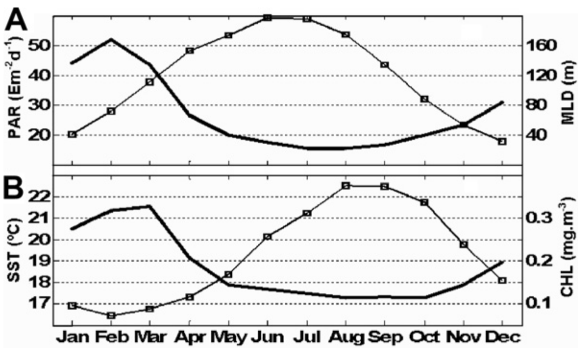

Fig. 5. Monthly averages of sea surface temperature (SST), photosynthetic available radiation (PAR), mixed layer depth (MLD), and satellite chlorophyll (CHL) for open ocean waters in the GoC. Values for SST, PAR and CHL were obtained from AVHRR and SeaWiFS data according to the methods in Navarro and Ruiz (2006). Values for MLD were obtained from Kara et al. (2003). Panel A shows PAR (thin line with squares) and MLD (thick line). Panel B is SST (thin line with squares) and CHL (thick line).

the North Atlantic Gyral Province (Longhurst, 1998). The NACW affected by this mixing is modified by surface processes such as shortwave absorption or heat exchange with the atmosphere, changing its thermohaline characteristics as well as its nutrient content.

The isopycnal $\sigma_t = 26.66\ \mathrm{kg\,m^{-3}}$ represents the lower limit of the NACW modified by the seasonal cycle: water lighter than $26.66\ \mathrm{kg\,m^{-3}}$ is modified by surface processes while water heavier is not (Navarro et al., 2006). Although this limiting value is originated during winter mixing, it has a significant role in the vertical distribution of chlorophyll during summer. In summer, the water column becomes stratified and a subsurface chlorophyll maximum (SCM) develops. Navarro et al. (2006) demonstrate that the vertical location of the SCM in the GoC is not connected either with the sharp density change at the bottom of the mixed layer as some authors suggest (Mann and Lazier, 1996; Longhurst, 1998) or with the depth where light reaches the compensation point for phytoplankton, as other authors have proposed (Tett et al., 2002; Fennel and Boss, 2003). In this basin, the SCM and the maximum gradient of nutrients are associated with the $\sigma_t \approx 26.66\ \mathrm{kg\,m^{-3}}$ surface, regardless of its geographical position, its depth, or whether the $26.66\ \mathrm{kg\,m^{-3}}$ surface coincides with the bottom of the mixed layer or with the compensation point.

Navarro et al. (2006) propose a novel but simple model to explain this feature in the GoC (Fig. 6), which can probably be extended to the entire North Atlantic Gyral Province. The model is based on the concept that the vertical location of the SCM cannot be explained without considering the history, i.e., the seasonal cycle, of the water column (Fig. 6). The thermohaline characteristics of the NACW lighter than $26.66\ \mathrm{kg\,m^{-3}}$ are homogenized during the winter mixing, when the mixed layer is thickest. Nutrients within this density-homogeneous layer are progressively consumed because the level of sun radiation, although low, is still enough to make feasible a low positive phytoplankton growth. The progressive growth generates a late-winter maximum of surface chlorophyll. By the end of winter, the surface layer with $\sigma_t < 26.66\ \mathrm{kg\,m^{-3}}$ is depleted of nutrients, and $\sigma_t = 26.66\ \mathrm{kg\,m^{-3}}$ becomes the isopycnal where the maximum nutrient gradient (and, therefore, nutrient flux) is initially located for the incoming spring–summer season. The SCM starts to develop in this gradient, a development that is reinforced concomitantly by the phytoplankton's consumption of upward-diffusing nutri-

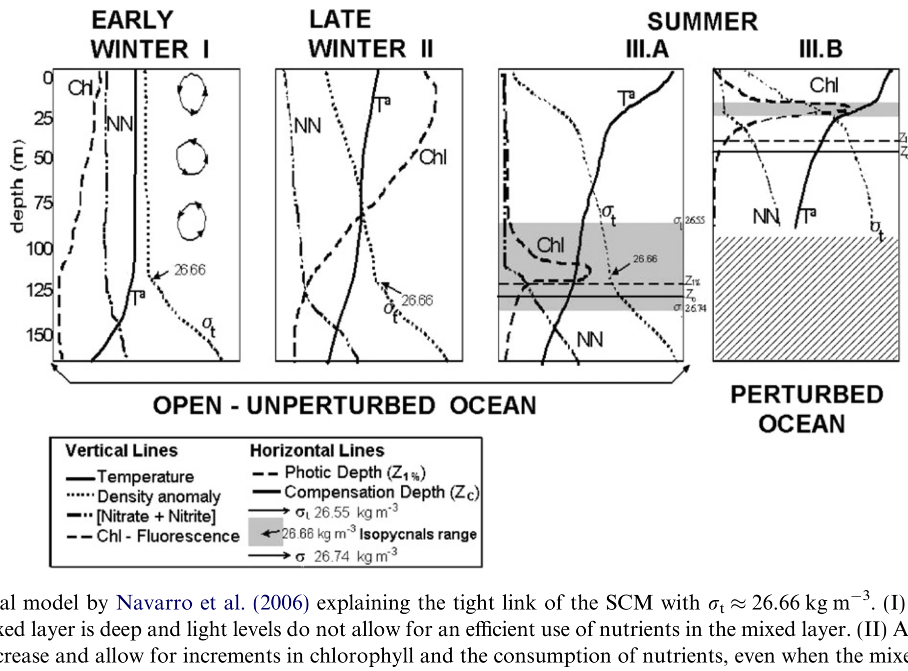

Fig. 6. Conceptual model by Navarro et al. (2006) explaining the tight link of the SCM with $\sigma_t \approx 26.66\ \mathrm{kg\,m^{-3}}$. (I) In early winter the bottom of the mixed layer is deep and light levels do not allow for an efficient use of nutrients in the mixed layer. (II) As winter progresses, the light levels increase and allow for increments in chlorophyll and the consumption of nutrients, even when the mixed layer is still thick because of the wind conditions in the GoC. The entire mixed layer becomes nutrient-depleted by this time of the year and the σ_t at the bottom of this winter layer becomes the interface separating waters exhausted of nutrients from those that are not. (III.A) The nutricline is fixed at this σ_t along the remainder of the seasonal cycle. (III.B) Further modifications of the depth $\sigma_t \approx 26.66\ \mathrm{kg\,m^{-3}}$ are followed by the SCM (figure adapted from Navarro et al., 2006).

ents. This positive feedback makes stable the connection between the SCM and $\sigma_t \approx 26.66\ \mathrm{kg\ m^{-3}}$ and explains the locking of the SCM to this specific σ_t surface in the GoC, even if the isopycnal is much deeper than the bottom of the mixed layer or if it does not coincide with the compensation point. Seasonal changes in basin-scale circulation (Section 3.1) or mesoscale processes (Criado Aldeanueva et al., 2006) generate isopycnal tilting and modify the depth of $\sigma_t \approx 26.66\ \mathrm{kg\ m^{-3}}$ from shallower than 20 m to deeper than 100 m. However, the SCM remains strongly linked to this particular isopycnal, wherever its depth occurs in the water column.

4. Open-sea mesoscale features

4.1. The upwelling off cape San Vicente

The accumulation of cold water in the northern GoC off CSV is a recurrent feature evident in most SST images of the area. The empirical orthogonal analysis of a seven-year long time series of SST images carried out by Vargas et al. (2003) includes this structure in the spatial map of the first empirical mode, which explains the 60% of the total variance, thus suggesting that it is a rather permanent feature. The similar analysis performed by Navarro and Ruiz (2006) on a seven-year series of satellite SeaWiFS images also identifies a persistent pattern of high chlorophyll concentration off CSV during summer.

The origin of this cold and chlorophyll-rich water has been related to the Ekman pumping driven by the prevailing positive z-component of the wind curl in the zone (Mazé et al., 1997; Sánchez and Relvas, 2003). Westerlies induce coastal upwelling that enhances the open ocean process and originate a second core just east of CSM that merges with the now increased upwelling area off CSV, thus generalising the upwelling along the southern Portuguese coast (Fiúza, 1983; Folkard et al., 1997; García et al., 2002; Criado Aldeanueva et al., 2006). But the cold signature off CSV is also detectable without favourable upwelling winds there. Other pos-

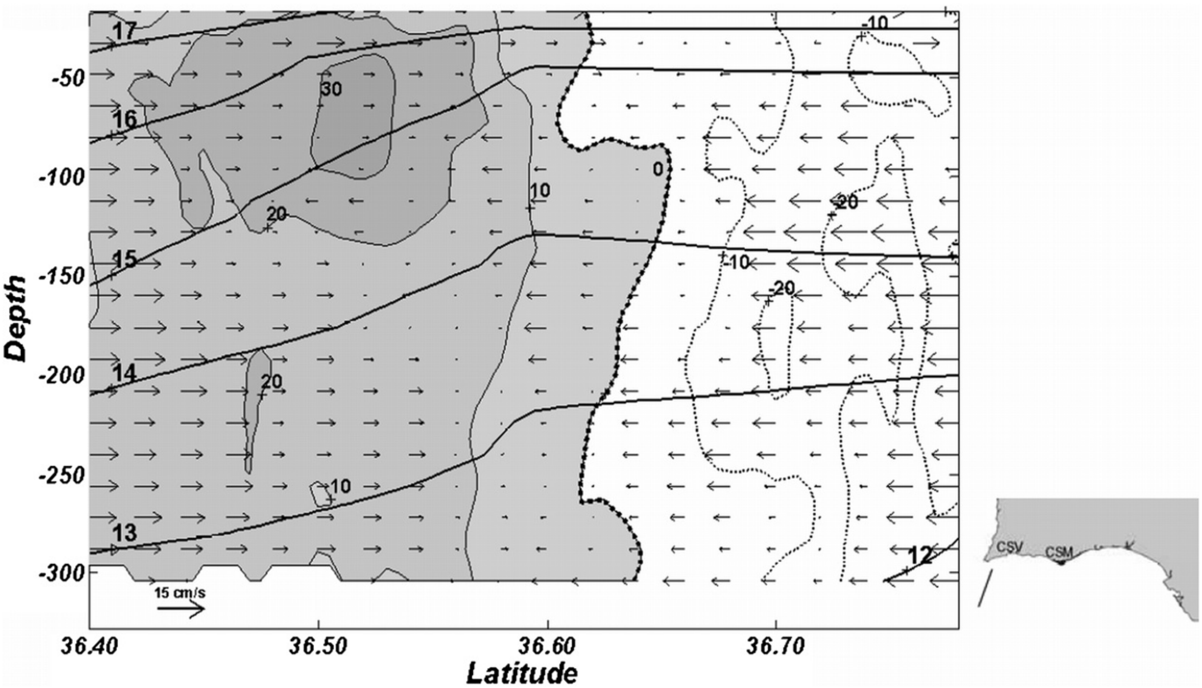

Fig. 7. Vertical profile of ADCP velocities along the perpendicular-to-shore transect shown in the insert of the lower right corner. Contours are for the normal-to-transect component, shadowed contours indicating positive (eastwards) velocities, and arrows indicate the along-transect component. The arrow in the lower left corner shows the scale for this component. Thick near-horizontal lines are contours of temperature (figure adapted from García Lafuente et al., 2006).

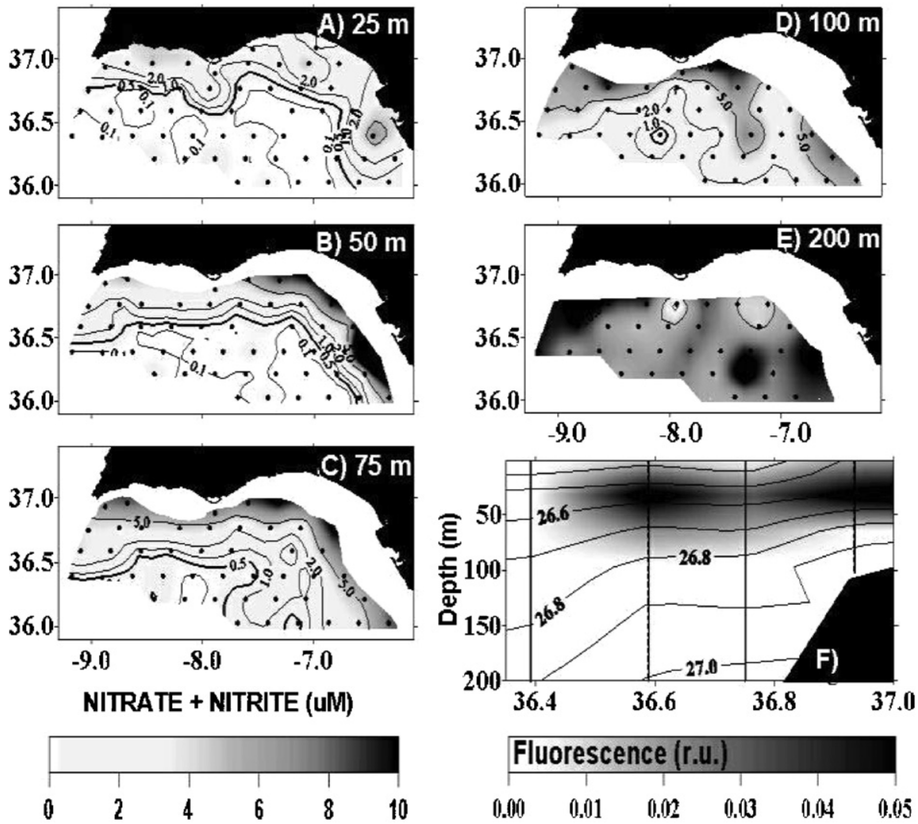

Fig. 8. Panels A–E: Contours of nitrate + nitrite concentration at different depths in the GoC during May 2001. Panel F: Vertical distribution of chlorophyll fluorescence at the same transect of Fig. 7.

sible origins of this feature are the separation of the Portuguese current from the coast at the latitude of CSV and its subsequent eastward veering, which will induce a cell of cyclonic circulation in the area. The map of Fig. 2 provides clear hints of this cyclonic circulation and so it does the vessel-mounted Acoustic Doppler Current Profiler (ADCP) observations of May 2001, which shows a vertically coherent and deep reaching eddy-like cell in the area (Fig. 7; see also García Lafuente et al., 2006).

Biogeochemical tracers of this cyclonic circulation are also evident in the nutrient and chlorophyll fields. Fig. 8 shows that the area affected by this cyclonic circulation (west of 8.5°W in Fig. 2) has a nutricline shallower than areas where circulation is anticyclonic. This is the result of the upward tilting of isopycnals associated with the geostrophic balance. Since the nutricline is connected with $\sigma_t \approx 26.66\ \mathrm{kg\ m^{-3}}$, the upward tilting of isopycnals also raises the nutricline in the area of cyclonic circulation. In accordance with Navarro et al. (2006) model, the tilting also enhances chlorophyll fluorescence at the SCM (Fig. 8F) since it exposes the nutricline to mechanical energy from the surface, which increases diffusion and nutrient flux towards the SCM. This is evident in the magnification of the SCM at about 36.6N in Fig. 8F which coincides with the core of the cyclonic circulation in Fig. 2.

4.2. Filaments

Filaments of cold upwelled-waters are usually found in the upwelling jets of the eastern boundary currents (see for instance Strub et al. (1991) and Huyer et al. (1991) for the California Current system or Barton et al. (2001) for the Iberian Peninsula). Filaments seem to develop by baroclinic instability and further interaction with the offshore vorticity field (Røed and Shi, 1999) and show preference to be anchored to coastline irregularities. In the GoC, CSV presents suitable conditions for filament anchoring and they are often found here, extending offshore with various orientations (Relvas and Barton, 2002). Although the most frequent is the zonal direction, filaments have been also detected stretching southwards along the western boundary of the GoC.

Inside the GoC, CSM is another coastline irregularity propitious to anchor cold water filaments sporadically (Criado Aldeanueva et al., 2006). Data collected in May 2001 showed the presence of a filament formed after an intense episode of coastal upwelling along the south coast of Portugal forced by westerlies. The filament extended southwards more than 100 km beyond the southern limit of the sampled area (Fig. 9), its transport was estimated in 0.25 Sv and its core was situated around 40–50 m depth, becoming almost indistinguishable at around 200 m depth (Figs. 9 and 10).

The characteristics above classify the filament as moderate if compared with fully-developed filaments associated with upwelling jets in the eastern boundary current systems, but represents an important mechanism for offshore transport in the reduced geographical area of the GoC. The vertical distribution of chlorophyll in the two perpendicular-to-shore consecutive transects presented in Fig. 11 shows high concentration of chlorophyll some tens of meters below the sea surface in the stations marked with crosses in Fig. 9C, and illustrate the offshore advection of products originated in the shelf during the previous coastal upwelling event. Curiously, the area under the direct influence of the filament is the only region of the GoC where the tight link between $\sigma_t \approx 26.66$ kg m^{-3} and SCM relaxes slightly. Here, the SCM occupies a wider range of σ_t because the energetic processes that lead to the development of the upwelling filament distort the vertical structure generated along the seasonal cycle.

Due to their likely moderate category, filaments originated in the neighbourhood of CSM are highly sensitive to wind conditions. For instance, the area occupied by the filament observed in May 2001 was visited 10 days later under different wind conditions (easterlies) to find that its distinctive thermohaline characteristics had been almost faded out and its transport reduced to 20% (hardly 0.05 Sv) of the initial value (Criado Aldeanueva et al., 2006).

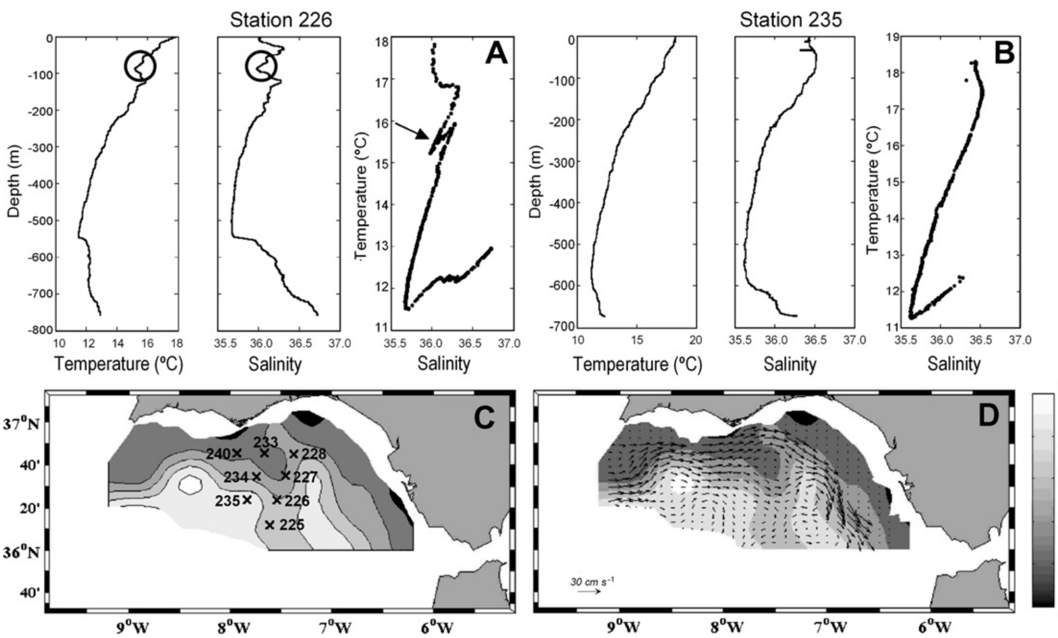

Fig. 9. Filament off cape Santa Maria from observations collected in May 2001. Panel A shows the vertical profile of temperature, salinity and the temperature-salinity diagram for a station inside the filament and Panel B shows the same for a station outside the filament. The signature of upwelled (cold and low salinity) water inside the filament has been marked in the plots of Panel A. Panel C: salinity at 50 m depth, the depth where the filament exhibits more distinguishable characteristics. Crosses in this panel indicate the stations in which the signature was found, thus depicting the shape of the filament. Panel D: geostrophic velocity superposed to the salinity field at 50 m depth. The geostrophic flow has offshore components in the filament, as expected (figure adapted from Criado Aldeanueva et al., 2006).

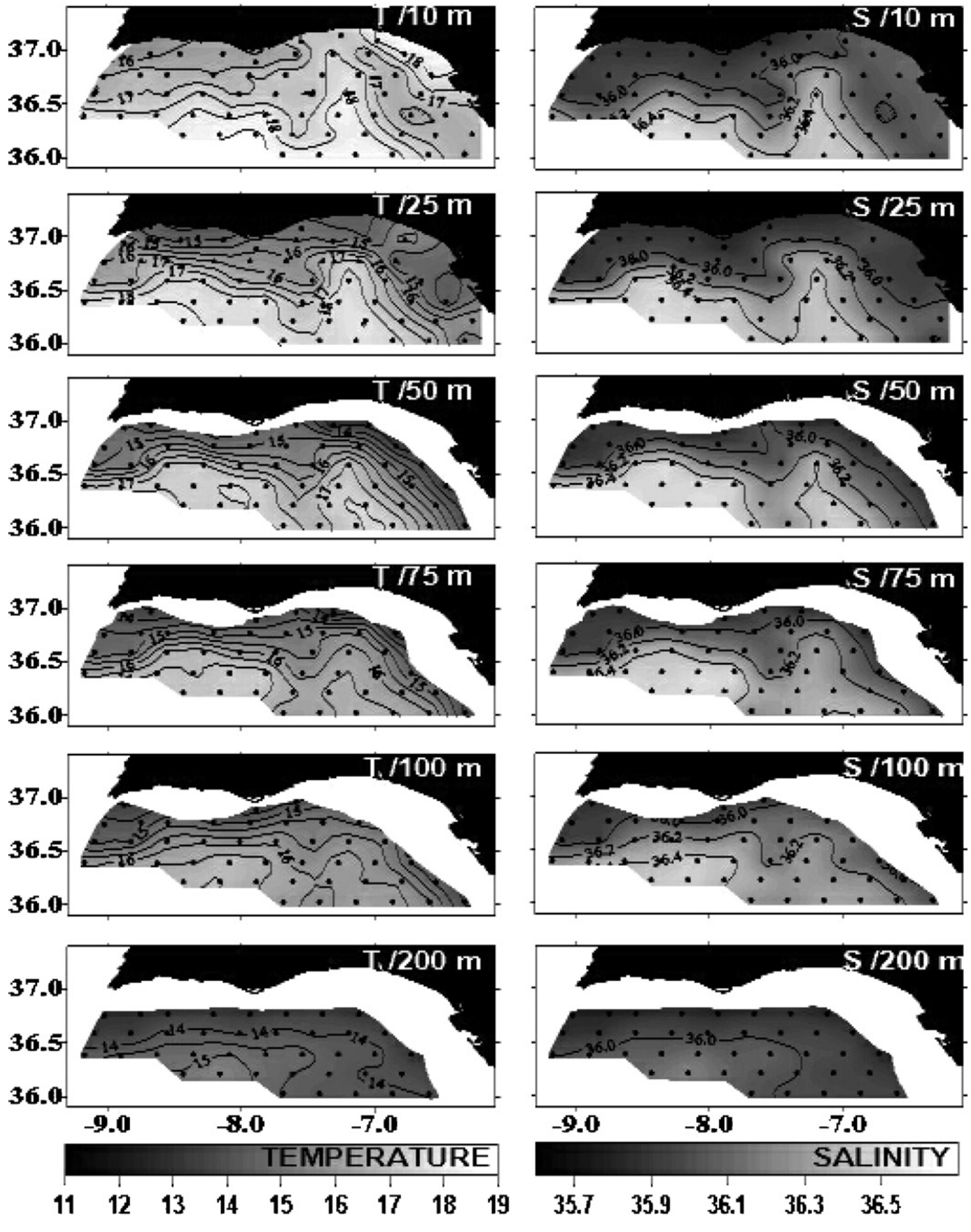

Fig. 10. Contours of temperature and salinity at different depths in the GoC in May 2001.

5. The continental shelf

5.1. Tidally-related processes

Tides and tidal currents are of secondary importance to the general circulation of the GoC except for the small area close to the Strait of Gibraltar. At first, it seems somewhat surprising because semidiurnal tidal currents are O(1 m s^{-1}) in the Atlantic side of the Strait (Candela et al., 1990). However, the standing-wave-like nature of the tide in this region (García Lafuente et al., 1990) makes tidal currents to vanish at some tens of

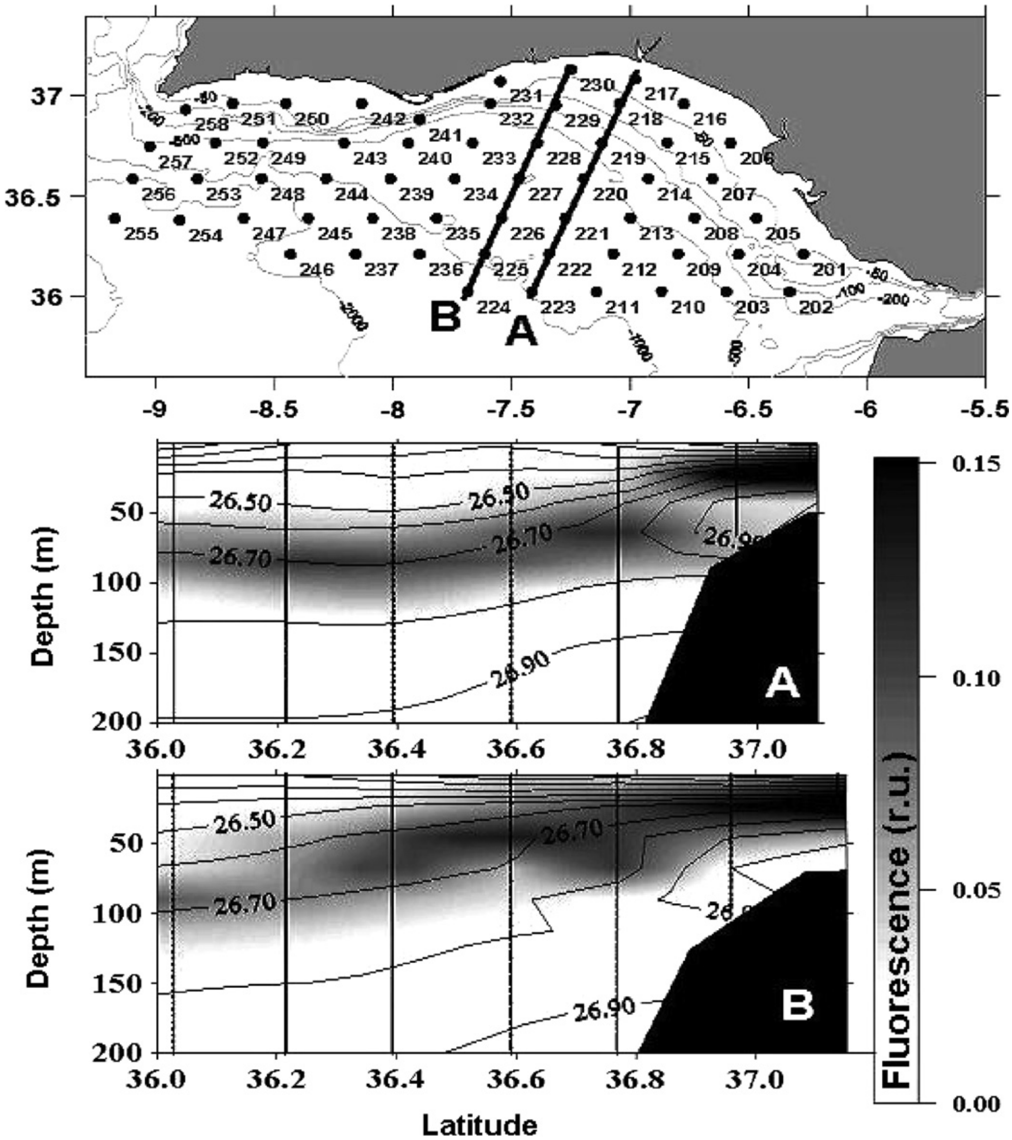

Fig. 11. Vertical distribution of chlorophyll fluorescence (shadowed contours, grey scale) and σ_t (contours) at the two consecutive transects indicated in the upper panel. The transect A (middle panel) does not contain stations with the cold and low salinity signature of upwelled waters inside the filament (marked with crosses in Fig. 9) while the adjacent transect B does (bottom panel). Notice the subsurface patch of high chlorophyll concentration in the middle of this transect.

kilometres west of the Strait. Actually, semidiurnal currents are negligible in the position of the RAP oceanographic buoy (see Fig. 1 for location).

5.1.1. The Cape Trafalgar area

In spite of their low dynamic significance at basin-scale, tides trigger oceanographic processes with impact on biological processes and on the ecosystem, particularly in the eastern continental shelf. The easternmost area of this part of the shelf is under the influence of the intense tidal-current regime of the Strait. Off cape Trafalgar (see Fig. 1 for location), SST images persistently show a patch of cold water which has been related to the strong topographic interaction between the swift along-shore tidal flow and a submerged ridge running perpendicular to the shoreline (Vargas et al., 1999). Mixing induced by the flow-topography interaction fertilises the area (García et al., 2002) resulting in high concentrations of chlorophyll at this site. The empirical orthogonal functions decomposition of SeaWiFS data carried out by Navarro and Ruiz (2006) confirms the zone as one of the most chlorophyll-rich area of the GoC. Moreover, the fertilising mechanism does not depend on wind but on tides, which represents a rather continuous process of enrichment. The monthly averages of satellite chlorophyll concentration shown in Fig. 12A depicts maxima coinciding with the vernal and autumn equinox and minima in coincidence with winter and summer solstices.

5.1.2. Waters near the Guadalquivir River mouth

The flood and ebb of the tidal wave along the rivers that discharge in the GoC and inside Cádiz embayment imprint signatures on nearby waters. SST images illustrate the presence of a pool of warm water that systematically appears in and near the Guadalquivir River mouth and Cádiz embayment from April to October (Folkard et al., 1997; Vargas et al., 2003; Navarro and Ruiz, 2006) regardless of the wind direction. The maintenance of the warm signature against heat advection and diffusion requires a source of heat, which, apparently, is the land. According to García Lafuente et al. (2006), the inland propagation of a tidal wave with amplitude greater than 1 m for around 100 km along the Guadalquivir River and associated arms and marshes and also along the marshes around Cadiz embayment and minor rivers over there is a mechanism capable to maintain the warm spot. The physical processes invoked were the greater heat absorption per mass unit in the river than offshore during spring–summer due to the greenish colour of the water in the river and its shallowness, the increased length of daylight during these seasons and, specially, the flooding of marshes heated by

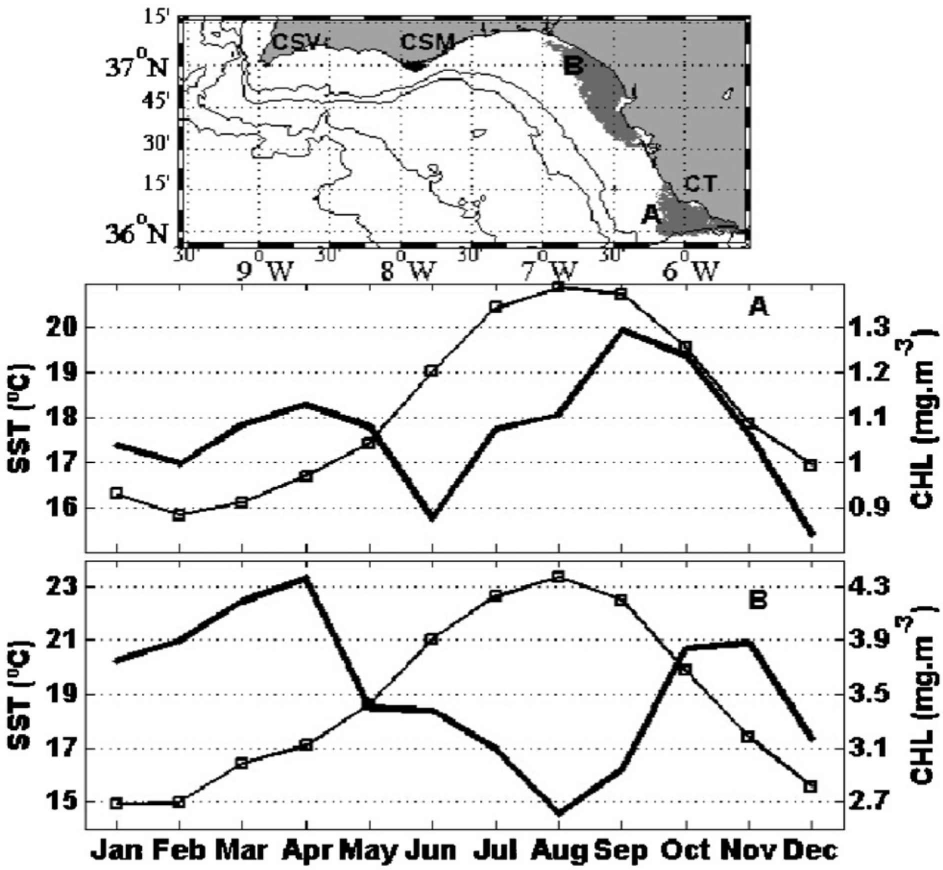

Fig. 12. Monthly averages of satellite-derived SST (thin line with squares) and satellite-chlorophyll (CHL, thick line) obtained from AVHRR and SeaWiFS data, respectively, according to the methods in Navarro and Ruiz (2006) for (A) the Cape Trafalgar area and (B) the area near the Guadalquivir River mouth. The insert on the top depicts the geographical extent of both regions as diagnosed by the empirical orthogonal function analysis of SeaWiFS data by Navarro and Ruiz (2006).

sun radiation during the previous low tide. Most of this energy is brought back to the sea during ebb tide. During night, there would be no difference between the amount of heat a parcel of water in the river or offshore gains or loses and therefore the daily-averaged heat export from land to the sea is positive in spring–summer. The results of a short field experiment spanning four tidal cycles carried out during June 2006 in the mouth of San Pedro River, which flows in the Cadiz embayment (see arrow in the map inserted in Fig. 15 and explanations in the caption), support this hypothesis. In winter–autumn, the process reverses and the land imports heat from the sea. The monthly SST climatology shown by Navarro and Ruiz (2006) confirms that the area becomes cooler than average from November to March.

This mechanism can be extended to nutrient pumping from land into the sea which, contrary to heat, would be positive all the year round. Nutrient concentrations are indeed higher in the area off Guadalquivir River mouth along the whole seasonal cycle (Ruiz et al., 2006), a fact invoked by Reul et al. (2006) to explain some unusual features in the coastal phytoplankton distribution. Therefore, tidal forcing in the region under the influence of Guadalquivir River and nearby Cádiz embayment generates a pool of warm and chlorophyll-rich water that makes the area be the most productive of the GoC (Navarro and Ruiz, 2006), offering very favour-

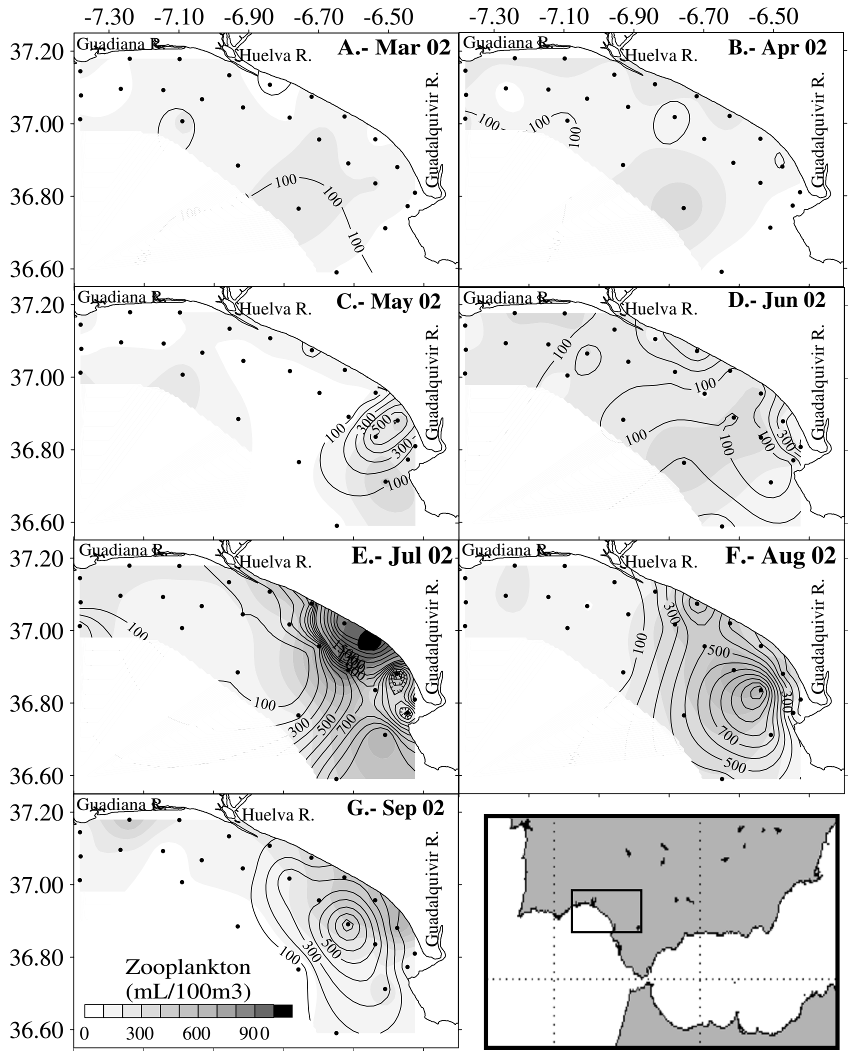

Fig. 13. Anchovy larvae concentration (# larvae/100 m^{-3}, contour lines) and zooplankton biovolume (mL/100 m^{-3}) in the area near the Guadalquivir River mouth from March to September 2002. Data were obtained following the methods in Ruiz et al. (2006). Dots show the location of the sampled stations. The insert of the lower right corner depicts the geographical extent of the sampled area (figure adapted from Ruiz et al., 2006).

able environmental conditions for the development of eggs and larvae. The high productivity remains during summer, when the rest of the basin is severely oligotrophic (Fig. 12B). Contrasting with other more intermittent mechanisms of fertilization such as wind-driven upwelling or other mesoscale features, this tidally-driven mechanism represents a continuous source of nutrients. The permanent nutrient input favours an efficient transfer of primary production towards higher trophic levels as illustrated by Fig. 13, which shows the greatest zooplankton concentration nearby the Guadalquivir mouth. Anchovy, whose larvae are known to feed on copepods in this area (Baldó and Drake, 2002), as well as many other fish species, all exhibit high concentrations of early life stages at this region of the inner eastern shelf (Fig. 13; Baldó et al., 2006).

In addition to tidal fertilization, the shelf east of CSM is also influenced by episodic inputs of nutrients in connection with meteorology. Shoreline orientation favours Ekman pumping of nutrient and chlorophyll accumulation under westerlies (Fig. 14 is an example for year 1999). Also, sporadic inputs of fresh and nutrient-rich waters from the rivers that follow episodes of precipitation can increase the primary production whenever light conditions are not limiting (Ruiz et al., 2006; Fig. 14).

5.1.3. Internal waves in Portimao canyon

Another feature that affects the western continental shelf, whose biological impact has not been fully assessed yet, is the internal tide generation and its further shoreward progression through the Portimao canyon (see PC in Fig. 1 for location) reported by Bruno et al. (2006). It is a well known fact that tidal energy can be transmitted easily to the continental shelves through the interior of submarine canyons (Baines, 1983) where it is dissipated. Bruno et al. (2006) showed that tidal energy flux in Portimao canyon is of secondary importance but other shorter internal waves co-existing with internal tides carry enough energy into the shelf to fully mix thick portions of the upper water column, accumulating relatively cold and chlorophyll-rich water around the shelf break.

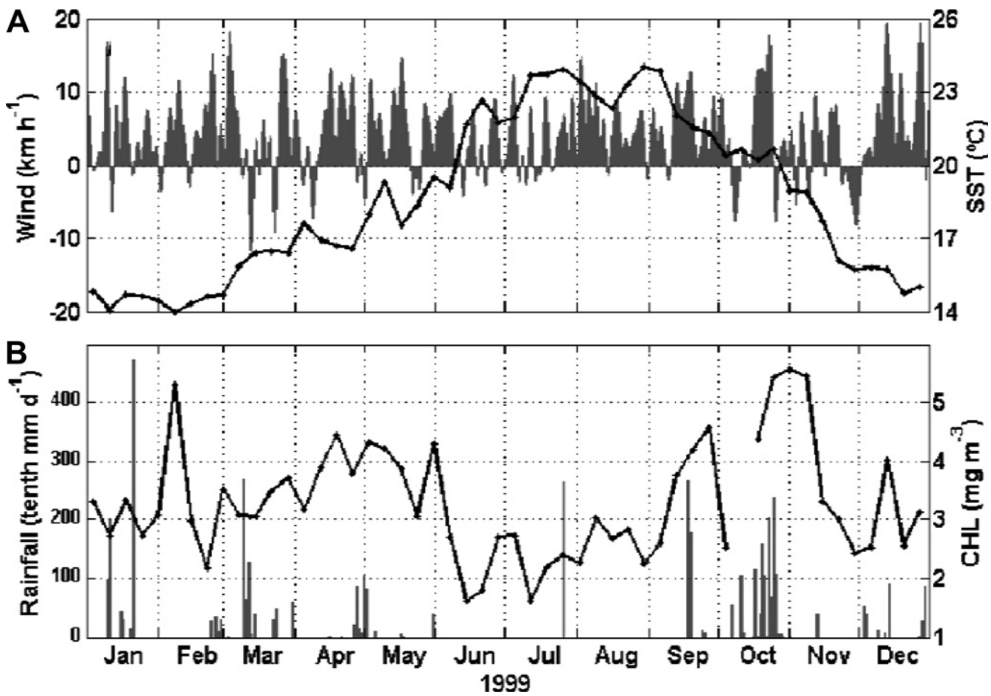

Fig. 14. Meteorological forcing of primary production in the area near the Guadalquivir River mouth (see insert in Fig. 12) during 1999. Bars in Panel A shows the time series of local wind speed (km h^{-1}, positive/negative values for westerlies/easterlies, respectively) and solid line is SST (°C). Bars in Panel B are daily rainfall values (tenth of mm d^{-1}) and solid line is satellite chlorophyll concentration (mgChl m^{-3}). SST and chlorophyll are weekly composites of AVHRR and SeaWiFS data processed according to the methods in Navarro and Ruiz (2006).

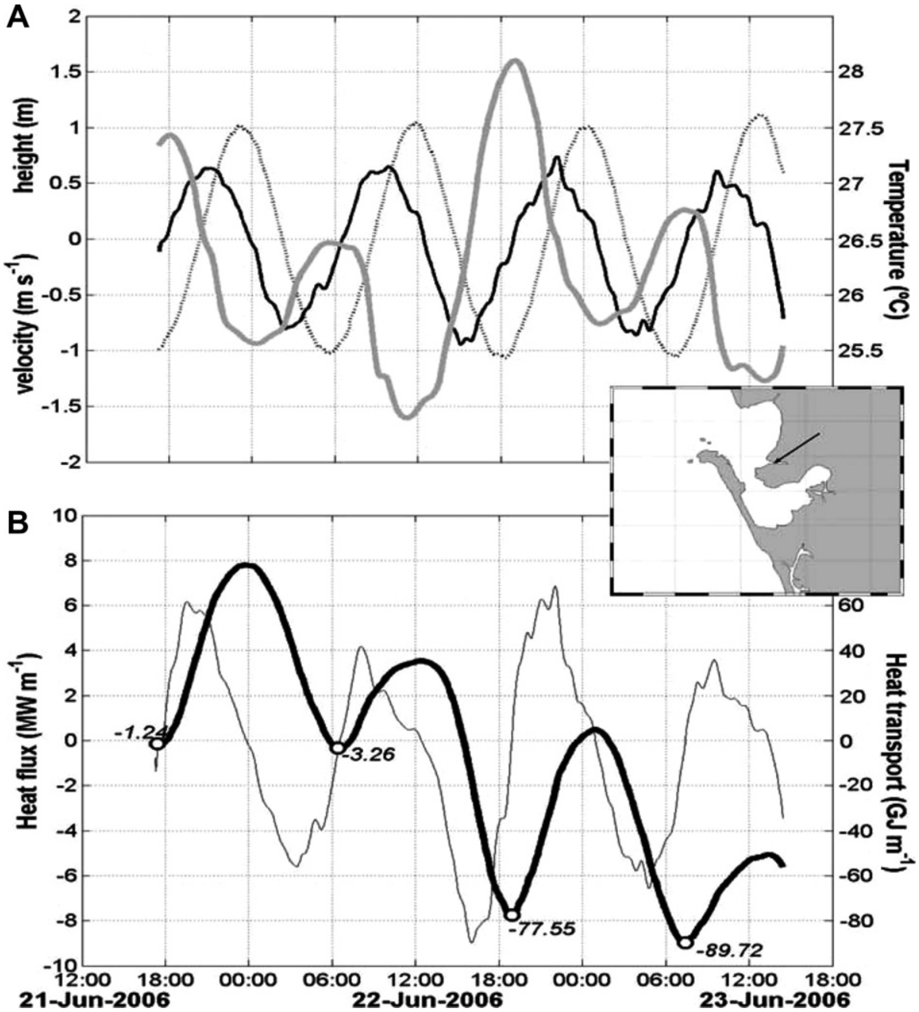

Fig. 15. (A) Demeaned tidal elevation (dotted line, left scale), depth-averaged velocity (solid black line, left scale; negative values indicate seawards motion) and near-bottom temperature (thick grey line, right scale) observed in June 2006 several hundreds of meters upstream of the mouth of San Pedro River, which flows in the inner Cádiz Bay. The location of the observations is marked by the arrow in the map on the middle-right. Temperature starts increasing as soon as the velocity becomes negative (seawards) and *vice versa*. Notice the strong diurnal inequality in temperature indicating an enhanced heat gain during daylight. (B) Heat flux per unit width (thin line, left scale) at the observation site, which is either positive (landwards) or negative (seawards) depending on the phase of the tide, and accumulated heat transport per unit width (i.e., the integral of the heat flux; thick line, right scale) computed from the observations. Heat in our case means the excess of heat content relative to 24.5 °C, which is slightly below the minimum recorded (Panel A). Open circles and the numbers indicate the accumulated energy transport from the initial time until the moment when velocity changes from negative to positive. The circles are therefore separated by one tidal cycle and the net energy transport per unit width in a given tidal cycle is readily determined as the difference between the values of the two consecutive circles defining the cycle. Notice that the three full cycles resolved by the data have negative differences (net seaward energy transport) and that the daylight tidal cycle has a much larger difference than the other two, which are only slightly different from zero.

5.2. The coastal countercurrent and the circulation on the continental shelves

There are many references to a coastal current of relatively warm water that flows westward near the shore on the eastern shelf and, eventually, on the western shelf, where it may reach CSV and, even, proceed northwards (Fiúza, 1983; Relvas and Barton, 2002; Sánchez and Relvas, 2003; Relvas and Barton, 2005; García Lafuente et al., 2006). Most of the references are based on the analysis of SST images but it has been also detected from field observations (Fig. 16). The origin of the alongshore pressure gradient necessary to drive the flow is not clear. Relvas and Barton (2002) as well as Sánchez et al. (2006) suggests the effect of a positive wind curl associated with the sharp protrusion of CSV and to the dissimilar wind stress forcing at either side of the cape. More recently, García Lafuente et al. (2006) have suggested that tidally-driven buoyancy inputs from Guadalquivir River and marshes nearby Cádiz embayment can contribute to set out the alongshore pressure gradient.

The current responds to wind stress in the sense that westerlies prevent or, at least, hamper its westward progression and confine the current to the eastern continental shelf, while easterlies push it in that direction (Fiúza, 1983; Folkard et al., 1997; Relvas and Barton, 2002; García Lafuente et al., 2006). It follows that, under westerlies, the countercurrent must recirculate within the eastern shelf, the compensating current flowing to the east along the outer shelf, thus establishing a cell of cyclonic circulation in the area. The cross-shelf transect shown in Fig. 16 illustrates the current system with the outer branch of the cyclonic cell (labelled N1 in Fig. 16) flowing over the continental shelf break and slope parallel to the main circulation of the open basin (see explanations in the figure caption). In these circumstances, the western shelf remains isolated from the eastern one, a fact that is enhanced by the generalised basin-scale anticyclonic circulation, while the cyclonic circulation on the eastern shelf is reinforced and the shelf enriched with waters recently upwelled by the favourable wind.

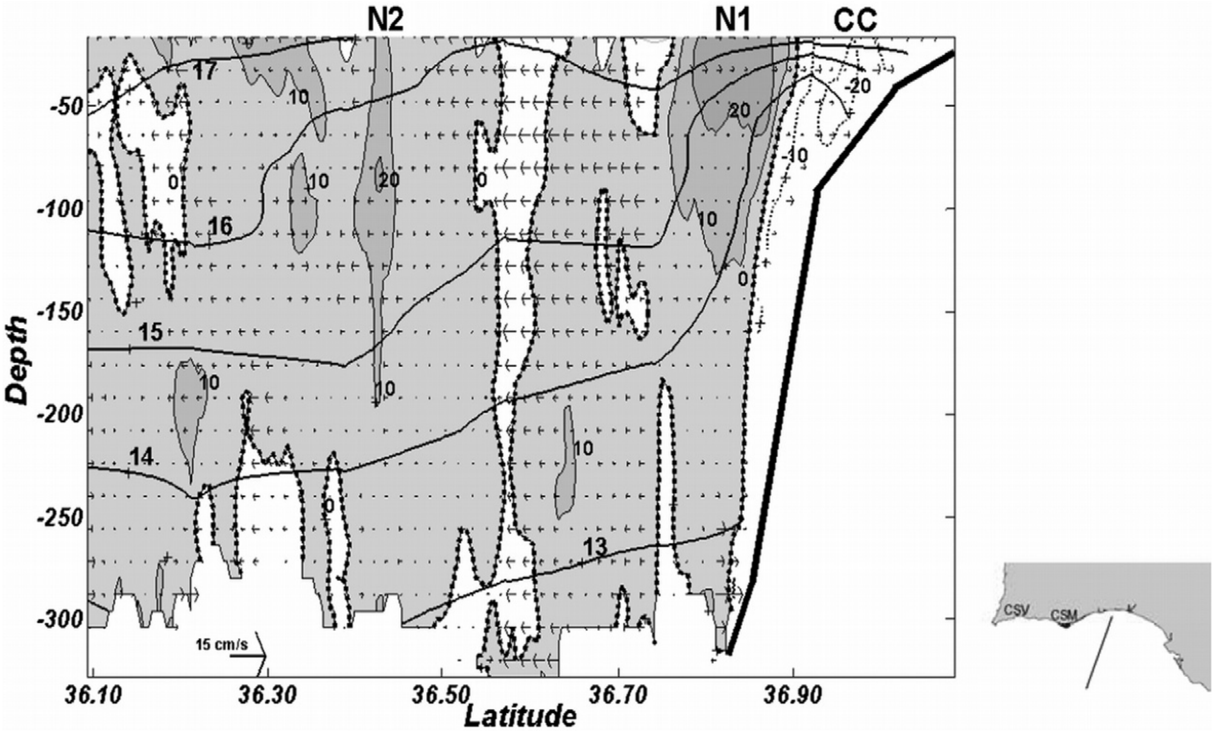

Fig. 16. Vertical profile of ADCP velocities along the perpendicular-to-shore transect shown in the insert of the lower right corner. Contours are for normal-to-transect component, shadowed contours meaning positive (eastwards) velocities. Arrows indicate the along-transect component (arrow in the lower left corner shows the scale). The thickest line on the right is the seafloor. Labels CC and N1 indicate, respectively, the position of the coastal countercurrent and the compensating eastwards current that closes the cyclonic cell in the eastern continental shelf. Label N2 indicates the main branch of the open ocean circulation (see also snapshot in Fig. 17). Thick near-horizontal lines are contours of temperature. The doming of isotherms on the side of the continental shelf suggests cyclonic circulation there, leaving warmer water near the shore flowing to the west, which would be the distinctive pattern of the coastal countercurrent (figure adapted from García Lafuente et al., 2006).

5.3. East versus west shelf processes

Coupled to the open ocean circulation, the continental shelf dynamics has specific characteristics. Due to the different morphology of the continental shelf, water mass circulation in or near the shelf has distinctive patterns east and west of CSM. Moreover, each shelf is sensitive to different forces and responds to specific processes. Under easterlies, the coastal countercurrent flows beyond CSM and invades the western shelf, providing transport of biological material from the east to the west and the biological connection between shelves. A second consequence is the southward displacement of the cold water area off CSV as the warm countercurrent progresses attached to the shore. The schematics of Fig. 17 illustrate the near-shore surface circulation and the way it couples to the open ocean circulation. There are two cells of cyclonic circulation and of different nature located over the eastern and western continental shelves. The one over the eastern shelf has a moderate volume transports of around 0.05 Sv and appears to be linked to coastal processes such as the pool of warm water off the Guadalquivir River and/or the establishment of an alongshore sea level slope forced by spatial inhomogeneities of wind stress. On the contrary, the cell over the western shelf is part of the larger cyclonic eddy associated with the upwelling off CSV (Section 4.1) and is more related to the open ocean process of Ekman pumping induced by a positive wind stress curl (Mazé et al., 1997; Sánchez and Relvas, 2003). Its volume transport is one order magnitude greater (around 0.5 Sv).

Easterly winds connect both cells by pushing the warm coastal countercurrent west of CSM, a process repeatedly illustrated by sequences of SST images (Fiúza, 1983; Relvas and Barton, 2002). Actually, the relaxation of upwelling favourable winds (westerlies) could be enough to trigger the westward intrusion of the warm counter current (Relvas and Barton, 2002). However and according to García Lafuente et al. (2006), only part of this coastal current floods the western shelf and the rest re-circulates eastwards to maintain the cyclonic cell in the eastern shelf. Westerlies are not as effective in connecting western and eastern shelves. They induce generalised upwelling along the southern coast of the Iberian Peninsula that is specially noticeable around CSM, where upwelling favourable wind advects cold water from intermediate depths nearby the cape vertically and also surface water from the CSV upwelling area horizontally. The upwelled water is then

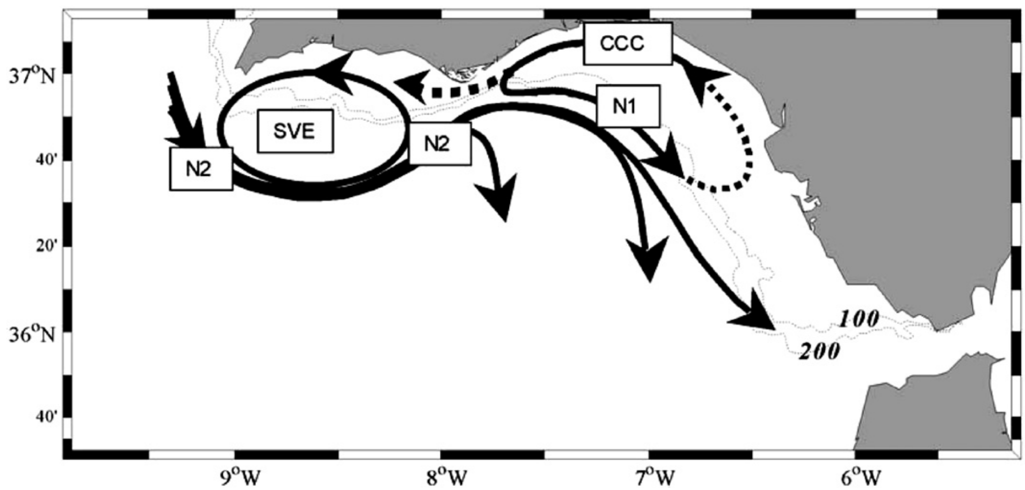

Fig. 17. Sketch of the surface circulation in the Gulf of Cádiz proposed by García Lafuente et al. (2006). Core N2 is a branch of the longer-scale Portuguese-Canary eastern boundary current that veers eastward into the Gulf of Cádiz. It moves around a cyclonic eddy off cape San Vicente (SVE), which is a quasi-permanent feature of the circulation in the Gulf associated probably with the quasi-permanent positive wind stress curl there. Part of core N2 moves further east toward the Strait of Gibraltar to feed the Atlantic inflow of nearly 1 Sv into the Mediterranean Sea and the remaining veers southwards to re-join the Canary current or detach from shore as a filament off Cape Santa Maria. The eastern shelf is dominated by a cyclonic circulation bounded by core N1 (identified with the Huelva front) at the south and a – warmer – coastal counter current (CCC). The presence of Cape Santa Maria seems necessary to close the cyclonic cell by the west. Under easterlies, the coastal counter current bifurcates off Cape Santa María and a branch invades the western shelf (dashed arrow) making the SVE drift to the south. The spatial extension of SVE is exaggerated in the sketch (figure adapted from García Lafuente et al., 2006).

transported either by the mean circulation along the continental slope depicting the so-called Huelva front first mentioned by Stevenson (1977) or directly offshore by the upwelling filament of CSM.

The general scheme of the surface GoC circulation in Fig. 17 has important feedbacks to processes relevant for the recruitment of exploited fish populations in the basin. Some species like anchovy have probably adapted its reproductive strategy to this pattern of circulation. Fig. 18 shows the egg distribution during the reproductive season of this species. Spawning grounds are found in the zone of the eastern continental shelf-break that is under the influence of the eastward branch of the cyclonic-cell labelled N1 in Fig. 17. Therefore, these eggs are advected towards the area of the inner-shelf influenced by the Guadalquivir River. As described in Section 5.1.2, this area has temperature and trophic characteristics suitable for the survival of fish larvae, which in turn explains the great larval abundance found a month later (Fig. 14). The coupling between spawning and circulation is particularly beneficial under westerlies, when productivity in the eastern shelf is likely enhanced and the plankton is confined within the cyclonic cell (Section 5.2). On the contrary, easterlies favour oligotrophy (Fig. 14) as well as the westward export of plankton across CSM and, if persistent, beyond CSV into the open waters of the Atlantic Ocean. A clear signature of this westward transport of ichthyoplank-

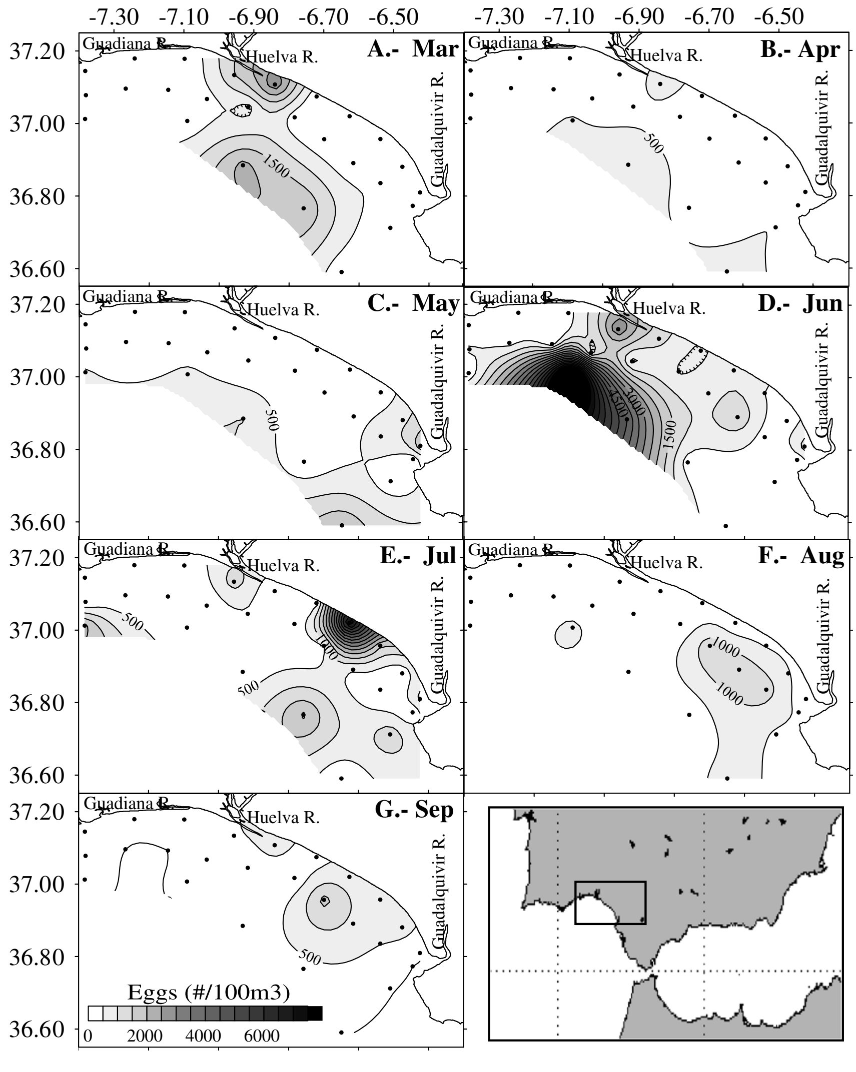

Fig. 18. Anchovy egg concentration (# eggs/100 m^{-3}) in the area near the Guadalquivir River mouth from March to September 2002. Data were obtained according to the methods in Ruiz et al. (2006). Dots show the location of the sampled stations. The insert of the lower right corner depicts the geographical extent of the sampled area (figure adapted from Ruiz et al., 2006).

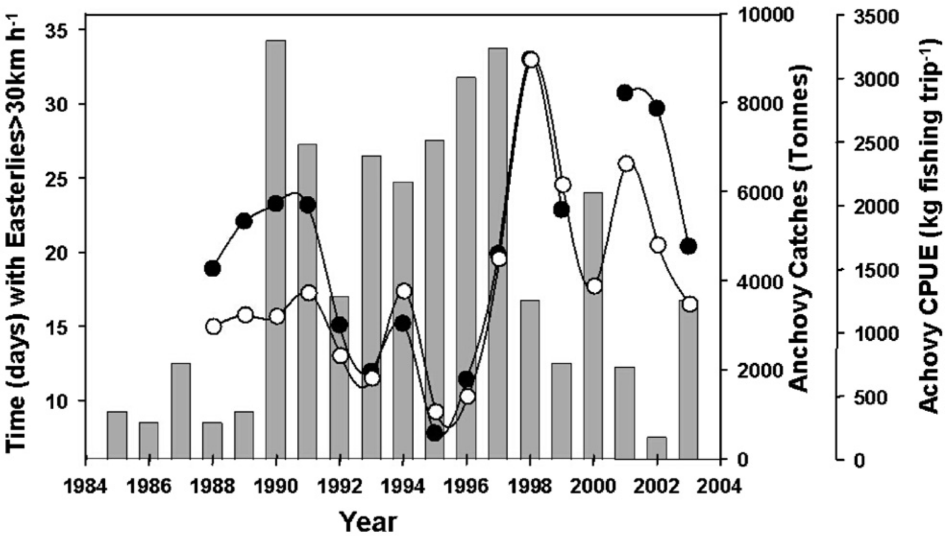

Fig. 19. Anchovy catches (black circles) in the Gulf of Cádiz (ICES report for sub-division IX.a South) and CPUE (white circles, kg/fishing trip) in Barbate by a single purpose pursue-seine fleet. Barbate is considered as a reference harbor for catches in the Gulf of Cádiz (ICES data; Anonymous, 2004). Catch data for year 2000 are not included in the graph as catches were not representative due to social conflicts in the fleet. Bars represent the cumulative sum of days from March to September with easterlies stronger than 30 km h^{-1} in Cádiz meteorological observatory (figure modified from Ruiz et al., 2006).

ton patches has been detected by Catalán et al. (2006) by comparing the observations collected during two synoptic surveys performed only several days apart under westerly and easterly wind regimes, respectively. Under westerlies, an assembly of fish larvae was detected close to the Guadalquivir mouth and several days later, under easterlies, what seemed to be the same assembly was nearby CSM. The potential impact of this early life-stages advection on the catches of anchovy or other species that spawn in the area was explored by Ruiz et al. (2006) who suggest that periods of low anchovy catches in the GoC are connected with inter-annual fluctuations of easterlies intensity (Fig. 19). This connection would indicate a tight dependence of higher trophic levels on the shelf circulation and on its response to wind forcing.

6. Summary and conclusions

6.1. Final remarks

From an oceanic-scale point of view, the GoC is a small area embedded in the large-scale eastern-boundary current of the North Atlantic subtropical gyre and, therefore, under a dynamics similar to other eastern boundaries of subtropical gyres. There are, however, two distinctive features that confer specific characteristics to this area. The first one is the sharp protrusion of CSV where the shoreline orientation changes abruptly from north–south to east–west. One consequence is that the upwelling favourable northerly winds that blow along the western Iberian Peninsula in summer are weakly effective to upwell water along the northern shore of the GoC (southern Portuguese coast) due to the dissimilar wind stress forcing at either side of the cape (Relvas and Barton, 2002). Even more, large-scale upwelling-favourable winds from the north or the northeast in the North Atlantic can be locally modified in the GoC to become downwelling-favourable easterlies (Sánchez et al., 2006). The second and more important feature is the presence of the Strait of Gibraltar. The GoC supplies the nearly 1 Sv of Atlantic surface waters that feeds the inflow into the Mediterranean Sea. In addition, the energetic plume of nearly 1 Sv of Mediterranean water overflowing the sills of the Strait entrains a considerable amount of the overlying NACW in the GoC, increasing the Mediterranean outflow by a factor of 3 in the western limit of the basin (Ambar and Howe, 1979; Baringer and Price, 1997). Therefore, open ocean surface waters must flow eastward through the GoC western limit in order to compensate for the entrainment of the Mediterranean plume and the surface inflow into the Mediterranean Sea. To a great extent, this compensating flow is responsible for the eastern penetration of the Azores current, according to the numerical models of Jia (2000) and Johnson and Stevens (2000). It would explain why the GoC is a basin of relatively warm and oligotrophic waters that interrupts the fringe of cold and nutrient-rich upwelled water during the upwelling season, dividing the North Atlantic Coastal Province into the European and African sectors. The lack of surface chlorophyll maximum in the basin during summer is consequence of these specific features that contrast with the situation in the more continuous band of upwelling waters in other eastern boundary current systems.

At the scale of the GoC basin, the prevailing surface circulation of the GoC is anticyclonic, particularly in summer, with probability to change to cyclonic during short periods in winter. The seasonal cycle modifies the vertical distribution of chlorophyll, which does not show SCM at any depth during winter, but does so in summer when the water column becomes stratified. This SCM remains associated with the surface of $\sigma_t \approx 26.66\ \mathrm{kg\,m^{-3}}$, which represents the lower limit of the NACW modified by air–sea interactions during the seasonal cycle. The tight link between the SCM and $\sigma_t \approx 26.66\ \mathrm{kg\,m^{-3}}$ does not depend on the geographical location, on the depth where this σ_t value occurs, or on whether it coincides with the bottom of the mixed layer or with the compensation point. According to Navarro et al. (2006), the tight connection between the SCM and $\sigma_t \approx 26.66\ \mathrm{kg\,m^{-3}}$ during summer is not the consequence of processes with a timescale of days or shorter (e.g., mixing, respiration or photosynthesis) but is a result of the seasonal 'history' of the water column. This history involves the thermohaline homogenisation of NACW lighter than $26.66\ \mathrm{kg\,m^{-3}}$ by mixing during the previous winter, the slowly but progressive consumption of nutrients within this layer that turns $\sigma_t = 26.66\ \mathrm{kg\,m^{-3}}$ into the isopycnal of maximum nutrient gradient by the end of winter, and the presence of high sun radiation in spring–summer that starts developing a SCM in this gradient and establishes a positive feedback mechanism originated by the fact that phytoplankton consumes upward-diffusing nutrients. All these mechanisms lock the SCM to this specific σ_t surface in the GoC, a mechanism that may be relevant to other places of the world ocean, in particular to the entire North Atlantic Gyral Province.

At even smaller scales, the GoC shows a wide variety of shelf processes. An almost-permanent upwelling occupies the south of CSV, which has been related to the prevailing positive wind-stress curl in the area (Mazé et al., 1997; Sánchez and Relvas, 2003). Westerly winds enhance this upwelling, create a second intense core of upwelling off CSM and generalize the upwelling along the southern Portuguese coast. Upwelling episodes in the area can be so vigorous that they generate spots of surface water which are rich in nutrients but poor in chlorophyll (Ruiz and Navarro, 2005, 2006). They also generate the moderate filament of cold water that can be seen emanating from CSM toward the open ocean (Criado Aldeanueva et al., 2006). Easterlies favour biological connections between both basins in the sense that the coastal countercurrent existing in the eastern shelf can overshoot CSM and proceed into the western continental shelf. The intrusion of this tongue of warm water is an interesting process repeatedly illustrated by SST images whose biological consequences are not yet well studied. The continental shelf dynamics is therefore strongly dependent on wind regime, although the eastern continental shelf exhibits a pattern of cyclonic circulation that seems to persist independently of the wind regime. Some species of great commercial interest like anchovy have probably adapted its reproductive strategy to this pattern of circulation, spawning in a zone near the continental shelf-break from which the spawning products are easily advected toward the area of influence of the Guadalquivir River and Cádiz embayment, which gather suitable high temperature and trophic conditions for the survival of fish larvae. The greater-than-average temperature observed in this area in spring–summer has been related to the landward propagation of the tide which would export heat (and other dissolved substances) from land during the ebb phase (García Lafuente et al., 2006; see also Fig. 15). The coupling between spawning and circulation is better met under westerlies, when upwelling enhances productivity in the eastern shelf and plankton is confined inside the cyclonic cell. On the contrary, easterlies favour oligotrophy and the westward export of plankton across CSM, which would partially explain the positive correlation between periods of low anchovy catches and easterly intensity suggested by Ruiz et al. (2006).

6.2. Future work

In spite of the recent improvement of our knowledge of the GoC oceanography, there are issues that must be addressed in the next future. One of them is to elucidate whether or not the basin-scale circulation has a regular seasonal pattern that changes from anticyclonic to cyclonic, as is suggested by the summer-biased information reviewed in this paper and, if so, to assess the importance of the interannual variability of this seasonal pattern. The response to this question needs more (winter) field studies and modelling efforts and is of concern in order to understand the changes that this seasonality and/or interannual variability would induce in the continental shelf circulation which in turn will affect the recruitment of fish species of commercial interest. Regarding this point, the quantification and investigation of the impact that the tidally-driven energy and mass inputs from the land into the GoC has on the ecosystem is of great importance. On the one hand, the buoyancy input into the shelf nearby the Guadalquivir River's mouth and Cádiz embayment may partially account for the setup of the along-shore pressure gradient necessary to drive the coastal countercurrent in the eastern shelf and, hence, to play a significant role in the shelf dynamics (García Lafuente et al., 2006). On the other hand, the heat and nutrient pumping supplied by the tidal flow makes this region of the GoC gather suitable environmental conditions for nursery and fishing grounds. The continental shelf processes taking place in the GoC are highly sensitive to wind forcing. High trophic levels are sensitive to these wind-driven processes, as it is suggested by the correlation between anchovy catches and easterly dominance. The apparently tight dependence of higher trophic levels on the shelf circulation and on its response to wind forcing must be explored for species other than anchovy in one of the traditionally most prominent fishing grounds of the Iberian Peninsula.

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