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Recent advances in observing the physical oceanography of the western Mediterranean Sea

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Abstract

The Mediterranean Sea has been investigated intensively since the early nineties, using modern techniques and collaborative approaches. This overview summarizes some of the resulting advances that were made concerning the physical oceanography of the western Mediterranean. The water mass formation processes are now much better understood and have been quantified to a large extent. The boundary conditions of the system in terms of surface fluxes and strait transports can be determined with improved accuracy, thus enabling future investigation of interannual variability. The dynamics of the surface and intermediate layers have revealed a variety of eddy and mesoscale processes that are important for the circulation and spreading of water masses. The deep circulation is being investigated with Lagrangian techniques (tracers and floats). First results show a large component of the deep water originating from the Tyrrhenian Sea and intense cyclonic and anticyclonic eddy flows.

Contents

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1. Introduction

The western Mediterranean Sea has great significance for the European and North African countries bordering it, and important studies of its physical oceanography have been conducted in the past (e.g. Wüst, 1961; Miller, Tchernia & Charnock, 1970; Stommel, 1972). Yet many aspects of the physical processes governing it have remained unknown or unclear for many years. A resurgence of interest in Mediterranean oceanography took place in the early nineties, largely as a result of the European funded MAST programs. These enabled more ambitious and larger-scale studies to be undertaken, using modern techniques and collaborative approaches. These have provided new insights into the functioning of the system, and the present overview is meant to give a short account of some of the advances that have been achieved by these projects.

2. Water mass formation

In the western Mediterranean, a variety of water masses are formed. The surface circulation consists of the Modified Atlantic Water (MAW), which originates from the inflowing Atlantic water and is progressively modified by air-sea interaction and mixing along its path through the basin. While the main intermediate water mass, the Levantine Intermediate Water (LIW), is generated in the eastern Mediterranean, the so-called Winter Intermediate Water (WIW) is formed in the western basin. The latter is a product of moderate winter cooling of the surface layer, which is insufficient to cause mixing with the high-salinity LIW. Thus a cold water type is generated that has lower salinity than both the LIW and the water formed by deeper winter mixing/convection. In seasons or areas with surface stratification, it is frequently found between the warm surface layer and the LIW.

The most characteristic water mass formed in the western Mediterranean is the Western Mediterranean Deep Water (WMDW). A subsequent mixing product of this water mass is also the Tyrrhenian Deep Water (TDW), which will be discussed later in Section 6. The WMDW is formed via deep convection in the Gulf of Lions, and fills the deeper levels of the western basin. The process of deep convection and the subsequent fate of the water thus generated is discussed in the following subsections.

An example of the distribution of the main water masses of the western Mediterranean is given in the cross-basin sections of temperature and salinity in Fig. 1.

2.1. The convection process

Deep convection has been known to take place in the Gulf of Lions since the pioneering so-called ‘Medoc’ experiments in the late sixties and seventies (Stommel, 1972). This process occurs when in winter the cold and dry winds cause sufficient loss of surface buoyancy for mixing to large depths. The section in Fig. 2 shows the effect of this process on the stratification. The convection is facilitated, and limited in space, by an upward doming of the isopycnals which results from the local cyclonic circulation in the Gulf of Lions. This brings dense water closer to the surface, so that less buoyancy needs to be extracted for mixing down to the deep layers to take place. This convection process was observed again in 1987 using modern ADCP techniques (Schott & Leaman, 1991), when the existance of cells was demonstrated in which O(10 cm/s) downward velocities were coherent over several hundred meters in the vertical. The horizontal scale of these downward ‘plumes’ was estimated to be 500–1000 m.

In the winter of 1991/92 another convection experiment was carried out in the area as part of the European MAST-1 program. It combined intensive ship-board observations with modern moored techniques for simultaneously observing the small and large-scale processes and evolution of the regime (THETIS Group, 1994). One part of the experiment was the use of an acoustic tomography array using acoustic transmissions over distances of 60–200 km to sense mainly the evolution of the interior temperature stratification (Send, Schott, Gaillard & Desaubies, 1995). Good simultaneous time-series are available from that experiment for the surface forcing (wind speed, surface heat fluxes, etc.), the changes in the vertical temperature and salinity profiles at the center of the region, the local horizontal and vertical currents, and the large-scale stratification (Schott, Visbeck, Send, Fischer, Stramma & Desaubies, 1996). The three phases in a convection regime were well documented using

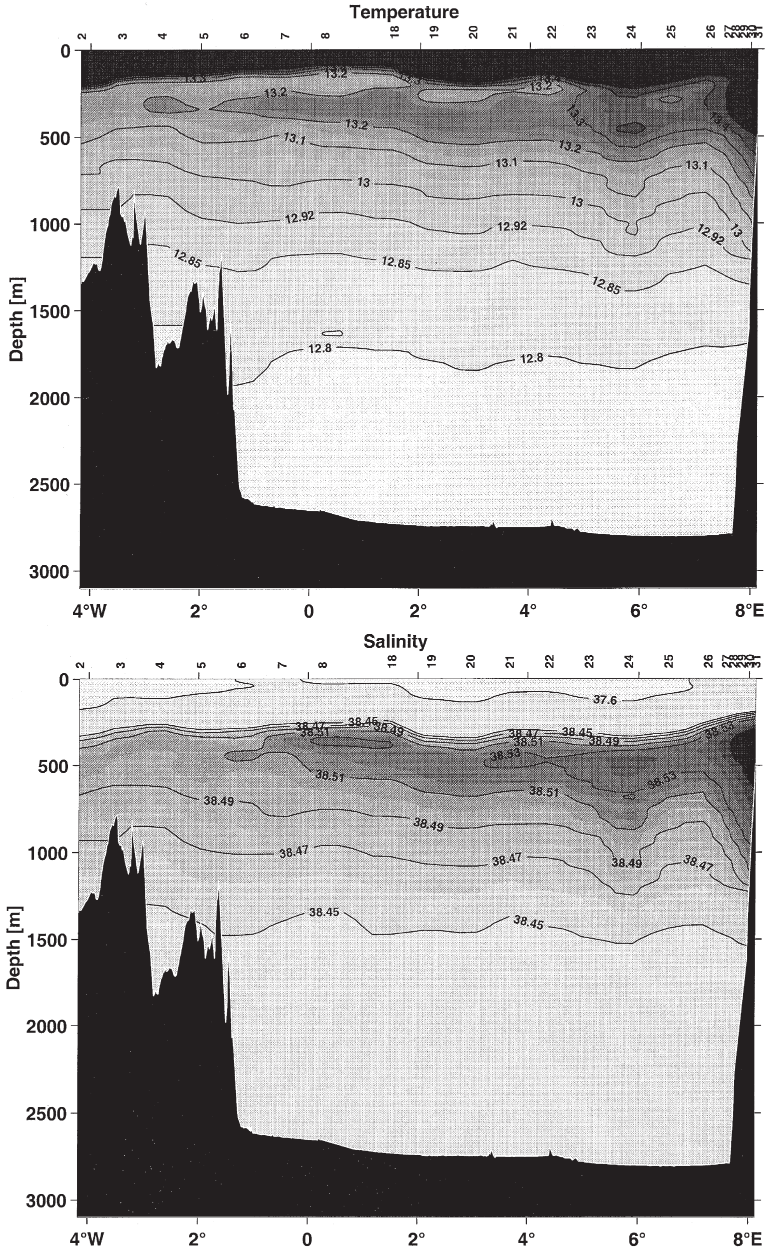


Fig. 1. Near-zonal temperature and salinity sections through the Algerian basin (from the Alboran Sea, 36°N, to the southern tip of Sardinia, 38.8°N). The warm, low-salinity surface layer is the MAW. Centered around 500 m (at this latitude) is the saline and warm LIW. Below 800–1000 m, the deep water is found, which will be shown in Section 6 to consist of two distinct water masses.

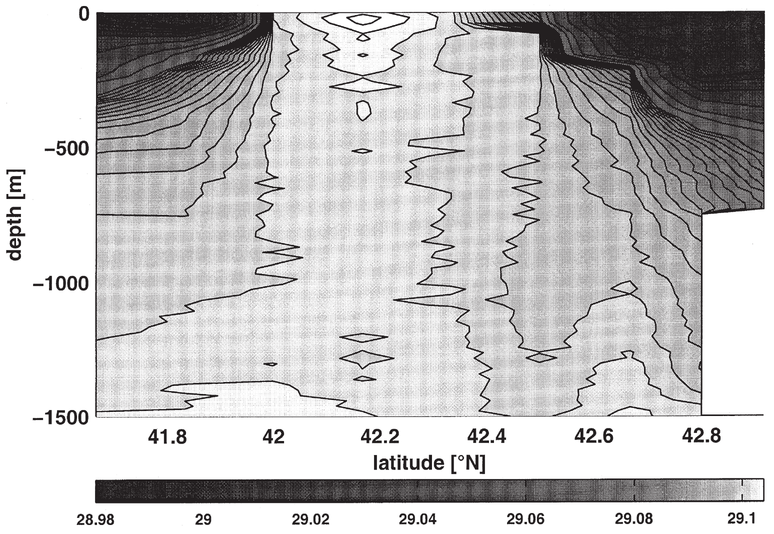


Fig. 2. Potential density section along 5°N through the Gulf of Lions during ongoing convection. Lighter shades represent denser water. In the center, the stable stratification has been eroded and mixing to large depth is visible. (Note the nonlinear gray scale.)

these data, a 'preconditioning' phase when the upper-layer stratification is gradually eroded during winter, the 'deep mixing' phase when intense buoyancy loss for a few days is sufficient to penetrate the slight remaining stratification to allow mixing to large depths, and the 'spreading' phase during which the dense water that has formed escapes from the region, and stratified conditions gradually re-appear.

In contrast to the earlier observations, the new and improved moored ADCP data showed no significant mean downward velocity during ongoing convection, neither did the tomography data reveal an increase in the cyclonic circulation around the region. Both observations are consistent with theoretical and model results from an accompanying study (Send & Marshall, 1995), in which it was demonstrated that the overall effect of the convection is essentially to cause vertical mixing, without significant sinking motion. Both the local and area-average data from the experiment further showed that the heat balance is largely 1-dimensional in the vertical, with the contribution of horizontal (warming) heat fluxes being only 15–25%. The tomography results also gave an indication of the size of the convectively homogenized area (approx. 100 km) and of the rate at which the restratification occurs in the region (40 day time scale). The latter result now serves as a comparison with concepts that seek to explain and quantify the spreading process (e.g. Jones & Marshall, 1997).

2.2. Spreading of the water

The typical condition resulting from convection resembles Fig. 2, in which a central region with densities that are normally only found in the deep water, now extend all the way to the surface. The fate of this dense water is important for the evolution of the water masses and the circulation features in the basin. While the density field shown in Fig. 2 can be in geostrophic equilibrium with a circulation around it, there is available potential energy stored in it, which will drive the system to a state whereby all the dense water settles into the deep water reservoir. Baroclinic instability or bleeding of the dense water into a boundary current flow are the prime mechanisms for allowing the water to escape and drain out of the region. The existence of the latter process was sought in 1994 with a simple mooring in the deep boundary current some 100 km downstream of the Gulf of Lions. A pulse-like temperature signal was found, which had a timing, amplitude and vertical structure that was consistent with the water having originated from convection in the Gulf of Lions (Send, Font & Mertens, 1996). Crude estimates of its volume suggested that a significant part of the dense water that had been convectively generated had been drained off in this way.

Baroclinic instability is undoubtedly important in extracting the potential energy available after convection. Early float observations (Gascard, 1978) documented intense eddy motions, and numerical models clearly show that meanders and eddies feed on this energy and thus lower the dense water, at least to some degree (Hermann & Owens, 1991; Madec, Chartier, Delecluse & Crepon, 1991; Jones & Marshall, 1997). It is not clear yet what the subsequent fate of the water is. Models suggest that the eddies resulting from the decay of the convection region (both cyclonic and anticyclonic, with large barotropic components) can be stable, long-lived features with a high-density core, which not only transport the water over long distances but also generate appreciable diapycnal mixing with the surrounding deep and upper-layer water masses (Send & Käse, 1998). Observational evidence for such 'convection lenses' remains sketchy, but the model results suggest that approximately 75% of the dense water formed during convection eventually sinks into the deep water. For a typical convection region of 100 km size, this gives an estimated annual deep water replenishment rate of about 0.2 Sv.

3. Interannual variability of the forcing

3.1. Effect on water mass formation

The water mass formation is controlled by surface heat and freshwater fluxes which change the buoyancy and water mass properties. For the generation of deep and intermediate water masses, sufficient buoyancy loss needs to take place for mixing to several hundred or thousand meters. The actual depth reached depends to a large extent on the stratification at the beginning of winter and on the integrated buoyancy loss during the course of the winter. It turns out that the typical fall stratification is less variable interannually than the surface buoyancy fluxes. Thus, an idea of the convection activity and water mass formation intensity can be obtained from time series of these fluxes over many years.

In the Mediterranean, the surface buoyancy loss is dominated by the heat flux (accounting for about 80%). Mertens and Schott (1998) used historical meteorological data from coastal stations for such an analysis. The data were calibrated with observations in the ocean from moored platforms and research vessels, and were further verified against modern weather prediction models (such as Peridot, ECMWF). The skill of this procedure was developed and tested in the framework of the MAST-1 convection experiment THETIS.

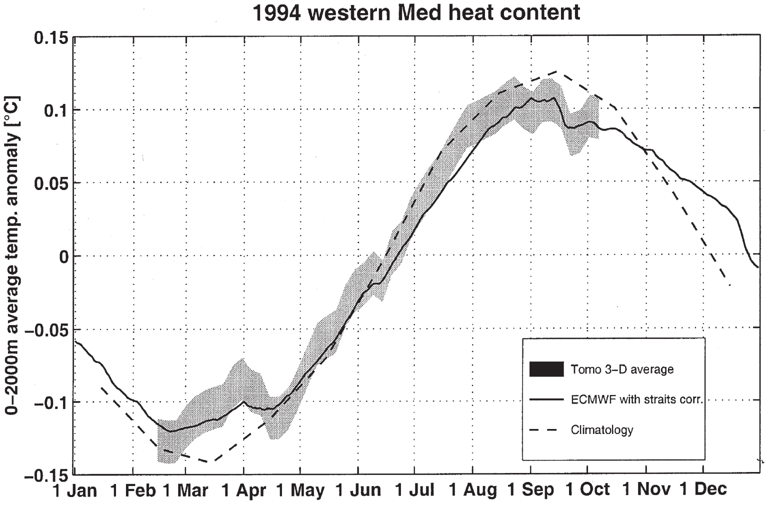
As a result, the winter surface buoyancy loss in the Gulf of Lions could be estimated for the years 1968 until 1994. Driving a mixed-layer model with these fluxes then resulted in a timeseries of convection depths and water mass properties. It shows clearly that convection does not always penetrate to great depth, even though this is the case for the majority of years. Such information is important for estimating the mechanisms and their efficiency for renewing the deep water in the Mediterranean.

3.2. Assessing surface heat fluxes

Surface heat fluxes are one of the boundary conditions for the ocean system, and thus it is important to know them with sufficient accuracy. Since direct measurement is difficult, these fluxes are usually estimated from readily available atmospheric and oceanic properties via the use of bulk-formulae.

The semi-enclosed Mediterranean has, in the past, been used to verify the longterm averages of bulk-formula derived surface heat fluxes (Bunker, Charnock & Goldsmith, 1982; Garrett, Outerbridge & Thompson, 1993; Gilman & Garrett, 1994). These authors compared the known average heat transport through the Strait of Gibraltar to the integrated surface heat flux of the Mediterranean. The analyses revealed differences of about 30 W/m^2 between the oceanographic estimate and the formula-derived heat fluxes (Bunker et al., 1982; Garrett at al., 1993). In a follow-up study the inclusion of the effects of aerosols and the correction of one of the formulae reduced the difference to $<$7 W/m^2 (Gilman & Garrett, 1994). Analyses of the long-term average do not, however, allow statements on the accuracy of the seasonal heat flux variations which largely control the deep water formation process in winter (see Section 2.1).

In the last few years experiments and analyses have concentrated more on these seasonal variations. The ocean acoustic tomography experiment THETIS-2 (Send et al., 1997) provided a new means of observing the seasonal changes in the heat content of a large part of the western Mediterranean. The comparison of these seasonal variations with the integrated surface heat fluxes of the ECMWF operational analyses showed agreement to within the uncertainty of the oceanographic estimate (Fig. 3 top). Another approach was followed by Krahmann (1997) who compared different seasonal surface heat flux data sets with a reference derived from a temperature climatology of the western Mediterranean (see Fig. 3 bottom). The resulting rms-differences ranged from 10 to 25 W/m^2 depending on the data set. Both analyses indicated that the recent improvements in measuring surface heat fluxes now allow the heat flux boundary conditions to be defined with sufficient accuracy on seasonal time scales.



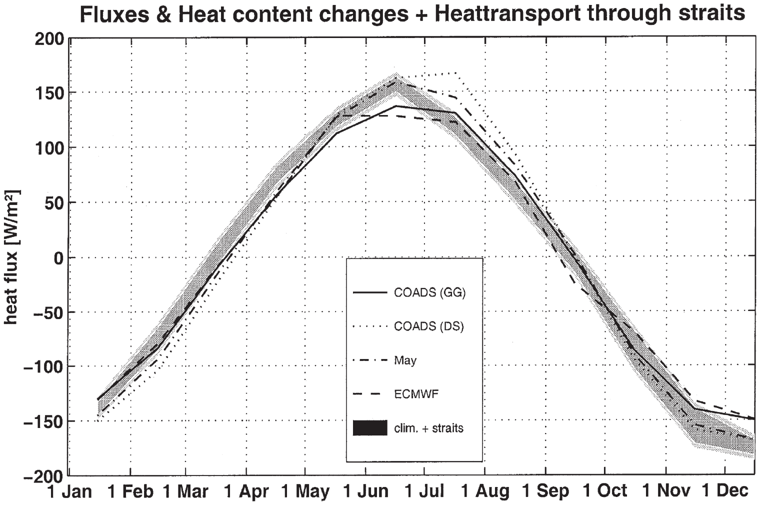


Fig. 3. Seasonal heat content changes and heat fluxes of the western Mediterranean. The upper panel shows the 1994 heat content evolution of the central part of the western Mediterranean as observed by the THETIS-2 tomography network (the shaded area denotes the uncertainty of the estimate) together with the integrated surface heat flux of the ECMWF operational analysis (solid line). Both estimates of this single year agree within their uncertainty (see Send et al., 1997, for more information), giving confidence in both methods. They also reveal the deviations from the average seasonal development (dashed line, from climatological data). The lower panel compares four different climatological heat flux data sets (different lines) of the western Mediterranean and an estimate derived from the climatological heat content changes (shaded area). During the summer and the winter period, deviations of some of the heat flux fields from the oceanographic estimate are evident, while the overall amplitude agrees for all data sets. It is possible that the deviations are related to the effect of aerosols in summer (see Gilman & Garrett, 1994) and the weaker data coverage during times of bad weather (e.g. Bunker, 1982).

3.3. Relation to the North Atlantic oscillation

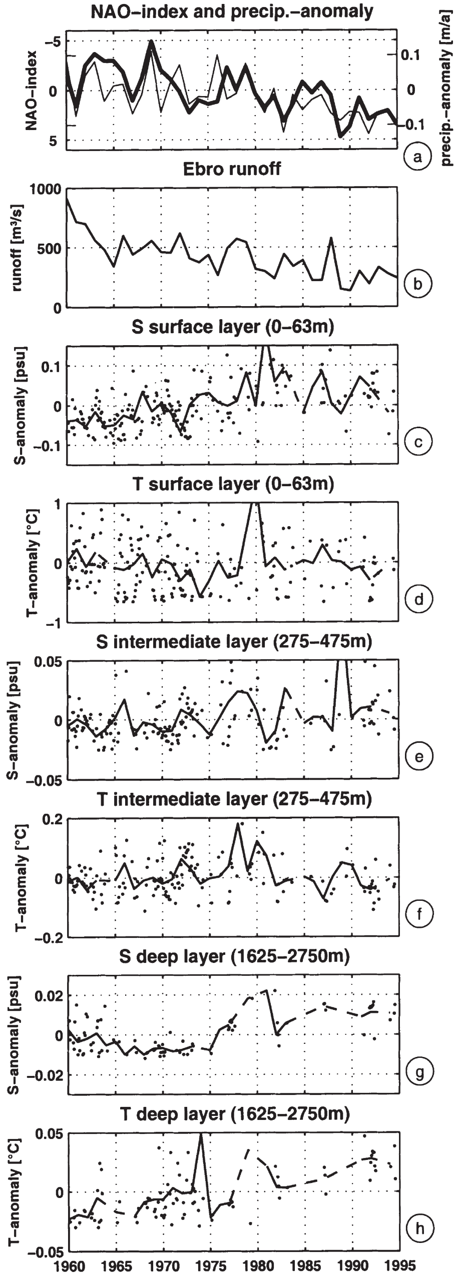
As stressed in Sections 3.1 and 3.2 the water mass formation is controlled to a large extent by surface heat and freshwater fluxes. The interannual variability of the thermohaline forcing thus leads to variations in watermass formation and properties. For the Mediterranean, Garrett et al. (1993) investigated the COADS data set (Woodruff, Sleutz, Jenne & Steurer, 1987) for interannual variability of the surface fluxes. Though both the heat flux and the SST anomalies showed significant decadal variability the authors found no obvious relation between them. Analyses of land based precipitation data showed that the distribution of precipitation over Europe is highly correlated with the North Atlantic Oscillation, a large scale change in atmospheric transport patterns in the North Atlantic region (Hurrell, 1995). He found that between the end of the 1960s and the mid 1990s the increasing NAO-index was accompanied by decreasing precipitation in the Mediterranean area (while northern Europe observed an increase). The overall reduction amounted to about 15% of the annual rainfall.

A recent analysis of longterm salinity and temperature variations in the western Mediterranean (Krahmann & Schott, 1998) has revealed that not only was the WMDW subject to changes (Bethoux, Gentili & Tailliez, 1998; Rohling & Bryden, 1992; Leaman & Schott, 1991) but also the surface salinities increased significantly in the northwestern Mediterranean. The salinity anomalies (relative to the local climatological monthly values) indicate an increase of 0.13 ± 0.03 over the past 30 years (see Fig. 4). Since the location of these surface trends coincides with the area of deep water formation, the varying freshwater fluxes not only link the western Mediterranean Sea to large scale atmospheric variations but also offer a realistic explanation for the well known trends to higher salinities and temperatures in the WMDW. During the same period the temperatures at the surface did not show a significant trend, but instead showed decadal variations similar to those observed in the North Atlantic at the same latitude (Kushnir, 1994).

3.4. Flow through the Strait of Gibraltar

Apart from surface buoyancy and momentum fluxes, the other major boundary condition for the Mediterranean is found at the Strait of Gibraltar. The detailed oceanography of the straits is covered elsewhere in this volume, so here only recent progress in our capability of observing the strait transport variability with sufficient accuracy is discussed. For the Strait of Gibraltar 'sufficient' means an accuracy of better than 0.05–0.1 Sv, because seasonal variability is expected to have this order of magnitude, and sea-level drops (non-steric) in winter that have been observed by altimetry of the Mediterranean (P.Y. Le Traon, personal communication) would cause a similar size of signal. Furthermore, it is possible that changes in the hydraulic state are causing transport changes of comparable magnitude, assuming that this process is a factor in the seasonal changes.

In 1996 and 1997, pilot studies and intensive observations in the Strait of Gibraltar were carried out in the framework of the MAST-3 CANIGO project, mainly at the


NAO-index and precip.-anomaly
NAO-index
precip.-anomaly [m/a]
-5
0
5
0.1
0
-0.1
a
Ebro runoff
runoff [m³/s]
1000
500
0
b
S surface layer (0-63m)
S-anomaly [psu]
0.1
0
-0.1
c
T surface layer (0-63m)
T-anomaly [°C]
1
0
-1
d
S intermediate layer (275-475m)
S-anomaly [psu]
0.05
0
-0.05
e
T intermediate layer (275-475m)
T-anomaly [°C]
0.2
0
-0.2
f
S deep layer (1625-2750m)
S-anomaly [psu]
0.02
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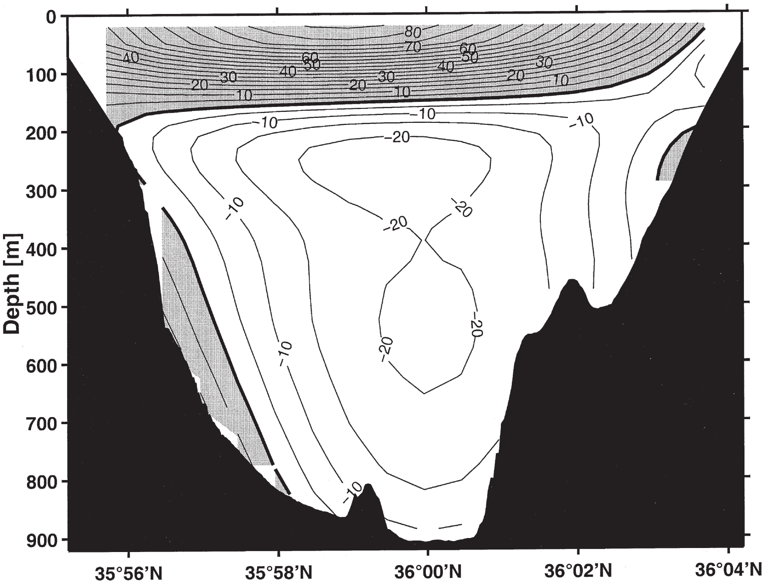

Fig. 5. Mean flow at the eastern entrance of the Strait of Gibraltar, based on fitting a 2-D distribution for the time-mean and 5 tidal flow constituents to ship-based ADCP and current meter data. After binning into 2-hour intervals and spatial boxes, about 80,000 data points entered the analysis. Negative values are outflow, positive are inflow.

eastern entrance, where the flow is easier to observe. A large data set of ship-board and lowered ADCP current data, combined with several years of mooring data (by WHOI, IHM), was used to construct a horizontal/vertical distribution of the mean flow, by fitting and removing the tidal variability (Fig. 5). From this, the mean outflow was calculated to be 0.88±0.06 Sv. The inflow is not signficantly different from this, given the rms error of both values. The uncertainty allows for model misfit (high-frequency and sub-inertial), various instrument errors, and errors in defining and following the interface.

Long-term monitoring of the transport variability through the strait will be an important issue in the years to come. In 1996 a promising method was tested jointly by IfM Kiel and Scripps Institution of Oceanography, using acoustic transmissions across the strait. The horizontal current integral obtained was nearly indistiguishable

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Fig. 4. Long term development of salinity and temperature (panels c to h) in the northwestern Mediterranean and variations in boundary conditions (panels a and b). A decreasing freshwater input into the western Mediterranean is evident from the precipiation at coastal stations (a) and the volume transport of the Ebro river (b). For the same time period the changes of the watermass properties are shown in the other panels.The watermasses which are directly subject to the local boundary conditions (MAW and WMDW) reveal increasing salinities with magnitudes in agreement with the freshwater budget changes, while the LIW which is formed in the eastern Mediterranean shows no longterm trend. The lack of a longterm temperature increase in the surface layer also indicates that the deep temperature increase is controlled by the salinity increase together with an unchanged density.

from our best comparison estimate based on the spatial fit to mooring and ship-board data (Fig. 6). Shore-based versions of such acoustic measurements could be an element of future operational systems for observing the transport variability through straits and for providing ‘boundary conditions’ for modelling studies.

4. The near-surface circulation

The primary features of the mean near-surface circulation have been known since the works by Millot (1985, 1987a, 1987b, 1999). Recently, the attention has shifted to the observation of the variability and mesoscale effects of this circulation. For example, altimeter observations have highlighted both the mesoscale energy and seasonal changes in the ‘mean’ circulation (Larnicol, Le Traon, Ayoub & De Mey, 1995). In the past years significant emphasis has been placed on studying the eddy activity, fronts, and regional circulation features. This section gives a short overview of these aspects of recent work.

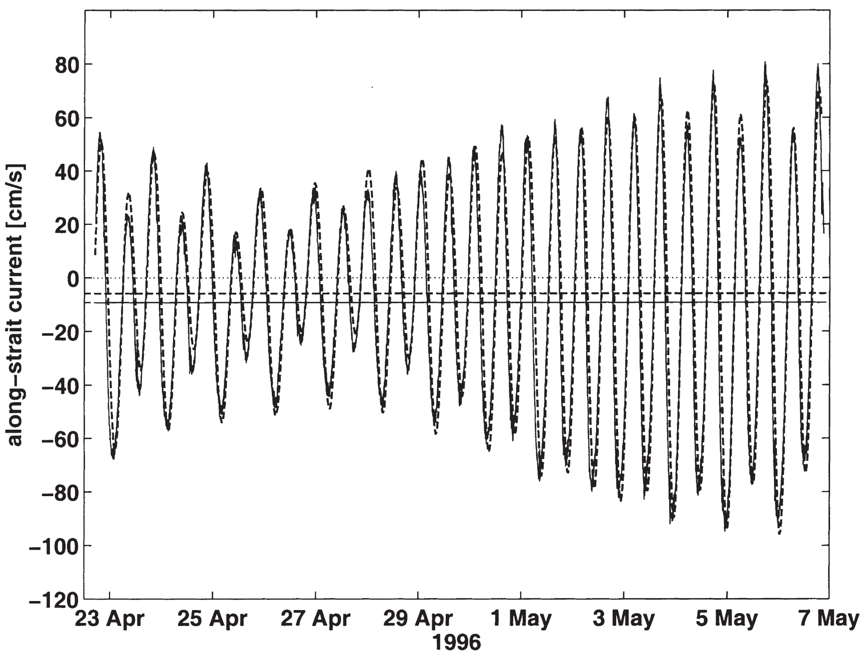

Fig. 6. Lower layer along-strait current integrated across the strait of Gibraltar along an acoustic ray path which travels between 200 m and 700 m depth. The thin solid curve results from the acoustic measurements, the heavy dashed one from the fit to the ship and mooring current data and the low-frequency residuals of the fit. (The dashed and solid straight lines represent the corresponding means.)

4.1. Seasonal variability

The Mediterranean Sea, because of its geographical and hydrological characteristics, displays a strong seasonal signal. The development of an upper mixed layer by summer solar heating, and the convective processes caused by winter cooling and strong winds causes seasonal changes in the near-surface circulation. The effects observed mainly consist of modulations in the intensity and smaller scale variability of the current systems. For example, in spring-summer and in some specific places, the upper layer circulation can be locally decoupled from the circulation below (driven by the large scale flows) and affected by the local atmospheric variability, as repeatedly observed in satellite imagery (Lopez-Garcia, Millot, Font & Garcia-Ladona, 1994).

Astraldi and Gasparini (1992), by analysing several years of current meter records in the Corsican channel, have demonstrated seasonal variability in the transport (maximum in winter, minimum in summer) which is linked to the overall air-sea interactions in the NW basin. This variability was related to the winter cooling and convection processes, which in addition to the seasonal modulation also have interannual variability (see Section 3.1).

A seasonal together with a possibly interannual effect also results from the formation of WIW during the winter months (see Section 5). The changes in stratification in the formation region, when this water sinks and spreads, must accompany transitions in the circulation. The lenses that form from it can block even the surface circulation, at least in narrow passages (see below), but this occurs downstream along the Spanish shelf where there is no more seasonality in the WIW to be found.

The seasonal variability of the Northern Current has been quantified in the Ligurian Sea (Alberola, Millot & Font, 1995) from changes in its intensity, vertical structure and distance to the coast. There is a clear seasonal signal in the mesoscale activity of this alongslope flow (Fig. 7), which undergoes a strong increase in autumn, followed by a rapid decrease in winter and then by a continuous decline until the end of the summer (Font, Garcia-Ladona & Garcia-Gorriz, 1995; Sammari, Millot & Prieur, 1995). Fig. 7 shows the weekly evolution of the mesoscale variability of the Northern Current at the shelf break off the Ebro river delta for the four seasons. As a mesoscale activity index, the variances of the north and east components of the velocity vector have been computed in 30-days intervals, from almost five years of current meter records (May 1987–March 1992).

In the southern part of the western Mediterranean (Algerian basin) there is no clear manifestation of any seasonal variability of the circulation. The regional dynamics are driven not by thermohaline processes linked to atmospheric seasonality, but are dominated by turbulent regimes resulting from the adjustment between the surface Mediterranean and incoming Atlantic waters. This generates large mesoscale structures that can evolve over time scales of several months, but are not related to seasonality.

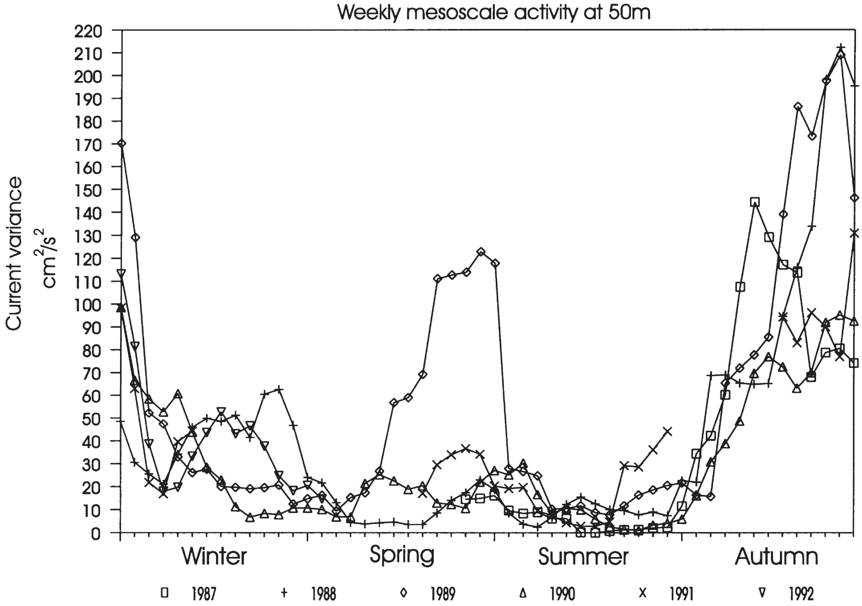

Fig. 7. Seasonal evolution of the mesoscale variability of the Northern Current, as measured from current meter records at 50 m off the Ebro river. The seasons marked are winter (January to March), spring (April to June), summer (July to September) and autumn (October to December).

4.2. Mesoscale and regional features

The studies over the last 10 years have revealed significant mesoscale structures in different sub-basins of the western Mediterranean. It is important to note that since the internal Rossby radius is usually close to 10 km, the detection of mesoscale structures in the Mediterranean requires very intensive sampling. These structures (eddies and filaments mostly) are usually found in the shelf/slope areas and are characterised by strong density gradients that can give rise to transient currents in the upper hundred meters, that attain velocities of up to 100 cm/s (while the mean slope current is usually of the order of 20–30 cm/s). However, these mesoscale structures also rapidly evolve with time, thus implying that there is generation of areas of convergence and divergence that will affect the whole ecosystem. Especially in Mediterranean studies, therefore, the hypothesis of synopticity of the data collected needs to be carefully evaluated each and every time and for each sub-basin. All this complexity of small spatial scales and intense gradients interacting with small temporal scales (highly variable features) makes the understanding of mesoscale dynamics challenging in the western Mediterranean. The mesoscale dynamics are important since the structures not only affect the circulation at local and sub-basin scale but also influence the exchanges between the different sub-basins and the basin-scale flow.

Eddies and filaments modify the upper layer circulation in most sub-basins, and good examples were shown in the Alboran Sea by Tintoré, Gomis, Alonso and Parrilla (1991) and Viudez, Tintoré and Haney (1996) and in the Balearic Sea by Pinot, Tintoré and Gomis (1995) and Pinot, Lopez-Jurado, Riera, Jansa, Font and Tintoré (1998). In all these studies, detailed analysis of the spatial variability associated with these structures showed that there were intensified density gradients with associated vertical motions up to 50 m/day, almost two orders of magnitude higher than the classical vertical motions associated with coastal upwelling. The temporal variability of mesoscale structures was analysed by Alvarez, Tintoré and Sabates (1996) who studied the interaction between the Northern Current and deep topographic canyons off the Spanish coast using three consecutive ship surveys. They observed variability in a jet flowing in the onshore-offshore direction and showed that there were different interactions with the canyon which were associated with separate regimes of shelf/slope exchange, eddy formation and biomass patterns in the area.

4.2.1. Effects on biology

In order better to understand both the spatial and the temporal variability of the three-dimensional ageostrophic circulation in a strong upper ocean density front and to establish the relationship between biological variability and mesoscale physics, an intensive field study was carried out in the Alboran Sea from October to December, 1996. The Alboran Sea was chosen because there are large density gradients there which result from the adjustment occurring between Atlantic and Mediterranean waters (a difference of approximately 1.5 σ_t units over 10 km). To address in detail the synopticity issue, data were obtained by 4 consecutive samplings of the same area using Seasoar, ADCP, fluorescence, acoustic backscatter, nutrients, flowcytometry, Lagrangian floats, etc. On-board flow cytometry analyses and size-fractionated chlorophyll demonstrated there was strong mesoscale biological patchiness along the fronts (Rodriguez & Li, 1994). Fig. 8a shows the horizontal density structure of the inflow of Atlantic water at 100 m during the first survey. The dimensions of the Alboran gyre were particularly large in October 1996, and there were significant changes of curvature suggesting that intense vertical motions were occurring. Fig. 8b–d show the vertical structure in the eastern part of the gyre for density, ADCP backscatter and fluorescence, suggesting clearly that there were downward motions along the isopycnals in the area at the time. Similar indirect evidence was also observed by Tintoré, La Violette, Blade and Cruzado (1986) in the eastern Almeria–Oran front, and were confirmed by independent computations of the vertical motions using a variety of observational and numerical approaches (Tintoré, Allen, Font, Corsini, Rodriguez, Gascard et al., 1998).

4.2.2. Algerian eddies

The Algerian basin frequently shows the presence of mesoscale structures, mainly large anticyclonic eddies, that are related to the instability of the coastal Algerian current (EUROMODEL Group, 1995). The complete analysis of in situ data collected off Algeria during the eighties has allowed the characteristics of the eddies encountered there to be specified (Millot, Benzhora & Taupier-Letage, 1997). All eddies detected from space with infrared and visible sensors are associated with intense currents in the MAW layer, but only some of them induce large currents in the

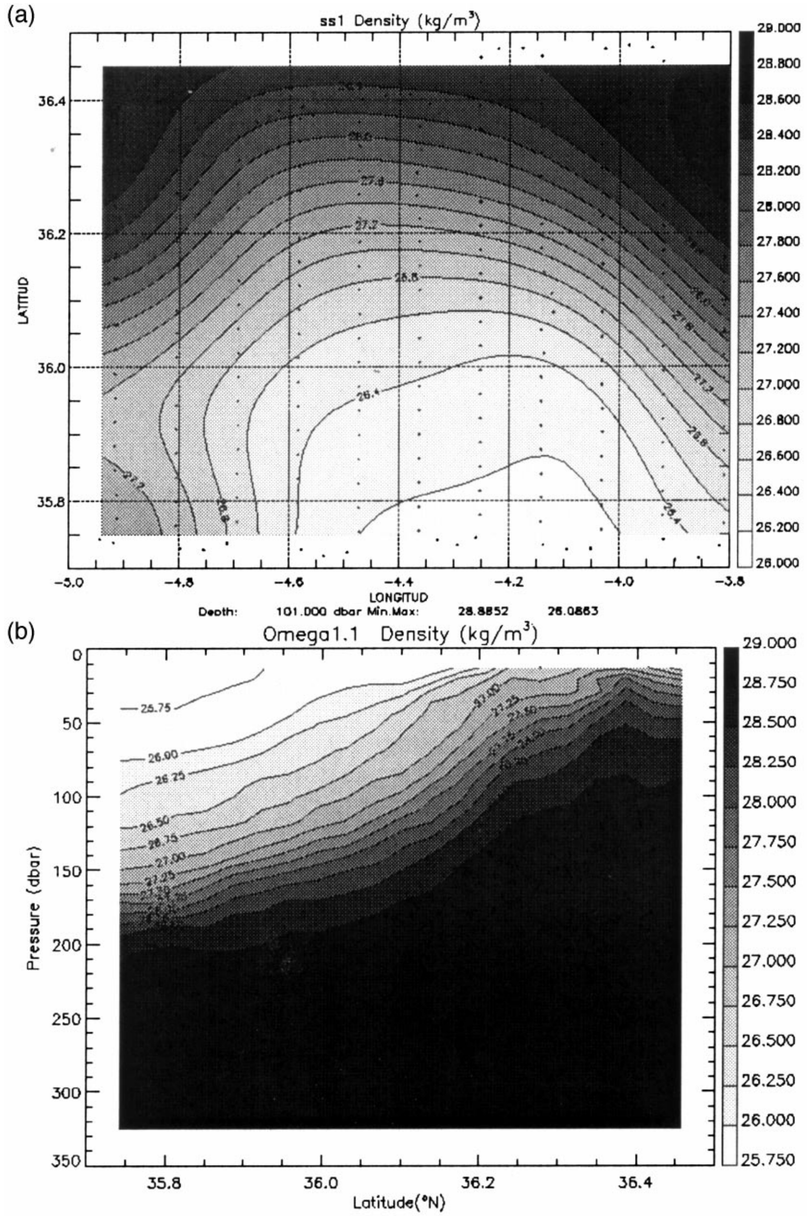

Fig. 8. Observations in the western Alboran Sea in October 1996. (a) Horizontal density field at 100 m. (b)–(d) Meridional sections along 4°W of density, fluorescence, and ADCP backscatter structure.

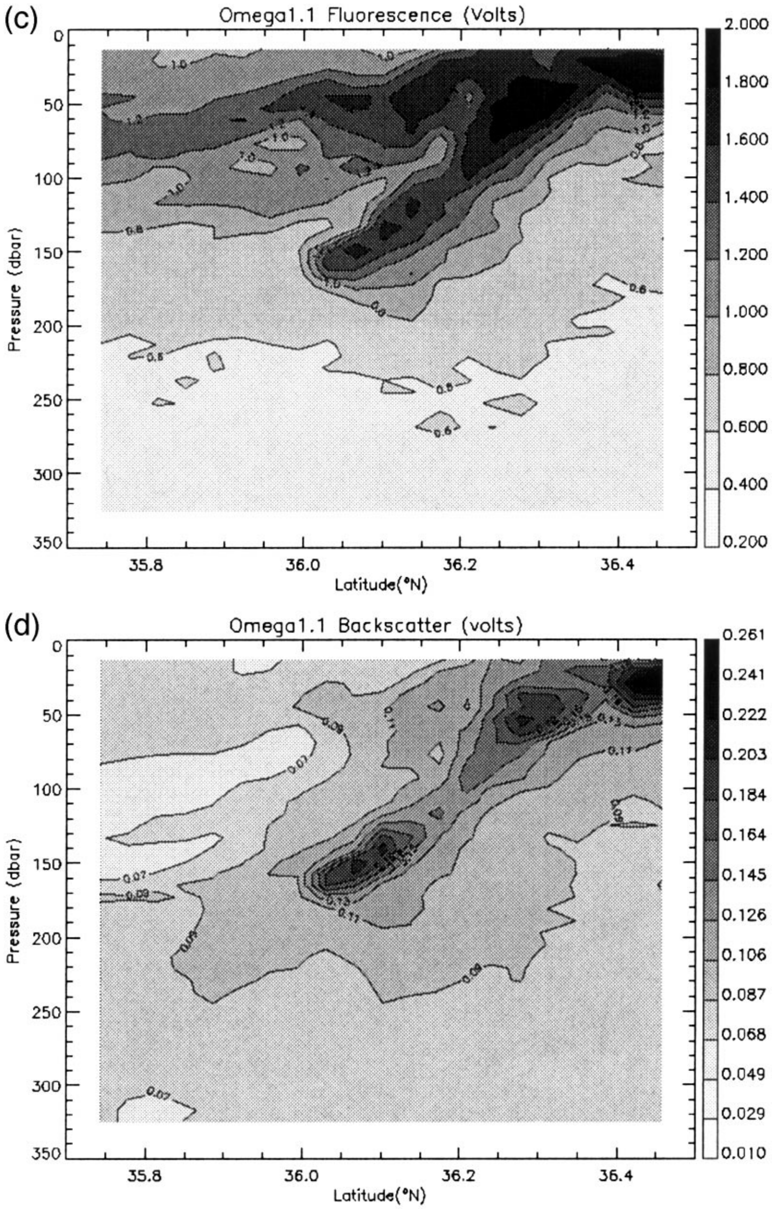

Fig. 8. Observations in the western Alboran Sea in October 1996. (a) Horizontal density field at 100 m. (b)–(d) Meridional sections along 4°W of density, fluorescence, and ADCP backscatter structure.

deeper layers, as well. The latter are events that rapidly reach a mature stage and are thought to consist of a meander (width 50–150 km) of the Algerian Current, extending up to ~100 km from the coast and mainly associated with two superimposed anticyclonic eddies. The surface eddy, enclosed within the meander, is depicted from space as being 30–120 km in diameter. The deep eddy appears to involve the whole deep layer, and rapidly becomes barotropic and large in diameter (up to ~150 km). The cyclonic surface eddy seen during the initial stage of the event is a superficial and short-lived structure. Both anticyclonic eddies propagate downstream at a few km/day for months at least and probably eventually merge. Before reaching the Sardinian Channel the eddies leave the coast and follow an anticlockwise circuit around the Algerian basin, maintaining their strong anticyclonic signature in sea surface height (Ayoub, Le Traon & De Mey, 1998; Vignudelli, 1997; Bouzinac, Vazquez & Font, 1998; Bouzinac, Font & Millot, 1999; Fuda et al., personal communication). They are formed once or twice a year, which is consistent with their relatively long lifetime and large diameter, which allows only few of them to occupy the Algerian Basin at any one time. These anticyclonic eddies interact strongly and frequently with their parent current.

The study of the three-dimensional structure, dynamics, and effects on the ecosystem of these mesoscale features, is one of the tasks included in the ongoing MATER Mediterranean Targeted Project-II. In situ observations in October 1996 (Font & the ALGERS Group, 1998a) have clearly related the evolution of a coastal meander, tracked by satellite infrared imagery, with the formation of a pair of cyclonic and anticyclonic structures that influence the distribution of several chemical and biological variables. The cyclonic eddy was only 150 m deep, while the anticyclonic one was still detected by the tilting of isopycnals at 1000 m. Surface drifters launched across this meander have documented the large scale characteristics of the Algerian current (Font, Millot, Salas, Julia & Chic, 1998b) and its mesoscale variability has been observed by remote infrared sensing (Salas, Garcia-Ladona, Font & Millot, 1998). Fig. 9 shows an example for the 1996–97 winter, when the Algerian current

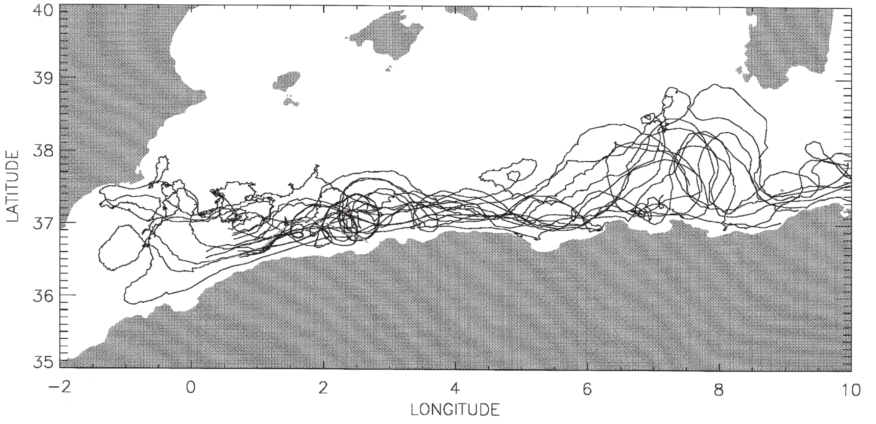

Fig. 9. Trajectories of surface drifters in the Algerian Current during the winter 1996–97.

was developing at least one coastal instability, and was interacting with others, but was not disrupted in its eastward path. Recent observations (MATER cruise, May 1998) have demonstrated that a large offshore anticyclonic eddy, located near 38°N 2°E, had a clear density signature (depression of isopycnals) down to a depth of 2500 m.

5. The intermediate layer circulation

The most prominent and best-known intermediate water mass of the western Mediterranean is the Levantine Intermediate Water (LIW). It is easily recognized by its high salinities and temperatures. After entering through the Strait of Sicily, it follows a mainly cyclonic path around the periphery of the basin as was already depicted in the diagrams of Millot (1987a). Consequently, the signature of this water is most pronounced near the eastern and northern boundaries (along Sicily, Corsica, France, Spain), but in the interior and in the south of the basin it generally displays rather weak intermediate maxima in temperature and salinity (see also Fig. 1).

However, isolated anomalies of LIW can be found in the interior of the basin. From observations during the THETIS-2 and ELISA experiments, the view is now emerging that these anomalies result from entrainment of LIW from the Sardinian coast into Algerian eddies (Section 4.2). These surface-intensified structures still have an anticyclonic circulation at the LIW level, and filaments of LIW can be drawn in when the eddy approaches the strong LIW characteristics near Sardinia. Fig. 10 shows a direct observation of this process. It is not clear at present whether pure LIW eddies/lenses may also be formed from an instability of the LIW flow itself.

The presence of the mid-basin LIW anomalies in historical data can then lead to values of temperature and salinity being enhanced in averaged horizontal maps, giving the impression of a flow path of LIW away from the coast. The data available at present do not support a direct flow, but clearly indicate the propagation of LIW characteristics in eddies. A consequence of this is that the intermediate water, which flows eastward along the Algerian slope as part of the mentioned boundary circulation, mixes with the warm and saline water which is entrained into the interior from Sardinia so that, along the Algerian slope too, temperature and salinity increase eastward.

The other intermediate water mass mentioned at the beginning of Section 2 is the Winter Intermediate Water, WIW (Salat & Font, 1987). The significance of this water mass seems to have been underestimated or, at least, neglected in the past. The THETIS-2 and ELISA experiments documented the wide-spread presence of the WIW. It is formed in the Gulf of Lions at locations where, or during winters when, vertical mixing does not penetrate to the depth of LIW. For instance, the WIW formed during the 1994 winter season was observed to spread in the form of lenses, only slightly modifying its characteristics. Such lenses of WIW, advected along the French/Spanish shelf by the Northern Current, can play an important role in the variability of water exchanges in the Balearic channels (Pinot et al., 1998). Occasionally they block the surface and intermediate circulations across the Ibiza channel,

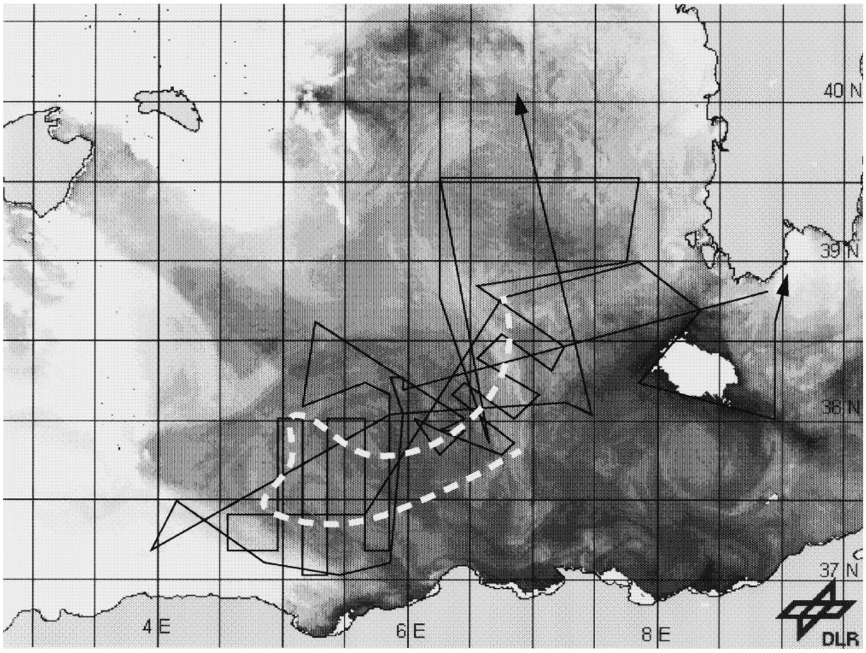

Fig. 10. Entrainment of an LIW filament into an Algerian eddy. The satellite SST image (30/7/1997, courtesy of DLR) shows the anticyclonic surface structure of about 200 km diameter centered near 38°N, 5.5°E. A CTD/XBT survey allowed the definition of the temperature field at the LIW level. The resulting approximate location of the 13.5°C contour at that depth is shown in white (cruise track in thin black lines).

and so divert large volumes of water to the region of the northeastward Balearic current (Salat, 1995; Garcia-Ladona, Castellon, Font & Tintoré, 1996). Fig. 11 shows the presence of one of these cold water lenses occupying the Ibiza channel below the thermocline to depths which are usually filled with warm LIW.

The overall occurence of WIW in the basin appears to be rather patchy, and no systematic flow path has been found yet. Care is necessary in interpreting low temperatures without knowledge of salinity; a temperature anomaly of WIW has low density associated with it (depression of isopycnals), whereas low temperatures at intermediate depth can also result from deep convection, in which case both the salinity and density would be high. The WIW anomalies have been found as far south as the Algerian coast (Benzohra & Millot, 1995) and also in the Channels of Sardinia and Sicily (Sammari, Millot, Stefani & Brahim, 1999), where because the deep layers of the MAW have rather low salinities compared with the northern basin, the WIW appears as a local salinity maximum. The observations suggest that the WIW can spread throughout the Western Mediterranean Sea and even penetrate into the Eastern Mediterranean.

Finally, a third intermediate water mass exists which enters the western basin, but has been ignored until recently. For decades all hydrographic data collected in the Channel of Sicily have shown not only the occurrence of LIW along the Sicilian

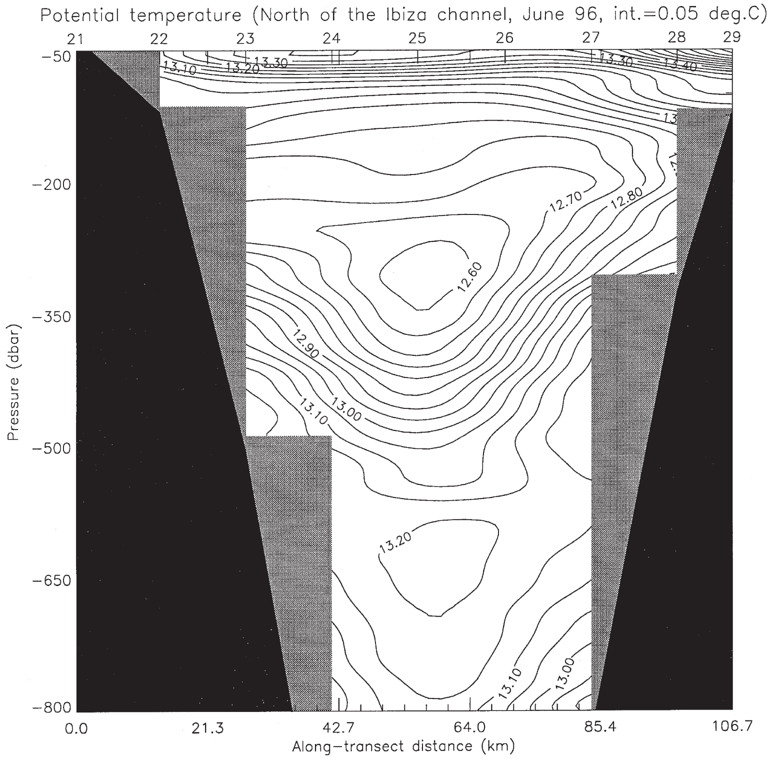

Fig. 11. Potential temperature section showing a lense of WIW occupying the Ibiza channel. Normally warmer and more saline LIW is found in these depths.

slope, but also a very much cooler and denser water that occurs at the bottom and along the Tunisian slope. This intermediate water incorporates components from the southern Adriatic and/or Aegean Seas, and therefore the acronym AIW has been proposed for it (Sammari et al., 1999). This inflowing water mass is as dense or even denser than the Western Mediterranean Deep Water (WMDW), which implies that it cascades along the bottom into the Tyrrhenian Sea (Sparnocchia, Gasparini, Astraldi, Borghini & Pistek, 1999), where it is expected to mix with the other water masses and hence contribute to TDW (see next section).

6. The deep circulation

As mentioned above, the deep water of the Western Mediterranean is formed by deep convection in the Gulf of Lions. Because it has recently been in contact with the surface, the WMDW is characterized by having high chlorofluorocarbon (CFC) content, as observed in the MAST-1 program (Rhein, 1995). It was thought that it is mainly WMDW that fills the western basins below the LIW. The other regions were considered to be of minor importance in determining the intermediate and deep water mass characteristics in the Algero–Provencal Basin. However, new data from the MATER project have revealed that it is water from the Tyrrhenian Sea (TDW) that occupies much of the western basin.

The Tyrrhenian Sea, which is located east of Sardinia, is a basin that is nearly totally enclosed below about 400m depth. Its only deep connnection is via the narrow Tyrrhenian Trough (1900 m depth) in the Sardinia Channel. Deep water in the Tyrrhenian Sea is warmer and more saline than WMDW and is formed by inflowing WMDW (along the bottom) mixing with overlying warmer and more saline LIW. (The AIW described in Section 5 also must be mixed into it to some extent, but the quantitative contribution is not clear at present.) It was long thought that this deep water mass, the TDW, remains in the Tyrrhenian Sea and is unimportant for the circulation in the Algero–Provencal Basin. However, to compensate for an observed WMDW inflow into the Tyrrhenian Sea, Hopkins (1988) postulated an outflow of intermediate water in the depth range 700–1000 m from the Tyrrhenian Sea into the Algero–Provencal Basin. As Hopkins points out, this outflow is undetectable outside the Tyrrhenian Sea since its hydrographic characteristics could also be produced locally in the Algero–Provencal Basin, and there was then no direct flow observation to verify the outflow.

In autumn 1997, CTD and CFC analyses were combined with direct velocity measurements (LADCP and floats) to study the circulation of the deep and intermediate waters. The CFC distributions turned out to be a unique tool to follow and identify the outflow from the Tyrrhenian Sea in the Algero–Provencal Basin. It was found that the TDW is present everywhere in the Algero–Provencal Basin extending from 600m down to 1600–1900 m (Rhein, Send, Klein & Krahmann, 1999). With a simple CFC box model the outflow from the Tyrrhenian Sea was estimated to be 0.4 Sv, similar to the estimated rate of deep water formation rate in the Gulf of Lions. Although neglected up to now, the Tyrrhenian Sea seems to be of equal importance for the water mass modification and circulation in the Algero–Provencal Basin as the Gulf of Lions.

The unique feature which identifies the outflow from the Tyrrhenian Sea is the intermediate CFC minimum. Throughout the Algero–Provencal Basin it is located between 900 and 1300 m depth, Fig. 12. The concentrations are 40% lower than in the WMDW below 1900 m depth. The minimum originates in the Tyrrhenian Sea and results mainly from the longer ventilation times of the deep Tyrrhenian Basin compared to the Algero–Provencal Basin, i.e. the present TDW represents the lower CFC values of earlier years. The minimum is most pronounced close to the Corsican and Sardinian coast and similar to the values found in the Tyrrhenian Sea. Further west, the concentrations in the minimum increase as a result of mixing. The salinity-CFC correlation shows that the values observed between 600 and 1600 m depth in the Algero–Provencal Basin lie along the mixing line between the data from the Tyrrhenian Sea and WMDW at 1700–1900 m depth. The horizontal distribution of the CFC minimum reflects the cyclonic circulation around the basin, which was also confirmed by the LADCP data.

Additional eddy activity transports the characteristics of the boundary current into

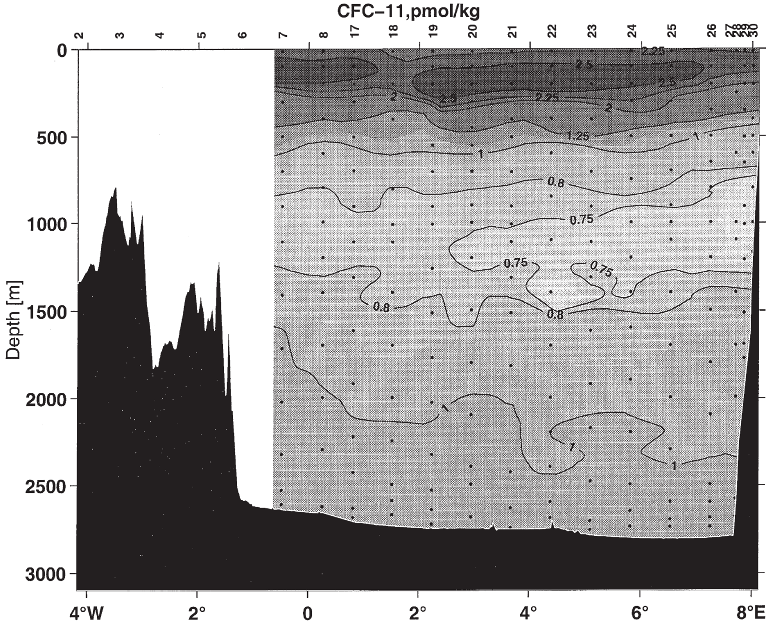

Fig. 12. Freon-11 distribution along the same section as that of Fig. 1.

the interior. The flow field in the boundary currents and the interior was studied by the release of floats at 1200 m depth. The float paths confirm the boundary circulation and the turbulent nature of the velocity field in the interior. The velocities are of the same order of magnitude (5–10 cm/s) in the interior and in the boundary currents (Fig. 13). Note that two floats appear to have sampled a large cyclonic eddy in the Algerian Basin (near 38°N, 6.5°E), but currently it is not known whether this eddy was associated with an overlying anticyclonic Algerian eddy.

7. Conclusions

Studies of the western Mediterranean oceanography have been able to quantify the deep water mass formation and related processes. Not only the processes are becoming clearer but also the interannual variability and the relation to the forcing has been investigated. The ultimate fate of the dense water generated is still uncertain in terms of its entry into the general circulation, but studies addressing this are under way.

The seasonal and interannual variability of the surface fluxes which drive much of the system have recently been studied. It is now possible to achieve higher accuracies in determining/calibrating these fluxes and their relation to larger-scale phenomena like the NAO has been elucidated. The water masses, the heat and freshwater budgets, the circulation and possibly the outflow all respond to these fluxes

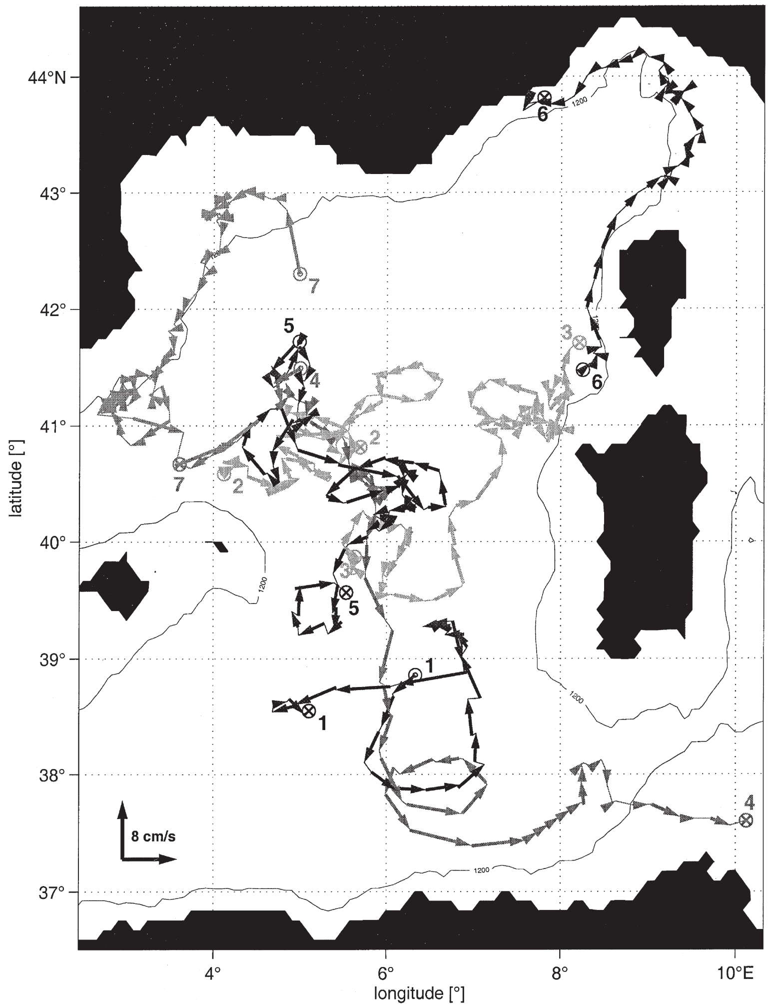

Fig. 13. Trajectories of deep profiling floats (similar to ALACE floats) from October 1997 until February 1999 at 1200 m depth. The single depth contour shown on the map is the 1200 m isobath. The submerged float displacements are shown as arrows, connected with thin lines for the surface drift intervals. The deployment and last surface locations are marked by symbols and labelled with the float number. Note that the floats in the boundary current occasionally were grounded, so the displacement during those periods is not significant.

and their variability. Monitoring of some of the resultant changes in the system is now becoming feasible with modern techniques, and will probably be an element of a future Mediterranean GOOS programme.

The near-surface and intermediate circulation has revealed ever greater complexity. There are energetic and transient regional features and changes in the local circulation (islands, passages, etc.). The features can have a prominent impact and significance for biological processes. Much of the flow and the spreading of water masses is eddy-dominated and highly variable. Two types of eddies have been clearly documented. First are the anticyclonic Algerian eddies that occur mainly in the MAW layer, but have a residual circulation at the LIW level whereby LIW is entrained into these structure. Second are the lense-like WIW anomalies which, based on preliminary data, also appear to be anticyclonic.

The deep circulation is currently being investigated in MATER. First results have revealed the prominence of Tyrrhenian water over a large depth range throughout most of the basin. The WMDW proper must therefore lie below approximately 1800 m. Apart from boundary currents, this layer is also dominated by eddies (of both signs), and the interior circulation appears to be very transient.

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References

Alberola, C., Millot, C., & Font, J. (1995). On the seasonal and mesoscale variabilities of the Northern current during the PRIMO 0 experiment in the western Mediterranean Sea. *Oceanologica Acta*, *18*, 163–192.

Alvarez, A., Tintoré, J., & Sabates, A. (1996). Flow modification and shelf/slope exchange induced by a submarine canyon off the northeast Spanish coast. *Journal of Geophysical Research*, *101*, 12043–12055.

Astraldi, M., & Gasparini, G. P. (1992). The seasonal characteristics of the circulation in the north Mediterranean basin and their relationship with the atmospheric-climatic conditions. *Journal of Geophysical Research*, *97*, 9531–9540.

Ayoub, N., Le Traon, P. Y., & De Mey, P. (1998). A description of the Mediterranean surface variable circulation from combined ERS-1 and TOPEX/POSEIDON altimetric data. *Journal of Marine Systems*, *18*, 3–40.

Benzohra, M., & Millot, C. (1995). Characteristics and circulation of the surface and intermediate water masses off Algeria. *Deep-Sea Research*, *42*, 1803–1830.

Bethoux, J.-P., Gentili, B., & Tailliez, D. (1998). Warming and freshwater budget change in the Mediterranean since the 1940s, their possible relation to the greenhouse effect. *Geophysical Research Letters*, *25*, 1023–1026.

Bouzinac, C., Font, J., & Millot, C. (1999). Hydrology and currents observed in the Channel of Sardinia during the PRIMO-1 experiment from November 1993 to October 1994. *Journal of Marine Systems*, *20*, 333–355.

Bouzinac, C., Vazquez, J., & Font, J. (1998). CEOF analysis of ERS-1 and Topex/Poseidon combined altimetric data in the region of the Algerian current. *Journal of Geophysical Research*, *103*, 8059–8071.

Bunker, A. F., Charnock, H., & Goldsmith, R. A. (1982). A note on the heat balance in the Mediterranean and Red Seas. *Journal of Marine Research*, *40*, (suppl.), 73–84.

EUROMODEL Group (1995). Progress from 1989 to 1992 in understanding the general circulation of the western Mediterranean sea. *Oceanologica Acta*, *18*, 255–271.

Font, J., Garcia-Ladona, E., & Garcia-Gorriz, E. (1995). The seasonality of mesoscale motion in the Northern Current of the western Mediterranean: several years of evidence. *Oceanologica Acta*, *18*, 207–219.

Font, J., & the ALGERS Group (1998a). Interdisciplinary study of the Algerian basin mesoscale instabilities, ALGERS cruise, October 1996, *Rapport des Reunions Commission International de la Mer Mediterranee*, *35*, 140–141.

Font, J., Millot, C., Salas, J., Julia, A., & Chic, O. (1998b). The drift of Modified Atlantic Water to the eastern Mediterranean. *Scientia Marina*, *62*, 211–216.

Garcia-Ladona, E., Castellon, A., Font, J., & Tintoré, J. (1996). The Balearic current and volume transports in the Balearic basin. *Oceanologica Acta, 19*, 489–497.

Garrett, C., Outerbridge, R., & Thompson, K. (1993). Interannual Variability in Mediterranean Heat and Buoyancy Fluxes. *Journal of Climate*, *6*, 900–910.

Gascard, J.-C. (1978). Mediterranean Deep Water Formation, Baroclinic Instability and Oceanic Eddies. *Oceanologica Acta*, *1*, 315–330.

Gilman, C., & Garrett, C. (1994). Heat flux parametrizations for the Mediterranean Sea: The role of atmospheric aerosols and constraints from the water budget. *Journal of Geophysical Research*, *99*, 5119–5134.

Hermann, A. J., & Owens, W. B. (1991). Modelling the geostrophic adjustment and spreading of waters formed by deep convection. In P. C. Chu, & J.-C. Gascard, *Deep convection and deep water formation in the oceans* (pp. 283–308). Elsevier.

Hopkins, T. S. (1988). Recent observations in the intermediate and deep water circulation in the Southern Tyrrhenian Sea. *Oceanologica Acta*, *9*, 41–50.

Hurrell, J. W. (1995). Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science*, *269*, 676–679.

Jones, H., & Marshall, J. (1997). Restratification after deep convection. *Journal of Physical Oceanography*, *27*, 2276–2287.

Krahmann, G. (1997). *Saisonale und zwischejaehrliche Variabilitaet im westlichen Mittelmeer — Analyse historischer Daten*. PhD thesis, University Kiel.

Krahmann, G., & Schott, F. (1998). Long-term increase in Mediterranean salinities and temperatures: mixed anthropogenic and climatic sources. *Geophysical Research Letters*, *25*, 4209–4212.

Kushnir, Y. (1994). Interdecadal variations in North Atlantic Sea surface temperature and associated atmospheric conditions. *Journal of Climate*, *7*, 141–157.

Larnicol, G., Le Traon, P.-Y., Ayoub, N., & De Mey, P. (1995). Mean sea level and surface circulation variability of the Mediterranean Sea from 2 years of TOPEX/POSEIDON altimetry. *Journal of Geophysical Research*, *199*, 25163–25177.

Leaman, K. D., & Schott, F. (1991). Hydrographic structure of the convection regime in the Gulf of Lions: Winter 1987. *Journal of Physical Oceanography*, *21*, 573–596.

Lopez-Garcia, M. J., Millot, C., Font, J., & Garcia-Ladona, E. (1994). Surface circulation variability in the Balearic basin. *Journal of Geophysical Research*, *99*, 3285–3296.

Madec, G., Chartier, M., Delecluse, P., & Crepon, M. (1991). A three-dimensional numerical study of deep-water formation in the northwestern Mediterranean Sea. *Journal of Physical Oceanography*, *21*, 1349–1371.

Mertens, C., & Schott, F. (1998). Interannual variability of deep-water formation in the Northwestern Mediterranean. *Journal of Physical Oceanography*, *28*, 1410–1424.

Miller, A. R., Tchernia, P., & Charnock, H. (1970). Mediterranean Sea Atlas of temperature, salinity, oxygen profiles and data from cruises of R.V. *Atlantis* and R.V. *Chain*. Woods Hole Oceanographic Institution Atlas Series 3. In .

Millot, C. (1985). Some features of the Algerian Current. *Journal of Geophysical Research*, *90*, 7169–7176.

Millot, C. (1987a). Circulation in the Western Mediterranean. *Oceanologica Acta, 10*, 143–149.

Millot, C. (1987b). The circulation of the Levantine Intermediate Water in the Algerian Basin. *Journal of Geophysical Research*, *92*, 8265–8276.

Millot, C. (1999). Circulation in the Western Mediterranean. *Journal of Marine Systems, 20*, 423–442.

Millot, C., Benzhora, M., & Taupier-Letage, I. (1997). Circulation in the Algerian Basin inferred from the MEDIPROD-5 current meter data. *Deep Sea Research*, *44*, 1467–1495.

Pinot, J. M., Tintoré, J., & Gomis, D. (1995). Multivariate analysis of the surface circulation in the Balearic Sea. *Progress in Oceanography*, *36*, 343–376.

Pinot, J. M., Lopez-Jurado, J. L., Riera, M., Jansa, J., Font, J., & Tintoré, J. (1998). Time flow variability in the Balearic channels and its relevance to the western Mediterranean circulation. *Rapport des Reunions du Commission International de la Mer Mediterranee*, *35*, 188–189.

Rhein, M. (1995). Deep water formation in the Western Mediterranean. *Journal of Geophysical Research*, *100*, 6943–6959.

Rhein, M., Send, U., Klein, B., & Krahmann, G. (1999). Interbasin Deep and Intermediate Water Exchange, Western Mediterranean. *Journal of Geophysical Research*, (in press).

Rodriguez, J., & Li, W. K. W. (1994). The size structure and metabolism of the pelagic ecosystem. *Scientia Marina*, *58*, 1–167.

Rohling, E. J., & Bryden, H. L. (1992). Man-induced salinity and temperature increase in western Mediterranean Deep Water. *Journal of Geophysical Research*, *97*, 11191–11198.

Salas, J., Garcia-Ladona, E., Font, J., & Millot, C. (1998). Drifter and satellite thermal observations of the Algerian Current in autumn and winter 1996–97. *Rapport des Reunions du Commission International de la Mer Mediterranee*, *35*, 192–193.

Salat, J. (1995). The interaction between the Catalan and Balearic currents in the southern Catalan Sea. *Oceanologica Acta*, *18*, 227–234.

Salat, J., & Font, J. (1987). Water mass structure near and offshore the Catalan coast during the winter of 1982 and 1983. *Annales Geophysicae*, *5*, 49–54.

Sammari, C., Millot, C., & Prieur, L. (1995). Some aspects of the seasonal and mesoscale variabilities of the Northern current inferred from the PROLIG-2 and PROS-6 experiments. *Deep-Sea Research*, *42*, 893–917.

Sammari, C., Millot, C., Stefani, A., & Brahim, M. (1999). Hydrological characteristics in the Tunisia-Sicily-Sardinia area during spring 1995. *Deep-Sea Research*, (in press).

Schott, F., & Leaman, K. D. (1991). Observations with moored acoustic doppler current profilers in the convection regime in the Golfe du Lion. *Journal of Physical Oceanography*, *21*, 558–574.

Schott, F., Visbeck, M., Send, U., Fischer, J., Stramma, L., & Desaubies, Y. (1996). Observations of deep convection in the Gulf of Lions, northern Mediterranean, during the winter of 1991/92. *Journal of Physical Oceanography*, *26*, 505–524.

Send, U., & Marshall, J. (1995). Integral effects of deep convection. *Journal of Physical Oceanography*, *25*, 855–872.

Send, U., Schott, F., Gaillard, F., & Desaubies, Y. (1995). Observation of a deep convection regime with acoustic tomography. *Journal of Geophysical Research*, *100*, 6927–6941.

Send, U., Font, J., & Mertens, C. (1996). Recent observation indicates convection's role in deep circulation. *EOS*, *77*, 61–65.

Send, U., Krahmann, G., Mauuary, D., Desaubies, Y., Gaillard, F., Terre, T., Papadakis, J., Taroudakis, M., Skarsoulis, E., & Millot, C. (1997). Acoustic observations of heat content across the Mediterranean Sea. *Nature*, *385*, 615–617 (London).

Send, U., & Käse, R. (1998). Parameterization of processes in deep convection regimes. In E. Chassignet, & J. Verron, *Ocean modelling and parameterization* (pp. 191–214). Kluwer Academic Publishers.

Sparnocchia, S., Gasparini, G. P., Astraldi, M., Borghini, M., & Pistek, P. (1999). Dynamics and mixing of the Eastern Mediterranean Outflow in the Tyrrhenian Basin. *Journal of Marine Systems*, *20*, 301–317.

Stommel, H. (1972). Deep winter-time convection in the western Mediterranean Sea. In A. L. Gordon, *Studies in physical oceanography, a tribute to Georg Wüst on his 80th birthday* (pp. 207–218). Gordon and Breach Science.

THETIS Group (1994). Open-ocean deep convection explored in the Mediterranean. *EOS*, *75*, 217–221.

Tintoré, J., La Violette, P. E., Blade, I., & Cruzado, A. (1986). A study of an intense density front in the eastern Alboran Sea: the Almeria-Oran front. *Journal of Physical Oceanography*, *18*, 1384–1397.

Tintoré, J., Gomis, D., Alonso, S., & Parrilla, G. (1991). Mesoscale dynamics and vertical motion in the Alboran Sea. *Journal of Physical Oceanography*, *21*, 811–823.

Tintoré, J., Allen, J., Font, J., Corsini, G., Rodriguez, J., Gascard, J.C., & OMEGA collaborators (1998). Observations and modelling of eddy scale geostrophic and ageostrophic circulation. European Marine Science and Technology Conference. CEC. edt. ISBN92-828-2898-0, (pp. 5–22).

Vignudelli, S. (1997). Potential use of ERS-1 and Topex/Poseidon altimeters for resolving oceanographic patterns in the Algerian Basin. *Geophysical Research Letters*, *24*, 1787–1790.

Viudez, A., Tintoré, J., & Haney, R. L. (1996). Circulation in the Alboran Sea as determined by quasi-synoptic hydrographic observations. I. Three dimensional structure of the two anticyclonic gyres. *Journal of Physical Oceanography*, *26*, 684–705.

Woodruff, S. D., Sleutz, R. J., Jenne, R. L., & Steurer, P. M. (1987). A comprehensive ocean-atmosphere data set. *Bulletin of the American Meteorological Society*, *68*, 1239–1250.

Wüst, G. (1961). On the vertical circulation of the Mediterranean Sea. *Journal of Geophysical Research*, *66*, 3261–3271.