ELSEVIER

Journal of Marine Systems 35 (2002) 229–248

JOURNAL OF MARINE SYSTEMS

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About the seasonal variability of the Alboran Sea circulation

M. Vargas-Yáñez [a,*], F. Plaza [b], J. García-Lafuente [b], T. Sarhan [a], J.M. Vargas [b], P. Vélez-Belchi [c]

[a] Instituto Español de Oceanografía, C.O. Málaga (Fuengirola), Puerto Pesquero de Fuengirola, 29640, Fuengirola, Málaga, Spain
[b] Dept. Física Aplicada II, Universidad de Málaga, Málaga, Spain
[c] Instituto Español de Oceanografía, C.O. Canarias, Spain

Received 13 September 2000; accepted 28 March 2002

Abstract

Data from a mooring line deployed midway between the Alboran Island and Cape Tres Forcas are used to study the time variability of the Alboran Sea from May 1997 to May 1998. The upper layer salinity and zonal velocity present annual and semiannual cycles characterised by a minimum in spring and autumn and a maximum in summer and winter. Temperature has the opposite behaviour to that of salinity indicating changes in the presence of the Atlantic water within the Alboran Passage. A large set of SST images is used to study these cycles. The decrease of salinity and velocity in our mooring location in spring and autumn seems to be related to the eastward drifting of the Western Alboran Gyre (WAG). The increase of salinity and velocity is caused by the Atlantic current flowing south of the Alboran Island and its associated thermohaline front. Conductivity–temperature–depth (CTD) data from two cruises along the 3°W are coherent with current meters and SST interpretations. During the period analysed, summer months are characterised by the stability of the two-gyre system, while in winter, the circulation is characterised by a coastal jet flowing close to the African shore. We use sea level differences across the Strait of Gibraltar for studying the variability of the Atlantic inflow. We discuss the changes in the Alboran Sea circulation and its relation with the variability of the inertial radius of the Atlantic inflow. Though our results are speculative, we find a possible relation between the disappearance of the two-gyre system and a reversal of the circulation in Gibraltar. Longer time series are needed to conclude, but comparison with previous works makes us think that the seasonal cycle described from May 1997 to May 1998 could be the most likely one for the Alboran Sea upper layer.

Keywords: Alboran Sea; Seasonal variability; Gibraltar Strait

1. Introduction

The Alboran Sea is the westernmost basin of the Mediterranean Sea. Its circulation and water masses are coupled to the exchange through the Strait of Gibraltar, originated by the excess of evaporation over precipitation and river runoff in the Mediterranean. This deficit produces a thermohaline circulation that can be summarised as Atlantic water flowing at the surface of the strait into the Alboran Sea, and saltier and denser Mediterranean water flowing at depth toward the Atlantic. As the Atlantic current progresses into the Mediterranean, it changes its properties due to sea-air fluxes and mixing with resident Mediterranean waters. These changes start in the Alboran Basin, so

* Corresponding author. Tel.: +34-95-2471907; fax: +34-95-2463808.
E-mail address: manolo.vargas@ma.ieo.es (M. Vargas-Yáñez).

PII: S0924-7963(02)00128-8

we can consider its upper layer as filled by surface Atlantic water, more or less modified, and with a variable thickness depending on its geographical location.

The classical circulation pattern in the upper layer of the Alboran Sea is a swift Atlantic current surrounding and feeding two anticyclonic gyres: The Western Alboran Gyre and the Eastern Alboran Gyre (WAG, EAG). The strong thermohaline gradient associated to the Atlantic current makes both gyres clearly visible in SST satellite images. Nevertheless, this scheme presents a high temporal variability.

First works in the Alboran Sea are based on hydrology surveys where data are considered as synoptic. Time variability cannot be studied directly from these surveys. Nevertheless, the comparison between different cruises evidences the existence of time variability.

Lanoix (1974) analysed a cruise carried out in August 1962. In this work, the Atlantic current surrounds the WAG and then flows into the eastern basin close to the African shore. The eastern basin is occupied by a large area of cyclonic vorticity. In May/June 1973 and November 1978 (Cano, 1977; Cano and Gil, 1984), the situation was very similar to that described by Lanoix. In August 1976 (Cano, 1978), both the WAG and the EAG were fully developed.

A first attempt to study time variability in the Alboran Sea upper layer is due to Cheney and Doblar (1982). These authors compare two cruises (by aircraft and ship) 10 days apart. During the first cruise, the WAG was displaced to the east, and a second and smaller anticyclonic gyre was constrained against the African coast, southeast of Ceuta. During the second cruise, the WAG was well developed and had recovered its usual position. These authors, following Crepon (1965), argue that the anomalous situation during the first cruise was due to a decrease of the atmospheric pressure over the Western Mediterranean and westerly winds in Gibraltar.

In April 1980 (Parrilla, 1984), the WAG was in a similar situation to that reported by Cheney and Doblar (1982). Parrilla (1984) also reported an important decrease of atmospheric pressure over the Western Mediterranean previous to the cruise.

Conclusions of Crepon (1965), Cheney and Doblar (1982) and Parrilla (1984) can be summarised as follows: The decrease of atmospheric pressure over the Western Mediterranean produces a larger and faster Atlantic inflow. In this situation, the Atlantic jet is displaced southward pushing the WAG to the east.

Perkins et al. (1990) show an even more dramatic southward drift of the Atlantic jet during September 1982. In this case, the Atlantic jet flows close to the African coast once it exits the Strait of Gibraltar. This episode was reported by in situ current measurements and SST satellite images. Authors also consider that these changes are due to the variability of the Atlantic inflow forced by meteorological factors, but in this case, the explanation proposed is different: Low pressure over Azores Islands produced downwelling in the Gulf of Cadiz and the consequent increase of positive vorticity in the Atlantic inflow.

According to first works already commented, it could be concluded that the WAG was a quasi-permanent feature of the Alboran Sea circulation while the EAG was more elusive (Lafuente et al., 1998). Heburn and La Violette (1990) conclude from the analysis of a large set of SST images covering the years 1982 and 1986 (and two months of 1985), that both gyres have a similar time variability.

The more recent use of remote sensing techniques allows the study of very low frequency variability as seasonal cycles. Parada and Cantón (1998a) conclude from the analysis of SST images corresponding to 1993, that the WAG is a more stable structure while the EAG is more variable. García-Górriz and Carr (1999) also study the seasonal variability of the Alboran Sea using SST images, but they do not focus on the different circulation patterns. These authors find that there is a seasonal cycle in the temperature differences between the Alboran Sea and the Atlantic, being the former warmer in summer and cooler in winter. Vázquez-Cuervo et al. (1996) use altimeter data corresponding to years 1992 and 1993 to study the Alboran Sea circulation. Viúdez et al. (1998a) present part of the semiannual cycle of sea level residuals. These authors also report that annual and semiannual cycles account for the 50% of the time variability in sea level residuals.

Bormans and Garrett (1989) relate the presence of the WAG to the variability of the Atlantic jet through Gibraltar. After an extensive review of different numerical, analytical and laboratory models, Bormans and Garrett conclude that the key parameter for the formation of the WAG is the ratio between the inertial radius of the Atlantic inflow and the topographic curvature radius at the eastern side of Gibraltar. The Atlantic jet will develop the WAG for values of this parameter higher than 1, and will flow close to the African coast for values lower than 1.

Parada and Cantón (1998b) consider that the highest probability of formation of the WAG is in summer when, according to Ovchinnikov (1974), the Atlantic inflow is higher. On the other hand, Parada and Cantón report that the two-gyre system is not present in winter for the year 1993, when the Atlantic inflow is minimum. If we accept the theory by Bormans and Garrett (1989), higher inflow in summer will produce larger values of the ratio inertial radius/topographic radius, while this will be lower in winter. Lafuente et al. (accepted for publication) also obtain maximum values for the Atlantic inflow in summer, in agreement with Ovchinnikov and Parada and Cantón. Nevertheless, this point is subject to some controversy as Garrett et al. (1990) report a clear seasonal cycle in the along strait sea level drop. They infer from this cycle that the maximum inflow is in March.

Despite the discrepancies between the different works reviewed, there seems to exist a certain agreement in that the Alboran Sea presents both annual and semiannual variability and that it is related to the Atlantic inflow through Gibraltar. This inflow also exhibits time variability, both at seasonal and at shorter time scales. The atmospheric forcing (mainly atmospheric pressure in the Western Mediterranean and winds in Gibraltar) also plays an important role.

The presence or absence of the two-gyre system has important consequences, not only on the physical oceanography of the Alboran Sea, but on its biological productivity, as their north and northeast contours form very intense fronts with high productivity (Rodríguez et al., 1994; Rubín et al., 1995, 1997; Tintoré et al., 1988). Vertical velocities associated to these structures have been studied at different length scales (Tintoré et al., 1991; Viúdez et al., 1996) showing that large vertical velocities are associated to mesoscale eddies along the Atlantic current. Sarhan et al. (2000) have evidenced that southward drifts of the Atlantic jet are responsible for the upwelling of cool subsurface waters to the area left by the jet. During these transient episodes, there would be an increase in the nutrient supply to the surface layer.

To understand better this variability and to obtain some more evidences of a possible seasonal variability, the Instituto Español de Oceanografía (IEO) and Málaga University (UMA) deployed a mooring line in the Alboran Passage, midway between the Alboran Island and Cape Tres Forcas for a period of 1 year and in the frame of MATER II project. This information was analysed to the light of a large set of SST images covering the mooring period, and sea level data at the eastern side of the Strait of Gibraltar and meteorological data, both at the strait and in the Western Mediterranean. The data set analysed is presented in Section 2, and results in Section 3. A final summary and discussion are in Section 4.

2. Data set

From May 1997 to May 1998, an array with five current meter recorders was placed at $35°41.6'$ N $3°0.9'$ W, midway between Alboran Island and Cape Tres Forcas (Fig. 1). All instruments measured temperature, conductivity, pressure and velocity (intensity and direction) at a sample interval of 1 h. The actual depth of the current meters (averaged values from pressure sensors) was 74, 117, 178, 358 and 770 m (hereon CM 1, 2, 3, 4, 5). Salinity time series were obtained using the Practical Salinity Scale (PSS78; Lewis, 1980). This location was chosen because it is into the theoretical path of the Atlantic jet flowing from the western to the eastern basin, so changes in both basins are supposed to have some influence on our mooring location. The three upper instruments were located at depths corresponding to the Alboran Sea upper layer, which is usually taken as the upper 200 m. The two deepest instruments were supposed to be placed under the influence of the Levantine Intermediate Water (LIW), between 200 and 600 m and the West Mediterranean Deep Water (WMDW), which flows below the former (Parrilla et al., 1986).

Meteorological data covering the mooring period (and a longer period in some cases) were obtained from the Instituto Nacional de Meteorología (INM). Daily atmospheric pressure averaged over the Western Mediterranean was collected from May 1997 to May 1998 from the daily bulletin of the INM. Values were obtained from synoptic maps representing weather conditions at 12:00 GMT. Atmospheric pressure

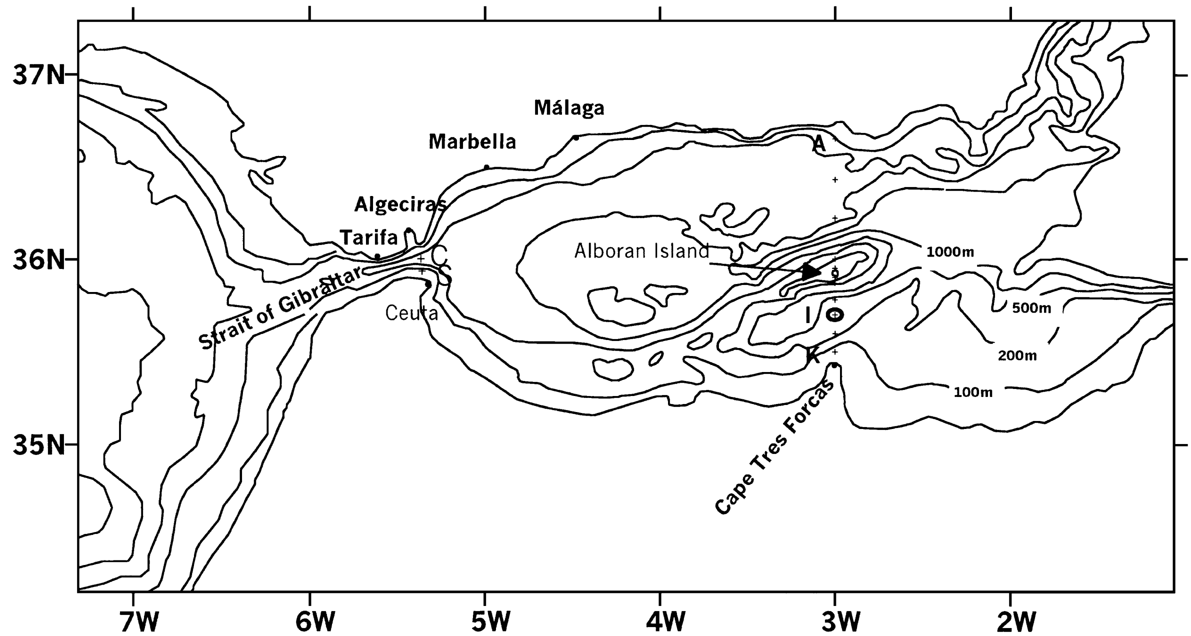


Fig. 1. Map of the Alboran Sea. CTD stations from the first cruise on May 1997 are marked with crosses and named with letters from A to K. Positions are the same for the November 1997 cruise; the only exception is that stations E and F were suppressed for being too shallow, and stations A and B could not be accomplished because of the weather conditions. The mooring line position is that of station I, marked with a circle. Letters C (centre) and S (south) in the eastern side of the Strait of Gibraltar are the positions of current meter moorings deployed in the frame of CANIGO project.

measured at Ceuta and Tarifa was recompiled from January 1995 to September 1998 while wind data (intensity and direction) at the same locations extend from January 1995 to December 1998. Pressure and wind series at Ceuta and Tarifa have four samples per day at 0:00, 06:00, 13:00 and 18:00 GMT.

Sea level data at Ceuta and Algeciras were used to get some information about the variability of the cross-strait sea surface slope, which can provide an estimation of the Atlantic inflow variability. Hourly data from January 1995 to May 1998 were obtained from the tide gauge network of the IEO. These estimates are also checked using direct measurements of currents in the eastern side of the Strait of Gibraltar taken in the frame of CANIGO project. We use data from two current meters placed at locations C (centre) and S (south) at the depths of 40 and 35 m (see Fig. 1). For each of these two locations, there were two periods overlapping that of our mooring. We call them C-I and C-II for the two current series at location C. They extend from July to September 1997, and from October 1997 to April 1998. For location S, the two subperiods used are S-I and S-II extending from July to November 1997 and from February to May 1998.

A large set of 208 SST satellite images from May 1997 to May 1998 was obtained from the DLR agency to infer time variability in the Alboran Sea circulation and contrast it with those patterns estimated from our current meter series.

Two oceanographic cruises were carried out for the deployment (May 1997) and service of the line (November 1997) on board the R/V Odón de Buen from IEO. These two cruises were used to perform two transects with a conductivity–temperature–depth (CTD) probe from the African to the Spanish shore, following approximately the 3°W where the mooring line was deployed (Fig. 1). CTD data were used to check those circulation patterns inferred from satellite images and the uppermost instruments during the days of the two surveys and for comparison with current meter sensors.

The time variability in which we are interested is the subinertial one. This term designs in this work those phenomena with periods ranging from several

Table 1
Length of the time series analysed

	Initial date	Time (GMT)	Final date	Time (GMT)
CM (1–5)	15/05/97	18:00	16/05/98	12:00
C-I	17/07/97	00:00	20/09/97	18:00
C-II	25/10/97	00:00	02/04/98	18:00
S-I	18/07/97	00:00	04/11/97	18:00
S-II	22/02/98	00:00	14/05/98	18:00
$P_{c,t}$	04/01/95	00:00	27/09/98	18:00
$W_{c,t}$	04/01/95	00:00	28/12/98	18:00
$\Delta\xi$	04/01/95	00:00	28/05/98	18:00
P_m	06/05/97	06:00	18/05/98	18:00

CM stands for the five current meter time series in location I (Fig. 1), C-I and C-II for subperiods 1 and 2 of mooring in site C, S-I and S-II are the same for the mooring in S. $P_{c,t}$ are atmospheric pressure series at Ceuta and Tarifa (Fig. 1), $W_{c,t}$ is the wind at the same locations, $\Delta\xi$ is the sea level difference between Ceuta and Algeciras, and P_m is the mean atmospheric pressure over the Western Mediterranean.

days to semiannual and annual cycles if existing. For this purpose, we eliminate from all time series (current meters, sea level and wind in Gibraltar) diurnal and semidiurnal variability and other high-frequency signals contributing to the variance of our original series. To do so, we use a cosine-Lanczos filter with a half power point at 0.44 cycles per day (cpd). This filter allows almost the total variance for frequencies higher or equal than 0.28 cpd, and eliminates practically all the variance for frequencies higher than 0.68 cpd. The definitive time series analysed in following sections were decimated (and interpolated in the case of meteorological data) to four daily data at 0:00, 06:00, 12:00 and 18:00 GMT. Table 1 shows the length of the final data set. The shortest time series are those from current meters in the Alboran Passage. This is considered in this work as the central period that we want to study. Longer time series were used only when necessary and for the main body of this work, the length of the different series was unified to that of the minimum one.

3. Results

3.1. Current meter time series

The Alboran Sea is usually considered as a two-layer sea. The upper Atlantic layer flows eastward while the lower Mediterranean layer flows westward. For dynamical proposes, the 200-db level is considered as the no motion level separating both layers. According to this simplistic scheme, the three upper instruments of our mooring line would be within the upper layer (74, 117, 178 m).

When averaging the zonal component of velocity (hereafter u, positive eastward), CM 1 and 2 have positive values different from zero at the 95% confidence level (Table 2). Though CM 3, 4 and 5 have also positive values, they are not different from zero at the same confidence level.

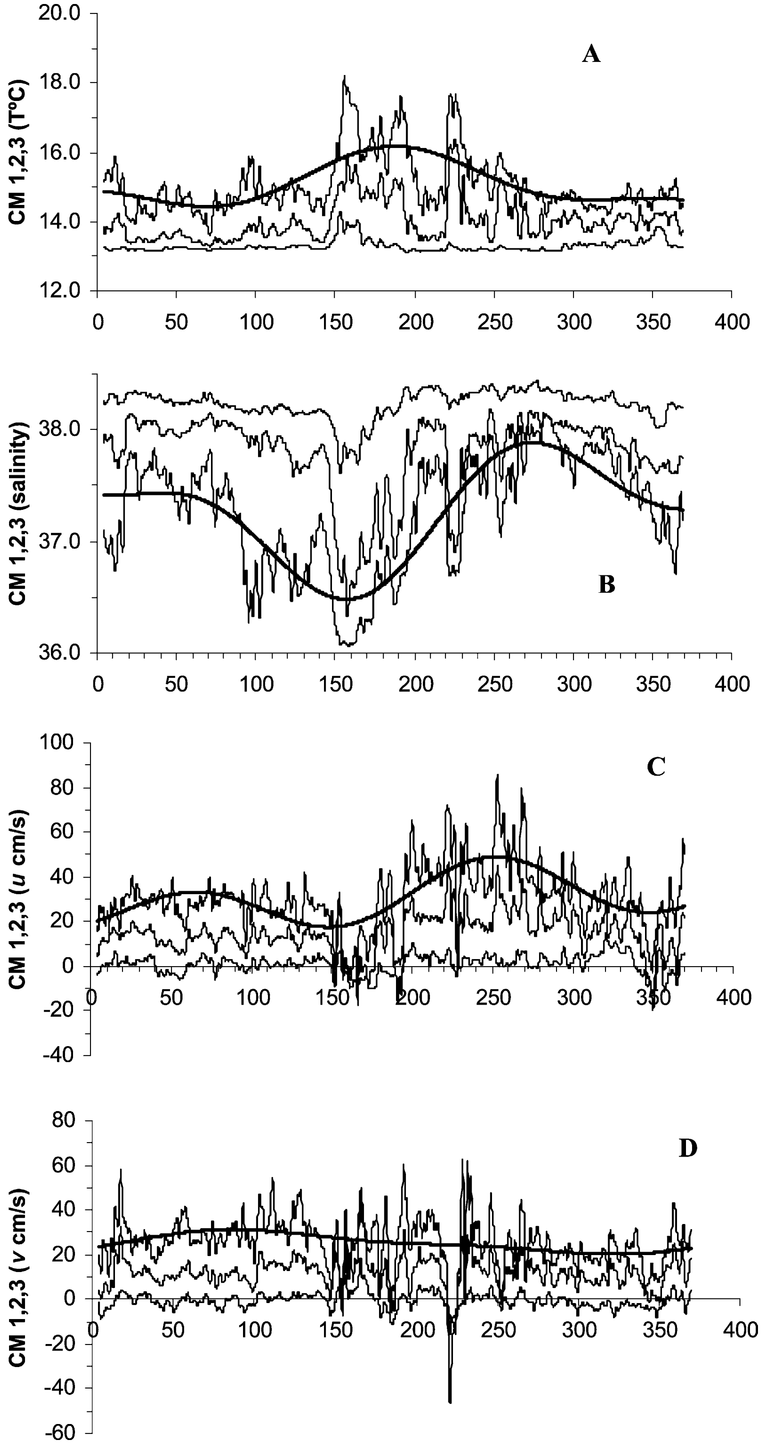
Fig. 2A–D show the low-pass series of temperature, salinity, u and v components of velocity for the three upper current meters. The variability of CM 3 seems to be similar to that of CM 1 and 2 and so we could consider that CM 3 belongs to the upper layer. Cross-correlation coefficients between CM 1 and 3 for the four variables analysed are 0.4, 0.8, 0.6 and 0.5. The same calculations for CM 3 and 4 are 0.3, 0.7, 0.4 and 0.6. The correlation between CM 1 and 3 is higher than between CM 3 and 4, except for the v component of velocity. If we compare CM 3 with CM 2, then the correlation is always higher than with CM 4. Cross-spectral coherence between u time series for CM 1 and 3 is around 0.6 (statistically significant at the 95% confidence level) for a range of frequencies between 0 and 0.15 cpd. For the same range of frequencies, the coherence between u component of velocity of CM 3 and 4 is around 0.4.

To investigate the vertical structure of the flow, we did an analysis in Empirical Orthogonal Functions (EOFs) for the u component of velocity of the five current meters. Fig. 3A is the vertical structure of the first EOF, accounting for the 52% of the total var-

Table 2
Mean values for temperature (T), salinity (S), u and v components of velocity for the five current meters in the Alborán Passage

	T (°C)	S	u (cm/s)	v (cm/s)
CM 1	15.08±0.47	37.26±0.24	10.86±4.88	5.43±5.34
CM 2	14.01±0.33	37.79±0.22	4.58±3.33	1.98±3.18
CM 3	13.30±0.12	38.23±0.10	0.89±2.65	−0.52±1.43
CM 4	13.13±0.02	38.49±0.01	0.41±0.54	−0.48±0.83
CM 5	12.97±0.01	38.48±0.04	0.43±0.54	0.58±0.75

Ninety-five percent confidence intervals are calculated according to Eq. (2a) and (2b).


20.0
18.0
16.0
14.0
12.0
CM 1,2,3 (TºC)
A
0 50 100 150 200 250 300 350 400
38.0
37.0
36.0
CM 1,2,3 (salinity)
B
0 50 100 150 200 250 300 350 400
100
80
60
40
20
0
-20
-40
CM 1,2,3 (u cm/s)
C
0 50 100 150 200 250 300 350 400
80
60
40
20
0
-20
-40
-60
CM 1,2,3 (v cm/s)
D
0 50 100 150 200 250 300 350 400

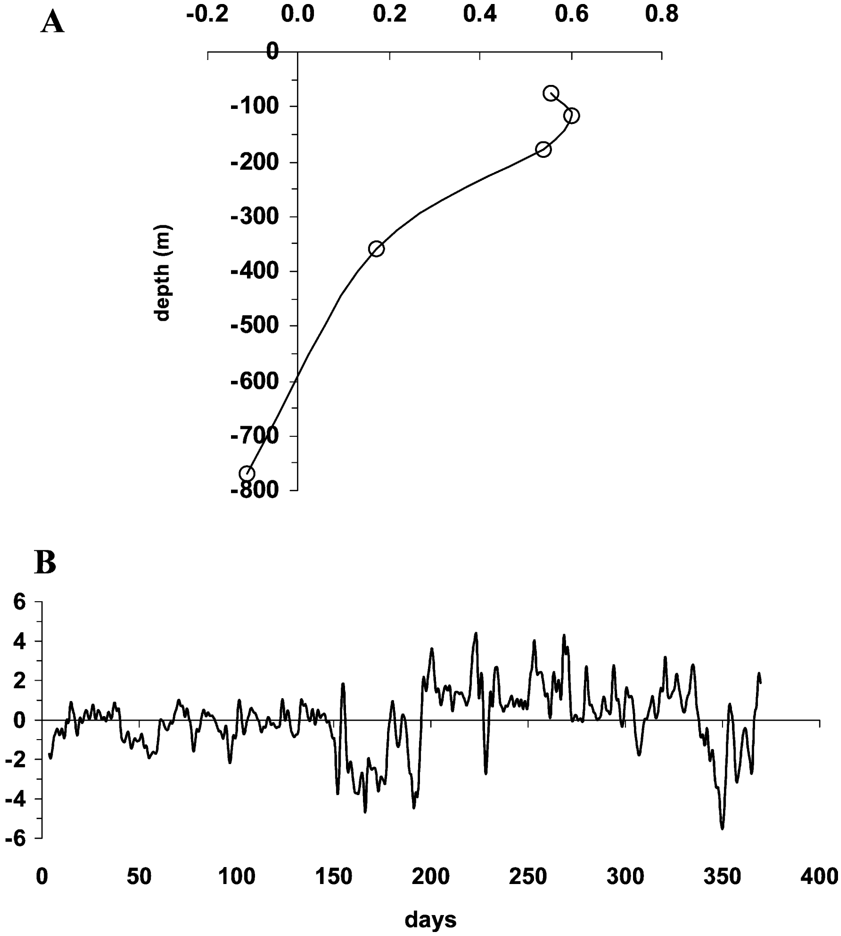


Fig. 3. (A) Spatial weights for the first EOF corresponding to u component of velocity. (B) Time evolution of the first EOF. Time origin is the same as in Fig. 2.

iance. Fig. 3B is its time evolution that is very similar to that of CM 1. Spatial (vertical) weights corresponding to this first EOF show very similar values for CM 1, 2 and 3. If we reconstruct time series of u component of velocity using only the first mode, we recover the 79% of the variance of the original series for the CM 1, and the 75% for CM 3.

We conclude that the upper 200 m can be considered as the upper layer attending to its similar variability. Nevertheless, the high correlation between the third and fourth current meter evidences that a two-layer scheme is too simplistic and a transition layer should be considered. High salinity values of CM 2 and 3 (see Table 2) also indicate that waters with

Fig. 2. (A) Thin lines are temperature low-pass series for current meters 1, 2 and 3. Time is expressed in days, being the origin the day 0 = 12/05/97. Thick line superimposed on CM 1 series is its annual and semiannual fit (see text, Section 3). As a reference, consider that day 234 is 01/01/98. (B) Thin lines are salinity series for CM 1, 2 and 3. Thick line is the least squares fit for CM 1. (C) Thin lines are u component of velocity (positive eastward) for CM 1, 2 and 3. To make distinguishable the three series, we have added a constant value of 20 cm/s to CM 1 and 10 cm/s to CM 2. Thick line is the fit for CM 1. See Table 2 for the true mean values of the series. (D) The same as in C for the v component of velocity (positive northward).

Mediterranean properties can be considered from a dynamical point of view as part of the upper layer. This fact simply reflects the different diffusion of properties as momentum and salinity.

Once we establish the common behaviour of the uppermost instruments, we will mainly focus on the first one, considering it as representative of the upper layer. We use these time series because of their larger variance, which makes more clearly visible the different phenomena we want to study.

CM 1 salinity series exhibits two relative minima at the beginning and the end of the series (May 1997 and May 1998) and a more pronounced minimum around day 160 (mid-October). Relative maximum are around days 60 and 280 (July and February). These values had a behaviour right opposite to that of temperature. Fresher waters are also warmer, while more saline waters are cooler. This indicates that these very low frequency fluctuations correspond to changes in the presence of Atlantic water and the depth to which its influence is felt. We can conclude for the moment, that the Atlantic water has a stronger signal in spring and autumn, while it is weaker in summer and winter. This visual analysis suggests the existence of a semiannual cycle, and the difference between the minimum (maximum) values for salinity (temperature) in autumn and spring could be explained by the presence of an annual cycle.

The u component of velocity has also this sort of seasonal variability but it is more difficult to find an explanation for it. Again maximum values are in summer and winter and minimum ones at spring and autumn, following a similar curve to that of salinity. Also, the autumn minimum is deepest than those of spring 1997 and 1998. More interesting is that between days 150 and 200 (9th October to 28th November), there is a reversal in velocity (though with some interruptions). We understand by a reversal, that the upper layer flows westward, that is, on the opposite direction to the expected. Other reversal occurred at the end of the series (though not so clear). At the beginning of the series, we can see a slow increase of the u component that suggests that velocity could be negative some days before the start of the plot. In fact, mean values for days 0–3, which have been eliminated by the filtering process, are clearly negative. It seems somewhat contradictory that the strongest signals of Atlantic water are coincident with the reversal episodes. Nevertheless, this is a point on which we will come back along the following sections.

3.2. SST, CTD and CM 1

Fig. 4a shows a SST image corresponding to 11/05/97. According to this image, we can think that the Atlantic current is flowing to the north of the Alboran Island during the beginning of the mooring period. The accumulation of warm waters to the south of the Island suggests the existence of an anticyclonic area. The first available data from the mooring line correspond to 18:00 GMT 12/05/97. The u component of velocity is negative for 12th May. Daily average of velocity vector for CM 1 on 13th May shows that the current is flowing to the NW (insert in Fig. 4a). This is compatible with the anticyclonic circulation inferred from the SST image. Fig. 7a is the salinity and geostrophic velocity (zonal component) corresponding to the 13th May transect. The current flows eastward to the north of the Island and westward to the south of it. Low salinity values (~ 36.6) indicate that waters circulating anticyclonically have an Atlantic character. The daily averaged value of u for CM 1 is -7 cm/s. Geostrophic values around -8 cm/s can be found at 50 m depth and to the north of the mooring location. The intercomparison between geostrophic velocities, in situ measurements and SST images makes us conclude the existence of an area of negative vorticity around the Alboran Island during the beginning of the mooring period. According to Fig. 4a, the Alboran Sea would be occupied by three anticyclonic gyres, a circulation pattern quite unusual, but already described by Viúdez et al. (1998b) during autumn 1996.

Geostrophic calculations are referred to the 200-db reference level. This is widely used in the Alboran Sea literature. Nevertheless, we checked the validity of it. We calculated the daily averaged u component of velocity for CM 3 (178 m depth) and 4 (358 m depth) corresponding to 13th May. These values are 1 and 0.1 cm/s, indicating that real velocities between 178 and 358 m are likely to range between 1 and 0.1 cm/s. This result makes the 200-db level a good choice as no motion reference level. We also repeated calculations using the 300-db reference level and no changes were found in the sense of the flow. We only observed

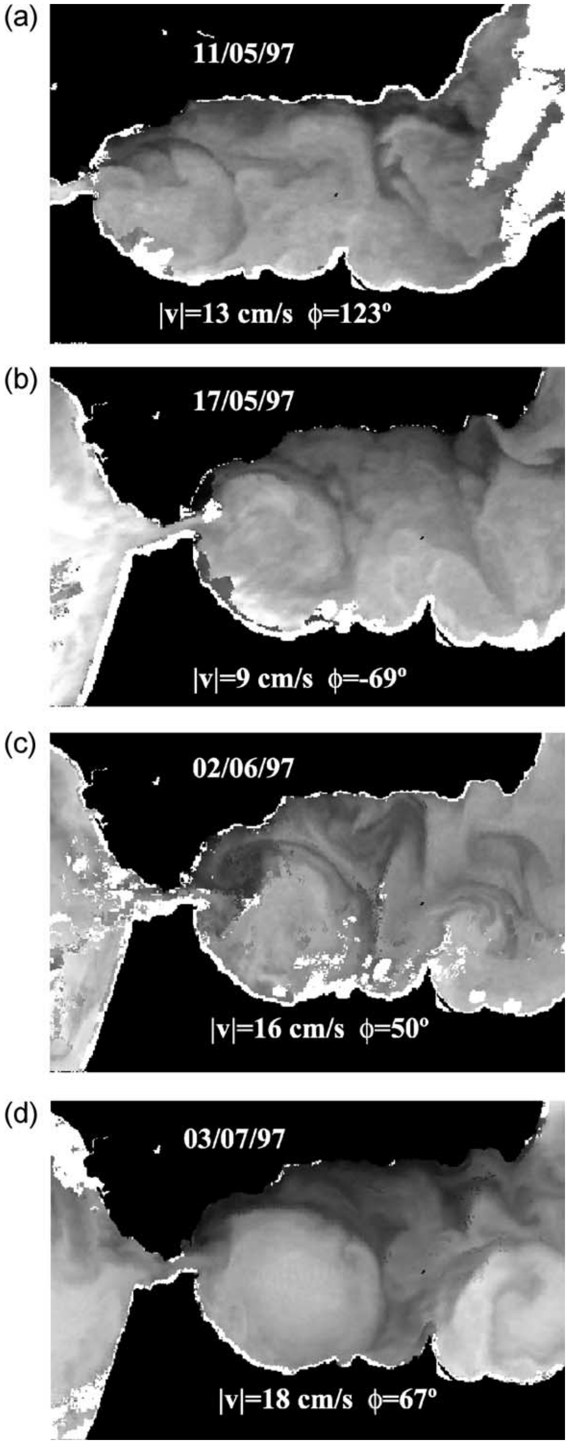


Fig. 4. (a–c) SST images from NOAA satellite corresponding to spring 1997. Darker tones correspond to colder waters and light tones refer to warmer waters. The date for each image has been included in the upper left corner. Daily averaged velocity vectors measured by the uppermost current meter in the Alboran Passage for the same day as the images are included in the bottom. (The angle referred to the east, positive counterclockwise.) (d) SST image representative of the summer conditions.

a slight intensification of the modulus of the currents around 1 or 2 cm/s.

Due to the cloudiness of the images, it is difficult to establish the duration of this three-gyre episode. Nevertheless, it was still present at 17th May (Fig. 4b). On 2nd June, we identify a well-developed WAG, occupying its usual position (Fig. 4c). Current vector from CM 1 for the same date shows that the upper layer flows to the NE.

Other three-gyre episodes could have happened in May 1998 (not shown). This is also supported by the low and even negative values of *u* velocity at the end of the time series.

The existence of both the WAG and EAG was the prevailing situation during the summer months. In this situation, we expect that the Atlantic current flows south of the Alboran Island in a NE direction. This was in agreement with velocity vectors corresponding to the uppermost current meter (angles $> 45°$). A quite representative image of this situation is presented in Fig. 4d. The insert shows the intensity and direction of the flow in CM 1.

A similar situation to that of spring, took place in autumn 1997, being available some cloud-free images to describe it. The sequence of Fig. 5 shows how a southward drift of the Atlantic current getting into the Alboran Sea, pushes the WAG eastward at the same time that a new gyre is being formed SE of Ceuta (Fig. 5a). Some days later (Fig. 5b and c), the "old" WAG is displaced to the east, being its centre close to our mooring line, in a very similar situation to that presented in May 1997. It is worth noticing that CM 1 velocity vector is within the third and second quadrant (current flowing to the SW and NW) while the three gyres are present. Though we have no in situ measurements to confirm our interpretation of the "first and third" anticyclonic gyres, CM 1 seems to agree with the existence of an anticyclonic area centred in the Alboran Island.

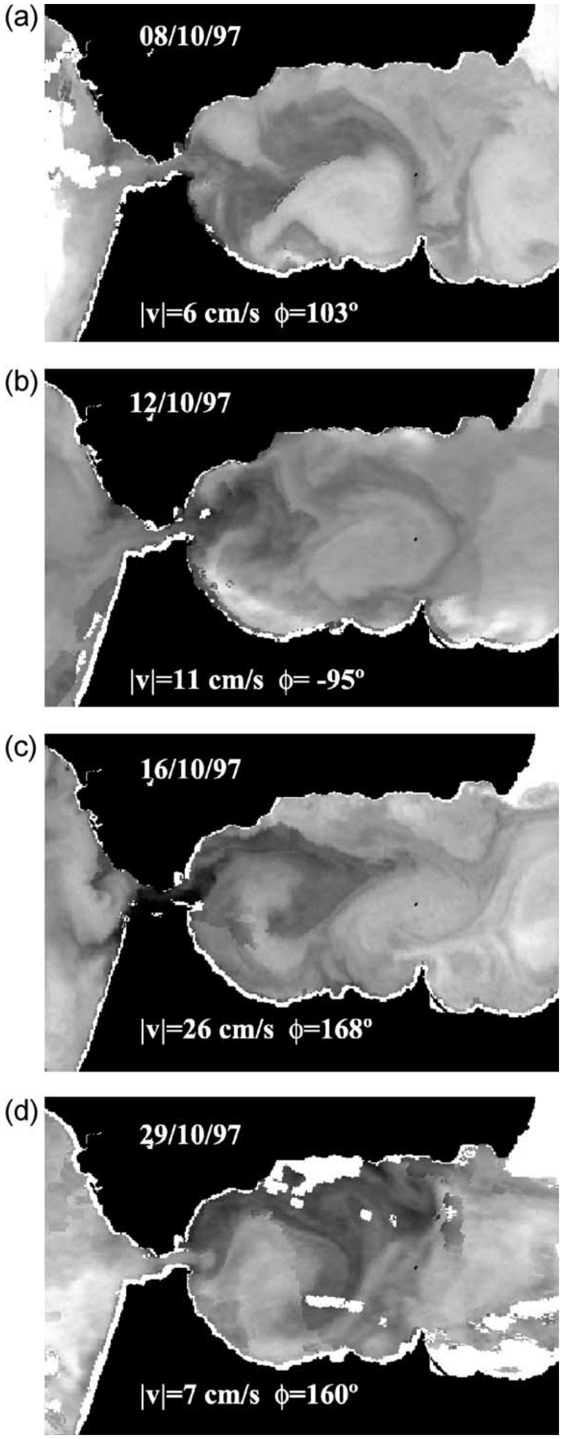


Fig. 5. (a–d) Time sequence corresponding to autumn 1997. This sequence is quite representative of an episode of southward drift of the Atlantic current and the formation of a new WAG and its coexistence with a three-gyre circulation.

Fig. 6a shows the Atlantic current flowing close to the African coast once it exits the Strait of Gibraltar. This image corresponds to 20/01/98, and this is the first time that we could identify this coastal mode unambiguously. Due to the cloudiness of images, we cannot be sure if the transition to this state of the Alboran circulation took place some days before. One month later (Fig. 6b), the coastal mode of circulation stood almost in the same situation. More than 2 months later from the identification of the coastal mode (Fig. 6c), the Atlantic current starts to detach from the African coast, and an anticyclonic gyre could be developing SE of Ceuta. Once again, we have to remark that it is difficult to associate a date for the definitive installation of a new circulation pattern, due to the cloudiness of the images, but we can see that at least on 13th April, the WAG could be considered developed. This new circulation pattern in winter is also reflected in current measurements. Though currents flow eastward, they do with a lower angle than when the WAG and EAG are developed. Inserts in Fig. 6a–c show that velocity vectors from CM 1 are within the fourth quadrant (to the SE).

A second CTD transect was accomplished on 9th November 1997. Fig. 7b presents salinity and geostrophic velocity for this transect. Geosthrophic velocity at the depth of CM 1 (77 m) and the position of our mooring line is around 18 cm/s, the same as the daily averaged u component from CM 1. The closest cloud-free SST image corresponds to 16th November and shows both the WAG and EAG. We can infer a Northeast flowing Atlantic current south of the Alboran Island. This is in agreement with CTD calculations that show that the main body of the Atlantic current flows south of the Island. Geostrophic calculations were checked in the same way as that for the 13th May CTD transect.

These results make us think that circulation patterns inferred from SST images are consistent with in situ current measurements and geostrophic calculations. They also allow us to understand the annual and semiannual cycles described in the previous section. Atlantic waters with low salinity and higher temper-

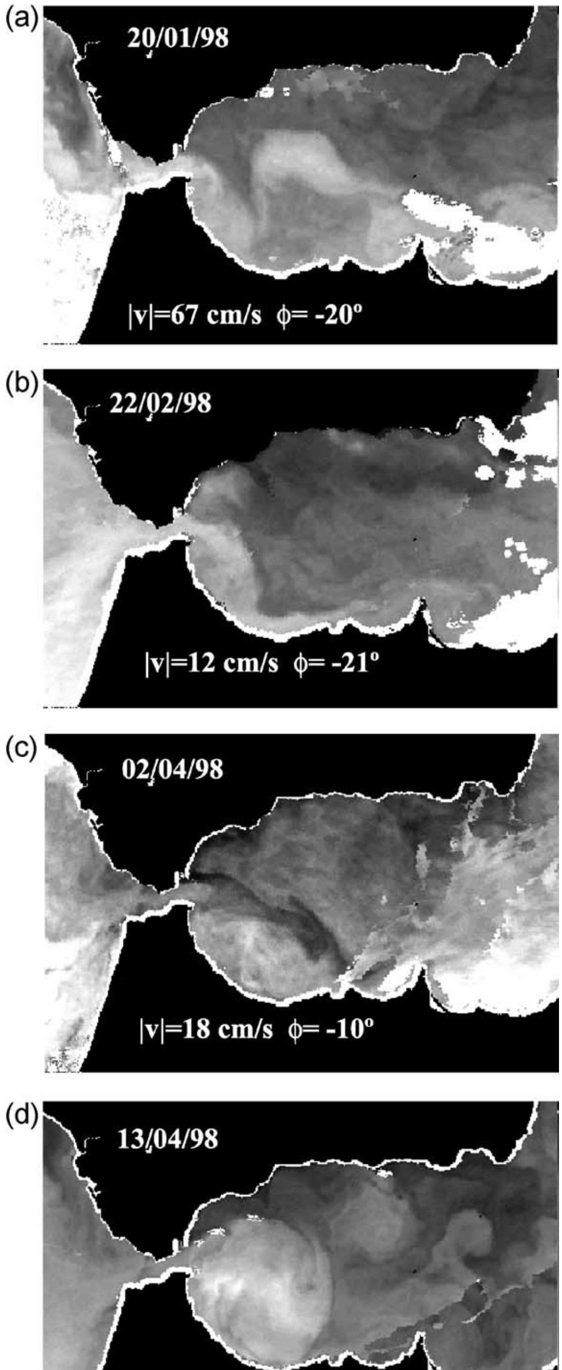


Fig. 6. a and b are the SST for the first time that a coastal mode was identified in winter and its permanence more than a month later. c and d show the initial detachment of the Atlantic jet from the African coast and an early stage of the WAG.

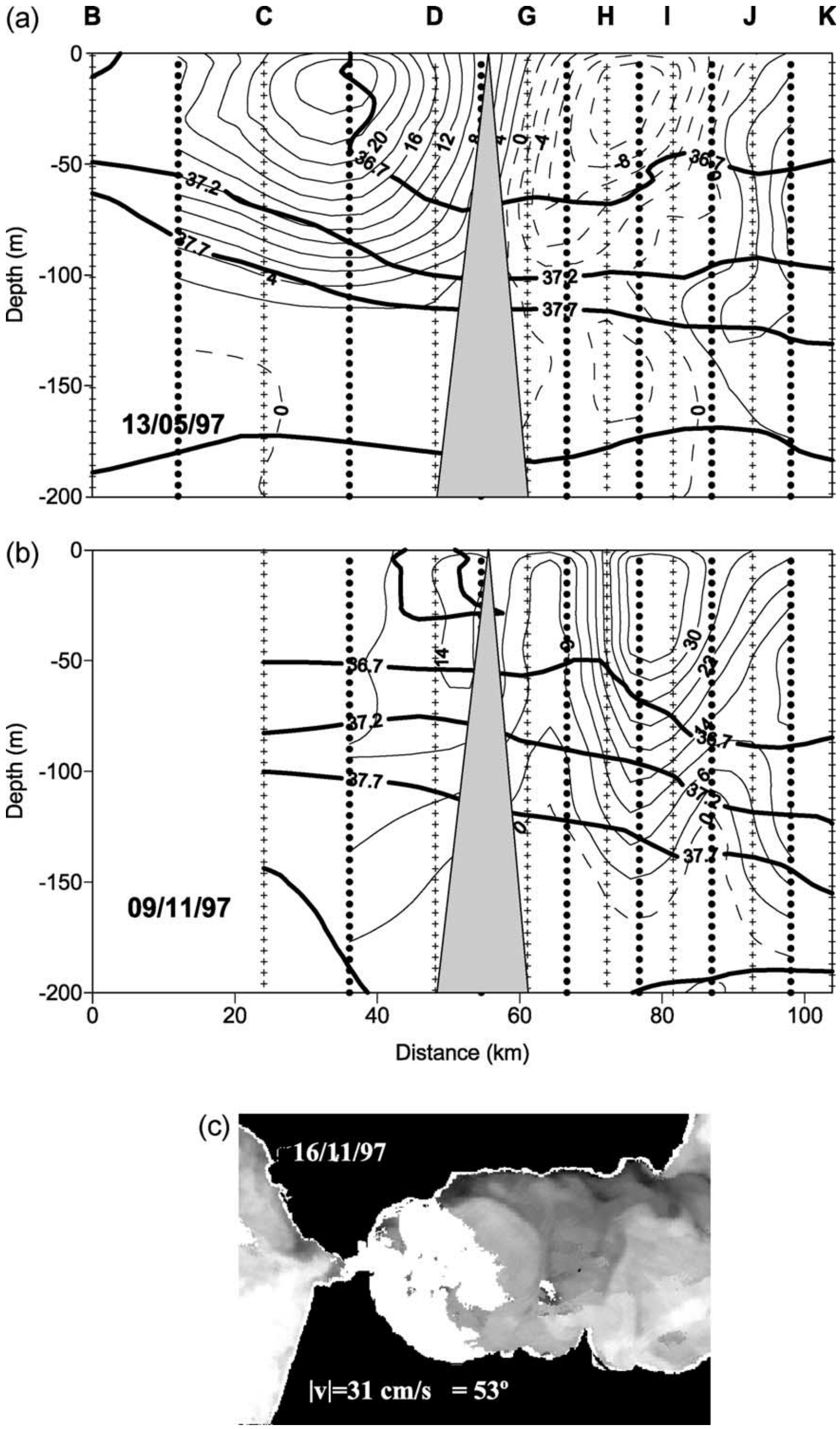
atures accumulate in the centre of the WAG. If it is displaced to the east, occupying the area of Alboran Island, salinity recorded by the three upper instruments (within the upper 200 m) will decrease, at the same time that temperature will increase. This is the case for springs 1997 and 1998 and autumn 1997. As the centre of the anticyclonic gyre is displaced close to our mooring position, velocities will decrease and even reverse, producing the minima in the u component of velocity and the reversal episodes. On the other hand, if the Atlantic current is flowing south of the Alboran Island, the strong thermohaline gradient associated to this current will be placed south of the Island. This will produce an increase of the zonal velocity and salinity, and a decrease of temperature.

Differences between spring and autumn situations can be attributed to summer heating of the WAG.

3.3. The Atlantic jet variability

One of the factors influencing the variability of the Alboran Sea is the variability of the Atlantic inflow through Gibraltar (i.e. Ovchinnikov, 1974; Bormans and Garrett, 1989; Lafuente et al., 1998...). Time series of current measurements within the eastern side of the strait were available for some periods overlapping that of our mooring (sites C and S in Fig. 1, Table 1). Time series of sea level gauges covering the whole period were also available at the north and south shores of the strait (Algeciras and Ceuta, Fig. 1). If we consider that the Atlantic inflow is in geostrophic balance with the cross-strait sea level slope, then we can calculate the inflow velocity using the expression $-g\Delta\xi/fL$; g is the gravity acceleration, f the Coriolis parameter for a latitude 36°N (8.5×10^{-5} s^{-1}), L some effective width of the strait, and $\Delta\xi$ is the sea level difference between Ceuta and Algeciras.

Possible errors in the tide gauges levelling do not allow us to calculate absolute velocities. Another source of error is the choice of L, which in our case is 18 km. We have used the same value as in Bormans and Garrett (1989) for later comparison with these


(a)
B C D G H I J K
Depth (m)
13/05/97
(b)
09/11/97
Distance (km)
(c)
16/11/97
|v|=31 cm/s = 53º

authors. Nevertheless, though absolute values can be erroneous, variability in $\Delta\xi$ must be similar to that of the along strait component of velocity.

Fig. 8A are velocities calculated using the geostrophic balance and measurements in sites C and S in the Strait of Gibraltar. A visual analysis suggests that there is a similar variability in both series, indicating a geostrophic adjustment of the current. Absolute values seem to be underestimated in the first half of the series while they seem to be right at the second one. Numerical correlation between in situ velocity measurements and geostrophic estimations were 0.6 for the current meter at site S and 0.7 for site C.

Cross-correlation and cross-spectral analysis between $\Delta\xi$ and variables measured by CM 1 in the Alboran Passage did not show any clear relation. Neither we found any seasonal cycle in $\Delta\xi$ that accounts for those in CM 1. For this reason, we conclude that the relation between the Atlantic inflow in the Strait of Gibraltar and the Alboran Passage must be in a more subtle way.

Another important question is to determine the mechanisms forcing the variability in the Strait of Gibraltar. Lafuente et al. (submitted for publication) inspected the influence of winds in the strait on the exchange. These authors consider the zonal component of the wind in Tarifa and Ceuta (Fig. 1) and argue that winds in Tarifa are more appropriate. The correlation coefficient calculated between the low-pass series of east component of the wind in both locations, using a series of 4 years (1995–1998) is 0.92. We conclude that both locations are equally useful for studying the wind variability. The only difference is an amplification of wind intensity in Tarifa, and a divergence in the wind field in the strait. Mean winds are from the east in Tarifa, and from the west in Ceuta, as already pointed out by Parrilla and Kinder (1987). This can be summarised by the relation $W_t = -3.7 + 3.4 W_c$ (obtained from a fit using the 4-year-long series), where W_t is the east component of the wind in Tarifa, and W_c the same for Ceuta, both expressed in meters per second and positive for westerlies. We find that the sea level difference across the strait is influenced by winds as indicated by a cross-correlation of 0.7.

Crepon (1965) finds a visual correlation between atmospheric pressure in the Western Mediterranean (P_m) and the Atlantic inflow through Gibraltar. He also points out the paradox that both variables were in phase opposition (or in phase if we consider $-P_m$ instead of P_m). The inflow should lead $-P_m$ by 90° due to volume conservation (i.e. the inflow should be directly correlated with the derivative of $-P_m$). Candela et al. (1989) confirmed this correlation between the first empirical mode of P_m (accounting for the 65% of the total variance) and the barotropic transport through the strait. They explained the former paradox using a model that considered the exchange between the western and eastern Mediterranean through the Strait of Sicily. Correlation between our low-pass series of $\Delta\xi$ and P_m and between direct measurements of velocity in the strait (in the periods available) and P_m are around -0.5. This correlation and the visual analysis of these series agree in a rough way with previous results from Crepon (1965) and Candela et al. (1989), but a detailed inspection indicates that a more complex relationship between these variables must exist.

3.4. Atmospheric pressure in the Western Mediterranean

A deep fall of atmospheric pressure over the Western Mediterranean was observed around the beginning of February (Fig. 8C). Fig. 8D presents a zoom of the dates of the pressure anomaly, from the day 240 to 270 (07/01/98–06/02/98). Fortunately, this is a period when velocity in the central point of the strait (C in Fig. 1) was available, and so we use this series (u_c in the following discussion) and in Fig. 8D instead of

Fig. 7. (a) CTD section for the May 1997 cruise. Thick lines represent the salinity distribution of the upper 200 m and thin lines are the cross-section geostrophic velocities in centimeter per second calculated with respect to the 200-db no motion level. Dashed lines represent negative (westward) velocities and solid lines are for positive values (eastward). Stations A, E and F were not included for being shallower than 200 m. Crosses indicate the CTD station positions, and circles are the positions of velocity calculations by first differences of the dynamic topography. (b) is the same as in Fig. 7a for the second CTD cruise. As already mentioned in the text, stations A and B could not be accomplished because of weather conditions. (c) is the SST image for 16/11/97, the cloud-free image closest to the date of the second CTD transect.

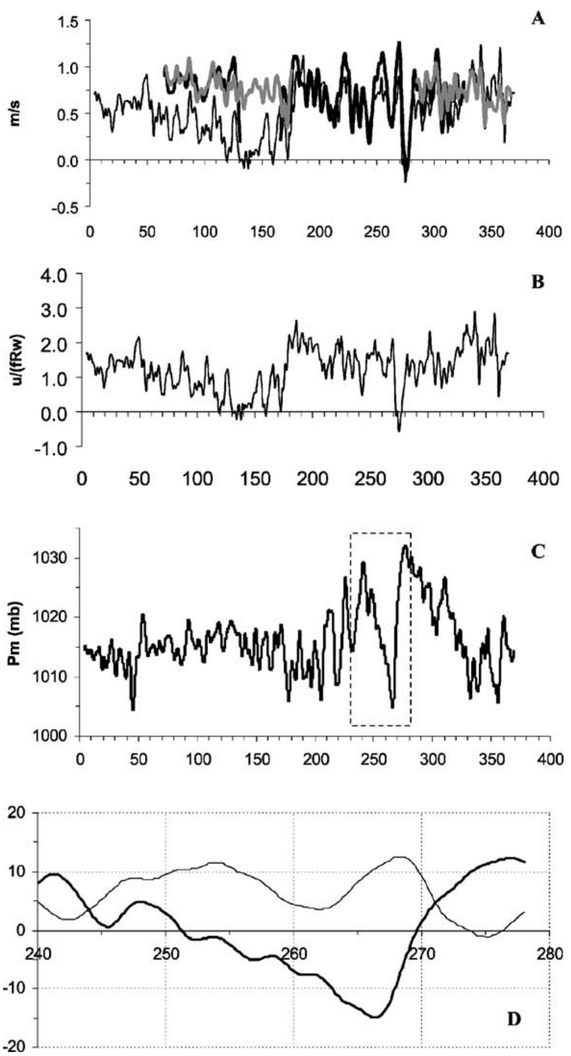


Fig. 8. (A) Thin dark line is the zonal component of velocity in the Strait of Gibraltar estimated by geostrophy from the cross-strait sea level drop (Ceuta—Algeciras). Dark thick line is the zonal component measured in site C (centre) of the strait, while light thick line is the same for site S (south), (B) is the ratio between the inertial radius of the Atlantic current in the strait (using geostrophic estimations) and the radius of curvature of the 100-m isobath in Ceuta. (C) is the mean atmospheric pressure over the Western Mediterranean expressed in millibar. (D) is a zoom of time series A (velocity in site C of Gibraltar, thin line) and C (thick line) inside the rectangle. To plot both series, velocity is expressed in centimeters per second and the mean value has been subtracted to pressure time series. In all the time series, as in Figs. 2 and 3, the time is expressed in days being day 0 = 12/05/97. As a reference, consider that day 234 is 01/01/98.

any estimation of the inflow. A first comment related to conclusions of Crepon (1965) and Candela et al. (1989) is that $-P_m$ leads the inflow velocity by 1 or 2 days. At the day 241 (08/01/98), there is a relative maximum of P_m, followed by a relative minimum of u_c at the day 242. Then P_m falls during 26 days, reaching a minimum on the day 266 (02/02/98). The drop of P_m is 25 mb. While the inflow rises for this period, there is an exception between days 254 and 262 (21/01/98–29/01/98). At the end of this episode of pressure decrease, the inflow takes a maximum 2 days later than the P_m minimum.

Even more surprising than this anomalous behaviour of u_c between the days 254 and 262 is the sharp increase of pressure between the days 266 and 277 (13/02/98). In 10 days, the pressure increased more than 25 mb, producing a reversal of the surface layer circulation in the Strait of Gibraltar around the day 277. It is worth noticing that this reversal is not only evidenced by negative values of velocity in the site C of the strait, but also in the cross-strait sea level drop which took negative values this date (i.e. level in Ceuta lower than in Algeciras).

According to Fig. 6a, 20/01/98 was the first day that the coastal mode state of circulation in the Alboran Sea was clearly observed. This is 1 day before the atypical behaviour of u_c versus P_m was observed, and so, some relation could exist between these two phenomena. Nevertheless, as we stated previously, we are not sure that the transition from the WAG mode of circulation to the Coastal mode occurred some days before, and so we are aware of this causal relationship.

The changes both in atmospheric pressure and in the circulation of the Alboran Sea around the day 277 are so exceptional, that we believe that some sort of relation must exist. Bormans and Garrett (1989) concluded that the key parameter for the formation of the WAG is the ratio between the inertial radius of the inflow (u/f) and the topographic radius of curvature at the southeastern edge of the strait (that is in Ceuta). They also argue that this radius should not be taken as that of the coast, but of the isobath of 100 m, where the interface between the Atlantic and Mediterranean waters approximately intersects the sea bottom. They consider a value $R_w = 5$ km. Fig. 8B shows the calculation of this ratio (u/fR_w) using the geostrophically estimated velocity of the inflow to get a time series covering the whole mooring period. Bormans and Garrett (1989) state that the inflow will detach from the African coast, developing an anticyclonic gyre, when this parameter is higher than 1. A coastal mode will be associated to values lower than 1. Values under the critic value 1 are clear between days 100 and 150 (21/08/97–09/10/97), but we have to remember that this period corresponds to that when geostrophic velocities subestimate real velocities. Comparison between both velocities in Fig. 8A suggests that these values lower than 1 could not be real. On the other hand, the fall of u/fR_{w} under 1 is clearly real, the day 277 (13/02/98) as geostrophic and real velocities in the strait are coincident for this date. The main problem to fit these observations with results in Bormans and Garrett (1989) is that this clear event, associated to the already commented reversal of the circulation in the strait, took place 24 days after we identified the installation of the coastal mode circulation in the Alboran Sea. After the day 277, this parameter recovered values higher than 1, but the WAG was not developed, at least for more than 1 month (see Fig. 6).

A careful look at Fig. 8B reveals that, though not so dramatic as that of day 277, there are three falls of u/fR_{w} before 20th January. They correspond to days 227, 234 and 242 (25/12/97, 01/01/98 and 09/01/98). We also found that between 20/12/97 and 06/01/98, several southward drifts of the Atlantic current were observed in SST images, generating three-gyre circulation episodes during this period. Though we are aware of the speculative character of our conclusions, we think that these frequent falls of the inflow velocity could be responsible for the unstable circulation in December 1997 and January 1998. They would produce the southward drifts of the Atlantic current, which is the initial situation for both a three-gyre circulation (if the WAG is rapidly recovered) or a coastal mode if this does not happen. The reversal of the circulation in the strait could not be the cause of the drift of the current on 20th January (or some days before), but could be the reason why the WAG did not develop as fast as in other occasions.

As we stated before, there is no direct correlation between the Atlantic inflow through Gibraltar and in the Alboran Passage. Variability in Gibraltar can be considered responsible for that in the Alboran Passage only through its influence on the existence of different circulation patterns in the Alboran Sea.

3.5. Statistical model

We have described the annual and semiannual cycles of velocity, temperature and salinity in the upper layer of the Alboran passage. We have already reported that these cycles do not have a clear correspondence with the Atlantic inflow through Gibraltar. We now inspect the existence of these cycles from a statistical point of view.

We adopt the following model for the time series analysed:

$$\begin{aligned} y_i &= \sum_{k=1}^{M} \theta_k p_{k,i} + z_i \\ &= \theta_1 + \theta_2\cos(\omega_{\mathrm{a}} t_i) + \theta_3\sin(\omega_{\mathrm{a}} t_i) \\ &\quad + \theta_4\cos(\omega_{\mathrm{s}} t_i) + \theta_5\sin(\omega_{\mathrm{s}} t_i) + z_i \end{aligned} \tag{1}$$

where y_i is the value of the variable at the time $t_i=(i-1)\Delta$, and Δ is the time step, 0.25 days for the low-pass series. Time origin is the day 0=0:00 GMT 12/05/1997.

P_k constitutes a basis of functions with coefficients θ_k. In our case, θ_1 accounts for the mean value, θ_2 and θ_3 for the cosine and sine parts of the annual cycle, and θ_4 and θ_5 for that of the semiannual one (ω_{a} and ω_{s} are $2\pi/365$ and $2\pi/180$ day^{-1}).

In this model, we consider these cycles as harmonic functions. This is a usual approach due to its simplicity (Yashayaev, 2000; Koutsikopoulos et al., 1998). Viúdez et al. (1998a) also fit a semiannual harmonic to study the variability in sea level residuals in the Alboran Sea. Álvarez et al. (2000) consider monthly averaged SST images of the Alboran sea and analyse them by means of EOFs. They find analytical expressions for the time evolution of the three first modes using genetic algorithms. Though authors do not accomplish any spectral analysis of these functions, it is easy to see that the function corresponding to the first mode is an annual harmonic with decreasing amplitude and that for the second mode is a semiannual harmonic (see Appendix A in Álvarez et al., 2000).

We consider that our time series can be decomposed as f_i+z_i where f_i is a deterministic or predictable part of the time series, and is the value of the function f at the time t_i. If parameters θ_k with $k=1\ldots5$ were known, the value of f would be known at any time. z is a stochastic process; for this reason, we consider our time series as a single realisation of the infinite possible realisations that constitute the ensemble of the process (Jenkins and Watts, 1968, pp. 144). This is equivalent to say that y is a stochastic process that is not stationary for the mean.

We fit to our time series a function like that in Eq. (1) minimising the sum of squared residuals, which leads to the classical set of normal equations. If the residuals (z_i) were uncorrelated and Gaussian, this method would be equivalent to maximum likelihood estimation, and the calculation for the $100(1-\alpha)\%$ confidence intervals could be accomplished, according to Jenkins and Watts (1968, pp. 137) using the expression:

$$\pm\left[M\frac{\{\hat{z}^2\}}{N-M}\,\frac{F(1-\alpha,M,N-M)}{\{p_k^2\}}\right]^{1/2} \tag{2a}$$

While z stands for the value of the residuals or stochastic process, $\hat{z}$ is the estimation of the residuals. Brackets are used to express the usual average over a single realisation of N points. N is the number of data points and M the number of estimated parameters, and F the inverse Fisher cumulative distribution for M and $N-M$ degrees of freedom. Following Chelton (1983), we keep this expression by substituting N by N^*, which is the effective degrees of freedom. In our case, our time series are strongly autocorrelated, diminishing considerably the number of degrees of freedom. Adapting the expression in Chelton (1983) or Emmery and Thomson (1998, pp. 260), we calculate N^* as:

$$N^*=\frac{N}{\left[1+2\sum_{r=1}^{\infty}\rho_{zz}^2(r)\right]} \tag{2b}$$

where the theoretical autocorrelation function is substituted by the sampling function calculated for our particular realisation. That is

$$\rho_{zz}(k)=\frac{\sum_{i=1}^{N-k}\hat{z}_i\hat{z}_{i+k}/(N-k)}{\sum_{i=1}^{N}\hat{z}_i^2/N}$$

The main point in our approach is that to determine the existence of the annual and semiannual cycles, it is important to determine their statistical significance. Bryden et al. (1994) argue that it is meaningless giving error bars for their estimations because they were based on time series shorter than a year. Lafuente et al. (accepted for publication) give significant estimations of annual and semiannual cycles for the inflow, outflow and interface depth in the eastern side of the Strait of Gibraltar. These estimations are based on a 3-year-long experiment. Phases for the inflow do not agree with those in Bormans et al. (1986), who estimate the variability in the inflow also from a 3-year-long time series of sea level differences across the strait.

Table 3a presents the estimation of the parameters in Eq. (1) and their 95% confidence intervals for temperature, salinity, u and v components of velocity for CM 1. Amplitudes and phases for annual and semiannual cycles can be reconstructed from the cosine and sine parts of the harmonics. When both parameters defining a cycle enclose the value zero, it is not statistically significant at the 5% degree of significance. If, at least, one of the parameters defining the cycle is statistically significant, we can think that there is a probability lower than 5% that the amplitude of this harmonic is zero, and a confidence interval for the phase can be calculated (note that if both intervals enclose the zero value, phase can be whatever in the range $-180°$, $180°$).

This analysis reveals that annual cycles for temperature, salinity and u are significant, as could be expected from the clear variability observed in Fig. 2. Phases are in agreement (within the error bars) with our previous conclusions that warmer and fresher waters occupy our mooring location in autumn, while cooler and saltier waters are in summer and winter. Also cycles for u agree with those inferred visually.

When considering the inflow in Gibraltar (sea level difference), and atmospheric variables, the semiannual cycle in W_c is the only one significant at the 5% degree of significance. The phase from the values of θ_4 and θ_5 in Table 3b indicates that this signal peaks between 20 April and 23 June, and so will be minimum between 23 June and 20 October, being again maximum (because of its semiannual nature) between 20 October and 23 December. Wind time series in Ceuta are available for the years 1995–1998, so we repeated this analysis for the 4 years. We found that semiannual signals took

Table 3a
Fit parameters (see Expression 1 in Section 2), for temperature, salinity, u and v components of velocity in the CM 1

	θ_1	θ_2	θ_3	θ_4	θ_5
T	**15.08**±0.47	−**0.71**±0.67 (190)	−0.10±0.67	0.38±0.67 (0)	0.01±0.67
S	**37.26**±0.24	**0.34**±0.33 (316)	−**0.38**±0.33	−0.24±0.33 (77)	0.21±0.33
U	**10.86**±4.88	−1.44±6.89 (263)	−**8.27**±6.89	−6.07±6.89 (65)	**7.22**±6.89
V	**5.43**±5.34	−1.14±7.54 (105)	4.62±7.54	−1.18±7.54 (68)	1.20±7.54

Numbers in brackets are the days when annual and semiannual cycles take their maximum values. These numbers are referred to the same time origin as Fig. 2, that is, day 0 = 12/05/97. Statistically significant values are typed in bold. Their equivalencies are 190 = 18/11/97. Confidence interval is between 10/08/97 and 06/02/98 for the annual cycle of temperature. 316 = 24/03/98. Confidence interval is from 10/02/98 to 23/05/98 for salinity annual cycle. Finally, 263 = 30/01/98. Confidence interval is between 20/11/97 and 13/05/98 for the annual cycle of u.

maximum values in mid-July and beginning of August for the years 1995 and 1996, while they were in agreement with results in Table 3b for the years 1997 and 1998. Results for years 1997 and 1998, and its agreement with those in Table 3b (using a 1-year period from May 1997 to May 1998), are not surprising, as time series for these 2 years overlap with that used for calculations in Table 3b. It is very unlikely that results in two of four experiments relay out of the 95% confidence interval when by definition, one should expect this to happen in 1 of 10 experiments.

Analysis for cross-strait sea level drop for years 1995, 1996 and 1997 also shows different results, though in this case, none of the cycles calculated were significant. Though these results deal with variability in the strait, and cannot be directly extrapolated to that of CM 1, they make us consider that model in Eq. (1) could not be right, that is, annual and semiannual cycles may not be deterministic functions. A more appropriate model could simply be $y_i = z_i$, being harmonics calculated part of the variance of the process z in the very low frequency band corresponding to 365 and 182 days of period. In this later case, amplitudes of annual and semiannual cycles could be different from zero when averaging over several years. This average would account for the part of the spectrum of z in this frequency band, but the phase would be undetermined. Statistically significant values of the parameters in Eq. (1) are only useful to define such a function as f if we are sure from a previous (theoretical) knowledge of its existence, and for one single realisation of 1-year length, it can simply be the result of the difference in the variance distribution between the annual and semiannual frequencies and higher subinertial frequency bands.

This would explain the discrepancy in phases between Bormans et al. (1986) and Lafuente et al. (accepted for publication) and Bryden et al. (1994).

Table 3b
The same as in Table 3a for the cross-strait sea level difference, mean atmospheric pressure in the Western Mediterranean and east component of the wind in Ceuta

	θ_1	θ_2	θ_3	θ_4	θ_5
$\Delta\xi$	**9.13**±2.08	1.45±2.94 (306)	−2.36±2.94	2.17±2.94 (18)	1.53±2.94
P_m	**1016.1**±2.6	−0.5±3.6 (263)	−2.8±3.6	−3.6±3.6 (95)	−0.5±3.6
W_c	0.60±0.88	0.26±1.25 (2)	0.01±1.25	**1.54**±1.25 (15)	0.90±1.25

The period analysed for this table is the same as in Table 3a (May 1997–May 1998). The only significant cycle at the 5% degree of confidence is the semiannual cycle of W_c. Maximum value is at day 15 = 27/05/97. Ninety-five percent confidence interval is from 20/04/97 to 23/06/97.

The only possibility to discern between the two models is to use longer time series.

4. Summary and conclusions

The Alboran Passage upper layer exhibited an annual and semiannual cycle during the period May 1997–May 1998. This variability was characterised by a minimum of salinity and zonal component of velocity in spring and autumn and a maximum in winter and summer. The temperature had a behaviour right opposite to that of salinity.

The cross-strait sea level difference in the eastern edge of Gibraltar was considered to study the variability of the Atlantic inflow through Gibraltar. It did not show similar cycles to those reported in the Alboran Passage. Neither we could find a clear relation at the rest of the subinertial band.

The analysis of SST images suggests that the decreases of salinity and u component of velocity (increases of temperature) are due to displacements of the WAG to the east. During these episodes, the Alboran Sea seems to be occupied by three anticyclonic gyres. The increases of salinity and u component of velocity (decreases of temperature) are linked to the thermohaline front associated to the Atlantic current. This would pass south of the Alboran Island when the WAG and EAG are well developed (with a northeast direction) or when the coastal mode circulation is installed in the Alboran Sea (with an east or southeast direction).

The circulation patterns inferred from SST images are coherent, at least in a rough way, with current measurements in CM 1, and with geostrophic calculations from two cruises in May 1997 and November 1997, giving us confidence on our image interpretations.

We have discussed these results using the work by Bormans and Garrett (1989). According to these authors, u/fR_w is the critic parameter for the formation of the WAG. This would happen when such parameter is over the value 1. Values lower than 1 would lead to a coastal mode circulation. We have observed several falls of u/fR_w in autumn 1997 and spring 1998 coinciding with three-gyre episodes. A more dramatic fall was observed in January 1998. A fast increase of atmospheric pressure over the Western Mediterranean was followed by a reverse in the circulation in the Strait of Gibraltar. Though our arguments are speculative, we believe that this is related to the installation of a coastal mode of circulation in the Alboran Sea for more than 2 months.

Summarising these results, during summer months, the Alboran Sea circulation had a period of stability with both the WAG and EAG well developed. In winter, the prevailing situation was the coastal mode. Spring and autumn are transition periods with frequent three-gyre episodes. The question is if this can be considered as the seasonal variability of the Alboran Sea, that is, if these different circulation patterns are the most likely situations in each season of the year. A statistical analysis of time series in CM 1 confirmed the significance of the annual and semiannual cycles already described. Nevertheless, we simply test the significance of a certain statistical model (that in Eq. (1)). The short length of our series does not allow to test other models. This makes convenient a discussion of our results to the light of previous works. Parada and Cantón (1998b) point out the same problem, as they use one single year of observations, but they also conclude that in the year 1993, the WAG and EAG are more stable in summer while in winter, the Atlantic current flows in a coastal mode. Monthly averaged SST in January 1999 also suggests a coastal mode (Álvarez et al., 2000, Fig. 3e,f). To our knowledge, the only work that presents a three-gyre episode is that of Viúdez et al. (1998b). These authors report this episode to happen in autumn 1996.

We conclude from our results and from the revision of previous works that the two-gyre system (WAG and EAG) is the dominant pattern in summer, and that the coastal mode is more likely in winter. Nevertheless, we also believe that longer experiments are needed to address the problem of seasonal variability and, of course, of interannual variability.

Other experiments covering, at least, a 1-year period could be useful for providing new information about the probability of occurrence of the different circulation patterns.

Acknowledgements

This work has been founded by MTPII-MATER: MAS3-CT96-0051. Financial contribution from

CANIGO project: MAS3-CT96-0060 is also acknowledged.

References

Álvarez, A., López, C., Riera, M., Hernández-García, E., Tintoré, J., 2000. Forecasting the SST space–time variability of the Alboran Sea with genetic algorithms. Geophys. Res. Lett. 27 (17), 2709–2712.

Bormans, M., Garrett, C., 1989. A simple criterion for gyre formation by the surface outflow from a strait, with application to the Alborán Sea. J. Geophys. Res. 94 (C9), 12637–12644.

Bormans, M., Garrett, C., Thompson, R., 1986. Seasonal variability of the surface inflow through the Strait of Gibraltar. Oceanol. Acta 9 (4), 403–414.

Bryden, H., Candela, J., Kinder, T.H., 1994. Exchange through the Strait of Gibraltar. Prog. Oceanogr. 33, 201–248.

Candela, J., Winant, C.D., Bryden, H., 1989. Meteorologically forced subinertial flows through the Strait of Gibraltar. J. Geophys. Res. 94 (C9), 12667–12679.

Cano, N., 1977. Resultados de la campaña Alborán 73. Bol. Inst. Esp. Oceanogr. Tomo I, 103–176.

Cano, N., 1978. Resultados de la campaña Alborán 76. Bol. Inst. Esp. Oceanogr., 3–50.

Cano, N., Gil, J., 1984. Campaña hidrológica Alborán 78. Bol. Inst. Esp. Oceanogr. 1 (2), 114–125.

Chelton, D.B., 1983. Effects of sampling errors in statistical estimation. Deep-Sea Res. 30, 1083–1103.

Cheney, R.E., Doblar, R.A., 1982. Structure and variability of the Alborán Sea frontal system. J. Geophys. Res. 87 (C1), 585–594.

Crepon, M., 1965. Influence de la pression atmospherique sur le niveau moyen de la Mediterranee Occidentale et sur le flux a travers le detroit de Gibraltar. Cah. Oceanogr. 1 (7), 15–32.

Emmery, W.J., Thomson, R.E., 1998. Data analysis methods in physical oceanography. Pergamon, Oxford, 634 pp.

García-Górriz, E., Carr, M., 1999. The climatological annual cycle of satellite-derived phytoplankton pigments in the Alboran Sea. Geophys. Res. Lett. 26 (19), 2985–2988.

Garrett, C., Thompson, K., Blanchard, W., 1990. Are changes in the sea level drop through the Strait of Gibraltar due to hydraulic state flips? Nature 348, 292.

Heburn, G.W., La Violette, P.E., 1990. Variations in the structure of the anticyclonic gyres found in the Alborán Sea. J. Geophys. Res. 95 (C2), 1599–1613.

Jenkins, G.M., Watts, D.G., 1968. Spectral Analysis and Its Applications. Holden-Day, San Francisco, 525 pp.

Koutsikopoulos, C., Beillois, P., Leroy, C., Taillefer, F., 1998. Temporal trends and spatial structures of the sea surface temperature in the Bay of Biscay. Oceanol. Acta 21 (2), 335–344.

Lafuente, J.G., Cano, N., Vargas, M., Rubín, J.P., Hernández-Guerra, A., 1998. Evolution of the Alborán Sea hydrographic structures during July 1993. Deep-Sea Res. 45 (1), 39–65.

Lafuente, J.G., Delgado, J., Vargas, J.M., Vargas, M., Plaza, F., Sarhan, T., 2001. Low frequency variability of the exchanged flows through the Strait of Gibraltar during CANIGO. Deep-Sea Res., accepted for publication.

Lanoix, F., 1974. Projet Alboran. Etude hydrologique et dynamique de la Mer d'Alboran. NATO Tech. Rep. 66. Brussels, 39 pp.

Lewis, E.L., 1980. The practical salinity scale 1978 and its antecedents. IEEE J. Oceanic Eng. OE-5, 3–8.

Ovchinnikov, I.M., 1974. On the water balance of the Mediterranean Sea. Oceanology 14, 198–202.

Parada, M., Cantón, M., 1998a. Sea surface temperature variability in the Alborán Sea from satellite data. Int. J. Remote Sens. 19 (13), 2439–2450.

Parada, M., Cantón, M., 1998b. The spatial and temporal evolution of thermal structures in the Alboran Sea Mediterranean basin. Int. J. Remote Sens. 19 (11), 2119–2131.

Parrilla, G., 1984. Mar de Alborán. Situación del giro anticiclónico en Abril de 1980. Bol. Inst. Esp. Oceanogr. 1 (2), 106–113.

Parrilla, G., Kinder, T.H., 1987. Oceanografía física del Mar de Alborán. Bol. Inst. Esp. Oceanogr. 4 (1), 133–166.

Parrilla, G., Kinder, T.H., Preller, R.H., 1986. Deep and Intermediate Mediterranean Water in the Western Alborán Sea. Deep-Sea Res. 33 (1), 55–88.

Perkins, H., Kinder, T.H., La Violette, P.E., 1990. The Atlantic inflow in the northwestern Alborán Sea. J. Phys. Oceanogr. 20, 242–263.

Rodríguez, V., Bautista, B., Blanco, J.M., Figueroa, F.L., Cano, N., Ruíz, J., 1994. Hydrological structure, optical characteristics, and size distribution of pigments and particles, at a frontal station in the Alborán Sea. In: Rodríguez, J., Li, W.K.W. (Eds.), The Size Structure and Metabolism of the Pelagic Ecosystem. Sci. Mar. 58, 31–41.

Rubín, J.P., Rodríguez, V., Blanco, J., Jiménez-Gómez, F., Rodríguez, J., Lafuente, J.G., Echevarria, F., Guerrero, F., Escánez, A., Hernández, A., Chabani, M., 1995. Relaciones del ictioplancton con la hidrología, biomasa fitoplanctónica, oxígeno disuelto y nutrientes en el Mar de Alborán y Estrecho de Gibraltar (Julio 1993). Publ. Esp. Inst. Esp. Oceanogr. 24, 75–84.

Rubín, J.P., Cano, N., Arrate, P., Lafuente, J.G., Escánez, J., Vargas, M., Alonso, J., Hernández, S., 1997. Ictioplancton, el mesozooplancton, y la hidrología en el Golfo de Cádiz, Estrecho de Gibraltar y sector noroeste del Mar de Alborán en Julio de 1994. Inf. Téc. Inst. Esp. Oceanogr. 167, 44 pp.

Sarhan, T., Lafuente, J.G., Vargas, M., Vargas, J.M., Plaza, F., 2000. Upwelling mechanisms in the northwestern Alborán Sea. J. Mar. Syst. 23 (4), 317–331.

Tintoré, J., La Violette, P.E., Bladé, I., Cruzado, A., 1988. A study of an intense density front in the eastern Alborán Sea: the Almería–Orán front. J. Phys. Oceanogr. 18, 1384–1397.

Tintoré, J., Gomis, D., Alonso, S., Parrilla, G., 1991. Mesoscale dynamics and vertical motion in the Alborán Sea. J. Phys. Oceanogr. 21 (6), 811–823.

Vázquez-Cuervo, J., Font, J., Martínez-Benjamin, J.J., 1996. Observations on the circulation in the Alboran Sea using ERSI altimetry and sea surface temperature data. J. Phys. Oceanogr. 26 (8), 1426–1439.

Viúdez, A., Tintoré, J., Haney, R.L., 1996. Circulation in the Alborán Sea as determined by quasi-synoptic hydrographic observations: Part I. Three-dimensional structure of the two anticyclonic gyres. J. Phys. Oceanogr. 26 (5), 684–705.

Viúdez, A., Haney, R.L., Vázquez-Cuervo, J., 1998a. The deflection and division of an oceanic baroclinic jet by a coastal boundary: a case study in the Alboran Sea. J. Phys. Oceanogr. 28, 289–308.

Viúdez, A., Pinot, J.M., Haney, R.L., 1998b. On the upper layer circulation in the Alboran Sea. J. Geophys. Res. 103 (C10), 21653–21666.

Yashayaev, I.M., 2000. 12-year hydrographic survey of the Newfoundland Basin: seasonal cycle and interannual variability of water masses. ICES CM 2000/L: 17. North Atlantic Processes.