Simulation of the barotropic circulation in the Western Mediterranean Sea

David Alberto Salas de León*
María Adela Monreal Gómez*

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Resumen

Se utilizó un modelo numérico con el fin de simular las principales características barotrópicas de la circulación en el Mar Mediterráneo Occidental, inducidas por flujos a través de los Estrechos de Gibraltar y de Sicilia. El modelo se resuelve numéricamente sobre una malla descentrada tipo Arakawa C, con resolución de 41.5 km en x y 39 km en y. Los resultados del modelo reproducen los giros ciclónicos del Mar Tirreno, del Mar Ligurio y de la región que se encuentra entre la cuenca de Argelia y la parte occidental de las islas Baleares. La solución muestra la circulación anticiclónica de la Planicie Abisal, de la cuenca de Argelia y de la región de las islas Baleares.

Abstract

A numerical model is used to reproduce the main barotropic features of the Western Mediterranean currents, induced by the inflow through the Strait of Gibraltar and the outflow at the Sicily Channel. The model is solved numerically on a staggered Arakawa C-grid with a 41.5 km in x and 39 km in y resolution. Results reproduce the presence of cyclonic features at the Tyrrhenian Sea, in the region between the Algiers basin and the western part of the Balearic islands and anticyclonic features between the Abyssal plane, Algiers Basin and the Sardinian-Balearic Pass.

* Laboratorio de Oceanografía Física, Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México, Apdo. Postal 70-305, 04510 México, D.F., Correos electrónicos: salas@mar.icmyl.unam.mx y monreal@mar.icmyl.unam.mx

Introduction

The Mediterranean Sea is a semi-enclosed sea (Figure 1) that receives inflowing of Atlantic waters through the Strait of Gibraltar (Chic *et al.*, 1997). Evaporation creates a mass deficit in the basin which is compensated by this inflow (Loth and Crepon, 1984). The inflowing waters are lighter than the Mediterranean waters, producing a well defined two layers system. Observations of the vertical structure of water density, low frequency atmospheric fluctuations, and the application of an analytical model over the Ligurian Sea, show the importance of the barotropic and first baroclinic modes (Gasparini and Manzella, 1984). The general circulation of the Western Mediterranean Sea has been widely documented by numerous authors (Ovchinnikov, 1966; Gascard, 1978; Crepon *et al.*, 1982; Bethoux *et al.*, 1982; Philippe and Harang, 1982; Heburn, 1995; Beckers *et al.*, 1997, among others). Millot (1987; 1991; 1999) and Send *et al*. (1999) presented an accurate description of the circulation in the Western Mediterranean Sea from data and most of the available papers, and assembled them in schematic charts.

Several hypothesis, summarized by Vakalyuk *et al.* (1986), were formulated trying to explain the origin of the cyclonic and anticyclonic eddies in the Western Mediterranean. The first one assumes that the cyclogenesis in the Ligurian Sea is induced by specific conditions of large-scale atmospheric circulation over the Western Europe and Eastern part of the Atlantic Ocean. The second hypothesis assumes that the origin and development of this cyclonic feature depend on specific hydrological conditions in the surface layer of the ocean. Perilli and Salusti (1993) show for the Tyrrhenian Sea, a constant – stratification flow, this is in agreement with the theoretical idea of a one layer flowing in this sea.

Heburn (1990), using results of several numerical models (one-active layer, reducing gravity model forced by winds, inflow/outflow mass, and/or density variations), and satellite observations shows that the Mediterranean Sea has complex circulation patterns which are time-dependent. On the other hand, historical satellite images, aircraft, and *in situ* data, have shown two anticyclonic gyres: one at the western part of the Alboran Sea and the other at its eastern part. These are major oceanic features of this sea (Heburn and La Violette, 1990).

On the large scale, an evaluation of the associated surface circulation in the Gulf of Lion made by Johns *et al*. (1992) confirms the presence of a prominent anticyclonic eddy in the southwest part of the gulf. On the Balearic sides, two fronts follow the continental shelf break. This mesoscale phenomena is proposed in terms of cyclonic eddies generated by some kind of instability mechanism in the two frontal systems by Font *et al.* (1988).

It appears from all the large international programs (WMCE, POEM, and the Gibraltar Experiment) that the main control of the physical character of the Western Mediterranean Sea is the continental climate and their seasonal variability (La Violette, 1995).

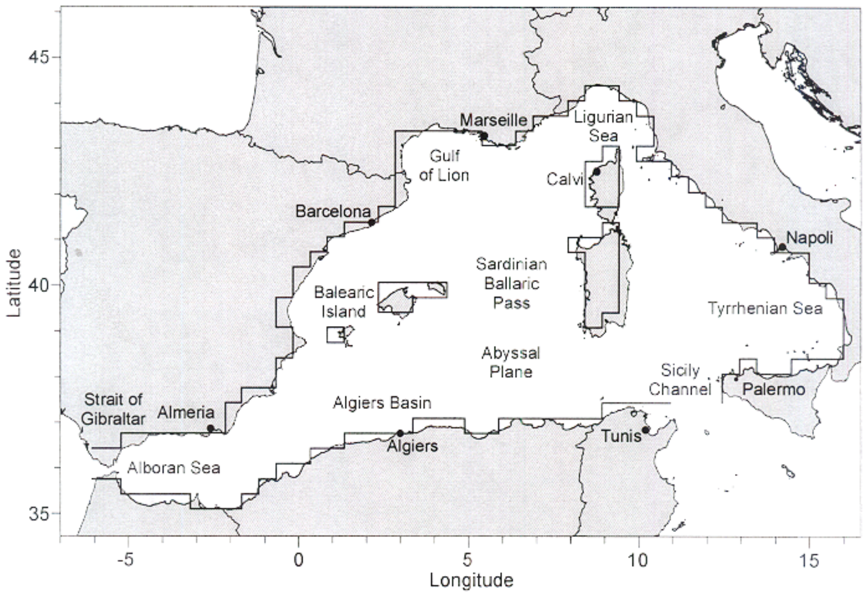

Figure 1. Western Mediterranean sea and integration domain of the numerical model.

The barotropic response of the Western Mediterranean Sea is always associated to the atmospheric pressure (Lacombe, 1961; Crepon, 1965; Garrett, 1983; Candela and Lozano, 1995; Puig *et al.*, 2000). On the other hand, strong baroclinic processes can be observed in this basin (e.g. complex patterns related to eddies, frontal meanders and filaments, deep water formation, etc.). For this reason barotropic processes induced only by the inflow through the Strait of Gibraltar have not been studied intensively. In this study, in order to understand better the barotropic dynamics in the Western Mediterranean Sea, a very simple barotropic depth-integrated model, forced by the flow in the upper layer, through the Strait of Gibraltar and the Strait of Sicily is considered.

Basic Equations

The barotropic mode can be simulated using a numerical model vertically integrated in a flat tangent plane to the earth surface (β-plane). This model uses momentum and continuity equations for a hydrostatic, Boussinesq fluid with a free surface in a rotating coordinate system with *z* upwards. The vertically integrated nonlinear model equations on a β-plane are (e.g. Monreal-Gómez and Salas-de-León, 1985):

$$\frac{\partial \vec{V}}{\partial t} + \left(\nabla \cdot \vec{V} + \vec{V} \cdot \nabla\right)\vec{v} + \hat{k} \times f\vec{V} = -hg\nabla\eta - \frac{\vec{\tau}_b}{\rho} + \tilde{V}_H \nabla^2 \vec{V} \qquad (1)$$

$$\frac{\partial \eta}{\partial t} + \nabla \cdot \vec{V} = 0 \qquad (2)$$

where:

$\vec{V}$ two dimensional horizontal transport vector, $\vec{V} = \hat{\imath}U + \hat{\jmath}V$; $\vec{V} = (\vec{v}h)$

$\vec{v}$ instantaneous velocity of the layer

h instantaneous local thickness of the layer

η free surface anomaly

t time

∇ the horizontal vectorial nabla operator, $\nabla = \hat{\imath}\frac{\partial}{\partial x} + \hat{\jmath}\frac{\partial}{\partial y}$

$\hat{\imath}, \hat{\jmath}, \hat{k}$ unit vector, $\hat{k}$ upwards

f Coriolis parameter, $f = f_0 + \beta y$; $\beta = \frac{\partial f}{\partial y}$

ρ density of sea water

g acceleration due to gravity

$\vec{\tau}_b$ tangential stress at the bottom

$\tilde{\nu}_H$ horizontal eddy viscosity

∇^2 two dimensional Laplacian operator, $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$

Appropriate boundary conditions are imposed in order to close the system. The free-slip conditions on the lateral boundary are represented by:

$U = 0$ and $\frac{\partial V}{\partial x} = 0$ on a meridional coast

$V = 0$ and $\frac{\partial U}{\partial y} = 0$ on a zonal coast

The influence of bottom topography and wind stress is neglected in this study. This does not imply that we believe wind forcing and bottom form are unimportant to the basin circulation. Our purpose is to enhance the barotropic circulation induced only by the inflow-outflow through the Gibraltar and Sicily Straits.

The role of the straits and channels in the Mediterranean circulation is well know (Astraldi *et al.*, 1999). Candela *et al.* (1989) observed transport related to subinertial flows, with periods ranging from days to few months through the Strait of Gibraltar. This transport reaches values up to 10^6 m^3s^{-1}. On the other hand, Ochoa and Bray (1988) estimate values of 0.64 x 10^6 m^3s^{-1} and 0.55 x 10^6 m^3s^{-1}. Del Cañizo (1988) presented an evaluation of the average regimen on the Strait of Gibraltar using triangular sections, and found a flow of 1.22 x 10^6 m^3s^{-1} and an interface depth of 159 m in a steady state regimen. Nevertheless the work developed to estimate the Gribraltar inflow, Carter's (1956) data is the only series that shows seasonal variations as mean monthly flows (Figure 2). For this reason we used it as open boundary conditions.

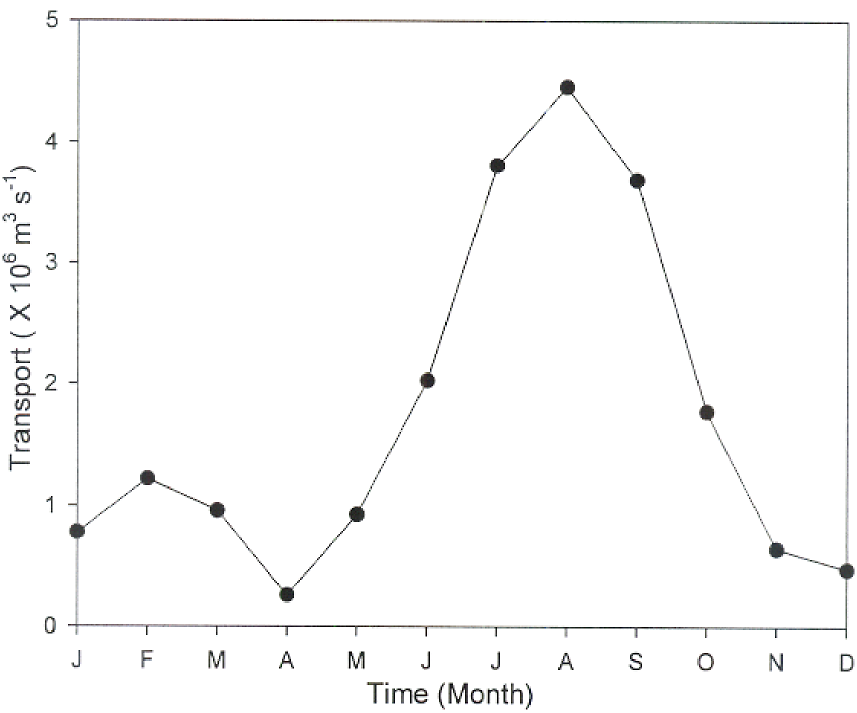

Figure 2. Mean monthly transport at the Strait of Gibraltar (After Carters, 1956).

The Strait of Sicily is the critical region of the water exchanges between the eastern and western Mediterranean basins. In this region transport calculations are subjected to great uncertainty due to the large channels at the west and small channels at the east entrances (Manzella, 1995). The circulation and the water exchanges at the Strait of Sicily have been studied in detail by Garzoli and Maillard (1979), Garzoli *et al.* (1982), Frassetto (1964), and Astraldi *et al.* (2001). These authors found circulation mainly dependent on the complex bottom topography. Using the dynamic method, Garzoli and Maillard (1979) and Morel (1969) also estimated a flow of 10^6 m^3s^{-1}. Nevertheless, in order to satisfy the mass continuity we use an equal meridional flow of water in this zonal boundary similar to the Strait of Gibraltar flow.

The model is driven from rest by inflow through the Strait of Gibraltar which is exactly compensated by outflow through the Strait of Sicily.

Numerical approximation and model parameters

The model equations (1) and (2) were solved numerically on a Modified staggered Arakawa C-grid with their appropriate boundary conditions using a layer thickness of 200 m. The water below this depth flows out of the Mediterranean, we then take into account only the upper layer. The barotropic Rossby deformation radius equation (e.g. Holland, 1986) is taken into account:

$$R = \frac{(gD)^{1/2}}{f} \tag{3}$$

where D is the layer depth, and f the Coriolis parameter. Equation (3) gives $R \approx 460$ km for the Mediterranean Sea. The numerical solution is obtained using a semi-implicit finite-difference scheme on a rectangular mesh of 41.5 km in x (East-West) by 39 km in y (North-South) resolution. The time differencing is leapfrog; it means a double time-step operation, which is made on a spatial staggered grid. The Coriolis term is calculated on a four points average, an upstream differencing procedure is used in the advection terms. The bottom friction term was calculated using the quadratic law. Because the differences are centered, the scheme has a second order approximation in space and time. Analyzing the numerical stability of the scheme, using the von Neumann condition, the time step is limited by (e.g. Salas-de-León, 1986):

$$\Delta t \leq \frac{\Delta x^2}{4\tilde{\nu}_H} \tag{4}$$

The semi-implicit scheme, as well as its characteristic of the order approximation, produce a numerical stability condition as expression (4), which allows use as a relatively large time step. In the numerical solution, the following parameters are used: Δt = 1200 s, thickness layer of 200 m (Djenidi *et al.*, 1987; Del Cañizo, 1988); an eddy viscosity coefficient of 500 m^2s^{-1}; a dimensionless drag coefficient of 10^{-3}, β parameter equal to 2 x 10^{-11} $m^{-1}s^{-1}$, and according to observations an inflow angle of 21^0 at the Strait of Gibraltar, which is measured from x axis. The boundary conditions for the transport at the Gibraltar Strait is northeasterly (Lacombe, 1971; Lacombe and Tchernia, 1972; Preller and Hurlburt, 1982) and a normal outflow at the Sicily Channel. The inflow-outflow varying along the year according to Carter's (1956) data. The approximation of the Mediterranean geometry to the model is shown in Figure (1).

Results and Discussion

The model was spin-up with high viscosity, considering a mean transport of 1.75 x 10^6 m^3s^{-1} through the Strait of Gibraltar. This transport value was calculated from the Carter's (1956) data set. The model was integrated to statistical equilibrium. Afterwards, smaller values of eddy viscosity were considered in order to analyze the numerical solution under more realistic conditions. The monthly variability is taken into account according Carter's values.

The general circulation of the Alboran Sea has been documented by numerous authors (Ovchinnikov, 1966; Lanoix, 1974; Padilla and Kinder, 1984; Preller, 1986; Tintore *et al.*, 1995; Allen *et al.*, 2001). The large scale circulation in this sea depicts two well defined anticyclonic gyres, which are not reproduced by the model. In the numerical experiment the Atlantic water goes into the basin and flows northeast deflecting water southward at the western part of the Strait of Gibraltar, changing the 21^0 inflow angle, and forming a persistent cyclonic eddy (Figures 3 to 5). This result could be an effect of the low model discretization, and the elimination of the Alboran island in the model domain. Makarov and Jimémez-Illescas (2003) found similar conditions in a barotropic model for the Gulf of California when they eliminate several islands of the model. A very important result obtained by Gleizon *et al.* (1996) shows that the internal radius of deformation plays an important role in the structure and the stability of the western gyre, pointing out a strong baroclinic dependence. Regarding the hydrographic structure of the Strait of Gibraltar, Kinder *et al.* (1988), have shown a shallow thermocline of 50 to 30 m, and the halocline slope upward from 300 to 100 m, from west to east. From the results it seems clear that a more realistic upper layer thickness will be needed to be used in the Strait of Gibraltar to find better results.

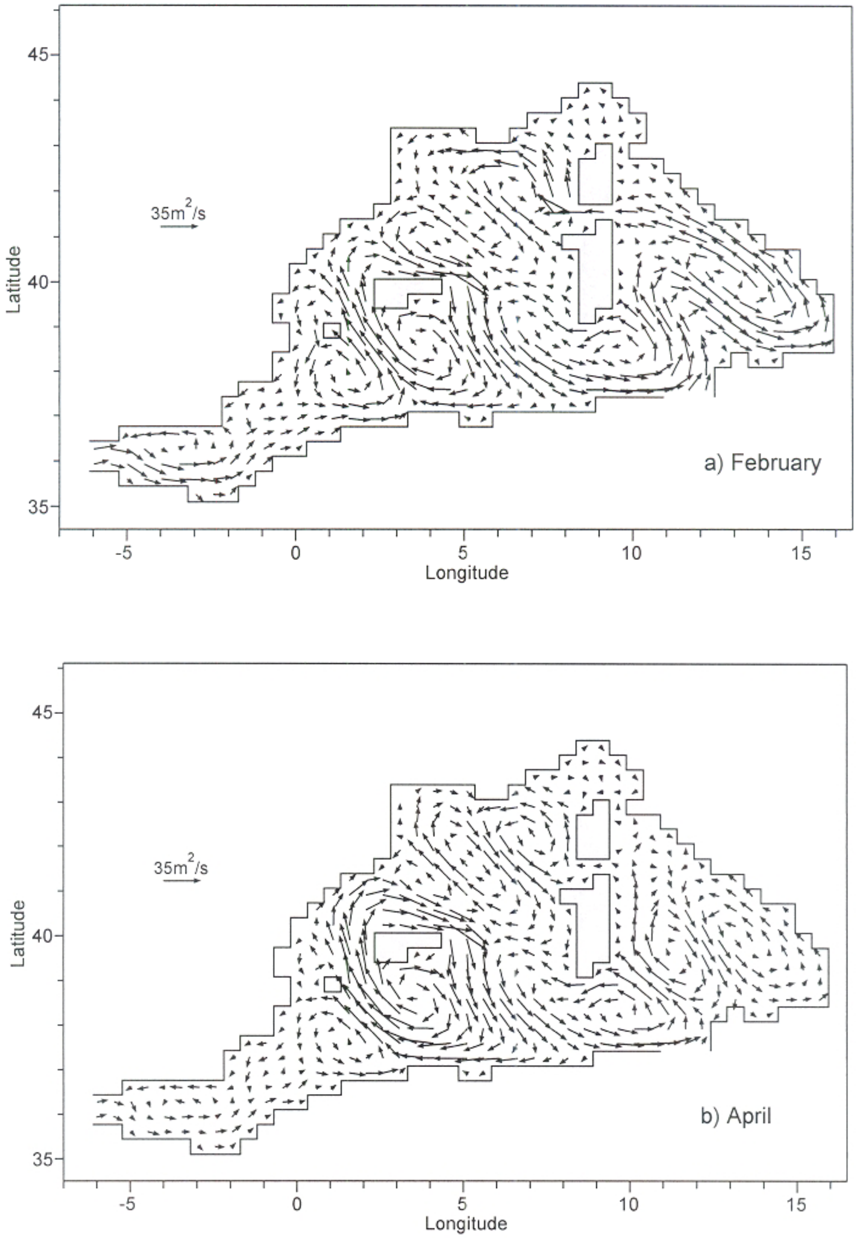

Figure 3. Circulation pattern obtained by the barotropic numerical model. Horizontal transport (m^2s^{-1}). (a) February and (b) April.

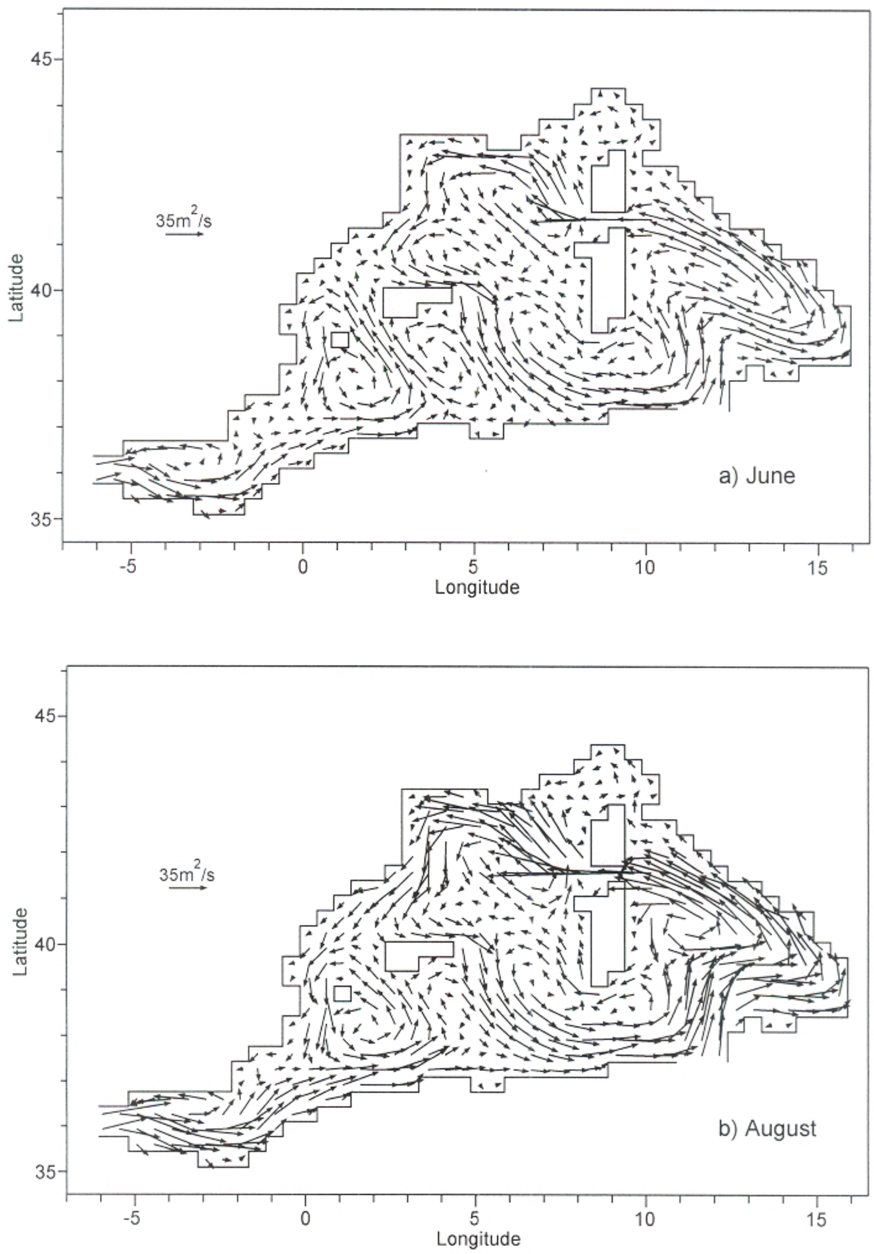

Figure 4. Circulation pattern obtained by the barotropic numerical model. Horizontal transport (m^2s^{-1}). (a) June and (b) August.

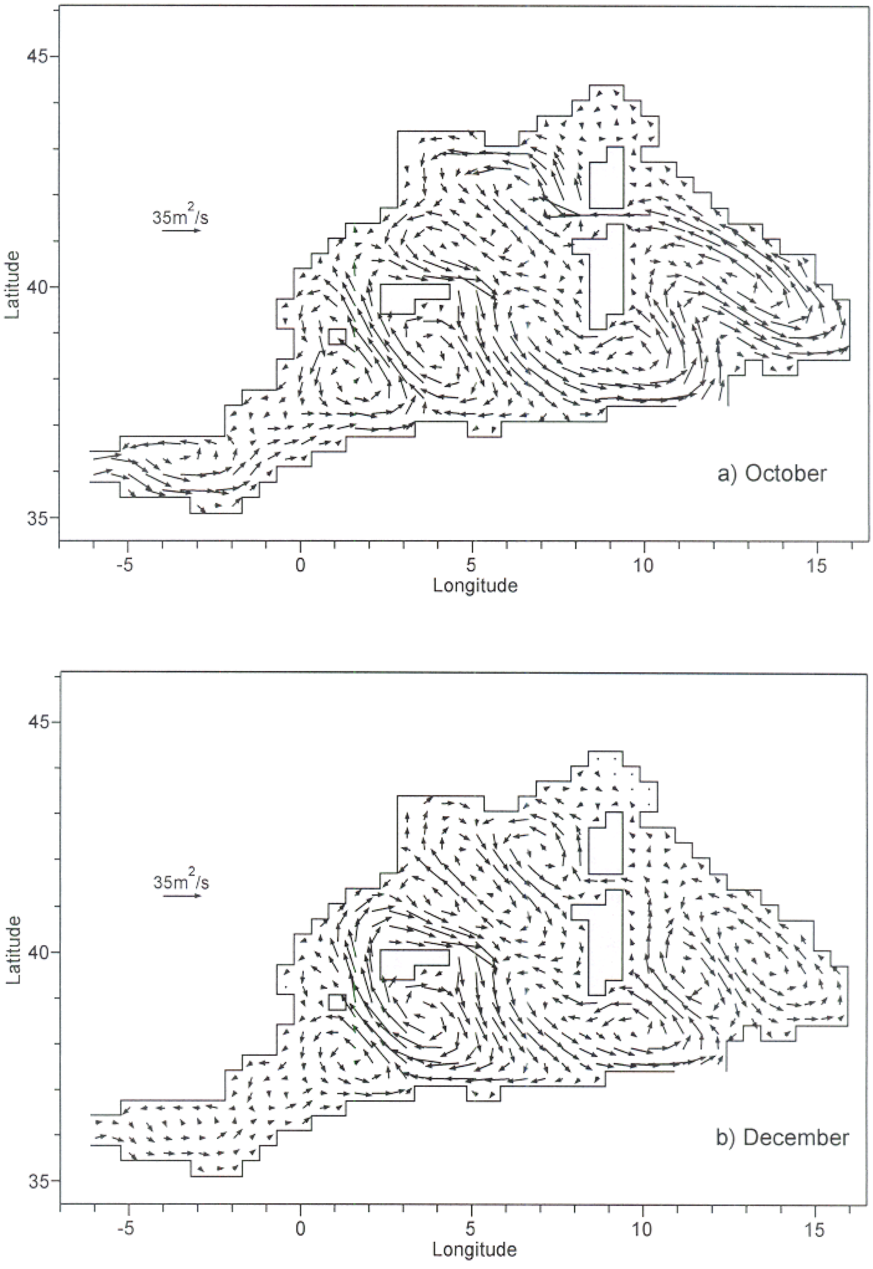

Figure 5. Circulation pattern obtained by the barotropic numerical model. Horizontal transport (m^2s^{-1}). (a) October and (b) December.

In the Algiers Basin, namely between the Balearic island and Algier, the infrared imagery and other numerical models revealed the occurrence of an anticyclonic eddy (Millot, 1987; Beckers and Nihoul, 1992). This mesoscale eddy migrates from the Algiers Basin to the Sardinia Channel (Bouzinac *et al.*, 1999; Send *et al.*, 1999; Puillat *et al.*, 2002). The results of the model show an anticyclonic current in this place (Figures 3, 4 and 5). This feature vanishes during maximum flow and a meandering current is exhibited (Figure 4b).

Time variations of the model results show cyclonic eddies between the Algiers Basin and the western part of the Balearic islands (Figures 3 to 5) and also at the Abyssal Plain, the eastern part of the Tyrrhenian Sea, to the west of Calvi and at the northeastern Balearic islands. Anticyclonic currents can be seen between the Abyssal Plain, the Algiers Basin and around of the Balearic islands, between the Sardinian-Balearic pass and the Gulf of Lion, and at the western part of the Tyrrhenian Sea. These characteristics remain almost all the year.

Pinot *et al.* (1995) shows the existence of two energetic frontal jets in the Balearic Sea, a southward continental current and a northward Balearic current. The continental currents veer cyclonically during the winter season. The results of the model show this jets and the winter cyclonic eddy in the southwest part of the region (Figure 3a).

The numerical results show that a cyclonic feature takes place at the Ligurian Sea, coincident with the horizontal distribution of temperature and salinity observed by Gostan (1967), Hela (1963), Stocchino and Testoni (1977), Taupier-Letage and Millot (1986), Trotti (1954), Vakalyuk *et al.* (1986) and Astraldi *et al.* (1995). The conclusion of these authors is that the mean circulation in the Ligurian Sea is cyclonic. According to the model, this cyclonic gyre is more intense during August (Figure 4b), when the flow through the Gibraltar Strait is maximum.

Concerning the Tyrrhenian Sea, along the Italian peninsula, a northward circulation has been observed (Elliott, 1979; Astraldi and Manzella, 1983; Millot, 1987). At the western side of the basin the water is encountered (Figure 5b) by a southwestward flow (Krivosheya and Ovchinnikov, 1973; Astraldi and Gasparini, 1995; and Marullo *et al.*, 1995). This SW feature is well reproduced by the model, in June, August (Figure 4) and October (Figure 5a). This feature takes place in all of the Basin. However in February (Figure 3a) in the southern part a meandering ocurrs, which in April (Figure 3b) and December (Figure 5b), when the minimum flow is present, becomes a cyclonic gyre and a dipole cyclone-anticyclone is developed. The origen of these eddies and meanders are attributed to the wind (Perilli *et al.*, 1995), but the model reproduces this feature well.

The open boundary conditions at the Strait of Sicily were imposed considering that the tangential horizontal transport vanishes, and the normal component compensates the inflow at the Strait of Gibraltar. Both open boundaries are part of the computational domain, but they are not shown in the figures of the numerical results. Nevertheless, the outflow was prescribed normal to the open boundary, near to the Strait of Sicily where the circulation pattern exhibits a large tangential component. This feature is in accordance with the mean annual circulation and weekly average current at the upper layer, obtained by Beckers *et al.* (1997) using real depth and winds in a three dimensional numerical model. On the other hand, Oken and Sellschopp (1998) report the existence of stationary eddies near the Sicily. The model results reproduce this very small eddy on the northwestern part of the Sicilian island (Figure 3a). Zavatarelli and Mellor (1995) using a primitive equation oceanic model with a curvilinear grid and a sigma-coordinate system, forced with monthly climatological values of the wind stress, heat, and salinity flux show a tangential flow from west to east in the western Sicilian Channel, outflow at the central channel, and an inflow in the Eastern channel. In our model we don't have an inflow at the Sicilian Channel, and the apparent inflow in the eastern channel is the barotropic lateral boundary runoff induced by the Sicilian Island and by the outflow at the open boundary conditions.

When the transport through the Strait of Gibraltar is maximum, the currents inside the Western Mediterranean are maximum too. At this time, anticyclonic and cyclonic eddies are almost all masked by the strong currents.

Summary and Conclusions

The barotropic circulation in the Western Mediterranean Sea were inferred from a numerical model, where the perturbation is a basic flow through the Strait of Gibraltar and the Strait of Sicily. The solution summarize the semi-permanent features of the circulation. Despite the simplification of the model, and the big grid size, it can be seen that the general trends of the mesoscale synoptic variability are well reproduced.

The results show that cyclonic features are depicted in the Tyrrhenian Sea, the Abyssal Plain and the Ligurian Sea, and anticyclonic in the Algiers Basin and the Sardiniono-Balearic Pass.

The barotropic effect induced by the inflow-outflow are significant in the general circulation pattern in the study area. Moreover, it does indicate that the barotropic effects induced by the inflow through the Strait of Gibraltar are significant in the general circulation in this sea.

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