# Progress from 1989 to 1992 in understanding the circulation of the Western Mediterranean Sea

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ABSTRACT

The present paper describes the major results obtained from 1989 to 1992 by the EUROMODEL group in studying the circulation in the Western Mediterranean Sea. Particular emphasis has been given to the physical processes responsible for seasonal and mesoscale variabilities. Observations (*in situ* and satellite), together with theoretical, physical and numerical models, have been widely used in the course of these studies.

Attention has been focused on the dynamics of the northern basin (deep water formation, dynamics of the Northern Mediterranean Current, circulation and shelf / slope interaction in the Balearic Sea) and of the southern basin (Alboran Sea circulation, instabilities of the Algerian Current). The straits dynamics have been studied with particular reference to the Corsica channel. Preliminary runs of a basin-scale circulation model of the Western Mediterranean Sea forced by the straits are also presented. They are shown to be capable of generating a cyclonic circulation in the western basin.

RÉSUMÉ

La circulation de la Méditerranée Occidentale: principaux résultats obtenus de 1989 à 1992.

La circulation de la Méditerranée Occidentale a été étudiée par le groupe EUROMODEL de 1989 à 1992. Les principaux résultats sont présentés en mettant l'accent sur les processus physiques responsables de la variabilité saisonnière à moyenne échelle. Cet article est une synthèse des observations (*in situ* et satellitaires), des modèles théoriques, physiques et numériques qui ont été utilisés au cours de ce travail.

Les études ont porté sur la partie nord du bassin (formation des eaux profondes, dynamique du courant Nord Méditerranée, circulation et interactions entre le plateau et la pente continentale dans la mer des Baléares) et sur la partie sud du bassin (circulation en mer d'Alboran, instabilités du courant Algérien). La dynamique du détroit de Corse a été particulièrement étudiée. Des résultats préliminaires d'un modèle numérique de circulation de la Méditerranée Occidentale forcé uniquement par les détroits montrent que ceux-ci peuvent engendrer une circulation cyclonique dans le bassin ouest.

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## INTRODUCTION

The Mediterranean Sea can be considered as a reduced ocean where a large variety of processes and phenomena affecting the world's ocean circulation is present : deep water formation; stability of coastal currents; fronts; eddies; mesoscale turbulence; strait dynamics; interaction between basin-scale and coastal / shelf circulations. Because of its semi-arid climate, its geographical location in the middle latitudes, its occasionally violent meteorological conditions and its relative isolation, the Western Mediterranean is suitable for investigating these processes and phenomena. *In situ* observations are facilitated by the fact that there are no significant tidal currents, while the sparse cloud cover is conducive to satellite observations. It is a readily accessible region and hence constitutes an excellent laboratory. As a semi-enclosed basin, it lends itself readily to ocean modelling since it is small in size and virtually confined with well-defined boundaries. In sum, the Mediterranean Sea is ideally suited to synthetic interaction between observations and modelling.

At the end of the 1980s several scientists involved in the study of the circulation in the Western Mediterranean Sea decided to pool their efforts and set up the EUROMODEL research programme, whose objective is to describe, understand and simulate the circulation in the Western Mediterranean with particular emphasis on seasonal and mesoscale variabilities. Synergy between observations, theoretical, physical and numerical models is foreseen.

The Mediterranean Sea is a thermodynamics machine which transforms oceanic waters into denser ones through processes basically dependent on interaction with the atmosphere. The density gradient between the western basin, the Atlantic Ocean and the Eastern Mediterranean basin conditions the transports through the Strait of Gibraltar and the Strait of Sicily which both contribute to drive the basin scale cyclonic circulation of the Modified Atlantic Water (MAW hereinafter) and the Levantine Intermediate Water (LIW hereinafter).

The methodology adopted by the EUROMODEL group involved, in the first place, investigation of some of the major processes responsible for the Western Mediterranean Sea circulation. Deep water formation was carefully analysed as a possible candidate for driving the large cyclonic gyre observed in the northwestern basin. Due to the seasonal variability of the atmospheric forcing, a seasonal variability of the hydrological and dynamical characteristics is expected. The path of the Atlantic Water in the southern basin was investigated through specific studies devoted to the Alboran Sea circulation, the Almeria-Oran jet and the Algerian coastal current and its instabilities.

Also important are the circulation and dynamics of regional seas as the Balearic Sea between the northern Gulf of Lions and the southern Alboran Sea. Mesoscale dynamics is significant and can strongly modify the basin-scale circulation. The Balearic Sea acts as a buffer zone and controls the southward spreading of Mediterranean Water and the northward inflow of Modified Atlantic Water, and has been carefully studied.

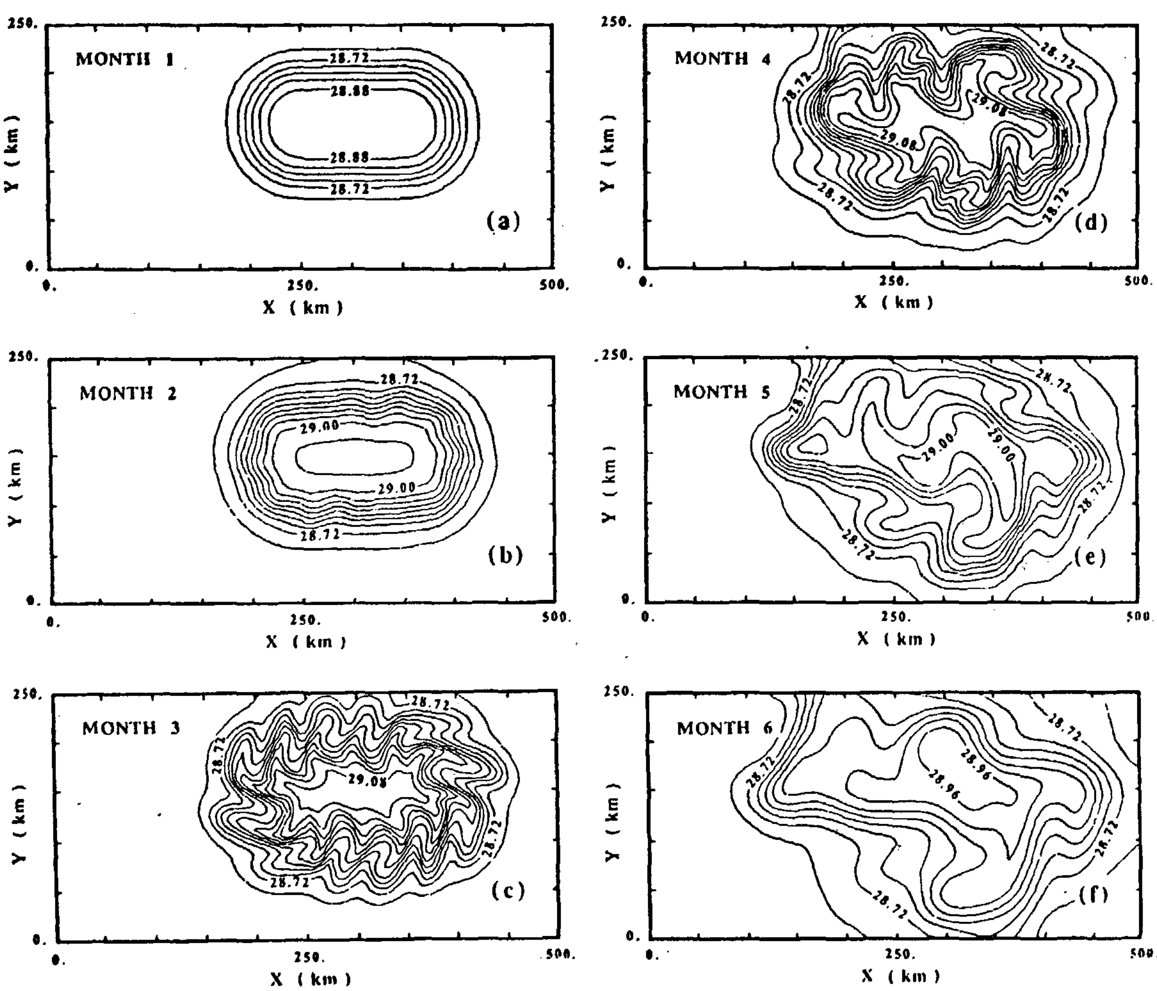



Figure 1

*Sea surface density at different times for an oval thermohaline forcing. The first month density field fits the thermohaline forcing pattern. Starting at month 2 we denote wavy motions due to baroclinic instability. The deep water formation occurs at month 3.*

Understanding the mass, salt and heat budgets of the entire Western Mediterranean requires an accurate knowledge of advective transports and of the connection of the different basins through straits and channels. This budget understanding will be achieved by analysing a basin-scale circulation model with realistic configuration and atmospheric forcing.

## THE NORTHERN BASIN

One important component of the circulation in the Western Mediterranean involves the entire northern part of the basin, where a large permanent cyclonic gyre is observed. In winter, this northern part can be considered as an Arctic ocean where deep water is formed under the action of the Mistral and the Tramontana (strong cold and dry winds) responsible for intense evaporation (Stommel, 1972; Gascard, 1978; Killworth, 1983). Theoretical work (Crépon *et al.*, 1989) showed that buoyancy forcing *via* deep water formation processes is a possible candidate for driving the cyclonic circulation.

### Deep water formation

Deep water formation was investigated by performing numerical experiments with the three-dimensional primitive equation model of the LODYC (Laboratoire d'Océanographie Dynamique et de Climatologie). Convective processes have been parameterized by a non-penetrative convective adjustment algorithm which instantaneously restores at each time step the static stability of the water column (Madec *et al.*, 1991*b*). Such parameterization of convective processes is consistent with winter observations in the MEDOC area (Anati, 1971) and its success was demonstrated in the different studies (Madec *et al.*, 1991*a*, *b*; Madec and Crépon, 1991).

A first experiment was able to reproduce the violent mixing phase and the ensuing sinking and spreading phase (Madec *et al.*, 1991*b*). During the first two months, the dynamics response fits the linear theory developed by Crépon *et al.* (1989). After two months, meanders due to baroclinic instability begin to develop with a wavelength of 40 km (Fig. 1) as observed in Crépon *et al.* (1981). This baroclinic instability contributes to deep water formation by amplifying vertical motions, but tends to restabilize the water by advective motions. Sensitivity studies done in Madec *et al.* (1991*a*) showed that time variability of the forcing enhances the convective processes. At the end of the forcing period, the water column reaches the bottom. The numerical simulation is in good agreement with the observations of the MEDOC group (Fig. 2).

Sensitivity experiments were performed with a more realistic forcing whose pattern is tongue-shaped with the main characteristics of the MEDOC area. The effects of thermohaline *versus* wind forcing, of coastline geometry and bottom topography are investigated (Madec and Crépon, 1991). The localization of the thermohaline flux is shown to be a powerful mechanism for triggering the preconditioning phase of deep water formation. Besides, the wind curl generates a barotropic gyre whose central water masses remain at rest, thereby helping to increase their residence time under the thermohaline fluxes. It was noted that the $\beta$-effect plays an important role during this phase by triggering the eddy dynamics (Madec *et al.*, 1995). The wind stress also acts on the violent mixing phase by inhibiting the meander development at the vortex periphery found in the buoyancy-wind driven experiment. The existence of a continental shelf to the north does not modify the mechanism of the preconditioning phase of deep water. On the other hand, the introduction of a deep-sea fan abutted to the continental slope completely changes this mechanism by modifying the barotropic circulation which is trapped by the topography (Madec *et al.*, 1995). The water above the fan remains quiescent, allowing the atmospheric forcing to act longer and to remove a larger amount of heat. Topography dominates the $\beta$-effect. This may contribute to the formation of the preconditioning phase as suggested by Hogg (1973). In the deep water formation, the convective process is promoted to the detriment of the baroclinic adjustment process.

### The Northern Mediterranean Current

The above numerical studies (Madec *et al.*, 1991*a*, *b*; Madec and Crépon, 1991) confirmed that buoyancy forcing *via* deep water formation can drive the cyclonic circulation in the northern basin. Its northern part forms the Liguro-Provençо-Catalan Current which follows the continental slope along the coast of Provence, in the Gulf of Lions and the Catalan Sea where it has been studied by Font *et al.* (1988) and more recently by La Violette *et al.* (1990), Castellon *et al.* (1990) and Lopez-Garcia *et al.* (1994). Since such a current is characteristic of Mediterranean basins, it will further be referred to as the Northern Mediterranean Current (Millot, 1991). Its transport is of the same order of magnitude as the baroclinic transport at Gibraltar (Lacombe and Tchernia, 1972; Béthoux *et al.*, 1982; Albérola *et al.*, this issue; Conan and Millot, this issue). It displays a distinct seasonal variability with a larger transport in winter and a mesoscale variability marked by the growth of meanders which break down into small eddies.

### The Liguro-Provençal Basin

The coastal current transport referenced to 800 m computed from observations in the Ligurian Sea is 2.2 Sv (Béthoux *et al.*, 1982). It appears to be linked to density field modifications induced by the thermohaline forcing. However, the westward transport referenced to 800 m obtained in the buoyancy-wind driven model remains smaller (1.8 Sv) than the observed one and its evolution in time, with a maximum reached at the end of the cooling period, is not in agreement with the observed early winter

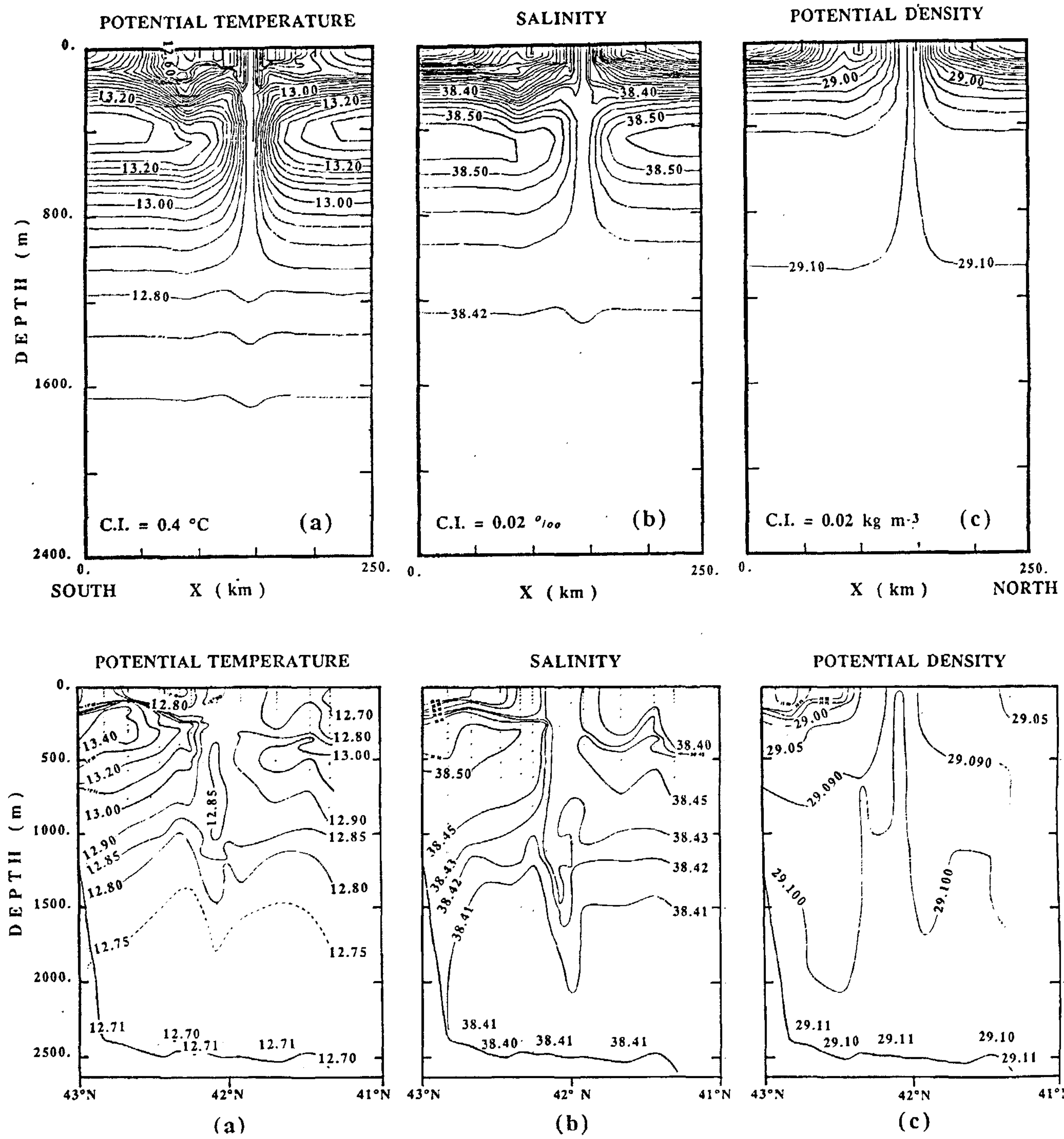



Figure 2

*(upper) - North-south vertical section in the centre of the forcing area (x = 300 km) at the end of month 3: a) potential temperature, b) salinity, c) potential density. The contour intervals (CI) are as indicated.*
*(lower) - North-south vertical section along 6° E during Medoc 69, 15-19 February (from Tchernia and Fieux, 1971): a) potential temperature, b) salinity, c) potential density.*

increase. These differences could result from the seasonal variations of the coastal current water T-S characteristics with respect to the central waters of the northern basin: a winter increase of the density difference between central and peripheral water masses would reinforce the coastal current and thus the westward transport. Recent measurements made by Astraldi and Gasparini (1992) support this statement, as described below. Another cause might be the winter increase of river runoff (Bong, 1983; Béthoux *et al.*, 1988).

From October 1990 to May 1991, the seasonal variability of the entire Northern Mediterranean Current was investigated through an *in situ* experiment conducted within the frame of PRIMO-0 (a complete description of PRIMO is given in the general introduction of this volume). The first results support those previously obtained from the Prolig-2 experiment, the Dyomé experiment and the SO La Spezia team. Essentially, the Northern Mediterranean Current flows nearer to the coast and intensifies at the end of the deep water formation season (Albérola *et al.*, this issue). The seasonal variability is characterized by an intense mesoscale activity in winter. These measurements, completed by hydrological data, revealed that current values down to about 150 m in the Northern Mediterranean Current are similar in winter, so that the upper part of this current more or less reacts as a slab layer during the studied period. A significant vertical component (measured from ADCP) of the current was recorded in the central Ligurian Sea in winter (Astraldi and Gasparini, 1994).

## The Catalan-Balearic Sea

Font *et al.* (1988) showed that the large scale dynamics in the Catalan-Balearic Sea is related to the presence of two well defined and permanent shelf / slope fronts located on the continental and island slopes, respectively linked to the Northern Mediterranean Current and the Balearic Current.

Along the Catalan coast, the circulation in the upper 300 m is dominated by along shore flows approximately located over the slope regions and characterized by mean velocities of the order of 20 cm/s as found by shipboard ADCP measurements in June 1989 (Castellon *et al.*, 1990). From data collected in 1983 and 1984, Maso and Duarte (1989), Font (1990), Maso *et al.* (1990), Maso and Tintore (1991) showed that the shelf region in the northern Balearic Sea is characterized by a strong spatial and temporal variability mainly associated with the southward spreading of low salinity continental waters from the Rhône river in the northern Gulf of Lions and by the intrusion of high salinity open sea water through submarine canyons.

The seasonal variability of the characteristics of the Northern Mediterranean Current in the Balearic Sea was studied with data obtained from three currentmeters deployed at depths of 15, 50 and 100 m from May 1987 to May 1992 near the shelf break off the Ebro delta (Font and Wang, 1991; Font *et al.*, this issue ). The velocity is maximum in autumn, minimum in summer and presents a strong barotropic component. Current inversions are observed. They could be related to the passage of mesoscale structures (eddies, filaments), not identifiable with a single mooring but which seem to have an important role in the circulation and in shelf / slope exchanges (Wang *et al.*, 1988). A clear trend of the current to the south-southwest, along the local isobaths, is evidenced although slightly deviated to the shelf in the upper level, due to a topographical induced upwelling. Both topography and density gradients are essential factors that will have to be included in numerical simulations of the circulation in this region of the Western Mediterranean. This raises the question of the efficiency of the numerical methods used near the shelf break. Indeed, Deleersnijder and Beckers (1992) showed that strong topographic variations induce numerical problems in models based on the classical $\sigma$-coordinate: a double $\sigma$-coordinate, such as that used in the GHER model, offers one possibility to overcome the difficulty.

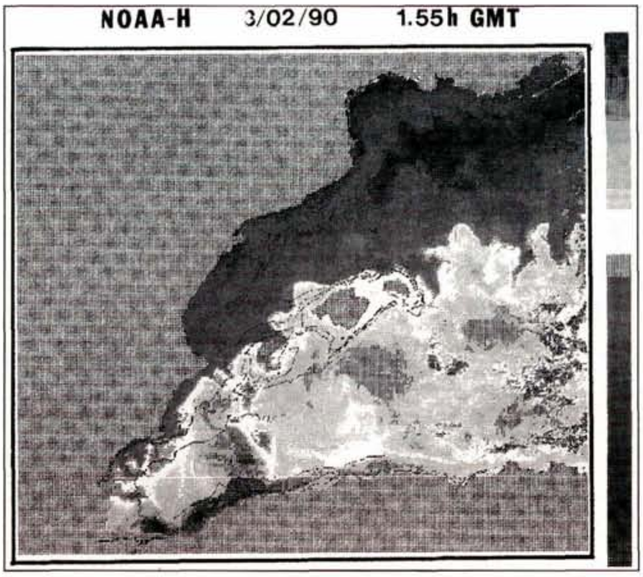



Figure 3

*NOAA-AVHRR sea surface temperature on 3 February 1990. Warm waters (yellow) in the Algerian basin are separated from cold waters (blue) of the Liguro-Provençal Basin by the Balearic-North Balearic Front. Mesoscale structures are clearly visible along the front.*

The sea surface circulation variability was also investigated from satellite images. Analysis of a series of AVHRR-NOAA images, mainly from the autumn-winter period during 1981-1988, together with various *in situ* data, revealed new aspects of the surface circulation variability (Le Vourch *et al.*, 1992; Lopez-Garcia *et al.*, 1994) (Fig. 3). In summer, a surface warm layer forms over most of the region and covers the Northern Mediterranean Current, which continues below to flow southwards along the Iberian peninsula slope. This local warming, delimited by the sheltering effect of the Pyrenees with respect to the northwesterly winds, creates one of the most intense thermal fronts in the Western Mediterranean, enhancing the so-called Catalan front linked to the Northern Mediterranean Current. Near the Balearic islands, the flow of recent Modified Atlantic Water transported through the Balearic sills by anticyclonic eddies detached from the Algerian Current, creates the Balearic front and contributes to its intense mesoscale variability. The Balearic front is the westward continuation of the North-Balearic front, already defined in the open sea as the northern limit of the recent Modified Atlantic Water reservoir (Deschamps *et al.*, 1984). Consequently, the Gulf of Valencia is frequently influenced by water issued from the Algerian Basin, and this appears to be important for the disruption of the Northern Mediterranean Current and the formation of the Balearic Current, which is the geostrophic flow associated with the Balearic front.

The circulation of these regional seas strongly interacts with the basin-scale circulation basin. A numerical study with a reduced-gravity model showed the high sensitivity of the Catalan-Balearic Sea to the boundary conditions (Garcia-Ladona and Djenidi, 1991). The use of realistic

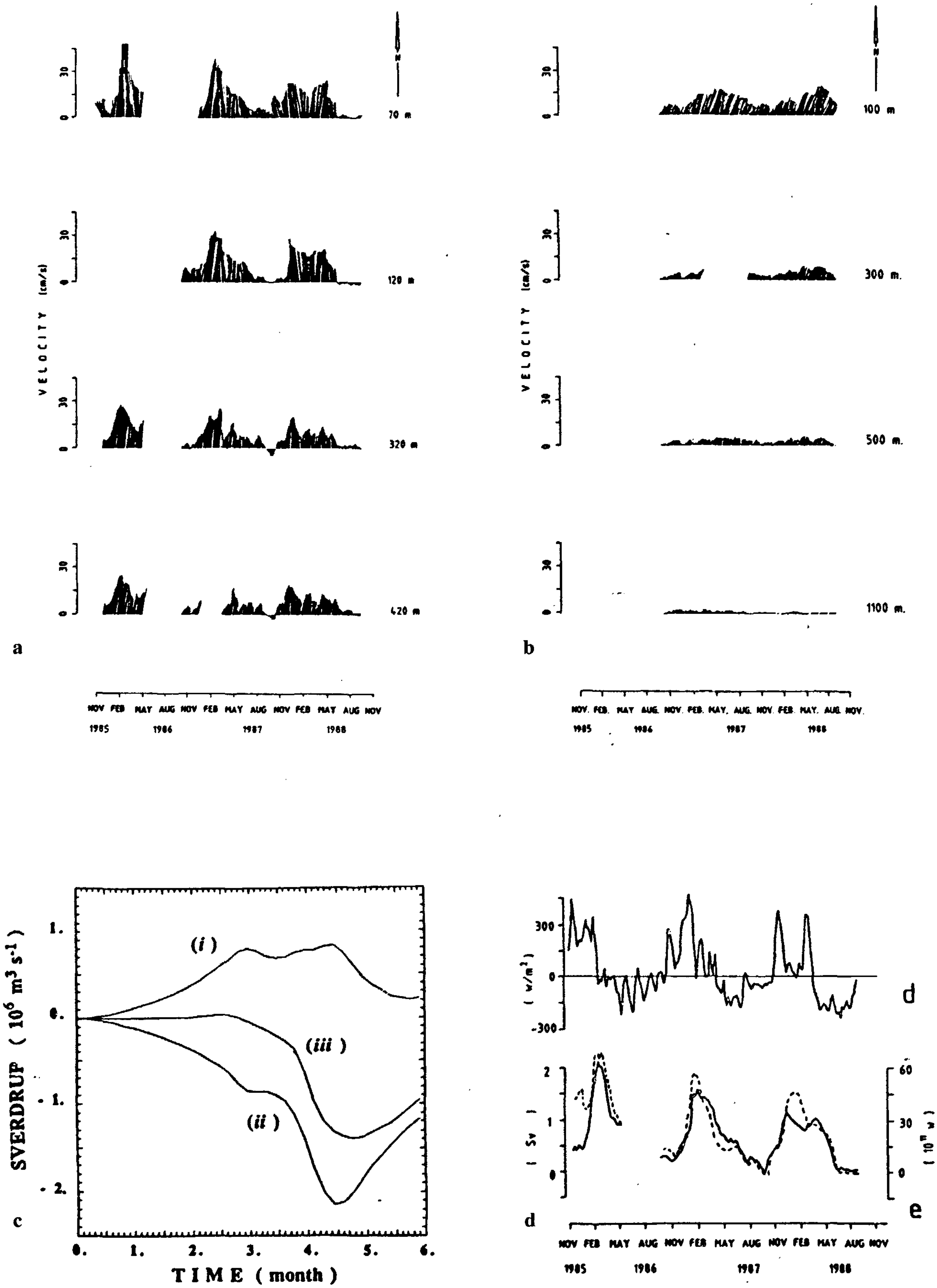



Figure 4

*Time evolution of the current east (a) and west (b) of Corsica. The original data have been low-pass filtered to remove oscillations below 168 h, and 48 h time series have been reconstructed. (c) Time evolution of the horizontal volumetric transport of water between the centre of the forcing area and the northern coast :* (i) *transport of the eastward deep countercurrent,* (ii) *transport of the westward and mainly surface current, and* (iii) *vertical averaged transport (from Madec* et al., *1991b). (d) upper time series : total heat flux between sea and atmosphere lower time series : total water transport (solid line) and total heat advected (dashed line) through the Corsica Channel.*

conditions at the open boundaries calculated from CTD casts distributed according to the scheme of frontal currents (Garcia-Ladona *et al.*, 1994*b*), gave much more realistic model results. Conversely, the regional circulation could trigger some aspects of the basin-scale circulation.

### Near-inertial motions

Spectral analysis of the above currentmeter data (Font and Wang, 1991; Font *et al.*, this issue) shows the dominance of the low-frequency fluctuations, with a remarkable contribution of inertial motion, especially during the stratified season. A spreading and shifting of the inertial energy to neighbouring bands is due to the interaction of the inertial oscillations with the main flow.

Using the UIB three-dimensional primitive equation model with a turbulence closure mixed layer, Tintore *et al.* (1994) investigated the dynamics in the near-inertial frequency band. They showed that the energy transfer is associated with the offshore propagation of a sharp wavefront generated at the coast and that the near-inertial energy propagates downward in the coastal ocean with a shift to higher frequencies as qualitatively explained by Millot and Crépon (1981) and Kundu (1986). Non-linearities are responsible for increasing the currents in the lower layer. This study is supported by the analysis of an experiment with surface drifters and moored currentmeters in June 1987 near the Catalan front (Salat *et al.*, 1992). On the shelf, strong inertial currents were generated by a wind burst. The inertial current amplitude was about 70 cm/s at the surface, 30 cm/s at the base of the mixed layer and 10 cm/s in the interior. The observed near-inertial frequency on the shelf was 10% lower than the local inertial frequency, suggesting that the near-inertial motion was embedded in a region of strong anticyclonic shear. The phase increased through the water column, indicating that the energy propagation was downward. By contrast, the surface inertial currents were only about 10 cm/s in the centre of the shelf / slope front. Inertial motions can interact with the shelf / slope current and can therefore affect the local biomass (Garcia-Ladona *et al.*, 1994*a*)

### The Corsica Channel

A large amount of the exchanges between the Northern and the Southern Western Mediterranean basins occurs through the Corsica Channel. The associated mass transports participate in the forcing of the circulation in the Liguro-Provençal Basin. These transports were investigated through a long-term monitoring of the current in the Corsica Channel (Astraldi and Gasparini, 1992). The measurements started in 1985 and, with only a few interruptions are still under way. These data represent the longest time series collected in the whole Mediterranean Sea, capable of providing basic information on the climatic changes of the basin. From 1986 to 1988, an additional current series has been collected on the western Corsican side.

Figure 4 (*a* and *b*) shows the current behaviour on both sides of Northern Corsica up to 1988. Though both flowing northward, the basic properties of the two currents significantly differ. Starting from the lowest values in late summer and autumn (Fig. 4*b*), the Western Corsica Current progressively increases to reach the highest values in early summer, from May to June. Even though this seasonal oscillation affects the whole water column, it is particularly evident in the surface layer. The annual value of the transport amounts to some 1.2 Sv, and is almost equally shared between the surface layer of Modified Atlantic Water and the Levantine Intermediate Water below. Figure 4*c* indicates that the occurrence of the highest current velocity closely corresponds to the period of the maximum transport of the boundary current as indicated by the numerical simulation by Madec *et al.* (1991*b*). This could mean that the seasonal oscillation of the Western Corsica Current might be related to the deep water formation processes occurring in the Gulf of Lions during winter.

The current crossing the Corsica Channel (the so-called Tyrrhenian Current) also shows a clear seasonal oscillation independent from that in the western side of Corsica (Fig. 4*a*). In fact, the Tyrrhenian water intrusions into the northern basin occur during the colder season and almost cease in summer and autumn. In contrast with the Western Corsica Current, they show a relevant inter-annual variability. In the three consecutive years of measurements, annual values of 0.72, 0.65 and 0.54 Sv have been found, mostly concentrated (80 %) in the surface layer. Outflowing from a warmer basin, the Tyrrhenian Current conveys a remarkable heat amount into the northern basin. Figure 4*d* shows that the water and transport variations in the Corsica Channel closely follow the variations of the basin total heat budget. This means that the seasonal intrusions of the Tyrrhenian water might be driven by the heat losses sustained by the basin in winter, through the thermohaline effects they induce in the basin surface layer.

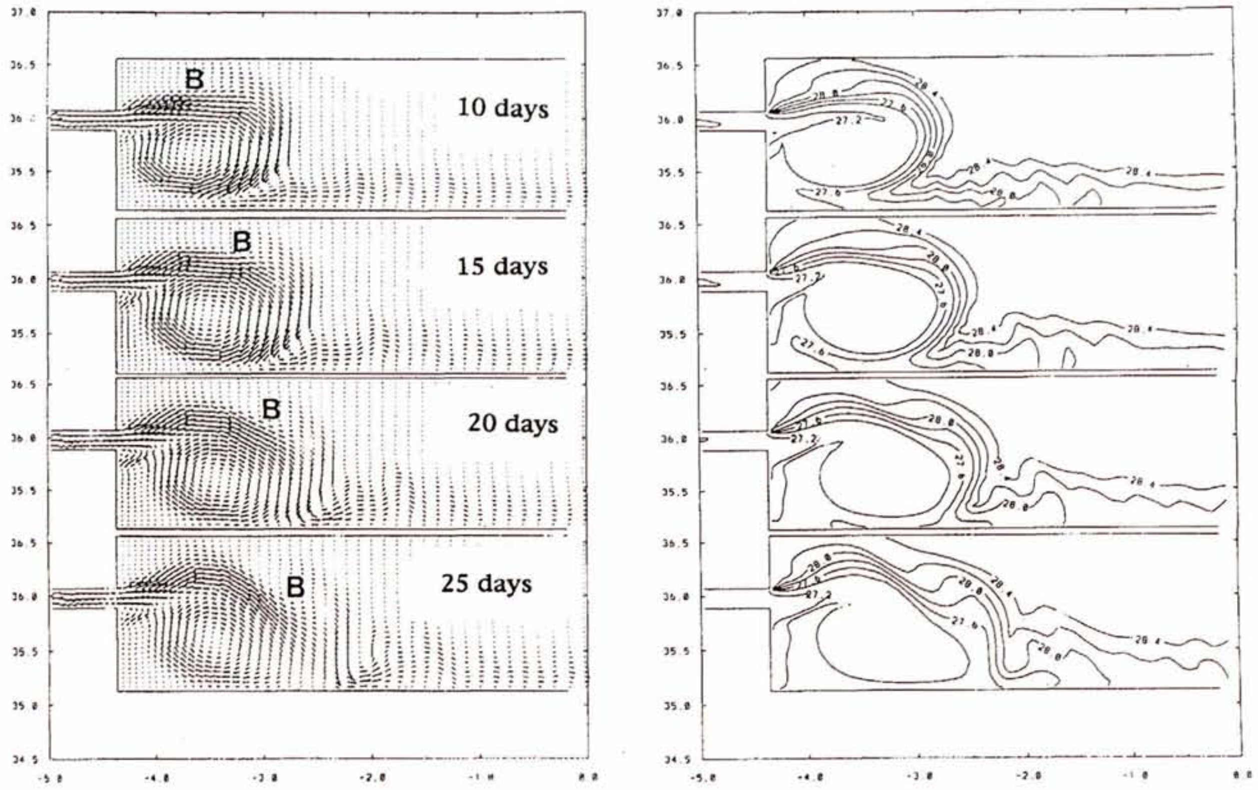
## THE SOUTHERN BASIN

The southern basin dynamics is rather different from that of the northern basin. The density gradient between the Western Mediterranean basin, the Atlantic Ocean and the Eastern Mediterranean basin conditions the transports through the Strait of Gibraltar and the Strait of Sicily, which drive the circulation of the Modified Atlantic Water and the Levantine Intermediate Water in the southern part of the Western Mediterranean basin.

### The Strait of Gibraltar and the Alboran Sea

Of all the straits in the Western Mediterranean Sea, the Strait of Gibraltar has been the most closely investigated (Lacombe and Richez, 1982; Candela, 1991). It has been first studied in terms of mass and salt conservations (Lacombe and Tchernia, 1972; Béthoux, 1979). Water exchange can be constrained by hydraulic control (Bryden and Stommel, 1984; Armi and Farmer, 1985; Kinder and Bryden, 1990).

(a)




(b)

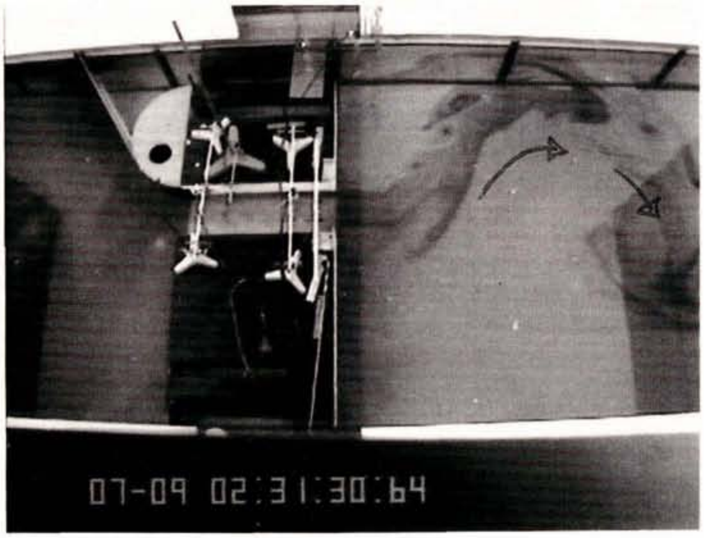



Figure 5

*(a) Alboran Sea surface circulation (left) and density contours (right) after 10, 15, 20 and 25 days. The anticyclonic eddy is well developed. At 25 days, it overshoots to the north. A small cyclonic eddy (identified as a 'B' on the figure) is associated to the large anticyclonic one and moves around it.*

*(b) Alboran Sea experiment on the IMG rotating tank, showing the deflection of the jet to the «north-east» as it exits from the strait, the large anticyclonic gyre with small cyclonic structures (advected by the jet) on its northern side.*

The Atlantic Water entering the Mediterranean Sea forms one or two anticyclonic gyres in the Alboran Sea (Tintore *et al.*, 1988; Arnone *et al.*, 1990). As recently observed on thermal infrared satellite images, they can show vacillations of a period of weeks (Heburn and La Violette, 1990).

During MAST1, academic numerical studies done with the LODYC model in the Strait of Gibraltar provide information on the dynamics of the Alboran Sea (Speich, 1992; Speich *et al.*, 1995).

The forcing of the Mediterranean circulation by the Strait of Gibraltar has been investigated with the LODYC three-dimensional primitive equation model. The strait circulation has been initiated by connecting two reservoirs filled with homogeneous waters of different density to permit the strait dynamics to adjust to the hydrological conditions (Speich, 1992). The results are in agreement with observations. In the strait, a baroclinic circulation is installed: the light Atlantic Water flows into the Mediterranean Sea in the form of a surface layer, while the dense Mediterranean

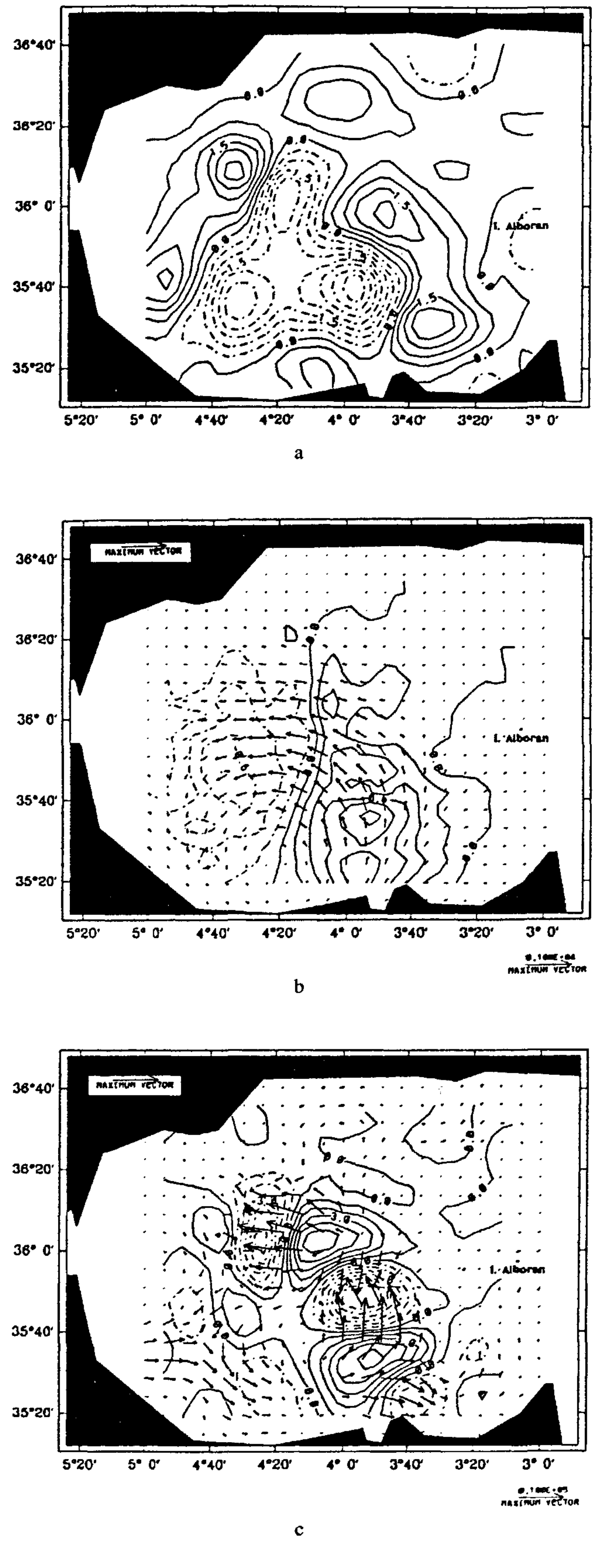



Figure 6

*(a) Geostrophic relative vorticity ($10^{-5}$ $s^{-1}$) distribution at 100 m in the western Alboran Sea.*
*(b) Macroscale Q vector (reference vector equal to $10^{12}$ $s^{-3}$) and its divergence ($10^{-17}$ $s^{-3}$ $m^{-1}$) at 100 m.*
*(c) Total field Q vector (reference vector equal to $10^{11}$ $s^{-3}$) and its divergence ($10^{-16}$ $s^{-3}$ $m^{-1}$) at 100 m.*

water flows out to the Atlantic Ocean near the bottom. The surface water enters the Alboran Sea in the shape of a shallow and narrow buoyant jet with current velocities exceeding 1 m $s^{-1}$. After a three-day spin-up period, the flow transport in the strait reaches a steady realistic value of about 1 Sv. Hydraulic control does not appear to play a fundamental role, as the Froude number is smaller than one in the strait.

The anticyclonic gyres (Arnone *et al.,* 1990) are well reproduced during the spin up phase (Fig. 5*a*). The high variability of the Alboran Sea circulation is correctly simulated. In particular, some mesoscale cyclones develop north of Gibraltar and displace around the bigger anticyclone, as has been observed both experimentally and through satellite imagery (La Violette, 1984; Tintore *et al.,* 1991*a*). Systematic series of sensitivity experiments have been performed in order to specify the conditions that control the gyre formation, its space scale and the major characteristics of the inflow and outflow in the strait. The results reveal that the gyre dimensions are very closely related to the density gradient between the two basins and, by a secondary effect, to the presence of the southern coastline in the Alboran Sea. The boundary conditions at the coast as well as a slight inclination towards the north of the strait, although sometimes argued, do not exhibit any relevant role in the gyre formation and in the overshooting of the inflowing jet.

The eastward motion of the Atlantic water in the strait is associated with a zonal positive slope of the interface which generates negative vorticity in the surface fluid by a squeezing of the fluid columns. It can thus be stated that the strait is a source of negative vorticity. This effect has been studied in detail by Gleizon *et al.* (1994) who conducted similar experiments in a rotating tank. The non-linearities of the equation of motion force the Atlantic water to penetrate into the Alboran Sea as a shallow buoyant jet. They constitute an essential ingredient of the gyre formation by advecting the negative vorticity associated with the Atlantic water into the interior of the Alboran Sea. The Coriolis acceleration then deviates the jet to the right and initiates the anticyclonic gyre (Speich *et al.,* 1995).

The negative vorticity of the gyre is reinforced by the strong dome of the isopycnals located in the Alboran Sea at the vicinity of the strait which compresses the fluid columns as the Atlantic water moves eastward. This dome is driven by the upward velocity associated with the divergence of the Atlantic water at the strait exit when intruding into the Mediterranean Sea.

The above mechanisms are related to the three-dimensional aspect of the problem and can only be reproduced with three-dimensional models. Non-linearities, Coriolis acceleration and production of negative vorticity by vortex stretching play a major role in the gyre dynamics.

Physical experiments have been also performed with a large rotating tank at IMG (Chabert d'Hières and Gleizon, 1992). Two basins filled with different density waters are connected by a channel schematizing the Strait of Gibraltar. A large anticyclonic gyre develops, as simulated in the numerical model and observed by satellite infrared imagery (Fig. 5*b*). The structure of the Atlantic inflow is clearly related to the internal Rossby radius. Variations of climatic conditions modifying the density gradient, and thus changing the internal Rossby radius, could explain the evolution of the gyres in the Alboran Sea. The number of gyres depends on the discharge.

The mesoscale circulation in the Alboran Sea was investigated using the existing data set. An objective analysis technique for quantitative scale separation was applied to CTD data collected in October 1986 (Tintore *et al.*, 1991*a*). The large scale is clearly dominated by an anticyclonic gyre. Smaller-scale analysis shows the existence of several mesoscale cyclonic eddies along the northern boundary of the western Alboran Sea anticyclonic gyre (Fig. 6). Using the Q vector formulation introduced by Hoskins *et al.* (1978), vertical motion associated with the mesoscale eddies is found to be an order of magnitude higher than the large-scale vertical motion. These patterns of large-scale and mesoscale vertical motions are confirmed by an extensive sensitivity analysis and by an independent estimate of the large-scale vertical velocity.

## The Almeria-Oran jet

As the flow emerges from the Alboran Sea, it is driven almost permanently from the Spanish coast (from 2° W) towards the Algerian coast (1° W) and gives rise to an intense frontal jet, known as the Almeria-Oran jet (Tintore *et al.*, 1988).

Satellite imagery indicates that the surface front changes by more than 60 miles depending on whether one or two gyres are present in the Alboran Sea. A field experiment was organized by ICM and UIB from March 6 to April 30 1990. The Almeria-Oran front is present only below 70 m with no strong southeast flowing "jet" as previously reported in 1986 (Viudez *et al.*, 1992). The upper layer appears distorted as influenced by recent strong gales and mild winter conditions. However, a strong eastward Modified Atlantic Water jet (>150 cm/sec) was detected in the south of the basin, along the Algerian coast, and has significant biological and chemical implications.

The theoretical study on the circulation and dynamics of the Almeria-Oran front concentrates on the analysis of the cross-frontal circulation of this very intense density front using the UIB 3D primitive equation model (Tintore *et al.*, 1991*b*). The recirculation of the buoyant fluid and the vertical motions near the front with special emphasis on the effects of internal-inertial waves were studied to clarify the importance and the effects of internal-inertial waves on the observed double cell cross-frontal circulation of oceanic density fronts. These waves, generated by a process of geostrophic adjustment, are found to play an essential role and enhance both cross-frontal circulation and mixing in oceanic density fronts. The formation of the permanent Almeria-Oran front can be explained in terms of the geostrophic adjustment of Modified Atlantic Water and Mediterranean water.

## The Algerian basin

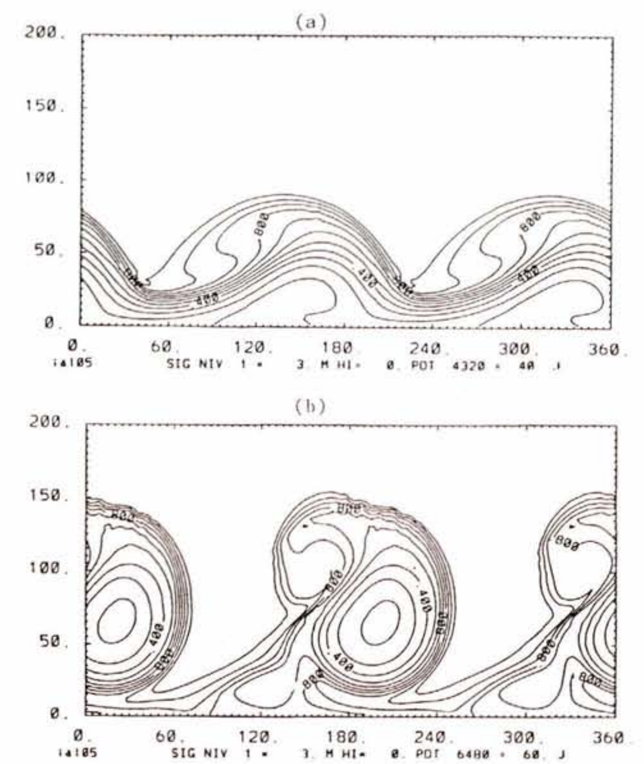
### *The Algerian Current*

The Atlantic Water flows eastward along the coast and becomes unstable from 1°-2° E (Millot, 1985). Meanders, cyclonic and anticyclonic eddies are formed. The hypothesis is that eddies drift eastward along the coast at velocities of a few cm/s, but only the anticyclonic ones grow to the extent where their diameters amount to about 100 km. They might then detach from the coast and would slowly migrate into the open ocean, forming the quasi-steady eddies identified from infrared satellite data for periods of several months. They may attain more than 200 km in diameter and may return to interact with the mean stream (Taupier-Letage and Millot, 1988). These eddies may disrupt the Levantine Intermediate Water circulation (Millot, 1987*a*) and contribute to drive the Modified Atlantic Water from the Algerian coast towards the north. Eddies might be prevented from advancing eastward by the extension of the continental shelf off the Tunisian coast. Those features warrant the adoption of the term "Algerian Current" and the importance attached to studying the mesoscale variability of that current.

Instabilities of the Algerian Current can be explained through hydrodynamic stability studies. Reduced gravity models have been shown to provide barotropic instability related to the peculiar horizontal shear of the velocity field (Beckers, 1992*a*, *b*). Two-layer shallow water simulations show that barotropic and baroclinic instability mechanisms both destabilize the current. However, the growth rate of the barotropic instability is one order of magnitude smaller than the growth rate of baroclinic instability. The most unstable wavelengths are shorter than those predicted by simple quasigeostrophic models as in Pedlosky (1979), but the growth rates are similar (Mortier, 1992).

Primitive equation models allow further investigations of these processes, specially for the large amplitude phase. Numerical modelling studies were performed with both the LODYC and the GHER primitive equation models by using a channel with periodic boundary conditions and a fine grid resolution (2.5 km by 2.5 km). The initial state of the Algerian Current was schematized by a two-layer fluid with low density water at the coast, the interface crossing the sea surface. Both models give similar results, any slight differences being readily explained by the advection schemes (Fig. 7*a*). During the spin-up phase, the classical baroclinic instability (two Rossby waves interacting) is the dominant process and the flow is in very good agreement with the linear model simulation. At larger amplitude, the surface current detaches from the coast and forms a large meander enclosing a coastal anticyclone of about 50 km diameter (Beckers and Nihoul, 1992; Beckers, 1992*a*, *b*; Mortier, 1992). The anticyclone moves offshore and splits: the flow appears as a system of two meandering jets, flowing westward near the coast and eastward offshore, both with an enhanced barotropic component. This system is barotropically unstable at wavelengths longer than the most baroclinically unstable wavelength of the initial instability. The barotropic instability generates an eastward mean flow

**b**




**c**

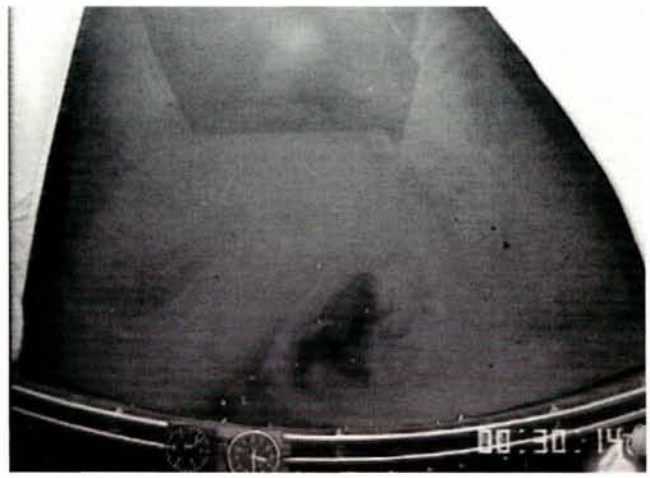
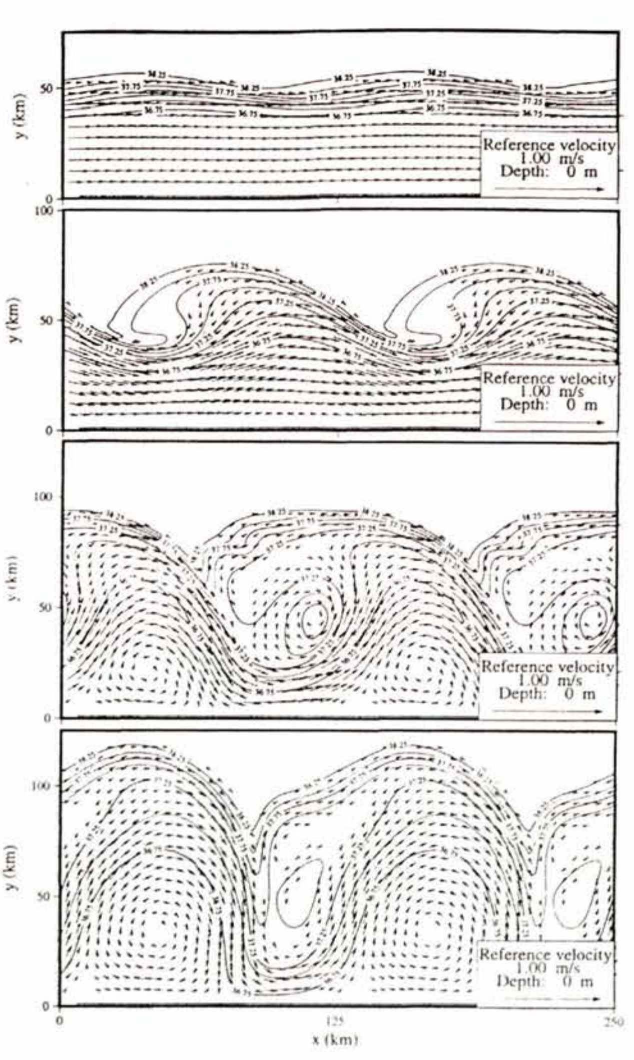


Figure 7

*(a) Development of the Algerian Current's instability shown on a surface salinity map from the GHER model. The off-shore boundary on the Algerian Current is indicated by the 38.25 isohaline. Wavy arrows show a schematic representation of the flow pattern.*
*(b) Surface density anomalies after 40 and 60 days from the LODYC model. Large anticylonic eddies develop along the coast and eventually split.*
*(c) Experiment in a rotating tank 13 meters in diameter, showing the anticyclonic eddy in the current after the equivalent of 30 days. Visualization by food-colouring dye.*

**a**




along the coast affecting the whole water column. In most cases, during the reversing of the two-jet system, the surface coastal anticyclones split, creating anticyclones offshore (Fig. 7*b*). Analytical stability analysis shows the main role of baroclinic instability of the Algerian Current in determining the characteristics of these eddies.

With a longer channel, the cascade of energy toward larger scales is a process capable of generating larger anticyclones offshore, through the successive merging of small coastal anticyclones or small offshore anticyclones previously generated by splitting. This cascade is inhibited by the planetary vorticity gradient (β-plane). Nevertheless, in this case, large anticyclones are directly created offshore by the meandering of the mean flow previously generated at the coast as in the f-plane case.

Laboratory experiments have been conducted on the rotating platform of IMG. The Algerian Current is modelled by intrusion of light water over dense water. A coastal current is formed along the wall of the tank. After a while the current may become unstable. The instability starts from small turbulent features that exist along the wall in the boundary layer and grows to form a large quasi-permanent anticyclonic eddy. The main current meanders around the eddy before reaching again the wall (Fig. 7*c*). The occurrence and number of instabilities along the wall depend on the Burger number, the ratio of the thickness of the current to its width and the Ekman number. A first analysis of the results is presented in Chabert d'Hières *et al.* (1991).

Comparisons between *in situ* measurements (CTD casts and currentmeters) and infrared satellite images taken during the Médiprod-5 experiment show that the above mesoscale features account for most of the observed characteristics of the circulation in the Algerian Basin. They were initially

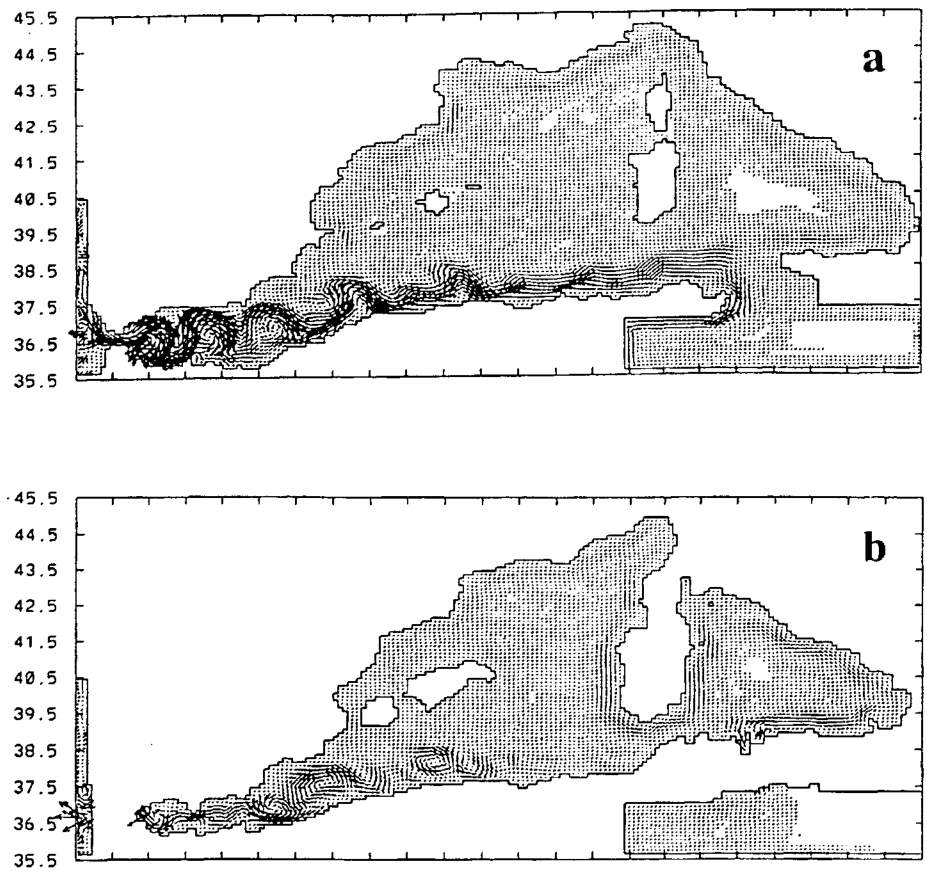



Figure 8

*Circulation in the Western Mediterranean Sea at 5 m (a) and 550 m (b), when the model is forced by the straits of Gibraltar and Sicily, after 84 days of integration.*

expected to grow both in diameter and depth as they progress eastward, extracting energy from the mean flow. Their vertical structure appears complex and quite similar to what is encountered in the atmosphere. These features correspond to meanders of the Algerian Current whose surface path closes anticyclonically as observed on infrared images while the deeper layer behaves like a relatively wide (100-150 km in diameter) barotropic anticyclonic eddy. These deep eddies might drift eastward, trapped below the surface meander, at least until the Sardinian Channel where the previous scenario can still be valid. The eddies can be disconnected from the surface flow, interact with the Levantine Intermediate Water flow around Sardinia, and then drift in the interior of the Algerian Basin, and thus becoming old offshore eddies. Besides, an offshore eddy, sampled during the June campaign (Benzhora and Millot, 1994*a*), presents a dynamic structure in the surface layers which is clearly V-shaped (in a vertical plane) with relatively large velocities at depth, thus being consistent with its expected history as described above. Indeed, after being disconnected from the surface flow in the Sardinia Channel, such an eddy would have to remain in the interior of the Algerian Basin and entrain surface water above it. In addition, its relationship with the Algerian Current is emphasized: the whole current is deviated seaward by the eddy, and part of the current is swept above the eddy and deflected against the coast where it continues eastward towards the Sardinia Channel.

*Intermediate Waters*

During the Médiprod-5 experiment (1987), the circulation (9-month average) of the intermediate and deep water masses (Winter Intermediate Water, Levantine Intermediate Water and Western Mediterranean Deep Water) was investigated (Benzhora and Millot, 1994*b*). These water masses are found to flow eastward along the Algerian continental slope, which does not agree with previous interpretations by other authors (Ovchinnikov, 1966), but is coherent with the scheme proposed by Millot (1987*a*). The intermediate waters path is probably mainly affected by the Almeria-Oran jet. Indeed, most of the intermediate waters, which initially flow southward along the Spanish continental slope, are not very deep when they come to interact with the jet of surface water. They are thus entrained first seaward, and then eastward off the Algerian coast. The Levantine Intermediate Water situation is very special: in the coastal zone, and flowing eastward, some old Levantine Intermediate Water which has made its way around the Western Mediterranean Sea; in the offshore zone a westward flow of recent Levantine Intermediate Water which has been entrained directly from Sardinia by mesoscale anticyclonic eddies. Due to the intense mesoscale activity in the Algerian Basin, the eastward flow of Levantine Intermediate Water is thus expected to become increasingly saltier and warmer. Combining the various observations of Western Mediterranean Deep Water, it appears that this water mass also flows

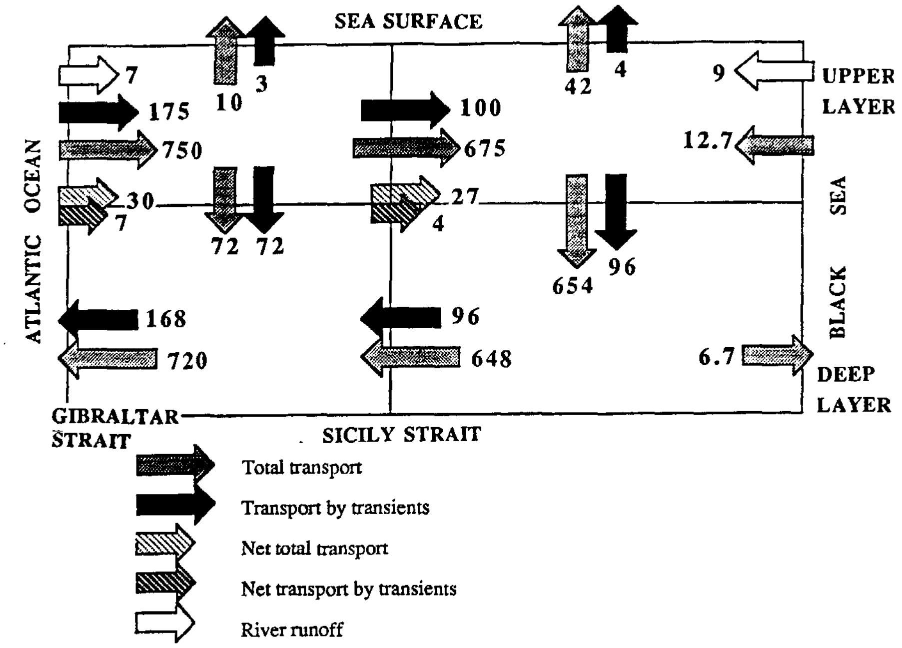



Figure 9

*Schematic description of the different water transport estimated from the aerological method. Units are $10^3$ $m^3/s$.*

cyclonically all around the continental slope throughout the Western Mediterranean (Millot, 1987*a*). The reasons for such a circulation are not understood and part of our future activity will be focused on the underlying problem.

### A Western Mediterranean Sea circulation model

Understanding the mass, salt and heat budgets of the entire Western Mediterranean and the exchanges between the different sub-basins requires an accurate description of the basin-scale circulation. This will be achieved by analysing a circulation model with realistic configuration and atmospheric forcing.

#### *Forcing by the straits of Gibraltar and Sicily*

The objective of this simulation was to understand the influence of the forcing by the straits on the surface and intermediate water circulations (Herbaut *et al.*, 1995). The primitive equation model of LODYC was forced by the Gibraltar and Sicily straits. Following Speich *et al.* (1995), the Mediterranean Basin is connected to academic Atlantic Ocean and Eastern Mediterranean Sea filled with waters of different density profiles. Hydrology is maintained constant in the Atlantic and Eastern Mediterranean basins by a Newtonian restoring. The horizontal grid mesh is 10 km * 10 km and 20 levels are used on the vertical.

The density gradients generate baroclinic coastal currents associated to Kelvin waves during the spin-up phase as in the Gill (1976) experiment. The inflowing Atlantic water flows as a coastal current and drives a large cyclonic circulation in the whole basin after some months. After three months, the transport in the Strait of Gibraltar stabilizes at about 1.2 Sv and several meanders have developed in the

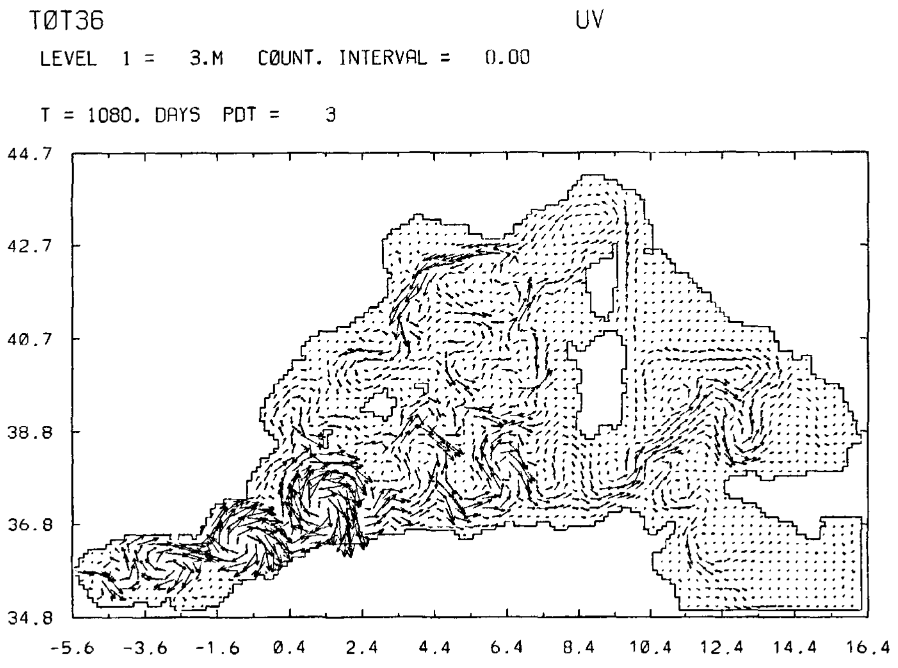



Figure 10

*Circulation in the Western Mediterranean Sea at 5 m (a) in February when the model is forced by the straits of Gibraltar and Sicily and the atmospheric fluxes after 3 years of integration.*

Algerian Current with velocity reaching up to 40 cm/s. At the level of the Sicily Strait, the Algerian current splits into two branches: one enters the strait while the other one continues along the Italian coast. The latter crosses the Corsica Channel and forms the Northern Mediterranean Current. Meanwhile intermediate water exits the Strait of Sicily, turns eastward along the Italian coast and flows cyclonically around the Tyrrhenian Sea. Outflowing south of Sardinia, the current follows the western coast of that island and progresses towards the northern basin. It then flows westward, trapped along the Italian and French coasts. Velocities in the current are typically 4 to 5 cm/s (Fig. 8). The surface and intermediate circulation are qualitatively consistent with Millot (1987*b*).

In a second experiment, the density field in the Western Mediterranean Sea was initialized from the annual values of Levitus (1982). The circulation is still cyclonic throughout the basin but is intensified in the northern part. The transport in the Gibraltar Strait stabilizes around 1.5 Sv after a few days while it reaches 0.9 Sv in the Sicily Strait.

These simulations show that the forcing through the straits helps to generate a realistic cyclonic surface and intermediate circulation in the Western Mediterranean Sea basin. The transport of the Northern Mediterranean Current reaches up to 50 % of its actual value. These simulations were not continued after a one-year integration : because there is no atmospheric forcing in the simulation to transform Atlantic Water into Mediterranean Water, the upper layers of the basin are filling up with Atlantic water.

*Air-sea fluxes*

Air-sea fluxes are a major forcing of the Mediterranean Sea circulation. Several studies have shown that the heat budget for the Mediterranean Sea is negative, indicating a net heat transfer towards the atmosphere (Béthoux, 1979; Garrett, 1992). An accurate knowledge of the time and space distributions of the air-sea fluxes is necessary to force the models correctly and to analyse the response of the sea.

*Net evaporation*

Net evaporation fluxes were estimated from European Centre for Medium-Range Weather Forecast atmospheric analysed fields for the period 1981 to 1985 by computing the atmospheric moisture divergence (Harzallah *et al.*, 1993). The resulting water budget of the Mediterranean Sea permits an estimation of the transport through the straits and water transformations (Fig. 9). A relatively important annual cycle of evaporation is found which may induce a significant annual cycle of water flows through the straits. Mean transport through the Strait of Gibraltar is slightly weaker (0.72 Sv) than commonly accepted values but is close to recent estimates (Millot *et al.*, 1992). Water sinking is mainly related to the mean component of atmospheric forcing in the eastern basin and to transient events in the western basin. Water loss towards the atmosphere by transient events may induce a net water inflow through Gibraltar. The latter flow is suggested as being related to fluctuations of Atlantic / Mediterranean waters interface.

*Realistic atmospheric forcing from the PERIDOT model*

The PERIDOT meteorological forecasting model was chosen to provide realistic atmospheric forcing because of its horizontal resolution (the highest available on the Western Mediterranean Sea, 1/3° × 1/3°), and the frequency of the outputs (once a day).

A complete evaluation of the integrated heat fluxes during 1988-1989 was needed to validate the forcing. The net heat budget shows an annual variability comparable to the May (1982) and Garrett (1992) climatologies. The variations of the different components of the heat flux, especially the latent heat flux, are sometimes significantly larger than the climatological values. However, since only the net budget and the solar heat flux are used in the model, the PERIDOT heat fluxes provide with a realistic forcing.

Wind analysis indicates the occurrence of classical situations of strong Mistral events. Winds appear to be sometimes overestimated in the Tyrrhenian Sea and in the Strait of Sicily. However, no strong Mistral events were evidenced in January-February 1989, which is a crucial period for deep water formation. Convection during the 1989 winter might have been less important, but there are no observations to confirm this. Use of the 1991-1992 atmospheric forcing might be more relevant to a more "classical" realistic simulation of the circulation.

*Forcing by atmospheric fluxes and by the straits*

A 32-month numerical experiment was forced with the daily atmospheric fluxes provided by PERIDOT model and the density gradients through the straits. The grid mesh is still 10 km * 10 km but 31 levels are now used on the vertical. The turbulence is parameterized by a second-order closure scheme based on the mixing length as defined in Blanke and Delecluse (1993).

The obtained circulation is similar to that found above but presents marked seasonal variations (Fig. 10). The oscillations of the Algerian current are more pronounced in autumn. In winter, the deep water formation is well reproduced and during summer, a realistic re-stratification is observed. The transport through the Gibraltar strait is maximum during the January-June period where it reaches a value of 1.3 Sv up to 1.5 Sv and minimum between July and October with 1.1 Sv.

## CONCLUSION

The EUROMODEL MAST1 programme was devoted to process studies related to the seasonal and mesoscale variability of the general circulation of the Western Mediterranean Sea. The major conclusions are summarized below.

As a candidate for driving the large cyclonic gyre observed in the northern basin, deep water formation was extensively investigated through numerical modelling. A non-penetrative adjustment algorithm of vertical convection is adequate to drive deep water formation. In the perspective of general circulation models, there is no need to implement a more complex scheme. Deep water formation effectively drives a significant horizontal cyclonic circulation, the Northern Mediterranean Current, corresponding to the northern part of the gyre. Recent *in situ* (PRIMO-0 experiment) and satellite observations are coherent with previous ones in specifying some seasonal and mesoscale characteristics of the Northern Current. Current measurements on both sides of Corsica reveal two main seasonal signals : heat losses in early winter occurring in the Liguro-Provençal basin increase the Tyrrhenian current while deep water formation in late winter reinforces the Western Corsica Current. Resulting from the merging of the two currents, the Northern Mediterranean Current shows an increase during the winter season with a complex modulation.

Mesoscale variability can strongly influence the basin-scale circulation in many regions. Internal near-inertial motions were investigated in relation to upper ocean mesoscale variability, through numerical modelling and observations near the Catalan front. Local downward penetration of energy is shown to have global-scale implications. Large-scale dynamics in the Balearic Sea is related to the presence of two shelf / slope fronts whose spatial and temporal variability is characterized.

In the southern basin, the path of the Atlantic Water from the Strait of Gibraltar to the Sardinian Channel was extensively studied. The forcing of the Mediterranean circulation by water exchanges through the Strait of Gibraltar was successfully modelled so that the dynamics is free to adjust to the hydrological conditions. The flow through the strait does not seem to be hydraulically controlled. The formation of the western Alboran Sea gyre can be explained in terms of potential vorticity conservation and of changes in the meridional pressure gradients. The existence of small cyclonic eddies at the periphery of the gyre is both observed and modelled. The permanent Almeria-Oran jet-front system is explained in terms of geostrophic adjustment of Modified Atlantic Water and Mediterranean Water. The instabilities of the Algerian Current are studied in terms of hydrodynamic stability. Baroclinic instability plays a major role in determining the characteristics of the meanders, cyclonic and anticyclonic eddies observed along and off-shore the Algerian coast. Intermediate and deep waters are also observed to flow eastward along the African coast, thus leading at depth to a cyclonic circulation pattern around the continental slope throughout the Western Mediterranean Sea.

In a first simulation with the LODYC primitive equation model of the basin scale circulation in the Western Mediterranean Sea, the sole forcing by the density gradients through the straits of Gibraltar and Sicily is able to qualitatively reproduce the basin-scale cyclonic surface and intermediate flows and the coastal currents. Preliminary experiments with the atmospheric forcings and the transports through the straits display realistic results. Deep water formation is well reproduced and strong seasonal variation in the circulation is observed.

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