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Seasonal and interannual variability of the surface circulation in the eastern Gulf of Cadiz (SW Iberia)

F. Criado-Aldeanueva,[1] J. García-Lafuente,[1] G. Navarro,[2] and J. Ruiz[2]

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[1] An 11-year (1996–2007) time series of current meter observations representative of the open sea circulation; a 4-year (2001–2005) time series of current meter records over the continental shelf and in situ data during different seasons have been compared in order to study the seasonal and interannual variability of the surface circulation in the eastern Gulf of Cadiz. The open sea velocity observations indicate southeastward flow along the northern continental slope of the Gulf of Cadiz, compatible with anticyclonic circulation, during most of the year and more intense during summer months. Flow reversals (northwestward circulation) at seasonal time scales in late autumn and early winter (preferably December and January) are a rather recurrent feature with variable intensity depending on the year. Anticyclonic circulation is associated with westerlies, whereas flow reversals usually take place under easterly episodes, suggesting wind-driven circulation. Negative North Atlantic Oscillation indices (indicative of southward displacement of the Azores high) are also linked to the reversals. Changes in this mainly wind-driven large-scale surface circulation are echoed by the shelf circulation: the coastal countercurrent that closes the mesoscale cyclonic cell over the eastern shelf in spring-summer (upwelling season) is replaced by and eastward current in autumn and winter.

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1. Introduction

[2] The Gulf of Cadiz is the subbasin of the North Atlantic that connects the Atlantic Ocean and the Mediterranean Sea through the Strait of Gibraltar. The most outstanding geographical features are Cape St. Maria (CSM), Cape St. Vincent, and Cape Trafalgar (see Figure 1, top). CSM divides the continental shelf into two halves and makes the circulation in each half rather independent from the other.

[3] Historically, the main part of the studies carried out in the Gulf of Cadiz have focused on the Mediterranean Water outflow through the Strait of Gibraltar [*Zenk*, 1970; *Bryden and Stommel*, 1982; *Zenk and Armi*, 1990; *Ochoa and Bray*, 1991; *Baringer and Price*, 1999; *Ambar et al.*, 2002] and its subsequent mixing with Atlantic waters. Moreover, the formation of eddies of Mediterranean origin, the so-called meddies, has also been matter of special interest [*Serra and Ambar*, 2002]. Research on the surface circulation first dealt with remotely sensed sea surface temperature (SST) images and climatological data. *Stevenson* [1977], combining in situ and SST satellite observations, identified a sequence of warm-cold-warm waters in NW–SE direction between Cadiz and Huelva and called it the Huelva Front. *Fiúza et al.* [1982] and *Fiúza* [1983], using wind data and SST images, correlated the occurrence of upwelling off the southwest coast of Iberia with westerlies and the development of a warm coastal countercurrent stretching east–west with easterlies. *Folkard et al.* [1997], *Relvas and Barton* [2002], and *Vargas et al.* [2003] have analyzed SST satellite images throughout the year and have reported a bimodal pattern in SST images related to wind regime in the summer months, and *Sánchez and Relvas* [2003], with databases of hydrographic stations corresponding to spring and summer in the southwest coast of the Iberian Peninsula for the whole 20th century, have depicted the climatic patterns of circulation in the Gulf of Cadiz during these seasons.

[4] An intensive oceanographic survey carried out in the Gulf of Cadiz in May–June 2001 (GOLFO 2001 cruise) provided a great amount of in situ data and more research has been recently carried out. *García-Lafuente et al.* [2006] and *Criado-Aldeanueva et al.* [2006a] have depicted the water mass circulation pattern on the continental shelf and the outer region of the Gulf of Cadiz. The surface circulation in the outer Gulf of Cadiz during spring-summer is predominantly anticyclonic with some mesoscale meanders. Off Cape St. Maria, the main current turns to the south and then to the north and continues flowing parallel to the Spanish coast. Further downstream the current separates into two branches, one of which feeds the Atlantic inflow through the Strait of Gibraltar while the other veers anticiclonically to join the Canary current more to the south

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[1] Grupo de Oceanografía Física, Departmento Física Aplicada II, E.T.S.I. Informática, Universidad de Málaga, Malaga, Spain.

[2] Instituto de Ciencias Marinas de Andalucia, CSIC, Puerto Real, Spain.

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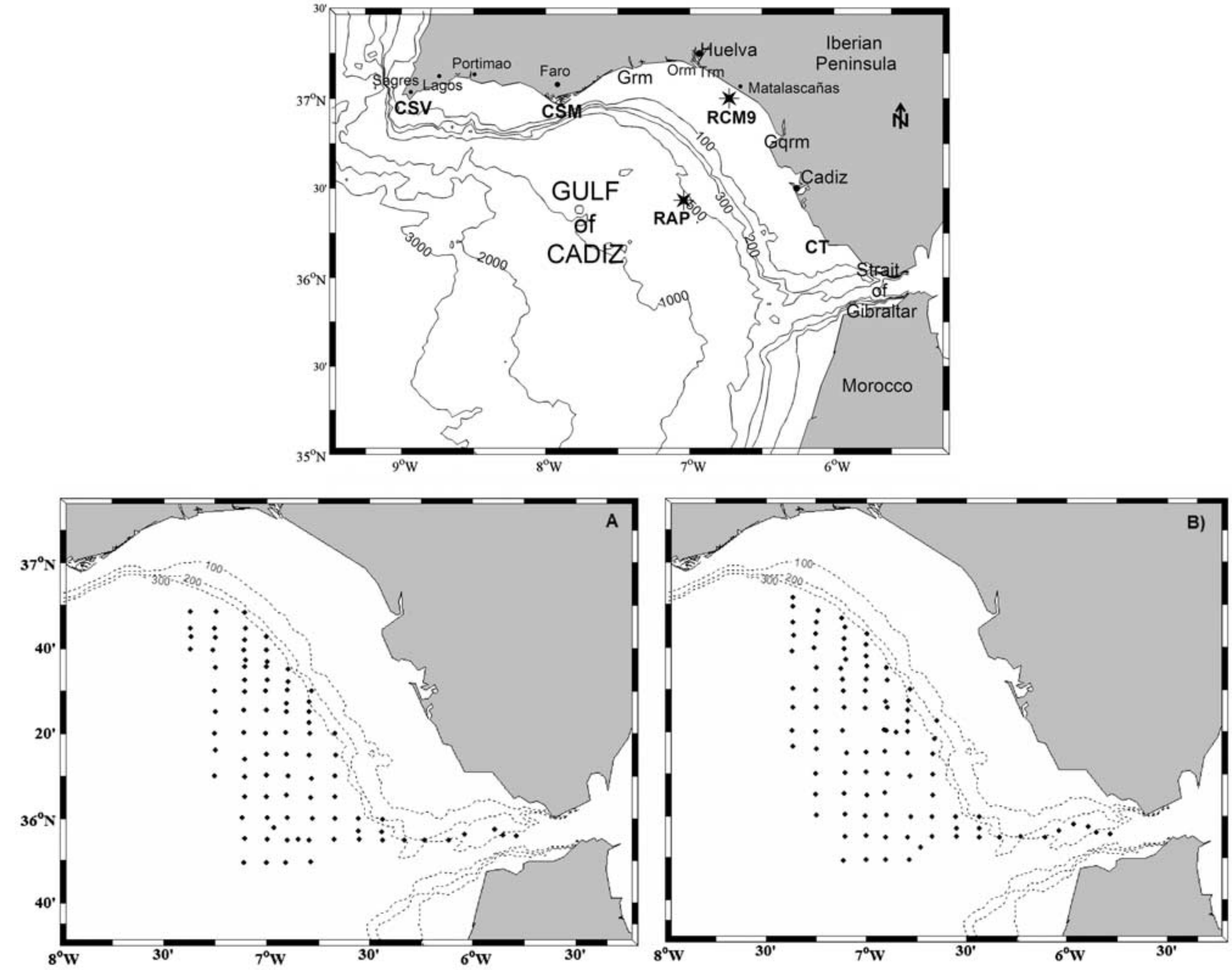

Figure 1. (top) Map of the Gulf of Cadiz showing the position of locations and other geographical features mentioned in the text. CT, CSM, and CSV stand for Cape Trafalgar, Cape St. Maria and Cape St. Vincent, respectively. Grm, Orm, Trm, and Gqrm stand for the mouths of Guadiana, Odiel, Tinto, and Guadalquivir rivers, respectively. The stars mark the position of the Red de Aguas Profundas (RAP) oceanographic buoy and the RCM9 current meter mentioned in the text. Figures 1a and 1b show the station grid of the two legs (February and June, respectively) of CANIGO survey.

[*Sánchez and Relvas*, 2003; *Criado-Aldeanueva et al.*, 2006a]. The surface circulation over the continental shelf during spring-summer has been suggested to consist in two cells of cyclonic circulation over the eastern and western continental shelves separated by CSM and coupled to the open sea surface circulation [*García-Lafuente et al.*, 2006]. The wind-induced variability of the surface circulation and hydrographic features (upwelling areas, Huelva Front, coastal countercurrent, etc.) is also widely addressed [*Criado-Aldeanueva et al.*, 2006a, 2006b; *García-Lafuente et al.*, 2006].

[5] The bias of oceanographic surveys toward spring-summer supports the existence of a permanent anticyclonic surface circulation in the Gulf of Cadiz. Current meter observations collected at 36°28.8′N, 6°57.8′W by the Red de Aguas Profundas (RAP) (see Figure 1) network of Puertos del Estado, Spain (available at http://www.puertos.es) analyzed for 1998 [*Álvarez Fanjul et al.*, 1999] confirmed a prevailing anticyclonic circulation throughout the year (southeastward currents at the position of the oceanographic buoy) but they also reported northwestward velocities in wintertime. *Mauritzen et al.* [2001] suggested a mid depth (100 to 180 m depth) cyclonic circulation in the Gulf of Cadiz after examining a set of hydrological data acquired in October 1995. *Vargas et al.* [2003] showed that the spatial pattern of the first empirical mode (explaining up to 60% of the variance) of the 8-year series of SST images indicates accumulation of warm (and, thus, light) water in the center of the basin compatible with anticyclonic geostrophic circulation. But the time coefficients of the mode showed important seasonal variability with minimum values in winter, which weaken the horizontal thermal gradient (hence, the pressure gradient) and the anticyclonic circulation during this season, which could eventually reverse under concomitant factors favoring cyclonic circulation. One of these factors could be the erosion of the seasonal

thermocline and the winter homogenisation of the water column that makes the velocity field be more barotropic, thus favoring the dynamic influence of the westward moving Mediterranean undercurrent on the water column above.

[6] The seasonal changes of surface circulation also tend to follow the wind regime off the Iberian Peninsula, which veers from northerly (upwelling season) to westerly or southwesterly in winter [*Fiúza et al.*, 1982; *Fiúza*, 1983; *Relvas and Barton*, 2002] forced by the seasonal displacement of the Azores high. Such displacement drives seasonal fluctuations in the circulation of the whole Subtropical Gyre, which in turn, and according to *Machín et al.* [2006], could promote seasonal changes in the circulation along the eastern boundary of the midlatitude North Atlantic. The equatorward upwelling jet along the Portuguese coast during the upwelling season, from May to October [*Wooster et al.*, 1976; *Fiúza et al.*, 1982; *Haynes et al.*, 1993; *Peliz and Fiúza*, 1999], is replaced by a poleward slope current flowing northward at the surface in winter, especially from December to February [*Frouin et al.*, 1990; *Haynes and Barton*, 1990; *van Aken*, 2000]. The circulation in the Gulf of Cadiz is sensitive to these large-scale variations. *Relvas and Barton* [2002] suggest that, when the upwelling jet formed in summer reaches Cape St. Vincent it spreads preferably to the east along the shelf break and slope of the north part of the Gulf of Cadiz, propitiating a generalized anticyclonic circulation in the basin. The connection of the poleward current with a cyclonic circulation in the Gulf of Cadiz is not so evident, since the Strait of Gibraltar plays a crucial role in the dynamics of the area. *Peliz et al.* [2007] show from numerical experiments that the Gulf of Cadiz circulation is rather independent of that of the west coast but is mainly forced to the east to compensate the necessary transport to feed the Atlantic inflow.

[7] In this work, new attention is paid to the seasonal and interannual variability of the surface circulation in the Gulf of Cadiz and its repercussions in the continental shelf circulation. An 11-year (1996–2007) time series of current meter observations from RAP buoy of Puertos del Estado, a 4-year (2001–2005) time series of current meter records over the continental shelf and in situ data from the Canary Islands, Azores, Gibraltar Observations (CANIGO) project during different seasons are compared. The paper is organized as follows: section 2 presents the data and methodology; section 3 discusses the main results both for the open sea (section 3.1) and continental shelf circulation (section 3.2); and, finally, section 4 summarizes the conclusions.

2. Data and Methodology

[8] An 11-year (1996–2007) time series of surface current velocity has been collected from a UCM-60 current meter settled in the Gulf of Cadiz Seawatch RAP oceanographic buoy of Puertos del Estado, Spain. The buoy is located at 36°28.8′N, 6°57.8′W (Figure 1) and it has provided oceanographic and meteorological data since August 1996. The current meter measures velocity at 3 m depth (range: 0 to 3 ms^{-1} with 1% accuracy and current direction within ±1°). Wind velocity (up to 70 ms^{-1}) and direction at 3 m over the surface are provided by the Aandera 2740 and Aandera 3590 meteorological sensors with an accuracy of 1.5% and 1%, respectively. Both oceanographic and meteorological data are obtained by averaging the measurements of the first 10 min of each hour, providing hourly data.

[9] A 4-year (November 2001 to December 2005) time series of subsurface current velocity has been collected from RCM-9 Aandera current meter deployed over the continental shelf in water of 15 m depth, 5 m above the seafloor at 37°01.64 N, 6°41.20 W, far enough from the coast to be representative of the circulation over the northern shelf (Figure 1). The current meter can measure velocities up to 300 cm s^{-1} within 0.3 cm s^{-1} resolution, 0.15 cm s^{-1} accuracy and ±5° current direction every 10 min. Gaps in RAP and RCM-9 time series are not unusual owing to maintenance or failure of the instruments. Small gaps have been linearly interpolated but large gaps have been left blank. Year 2003 from RCM-9 will not be analyzed since very few data are available. The present work focus on seasonal and interannual variability and, consequently, all time series have been low-pass filtered by a fifth-order low-pass Butterworth filter (cutoff frequency 40 days^{-1}) in order to remove high-frequency variability (tidal, short meteorological time scales, etc.).

[10] Monthly North Atlantic Oscillation (NAO) indices computed using the normalized sea level pressures in Gibraltar and in Southwest Iceland during the period 1996–2007 [*Jones et al.*, 1997] have been downloaded from the Climatic Research Unit (CRU) database.

[11] Hydrological data from a SeaBird SBE25 conductivity-temperature-depth (CTD) collected onboard the R/V Cornide de Saavedra during two surveys carried out in 1999 have been used for estimating the geostrophic velocity and transport in two different seasons. The winter survey consisted of 88 stations sampled between 18 February 1999 and 22 February 1999 and extended from ~6°W to ~7.4°W in longitude and from ~35.8 to 36.8 in latitude. The summer survey, with approximately the same spatial coverage, consisted of 96 stations sampled between 12 June 1999 and 19 June 1999 (Figures 1a and 1b). RAP buoy location is inside the sampled region and is suitable for comparison purposes. The interpolation of the hydrological data has been carried out by means of the optimal or statistical interpolation technique (OI). This method, widely presented in the literature [*Gandin*, 1963; *Thiébaux and Pedder*, 1987; *Ruiz Valero*, 2000; *Gomis et al.*, 2001], is based on the condition that the differences between real field values and the results of the analysis are minimized statistically. The OI technique requires the adjustment of several parameters: for the tendency's degree of the polynomial, as low values are recommended [*Thiébaux and Pedder*, 1987], n = 2 has been used. The spatial scale correlation, indicative of the size of structures that can be resolved, has been established in 20 km, and the noise-signal ratio in 0.001 for CTD data (for details, see *Criado-Aldeanueva et al.* [2006a]). The same spatial grid step has been chosen for the two legs: 0.1° in longitude and 0.0548° in latitude.

3. Results and Discussion

3.1. Open Sea Circulation

[12] Figure 2a displays the total velocity recorded by the RAP buoy. Higher values in the filtered series are up to 30 cm s^{-1} and tend to appear at midyear whereas lower

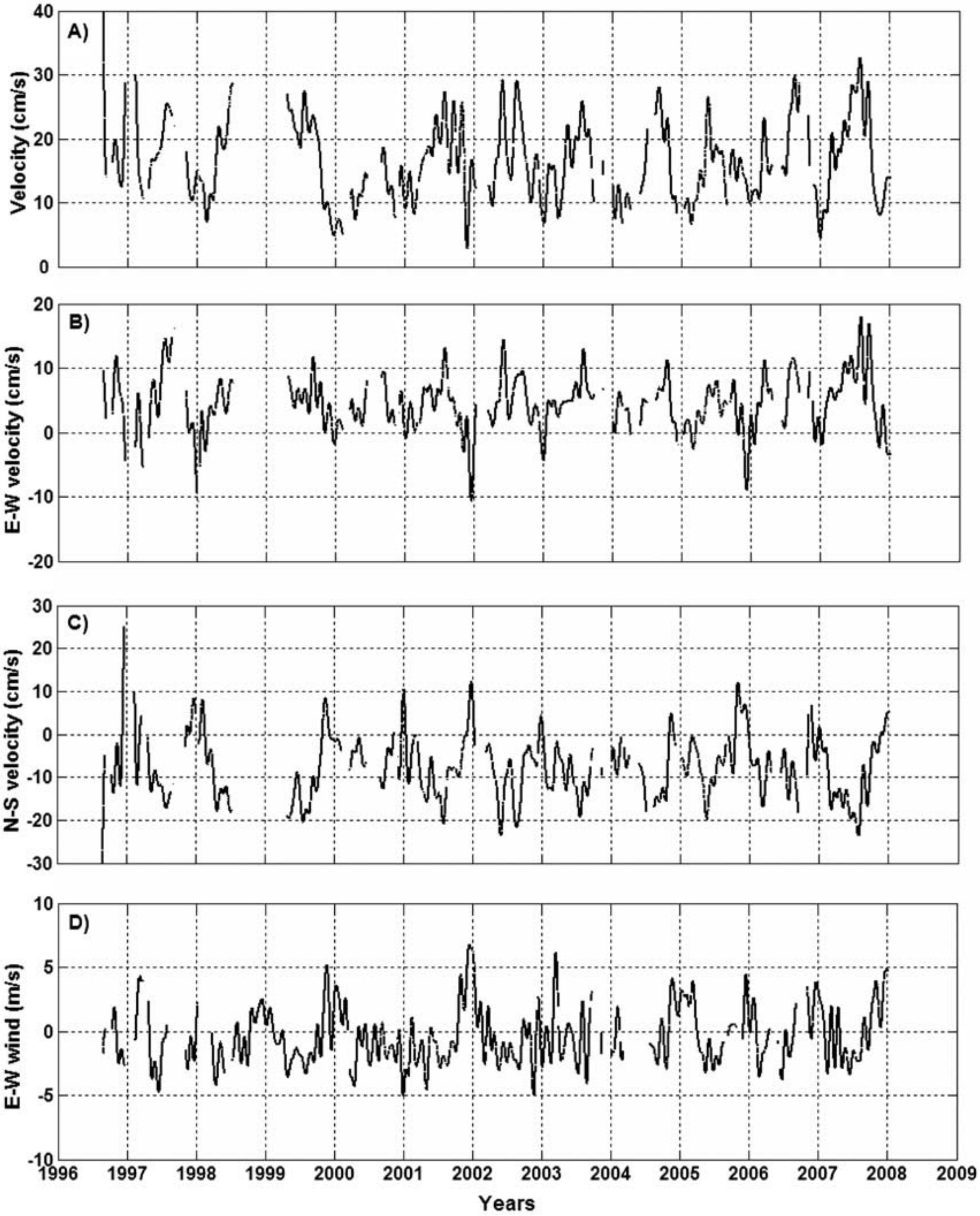

Figure 2. (a) Modulus, (b) zonal (positive eastward), and (c) meridional (positive northward) components of the low-pass filtered surface velocity and (d) zonal wind (positive easterlies, meteorological convention) registered by the RAP buoy (see Figure 1 for location) for the period 1996–2007.

values (~5 cm s^{-1}) concentrate at the beginning and end of the year. To estimate the seasonal cycle and diagnose trends, the series from 2000 onward (when gaps are less frequent and data become more reliable) has been least squares fitted to the following function:

$$y = a_0 + a_1 t + A_1 \cos(\omega_1 t - \varphi_1) + A_2 \cos(\omega_2 t - \varphi_2) \qquad (1)$$

that includes annual (ω_1) and semiannual (ω_2) frequencies. The semiannual amplitude turned out to be an order of magnitude smaller than the annual amplitude and results do not vary significantly when considering only the annual oscillation. An annual amplitude of 5.44 cm s^{-1} and a phase of 212°, which means maxima at the end of July and minima at the end of January is observed. Superposed to the annual oscillation, a positive trend of 0.63 cm s^{-1} a^{-1} is found, which probably arises as consequence of the 2006 and 2007 enhanced values (maximum of 29 cm s^{-1} and 32 cm s^{-1}, respectively).

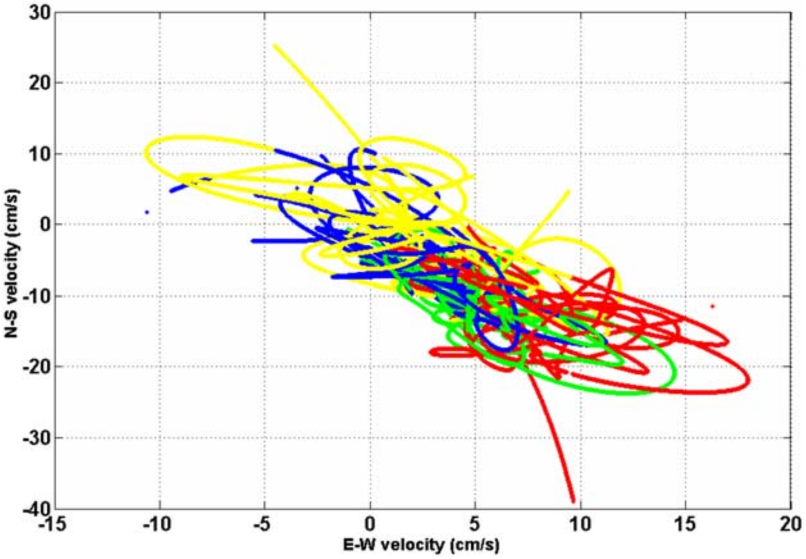

Figure 3. Combination of the zonal (E–W, positive eastward) and meridional (N–S, positive northward) components of surface velocity for spring (green), summer (red), autumn (yellow), and winter (blue) seasons for the period 1996–2007. A southeastward circulation pattern is observed during greater part of the year, more intense during spring and summer months. Flow reversals during autumn and winter months are also observed.

[13] The combination of the zonal and meridional components of velocity (Figure 3) points to a southeastward circulation during greater part of the year, more intense during spring and summer months (green and red dots in Figure 3). But there are also evidences of flow reversals during autumn and winter months (yellow and blue dots in Figure 3) that change to northwestward suggesting cyclonic surface circulation, a fact that was put forwarded by *García-Lafuente and Ruiz* [2007] and that agrees with the previous reports of *Álvarez et al.* [1999]. Figures 2b and 2c help to clarify this: zonal (positive eastward) velocity is positive during almost all the year. It is only during short periods at the beginning and end of the year (late autumn and early winter) that it becomes negative and the flow is westward (see years 1997, 2001, 2002, 2005 and also years 1999, 2000, and 2004 to a lesser extent). The meridional (positive northward) component of the velocity (Figure 2c) is negative during almost all the year (southward flow) but it changes sign during the short periods when the zonal component reverses, at the beginning and/or end of the year. This is a rather recurrent feature detected all years except at the end of 1998 and 2003, where data are not available. The reversals are also subject to interannual variability, being more intense at the end of years 2001 and 2005.

[14] The surface anticyclonic circulation in the northern Gulf of Cadiz has been extensively reported in the literature [*Rubín et al.*, 1997, 1999; *Sánchez and Relvas*, 2003; *Criado-Aldeanueva et al.*, 2006a; *García-Lafuente et al.*, 2006]. As far as observations at RAP position are representative of the open sea circulation, it is also confirmed from this data set and appears to be an almost permanent feature that reaches maximum strength by the end of July. However, owing to the bias of oceanographic surveys toward spring-summer, there are only few indirect indicators of the winter circulation. 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 is anomalously warm in winter and appears to come from the interior of the Gulf of Cadiz, which is suggestive of cyclonic circulation. The model of the northern Canary current system by *Batteen et al.* [2000] is suggestive of this seasonal bimodality, showing anticyclonic circulation in spring-summer and cyclonic-like in winter. From our data set, it has now been showed that seasonal flow reversals in late autumn-early winter (preferably December and January) are a rather recurrent feature with variable intensity depending on the year. However, it is difficult to find in situ observations that capture this cyclonic circulation. *Mauritzen et al.* [2001], based on data collected in October 1995, report cyclonic circulation with surface waters flowing westward along the western shelf but it might be more likely related to the cyclonic cell over the western continental shelf described by *García-Lafuente et al.* [2006] than to a general cyclonic circulation over the basin.

[15] Figure 4 shows that the geostrophic velocity referred to 300 db for the winter (Figure 4a) and summer (Figure 4b) computed from CTD data of year 1999 surveys also fails in evidencing this cyclonic pattern and anticyclonic circulation is found to prevail in both surveys. Since the flow reversals take place mainly in December and January, this result was expectable to a certain extent. It also happens that relatively short duration of the cyclonic-favorable conditions may be insufficient to produce the reversal in the geostrophic velocity field. However, it is worth to mention the sharp southward orientation of the flow from ~7°W in the winter survey, whereas in summer the southeastward orientation is preferred, a fact also observed in GOLFO 2001 (May–June 2001) surveys [*Criado-Aldeanueva et al.*, 2006a]. Although there are no data available from the RAP buoy in winter 1999, the observed reduction of the zonal velocity in the

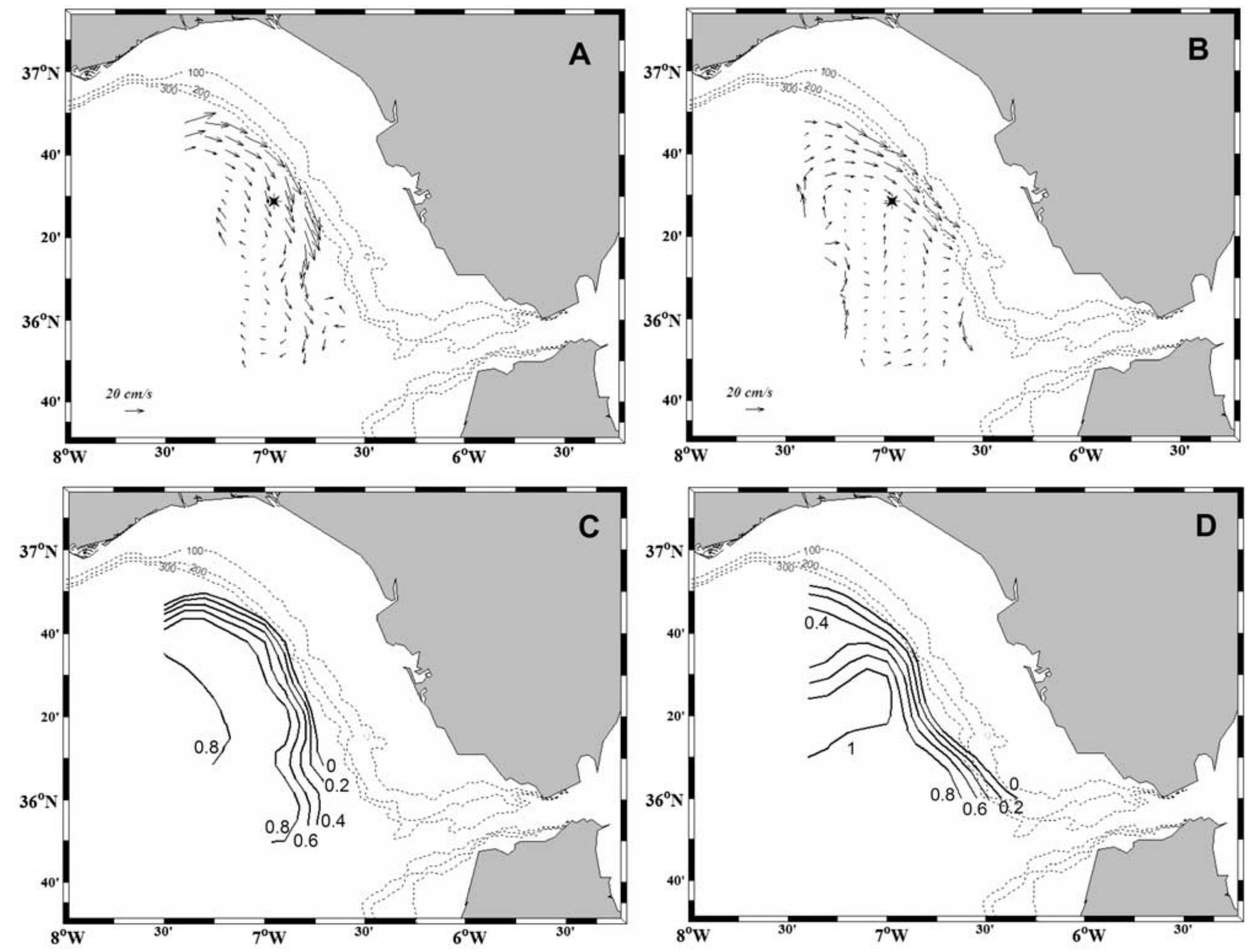

Figure 4. (a) Geostrophic surface velocity referred to 300 db for the winter (February 1999) survey, (b) the same as before for the summer (June 1999) survey, (c) geostrophic transport (Sv) referred to 300 db for the winter survey, and (d) the same as before for the summer survey. The stars mark the position of the Red de Aguas Profundas (RAP) oceanographic buoy. Notice the sharp southward orientation of the flow from ~7°W in the winter survey, whereas in summer the southeastward orientation is preferred.

winter survey agrees with current meter observations for the same period in other years (Figure 2b).

[16] The open sea geostrophic volume transport referred to 300 db (Figures 4c and 4d) also exhibits seasonal variability. In the summer survey (Figure 4c), ~0.8 Sv (Sverdrup, 1 Sv = 10^6 m^3 s^{-1}) are likely to flow toward the Strait of Gibraltar while the 1 Sv isoline veers southward toward the Atlantic to feed an anticyclonic gyre or to form an eastern boundary current that will merge the Canary Current further downstream in good agreement with both the spring-summer circulation pattern described in the literature [*Sánchez and Relvas*, 2003; *Criado-Aldeanueva et al.*, 2006a; *García-Lafuente et al.*, 2006] and the historical values of the estimated transport through the Strait [*Bryden et al.*, 1994; *Baringer and Price*, 1997]. In the winter survey (Figure 4d), less volume transport seems to enter the Strait (~0.6 Sv) and the 0.8 Sv isoline recirculates toward the Atlantic, a fact that may be ascribed to the lower velocities observed during this season (Figure 2a) and also to the inflow annual signal that reaches minimum in late winter [*García-Lafuente et al.*, 2002]. This result must be considered with caution since possible inputs from the continental shelf have been ignored as no data are available for its computation. In spring-summer, the circulation over the eastern continental shelf consists in a cyclonic cell [*García-Lafuente et al.*, 2006], so that the ignored transport cannot be all that considerable but in winter an eastward current replaces the cyclonic cell (see section 3.2 for details) and can contribute to increase the transport. Notice also that the sharp southward orientation of the isolines in winter suggests that the inflow toward the Strait of Gibraltar appears to come from the central/southern part of the Gulf of Cadiz, as suggested by *Folkard et al.* [1997], whereas in summer it would come from the northern Gulf of Cadiz.

[17] To explore the driving mechanism for the seasonal variability, wind records from the RAP buoy have been analyzed (Figure 2d). Owing to its offshore location, they are thought to be representative of the mean wind field over the Gulf of Cadiz. A predominantly negative zonal component (that is, westerlies, now meteorological criterion is

Table 1. Monthly North Atlantic Oscillation Indices of the Months Prone to Flow Reversals for the Period 1996–2006[a]

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Nov	−0.05	−0.99	1.13	0.30	−0.24	0.01	−0.27	0.31	−0.55	−1.01	1.70
Dec	−4.70	−0.20	1.95	2.13	−1.41	−2.25	−0.98	−0.85	1.27	−0.81	3.08
Jan	–	−1.95	−0.28	0.90	0.35	0.02	2.31	0.15	0.20	1.82	0.10

[a] North Atlantic Oscillation index for September and October 1999 (not shown) was −0.51 and −0.69, respectively. Flow reversals are November–January.

used) is observed. Easterlies tend to concentrate in late autumn-early winter. Winters of 1999–2000, 2001–2002, 2004–2005 and 2005–2006 present the most intense episodes, showing good correlation between the zonal wind and the surface circulation. Anticyclonic circulation seems to be associated with westerlies during great part of the year whereas autumn-winter flow reversals take place under easterlies, a good example of which are those at the end of years 2005 and, especially, 2001.

[18] Wind cannot be the only forcing mechanism however. For instance, the strong and persistent episode of easterlies of autumn-winter 2004–2005 was not followed by appreciable flow reversal. Anomalous large-scale atmospheric patterns over the North Atlantic are expected to influence the ocean circulation. For example, *Ambar et al.* [1986] suggested that the intense poleward current off Iberia during the winter of 1983 was associated to an anomalous southward displacement of the Azores high. Such displacements, which are well monitored by the NAO index, may influence similarly the surface circulation in the Gulf of Cadiz. For this reason, some correlation between the occurrence of flow reversals and anomalous NAO index is likely to take place. Table 1 shows this index for November, December, and January months from 1996 onward. During the enhanced flow reversal of year 2001, the December NAO index reached one of the highest negative values (anomalous southward displacement of the Azores high) of the decade. The highest value of December1996 was accompanied by the strongest reversal of the meridional component of the velocity. December 2005 also had a negative index which was preceded by the highest negative value of all Novembers. Similar comments are applied to the reversals of winters 1997–98 and 2002–03 (Figure 2b) and the negative NAO indices of the corresponding November and December months. However, the correlation is not a rule as can be observed in winters 2006–07 or 1999–2000 when flow reversals, though small, take place with positive NAO index. In this last case, the reversal seems to take place earlier, in midautumn rather than in December (Figure 2c) and the NAO index does become negative during these months (−0.51 and −0.69 in September and October, respectively). What seems to be drawn from this analysis is that the simultaneity of negative NAO index (remote atmospheric forcing) and negative zonal wind stress (easterlies) over the Gulf of Cadiz (local forcing) in winter months, triggers short-living flow reversals observed during this season. Although the agreement is quite suggestive, it is far from definitive and longer series are necessary to test the correlation.

[19] A third possibility worthy to be mentioned is the progressive homogenization of the water column that takes place in winter. As it happens, the baroclinic compensation originated by the inhomogeneous mass field that maintains the anticyclonic flow along the continental slope moving opposite over the swift Mediterranean undercurrent, tend to disappear and the entrainment of Atlantic water by the Mediterranean overflow can extent more easily to near-surface layers, propitiating a more barotropic motion of the whole water column. A similar seasonal behavior has been observed in the Balearic channels, inside the Mediterranean Sea [*García-Lafuente et al.*, 1995]. With this preconditioning, no particularly strong external forcing would be needed to reverse the surface circulation along the slope. Should this be the mechanism (or at least part of it), the Atlantic inflow in winter would approach the Strait of Gibraltar from the south propitiating a deep-reaching generalized cyclonic circulation in the Gulf of Cadiz in the manner described by *Mauritzen et al.* [2001]. The more likely situation is the concomitant effect of all three factors, that is, local (wind-stress) and remote (NAO index) atmospheric forcing along with the water column homogenization. All them exhibit interannual variability and so it does the pattern and strength of the surface circulation.

3.2. Circulation Over the Continental Shelf

[20] The 2001–2005 years of current meter observations in the inner continental shelf of the northeastern Gulf of Cadiz are now analyzed to investigate links with the open sea circulation. During winter and spring 2002 (Figure 5a), the along-coast velocity was predominantly positive (except for a short episode in March), thus flowing toward the Strait. From July (maybe from mid-June) to October the along-coast velocity was mainly negative, which indicates a westward flow compatible with the development of a coastal countercurrent during this period. During year 2004 (Figure 5b), the flow was eastward from January to June. In June and July, westward flow (that is, the coastal countercurrent) was dominant and a westward episode was also observed in September. From then onward, the eastward flow is recovered. During year 2005 (Figure 5c), the presence of the coastal countercurrent seems to be restricted to isolated events in March, July, and September–October. Perhaps the lack of data between April and June hampers the detection of the westward flow more continuously. The RCM-9 (continental shelf) and RAP (open sea) data have been superimposed in Figure 5 to highlight the anticorrelation between the circulation patterns over the two regions during certain parts of the year. This anticorrelation is more evident during summer 2002 and 2004, when the coastal countercurrent (westward flow) was well developed and the open sea circulation was clearly anticyclonic (eastward flow). But it is also worth mentioning the episode of December 2005, with an eastward flow over the continental shelf and a cyclonic reversal of the open sea circulation.

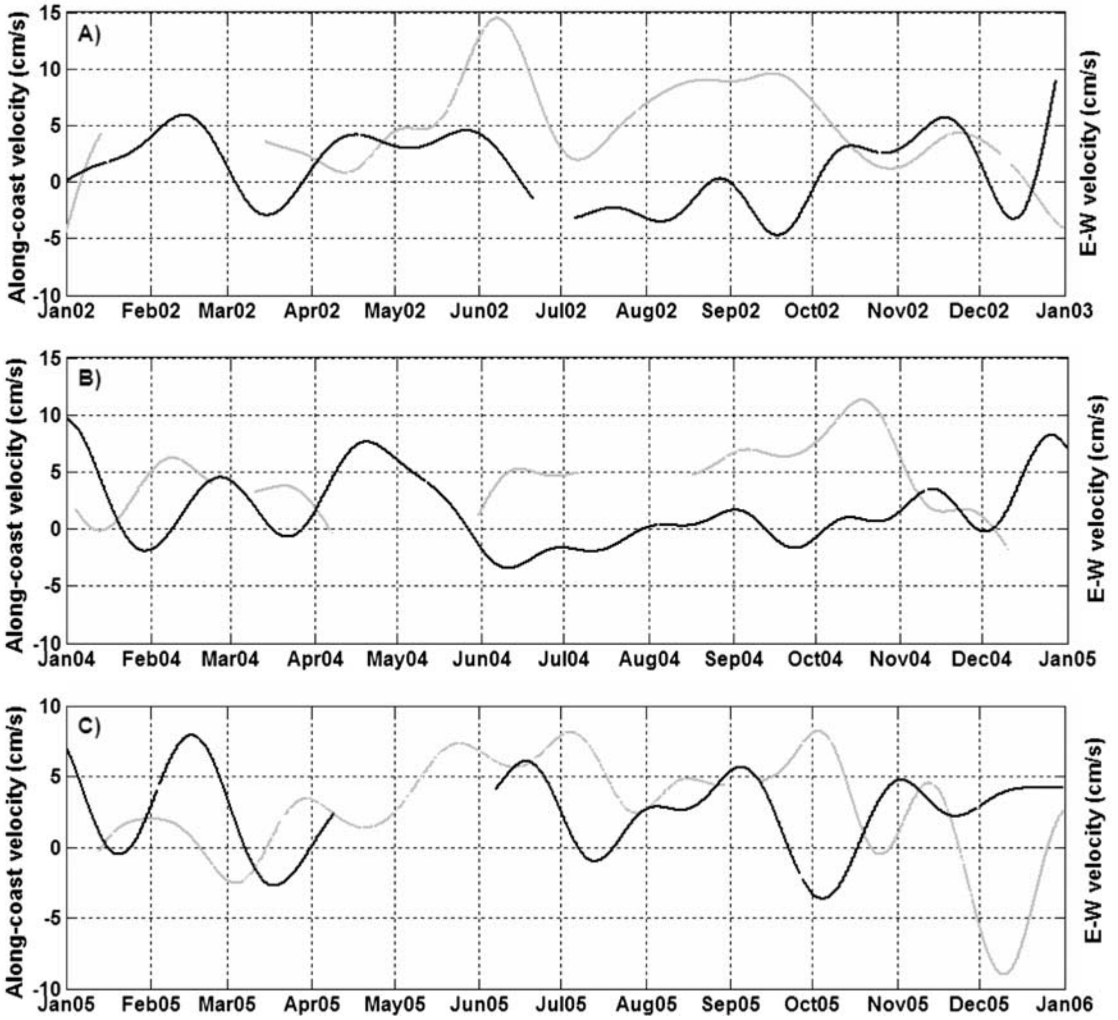

Figure 5. Along-coast (positive eastward) component of the low-pass filtered surface velocity (black line) registered by RCM-9 current meter (see Figure 1 for location) during years (a) 2002, (b) 2004, and (c) 2005. Year 2003 has not been analyzed because very few data are available. The RAP buoy data for the same period have been superimposed (grey line) to highlight the anticorrelation between the circulation patterns over the inner and outer regions during certain parts of the year.

This anticorrelation is also reflected in the circulation scheme proposed in Figure 6.

[21] There are many references to a coastal countercurrent of relatively warm waters that flow westward near the shore on the eastern shelf and, eventually, on the western shelf during spring-summer [*Fiúza*, 1983; *Relvas and Barton*, 2002, 2005; *Sánchez and Relvas*, 2003; *García-Lafuente et al.*, 2006]. *García-Lafuente et al.* [2006] have suggested that tidally driven buoyancy inputs from Gudalquivir river and marshes nearby Cádiz embayment can contribute to set out the alongshore pressure gradient necessary to drive the flow. The dominant physical process mentioned by these authors is the flooding of marshes heated by sun radiation during low tide and the energy brought back to the sea during ebb tide that produce a positive daily averaged heat export form land to sea (that is, positive buoyancy input) and help to maintain a signature of warm water in and near the Guadalquivir river mouth and Cádiz embayment from April to October [*Folkard et al.*, 1997; *Vargas et al.*, 2003; *Navarro*, 2004; *Criado-Aldeanueva et al.*, 2006a, 2006b]. The presence of Cape St. Maria makes the coastal countercurrent partially recirculate and feed an eastward flow that closes a cyclonic mesoscale cell over the eastern shelf during spring-summer.

[22] In winter, changes in the coastal countercurrent are expectable for two reasons: first, the eastward flow that closes the cyclonic cell would weaken or disappear if the open sea circulation reverses to cyclonic (see section 3.1). This would have an impact on the circulation over the eastern shelf, which could not hold the closed cyclonic cell any longer and therefore could not favor the maintenance of the coastal counterflow. Second, the buoyancy input at Guadalquivir river mouth stops because in autumn-winter 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. Therefore, the alongshore sea level slope that would drive the coastal current and the current itself tend to disappear.

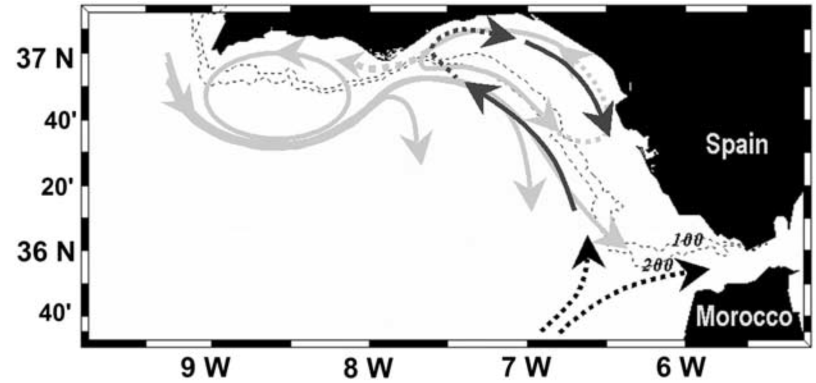

Figure 6. Sketch of the surface circulation in the Gulf of Cadiz as deduced from our analysis. Gray lines correspond to the spring-summer circulation proposed by *García-Lafuente et al.* [2006]. Black lines indicate the open sea late autumn–early winter flow reversals and the eastward current that replaces the cyclonic cell over the eastern continental shelf. The dashed lines indicate the likely closure of the cell and the suggested inflow to the Strait of Gibraltar from the interior of the Gulf of Cadiz, although there are no data to support these hypotheses.

[23] Our analysis has confirmed that the circulation over the continental shelf is subject to seasonal and interannual fluctuations. The coastal countercurrent that closes the mesoscale cyclonic cell over the eastern shelf is likely to be a spring-summer (upwelling season) feature that is replaced by and eastward current in autumn and winter. However, this behavior is sensitive to interannual variability: during year 2005 the presence of the coastal countercurrent in spring and summer seems to be less frequent and intense than during years 2002 and 2004. Of course, larger time series will be of great help to establish definitive conclusions.

4. Summary and Conclusions

[24] An 11-year (1996–2007) time series of current meter observations representative of the open sea circulation; a 4-year (2001–2005) time series of current meter records over the continental shelf and CTD data collected during oceanographic surveys carried out in different seasons have been compared in order to study the seasonal and interannual variability of the surface circulation in the eastern Gulf of Cadiz.

[25] A seasonal cycle with annual amplitude of 5.44 cm s^{-1} and phase of 212° (maxima at the end of July and minima at the end of January) have been observed for the open sea velocity. Some current intensification is also suggested during the last years (29 cm s^{-1} and 32 cm s^{-1} for 2006 and 2007, respectively) and an increasing trend of 0.63 cm s^{-1} a^{-1} is found for the whole decade. The open sea velocity records in RAP position points to a southeastward circulation during greater part of the year, compatible with a generalized open sea anticyclonic surface pattern circulation, which is enhanced during summer months in good agreement with in situ observations collected in summertime [*Rubín et al.*, 1997, 1999; *Sánchez and Relvas*, 2003; *Criado-Aldeanueva et al.*, 2006a; *García-Lafuente et al.*, 2006]. But there is also evidence of flow reversals during late autumn-early winter (preferably December and January) that change to northwestward suggesting cyclonic surface circulation (Figure 6). These reversals had been a rather speculative hypothesis based on indirect indicators and only confirmed by 1-year RAP records by *Álvarez Fanjul et al.* [1999]. Now, it is shown that flow reversals are a rather recurrent feature with variable intensity depending on the year. Correlation between the zonal wind and the surface circulation is also evidenced. The anticyclonic circulation seems to be associated with westerlies during greater part of the year whereas flow reversals take place under easterlies episodes. Large-scale atmospheric patterns over the North Atlantic, roughly represented by the NAO index, also influence the ocean circulation since the simultaneity of negative NAO index (remote atmospheric forcing) and negative zonal wind stress (easterlies) over the Gulf of Cadiz (local forcing) in winter months, triggers short-living flow reversals observed during this season. Finally, the progressive homogenisation of the water column that takes place in winter could extend the entrainment of Atlantic water by the Mediterranean overflow to layers closer to the surface, preconditioning the scenario of flow reversals that will not need strong external forcing to take place. This circumstance would also propitiate a deep-reaching generalized cyclonic circulation in the Gulf of Cadiz.

[26] Changes in the mainly wind-driven large-scale surface circulation in the Gulf of Cadiz are echoed by the shelf circulation, which is also subject to seasonal and interannual fluctuations. If the open sea circulation reverses to cyclonic, the eastward flow that closes the cyclonic cell would weaken or disappear. Also, the buoyancy input at Guadalquivir river mouth stops in autumn-winter because the land imports heat from the sea. It has been showed that the coastal countercurrent that closes the mesoscale cyclonic cell over the eastern shelf is a spring-summer (upwelling season) feature that is replaced by and eastward current in autumn and winter (Figure 6). However, this behavior is sensitive to interannual variability: during year 2005 the presence of the coastal countercurrent in spring and summer seems to be less frequent and intense than during years 2002 and 2004.

[27] Concluding, combination of the open sea and continental shelf circulation patterns has made it possible to complete the scheme proposed by *García-Lafuente et al.* [2006] for spring-summer and account for the late autumn-early winter flow reversals and the disappearance of the coastal countercurrent (and the cyclonic cell) over the eastern shelf in autumn and winter (Figure 6).

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F. Criado-Aldeanueva and J. García-Lafuente, Grupo de Oceanografía Física, Departmento Física Aplicada II, E.T.S.I. Informática, Universidad de Málaga, Campus de Teatinos, E-29071 Málaga, Spain. (fcaldeanueva@ctima.uma.es)

G. Navarro and J. Ruiz, Instituto de Ciencias Marinas de Andalucia, CSIC, E-11510 Puerto Real, Cadiz, Spain.