I - Executive Summary of CIESM Workshop 38

"Dynamics of Mediterranean deep waters"

by

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This synthesis was written by all participants of the workshop under the coordination of Jordi Font. Frédéric Briand, the Monograph Series Editor, reviewed and edited this chapter along with the entire volume, assisted by Valérie Gollino for the physical production process.

1. Introduction

All water masses in the deep ocean acquired their characteristics when they were in contact with the ocean surface. The ocean thermohaline circulation is responsible for the further spreading of the newly formed water masses to all ocean regions. The deep component of this conveyor belt, with its slow, but very relevant dynamics, is still poorly known, from both the physical and biological points of view.

The Mediterranean is a semi-enclosed sea whose geographical, morphological and hydrological characteristics allow several oceanographic processes, found at large scale in the open ocean, to occur, but on a reduced scale. One of these is the wintertime formation of dense water by atmospheric cooling and desiccation, as well as by sinking of cold dense waters cascading off the continental shelf. These processes can occur until most of the deep Mediterranean basin has been renewed.

From the late 1960s, starting with the international MEDOC project in the North-western Mediterranean, the dense water formation (DWF) processes and their impact on the overall circulation have been studied in both Eastern and Western basins. This effort led to the formation of various hypotheses and models for the complex mechanisms taking place. Furthermore, it pushed the oceanographic community to monitor and characterise the different water masses involved.

Analysis of measurements made in the deep layers of the Eastern basin revealed that a major change had been occurring in the late '80s / early '90s: a shift of the main deep water formation area from the Adriatic to the Aegean subbasins. This event, known as the Eastern Mediterranean Transient (EMT), was the subject of a CIESM science workshop held in Trieste in March-April 2000 (CIESM, 2000). It is a good example of the kind of relevant ocean circulation modification that has been induced by climate change scenarios. Two years later CIESM launched the Hydrochanges program to coordinate the monitoring of the deep water thermohaline characteristics of the entire Mediterranean basin (CIESM, 2002).

As highlighted in their respective introductions by Dr Frédéric Briand, Director General of CIESM, and Dr Jordi Font, Chair of CIESM Committee on Physics and Climate of the Ocean, the time had come for a joint analysis of recent observations in the deep Mediterranean some twenty years after the EMT. Further in 2009, 40 years after the first MEDOC cruise, with evidence that the EMT is decaying, and data that a major change occurred in the western basin deep water structure after the 2004/05 winter, a revisit of the DWF processes is in order. Towards this end thirteen specialists were invited by the Commission to St. Paul's Bay, Malta, 27-30 May 2009 to review advances and gaps in current knowledge on the dynamics of Mediterranean deep waters and propose priorities for future research. In welcoming the participants the Director General expressed his gratitude to Dr Aldo Drago, National Representative of Malta on CIESM Board for the superb logistic support provides.

After presenting the different communications developed in this Monograph, the group discussed the analysis of recent results, and through them reviewed the mechanisms of DWF in the Mediterranean. This discussion highlighted open questions concerning the interpretation of the observations, theoretical approaches, lack of information and of adequate modelling tools, finally producing a series of recommendations.

Three main topics were proposed to structure the discussion: update understanding of the Eastern Mediterranean Transient; the new situation of the deep Western Mediterranean; and processes of deep water formation. A working group was set up for each one of these topics to lead the discussions, present preliminary conclusions and finally draft the texts assembled here below. A section on general recommendations is included at the end of this executive summary.

2. Update on the Eastern Mediterranean Transient

2.1 Background

A particularly interesting phenomenon occurred in the Eastern Mediterranean (EMed) in the 1990s.The Aegean Sea replaced the previously dominating Adriatic Sea as the source of the EMed deep waters. This event is termed the Eastern Mediterranean Transient (EMT). The EMT was caused by the Aegean Sea forming and discharging massive amounts of unusually dense and saline waters (Roether *et al.*, 1996; Theocharis *et al.*, 1999a), which initiated a complete disturbance of the hydrography and circulation of the EMed (cf. Roether, this volume). The EMT primarily affected the deep waters but had influence also further up in the water column, as a result of shallower Aegean outflow and mixing, and in particular of mid-depth water lifting several hundred meters due to Aegean water addition deeper down. An effect was felt even at the nutricline, which was lifted by about 150 m in the eastern Ionian (Klein *et al.*, 1999). The distributions of all other biogeochemical parameters, such as nutrients, were changed. A special effect was an EMT-induced rise in oxygen consumption (Roether and Well, 2001; Klein *et al.*, 2003). The EMT is highly relevant oceanographically, but perhaps even more so on climatological grounds, as it is one of the first observed cases of a basin entirely changing its deep water circulation. One can expect that such episodes will play an increasing role in consequence of Global Climate Change.

The EMT started in about 1990 and peaked in 1992-94, with an average Aegean outflow rate of nearly 3 10^6 m^3/s (3 Sv). The outflow subsided strongly thereafter and reached only depths of 1,500 – 2,000 m (Theocharis *et al.*, 2002). A relevant ingredient in forming the EMT was accumulation of exceptionally saline waters in the eastern Levantine, possibly assisted by eddies south of Crete, observed in 1991, that suppressed inflow of lower-salinity waters from the Ionian (Malanotte-Rizzoli *et al.*, 1999). Various additional circulation changes of potential relevance have been noted, such as alternating cyclonic and anti-cyclonic upper water movement in the Ionian (Borzelli *et al.*, 2009; cf. also Gačić *et al.*, this volume) and intermediate water formation in the southern Aegean Sea, or Cretan Sea (Cretan Intermediate Water, CIW), more or less replacing formation in the Rhodes Gyre (Levantine Intermediate Water, LIW) that was dominating previously.

The evolution of the EMT has been documented up to 2001 (Roether *et al.*, 2007). In the Levantine Sea a rather clear picture of the deep circulation has been found, in consequence of strong topographic steering. But in the Ionian Sea west of the East Mediterranean Ridge, there is far less of such steering, and in consequence the circulation is more uncertain. Rather strong basin-scale mixing is however apparent, presumably with a strong role of eddy mixing.

Because of very low density gradients on level surfaces (horizontally) in the presence of substantial salinity differences, the common use of potential density is often misleading (cf. Roether, this volume). In extreme cases, lateral property gradients may show a direction opposite to that which is obtained if densities referenced to a close-by isobar are used.

2.2 New results

- From measurements taken during 1994-2002, the Aegean deep water (Cretan Deep Water, CDW) production rate was estimated to have fallen to 0.15 Sv. After 2002 no Aegean deep water was observed to leave through Kassos Strait due to the fact that such water was restricted in the Cretan Basin to the layers below sill depth, reaching recently (2005-2006) 1,200 m (Theocharis, this volume).

- Most of the water column in that strait has become occupied by Transitional Mediterranean Water (TMW), which is now located below the CIW layer (Theocharis *et al.*, 1999b; Sofianos *et al.*, 2007). This TMW, an old water body transitional in characteristics, which was lying between the LIW and the old Eastern Mediterranean Deep Water (EMDW, of Adriatic origin) all over the Eastern basin in the pre-EMT period, has entered the Aegean during the EMT and is considered there to be a water mass, although it is not included in the CIESM list of Mediterranean water masses. Note that the CIW has been observed also in the Strait of Sicily and beyond, demonstrating westward export (Gasparini *et al.*, 2005).

- The Adriatic resumed producing dense waters reaching again the bottom layer of the Ionian Sea. A strong effect is evident in 2007, when observations showed salinities distinctly higher than classically found (Rubino and Hainbucher, 2007). Already in 2002 deep convection in the southern Adriatic had been reinstated (Roether *et al.*, 2007; Gačić *et al.*, this volume).

- A major cause of the higher salinity is the inflow of saltier waters from the Ionian Sea as a consequence of cyclonic circulation of the upper waters. Such circulation provides a rather direct path for advection of higher-salinity waters from the Aegean or Levantine. An anticyclonic pattern, in contrast, supports advection of waters with a substantial fraction of lower-salinity waters from Strait of Sicily (Gačić *et al.*, this volume).

- The Ionian circulation reversals are due to baroclinic vorticity input rather than wind curl forcing. The later appears to have only a secondary influence (Gačić *et al.*, this volume).

- With the Adriatic producing bottom water and the Aegean outflow feeding mainly intermediate-depth layers, at most into the TMW, the two seas have reassumed their roles from the pre-EMT period. Since 2005, furthermore, the near-bottom properties of the Ionian and Levantine basins have moved toward a more Adriatic signature. But the deep waters are still far from any equilibrium distribution: the entire deep-water volume must be flushed out by newly produced bottom water. Additionally, the fact that deep waters are out of equilibrium with their sources will induce a time-dependent pre-conditioning of the DWF processes. Considering that during the quasi-steady-state pre-EMT situation the deep water turnover exceeded 100 years, one must indeed expect many more decades of transient EMed deep waters.

- Contribution of mesoscale anticyclonic eddies to the intermediate-water transport has been suggested (Sutyrin *et al.*, 2009; Taupier-Letage *et al.*, 2007), as reported for the Western Mediterranean (WMed) by Testor *et al.* (2005a).

- Modeling efforts have supported the idea that the unexpectedly large amplitude of EMT resulted from a combination of a decadal accumulation of high-salinity waters, severe regional winter conditions, a decrease of the Black Sea discharge into the Aegean Sea, and heavy inflow of LIW into the Cretan Sea (Nittis *et al.*, 2003; Skliris *et al.*, 2007).

- Beyond continued work in the Aegean and the Adriatic Seas including their surrounding waters, the large-scale hydrography of the EMed was surveyed in 2008 by the SESAME

(<http://www.sesame-ip.eu>) and in 2006-2008 by the VECTOR (<http://vector-conisma.geo.unimib.it>) programs. The achieved coverage should allow investigating the evolution of the EMT after 2001. Supplemental information is available from long-term current meter observations related to the planning of a "neutrino telescope" in the western Ionian Sea (Manca *et al.*, 2002a; Bouche *et al.*, this volume), and near the island of Pilos in the eastern Ionian Sea.

2.3 Open questions

- The EMT was primarily brought about by a pronounced increase of salinity in the Aegean deep waters, but the origin of this extra salinity is only known in a qualitative way (accumulation of high-salinity upper waters in the eastern Levantine). Additional influences on the salinity, such as reduced precipitation, reduced influx of fresher waters from the Black Sea, and inputs from shelf areas (cascading) possibly also have contributed to the increase.
- The influence of the EMT on the deep waters in the WMed is quantitatively unknown. For quantification, an important intermediate step would be to study the hydrographic relationship between the evolving EMed waters and the western outflow in Sicily Strait.
- Whereas the highly structured topography in the Levantine Sea appears to have governed the deep circulation of that basin, such steering is far less pronounced in the Ionian Sea, making that sea's deep circulation more uncertain (see also Millot and Taupier-Letage, 2005a).
- Mesoscale cyclonic and anticyclonic eddies are frequent phenomena in the EMed (Hamad *et al.*, 2005) contributing to the water transport. Their role, which may be particularly important for the Ionian Sea, must be studied.
- Deep water formation, in the Rhodes Gyre even though of limited density, has repeatedly been reported in the past. Under the modified hydrographic conditions, that role may have changed. More information is therefore needed concerning actual deep water formation in the Rhodes Gyre during 1996-2009, and future similar events should be monitored.
- Information is missing on the potential inputs from coastal areas feeding the deep waters, such as the western Adriatic shelf (Artegiani *et al.*, 1989; Bignami *et al.*, 1990), the Turkish coast, the Cyclades plateau (Durrieu de Madron *et al.*, 2005), and the Libyan coast (Gasparini *et al.*, 2008). Such contributions have met limited interest in the past, but it is also conceivable that cascading might have become more intense. Newly found special molecular-biological markers might be useful in detecting such contributions.

3. The new situation of the deep western Mediterranean

3.1 Background

During the last decades, the WMed heat and salt contents increased almost steadily. Past studies have demonstrated the tendency of the western deep waters towards higher temperatures and salinities since the '50s, with the process accelerating after the second half of the '80s (Rixen *et al.*, 2005). Those trends have been attributed to a number of possible causes, among others the changing environmental conditions, e.g. the greenhouse effect, local atmospheric conditions, and river damming.

Since 2005 the deep waters of the WMed have experienced significant physical changes, which are comparable to the ones that occurred in the EMed during the'90s (EMT), both in terms of intensity and observed effects. The major changes involve an abrupt increase in the deep heat and salt contents, and a change in the deep stratification, with the appearance of a "hook" in the deep temperature-salinity (θ/S) diagrams (see Figure 3 in contribution by Fuda *et al.*, this volume; and Figure 1 in contribution by Salat *et al.*, this volume). These changes started in winter 2004/05 with the production of an anomalously high volume of new deep water, which uplifted the old one by several hundreds of meters over almost the whole western basin.

The peculiar shape of the θ/S diagrams, with the presence of a "hook" at the end of the profiles, had already been partially observed in historical data. Similar anomalous structures were found in the past after severe winters (e.g. in 1972-73, 1981, 1988 and 1999), during which also deep cascading presumably occurred (cf. Salat *et al.*, this volume). This structure would correspond to the "occasional bottom water" reported by Lacombe *et al.* (1985). After 2005 this anomaly has been significantly enhanced by the huge amount of new deep water formed in winter 2004/05 and winter 2005/06. This allowed a basin-wide propagation of the "hook" and the abrupt increase in deep heat/salt contents (Salat *et al.*, this volume).

Different observational systems were essential in the detection and the overall description of those changes, at different temporal and spatial scales. Several basin-scale dedicated oceanographic cruises have witnessed the presence over a wide area of the anomalously different temperatures and salinities in the deep WMed. The contribution of these measurements facilitated the basin-wide assessment of the formation, extension, and spreading rates of these anomalies (Schroeder *et al.*, 2008b). Further, the mooring sites in the Gulf of Lions' submarine canyons, including the one deployed offshore the Catalan coast in the framework of the CIESM Hydrochanges program, allowed the descending plume of new dense water formed over the continental shelf to be observed (Lopez-Jurado *et al.*, 2005; Canals *et al.*, 2006; Font *et al.*, 2007; Puig *et al.*, 2008). In addition, long-term monitoring (by means of moorings) of the hydrographic properties of water masses crossing the key sites in the WMed (the Sicily Channel and the Corsica Channel) during the last 20 years has permitted the observation of water mass evolution under the influence of the EMT. The increasing trend, detected since the 1960s both in temperature and salinity, has been sensibly accelerated by this event (Gasparini *et al.*, 2005). Meanwhile, the new stratification was able to significantly influence the deep water formation in the NW Mediterranean. MedARGO floats allowed the intensity of convection in different locations in winters 2004/05 and 2005/06 (Smith *et al.*, 2008) to be observed. An important data source in directly detecting the anomalous deep water formation and long-term heat and salt accumulation is the DYFAMED site in the Ligurian Sea (which is part of the EuroSites network). The monthly CTD casts, which are available for the past 13 years, clearly evidence the heat and salt increases at intermediate levels, and directly documented the deep convection taking place in that region in early 2006 (Schroeder *et al.*, 2008b).

3.2 Main findings presented to the workshop

During the past five years, the NW Mediterranean seems to have become a very active DWF site. Very intense events have been reported in winter 2004/05 as well as in winter 2005/06, involving both open sea convection and shelf water cascading. There are new indications of DWF also in winter 2008/09 (Fuda *et al.*, this volume), and its extent requires assessment by future basin-scale investigations in that region.

Recent data collected by numerous groups have shown the appearance and spreading in the whole western basin of new deep water that is significantly warmer and saltier than previously, and that has substantially substituted the resident deep water. The new anomalous deep water has substantially modified the vertical stratification of the water column in almost the whole basin. Data collected between 2004 and 2006 showed that in this period the deep layer of the WMed experienced a temperature increase of about 0.038 °C and a salinity increase of 0.016. These increases are five to seven times greater than the increasing trends indicated by Béthoux and Gentili (1999) and about four times greater than the estimates given by Rixen *et al.* (2005) for the 1985-2000 period. The thermohaline anomaly has spread throughout the WMed, filling its deeper part below 1,500-2,000 m depth, significantly accelerating the ventilation of the deep layers. The peculiar "hook"-shaped θ/S diagrams found after the recent deep water formation events are a result of the interaction between old deep water (type O), new deep water formed by open sea convection (type N) and dense shelf cascading water (type C) (cf. Salat *et al.*, this volume). Preliminary analysis of the data available for the Channel of Sardinia sill between 2004 and 2009 suggests a possible passage of the new deep water towards the Tyrrhenian Sea (Fuda *et al.*, this volume; Schroeder *et al.*, this volume). Verification will be determined by future investigations. Evidence of the presence of the new deep water also has been found close to Gibraltar, in the shallower Alboran subbasin. Here the unequivocal identification of the winter 2004/05 formed deep water near Gibraltar was possible thanks to the particular shape in the θ/S diagram.

Furthermore, its recent detection (November 2008) at about 100-150 km from the Strait of Gibraltar, allows an accurate estimate of the temporal scales of its spreading to be made. Recently, a deep water mass formed in February-March 2005 in the NW Mediterranean had almost reached Gibraltar by January 2008 (Schroeder *et al.*, this volume; Bryden, this volume).

Winter 2004/05 set the beginning of a changed situation in the deep layers of almost the whole WMed. To distinguish between the present and the previous situation, the described changes are proposed to be referred to as *Western Mediterranean Transition* (WMT), in order to avoid confusion with the better known EMT. The two events for some aspects are similar (abrupt warming and salting of the deep layers in the whole basin, uplifting by several hundreds of meters of the resident old deep water), but there are a number of crucial differences (there is no identified additional deep water source in the WMed and no circulation changes have been reported for the WMed so far). With respect to the previous situation, starting from 2005 the deep basin has been filled by warmer, saltier and denser water, which at the same time is also more turbid and oxygenated. A thick bottom nepheloid layer (BNL) has formed in the whole WMed (with the only exception of the Tyrrhenian Sea) as a consequence of the intense shelf water cascading and the extraordinary high volume of new Western Mediterranean Deep Water (WMDW) produced between 2005 and 2006 (Puig *et al.*, this volume).

Garcia-Lafuente *et al.* in 2007 found a signature of these events in the Mediterranean Outflowing Water (MOW). They observed a decrease in temperature by the end of March 2005 and March 2006 and attributed it to a remote signature of the deep convection, which replenished the WMDW reservoir and raised its interface with the water above, making cooler water available for the outflow. According to the authors, even if this happened almost every year, in 2005 and in 2006 unusually sharp decreases were recorded. A climatological analysis of the Mediterranean Outflow (Medar/Medatlas II & World Ocean Database 2005) showed for the 1906-1999 period a positive trend in salinity and temperature values of the Mediterranean Waters (MW), with an acceleration in the last three decades (0.12 and 0.38 °C per decade, for salinity and temperature respectively). These trends are more linked with the North Atlantic trends than with Mediterranean ones, suggesting a relationship with the Mediterranean Outflow-Strait of Gibraltar system (Fusco *et al.*, 2008; Sannino *et al.*, 2005) by non-linear components of the heat, salt and momentum exchanges between the Atlantic Water (AW) and MW strait (Budillon *et al.*, this volume). Nevertheless, the extent to which the WMT will be able to affect the water mass properties, stratification and circulation in the North-Atlantic is still an open issue.

The new deep water was formed during massive convection events that took place during winters 2004/05 and 2005/06 in the NW Mediterranean. The deep convection is sustained by the combination of surface heat and freshwater losses and the lateral convergence of heat and freshwater. The deep water properties and their variability are due to the hydrographic preconditioning (heat and salt content and structure of the water column before the onset of convection), and to atmospheric forcing (heat, freshwater and buoyancy fluxes). Schroeder *et al.* (2006) related the new deep properties to a progressive increase of heat and salt content in the intermediate layer, due to the arrival of water of eastern origin which has been affected by the EMT event. Other authors (Font *et al.*, 2007; Lopez-Jurado *et al.*, 2005), attributed it to the extremely strong winter forcing in 2004/05. In terms of air-sea heat exchange, Lopez-Jurado *et al.* (2005) showed that the heat loss for this winter was 70 % above the winter average, with the highest values since 1948, using the NCEP/NCAR reanalysis. Additionally, in terms of air-sea freshwater exchanges, Font *et al.* (2007) asserted that in autumn and winter 2004-05 precipitation over the NW Mediterranean catchment area was greatly reduced, with the lowest absolute values ever recorded at many of the meteorological stations and that northerlies were strong and persistent. Furthermore, as suggested by Millot (2007), studies about DWF and circulation, which take into account the interannual variability of the forcing functions, must take into account the interannual variability of the inflow, in particular, the observed increasing salt content of the inflowing AW.

The results presented at the workshop and the subsequent discussion suggest that the DWF processes (both open-sea and on-shelf) are highly sensitive to any change in the forcing functions. In terms of preconditioning, the salinification of surface and intermediate waters (due either to local processes or the climate change) is likely to be the most important factor and would explain why the contribution by deep cascading from shelf regions seems to become more and more important.

3.3 Open questions and information gaps

Despite several advances in the recent years, there are still huge gaps in current knowledge. To fill these gaps would require a large monitoring program, focused not only on physical parameters, but also on biological, chemical, and sedimentological ones. Priorities for future research on the dynamics of Mediterranean deep waters should include attempts to answer the following questions:

Description of the WMT: What is the extent of the events occurring in the WMed, in terms of salt and heat contents increases in the deep layers and in terms of uplifting of the resident deep water? What are the involved mixing processes? What are the ventilation times and the ages of the involved water masses? What was the actual extent of the DWF region during the two winters (i.e. 2004/05 and 2005/06)? How fast is the anomaly propagating in the interior of the basin and to what extent are the straits controlling this propagation? Is it possible to assess this with appropriate models since there were no dedicated experiments during the DWF events? Does the "new" WMDW, as an "occasional BW (Bottom Water)," require an altered pattern of circulation to be formed (Salat *et al.*, this volume)?

Causes and effects: What has induced the WMT and what is the relative importance of the different forcing functions: salinification of the inflowing Atlantic Water (Millot, 2007); salinification of the LIW coming from the EMed; the EMT (Schroeder *et al.*, 2006; 2008b); and intense atmospheric forcing (Salat *et al.*, 2006; Font *et al.*, 2007)? What is the cause of the observed increasing temperature and salinity of the intermediate water (LIW/CIW) crossing the Strait of Sicily? To which degree will the anomaly contribute to the general warming and salinification of the Mediterranean basin? Are the signals observed at Gibraltar (Garcia-Lafuente *et al.*, 2007) due to the production of large volumes of new deep water in the NWMed? To which degree does a change in the MOW affect the oceanic circulation in the North-Atlantic and/or the deep water formation in the arctic regions? What are the expected biological changes associated with the WMT? Can the WMT induce a change in the role of the Mediterranean Sea as a source or a sink for anthropogenic carbon? Could the WMT modify the role of the marginal or semi-enclosed seas (e.g. the Tyrrhenian Sea) in the composition of the MOW?

4. Processes of deep water formation

4.1. Background

The NW Mediterranean is a well known region where winter deep convection and DWF can occur in a yearly basis due to winter heat losses and evaporation, caused by cold and dry northerly winds. Dedicated experiments in this region started 40 years ago, with the so called MEDOC campaigns, and further studies have been carried out in since then to advance the knowledge of such oceanographic phenomena. Remarkable sets of reference publications include the MEDOC group Nature paper (1970), the book edited by P. Chu and J.C. Gascard in 1991 (Elsevier oceanography series, 57), the review published by J. Marshal and F. Schott (1999) and many more.

The classical three phases proposed by the MEDOC group are still valid, starting with the preconditioning phase, followed by the violent mixing phase and ending with the spreading phase. The major and most important novelty is that these three phases are strongly coupled and interdependent. The new real discovery concerns long lived submesoscale vortices observed in the Greenland Sea, the Labrador Sea, the Weddell Sea and the Mediterranean Sea as well. Due to their longevity, the so called Submesocale Coherent Vortices (SCV) first introduced by J. McWilliams (1985) are active during the three phases of the deep open convection as observed in the Greenland Sea and the Mediterranean Sea in particular. The SCV are mainly characterized by a very low potential vorticity (close to 0). The internal core of the SCV, holding most of the newly formed deep water completely homogenised, has a relative vorticity close to –f. Accordingly, the absolute vorticity is close to 0 as is the vertical stratification. Both serve to decrease the potential vorticity to an extreme minimum. The ephemeral plumes described by J. Marshall and F. Schott (1999) are only contributing to accelerate the vertical mixing inside the eddy core (what the MEDOC group called the violent mixing). SCVs are contributing to the preconditioning phase for those waters remaining trapped inside the deep convective region. They also contribute to the spreading phase for those waters escaping the deep convective region and starting the long journey across the deep basins.

Convection involves wide ranges of space and time scales, with horizontal velocities up to 0.5 m s^{-1} near the bottom of the deep-sea basins. Waters cascading from the shelf can reach much higher downslope velocities, up to 1 m s^{-1}, and markedly mix with older ones over the slope. An heterogeneity of hydrological characteristics thus occurs in and close to a dense water formation area before waters mix progressively along their route and before being finally uplifted by and mixed with more recent and denser water. Spreading from the convection area is associated with small-scale (1-10 km) diameter sub-surface eddies. Near the outflow into the Atlantic Ocean and over sills in general, overmixing occurs. So far, internal wave mixing is thought to be less important.

In early studies of carbon oxidation in the deep western Mediterranean Sea Christensen *et al.* (1989) showed that the respiratory metabolism of the deep-sea microbial plankton community was unusually high compared with values from similar depths in the Atlantic and Equatorial Pacific Oceans. They hypothesized that such high metabolic rates might be supported by dissolved organic carbon transported to depth by wintertime dense water open-sea convection, since it could not be explained by the usual mechanism of vertically sinking particles. Recent observations of dense shelf-water cascading in the NW Mediterranean provide an additional mechanism for transporting organic matter into the deep WMed (Canals *et al.*, 2006; Puig *et al.*, this volume). This newly discovered source will inject both dissolved and particulate organic matter horizontally into the water column at the bottom of the continental slope. Furthermore this organic material will be relatively fresh and hence readily oxidizable to the deep sea biological community. The links between the cascading, the entrainment of organic matter, and the stimulation of the deep-metabolism need to be elucidated. They have not yet been demonstrated by critical time-series measurements nor by deep trans-basin sections. Nevertheless, the available evidence argues for such a connection. The stage is now set to demonstrate this connection by an interdisciplinary consortium of physical, geological, biochemical, and biological oceanographers.

4.2. Main findings presented during the workshop

As stated before, numerous hydrographic and hydrodynamic observations conducted recently in the Mediterranean Sea have resulted in a novel view of the functioning of dense water formation processes and the dynamics of deep waters in this land-locked sea. One of these novelties is the role played by dense shelf waters and the interactions of these waters with open-sea convection waters. In the past, cascading was thought to be a minor contributor of dense waters towards the ocean interior. However, models have reasonably reproduced mooring observations during cascading events. These model results for the northwestern Mediterranean have accounted for the transport of dense shelf waters at the level of 0.2 and 0.3 Sv for the winters 2003-04 and 2004-05, respectively (Ulses *et al.*, 2008a,b). Similarly, the water transport during the cascading event captured off Libya was estimated to have an order of magnitude of 0.1 Sv (Gasparini *et al.*, 2008). This amount is comparable to the ADW outflow rate from the southern Adriatic (Manca *et al.*, 2002a).

A new discovery concerns the fact that deep water convection is not the only process contributing to deep water formation and deep ocean ventilation. The dense waters formed on the shelves in winter can also contribute to renewing deep water in the Mediterranean Sea. This is not a new process. We know that in polar oceans, dense waters resulting from sea ice formation are formed on the shelves. The freezing process releases large volumes of brine at the same time the sea ice is formed. What is new, in the case of the Mediterranean Sea, is the role played by dense water formation on the shelves and its subsequent cascading over the slope. Because of its novelty, it has been intensively studied during the past three years.

The Mediterranean Sea has three well known areas of dense water formation, located in its northernmost continental shelves. Dense shelf-water cascading (DSWC) occurs almost every year in the Gulf of Lions, in the southern Adriatic Sea and on several Aegean shelves (Durrieu de

Madron *et al*., 2005). These areas are regionally linked and influenced by the same atmospheric forcing that operates in the open-sea convection sites described before. In addition, recent observations have revealed that DSWC can also occur on the Libyan continental margin (Gasparini *et al.*, 2008). The persistent, cold and dry northerly winds affecting these areas cause densification and mixing of coastal waters. Despite the buoyancy gain induced by freshwater inputs, desiccation and cooling decreases this buoyancy. Then, once these surface waters over the shelf are denser than surrounding waters, they sink, overflow the shelf edge, and cascade downslope until they reach their equilibrium depth. This resting depth changes from year to year. Cascades of DSW can last for several weeks and the associated strong currents can induce erosion and resuspension of surface sediments in the outer shelf/upper slope and generate bottom nepheloid layers (i.e. layers of water that contains significant amounts of suspended sediment). Such layers can be detached at intermediate levels when the density of the mixture of water and particles reach their equilibrium depth, or if the density is large enough, evolve into a thick bottom nepheloid layer that can reach the lower continental slope and basin (Puig *et al.*, this volume). Although rarely studied, this nepheloid layer is almost certain to be a zone of high biological activity. As far back as the Galathea expedition (1950-1952) oxygen was shown to be relatively depleted in deep-sea nepheloid layers. Transmissometers on CTDs often show turbidity increases in these layers, and where turbidity increases microbial activity increases. We would expect to see increases in POC, DOC, Electron Transport System (ETS) activity, phosphate, nitrate, and silicate in the nepheloid layer along with a decrease in oxygen.

One of the most important processes related to the dense water formation on the shelves concerns the interaction with the general circulation and the main stratification of different water masses interacting with dense shelf waters. In the NWMed, unless and until the density of the shelf waters reaches the density of the LIW, the shelf waters will accumulate along the continental shelf break and upper continental slope and will not penetrate deeper because of the stratification, generating the so called Western Intermediate Water (WIW). But, in harsh winter conditions, waters over the shelf can be exposed to stronger cooling than the surface waters sitting offshore. Under these conditions they will sink, contributing to the WIW. Accordingly, denser shelf waters will start cascading deeper through canyons. In the process they will resuspend sediments over the slope that have not been exposed to strong current velocities during years. In addition, they will entrain both the resuspended sediments and the LIW and flush the mixture down the canyons.

Depending on the characteristics of hydraulic plumes associated with the cascading dense shelf waters (width, thickness, density difference and speed) and depending on the excess density from suspended particles, the entrainment and mixing with ambient waters will determine the stabilization depth of the plumes. Supercritical flow during the cascading will increase mixing and reduce drastically the final depth reached by the plumes.

Therefore, dense shelf waters can spread along and across the margin reaching greater depths, and eventually merge with dense waters formed off-shelf by the open-sea convection process. In the case of the northwestern Mediterranean, the mixing of these two dense waters generates a thermohaline and turbidity anomaly that spreads throughout the entire basin (López-Jurado *et al.*, 2005; Schroeder *et al.*, 2006; see also Schroeder *et al.*, this volume). The signature of the two newly formed dense waters (i.e. cascading and convection) can be easily recognized in TS diagrams (see Salat *et al.*, this volume) and can persist in the deepest water layers for more than a year, depending on the volume of newly formed dense waters. The exceptional conditions that affected the northwestern Mediterranean after winter 2004-05 have resulted in a much longer presence of these anomalous dense waters, which can still be identified throughout the basin, covering several hundreds of meters in the near-bottom water column (see Schroeder *et al.*, this volume).

Horizontal spreading of these anomalous dense waters is a rapid process, irrespective of its source: through convection in the open basin or cascading from the shelf. Large variations in water mass properties and stability are observed near, but not directly caused by, dense-water formation area. These variations are dominated by local slantwise or tilted convection induced by small-scale eddies and propagation of near-inertial internal waves in stratified and homogeneous layers. This mixing is across layers, some 200-400 m thick (van Haren and Millot, this volume).

Near-bottom observations show episodic periods of a few days duration of large, typically 1,000 m/day, downward motions that are associated with eddies (van Haren *et al.,* 2006) or meanders in boundary currents. If extrapolated to the surface, they may transport material rapidly from surface to the bottom of deep basins. Due to the longevity of the SCVs, which appear to be one of the main carriers transporting newly formed deep water far away from the source region, the relevant issue concerns large scale eddy flux between SCV and general circulation that can also include large scale eddies (mesoscale), meanders and gyres advecting SCV over long distances as observed during the EU project Mater in the Western Mediterranean Sea.

4.3. Open questions and information gaps

Relative importance of cascading versus open ocean convection?

Quite visible on θ/S diagrams, deep and bottom waters exhibit an anomalous θ/S distribution (the so called "hook") that might be resulting from an interaction between deep ocean convection forming warmer and saltier deep water (possibly related to a saltier and warmer LIW) and denser but colder and fresher deep water formed on the shelves cascading through canyons and reaching the abyssal plain.

It is important to carefully investigate, via dedicated campaigns and long term observations, the formation of dense shelf waters at the head of submarine canyons, at intermediate depths and at the bottom of the canyons with appropriate instruments such as bottom moored Acoustic Doppler Current Profiler (ADCP) and CTD in order to document the characteristics of the plumes (size, speed and stratification).

Interactions between cascading along the canyons (shelf break) and open ocean convection (meandering of the boundary current). A trigger?

It is important to study the interaction between shelf and open ocean. The shelf break in particular is a critical area since it constrains both the dense waters formed on the shelf and the general circulation influenced by the main topography (continental slope) driving the boundary current. High resolution numerical modeling taking into account shelf dynamics and interaction with boundary current circulation will be relevant for this study.

How persistent would deep anomalies be? How deep waters might be eroded in the long term?

A key question is how rapid mixing of newly formed waters occurs, or, how long the particular characteristics of newly formed waters can be traced. Shear induced internal wave mixing is a turbulent, but slow process. Yet, it is considered to completely govern the large-scale meridional overturning circulation. Convective eddy mixing can be more vigorous, but it is unknown how well it keeps up with the rapid formation and spreading of newly formed waters.

How the knowledge gained from process studies in the WMed can be exported to the EMed and provide clues for the Eastern Mediterranean Sea and the EMT in particular?

We should point out that the same (or similar) processes, and derived effects, observed in the NW Mediterranean could be applicable to the southern Adriatic Sea and to the Aegean Sea and provide clues to understand the common processes of dense water formation. In that sense, the "origin" of the EMT could be better constrained with the help of numerical modeling if data are missing.

5. General recommendations and future work

Deep dense-water formation events are vigorous but relatively rare processes acting on a short time scale and occurring at local space scales, which have been often missed or undersampled. Yet the impact of such events has implications not only on the circulation at basin scale, but also on the global ocean circulation. Further, associated processes such as sediment transport, ventilation of deep layers or changes in heat content and distribution have impacts on a wide range of variables from marine resources to climate.

Recent events affecting the dynamics of Mediterranean Deep Waters have shown that all the processes involved in the formation and subsequent distribution of dense water masses are subject to a deep revision. Preconditioning factors such as ocean/atmosphere exchanges, ocean circulation patterns and water mass exchanges through sills, triggering of DWF, internal mixing processes, sinking and spreading require additional efforts to be better understood.

To address these issues and improve future results, the group proposes to maintain and complete the efforts devoted to observations, both long term and directed surveys, incorporate new methodologies in observations, such as gliders and Argo drifters, tagging water masses with new tracers. There is also a need to improve circulation and process-oriented modelling, as well as to perform physical and numerical experiments to identify relevant physical and chemical interactions with biology to interpret the implications and extent of present and future environmental changes. Of particular concern is improving forecasts under future climate evolution. The group therefore recommends the following actions:

5.1. Observations

Maintaining and improving the current observations:

- Basin-scale cruises along repeated relevant sections on the long-term including physical, chemical, biological, and radio isotopic tracers.
- Satellite data should be revisited in order to track mesoscale eddies and study the areas of deep water formation. Recent data from MODIS Aqua on SST and chlorophyll will be helpful. The results of satellite primary production estimates also proved to be important from the point of view of characterizing the circulation.

Long term observatories:

- The experience of long-term time-series monitoring programs such as CIESM Hydrochanges, ANTARES, DYFAMED, etc. has proven to be very useful in determining DWF events, evaluating their importance or and interpreting the evolution of the waters formed. These types of time-series monitoring programs should be maintained, equipped with more sensors such as oxygen and extended to all the regions of interest, namely South Adriatic, Gulf of Lions, etc.
- Long term observations of ocean/atmosphere fluxes of heat and water are required not only from land based time-series monitoring programs, with the collaboration of the weather services, and satellite measurements, but also attached on several of the above mentioned sea time-series monitoring programs.
- Permanent monitoring of parameters triggering DWF events could be used to detect the onset of cascading or convection events. Real time data transmission from fixed points, cabled observatories with sediment traps, moored ADCP, transmissometres, etc., combined with gliders, Argo profilers and isopycnal floats will be complementary to long term time-series stations and especially relevant as an "early warning system". The application of methods of pattern analysis for identifying changes in the dynamics of the measured variables could be used for "forecasting" new events and for determining when it will be necessary to conduct rapid-response oceanographic surveys.
- Continuous monitoring of Input/Output fluxes and water masses through sills (Gibraltar, Otranto, Corsica, Sardinian, Sicily and Cretan Arc straits) are essentially required for understanding the internal Mediterranean dynamics and long term variability in the surface and deep conveyor belts, to complete water balances and evaluate possible rapidly propagating barotropic responses of DWF. This is particularly crucial in the Strait of Gibraltar, where due to the traffic and strong currents, measuring water coming into the Mediterranean becomes especially difficult. It may be reasonable, taking advantage of the frequent ferries connecting both sides of the strait, to equip one or two of these vessels with an ADCP for this purpose.
- All sensors on long term observatories should be carefully calibrated.

Direct surveys:

- Future changes in both the EMed and WMed are to be expected. A general monitoring program by basin-wide hydrographical surveys, repeated at 5 to 10 year intervals, is therefore required. However, to resolve the temporal changes, such a program must provide high-quality data. Oxygen, ETS activity, and transient tracer (CFCs, etc.) observations should be included if possible. The surveys should be supplemented by deploying Argo floats and placing current meter moorings in critical locations. Higher frequency surveys (at yearly intervals) at the subbasin scale in key areas (Ionian, Adriatic, Aegean, Ligurian subbasins, etc.) would make the monitoring program even stronger.

- Special monitoring is needed in key areas such as the Rhodes Gyre, straits, and DWF sites. These could be implemented using glider transects and CTD moorings.
- A prepared set of equipment that can be launched at short notice from the "early warning system" to perform a dedicated sampling experiment to study direct DWF events will be very useful to avoid undersampling. This procedure will characterize the hydrographical structure and the preferential paths of dense shelf water cascades or convection cells at the time they are occurring.

New methods and approaches:

- In view of small horizontal gradients of density in connection with pronounced differences in salinity, the common use of potential temperature is often misleading. An effort should be made to introduce the concept of 'neutral density' in treating the Mediterranean deep waters.
- The capability of biochemical signatures and other new tracers to tag certain water masses must be explored. Combinations of classical and new biochemical tracers would be the most efficient way to proceed. Discussion is needed to resolve the most appropriate tracers.
- Molecular biology has techniques to "fingerprint" proteins, nucleic acids, and genes in biological samples. Organic chemistry can fingerprint lipids and biochemistry can do the same for enzyme activity. It is likely that water masses, because of their unique origins and biological histories, could be characterized by these different fingerprints. This research has not been done because the people with the skills in these techniques are not aware of the oceanographic problems to which their skills could be applied.
- A modern monitoring program would require an extensive use of Lagrangian and Eulerian methods for complementary observations. Ispopycnal floats able to follow an isopycnal layer would be quite adequate for measuring internal mixing induced by long lived sub mesoscale vortices. ADCP and Microcats moored at the shelf break and along canyons for transmitting data in real time would be highly appreciable for observing cascading of dense waters from shelf to the abyssal plain.
- Coordination with both the sediment-trap and mesopelagic-metabolism communities will be important to relate the physical processes of open sea convection, shelf cascading and gyre pumping to the fuelling process of mid and deep water organisms.

Data inventories

- An agreement with weather services with their commitment to measure and/or assess, from radar data, direct precipitation and evaporation over the sea, should be encouraged. It will be also advisable to incorporate accurate runoff data in water budgets and to integrate these data in process and circulation models.
- The hydrographical data taken in 2006-2009 by current programs in both EMed and WMed, e.g. the SESAME and VECTOR programs, must be evaluated in a coherent fashion to study the changes in the EMT-induced hydrographic fields that have occurred since 2001 and WMT since 2005. Any available data from other sources must also be included, e.g., European data base (issued from European projects). CIESM can play a major role in documenting and accessing such data.
- An attempt to recover and make available sparse data involving deep waters in the Mediterranean, e.g. data from cruises other than those oriented to DW analysis. There is a strong need for collecting, formatting, validating and archiving data in general for the Mediterranean Sea.

5.2. Modelling

Processes

- New algorithms and parameterisations on air/sea fluxes especially on latent heat should be required. The evaluation and extent of DWF events are largely dependent on these parameters.
- Attempts should be made to assess the deep ocean rates of oxygen consumption, CO_2 production and remineralization of nutrients. These rates will be strongly impacted by deep water renewal.
- Modelling shelf water-deep ocean interactions (Gulf of Lions/ Medoc area). Symphonie + offshore modelling. Integrate modelling and observations.

Circulation

- Are the available models adequate? What aspects should be improved?
- Modelling should play a greater role in explaining and describing the changes that have taken place, either directly or using data assimilation. Interannual climatologies are also needed to initialize the models. In addition, the MEDAR-MEDATLAS and SeaDataNet databases have to be continued.
- There is a need to better describe and model the 3D TS distribution of this anomaly and its evolution. This can be done in close cooperation with the CIESM Hydrochanges initiative.

Biological interactions

- Metabolic activity of the sea water and particles exported from surface and shelf waters to the deep layers should be monitored. Fluxes of organic compounds, oxygen, inorganic nutrient salts, and contaminants.
- Investigate the relationship between the occurrence of deep water formation events, cascading or open violent sinking, and the biological communities inhabiting deep sea environments affected by this phenomenon.

I - Executive Summary of CIESM Workshop 38

"Dynamics of Mediterranean deep waters"

by

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This synthesis was written by all participants of the workshop under the coordination of Jordi Font. Frédéric Briand, the Monograph Series Editor, reviewed and edited this chapter along with the entire volume, assisted by Valérie Gollino for the physical production process.

1. Introduction

All water masses in the deep ocean acquired their characteristics when they were in contact with the ocean surface. The ocean thermohaline circulation is responsible for the further spreading of the newly formed water masses to all ocean regions. The deep component of this conveyor belt, with its slow, but very relevant dynamics, is still poorly known, from both the physical and biological points of view.

The Mediterranean is a semi-enclosed sea whose geographical, morphological and hydrological characteristics allow several oceanographic processes, found at large scale in the open ocean, to occur, but on a reduced scale. One of these is the wintertime formation of dense water by atmospheric cooling and desiccation, as well as by sinking of cold dense waters cascading off the continental shelf. These processes can occur until most of the deep Mediterranean basin has been renewed.

From the late 1960s, starting with the international MEDOC project in the North-western Mediterranean, the dense water formation (DWF) processes and their impact on the overall circulation have been studied in both Eastern and Western basins. This effort led to the formation of various hypotheses and models for the complex mechanisms taking place. Furthermore, it pushed the oceanographic community to monitor and characterise the different water masses involved.

Analysis of measurements made in the deep layers of the Eastern basin revealed that a major change had been occurring in the late '80s / early '90s: a shift of the main deep water formation area from the Adriatic to the Aegean subbasins. This event, known as the Eastern Mediterranean Transient (EMT), was the subject of a CIESM science workshop held in Trieste in March-April 2000 (CIESM, 2000). It is a good example of the kind of relevant ocean circulation modification that has been induced by climate change scenarios. Two years later CIESM launched the Hydrochanges program to coordinate the monitoring of the deep water thermohaline characteristics of the entire Mediterranean basin (CIESM, 2002).

As highlighted in their respective introductions by Dr Frédéric Briand, Director General of CIESM, and Dr Jordi Font, Chair of CIESM Committee on Physics and Climate of the Ocean, the time had come for a joint analysis of recent observations in the deep Mediterranean some twenty years after the EMT. Further in 2009, 40 years after the first MEDOC cruise, with evidence that the EMT is decaying, and data that a major change occurred in the western basin deep water structure after the 2004/05 winter, a revisit of the DWF processes is in order. Towards this end thirteen specialists were invited by the Commission to St. Paul's Bay, Malta, 27-30 May 2009 to review advances and gaps in current knowledge on the dynamics of Mediterranean deep waters and propose priorities for future research. In welcoming the participants the Director General expressed his gratitude to Dr Aldo Drago, National Representative of Malta on CIESM Board for the superb logistic support provides.

After presenting the different communications developed in this Monograph, the group discussed the analysis of recent results, and through them reviewed the mechanisms of DWF in the Mediterranean. This discussion highlighted open questions concerning the interpretation of the observations, theoretical approaches, lack of information and of adequate modelling tools, finally producing a series of recommendations.

Three main topics were proposed to structure the discussion: update understanding of the Eastern Mediterranean Transient; the new situation of the deep Western Mediterranean; and processes of deep water formation. A working group was set up for each one of these topics to lead the discussions, present preliminary conclusions and finally draft the texts assembled here below. A section on general recommendations is included at the end of this executive summary.

2. Update on the Eastern Mediterranean Transient

2.1 Background

A particularly interesting phenomenon occurred in the Eastern Mediterranean (EMed) in the 1990s.The Aegean Sea replaced the previously dominating Adriatic Sea as the source of the EMed deep waters. This event is termed the Eastern Mediterranean Transient (EMT). The EMT was caused by the Aegean Sea forming and discharging massive amounts of unusually dense and saline waters (Roether *et al.*, 1996; Theocharis *et al.*, 1999a), which initiated a complete disturbance of the hydrography and circulation of the EMed (cf. Roether, this volume). The EMT primarily affected the deep waters but had influence also further up in the water column, as a result of shallower Aegean outflow and mixing, and in particular of mid-depth water lifting several hundred meters due to Aegean water addition deeper down. An effect was felt even at the nutricline, which was lifted by about 150 m in the eastern Ionian (Klein *et al.*, 1999). The distributions of all other biogeochemical parameters, such as nutrients, were changed. A special effect was an EMT-induced rise in oxygen consumption (Roether and Well, 2001; Klein *et al.*, 2003). The EMT is highly relevant oceanographically, but perhaps even more so on climatological grounds, as it is one of the first observed cases of a basin entirely changing its deep water circulation. One can expect that such episodes will play an increasing role in consequence of Global Climate Change.

The EMT started in about 1990 and peaked in 1992-94, with an average Aegean outflow rate of nearly 3 10^6 m^3/s (3 Sv). The outflow subsided strongly thereafter and reached only depths of 1,500 – 2,000 m (Theocharis *et al.*, 2002). A relevant ingredient in forming the EMT was accumulation of exceptionally saline waters in the eastern Levantine, possibly assisted by eddies south of Crete, observed in 1991, that suppressed inflow of lower-salinity waters from the Ionian (Malanotte-Rizzoli *et al.*, 1999). Various additional circulation changes of potential relevance have been noted, such as alternating cyclonic and anti-cyclonic upper water movement in the Ionian (Borzelli *et al.*, 2009; cf. also Gačić *et al.*, this volume) and intermediate water formation in the southern Aegean Sea, or Cretan Sea (Cretan Intermediate Water, CIW), more or less replacing formation in the Rhodes Gyre (Levantine Intermediate Water, LIW) that was dominating previously.

The evolution of the EMT has been documented up to 2001 (Roether *et al.*, 2007). In the Levantine Sea a rather clear picture of the deep circulation has been found, in consequence of strong topographic steering. But in the Ionian Sea west of the East Mediterranean Ridge, there is far less of such steering, and in consequence the circulation is more uncertain. Rather strong basin-scale mixing is however apparent, presumably with a strong role of eddy mixing.

Because of very low density gradients on level surfaces (horizontally) in the presence of substantial salinity differences, the common use of potential density is often misleading (cf. Roether, this volume). In extreme cases, lateral property gradients may show a direction opposite to that which is obtained if densities referenced to a close-by isobar are used.

2.2 New results

- From measurements taken during 1994-2002, the Aegean deep water (Cretan Deep Water, CDW) production rate was estimated to have fallen to 0.15 Sv. After 2002 no Aegean deep water was observed to leave through Kassos Strait due to the fact that such water was restricted in the Cretan Basin to the layers below sill depth, reaching recently (2005-2006) 1,200 m (Theocharis, this volume).
- Most of the water column in that strait has become occupied by Transitional Mediterranean Water (TMW), which is now located below the CIW layer (Theocharis *et al.*, 1999b; Sofianos *et al.*, 2007). This TMW, an old water body transitional in characteristics, which was lying between the LIW and the old Eastern Mediterranean Deep Water (EMDW, of Adriatic origin) all over the Eastern basin in the pre-EMT period, has entered the Aegean during the EMT and is considered there to be a water mass, although it is not included in the CIESM list of Mediterranean water masses. Note that the CIW has been observed also in the Strait of Sicily and beyond, demonstrating westward export (Gasparini *et al.*, 2005).
- The Adriatic resumed producing dense waters reaching again the bottom layer of the Ionian Sea. A strong effect is evident in 2007, when observations showed salinities distinctly higher than classically found (Rubino and Hainbucher, 2007). Already in 2002 deep convection in the southern Adriatic had been reinstated (Roether *et al.*, 2007; Gačić *et al.*, this volume).
- A major cause of the higher salinity is the inflow of saltier waters from the Ionian Sea as a consequence of cyclonic circulation of the upper waters. Such circulation provides a rather direct path for advection of higher-salinity waters from the Aegean or Levantine. An anticyclonic pattern, in contrast, supports advection of waters with a substantial fraction of lower-salinity waters from Strait of Sicily (Gačić *et al.*, this volume).
- The Ionian circulation reversals are due to baroclinic vorticity input rather than wind curl forcing. The later appears to have only a secondary influence (Gačić *et al.*, this volume).
- With the Adriatic producing bottom water and the Aegean outflow feeding mainly intermediate-depth layers, at most into the TMW, the two seas have reassumed their roles from the pre-EMT period. Since 2005, furthermore, the near-bottom properties of the Ionian and Levantine basins have moved toward a more Adriatic signature. But the deep waters are still far from any equilibrium distribution: the entire deep-water volume must be flushed out by newly produced bottom water. Additionally, the fact that deep waters are out of equilibrium with their sources will induce a time-dependent pre-conditioning of the DWF processes. Considering that during the quasi-steady-state pre-EMT situation the deep water turnover exceeded 100 years, one must indeed expect many more decades of transient EMed deep waters.
- Contribution of mesoscale anticyclonic eddies to the intermediate-water transport has been suggested (Sutyrin *et al.*, 2009; Taupier-Letage *et al.*, 2007), as reported for the Western Mediterranean (WMed) by Testor *et al.* (2005a).
- Modeling efforts have supported the idea that the unexpectedly large amplitude of EMT resulted from a combination of a decadal accumulation of high-salinity waters, severe regional winter conditions, a decrease of the Black Sea discharge into the Aegean Sea, and heavy inflow of LIW into the Cretan Sea (Nittis *et al.*, 2003; Skliris *et al.*, 2007).
- Beyond continued work in the Aegean and the Adriatic Seas including their surrounding waters, the large-scale hydrography of the EMed was surveyed in 2008 by the SESAME

(<http://www.sesame-ip.eu>) and in 2006-2008 by the VECTOR (<http://vector-conisma.geo.unimib.it>) programs. The achieved coverage should allow investigating the evolution of the EMT after 2001. Supplemental information is available from long-term current meter observations related to the planning of a “neutrino telescope” in the western Ionian Sea (Manca *et al.*, 2002a; Bouche *et al.*, this volume), and near the island of Pilos in the eastern Ionian Sea.

2.3 Open questions

- The EMT was primarily brought about by a pronounced increase of salinity in the Aegean deep waters, but the origin of this extra salinity is only known in a qualitative way (accumulation of high-salinity upper waters in the eastern Levantine). Additional influences on the salinity, such as reduced precipitation, reduced influx of fresher waters from the Black Sea, and inputs from shelf areas (cascading) possibly also have contributed to the increase.

- The influence of the EMT on the deep waters in the WMed is quantitatively unknown. For quantification, an important intermediate step would be to study the hydrographic relationship between the evolving EMed waters and the western outflow in Sicily Strait.

- Whereas the highly structured topography in the Levantine Sea appears to have governed the deep circulation of that basin, such steering is far less pronounced in the Ionian Sea, making that sea’s deep circulation more uncertain (see also Millot and Taupier-Letage, 2005a).

- Mesoscale cyclonic and anticyclonic eddies are frequent phenomena in the EMed (Hamad *et al.*, 2005) contributing to the water transport. Their role, which may be particularly important for the Ionian Sea, must be studied.

- Deep water formation, in the Rhodes Gyre even though of limited density, has repeatedly been reported in the past. Under the modified hydrographic conditions, that role may have changed. More information is therefore needed concerning actual deep water formation in the Rhodes Gyre during 1996-2009, and future similar events should be monitored.

- Information is missing on the potential inputs from coastal areas feeding the deep waters, such as the western Adriatic shelf (Artegiani *et al.*, 1989; Bignami *et al.*, 1990), the Turkish coast, the Cyclades plateau (Durrieu de Madron *et al.*, 2005), and the Libyan coast (Gasparini *et al.*, 2008). Such contributions have met limited interest in the past, but it is also conceivable that cascading might have become more intense. Newly found special molecular-biological markers might be useful in detecting such contributions.

3. The new situation of the deep western Mediterranean

3.1 Background

During the last decades, the WMed heat and salt contents increased almost steadily. Past studies have demonstrated the tendency of the western deep waters towards higher temperatures and salinities since the ’50s, with the process accelerating after the second half of the ’80s (Rixen *et al.*, 2005). Those trends have been attributed to a number of possible causes, among others the changing environmental conditions, e.g. the greenhouse effect, local atmospheric conditions, and river damming.

Since 2005 the deep waters of the WMed have experienced significant physical changes, which are comparable to the ones that occurred in the EMed during the’90s (EMT), both in terms of intensity and observed effects. The major changes involve an abrupt increase in the deep heat and salt contents, and a change in the deep stratification, with the appearance of a “hook” in the deep temperature-salinity (θ/S) diagrams (see Figure 3 in contribution by Fuda *et al.*, this volume; and Figure 1 in contribution by Salat *et al.*, this volume). These changes started in winter 2004/05 with the production of an anomalously high volume of new deep water, which uplifted the old one by several hundreds of meters over almost the whole western basin.

The peculiar shape of the θ/S diagrams, with the presence of a "hook" at the end of the profiles, had already been partially observed in historical data. Similar anomalous structures were found in the past after severe winters (e.g. in 1972-73, 1981, 1988 and 1999), during which also deep cascading presumably occurred (cf. Salat *et al.*, this volume). This structure would correspond to the "occasional bottom water" reported by Lacombe *et al.* (1985). After 2005 this anomaly has been significantly enhanced by the huge amount of new deep water formed in winter 2004/05 and winter 2005/06. This allowed a basin-wide propagation of the "hook" and the abrupt increase in deep heat/salt contents (Salat *et al.*, this volume).

Different observational systems were essential in the detection and the overall description of those changes, at different temporal and spatial scales. Several basin-scale dedicated oceanographic cruises have witnessed the presence over a wide area of the anomalously different temperatures and salinities in the deep WMed. The contribution of these measurements facilitated the basin-wide assessment of the formation, extension, and spreading rates of these anomalies (Schroeder *et al.*, 2008b). Further, the mooring sites in the Gulf of Lions' submarine canyons, including the one deployed offshore the Catalan coast in the framework of the CIESM Hydrochanges program, allowed the descending plume of new dense water formed over the continental shelf to be observed (Lopez-Jurado *et al.*, 2005; Canals *et al.*, 2006; Font *et al.*, 2007; Puig *et al.*, 2008). In addition, long-term monitoring (by means of moorings) of the hydrographic properties of water masses crossing the key sites in the WMed (the Sicily Channel and the Corsica Channel) during the last 20 years has permitted the observation of water mass evolution under the influence of the EMT. The increasing trend, detected since the 1960s both in temperature and salinity, has been sensibly accelerated by this event (Gasparini *et al.*, 2005). Meanwhile, the new stratification was able to significantly influence the deep water formation in the NW Mediterranean. MedARGO floats allowed the intensity of convection in different locations in winters 2004/05 and 2005/06 (Smith *et al.*, 2008) to be observed. An important data source in directly detecting the anomalous deep water formation and long-term heat and salt accumulation is the DYFAMED site in the Ligurian Sea (which is part of the EuroSites network). The monthly CTD casts, which are available for the past 13 years, clearly evidence the heat and salt increases at intermediate levels, and directly documented the deep convection taking place in that region in early 2006 (Schroeder *et al.*, 2008b).

3.2 Main findings presented to the workshop

During the past five years, the NW Mediterranean seems to have become a very active DWF site. Very intense events have been reported in winter 2004/05 as well as in winter 2005/06, involving both open sea convection and shelf water cascading. There are new indications of DWF also in winter 2008/09 (Fuda *et al.*, this volume), and its extent requires assessment by future basin-scale investigations in that region.

Recent data collected by numerous groups have shown the appearance and spreading in the whole western basin of new deep water that is significantly warmer and saltier than previously, and that has substantially substituted the resident deep water. The new anomalous deep water has substantially modified the vertical stratification of the water column in almost the whole basin. Data collected between 2004 and 2006 showed that in this period the deep layer of the WMed experienced a temperature increase of about 0.038 °C and a salinity increase of 0.016. These increases are five to seven times greater than the increasing trends indicated by Béthoux and Gentili (1999) and about four times greater than the estimates given by Rixen *et al.* (2005) for the 1985-2000 period. The thermohaline anomaly has spread throughout the WMed, filling its deeper part below 1,500-2,000 m depth, significantly accelerating the ventilation of the deep layers. The peculiar "hook"-shaped θ/S diagrams found after the recent deep water formation events are a result of the interaction between old deep water (type O), new deep water formed by open sea convection (type N) and dense shelf cascading water (type C) (cf. Salat *et al.*, this volume). Preliminary analysis of the data available for the Channel of Sardinia sill between 2004 and 2009 suggests a possible passage of the new deep water towards the Tyrrhenian Sea (Fuda *et al.*, this volume; Schroeder *et al.*, this volume). Verification will be determined by future investigations. Evidence of the presence of the new deep water also has been found close to Gibraltar, in the shallower Alboran subbasin. Here the unequivocal identification of the winter 2004/05 formed deep water near Gibraltar was possible thanks to the particular shape in the θ/S diagram.

Furthermore, its recent detection (November 2008) at about 100-150 km from the Strait of Gibraltar, allows an accurate estimate of the temporal scales of its spreading to be made. Recently, a deep water mass formed in February-March 2005 in the NW Mediterranean had almost reached Gibraltar by January 2008 (Schroeder *et al.*, this volume; Bryden, this volume).

Winter 2004/05 set the beginning of a changed situation in the deep layers of almost the whole WMed. To distinguish between the present and the previous situation, the described changes are proposed to be referred to as *Western Mediterranean Transition* (WMT), in order to avoid confusion with the better known EMT. The two events for some aspects are similar (abrupt warming and salting of the deep layers in the whole basin, uplifting by several hundreds of meters of the resident old deep water), but there are a number of crucial differences (there is no identified additional deep water source in the WMed and no circulation changes have been reported for the WMed so far). With respect to the previous situation, starting from 2005 the deep basin has been filled by warmer, saltier and denser water, which at the same time is also more turbid and oxygenated. A thick bottom nepheloid layer (BNL) has formed in the whole WMed (with the only exception of the Tyrrhenian Sea) as a consequence of the intense shelf water cascading and the extraordinary high volume of new Western Mediterranean Deep Water (WMDW) produced between 2005 and 2006 (Puig *et al.*, this volume).

Garcia-Lafuente *et al.* in 2007 found a signature of these events in the Mediterranean Outflowing Water (MOW). They observed a decrease in temperature by the end of March 2005 and March 2006 and attributed it to a remote signature of the deep convection, which replenished the WMDW reservoir and raised its interface with the water above, making cooler water available for the outflow. According to the authors, even if this happened almost every year, in 2005 and in 2006 unusually sharp decreases were recorded. A climatological analysis of the Mediterranean Outflow (Medar/Medatlas II & World Ocean Database 2005) showed for the 1906-1999 period a positive trend in salinity and temperature values of the Mediterranean Waters (MW), with an acceleration in the last three decades (0.12 and 0.38 °C per decade, for salinity and temperature respectively). These trends are more linked with the North Atlantic trends than with Mediterranean ones, suggesting a relationship with the Mediterranean Outflow-Strait of Gibraltar system (Fusco *et al.*, 2008; Sannino *et al.*, 2005) by non-linear components of the heat, salt and momentum exchanges between the Atlantic Water (AW) and MW strait (Budillon *et al.*, this volume). Nevertheless, the extent to which the WMT will be able to affect the water mass properties, stratification and circulation in the North-Atlantic is still an open issue.

The new deep water was formed during massive convection events that took place during winters 2004/05 and 2005/06 in the NW Mediterranean. The deep convection is sustained by the combination of surface heat and freshwater losses and the lateral convergence of heat and freshwater. The deep water properties and their variability are due to the hydrographic preconditioning (heat and salt content and structure of the water column before the onset of convection), and to atmospheric forcing (heat, freshwater and buoyancy fluxes). Schroeder *et al.* (2006) related the new deep properties to a progressive increase of heat and salt content in the intermediate layer, due to the arrival of water of eastern origin which has been affected by the EMT event. Other authors (Font *et al.*, 2007; Lopez-Jurado *et al.*, 2005), attributed it to the extremely strong winter forcing in 2004/05. In terms of air-sea heat exchange, Lopez-Jurado *et al.* (2005) showed that the heat loss for this winter was 70 % above the winter average, with the highest values since 1948, using the NCEP/NCAR reanalysis. Additionally, in terms of air-sea freshwater exchanges, Font *et al.* (2007) asserted that in autumn and winter 2004-05 precipitation over the NW Mediterranean catchment area was greatly reduced, with the lowest absolute values ever recorded at many of the meteorological stations and that northerlies were strong and persistent. Furthermore, as suggested by Millot (2007), studies about DWF and circulation, which take into account the interannual variability of the forcing functions, must take into account the interannual variability of the inflow, in particular, the observed increasing salt content of the inflowing AW.

The results presented at the workshop and the subsequent discussion suggest that the DWF processes (both open-sea and on-shelf) are highly sensitive to any change in the forcing functions. In terms of preconditioning, the salinification of surface and intermediate waters (due either to local processes or the climate change) is likely to be the most important factor and would explain why the contribution by deep cascading from shelf regions seems to become more and more important.

3.3 Open questions and information gaps

Despite several advances in the recent years, there are still huge gaps in current knowledge. To fill these gaps would require a large monitoring program, focused not only on physical parameters, but also on biological, chemical, and sedimentological ones. Priorities for future research on the dynamics of Mediterranean deep waters should include attempts to answer the following questions:

Description of the WMT*:* What is the extent of the events occurring in the WMed, in terms of salt and heat contents increases in the deep layers and in terms of uplifting of the resident deep water? What are the involved mixing processes? What are the ventilation times and the ages of the involved water masses? What was the actual extent of the DWF region during the two winters (i.e. 2004/05 and 2005/06)? How fast is the anomaly propagating in the interior of the basin and to what extent are the straits controlling this propagation? Is it possible to assess this with appropriate models since there were no dedicated experiments during the DWF events? Does the “new” WMDW, as an “occasional BW (Bottom Water),” require an altered pattern of circulation to be formed (Salat *et al.*, this volume)?

Causes and effects: What has induced the WMT and what is the relative importance of the different forcing functions: salinification of the inflowing Atlantic Water (Millot, 2007); salinification of the LIW coming from the EMed; the EMT (Schroeder *et al.*, 2006; 2008b); and intense atmospheric forcing (Salat *et al.*, 2006; Font *et al.*, 2007)? What is the cause of the observed increasing temperature and salinity of the intermediate water (LIW/CIW) crossing the Strait of Sicily? To which degree will the anomaly contribute to the general warming and salinification of the Mediterranean basin? Are the signals observed at Gibraltar (Garcia-Lafuente *et al.*, 2007) due to the production of large volumes of new deep water in the NWMed? To which degree does a change in the MOW affect the oceanic circulation in the North-Atlantic and/or the deep water formation in the arctic regions? What are the expected biological changes associated with the WMT? Can the WMT induce a change in the role of the Mediterranean Sea as a source or a sink for anthropogenic carbon? Could the WMT modify the role of the marginal or semi-enclosed seas (e.g. the Tyrrhenian Sea) in the composition of the MOW?

4. PROCESSES OF DEEP WATER FORMATION

4.1. Background

The NW Mediterranean is a well known region where winter deep convection and DWF can occur in a yearly basis due to winter heat losses and evaporation, caused by cold and dry northerly winds. Dedicated experiments in this region started 40 years ago, with the so called MEDOC campaigns, and further studies have been carried out in since then to advance the knowledge of such oceanographic phenomena. Remarkable sets of reference publications include the MEDOC group Nature paper (1970), the book edited by P. Chu and J.C. Gascard in 1991 (Elsevier oceanography series, 57), the review published by J. Marshal and F. Schott (1999) and many more.

The classical three phases proposed by the MEDOC group are still valid, starting with the preconditioning phase, followed by the violent mixing phase and ending with the spreading phase. The major and most important novelty is that these three phases are strongly coupled and interdependent. The new real discovery concerns long lived submesoscale vortices observed in the Greenland Sea, the Labrador Sea, the Weddell Sea and the Mediterranean Sea as well. Due to their longevity, the so called Submesocale Coherent Vortices (SCV) first introduced by J. McWilliams (1985) are active during the three phases of the deep open convection as observed in the Greenland Sea and the Mediterranean Sea in particular. The SCV are mainly characterized by a very low potential vorticity (close to 0). The internal core of the SCV, holding most of the newly formed deep water completely homogenised, has a relative vorticity close to –f. Accordingly, the absolute vorticity is close to 0 as is the vertical stratification. Both serve to decrease the potential vorticity to an extreme minimum. The ephemeral plumes described by J. Marshall and F. Schott (1999) are only contributing to accelerate the vertical mixing inside the eddy core (what the MEDOC group called the violent mixing). SCVs are contributing to the preconditioning phase for those waters remaining trapped inside the deep convective region. They also contribute to the spreading phase for those waters escaping the deep convective region and starting the long journey across the deep basins.

Convection involves wide ranges of space and time scales, with horizontal velocities up to 0.5 m s^{-1} near the bottom of the deep-sea basins. Waters cascading from the shelf can reach much higher downslope velocities, up to 1 m s^{-1}, and markedly mix with older ones over the slope. An heterogeneity of hydrological characteristics thus occurs in and close to a dense water formation area before waters mix progressively along their route and before being finally uplifted by and mixed with more recent and denser water. Spreading from the convection area is associated with small-scale (1-10 km) diameter sub-surface eddies. Near the outflow into the Atlantic Ocean and over sills in general, overmixing occurs. So far, internal wave mixing is thought to be less important.

In early studies of carbon oxidation in the deep western Mediterranean Sea Christensen *et al.* (1989) showed that the respiratory metabolism of the deep-sea microbial plankton community was unusually high compared with values from similar depths in the Atlantic and Equatorial Pacific Oceans. They hypothesized that such high metabolic rates might be supported by dissolved organic carbon transported to depth by wintertime dense water open-sea convection, since it could not be explained by the usual mechanism of vertically sinking particles. Recent observations of dense shelf-water cascading in the NW Mediterranean provide an additional mechanism for transporting organic matter into the deep WMed (Canals *et al.*, 2006; Puig *et al.*, this volume). This newly discovered source will inject both dissolved and particulate organic matter horizontally into the water column at the bottom of the continental slope. Furthermore this organic material will be relatively fresh and hence readily oxidizable to the deep sea biological community. The links between the cascading, the entrainment of organic matter, and the stimulation of the deep-metabolism need to be elucidated. They have not yet been demonstrated by critical time-series measurements nor by deep trans-basin sections. Nevertheless, the available evidence argues for such a connection. The stage is now set to demonstrate this connection by an interdisciplinary consortium of physical, geological, biochemical, and biological oceanographers.

4.2. Main findings presented during the workshop

As stated before, numerous hydrographic and hydrodynamic observations conducted recently in the Mediterranean Sea have resulted in a novel view of the functioning of dense water formation processes and the dynamics of deep waters in this land-locked sea. One of these novelties is the role played by dense shelf waters and the interactions of these waters with open-sea convection waters. In the past, cascading was thought to be a minor contributor of dense waters towards the ocean interior. However, models have reasonably reproduced mooring observations during cascading events. These model results for the northwestern Mediterranean have accounted for the transport of dense shelf waters at the level of 0.2 and 0.3 Sv for the winters 2003-04 and 2004-05, respectively (Ulses *et al.*, 2008a,b). Similarly, the water transport during the cascading event captured off Libya was estimated to have an order of magnitude of 0.1 Sv (Gasparini *et al.*, 2008). This amount is comparable to the ADW outflow rate from the southern Adriatic (Manca *et al.*, 2002a).

A new discovery concerns the fact that deep water convection is not the only process contributing to deep water formation and deep ocean ventilation. The dense waters formed on the shelves in winter can also contribute to renewing deep water in the Mediterranean Sea. This is not a new process. We know that in polar oceans, dense waters resulting from sea ice formation are formed on the shelves. The freezing process releases large volumes of brine at the same time the sea ice is formed. What is new, in the case of the Mediterranean Sea, is the role played by dense water formation on the shelves and its subsequent cascading over the slope. Because of its novelty, it has been intensively studied during the past three years.

The Mediterranean Sea has three well known areas of dense water formation, located in its northernmost continental shelves. Dense shelf-water cascading (DSWC) occurs almost every year in the Gulf of Lions, in the southern Adriatic Sea and on several Aegean shelves (Durrieu de

Madron *et al*., 2005). These areas are regionally linked and influenced by the same atmospheric forcing that operates in the open-sea convection sites described before. In addition, recent observations have revealed that DSWC can also occur on the Libyan continental margin (Gasparini *et al.*, 2008). The persistent, cold and dry northerly winds affecting these areas cause densification and mixing of coastal waters. Despite the buoyancy gain induced by freshwater inputs, desiccation and cooling decreases this buoyancy. Then, once these surface waters over the shelf are denser than surrounding waters, they sink, overflow the shelf edge, and cascade downslope until they reach their equilibrium depth. This resting depth changes from year to year. Cascades of DSW can last for several weeks and the associated strong currents can induce erosion and resuspension of surface sediments in the outer shelf/upper slope and generate bottom nepheloid layers (i.e. layers of water that contains significant amounts of suspended sediment). Such layers can be detached at intermediate levels when the density of the mixture of water and particles reach their equilibrium depth, or if the density is large enough, evolve into a thick bottom nepheloid layer that can reach the lower continental slope and basin (Puig *et al.*, this volume). Although rarely studied, this nepheloid layer is almost certain to be a zone of high biological activity. As far back as the Galathea expedition (1950-1952) oxygen was shown to be relatively depleted in deep-sea nepheloid layers. Transmissometers on CTDs often show turbidity increases in these layers, and where turbidity increases microbial activity increases. We would expect to see increases in POC, DOC, Electron Transport System (ETS) activity, phosphate, nitrate, and silicate in the nepheloid layer along with a decrease in oxygen.

One of the most important processes related to the dense water formation on the shelves concerns the interaction with the general circulation and the main stratification of different water masses interacting with dense shelf waters. In the NWMed, unless and until the density of the shelf waters reaches the density of the LIW, the shelf waters will accumulate along the continental shelf break and upper continental slope and will not penetrate deeper because of the stratification, generating the so called Western Intermediate Water (WIW). But, in harsh winter conditions, waters over the shelf can be exposed to stronger cooling than the surface waters sitting offshore. Under these conditions they will sink, contributing to the WIW. Accordingly, denser shelf waters will start cascading deeper through canyons. In the process they will resuspend sediments over the slope that have not been exposed to strong current velocities during years. In addition, they will entrain both the resuspended sediments and the LIW and flush the mixture down the canyons.

Depending on the characteristics of hydraulic plumes associated with the cascading dense shelf waters (width, thickness, density difference and speed) and depending on the excess density from suspended particles, the entrainment and mixing with ambient waters will determine the stabilization depth of the plumes. Supercritical flow during the cascading will increase mixing and reduce drastically the final depth reached by the plumes.

Therefore, dense shelf waters can spread along and across the margin reaching greater depths, and eventually merge with dense waters formed off-shelf by the open-sea convection process. In the case of the northwestern Mediterranean, the mixing of these two dense waters generates a thermohaline and turbidity anomaly that spreads throughout the entire basin (López-Jurado *et al.*, 2005; Schroeder *et al.*, 2006; see also Schroeder *et al.*, this volume). The signature of the two newly formed dense waters (i.e. cascading and convection) can be easily recognized in TS diagrams (see Salat *et al.*, this volume) and can persist in the deepest water layers for more than a year, depending on the volume of newly formed dense waters. The exceptional conditions that affected the northwestern Mediterranean after winter 2004-05 have resulted in a much longer presence of these anomalous dense waters, which can still be identified throughout the basin, covering several hundreds of meters in the near-bottom water column (see Schroeder *et al.*, this volume).

Horizontal spreading of these anomalous dense waters is a rapid process, irrespective of its source: through convection in the open basin or cascading from the shelf. Large variations in water mass properties and stability are observed near, but not directly caused by, dense-water formation area. These variations are dominated by local slantwise or tilted convection induced by small-scale eddies and propagation of near-inertial internal waves in stratified and homogeneous layers. This mixing is across layers, some 200-400 m thick (van Haren and Millot, this volume).

Near-bottom observations show episodic periods of a few days duration of large, typically 1,000 m/day, downward motions that are associated with eddies (van Haren *et al.*, 2006) or meanders in boundary currents. If extrapolated to the surface, they may transport material rapidly from surface to the bottom of deep basins. Due to the longevity of the SCVs, which appear to be one of the main carriers transporting newly formed deep water far away from the source region, the relevant issue concerns large scale eddy flux between SCV and general circulation that can also include large scale eddies (mesoscale), meanders and gyres advecting SCV over long distances as observed during the EU project Mater in the Western Mediterranean Sea.

4.3. Open questions and information gaps

Relative importance of cascading versus open ocean convection?

Quite visible on θ/S diagrams, deep and bottom waters exhibit an anomalous θ/S distribution (the so called "hook") that might be resulting from an interaction between deep ocean convection forming warmer and saltier deep water (possibly related to a saltier and warmer LIW) and denser but colder and fresher deep water formed on the shelves cascading through canyons and reaching the abyssal plain.

It is important to carefully investigate, via dedicated campaigns and long term observations, the formation of dense shelf waters at the head of submarine canyons, at intermediate depths and at the bottom of the canyons with appropriate instruments such as bottom moored Acoustic Doppler Current Profiler (ADCP) and CTD in order to document the characteristics of the plumes (size, speed and stratification).

Interactions between cascading along the canyons (shelf break) and open ocean convection (meandering of the boundary current). A trigger?

It is important to study the interaction between shelf and open ocean. The shelf break in particular is a critical area since it constrains both the dense waters formed on the shelf and the general circulation influenced by the main topography (continental slope) driving the boundary current. High resolution numerical modeling taking into account shelf dynamics and interaction with boundary current circulation will be relevant for this study.

How persistent would deep anomalies be? How deep waters might be eroded in the long term?

A key question is how rapid mixing of newly formed waters occurs, or, how long the particular characteristics of newly formed waters can be traced. Shear induced internal wave mixing is a turbulent, but slow process. Yet, it is considered to completely govern the large-scale meridional overturning circulation. Convective eddy mixing can be more vigorous, but it is unknown how well it keeps up with the rapid formation and spreading of newly formed waters.

How the knowledge gained from process studies in the WMed can be exported to the EMed and provide clues for the Eastern Mediterranean Sea and the EMT in particular?

We should point out that the same (or similar) processes, and derived effects, observed in the NW Mediterranean could be applicable to the southern Adriatic Sea and to the Aegean Sea and provide clues to understand the common processes of dense water formation. In that sense, the "origin" of the EMT could be better constrained with the help of numerical modeling if data are missing.

5. General recommendations and future work

Deep dense-water formation events are vigorous but relatively rare processes acting on a short time scale and occurring at local space scales, which have been often missed or undersampled. Yet the impact of such events has implications not only on the circulation at basin scale, but also on the global ocean circulation. Further, associated processes such as sediment transport, ventilation of deep layers or changes in heat content and distribution have impacts on a wide range of variables from marine resources to climate.

Recent events affecting the dynamics of Mediterranean Deep Waters have shown that all the processes involved in the formation and subsequent distribution of dense water masses are subject to a deep revision. Preconditioning factors such as ocean/atmosphere exchanges, ocean circulation patterns and water mass exchanges through sills, triggering of DWF, internal mixing processes, sinking and spreading require additional efforts to be better understood.

To address these issues and improve future results, the group proposes to maintain and complete the efforts devoted to observations, both long term and directed surveys, incorporate new methodologies in observations, such as gliders and Argo drifters, tagging water masses with new tracers. There is also a need to improve circulation and process-oriented modelling, as well as to perform physical and numerical experiments to identify relevant physical and chemical interactions with biology to interpret the implications and extent of present and future environmental changes. Of particular concern is improving forecasts under future climate evolution. The group therefore recommends the following actions:

5.1. Observations

Maintaining and improving the current observations:

- Basin-scale cruises along repeated relevant sections on the long-term including physical, chemical, biological, and radio isotopic tracers.
- Satellite data should be revisited in order to track mesoscale eddies and study the areas of deep water formation. Recent data from MODIS Aqua on SST and chlorophyll will be helpful. The results of satellite primary production estimates also proved to be important from the point of view of characterizing the circulation.

Long term observatories:

- The experience of long-term time-series monitoring programs such as CIESM Hydrochanges, ANTARES, DYFAMED, etc. has proven to be very useful in determining DWF events, evaluating their importance or and interpreting the evolution of the waters formed. These types of time-series monitoring programs should be maintained, equipped with more sensors such as oxygen and extended to all the regions of interest, namely South Adriatic, Gulf of Lions, etc.
- Long term observations of ocean/atmosphere fluxes of heat and water are required not only from land based time-series monitoring programs, with the collaboration of the weather services, and satellite measurements, but also attached on several of the above mentioned sea time-series monitoring programs.
- Permanent monitoring of parameters triggering DWF events could be used to detect the onset of cascading or convection events. Real time data transmission from fixed points, cabled observatories with sediment traps, moored ADCP, transmissometres, etc., combined with gliders, Argo profilers and isopycnal floats will be complementary to long term time-series stations and especially relevant as an “early warning system”. The application of methods of pattern analysis for identifying changes in the dynamics of the measured variables could be used for “forecasting” new events and for determining when it will be necessary to conduct rapid-response oceanographic surveys.
- Continuous monitoring of Input/Output fluxes and water masses through sills (Gibraltar, Otranto, Corsica, Sardinian, Sicily and Cretan Arc straits) are essentially required for understanding the internal Mediterranean dynamics and long term variability in the surface and deep conveyor belts, to complete water balances and evaluate possible rapidly propagating barotropic responses of DWF. This is particularly crucial in the Strait of Gibraltar, where due to the traffic and strong currents, measuring water coming into the Mediterranean becomes especially difficult. It may be reasonable, taking advantage of the frequent ferries connecting both sides of the strait, to equip one or two of these vessels with an ADCP for this purpose.
- All sensors on long term observatories should be carefully calibrated.

Direct surveys:

- Future changes in both the EMed and WMed are to be expected. A general monitoring program by basin-wide hydrographical surveys, repeated at 5 to 10 year intervals, is therefore required. However, to resolve the temporal changes, such a program must provide high-quality data. Oxygen, ETS activity, and transient tracer (CFCs, etc.) observations should be included if possible. The surveys should be supplemented by deploying Argo floats and placing current meter moorings in critical locations. Higher frequency surveys (at yearly intervals) at the subbasin scale in key areas (Ionian, Adriatic, Aegean, Ligurian subbasins, etc.) would make the monitoring program even stronger.

- Special monitoring is needed in key areas such as the Rhodes Gyre, straits, and DWF sites. These could be implemented using glider transects and CTD moorings.
- A prepared set of equipment that can be launched at short notice from the "early warning system" to perform a dedicated sampling experiment to study direct DWF events will be very useful to avoid undersampling. This procedure will characterize the hydrographical structure and the preferential paths of dense shelf water cascades or convection cells at the time they are occurring.

New methods and approaches:

- In view of small horizontal gradients of density in connection with pronounced differences in salinity, the common use of potential temperature is often misleading. An effort should be made to introduce the concept of 'neutral density' in treating the Mediterranean deep waters.
- The capability of biochemical signatures and other new tracers to tag certain water masses must be explored. Combinations of classical and new biochemical tracers would be the most efficient way to proceed. Discussion is needed to resolve the most appropriate tracers.
- Molecular biology has techniques to "fingerprint" proteins, nucleic acids, and genes in biological samples. Organic chemistry can fingerprint lipids and biochemistry can do the same for enzyme activity. It is likely that water masses, because of their unique origins and biological histories, could be characterized by these different fingerprints. This research has not been done because the people with the skills in these techniques are not aware of the oceanographic problems to which their skills could be applied.
- A modern monitoring program would require an extensive use of Lagrangian and Eulerian methods for complementary observations. Ispopycnal floats able to follow an isopycnal layer would be quite adequate for measuring internal mixing induced by long lived sub mesoscale vortices. ADCP and Microcats moored at the shelf break and along canyons for transmitting data in real time would be highly appreciable for observing cascading of dense waters from shelf to the abyssal plain.
- Coordination with both the sediment-trap and mesopelagic-metabolism communities will be important to relate the physical processes of open sea convection, shelf cascading and gyre pumping to the fuelling process of mid and deep water organisms.

Data inventories

- An agreement with weather services with their commitment to measure and/or assess, from radar data, direct precipitation and evaporation over the sea, should be encouraged. It will be also advisable to incorporate accurate runoff data in water budgets and to integrate these data in process and circulation models.
- The hydrographical data taken in 2006-2009 by current programs in both EMed and WMed, e.g. the SESAME and VECTOR programs, must be evaluated in a coherent fashion to study the changes in the EMT-induced hydrographic fields that have occurred since 2001 and WMT since 2005. Any available data from other sources must also be included, e.g., European data base (issued from European projects). CIESM can play a major role in documenting and accessing such data.
- An attempt to recover and make available sparse data involving deep waters in the Mediterranean, e.g. data from cruises other than those oriented to DW analysis. There is a strong need for collecting, formatting, validating and archiving data in general for the Mediterranean Sea.

5.2. Modelling

Processes

- New algorithms and parameterisations on air/sea fluxes especially on latent heat should be required. The evaluation and extent of DWF events are largely dependent on these parameters.
- Attempts should be made to assess the deep ocean rates of oxygen consumption, CO_2 production and remineralization of nutrients. These rates will be strongly impacted by deep water renewal.
- Modelling shelf water-deep ocean interactions (Gulf of Lions/ Medoc area). Symphonie + offshore modelling. Integrate modelling and observations.

Circulation

- Are the available models adequate? What aspects should be improved?
- Modelling should play a greater role in explaining and describing the changes that have taken place, either directly or using data assimilation. Interannual climatologies are also needed to initialize the models. In addition, the MEDAR-MEDATLAS and SeaDataNet databases have to be continued.
- There is a need to better describe and model the 3D TS distribution of this anomaly and its evolution. This can be done in close cooperation with the CIESM Hydrochanges initiative.

Biological interactions

- Metabolic activity of the sea water and particles exported from surface and shelf waters to the deep layers should be monitored. Fluxes of organic compounds, oxygen, inorganic nutrient salts, and contaminants.
- Investigate the relationship between the occurrence of deep water formation events, cascading or open violent sinking, and the biological communities inhabiting deep sea environments affected by this phenomenon.

Detailed evolution of the EMT in the Eastern Mediterranean Deep Waters

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Abstract

A moderate dense-water discharge from the Aegean began in 1990. Up to late 1991, its impact on the Eastern Mediterranean (EMed) deep waters remained confined to mid-depth waters within the Hellenic Trench. Outflow peaked in mid-1992 to late 1994, during which period the average outflow rate amounted to almost 3 10^6 m^3/year, with a maximum in 1993. By early 1995 the Aegean-derived waters were found dispersed through all of the EMed deep waters. Thereafter, outflow rates declined strongly and ended after 2002, when dense waters in the Aegean were restricted to depths deeper than the Cretan Arc sills. Adriatic outflow was interrupted and only recently resumed reaching the bottom of the Ionian Sea, even though with hydrographic characteristics different from those of the pre-EMT era. The latter is a result of the EMT-induced changes in these characteristics EMed-wide, which are highly transient and will stay so for decades to come; return to a steady-state distribution eventually is not even guaranteed. The main outflow route from the Aegean was Kasos Strait, which led to pronounced T-S inversions in the Levantine; the T-S changes in the Ionian were more complex, partly because of additional outflow through Antikithira Strait. By 2001, the T-S distribution had become comparatively more uniform. The spreading of the Aegean-derived waters through the EMed was governed by the bottom topography. Along-flow density gradients were always small, even between the Levantine and Ionian Seas. Resolving these not only required high-quality data, but also use of potential densities referenced to a suitable deep isobar.

1. Introduction

During the 1990s, the Aegean Sea temporarily replaced the Adriatic as a deep water source, delivering unusually dense waters in massive amounts, which totally disturbed the circulation and hydrography of the Eastern Mediterranean (EMed). This event has been termed the Eastern Mediterranean Transient (EMT). Understanding the evolution of the event is required if its impact on the deep waters further away from the source, such as those of the Western Mediterranean or even beyond, is to be assessed. Furthermore, any interpretation of deep-water observations of a hydrographic or biogeochemical quantity repeated over the past decades (e.g. Klein *et al.*, 2003) needs to take the EMT into account. Special aspects are lessons from the magnitude of the event and from the modes of deep-water dispersion and spreading. A first coherent description of the event, comparing observations obtained by F/S Meteor in 1987 and 1995, revealed heavy influx of dense, high-salinity waters from the Aegean Sea to be felt over the entire EMed, but with amplitudes decreasing strongly toward the western Ionian Sea (Roether *et al.*, 1996; Klein *et al.*, 1999). Early observations of Aegean dense outflow were reported by Theocharis *et al.* (1999a). More detail was added by two subsequent METEOR surveys in the EMed and by extensive Greek work in the Cretan Sea and Italian work in the Adriatic and Ionian Seas. That information was used to produce a consistent description of the evolution of the EMT up to 2001 (Roether *et al.*, 2007; therein numerous further references, colored versions of the figures below, and cruise and station information; colored figures also in the CIESM online version of this document). The present account represents largely a summary of that work with commentary and some remarks on more recent work. The Aegean water influx is readily recognized by its high salinity, which induced T-S inversions over much of the EMed.

While previous work has often relied on sections of hydrographic properties, T-S diagrams (and other property-property plots) allow a more detailed account. This is illustrated by T-S diagrams in the vicinity of Aegean outflow at different stages of the EMT (Figure 1). In 1987, prior to the EMT, there was a steady decline of T and S with depth, whereas in 1991 a property maximum at intermediate depths appears, resulting from the Aegean dense-water outflow. By 1995 the maximum has moved to the bottom with much-increased amplitude. The density isolines are σ_2 (i.e., potential density referenced to 2,000 dbar pressure), but two σ_0 isolines (referenced to the surface) and one σ_4 isoline are included for reference. The latter is even somewhat more inclined than σ_2. One finds that using σ_0 is quite problematic: it underestimates vertical stability in 1987, indicates the 1991 water column below 1,800 m to be unstable, and gives the Aegean-derived more saline waters an unrealistic density advantage.

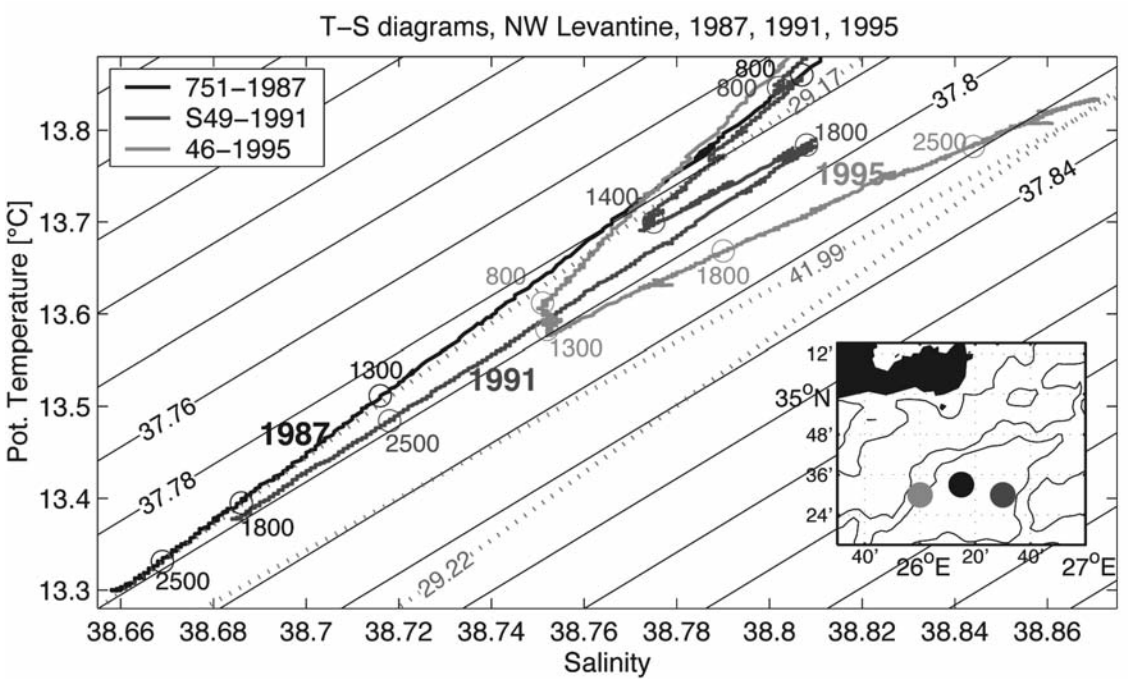

Figure 1. T-S diagrams of stations in the northwestern Levantine Sea taken in 1987 (cruise METEOR M5/6), 1991 (cruise SHIKMONA POEMBC-O91), and 1995 (cruise M31/1); for station numbers see legend, and for station locations see inset map (isolines are 750, 2,250, and 3,000 m). Density isolines are σ_2, also shown are contours for potential densities σ_0 = 29.17 and 29.22 and for σ_4 = 41.99 (dotted) [from Roether *et al.*, 2007].

The spreading of the Aegean-derived waters is to a large degree determined by the EMed bottom topography (Figure 2), which governs in particular the outflows from the Aegean and the transfers between the Levantine and Ionian Seas.

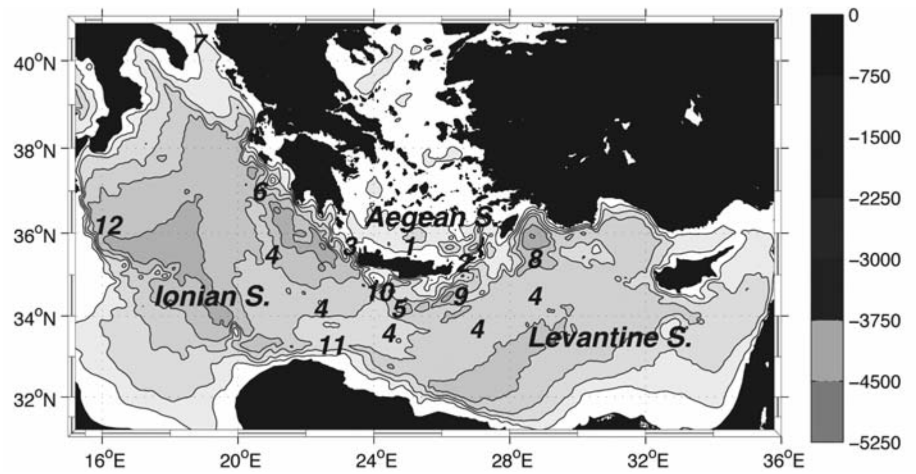

Figure 2. Bottom topography of the EMed (smoothed ETOPO 3 bathymetry).
Outflow from the Cretan Sea (north of Crete, 1) occurs through Kasos Strait (east of Crete, approx. 1,000 m sill, 2) and through Antikithera Strait (west of Crete, 560 m sill, 3). The EMed is subdivided into the Levantine and Ionian Seas (boundary south of Crete, 2,560 m sill, 5) and by the East Mediterranean Ridge (4, ~2,500 m crest through the Levantine, descending to 3,000 m toward its northwestern termination, 6). The inner part adjoining the Cretan Island Arc is the Hellenic Trench. Adriatic outflow occurs via Otranto Strait (800 m sill, 7) [from Roether *et al.*, 2007].

2. The basic features

Figure 3 shows the deduced outflow rates of Cretan Sea deep waters, 1987 – 2001. The onset in 1990 and the step during 1992 are based on T-S evidence. The integrated values for 1991 and 1995 are T-S census-based, comparing the distributions in 1991 and in 1995 to those in 1987. That for 2001 is CFC-12 census-based, comparing the increments of 1995 and 2001 relative to a 1987 census. The dashed lines indicate an expected maximum in 1993. The two winters of excess forcing (extra cooling of ~60 W/m^2 over four months; Josey, 2003) are marked. The peak period 1992-94 sustained huge outflow rates that averaged almost 3 Sverdrups (Sv), approximately three times the mean rate of Gibraltar outflow, and the total outflow up to 2001 represents as much as about three times the total volume of the Aegean Sea. The census values were referenced to observed values on the respective sills (Figure 2), so that the rates represent the actual outflow, prior to any entrainment further downstream.

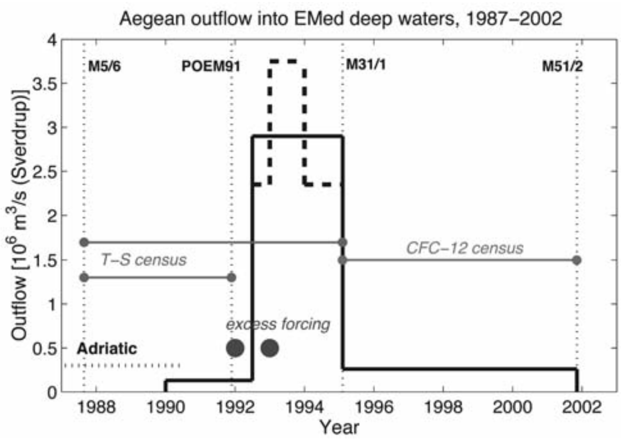

Figure 3. Aegean dense water outflow rates 1987 – 2002 (10^6 m^3/s; year marks indicate 1 January). The classical Adriatic outflow rate (~0.3 10^6 m^3/s, dotted; Roether and Schlitzer, 1991) is shown for comparison. Dots indicate the periods of excessive winter forcing. CFC-12 is the anthropogenic tracer CF_2Cl_2, apparent in the environment since about 1940 with strongly increasing concentrations thereafter; in the ocean interior, thus, relatively higher concentrations indicate a higher, or younger, fraction of near-surface waters added during the CFC-12 period.

Figure 4 summarizes the corresponding T-S evolution in the eastern Cretan Sea, 1987 – 1998, below 400 m (cf. Zervakis *et al.*, 2000). From 1987 on, there is a steady rise in salinity and density with a jump between 1989 and 1991 (left diagram). Later on (right diagram), one finds decreases in salinity but also in temperature, such that the density in the deepest strata became even larger. In total, bottom density increased by almost 0.17 kg/m^3. Note also that, while originally salinity decreased with temperature, that relationship was inversed from 1992 onward. The temperature drop after 1992 (essentially to pre-EMT values, so that the over-all density increase resulted from higher salinity only) was certainly due to the excess cooling in the 1991/92 and 1992/903 winters (Figure 3). The profile from the station in the western Cretan Sea marked 92 west in Figure 4 is the earliest indication of excessively dense waters, expected to arrive in the eastern Cretan Sea somewhat later (Zervakis *et al.*, 2000). The graphs for 1994 are particularly scattered. Those for March and September 1994 reveal comparably very low salinity upward of 600 m, with densities close to those near to the T-S inversion outside the Aegean (salinity minimum, cf. Figure 1). This feature is ascribed to intrusion of waters from outside the Aegean that were uplifted by the pile-up of Aegean-derived waters deeper down. More recent observations show that after about 1995 the Aegean outflow was restricted to 1,500 – 2,000 m depth (Theocharis *et al.*, 2002), and that after 2002, dense water in the Aegean was restricted to depths below that of the Kasos sill, which excludes any outflow (Theocharis, this volume).

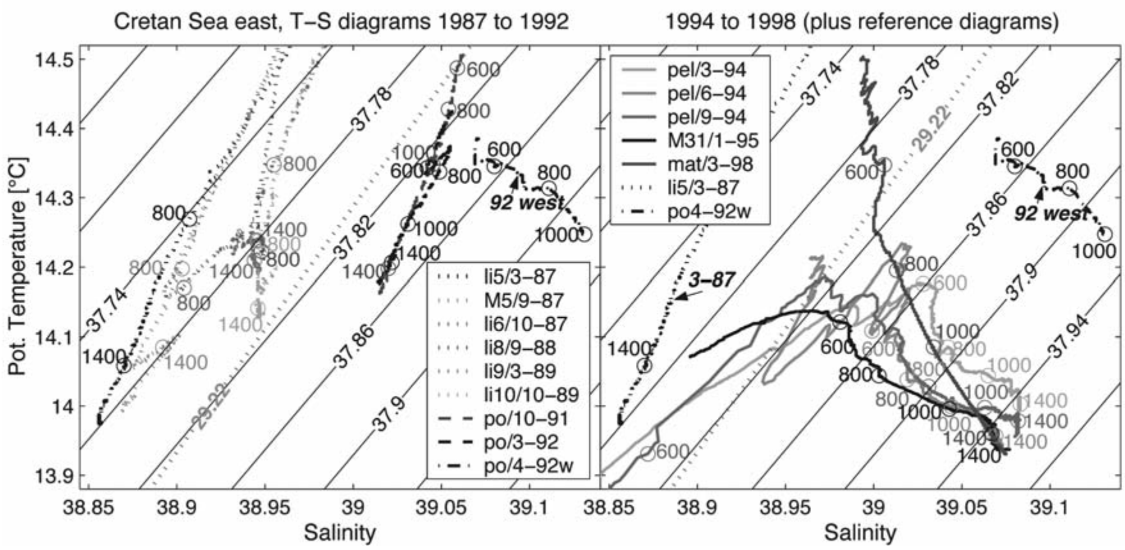

Figure 4. T-S diagrams and σ_2 isolines in the southeastern Aegean, 1987 – 1992 (left diagram), and 1994 – 2001 with 1987 and 1992 reference stations (right diagram). Density isolines are σ_2; a σ_0 = 29.22 contour (dotted) is shown for comparison. Some depths (dbar) are indicated, upper ends represent 400 dbar. Data of a 1992 western Cretan Sea station (dash-dotted, marked '92 west') demonstrate the first appearance of really high densities. Legends give cruise and station date (month-year) [from Roether *et al.*, 2007].

Figure 5 gives T-S diagrams in 1991. The stations within the Hellenic Trench show T-S peaks in about 1,800 m depth apparently generated by Cretan Sea outflow (Malanotte-Rizzoli *et al.*, 1999), but the bottom T-S values and densities have remained unchanged. The peak amplitudes decrease with distance from the sources, i.e., Kasos Strait (Figure 5, left) and Antikithira Strait (Figure 5, right). There is no significant effect beyond the East Mediterranean Ridge and east of 28°E in the trench. According to the limited horizontal and vertical extension of the Aegean-derived waters, the inventory of such water was still small (Figure 3).

T-S diagrams in the Levantine in 1995 (Figure 6), on the other hand, display distinctly increased salinities, temperatures, and densities (with some scatter superimposed) below a T-S inversion in about 1,500 m depth, extended over the entire sea. A decrease in amplitude with distance from the

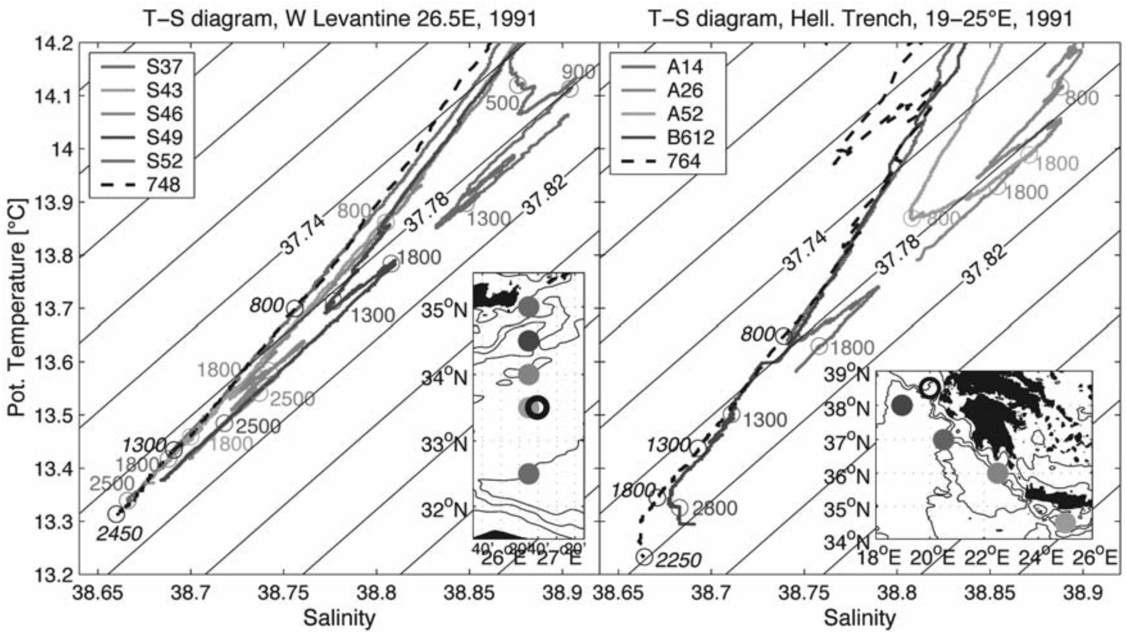

Figure 5. (left) T-S diagrams in 1991 with σ_2 isolines at 26.5°E in the Levantine Sea, Shikmona POEMBC-O91 (S in legend; salinities recalibrated, see Roether *et al.*, 2007), and Meteor M5/6 (1987) reference station (dashed), for station numbers see legend and for positions see inset map (open symbol corresponds to dashed curve; isolines are 750, 2,250, and 3,000 m). Some depths (in dbar) are noted (italics for dashed curve). Several stations display a T-S peak near to density 37.79, which stands out clearly above the rather more linear T-S relationships at stations further away. (right) same as Figure 4, left, but western Hellenic Trench and south of Crete, POEMBC-O91, with Meteor M5/6 (1987) reference station (dashed). [from Roether *et al.*, 2007].

source (smallest effect at the eastern Levantine station) is, however, apparent. The related temperature-CFC-12 diagram (right diagram in Figure 6) has a fully corresponding structure, even in detail. The concurrent distribution in the Ionian (west of the East Mediterranean Ridge; Figure 2) is rather more complex, with T-S maxima upward of the bottom (Figure 7). One notes two stations, located close to the northwestern end of the Hellenic Trench, that have very substantial Aegean-derived fractions, far larger than any of the stations further away. This demonstrates that the influx from the Levantine mostly follows the Hellenic Trench up to the northwestern end of the ridge. The signatures decrease strongly along the periphery of the basin in anticlockwise direction. All stations show distinct salinity increases relative to 1987.

By 2001, the Levantine T-S relationships became more uniform. The Ionian T-S relationships became also more uniform; there were no longer distinct T-S inversions present, and the properties had generally shifted further away from the pre-EMT (1987) values. Furthermore, some inflow from the Levantine through the Herodotus Channel in about 33°N (# 11 in Figure 2, sill ~ 2,100 m) was now apparent in the southeastern Ionian. The T-S relationships in the Hellenic Trench west of Crete (not shown) were consistently more scattered due to additional Aegean influx (of comparably lower density) via Antikithera Strait, and because of a near-bottom return flow from the Ionian toward the Levantine (first observed in 1999). Data for the critical year 1993 (for which Figure 3 shows the outflow maximum) are unfortunately extremely sparse, but they indicate TS inversions in the Hellenic Trench at depth as shallow as 400 m only, far shallower than in any other year for which inversions were observed. This is clear evidence of a maximum Aegean influx in that year, which is also plausible because that is the period following directly the two extreme winters. There is little evidence of deep water renewal from the Adriatic below about 1,500 m up to 2001. It appears that from about 2002 onward, the Adriatic produced waters of increasing density; a regional survey in 2007 revealed that Adriatic outflow had become dense enough to

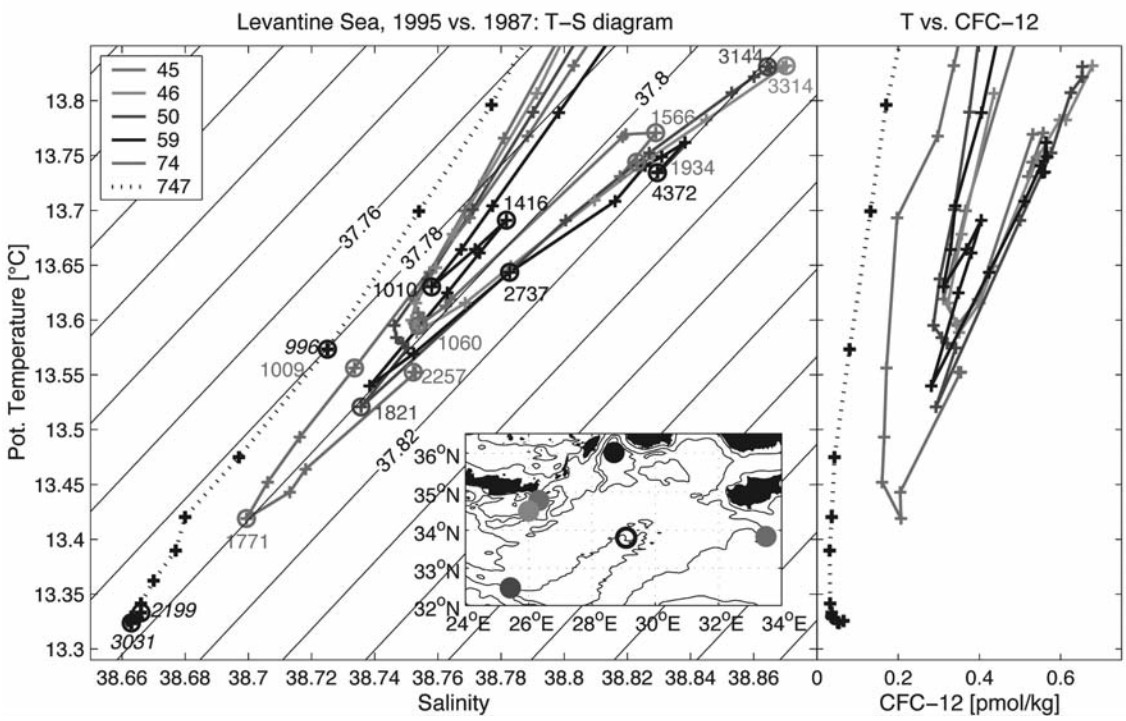

Figure 6. T-S diagrams with σ_2 isolines (left) and T vs. CFC-12 (right) for selected Levantine Sea stations, cruise METEOR M31/1 (1995), with reference station of cruise M5/6 (1987, dotted); some depths (dbar; italics for dotted graphs) are marked. For station numbers see legend and for positions see inset map (open circles for dotted graphs; isolines are 750, 2,250, and 3,000 m) [from Roether *et al.*, 2007].

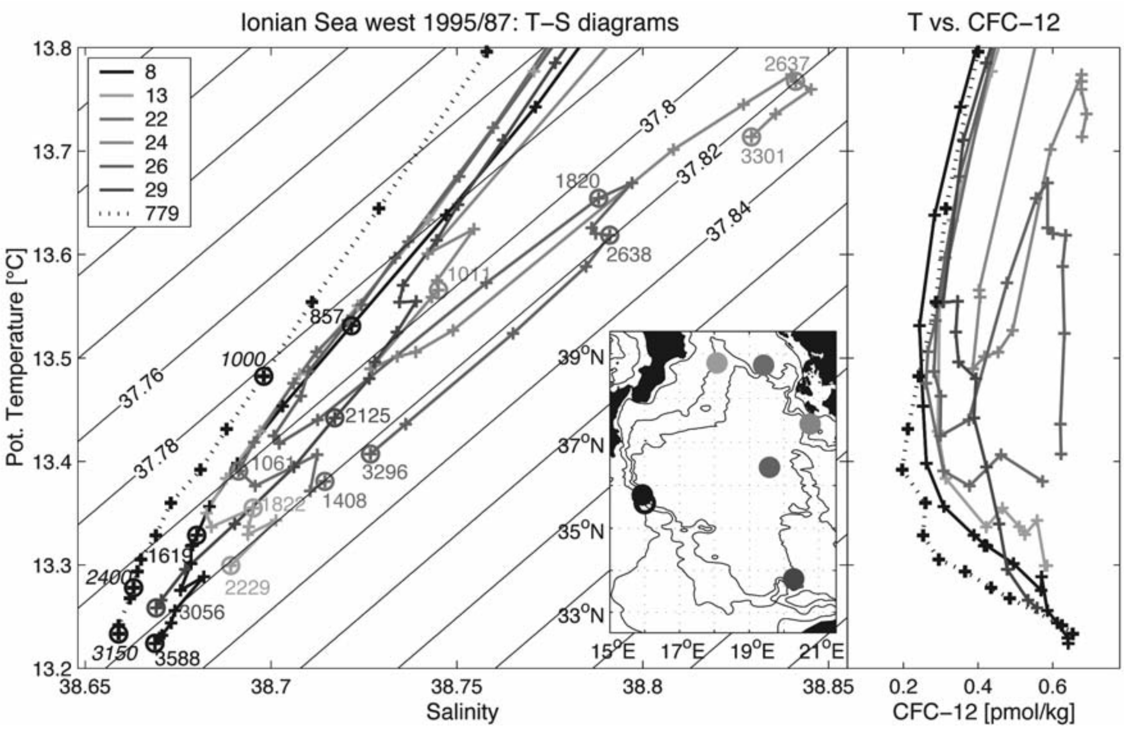

Figure 7. Same as Figure 6 but Ionian Sea west of East Mediterranean Ridge [from Roether *et al.*, 2007].

reach the bottom in the northern Ionian, but with temperature and salinity being higher than ever observed previously (Rubino and Hainbucher, 2007).

An illustration of the changes in deep-water properties is provided by the CFC-12 vs. depth profiles in Figure 8, on which the 1995-2001 increment of the Aegean influx is based (Figure 3). The pre-EMT distribution (1987), which is governed by renewal from the Adriatic, has everywhere the lowest concentrations. The near-bottom waters were subject to south- and eastward spreading with upwelling superimposed. Such basin-wide convection cell is reflected in bottom values being highest in the northern Ionian and lowest in the eastern Levantine, and in minimum values at mid-depths (1,200 – 1,500 m). The EMT-related, dominant addition of Aegean waters strongly raised the deep-water concentrations, swiftly so in the western Levantine and more gradually elsewhere. Mid-depth minima were still present (at depths somewhat shallower than previously), confirming the bottom-intensified addition of the Aegean influx.

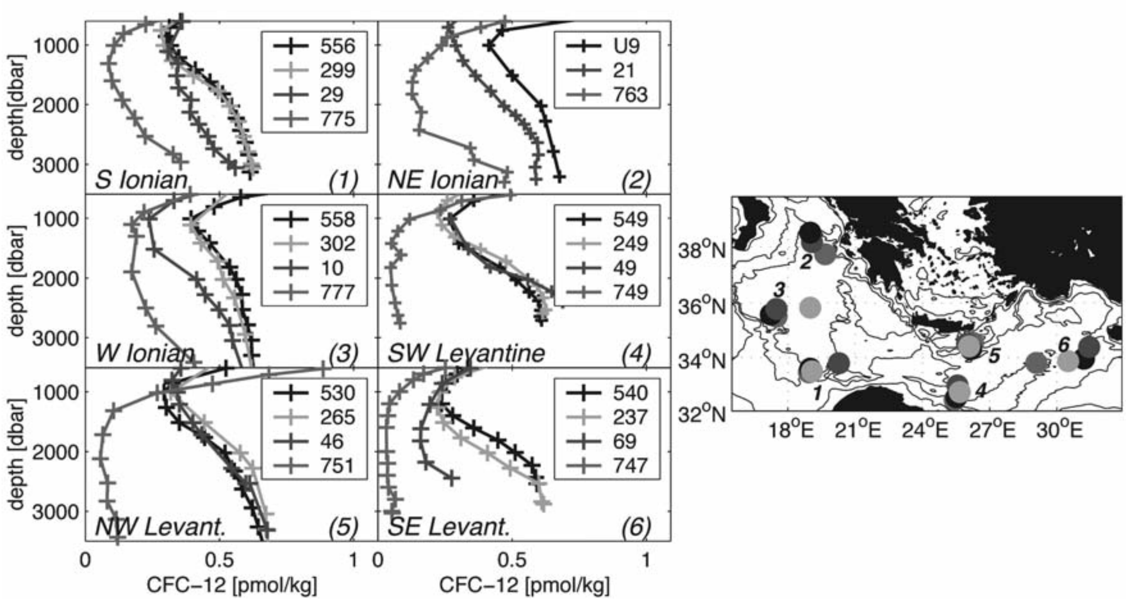

Figure 8. CFC-12 (pmol/kg) vs. depth (dbar) in subregions of the Eastern Mediterranean in 1987 (M5/6), 1995 (M31/1), 1999 (M44/4), and 2001/2002 (M51/2 plus SINAPSI-4 Sta. U9) below 800 m depth. For station positions see map (isolines are 750, 2,250, and 3,000 m; numbering in diagrams corresponds to numbering in map) [from Roether *et al.*, 2007].

3. Discussion and outlook

The transient nature of the T-S distribution allowed the deduction of an approximate flow scheme of the deep waters with an Aegean signature (Figure 9). The effects of sills (in Figure 2: ## 2, 3, 6, 10, 11, overflow over 4) are very evident, and currents are found to adjoin sloping topography (## 1, 5). Special evidence of the latter feature is that the pre-1992 Aegean outflow did not cross the East Mediterranean Ridge although its crest (2,400 – 2,500 m) distinctly exceeds in depth that of the maximum Aegean signature (~ 1,800 m, Figure 5). Later on, Aegean-derived waters apparently piled up high enough eastward of the sill that connects toward the western part of the trench (2,560 m; 5 in Figure 2) to support southward overflow. The constraints by topography are very strict; an example is that the flow of the waters with Aegean signature (1 in Figure 9) follows the Hellenic Trench essentially up to its northern end. It appears that in the Ionian west of the East Mediterranean Ridge topographic steering looses control, so that a more complex (and, apparently, fast) spreading results.

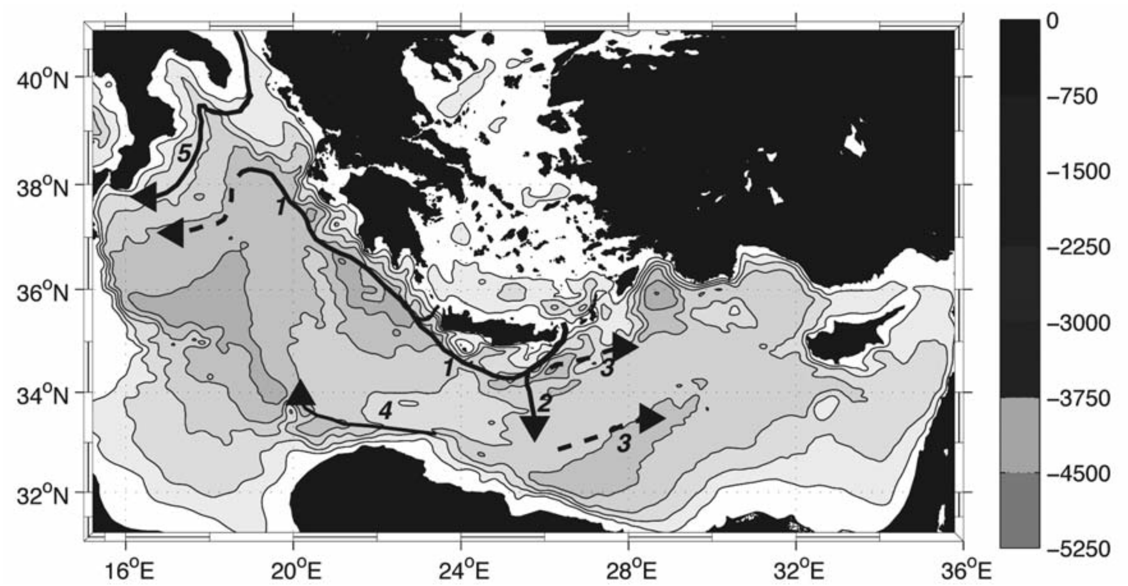

Figure 9. Schematic diagram of EMT-induced flow in the EMed deep waters (bathymetry as in Figure 2). Triangles indicate head of a streamline; dashed lines indicate less steady flow or 'spreading'. Thinner streamlines indicate relatively lower flow rates (Antikithira Strait, west of Crete; Herodotus Trough, 4). (1) = main route of waters carrying Aegean outflow, fed from Kasos and Antikithira Straits; later in the EMT, there has been near-bottom counter-flow in the Hellenic Trench. (2) = overflow of East Mediterranean Ridge during the EMT (only after 1991!). (3) = eastward spreading north and south of the EMR. (5) = Adriatic outflow, which until 2002 reached down only to mid-depths [from Roether *et al.*, 2007].

An important observation is that the peak densities (referenced to appropriate pressure) of the Aegean waters just downstream of Kasos Strait were quite similar to those of the pre-EMT Adriatic outflow downstream of Otranto Strait. The densities further away were less in comparison (by roughly 0.02 kg/m^3) in both cases. The dominance of the Aegean source was, thus, primarily one of rates and much less one of density. In 1995 and 2001, bottom densities (σ_4) were surprisingly uniform, i.e., within ± 0.005 kg/m^3, except for lower values in the southeastern Levantine in 1995. That small range in connection with large differences in salinity makes use of σ_0 rather obsolete. There was hardly any density decrease of bottom densities 1995 – 2001 in the Ionian west of the East Mediterranean Ridge, largely due to the fact that the intruding waters met resident Ionian bottom waters of a similar density, assisted by slow vertical mixing. The Levantine, in contrast, showed a very slight decrease (topography-driven?). This feature offers an explanation for a deep eastward counter-flow observed in the Hellenic Trench after 1995. Although higher density differences were presumably present in 1992 - 94, one lesson from the density observations is that after 1994 the near-bottom flow was driven by extremely low lateral density gradients that were also nearly invariant in time. It is far from trivial to determine such gradients with significant precision using routine hydrographic measurements. While densities thus showed little change, the temperature and salinity ranges appreciably shrank with time; in this connection mixing was well noticeable. Similarly, linear T-S relationships were present at various locations, brought about by mixing, partly in overflows, within just a few years.

While the general ingredients that brought about the EMT are more or less understood, a more elaborate, quantitative assessment of the generation of the EMT is timely. Another matter is that Adriatic outflow recently regained dominance in forming the EMed deep waters, but with temperatures and salinities significantly exceeding the pre-EMT values (Rubino and Hainbucher, 2007). These increases can be ascribed to preconditioning by intruding Aegean-derived higher-salinity waters (Klein *et al.*, 2000), which is one aspect of the fact that the distributions of hydrographic properties in the EMed deep and intermediate waters have been and still are far off any equilibrium. The future of the EMed deep waters is therefore hard to predict; they will certainly stay transient for a long period, and it is not even guaranteed that a distinct new equilibrium will evolve in the long run.

Items that invite further attention include:

- A quantitative study should be carried out on the generation of the high water densities in the Cretan Sea and the connected massive water through-flow; a special aspect is the early salinity rise in the Aegean deep waters.
- The EMT evolution after 2001 should be assessed on the basis of all recent observations in the EMed deep waters, using especially the data of the recent SESAME (<http://www.sesame-ip.eu/scientist/>) and VECTOR (<http://vector-conisma.geo.unimib.it>) programs. Careful intercalibration of the hydrographic data from different cruises will be required.
- Should it be found that the information available has gaps, additional observational efforts will be needed.
- It would be useful to provide a conversion of densities of the Mediterranean waters into 'neutral density' (Jackett and McDougall, 1997), which would entirely eliminate the problem of pressure-dependent density formulations.
- Since the EMT is not only a transient feature but is also governed by bottom topography, reproducing it by numeric modelling will be a tremendous challenge. A successful simulation of the EMT, reproducing the various EMT features noted here, would, however, provide a powerful model verification.

Acknowledgements: the contributions of my coauthors in the publications listed below and of my coworkers at Bremen are highly appreciated. Funding was provided by various EU research grants. The cruises of F/S Meteor were sponsored by the Deutsche Forschungsgemeinschaft, Bonn-Bad Godesberg, Germany. I greatly benefited from discussions at the CIESM 2009 Malta workshop.

Recent dense water formation in the Med western basin, as observed by HYDROCHANGES

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Abstract

Initiated in 2002, HydroChanges (HC) is one of the eight international programs supported by CIESM. It consists in a network of accurate autonomous SBE37 CTDs deployed in selected Mediterranean key-sites, with a typical 1-hr sampling interval.
In order to make deployments/recoveries as easy as possible, even from small ships, the CTDs are generally set on short moorings, so that they sample at ~10-20 m above the seafloor, most often associated with a current-meter. Moorings are serviced locally by individual partners every 1-2 years. Although the primary goal of HC is to monitor long-term variability, we illustrate in this paper the relevance of HC strategy also for accurately detecting, characterizing and monitoring effects of Dense Water Formation (DWF) processes in the western basin of the Med.

Introduction

Figure 1 displays θ time series collected up to now on the ANTARES site, in the central part of the offshore convection area (42°N 5°E), offshore the Catalan cost, at Gibraltar Camarinal Sill and in the Channel of Sardinia. Salinity and currents time series, not shown, are also available. Specific HC moorings recorded the DWF events that occurred in the western basin during the past 5 years.

We will first briefly summarize the results obtained offshore Spain regarding the 2005 and 2006 winters. We will then describe, for the first time, the data recently collected in the central part of the offshore convection area (42°N 5°E). These latter data clearly demonstrate that new and denser deep waters were formed also in 2009, replacing those previously generated in 2005 and 2006.

Potential impacts of DWF on the outflow at Gibraltar, as well as on the deep flow from the Algerian to the Tyrrhenian will also be briefly invoked, in the light of HC time series collected in those key-places since 2003.

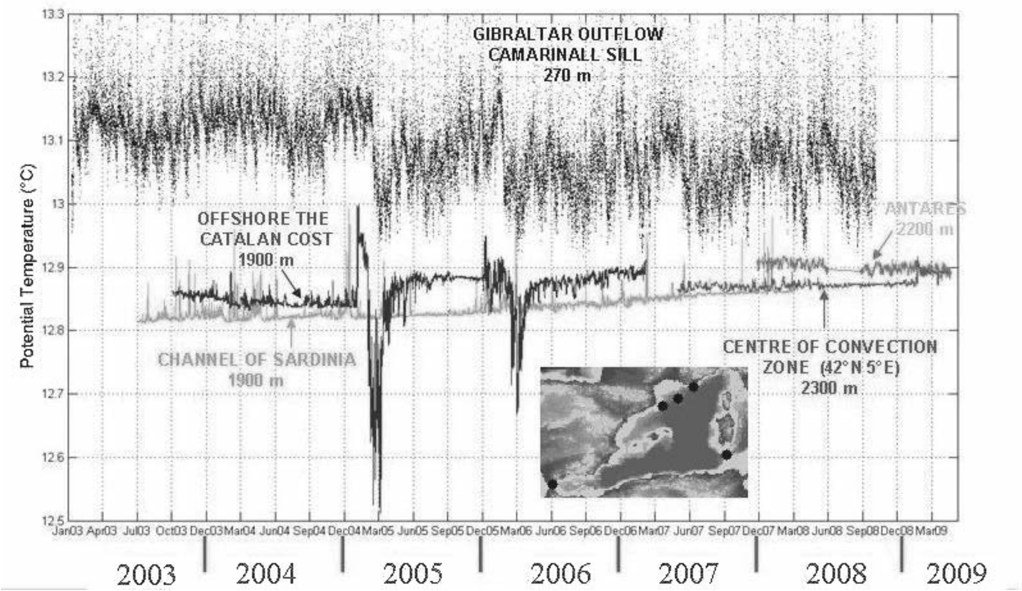

Figure 1. θ times series on ANTARES sites (ANTARES Group), on 42°N5°E (COM), offshore Spain (ICM-CSIC), in the strait of Gibraltar (Moroccan Royal Navy – Faculté des Sciences et Techniques de Tanger – COM), in the Channel of Sardinia (INSTM-COM).

OBSERVATIONS OF DWF

The 2005 and 2006 DWF episodes have been extensively documented in recent literature, thanks to several basin-wide cruises (Schroeder *et al.*, 2008a,b). Repeated CTD transects in 2005 and 2006 evidenced a rapid filling of the western basin with newly formed warmer and saltier deep waters, inducing dramatic changes of the hydrological structure and considerable renewal of previous waters. New deep waters were first sampled in spring 2005 within the Provençal sub-basin, the Ligurian and in few places within the Algerian. In fall 2006, another cruise showed that the western basin was almost entirely filled, below 1,800-2,000 m, with dense waters formed during both winters.

One HC mooring, deployed at ~1,900 m offshore the Catalan coast by ICM-CSIC, recorded major features related to those DWF events (Figure 1). The positive abrupt jumps of θ and S that occurred there in late January 2005 were attributed (Font *et al.*, 2007) to the start of the offshore convection process. In early March, θ-S dropped suddenly, fluctuated intensely during ~1 month and finally stabilized at values of 12.88°C/38.48, warmer and saltier than the steady 12.84-12.85°C/38.45-38.46 found before January 2005. The episode of rapid fluctuations was interpreted by the authors as the signature of an exceptionally intense shelf-cascading event (also described in detail in other papers, e.g. Puig *et al.*, 2008), and the resulting θ and S as a mixture of the two dense waters formed both by offshore convection and deep cascading. One year later, another significant cascading episode was recorded (Figure 1), without significant modification of the background θ-S properties that were reached at the end of the previous 2005 event.

Another HC mooring, maintained at the centre of the offshore DWF area (42°N-5°E) by COM-LOPB since October 2006, was serviced for the third time in early May 2009.
Figure 2 displays related times series of θ, S and σθ, together with associated current-meter data. The most striking features on these records are the abrupt positive jumps in θ and S that occurred in late February 2009, while previous values were stable at ~12.86-12.87°C/~38.47-38.48 for more than 2 years. Closer examination shows in fact that there were intense θ and S fluctuations at the very beginning of the event (not visible at the scale of Figure 2) during a couple of days, before definitive jumps of both parameters. It is interesting to note that θ first reached a maximum value of almost 12.92°C and slowly decreased during ~10 days before finally reaching 12.89°C. On the contrary, S did not display any marked variations after the jump and immediately reached (and

kept) its final value of ~ 38.49. The corresponding densification was consequently made at constant S and slowly decreasing θ, which explains the progressive pattern of the density increase from <29.12 to > 29.12.

Before the event, the current speeds remained relatively low (~5 cm/s) but significant, with very few episodes of no motion and sporadic peaks up to ~20 cm/s (e.g. in fall-winter 2007). Note however that inertial motions, which were not filtered out in the presented data, generally represent a significant part of the signal's energy. The progressive vector diagram of the whole series (not shown) indicates a southward average motion until October 2007, followed by a north-westward average motion until the end of records. This apparent change of general current direction is not associated with any hydrological variation on the θ-S records. During and after the event, currents were considerably intensified and reached peaks up to 40 cm/s. Inertial motions, that appeared permanently before the event, vanished during and after it. This is especially visible when focusing on u-v components (not shown). This feature might account for inertial motions favoured in relatively stratified near-bottom conditions (due to the 2005 and 2006 DWF events, see the July 2008 profile on Figure 3) while inhibited in the new much more homogeneous situation (see the May 2009 profile on Figure 3).

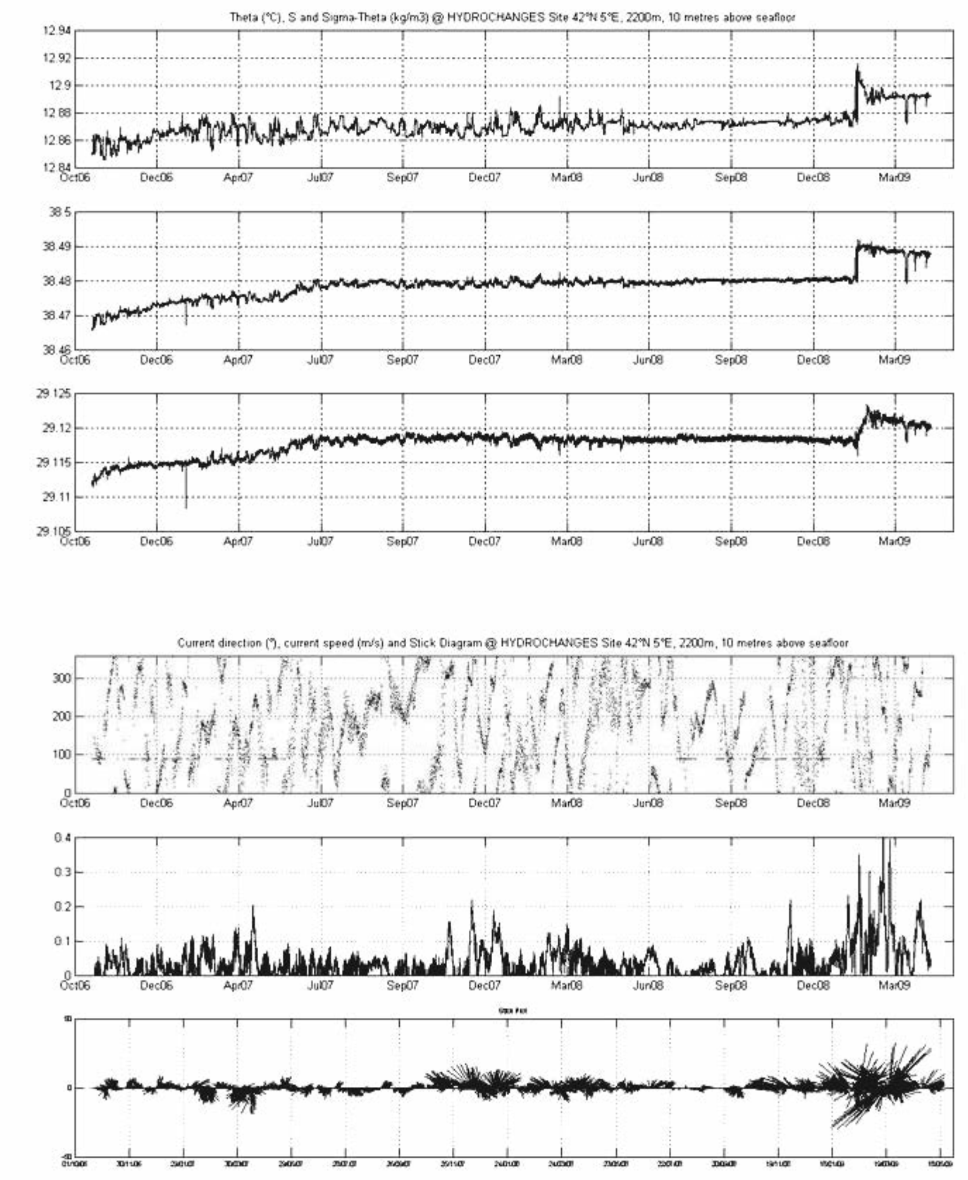

Figure 2. θ, S, σθ, current speed, current direction and stick diagram for the 42°N 5°E site.

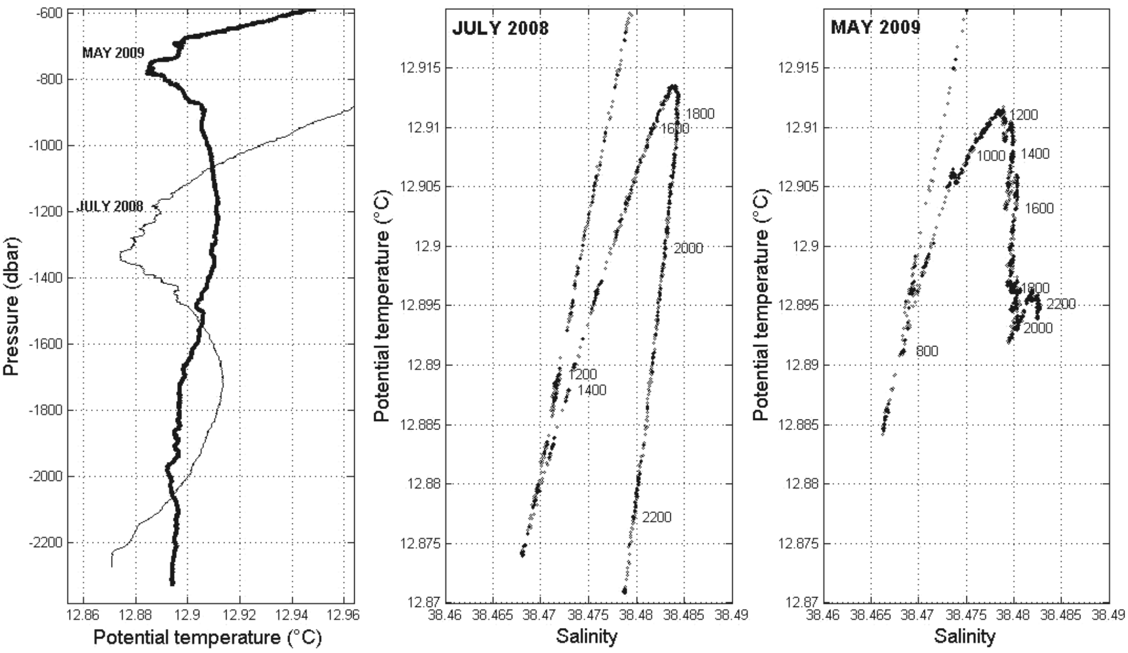

Figure 3. θ profiles on 42°N 5°E in July 2008 and May 2009 and related θ-S diagrams.

All these hydrological and dynamical features clearly indicate a new DWF episode also in winter 2009. They should now be explored further in order to understand and finely specify the event's chronology.

Focusing now on meteorological data collected near the cost on both eastern and western sides of the Gulf of Lions from late 2006, it appears clearly that the 2009 Jan-Feb months were exceptionally colder than the 2007 and 2008 ones (Figure 4a), with, for instance, a difference of up to ~4 °C (!) in Marignane airport (near Marseille): there, the monthly averaged temperature dramatically dropped down to 5.2 °C in Jan 2009, while it was around 9°C during the two previous winters. It is also noticeable that moderate to strong winds were persistent from late January to late February 2009, which was not the case in 2007 and 2008 (Figure 4b). Coherently, no specific signals were found on the θ-S time series during these two years characterized by relatively mild winters.
According to Météo-France (see <http://france.meteofrance.com/france/climat_france>), the 2009 winter is the 3rd colder winter of the last 20 years in France, behind the 2006 and 1991 winters. Further investigations on meteorological data, especially those collected by the Météo-France buoy anchored on 42°N 5°E, should now be conducted in order to specify more accurately the conditions at the origin of the 2009 DWF event, as well as the 2005 and 2006 ones.

In a preliminary attempt to examine the consequences of the 2009 DWF event, we have compared few data collected before and after it. Figure 3 displays temperature profiles from CTD casts performed at 42°N 5°E in July 2008 during the SESAME-BOUM experiment (Moutin, pers. comm.) and in May 2009 (~1 hour after the HC mooring recovery), together with corresponding θ-S diagrams. Differences between profiles appear dramatic. The typical bump that signed the 2005 and 2006 DWF between ~1,400 m and the bottom is replaced by a much more homogenous profile. Considering remarkable points, one may note that both θ relative minima at ~1,300 m (July 2008) and ~800 m (May 2009) and θ maxima at ~1,700 m (July 2008) and ~1,200 m (May 2009) appear separated by the same gap of ~500 m. These features are confirmed by the θ-S diagrams on which pressure levels are indicated, and might well suggest that the 2005-2006 waters were at their turn uplifted by the 2009 new water over several hundreds of metres. However, this must be confirmed by dedicated studies based on other existing data sets collected in the Provençal sub-basin, as well as those that will be collected in the whole western basin in the near future.

a) AVERAGE AIR TEMPERATURE

LOCATION MONTH	PERPIGNAN	MARIGNANE
JAN 2007	10.1 °C	8.7 °C
FEB 2007	10.3 °C	9.5 °C
JAN 2008	10.3 °C	9.1 °C
FEB 2008	10.1 °C	9.3 °C
JAN 2009	7.0 °C	5.2 °C
FEB 2009	8.7 °C	7.6 °C

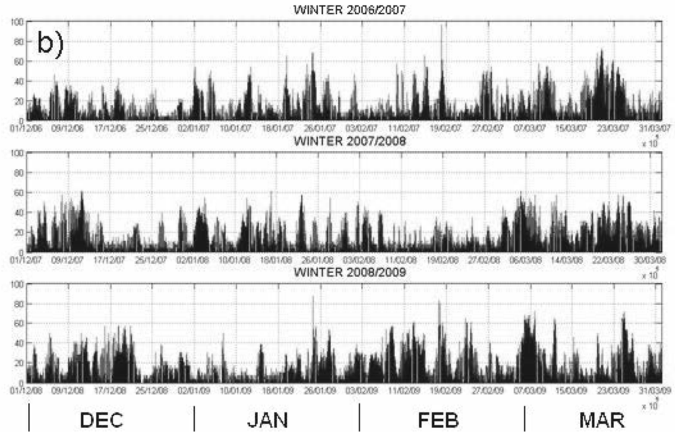

Figure 4. a) Average air temperature in Marignane and Perpignan airports, located on both sides of the Gulf of Lions b) Wind speeds - in km/h - in Marignane and Perpignan: winter 2006/2007 (top), winter 2007/2008 (middle), winter 2008/2009 (bottom).

Remarkable features on other HC time series and related pending questions

Even though it is too early to observe basin-scale consequences of the recent 2009 DWF, some specific features may be emphasized on other HC time series (Figure 1), potentially linked to the 2005 and/or 2006 events.

First of all, is the impressive and persistent θ drop observed from March 2005 at Gibraltar (with no significant associated S variation, not shown) directly related to the 2005 DWF event, recorded some weeks earlier by the HC mooring offshore the Catalan cost ? If so, what are the mechanisms able to explain such a dramatic feature? These questions should be addressed, taking into account all results and ideas concerning the interior of the western basin as well as recently published papers dealing specifically with the outflow at Gibraltar (Garcia-Lafuente *et al.*, 2007; Millot *et al.*, 2006; Millot, 2007; 2008; 2009).

Second, what is the reason for the parallel progressive increase of θ (and S and σθ, not shown) both on 42°N-5°E and in the Channel of Sardinia? Can it be coherently explained with respect to the 2005 and/or 2006 events? What can be inferred on the deep flow from the Algerian sub-basin to the Tyrrhenian sub-basin?

Note finally that the role of the AW inflow variability at Gibraltar should also be considered in the DWF processes and in the characterics of the resulting waters, especially regarding salinity variations (Millot, 2007; 2008).

Variability of the thermohaline properties in the Eastern Mediterranean during the post-EMT period (1995-2008) and SST changes in the Aegean (1985-2008)

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Introduction and review

The Mediterranean Sea dominates the environmental, cultural and economic life of its coastal states. The evolution of the physical parameters in response to climate variability (e.g. global warming) is of importance. Scientific evidence from the last decades indicates that environmental changes occur at all scales. The Mediterranean area is under the influence of some of the major large-scale to regional circulation patterns that are modified by the interaction of the surrounding continents, the Atlantic Ocean and the Mediterranean itself. The strong topographic variability is the key factor for the development of localized phenomena, although they remain linked with larger scale atmospheric forcing. From the oceanographic point of view, the Mediterranean, a miniature ocean, is classified as a concentration basin, where evaporation exceeds precipitation and river runoff, with high-density water production at well defined selected sites in its both sub-basins. The balance is achieved through the hydraulically controlled straits. Therefore, the Mediterranean is a fascinating semi-enclosed sea for studying important processes and the impacts of large and regional scale climatic forcing due to its rapid response to external forcing. Changes in the oceanic and atmospheric/climatic parameters have been documented although their forcing has not always been resolved in the context of climate variability.

The thermohaline circulation of the Mediterranean, which reflects the largest scale motion, is forced by the buoyancy exchanges and is driven by its negative heat and freshwater budgets. The intermediate and deep layers of the Mediterranean Sea are renewed through vertical mixing in winter through intense air-sea interaction processes under favorable meteorological and oceanic conditions. This process is effective in exchanging properties (i.e. heat, salt, oxygen, nutrients, etc.) between the euphotic zone and the abyssal depths. Two kinds of thermohaline cells result. The first, the upper open conveyor belt, consists of (i) the non-return flow of low salinity Atlantic Water (AW), entering from the Gibraltar Strait, to the easternmost end of the Levantine Basin in the upper 150-200 m and (ii) the formation and westward spreading of the warm and saline (S~39.00-39.1 at the source area) Levantine Intermediate Water (LIW), at depths 200-400 m, to the Gibraltar, where it enters the Atlantic Ocean. Secondly, there exist internal thermohaline cells (closed conveyor belts) in each of the Mediterranean sub-basins driven by deep water formation processes. As part of the steady-state concept, there is one main source of intermediate water (the northwest Levantine Basin) plus two main sources of deep waters (the Gulf of Lions for the WMDW and the Adriatic Sea for EMDW) in the Mediterranean. Additionally, there are other minor and sporadic sources in other parts of the Basin, e.g. in the north and south Aegean Sea, which under the synergy of extreme meteorological and hydrological conditions may become more effective and may considerably influence the thermohaline circulation in the long term. However, the amounts of dense waters produced up to the 1980s have never been enough to drastically influence the thermohaline structure of the eastern Mediterranean. LIW is considered the most important component of the large scale circulation and dynamics because it spreads throughout most of the Basin and affects the background stratification of other major areas (e.g. Adriatic and Aegean Seas) of deep water formation. It is also the main constituent (80%) of the high-salinity Mediterranean Water that is exported to the Atlantic Ocean (Lascaratos *et al.*, 1999). Another loop of the upper layers connects the Mediterranean with the Black Sea. In the latter case, the Aegean Sea acts as an intermediate machine that modifies the received LIW and exports it to the Black Sea via the Marmara Sea. The deep waters of the Mediterranean are confined in the deep and bottom layers of the respective sub-basins because of the existence of the sills at the Sicily and Gibraltar Straits. On average, the deep water annual production rate reaches 0.3 Sv at each sub-basin, vs 1-1.5 Sv for the intermediate water (Lascaratos, 1993). The renewal of the deep waters is estimated of the order of 80-120 years.

EMT PERIOD

Important changes in the circulation and temperature and salinity have been observed in the last decades, which indicate that the Mediterranean Sea is not in a steady state as it was believed up to the 1980s and is potentially very sensitive to changes in atmospheric forcing. In the late '80s-early '90s, abrupt significant consecutive changes, increase in salinity (1987-1992) and drop in temperature (1992-1994), caused continuous increase of density and massive deep water formation in the south Aegean and outflow through the Cretan Arc Straits in the eastern Mediterranean (Malanotte-Rizzoli *et al.*, 1999; Theocharis *et al.*, 1999) that altered the thermohaline circulation of the entire Basin (Roether *et al.*, 1995) with consequences also in the distribution of other environmental parameters, e.g. dissolved oxygen (Klein *et al.*, 1999). This major event evolved within 7-8 years and was called the "Eastern Mediterranean Transient" (EMT) (see CIESM, 2000). The engine of the conveyor belt was the convective cell of the Southern Adriatic up to 1987. In the early '90s the active convection region shifted to the Aegean. The new source was more effective since the estimated production rate was more than three times larger than the old one (1 Sv for seven years period [1987-1995] instead of 0.3 Sv). It is worth noting that during the period 1987-1992 dense water was formed by open-sea processes within the cyclonic eddies in the Cretan Sea, but also by shelf processes and cascading in the large Plateau of Cyclades in the central Aegean Sea (Durrieu de Madron *et al.*, 2005). Additionally, shelf processes also contributed to the high density water production in the north Aegean during the same period (Theocharis and Georgopoulos, 1993).

The signal of the above major changes has passed the Sicily Strait and has been felt in the western Basin. The EMT event has gradually decayed since 1995, indicating its transitional nature (Theocharis *et al.*, 2002). This abrupt change has been mainly attributed to important regional meteorological anomalies (extended reduced rainfalls, change in wind patterns, exceptionally consecutive cold winters), to changes of circulation patterns (routes of the AW and LIW) and to the reduced Black Sea Water outflow (Malanotte-Rizzoli *et al.*, 1999; Theocharis *et al.*, 1999a; Zervakis *et al.*, 2004). The relationship between the heat loss and large scale atmospheric patterns (e.g. NAO) is also investigated. These episodic hydrological changes have been superimposed to the long-term trends observed in the Mediterranean (Boscolo and Bryden, 2001). The produced Cretan Deep Water (CDW) being of particularly high density (29.3 kg/m^3) sank into the near-bottom layers, uplifting the older deep waters of Adriatic origin, thus strongly affecting the deep water column structure and influencing the exchange between the Aegean and the adjacent basins with the intrusion of Mediterranean Water, the origin of which is the deep-water lying between the Levantine Intermediate Water (LIW) and Eastern Mediterranean Deep Water of Adriatic origin (EMDW). This water, namely Transitional Mediterranean Water (TMW) has formed a distinct layer in the Cretan Sea (200-600 m) during the first stages of EMT, strongly affecting the stratification of the water column and the environmental parameters (Theocharis *et al.*, 1999b).

Finally, apart from the above mentioned main sources, there were sporadic events of deep water formation in the Levantine Basin during the past years. In early spring of 1986, 1992 and 1995, newly formed deep water, namely Levantine Deep Water (LDW), with density near that of the EMDW of Adriatic origin, occurred within the Rhodes cyclonic gyre at depths reaching ~1,000 m in 1995 and exceeding 1,000 m in 1986 and 2, 000 m in 1992 (Kontoyiannis *et al.*, 1999). The lateral scales of the newly formed water masses in cyclonic structures appear roughly proportional to the penetration depth of the convection, so that a large lateral scale indicating a massive production would be associated with a deep rather than an intermediate formation. There was not up to now any quantitative analysis of the LDW production during this period.

Additionally, during the EMT period, a new intermediate water mass was generated in the Cretan Sea, south Aegean Sea, namely the Cretan Intermediate Water (CIW), with similar to LIW characteristics, that replaced the LIW in its westward route (Ionian Sea), the latter being blocked and recirculating within the Levantine Basin (Malanotte-Rizzoli *et al.*, 1999; Theocharis *et al.*, 1999b). This saline water mass fed the Adriatic during the following years, thus strongly supporting the reactivation of the previous long-term dominance of the Adriatic (Theocharis *et al.*, 2006; Manca *et al.*, 2006).

Post-EMT evolution

Since 1995 the EMT event started to decay, but the rate of the Eastern Mediterranean system relaxation, the mechanisms involved, as well as its final state (old or modified) remains still unclear.

In 1998-1999, the Cretan Sea returned to the pre-EMT condition of exporting small amounts of dense water that does not reach the bottom of the Ionian and Levantine basins, but ventilates the depths of 1,500 – 2,000 m (Theocharis *et al.*, 2002). Now, it appears that the main contribution of dense water for the Eastern Mediterranean has already passed back again to the Adriatic (Klein *et al.*, 2000). The above findings show that significant changes in the functioning of the thermohaline circulation can occur rapidly. A more detailed account of the changing hydrography and the large-scale circulation of the deep waters of the Eastern Mediterranean is given by Roether in this volume.

Aiming at gaining a better understanding of the Aegean Sea dynamics within the post-EMT period, a series of CTD surveys and profiling ARGOS float deployments were conducted in various Aegean Sea basins and in the adjacent west Levantine region. The use of autonomous profiling floats gave us new tools to track the circulation and stratification in a region where systematic monitoring was previously lacking. Two cruises were carried out during the winter periods of 2005 (Figure 1) and 2006. In addition, four profiling floats, two at each cruise, were deployed.

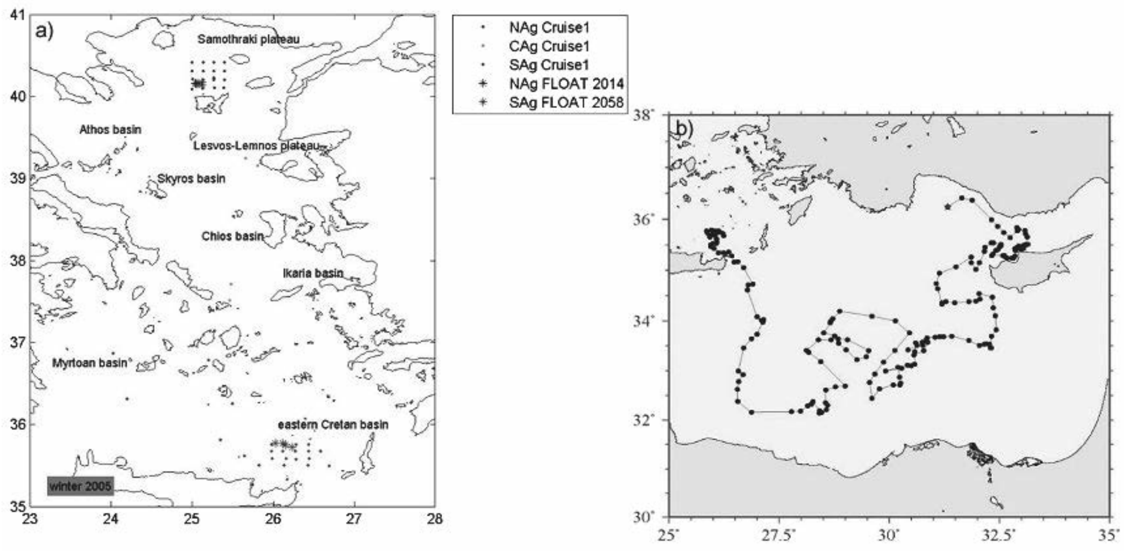

Figure 1. (a) Winter 2005: CTD data during Cruise-1 at 01-10/03/2005 and CTD Float 2014 (NAg, 09-29/03/2005)-Float 2058 (SAg, 14-29/03/2005) profiles. (b) Float 2058 trajectory from Cretan Sea (deployment: 09/03/2005) to Levantine basin (final position 'star dot': 09/09/2008) through Kassos strait.

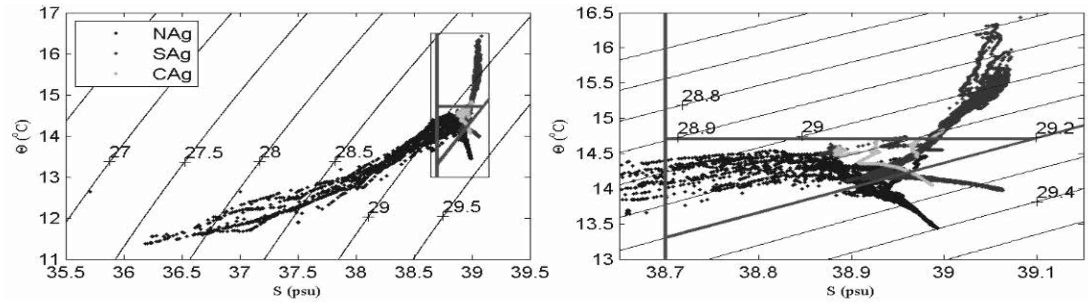

Figure 2. Θ-S from CTD data during Cruise-1 at 01-10/03/2005 and CTD Float 2014 (NAg, 09-29/03/2005)-Float 2058 (SAg, 14-29/03/2005) profiles. Data as a function of the geographical area (NAg-dark dots, SAg-medium dots, CAg-light dots).

The combined profiling floats and CTD surveys data sets, compiled with older observations, reveal a remarkable difference of Θ-S characteristics between the north and south Aegean. At the surface layers the large differences can be attributed to the influence of Black Sea Water (BSW) and the warmer and more saline waters of Levantine origin in the northern and southern basin respectively. The deep-water Θ-S differences are also important, indicating a possible intermittent decoupling of the two sub-basins (Vervatis *et al.*, 2009).

The X-shape Θ-S diagram denotes the importance of the central Aegean triggering the intermittent circulation across the sub-basins. The central Aegean seems to play a key role in the Aegean water mass formation processes, mainly over the shelf, for the entire Basin, as also indicated by earlier studies. During 2005 and 2006 dense intermediate-type water formation with densities about 29.2 kgr/m^3 was detected, attributed both to shelf and open ocean convection. These water mass formation processes, along with sea water characteristics (Θ-S-O_2) analysis strongly support the idea that central Aegean waters act as the connector in the basin-wide thermohaline cells. It is the combination of the high salinities of the surface waters reaching the central basin with the enhanced winter buoyancy loss that makes this area suitable for dense water formation.

In the northern Aegean important interannual variability is observed (Figure 3). The EMT event was accompanied by the storage of very high density, oxygen-rich waters in the deep basins, which progressively lost buoyancy and oxygen through vertical turbulent diffusion, a process of varying intensity among basins (Zervakis *et al.*, 2009). During 2005-2006, the very dense, low oxygen, deep waters formed during the EMT period were monitored in the Athos and Skyros sub-basins. Changes in the water column characteristics in the region are influenced by local water mass formation processes detected during the winter period. Such limited events took place in 2001 and 2005, while a more intense one took place in 2008. Dense water formation after 2000 may have accelerated the thermohaline circulation within this area, with potential effects on the Mediterranean circulation.

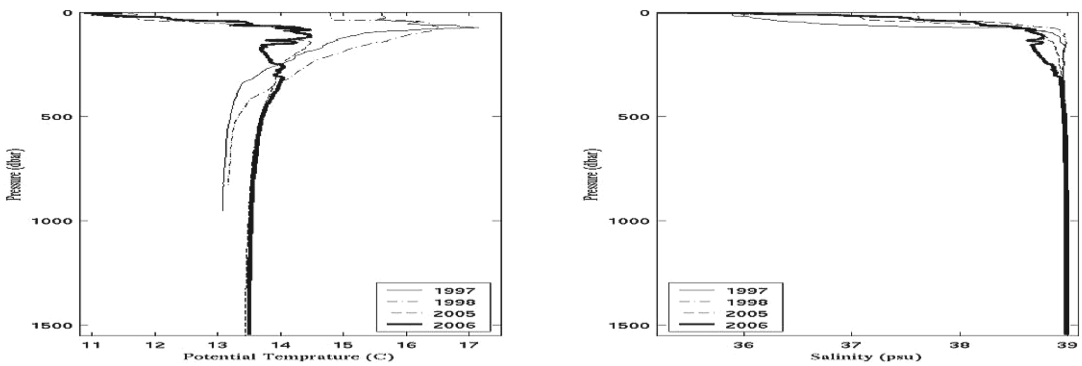

Figure 3. Potential temperature (left) and salinity (right) profiles in the Lemnos basin (NAg) during different years in the post-EMT period.

The changes associated with EMT started to decay dramatically, confirming its transitional character, but subsequent changes were slower and its signal still remains present (Sofianos *et al.*, 2007). The Cretan Sea underwent important changes in the stratification. The relatively less saline intermediate layer was produced by the TMW intrusion. Its core is continuously deepening and reached the 800 m level during the late observations (Figure 4). Its core salinity fluctuated but recently has reached the 1994 value. Comparison with older observations indicates important mixing processes within and outside the Aegean and a possible evolution of the exchange between the Cretan Sea and the Levantine basin. This current phase is characterized by no outflow of CDW (Figure 5). High saline but less dense waters fill up the reservoir of the Cretan Sea up to 1,200 m, far below the Kassos sill (max depth 1,000 m). The Aegean deep outflow to the Eastern Mediterranean has been minimized since 1995, with a non negligible rate of 0.15 Sv/y for the period 1994-2002, while by 2002 no outflow is observed. The deep waters in the Levantine basin are a mixture of Adriatic and Aegean origin with the former contributing to a higher percentage compared to earlier observations (Theocharis *et al.*, 2006; Vervatis *et al.*, 2009).

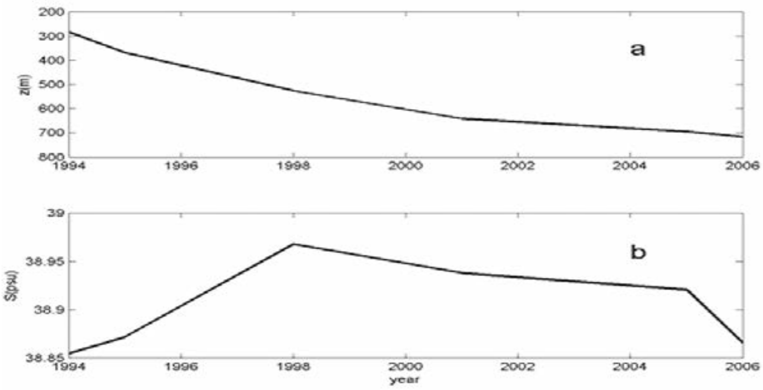

Figure 4.
Evolution of depth (a), salinity (b) of the TMW-core intrusion in the Cretan Sea.

Changes in the stratification in the Levantine basin outside the Cretan Arc straits and the deflation of the CDW layer in the Cretan Sea, modify the exchange between the Aegean Sea and the adjacent basins at deep and intermediate levels. Outside the Kassos strait, the water mass structure of the Levantine Sea (mixed layer, the subsurface Atlantic Waters (AW), the Levantine Surface Waters (LSW) with high surface salinity values of ~39.6 psu and the deep layers) was monitored with Argo profiling floats (2005-2008), following the general eastward cyclonic circulation of the basin. The old EMDW of Adriatic origin forms a core around 1,200 m. The results acquired recently together with historical data emphasize the spatial and temporal variability of the Aegean Sea stratification and circulation. The accumulation of large number of data in the region will eventually provide a valuable mean for better understanding the dynamics of the Aegean Sea.

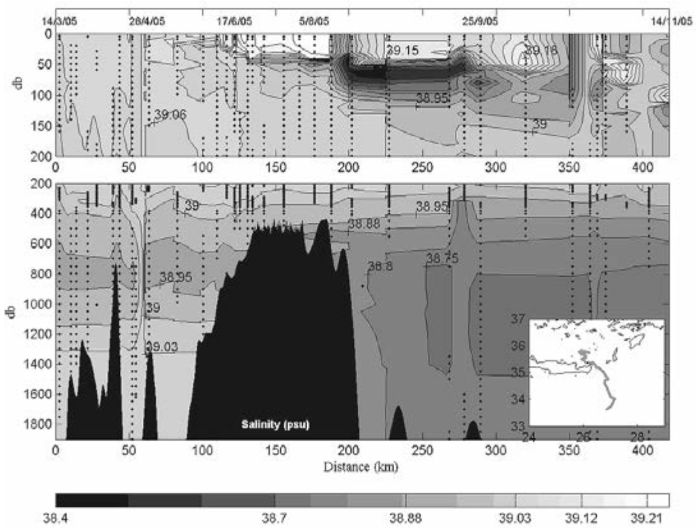

Figure 5.
Spatiotemporal transect of the CTD data Float 2058 during its drift from the Cretan Sea to Levantine basin through the deepest part of Kassos strait.

SST EVOLUTION (1985-2005)

It is obvious that temperature is a key parameter, along with the salinity, in the water mass formation process in the Mediterranean and in the revealed variability of the characteristics of the produced intermediate and deep waters, thus affecting the thermohaline circulation of the entire basin. This was evident during the decay of the deep water production period and the continuing intermediate water production after 1995 (Theocharis *et al.*, 2002). Recently, atmospheric time series have been used to explain the observed behaviour of upper layer ocean temperatures in the Mediterranean during recent decades, within the global warming context, and study their relationship to the large scale atmospheric circulation and air-temperature (Xoplaki *et al.*, 2009).

An interesting example of sea surface warming in the Aegean and the eastern Ionian Sea is shown by Raitsos *et al.*, 2009. The authors processed a 23-year series of satellite SST monthly means, derived from AVHRR (1985-2007) (Figure 6). There is a pronounced change during the last decade with evidence of a stepwise increase in 1994. It can be clearly seen that after that year the annual SST mean remains above the overall mean, whereas the opposite occurred before 1994. During the first decade the annual SST mean was 18.4 ºC (1985-1993), and 19.1 °C during the second decade (1994-2007). However, regionally within the Aegean Sea, the differences of the mean SST can be much larger and reach 2.5 ºC. The most prominent alterations occurred during the summer months and particularly in August (1.27 ºC difference between the two decades), along with smaller changes during the winter months. These changes are also evident in the surrounding areas of the Levantine and Ionian Seas. It is of importance that the evolution of the eastern Mediterranean temperature follows that of the North Hemisphere Temperature (NHT) thus confirming the link to global changes. Such trends will affect the water mass formation processes along with the increase of surface salinity as mentioned above. Such studies in combination with monitoring of the water properties and of heat and water air-sea fluxes will offer better insight in the thermohaline circulation changes in the Aegean and the Mediterranean. Importantly, the continuous effort for monitoring the deep water characteristics (e.g. The HydroChanges program of CIESM) will reduce the higher frequency variability and therefore, the climatic signals will be relatively enhanced. Besides, in combination with other bio-geo-chemical parameters, these studies will provide information on the CO2 absorption rates.

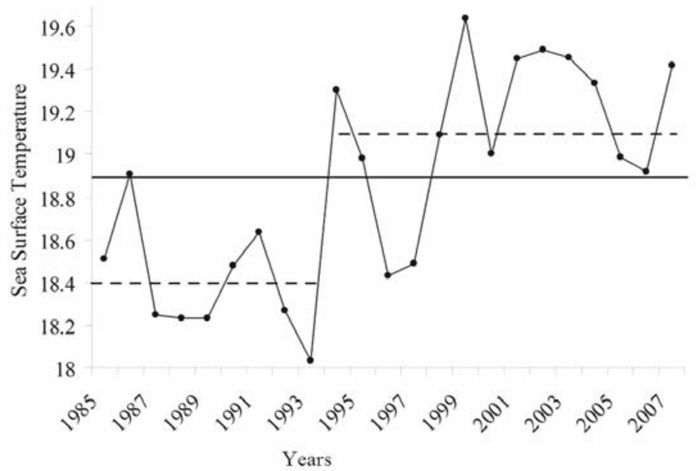

Figure 6. Overall mean SST (thick continuous horizontal line) and mean SST (dashed lines) for the periods 1985-1994 and 1994-2007 in the Aegean Sea for 23-year period (from Raitsos *et al.*, 2009).

The above results underline that the warming of the planet is now unequivocal and that its current impact on the biosphere has been documented in both terrestrial and marine ecosystems. In the Mediterranean this phenomenon leads to tropicalisation of the region, a process of ecosystem change due to the increasing occurrence of warm-water biota, which in turn does affect the biodiversity and functioning of marine ecosystems.

From Bottom Water (Lacombe, 1985) to New-WMDW since 2005. Possible shifts on Open Sea Deep Convection.

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INTRODUCTION

In a Workshop held at Santa Teresa, La Spezia (Italy) in September 1983 Prof. H. Lacombe (Lacombe, 1992, p. 59) reported that:

> …in certain years an "occasional bottom water" is present [in the Western Mediterranean]. It was first detected in 1972 (Tchernia) as a layer deeper than about 2,000 m in which a small positive gradient of both θ and S was present down to the bottom. Thus a minimum of θ and S layer appeared at about 2,000 m. The differences of θ and S between the bottom values and the minimal values at 2,000 m are only about 0.01°C and 0.01…
>
> …The mechanism of formation and spreading of these layers is still to be found.

Two years latter, a paper (Lacombe *et al.*, 1985) devoted to the observations of this "occasional Bottom Water mass" (BW) in several years, namely 1972-73 and 1981-82, was published. The paper concluded that these BW did not form on the shelf and were more likely a result of open-sea winter convection near the centre of the cyclonic gyres. The authors pointed out that understanding the process would require a careful look throughout the year to the factors affecting θ, S and σ_θ of the surface layer and in the core of the LIW reaching the convection area after having overflowed the Sicilian sill. The most important factors affecting θ, S and σ_θ locally are variations of the surface heat and water budgets but, in particular, at least for the salinity which "depends on the amount of precipitation in the area, no effect is clearly discernible from the rain statistics along the French coasts" (Lacombe *et al.*, 1985, p. 337). Therefore, the problem of formation of these bottom waters remained open and could be dependent on the properties of the waters making up the LIW, the winter Deep Adriatic Water (EMDW of Adriatic origin) and the Levantine Winter Water (the LIW at its origin). Thus a monitoring of LIW flowing through the Sicilian sill and an effort to investigate the details of the processes involved in the Deep Waters Formation (DWF) both from a theoretical and observational point of view was recommended.

Twenty years later, López-Jurado *et al.* (2005) reported an "abrupt shift in the WMDW characteristics" found in March 2005. Nowadays, in winter 2009, the WMDW[1] is still affected by some of those changes. The shift reported in 2005 has been also documented through data from the moorings of the CIESM HydroChanges program, placed on the Catalan slope (Font *et al.*,

[1] WMDW – Western Mediterranean Deep Water.

2007) as well as all the papers generated from CTD data obtained in the W. Mediterranean since that time (e.g. Canals *et al.*, 2006; Schroeder *et al.*, 2006; Smith *et al.*, 2008; Schroeder *et al.*, 2008b).

Essentially, since 2005 the structure of the WMDW has become more complex with an increase of both θ and S from ~800-1,200 m downward to a relative maximum, at a variable depth, from ~1,600 to 2,500 m, followed by a new decrease of both variables down to the bottom. The typical signature of this structure in the θS diagram is a V-shape at the bottom of the classical WMDW signature with a "curled end", like "a hook" (Figure 1). This structure suggests the participation of at least two different water types in addition to the 'classical' WMDW, both with higher salinity.

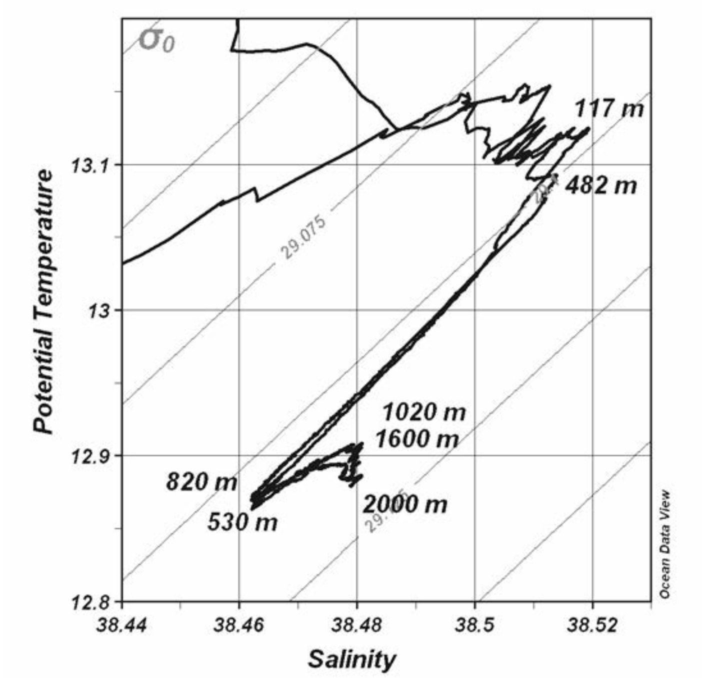

Figure 1. θS diagrams of two CTD casts of March 2005 showing the new characteristics of the WMDW and different positions of the water masses in the column. (Figures were prepared using Ocean Data View software) (Schlitzer, 2008).

The entire signature of this new structure in the θS diagram apparently was not found in any observation before 2005 but the upper part, i.e., the increase in θ and S below the typical WMDW and over the subsequent decrease of both variables, shows the same signature as the above mentioned BW, reported by Lacombe *et al.* (1985). It also presented a V-shape ending in the θS diagram but instead of being at the bottom has been raised more than 1,000 m above the previously reported observations. What does it mean?

The situation before 2005

Bethoux *et al.* (2002) reported V-shape structures at the end of θS diagrams in 1999 and 2000 which they called "θS anomalies", corresponding to waters found at depths of more than 2,000 m, thus having the same properties as the BW previously mentioned. This paper also reports an episode of deep cascading in the canyons of the western Gulf of Lions in 1999. The observation that waters affected by the "θS anomalies" showed an increase of suspended particles and the evidence of cascading lead up to the conclusion that such "θS anomalies" were due to the deep cascading. The authors evaluated the volume of this new water presumably produced by cascading and analysed their propagation and persistency. In particular they discussed the conditions for deep cascading in terms of atmospheric forcing and performed a review of historical data to find such "θS anomalies" back to 1972. What they found were three more episodes, those of 1972-73 and 1981-82 corresponding to the BW of Lacombe *et al.* (1985), and another in 1988-89. In all cases, at least the first year of each episode, coincided with periods of strong vertical convection in the MEDOC area. Therefore shallow coastal waters on the Gulf of Lions' shelf would also experience large heat losses and evaporation. The problem, as noted by Lacombe *et al.* (1985), is that this area receives freshwater inputs that oppose dense water formation. Nevertheless, either a strong cooling of the coastal water or a reduction of freshwater inputs may occasionally increase the density of these waters up to values larger than that of the LIW, as indicated by Person (1974). Bethoux *et al.* (2002) finally concluded that these cold coastal waters may reach the bottom and if dense enough could mix with the LIW, producing the positive θS anomaly in 1999. Therefore a similar behaviour for all the previous events was proposed.

Summarizing, there are two possible origins of the deep V-shape found prior to 2005: open sea mixing proposed, but not shown, by Lacombe *et al.* (1985), or cascading, proposed by Bethoux *et al.* (2002) and supported by the suspended particles and observations of deep cascading in 1999. Both origins would involve an important contribution of LIW.

In those previous observations, the V-shape θS structures or positive θS anomalies lasted only for two years and appear much deeper than nowadays. Is, then, the same process behind these structures? Moreover, the "hook" or "curly end" of the V-shape towards lower θS, at the bottom of the θS diagrams after 2005 was not found in any of those reported historical episodes. Is this last deep water mass that pushed up the positive θS anomaly in 2005?

The new structure, after winter 2005

In the previous section V-shaped ends of the θS structure were related to years of active convection in the MEDOC area but neither all those years or those most active in deep convection produced such structures (e.g. 1969 or 1987).

Winter 2004-2005 was cold but not the coldest of the last 50 years. It was dry but not the driest and it was windy but not the windiest. However, according to Rohling and Bryden (2007) from the NCEP/NCAR analysis, winter 2004-2005 recorded both the maximum total heat loss and E-P in the western sector of the NW Mediterranean. They also found from ARGO profilers data that deep convection has been extended far away from the typical MEDOC area in very unusual places like east of Menorca. This extension of the typical convection area has also been reported by López-Jurado *et al.* (2005), Salat *et al.* (2007) from *in situ* CTD data during March 2005 and has been reflected in the satellite images of chlorophyll. On the other hand, Canals *et al.* (2006) and Font *et al.* (2007) recorded deep cascading events along the western canyons of the Gulf of Lions and the Catalan continental slope. Therefore, all available information indicates that winter 2005 produced a large amount of Deep Water both by open-sea deep convection and by deep cascading. For instance, Schroeder *et al.* (2008b) estimated the total production of the period 2004-2006 at 2.4 Sv, which is the double of the previous maximum estimate. This figure can be considered as a lower bound for winter 2005 alone that, at least in terms of atmospheric forcing, was quite more severe than 2006.

According to the theory of Béthoux *et al.* (2002) the V-shape of the θS diagram should be a consequence of the deep cascading in a year with intense vertical mixing in the MEDOC area. Most of the CTD data in 2005 also showed a relatively high amount of suspended particles along the entire θS anomaly, just like in 1999. However, following the considerations of these authors, we should assume that as the amount of Deep Water formed has been at least doubled, this excess water would be originated from cascading, but this will contradict the reported extension of open sea convection.

> Therefore cascading is not, or at least not the only, factor responsible for the V-shape of the θS diagram.

Schroeder *et al.* (2006), based on data from an extensive CTD survey of the Western Mediterranean carried out in late spring 2005, attributed the V-shape of the θS diagram to the Eastern Mediterranean Transient (EMT)[2], transmitted through the LIW across the Tyrrhenian Sea. This

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[2] In the early 1990s, the structure of the deep Cretan Sea water column changed dramatically, as exceptionally dense ($\sigma t > 29.2$), very saline ($S > 39$) water of local origin started filling the deep Cretan basin and overflowed through the sills of the Cretan Arc straits (Theocharis *et al.*, 1999b; Roether *et al.*, 1996). Due to its high density, CDW displaced water from the deepest parts of the Levantine and Ionian basins in the eastern Mediterranean. Thus, the Aegean became the major contributor of warmer and more saline bottom water to the eastern Mediterranean. Immediately after cooling, the newly formed dense surface water sank rapidly and flowed southward directly above the seabed, thus flooding the deeper part of the Cretan basin. After filling the Cretan basin, the dense water overflowed the Cretan straits through the canyons of the southwest flanks of the straits and spreaded into the deep eastern Mediterranean, flooding the deep Ionian basin.

theory would be supported by the observations of Gasparini *et al.* (2005) who reported a progressive increase in salinity of LIW across the Tyrrhenian in the previous years. This approach would be consistent with the open-sea theory proposed by Lacombe *et al.* (1985) for their "occasional bottom water" and its relationship with variations in θ and S of the core of LIW reaching the convection zone.

However, EMT cannot be invoked for the reported historical events of the V-shape of the θS diagram.

Along the successive years, from 2005 onwards, the structure of this new WMDW remained. During winter 2006, according to Smith *et al.* (2008) the area of Deep Water Formation (DWF) was displaced towards the western Ligurian Sea. The properties of these new WMDW waters are clearly in line with the precedent year with slightly higher values of both θ and S. Deep cascading has also been reported in winter 2006 (Sánchez-Vidal *et al.,* 2008) but to a lesser extent than in 2005. In any case, the final situation after this winter did not change markedly. Winter 2007 was extremely mild and no episode producing WMDW has been recorded. The next winter, 2008, should have produced new WMDW, according to a reference found in Schroeder *et al.* (2009). Finally, we have collected recently (March, 2009) CTD data of this last winter, which are still not accurately explored but show clearly that there has been deep convection, and the characteristics of the WMDW remain similar (Figure 2). Fuda *et al.* (this volume) has also shown a new increase in θ and S during this last winter in the HydroChanges mooring located in the centre of the MEDOC convection area.

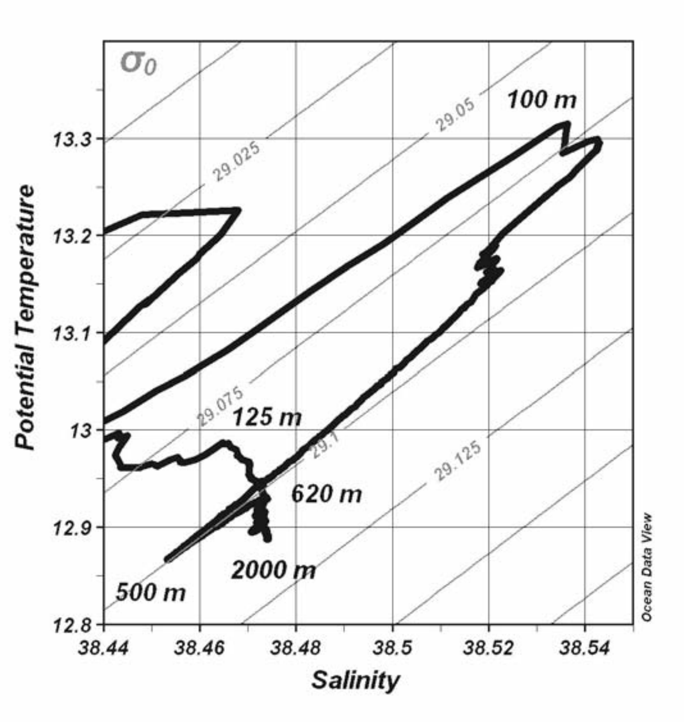

Figure 2. θS diagram of two winter 2009 CTD casts. One of them presents an almost homogeneous profile.

Summarizing, in winter 2005 an unusual amount of new WMDW was produced with a significant contribution from cascading. An increase of both θ and S of the LIW entering in the western sector of NW Mediterranean was also observed, due to the EMT. These two factors should be responsible for the new θ and S structure of the WMDW. The V-shape in the θS diagram has been related to changes in the LIW, due to the EMT, to cascading, or both. The new structure however presents a decrease of both θ and S from the end of the V down to the bottom, "the hook" in many of the stations sampled after 2005. To what can this be related? Is this is an unprecedented situation in the area? Can we find any similar structure other basins?

PRECEDENTS OF THE "HOOK"

In winter 1999 the Institut de Ciències del Mar/CSIC performed a cruise (Hivern 99) covering a grid of stations concentrated along the northern Catalan shelf and slope and in a section between Barcelona and the Balearic islands. During the cruise we suffered some strong episodes of northerlies and the data revealed that open sea deep convection was active in some stations. Some unusual features in the general circulation were also found (Estrada *et al.*, 2004), in particular a large anticyclonic gyre in the central Catalan sea, where typically the circulation is cyclonic (Pascual *et al.*, 2002). The presence of such a large eddy produced a reversal of the shelf-slope current in front of Barcelona, blocking the Northern current along the slope, forcing it to deflect towards open sea more to the north and restricting the cyclonic area where deep convection takes place. Such behaviour may have influenced the preconditioning phase not only restricting the area but enhancing the intensity of the deep convection according to Estrada *et al.* (2004). In winter 1999, deep cascading was observed in the Lacaze-Duthiers canyon in the western end of the Gulf of Lions (Bethoux *et al.*, 2002; Durrieu de Madron *et al.*, 2005). A careful examination of the θS diagram of the best well mixed station in the Hivern-99 cruise (Figure 3) showed probably the earliest evidence of the "hook" This is then a precedent of the post-2005 WMDW situation. In Puig *et al.* (this volume) a detailed explanation of the relations of these new bottom waters and the observed cascading will be found, giving us some new clues about the process occurring in 2005.

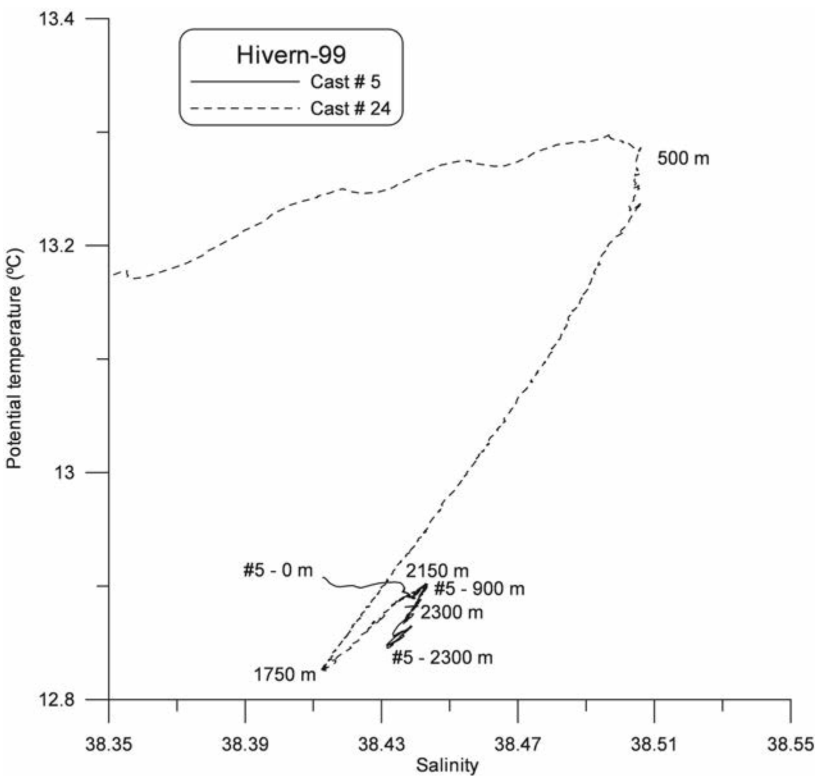

Figure 3. θS diagram of two winter 1999 CTD casts, at different stages of mixing, showing the "v-shape"(#24) and "hook"(#5) typical of the "new" WMDW.

THE EASTERN BASIN

Some structures that recall those of the recent WMDW can be found in papers dealing with the changes experienced by the EMDW during the EMT. In a summary report (Lascaratos *et al.*, 1999 - Figs 4, 6 and 12) V-shaped θS diagrams appear as a consequence of the EMT being the old EMDW of Adriatic origin at the vertex of the V, and its right upper end pointing to the water outflow of the Cretan straits after the EMT. The EMT was initiated by a strong increase in salinity in the Cretan Sea that was subsequently followed by a further decrease in temperature. Since 1989 CIW, an intermediate water mass that had been unnoticed before the transient because it was lying on the straight line between LIW and EMDW, changed to a higher salinity due to both significant anomalies in air-sea heat and freshwater budgets in the area. A disruption of the general circulation as a result of an anticyclonic eddy blocking the communication between the Ionian and Levantine basins led to salinity increasing in the Levantine upper waters as a result of a diminution in the intrusion of lower salinity waters from the Ionian Sea, and to a diversion of the high salinity waters into the Aegean. The increasing salinities in the Levantine and in the Aegean thus affected the preconditioning process of the water convection in the Cretan Sea. This is then a precedent of a V-shaped θS diagram that has been caused by open sea deep convection under high atmospheric forcing and a blocking of the typical circulation pattern.

THE OBSERVATIONS IN WINTER 2005

During March 2005, just immediately after the last northern storm of the winter, a cruise across the Balearic basin with incursions to the north, in the MEDOC area, has been conducted by the Institut de Ciències del Mar (CSIC). In this cruise (Eflubio 2005) the new structure of WMDW was found, although due to sampling constraints very few of the CTD casts were deep enough to capture the entire WMDW mass. The results have been presented in Salat *et al.* (2007). These authors suggested the contribution of three water types to explain the structure, named O, N and C, which corresponded respectively to the Old or "classical" WMDW, the New WMDW with higher θ and S values, and the water from Cascading (Figure 4). These three different source water masses in the deep layer were also identified by Schroeder *et al.* (2006), who suggested a major contribution of LIW to water mass N (B in their paper) and a higher portion of AW in water mass C. The C water formation was clearly identified by Font *et al.* (2007) as generated by deep cascading of dense shelf waters and, obviously, the origin of O is well known, although it was not clear whether this water had been renewed during winter 2005. However the origin and processes involved to give rise to the N water have not been completely elucidated yet. Salat *et al.* (2007) proposed that its origin should be from open sea deep convection in the periphery of the MEDOC area with a quantitatively important contribution of the LIW, as also suggested by Font *et al.* (2007), after the analysis of the time series of a deep CTD moored in the lower Catalan continental slope.

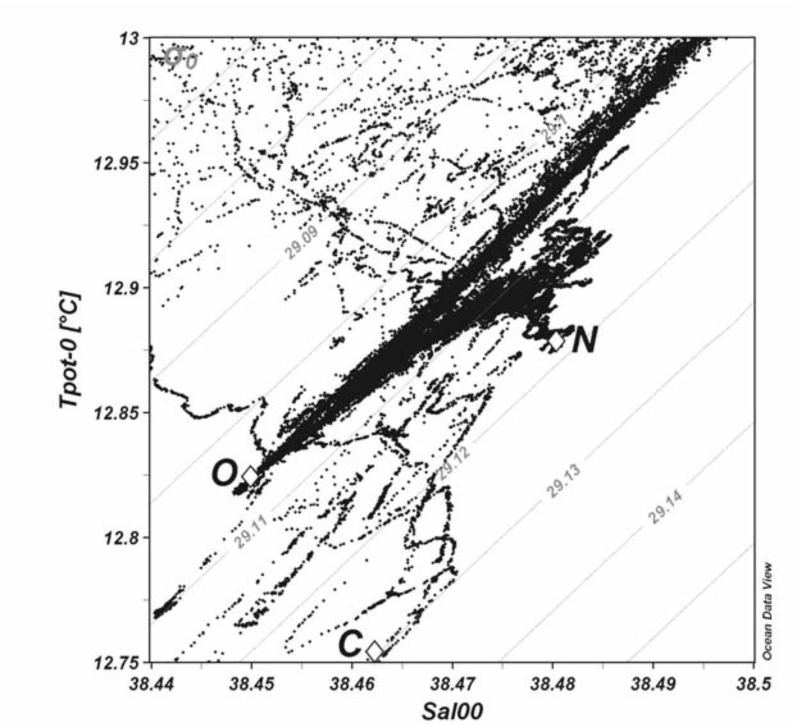

Figure 4. General θS diagram of WMDW found during Eflubio-2005 cruise (March 2005) showing the water types O, N and C involved on the water mass.

The data obtained in Eflubio 2005 cruise showed some interesting situations which may help explain the results and justify the above mentioned origin of N:

1. Very homogeneous water columns were found in many separates places like near Menorca and north of Mallorca, as well as in the MEDOC area, including several points along the track to it from the Balearic Islands.
2. A relatively shallow (~500 m) position of the old WMDW was found in some stations (Figure 1).
3. The thickness of the positive anomaly of θ and S was between 500 and 800 m (Figure 1).
4. A very high value of salinity (38.67) was found at 350 m in a CTD cast E of Menorca, structured in very thin layers of 20 to 50 m thick (Figure 5).
5. The highest salinity values at surface, up to 38.49, were found near the northern Catalan continental slope through continuous surface analysis underway.
6. The vertical structure of density found in the two transects across the Catalan continental slope in front of Barcelona was reversed than usual, suggesting a northward circulation and an uplifting of the LIW towards the shelf (Figure 6).

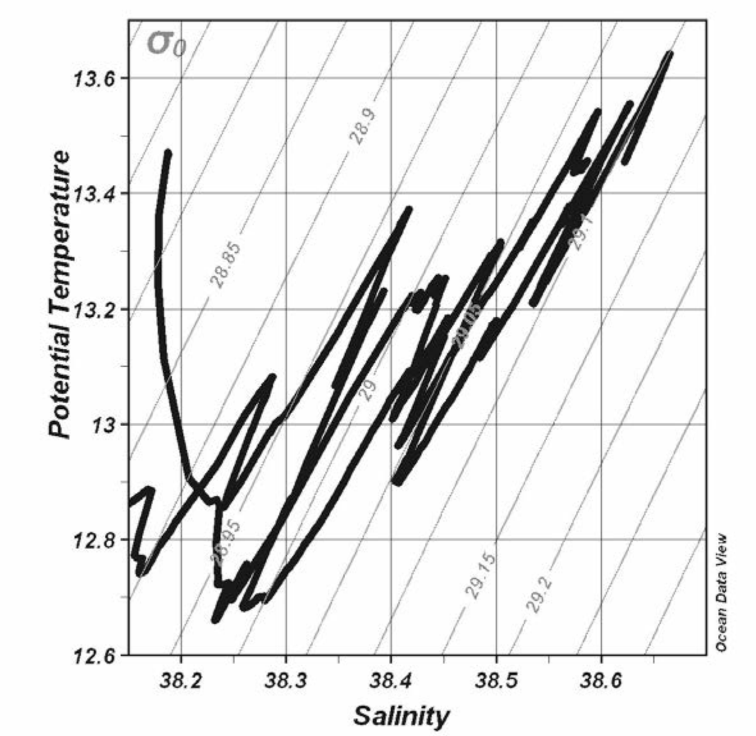

Figure 5. θS diagram of two winter 2005 CTD casts, east of Menorca (40°15'-40°25', 5°08'E, showing highly saline LIW at 250-350 m highly "layered".

These observations (points 1, 2 and 3 of the above listing) confirmed the large extension of the area where deep convection had been active and the high volume of WMDW produced during that winter. This convection required an important volume of LIW that has been uplifted to the surface thus forcing a rapid transport of LIW directly from the Sicily passage (points 4 and 5). The irruption of LIW from the south towards the deep convection area, when reaching the surface may contribute to reversing the circulation at the Catalan slope (point 6) blocking the transport of relatively fresher AW and continental shelf waters thus helping the deep cascading.

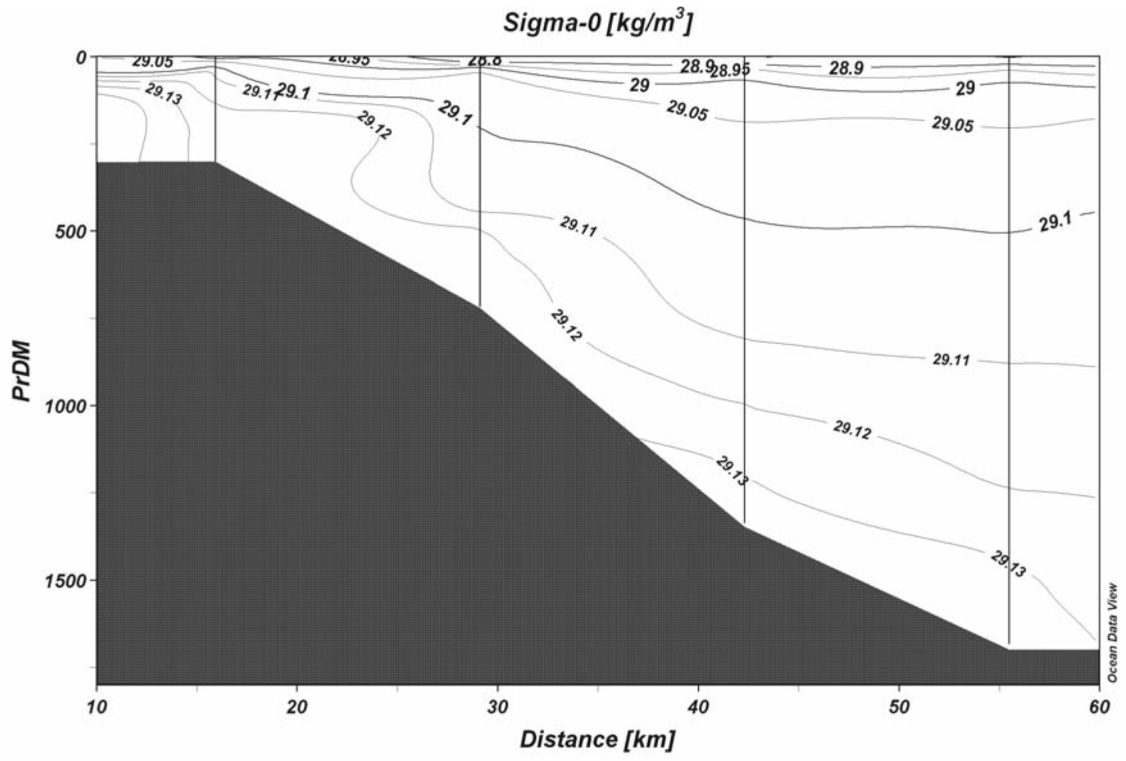

Figure 6. Vertical section of density across the continental slope in front of Barcelona in March 2005.

DISCUSSION

According to the above mentioned considerations, new WMDW type N could be formed by open sea deep convection with an important contribution of LIW in areas near the continental slope. During winter 2005 LIW has been found at surface near the slope (point 5) without any signature of the Northern Current (point 6). In other winters this area is occupied by relatively recent AW, carried by the Northern Current, and convection limited by the lower density of recent AW contributes to the formation of WIW (Salat and Font, 1987). While there are not enough data either to confirm or reject the above hypothesis, the process might be started by two important episodes of heat loss during November 2004 and January 2005, reported by Rohling and Bryden (2007) in conjunction with a long dry episode (very high E-P), that would precondition a large area. Then, the subsequent long episode of relatively high heat loss to early March would start pulses of violent mixing which "called" large compensating fluxes from everywhere, especially from the SE with a relevant component of recently imported LIW.

A rough estimate of the velocity of the water in the intermediate layers "called" by the DWF process, that is, entering the area to supply the requirements of DW formed, can be derived from the total volume of DW formed in 2005. Using the evaluation presented by Schroeder *et al.* (2008b) and assuming that the process had been active for 1.5 months, if we consider an intermediate layer 500 m thick and that the water has to reach the area through the Ligurian Sea or south of Sardinia in a joint section of around 200 km, we obtain a mean velocity of 23 cm/s. This velocity is surprisingly large as a mean but should not be unrealistic. This is especially evident if we look at the rapid expansion of the newly formed WMDW reported by Schroeder *et al.* (2006). Considering the high salinities of the LIW found east of Menorca during March 2005 (point 4) and the layered structure of this water mass one can imagine that this water has been moving in rapid filaments. Moreover, ARGO profiler #4900556, deployed during the March 2005 cruise, displayed speeds ranging between 16 and 25 cm/s drifting at 300 m depth.

Under these circumstances it is difficult to estimate to what extent the signal of the EMT through LIW played a significant role on this new WMDW of 2005 as proposed by Schroeder *et al.* (2006). According to these authors the signal had recently arrived to the NW part of the basin transported by the general cyclonic circulation thus reaching the region from the NE but most of the new WMDW has been formed in the western half involving the available resident LIW. Therefore it will be after the DWF process that, through a renewal by the compensating fluxes directly "called" from Sicily and probably from the Ligurian Sea, the new LIW would incorporate the signature of the EMT, being ready for the Deep Water Formation in subsequent years, provided adequate atmospheric forcing. Thus WMDW formed in 2006 and probably in 2008 and 2009, with "typical" atmospheric forcing would incorporate this new LIW that will help the perpetuation of the new structure. This mechanism would be consistent with the observations of Rohling and Bryden (2006) and Schroeder *et al.* (2008b) that pointed out to the Western Ligurian Sea for DWF in 2006 with a higher salinity LIW.

Some preliminary conclusions

- The "new" structure of the WMDW involves three water types: the old WMDW, a new DW formed in open sea by convection with higher salinity, and a DW formed on the NW shelves by cascading. The new DW formed in open sea would correspond to the "occasional bottom water" reported by H. Lacombe but in a larger amount than in precedent years and uplifted by the water from cascading that in turn had been produced in an unprecedented amount.
- The "new" structure of the WMDW after 2005 is not entirely new as there are some precedents, in particular in winter 1999, but at lower scales. There are certain similarities among the situations found in both years that may give us some clues about the mechanisms that triggered the formation of this "new" WMDW structure. Both years presented relevant atmospheric forcing and the normal flow of the Northern current along the Catalan slope had been blocked. In 1999 this was caused by an unusual large anticyclonic eddy in the centre of the Catalan basin, and in 2005, was probably due to an early irruption of intermediate waters from open sea or from the south. Such a blocking of a lower salinity AW input at surface increased the salinity and reduced the buoyancy of the upper layers over a large area exposed to the atmospheric forcing, the area where WIW is typically formed. This situation has similarities with the blocking of the Levantine to Ionian circulation that changed the characteristics of the CIW in the Eastern basin, triggering the EMT.
- The signal of the EMT through the LIW involved in the WMDW has played an important role to maintain the "new" structure of WMDW beyond 2006 but it is unclear that it triggered this "new" structure in 2005.
- It is not sure that in the recent winters any DW with the "old" characteristics had been produced by convection process, as shown by the relatively low oxygen content of the layer that this water occupies nowadays. However, the sharp vertex in the V-shape of the θS diagram is, four years later, still not eroded. A parallelism of what happened during the EMT in the Eastern Mediterranean cannot be invoked here because then, the EMDW from Adriatic origin was still active.

Experimental evidence of recent abrupt changes in the deep Western Mediterranean Sea

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Abstract

Recent studies suggest that the deep western Mediterranean is undergoing a drastic change, comparable to what happened in the eastern basin during the mid '80s and '90s, the Eastern Mediterranean Transient (EMT). An alteration of the stratification, associated to an abrupt temperature and salinity increase, has been observed, of which the extension, causes and effects are still largely unknown.

1. Introduction

Recent studies have evidenced important changes in the western Mediterranean (WMED), each giving partial description of specific processes and areas. Those studies provide an important mosaic, which now is ready for a synthesis as well as modeling effort.

Some 20 years after the EMT, which deeply changed the eastern basin (Roether *et al.*, 2007), the significant changes observed in the western deep water characteristics (Schroeder *et al.*, 2008b) definitively alter the old view of the Mediterranean as a steady system.

In the deep layers of the western basin, an almost constant trend towards higher salinity and temperature has been observed since the '50s. More recent observations evidenced an acceleration of this tendency, which has been related to the propagation of the EMT signature, from east to west (Gasparini *et al.*, 2005). Since 2005, the data collected in the deep western basin have revealed an abrupt change, with the appearance and spreading in the whole western basin of a new deep water, significantly warmer and saltier than previously, which has substantially substituted the resident deep water. This new deep water has been formed during massive convection events, that took place during the winters 04/05 and 05/06 in the north-western Mediterranean (NW-MED).

Between 2004 and 2009 the CNR-ISMAR (La Spezia) and the CNR-IAMC (Oristano) have jointly carried out an effort to monitor the anomaly at the basin scale (WMED), programming at least one oceanographic cruise per year in order to obtain the most comprehensive picture of its evolution. A summary of the temporal evolution of the anomaly, and the consequent uplifting of the resident deep water is given in Figure 1. The vertical profiles of potential temperature and of salinity in a station located south of the Balearic Islands (5 °E, 38 °N), are shown for the years 2004, 2005, 2006 and 2008. They clearly evidence the gradual uplifting of the resident deep water, replaced near the bottom by the warmer and saltier new deep water. The thin gray line refers to

2004, that is before the convection events, and it shows a rather homogeneous deep layer. A near-bottom salty and warm vein intrudes in 2005, shown by the thick black line; this layer had become 600 m thick in 2006 and almost 1,000 m thick in 2008.

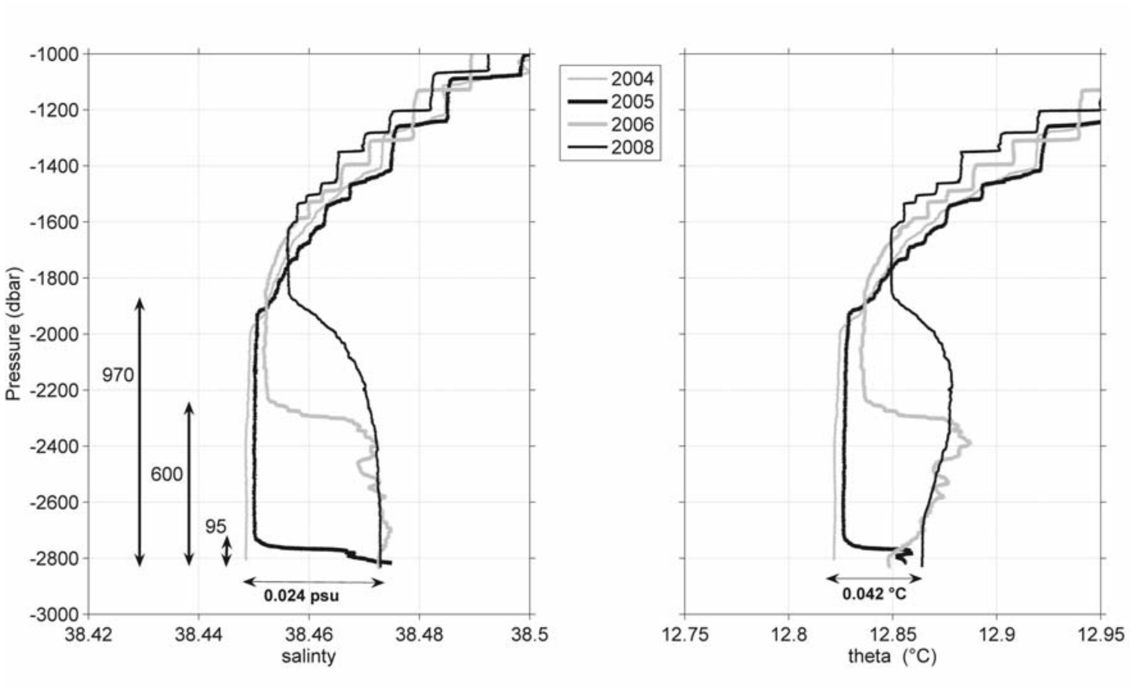

Figure 1. Vertical profiles of salinity (left) and potential temperature (right) measured at an example station in the Algerian basin (5 °E, 38 °N) in October 2004 (gray thin), June 2005 (black thick), October 2006 (gray thick) and November 2008 (black thin). The vertical arrows indicate the thickness of the new WMDW layer in the different years, while the black horizontal arrows indicate the total salinity and temperature increase at the bottom between 2004 and 2008.

2. Observed changes

The properties of the WMDW began to change after two winters in which new deep water has been formed by deep convection: winter 04/05 and winter 05/06. In winter 04/05 the deep water formation (DWF) events that led to this salty and warm new deep water mass occurred mainly in the Gulf of Lions and the Catalan subbasin, over an usually large area (Font *et al.*, 2007; Lopez-Jurado *et al.*, 2005; Canals *et al.*, 2006; Schroeder *et al.*, 2006; Smith *et al.*, 2008). The event has probably been triggered by strong atmospheric forcings and a very high salt content in the intermediate layer. In the following winter 05/06, the deep water formed mainly in the Ligurian Sea. This winter was characterized by a weaker buoyancy loss, but the LIW layer was saltier, warmer and shallower than in the previous winter and, at the surface, the Ligurian Sea was cooler and saltier than the Catalan subbasin in the previous winter (Smith *et al.*, 2008).

Schroeder *et al.* (2008b) described in detail how the new WMDW has spread, filling almost the entire WMED below 2,000 m depth, showing that the water rapidly propagated towards the interior of the basin. Figure 2 shows the stations visited in 2005, 2006 and 2008, distinguishing between those where no new deep water was observed and those which have been recently ventilated. In 2005 the new WMDW was found in a wide area of the WMED, along its spreading pathway, even in the northern part of the Algerian subbasin and in stations near the entrance of the Alboran subbasin. In 2006 the new WMDW was present in almost the whole WMED, excluding the Tyrrhenian and the western Alboran subbasins. More recent data, collected in 2008, clearly evidence that the only subbasin that has not yet been reached by the new WMDW is the Tyrrhenian Sea. In 2008 its signature was found at the entrance of the shallower Alboran Sea, where its interface with the overlying water was at 950 m depth. Here the univocal identification of the winter-04/05 formed deep water near Gibraltar was possible thanks to the particular shape in the theta-salinity diagram. Therefore, its recent detection (November 2008) at about 100-150 km from the Strait of Gibraltar, allows also an accurate estimate of the temporal scales of its spreading: a deep water mass formed in February-March 2005 in the NW-MED has almost reached Gibraltar in 33 months.

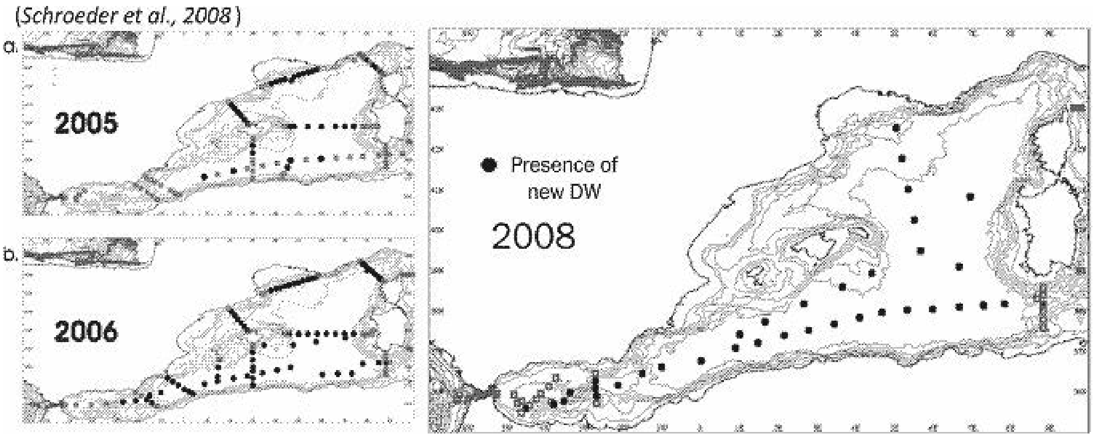

Figure 2. Spreading of the new WMDW (black dots) during 2005, 2006 (from Schroeder *et al.*, 2008b) and 2008. The distinction criterion between stations with (without) new deep water was the presence (absence) of the "hook" in the theta-S diagram with a significant increase of dissolved oxygen.

3. Forcings

The deep water properties and their variability are due to the hydrographic preconditioning (heat and salt content and structure of the water column before the onset of convection), and to the atmospheric forcings (heat, freshwater and buoyancy fluxes). The deep convection is sustained by the combination of surface heat and freshwater losses and the lateral convergence of heat and freshwater. In a steady state it is supposed that there is a balancing between the removal of heat and freshwater by the atmosphere and the supply of those properties by the ocean. But we have observed a changing situation, so it is likely that one or both of the two water masses that contribute to the formation of the WMDW have carried more salt and heat than previously to the formation region, in order to explain the abrupt increase in heat and salt contents of the newly formed deep water mass.

Different hypotheses have been adopted to explain the causes of the anomaly. Schroeder *et al.* (2006) related the new deep properties to a progressive increase of heat and salt content in the intermediate layer, due to the arrival of water of eastern origin which has been affected by the EMT event. Other authors, such as Font *et al.* (2007) and Lopez-Jurado *et al.* (2005), attributed it to the extremely strong winter forcings in 04/05. In terms of air-sea heat exchange, Lopez-Jurado *et al.* (2005) showed that the heat loss of this winter was 70 % above the winter average. Additionally, in terms of air-sea freshwater exchanges, Font *et al.* (2007) assert that in autumn and winter 04/05 precipitation over the NW Mediterranean catchment area was greatly reduced, with the lowest absolute values ever recorded at many of the meteorological stations and that northerlies were strong and persistent.

The atmospheric forcing was without doubt exceptional, especially during winter 04/05. We have determined time series of net evaporation anomalies and net heat flux anomalies (winter months in the NW-MED) from NCEP-NCAR (Figure 3). From here we may note that winter 04/05 showed the highest anomalies since 1948 for both net evaporation and net heat loss. Winter 05/06 also was characterized by strong heat loss, but with a quite low value for net evaporation.

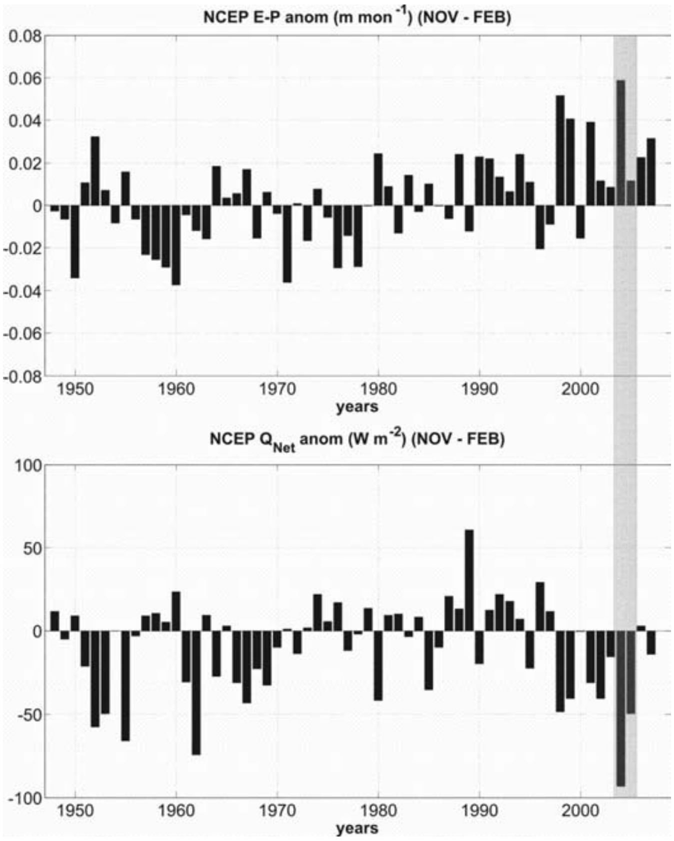

Figure 3. Winter (NDJF) net evaporation anomalies and net heat fluxes anomalies from 1948 to 2008, from NCAR-NCEP over the NW-MED.

With the term "hydrographic preconditioning" we refer to the heat and salt content in the water column before the onset of convection as opposed to the "dynamical" preconditioning, which is related to the doming of the isopycnals due to the cyclonic circulation. Previous studies investigated the advection of more salt and heat from the eastern to the western basin (Gasparini *et al.*, 2005). Schroeder *et al.* (2006) have attributed to such advection an important role in the formation of this new WMDW. Long time series in fixed stations (Sicily Strait, Tyrrhenian Sea, Corsica Channel, Ligurian Sea) coherently show a tendency towards higher heat and salt contents, especially in the intermediate layer, occupied by water coming from the Eastern Mediterranean. As a matter of fact, Figure 4 clearly shows that more salt and heat is continuously arriving from the eastern Mediterranean. It is relevant to remark that the eastern Mediterranean outflow is still experiencing an increase in temperature and salinity, suggesting that the eastern basin is far to have recovered the pre-transient condition. One important question that arises from these observations is whether there is any connection with the EMT, with the production of warm and salty Cretan Intermediate Water, or if the LIW formed in the Levantine basin shows similar trends and why.

Summarizing the issue of the hydrographic and atmospheric forcings that triggered the formation of the anomalous deep water, some possible explanations are that the anomalous properties of the new WMDW are due to a decadal salt and heat accumulation in the formation area advected from east to west and that on the other hand the anomalously high amount of new WMDW produced is due to the particularly intense winter heat and freshwater losses, mainly during winter 04/05, as we have seen. Further studies are currently ongoing, in order to evaluate the relative influence of atmospheric forcings and lateral heat/salt advection on the properties of the new WMDW (Schroeder *et al.*, in prep.).

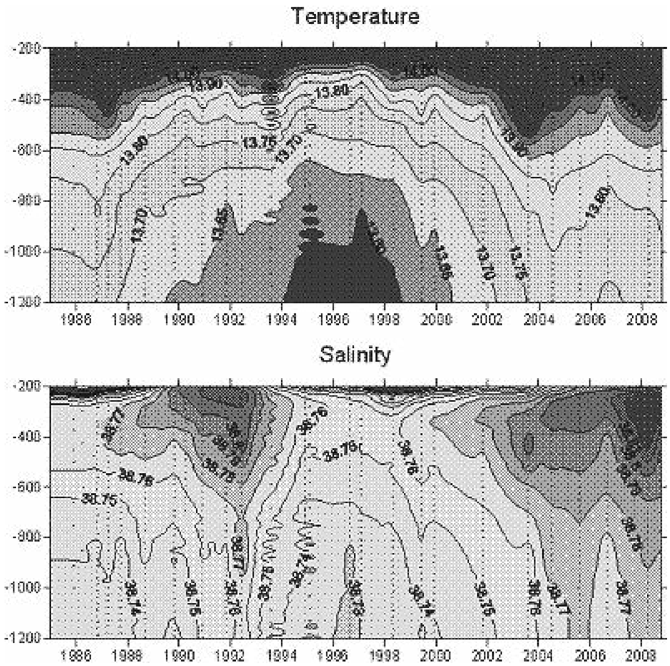

Figure 4. Temporal evolution of potential temperature and salinity in the central Strait of Sicily between 200 m and 1,200 m. In 2008 the highest temperature and salinity values since 1985 have been recorded.

4. Main research gaps

Despite several advances in recent years, there are still huge gaps in current knowledge, as well as the need of a monitoring effort of the anomaly, including not only physical parameters, but also biogeochemical, sedimentological and biological ones. The main knowledge gaps regarding this event are both specific and general (Table 1).

Table 1. Specific and general needs of further investigations.

Specific needs	**General needs**
Identification of the causes that triggered the event (atmospheric forcings vs lateral advection?)	Better understanding of the thermohaline stability and variability in the Mediterranean Sea, as well as identification of the factors that modulate this variability.
Determination of the origin of the greatly increased salt and heat transport across the Strait of Sicily (Cretan Intermediate Water, Levantine Intermediate Water…?), which is still continuing.	Reconstruction and monitoring of the post-transient evolution, which occurred and is still occurring in the eastern Mediterranean Sea.
	Reconstruction and monitoring of the event presently occurring in the western Mediter-ranean Sea.
	Assessment of the degree to which a relevant deep water production in a given year may influence the production of the following years (*memory* of the system).

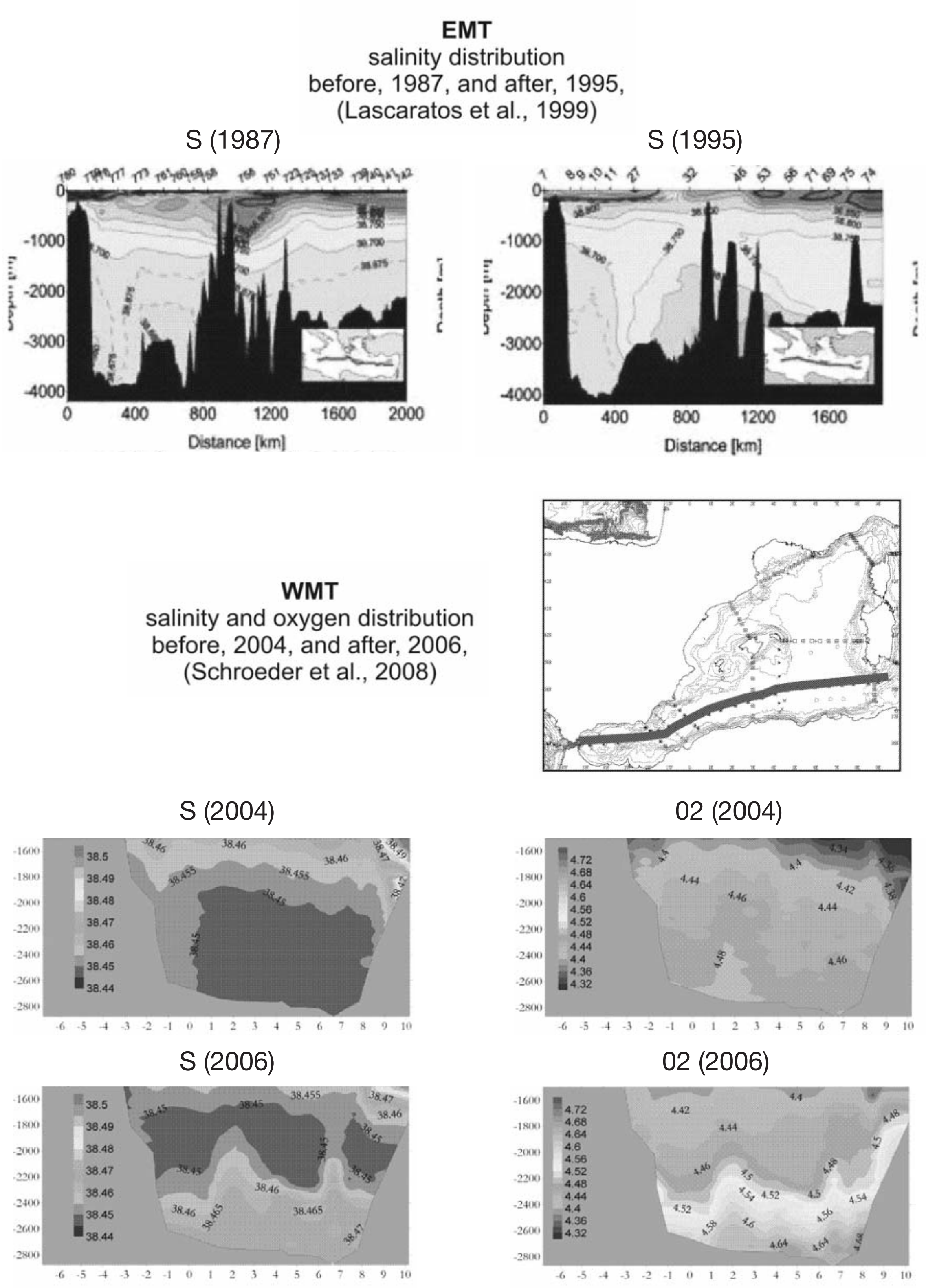

Figure 5. Comparison between observations of the EMT in the eastern basin and recent observations in the western basin.

Even though the described event (which in the Executive Summary is proposed to be called Western Mediterranean Transition, WMT) has several similarities with the EMT (Figure 5), it has not received the same attention. Therefore the future research priorities should aim to make up for this lack, scheduling the monitoring of the event and addressing the study of its causes (remote or local) and possible repercussions.

Variability of the Mediterranean deep and bottom waters: some recent evidences in the western basin

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ABSTRACT

Recent evidence of changes in the physical (temperature and salinity) and chemical (pH, total alkalinity, total inorganic carbon and the partial pressure of CO_2) parameters in different locations of the western Mediterranean basin is briefly summarized. In particular we report evidence of an increase in temperature and salinity of the Mediterranean outflow in the Gulf of Cadiz with an acceleration during the last decades. Further, some recent results obtained in the framework of the "CIESM-SUB" cruises and the VECTOR project in the Tyrrhenian Sea are also presented.

INTRODUCTION

Traditionally the observations of changes in the properties of ocean waters have been restricted to surface or intermediate-depth waters, because the detection of change in bottom water is extremely difficult owing to the small magnitude of the expected signals. Nevertheless, the small temporal changes in the properties of such deep waters across the basins are of strategic interest, as they can be used to constrain the transport of water at the bottom of the ocean and also to detect changes in the global thermohaline circulation which are crucial to study climatic evolution.

Even though the main aspects of the Mediterranean Sea circulation and thermohaline variability are relatively well known (e.g. Malanotte-Rizzoli, 1999; Robinson *et al.*, 2001), our knowledge of the processes taking place in some key (deep) areas is far from being exhaustive.

In the last decades the Western Mediterranean Deep Waters (WMDW) have shown a constant trend towards higher temperatures and salinities (e. g. $\Delta\theta = 3.5\ 10^{-3}$ °C yr^{-1} and $\Delta S = 1.1\ 10^{-3}\ yr^{-1}$ respectively for the period 1959-1996; Béthoux and Gentili, 1999). Moreover recent studies have shown a dramatic increase of such changes ($\Delta\theta$= 0.038 °C and ΔS = 0.016 in the period 2004-2006; Schroeder *et al.*, 2008b) which is 5-7 times greater than the previous estimations; this could be related to the westward propagation of the Eastern Mediterranean Transient (EMT) anomalies which crossed the Sicily Channel at the beginning of '90s (Gasparini *et al.*, 2005). The EMT has been studied, with an international effort, mainly in the Eastern Med, using physical (temperature and salinity), biogeochemical (dissolved oxygen and nutrients) and anthropogenic chemical tracers (chlorofluorocarbons or CFC). Similar changes that are now evident in the western basin of the Mediterranean could be ascribed to the EMT, could be a consequence of local anomalies, or a combination of both.

These aspects must be clarified in order to study the possible consequences of these changes on different compartments such as the Mediterranean outflow at the Gibraltar Strait, the marine biota and the role of the Mediterranean as a source or a sink of CO_2.

THERMOHALINE CHANGES IN THE GULF OF CADIZ AND ALBORAN SEA

Mediterranean Water (MW) released through the Strait of Gibraltar into the Gulf of Cadiz is basically a mixture of Levantine Intermediate Water (LIW) and Western Mediterranean Deep Water (WMDW) (Bryden and Stommel, 1982), although, as recently pointed out by Millot *et al.* (2006), other Mediterranean waters may, sometime, contribute to its formation. In either case, WMDW is always identified by high salinity values. In the Strait of Gibraltar, Millot *et al.* (2006), comparing temperature and salinity observations obtained within the last two decades, have noted an anomalous warming and increase in salinity, from the early 2000s, corresponding to ~0.3°C and to ~0.06 respectively. During the twentieth century also the Mediterranean Sea warmed quite significantly in the deep waters as well as in the surface layer (Béthoux *et al.*, 1990; Krahmann and Schott, 1998; Gasparini *et al.*, 2005; Rixen *et al.*, 2005).

Fusco *et al.* (2008) founded changes in water properties of MW outflow, with an average value of 0.16°C and 0.05 in temperature and salinity respectively per decade over the last fifty years (1948-1999). They observed that the layer thickness ventilated by MW increases almost regularly in time, but with an evident acceleration in the last three decades: about 1,000 m thickness and with salinity ranging between 36.0 and 37.0 (Figure 1). Moreover they provided an estimate of the temperature and salinity variations in the Cadiz Gulf by varying the transport through the Strait of Gibraltar and using thermohaline data of Alboran Sea integrated in the layers 50-800 m. The trends obtained through these relations are consistent with previous estimations. Correlation values 0.63 and 0.76, for salinity and temperature respectively, show the existence of a relation between the thermohaline characteristics of the water coming from the Alboran Sea and the properties of the Mediterranean Outflow in the Cadiz region (Figure 2). These results suggest also that the transport through the Gibraltar Strait, characterized by a multidecadal variability (Tsimplis *et al.*, 2006), is more likely one of the key factors to take into account to justify the difference between the trend in the Mediterranean Sea and those observed within the intermediate layer of the North Atlantic influenced by ML outflow.

However, there is no clear evidence that the observed trends can be due to climate change or to climate variability only; but the analysis does suggest that the natural or anthropogenic effect is accompanied by considerable decadal variability and that their relationship is more complex than previously thought, requiring further investigation.

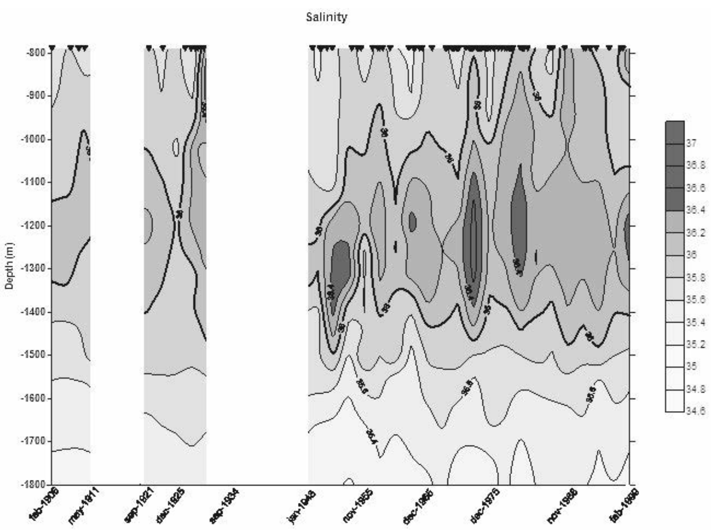

Figure 1. Properties of MW in the Gulf of Cadiz, depth versus time: monthly mean of salinity. Superimposed triangles show temporal distribution of monthly mean profiles.

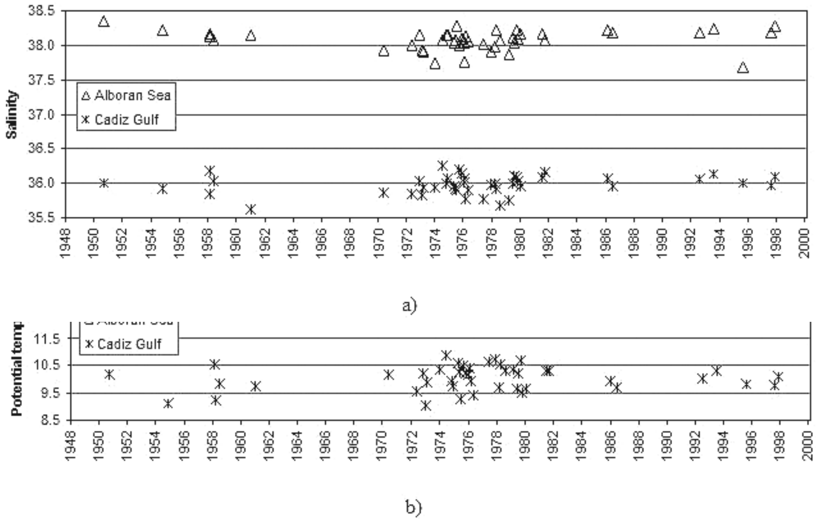

Figure 2. Salinity (a) and potential temperature (b) in the Gulf of Cadiz and Alboran Sea integrated respectively in the layer 800-1,600 m and 50-800 m.

TYRRHENIAN SEA

In the last year the observational activity focused on the Tyrrhenian Sea, because this area was not adequately observed in the past, since considered a marginal basin for the Mediterranean Sea.

During July and December 2005 two basin scale CIESM/SUB oceanographic campaigns cruises have been performed in the Tyrrhenian basin with the objective of monitoring the hydrographic conditions after the significant changes observed during the previous decades. Data collected along two section centered in the central part of the Tyrrhenian Sea (Figure 3a) where recently published in a DSRII special issue (Briand and Giuliano, 2009).

The analysis of the thermohaline field and the LADCP profiles evidenced, for the first time, the critical role played by an isolated topography to influence the interior Tyrrhenian circulation.

The Vavilov seamount, together with the weak mean current, seems to be responsible for the persistence of eddy structures (Figure 3b) in this region in the surface layer (Budillon *et al.*, 2009); below it the clockwise (anti-cyclonic circulation) extends over all the water column to the bottom.

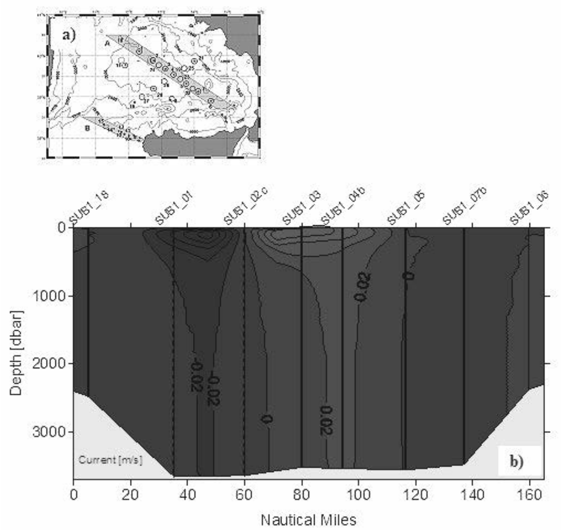

Figure 3. a) cast positions during CIESM-SUB1 (points, July 2005) and CIESM-SUB2 (circles, December 2005) cruises in the Tyrrhenian Sea; b) vertical section of geostrophic currents, the reference level was taken at 50 m depth imposing the velocity measured by the LADCP.

The observational data (hydrographic properties and dynamical parameters) supported the hypothesis that we observed the same structure in both periods (July and December 2005). Actually, the concurrent and long-term presence of a positive altimetric anomaly in the eddy area suggests that the anticyclonic signature might persist for a long period.

If the topographic effect is responsible for the permanence of the eddy in the region, it is important to understand if the observed eddy was locally generated or was advected in the region by large-scale circulation. We found that the hydrographic properties were very similar to those of the Western Intermediate Waters (WIW), which originates during the winter period in the Northwestern Mediterranean (Salat and Font, 1987). This might suggest that the eddy observed in the Tyrrhenian already existed and had a remote origin. WIW patches have been detected in different regions of the Western Mediterranean, sometimes with an eddy structure ("Weddy" see Millot, 1999), whose diameter can reach 100 km or more, allowing the Weddies to endure erosion processes and to cover long distances without losing their peculiarity.

Moreover the thermohaline profiles allowed us to update the results of Gasparini *et al.* (2005) on the intermediate and deep water column in the central/southern Tyrrhenian (Figure 4) suggesting that such changes can be explained in the terms of EMT.

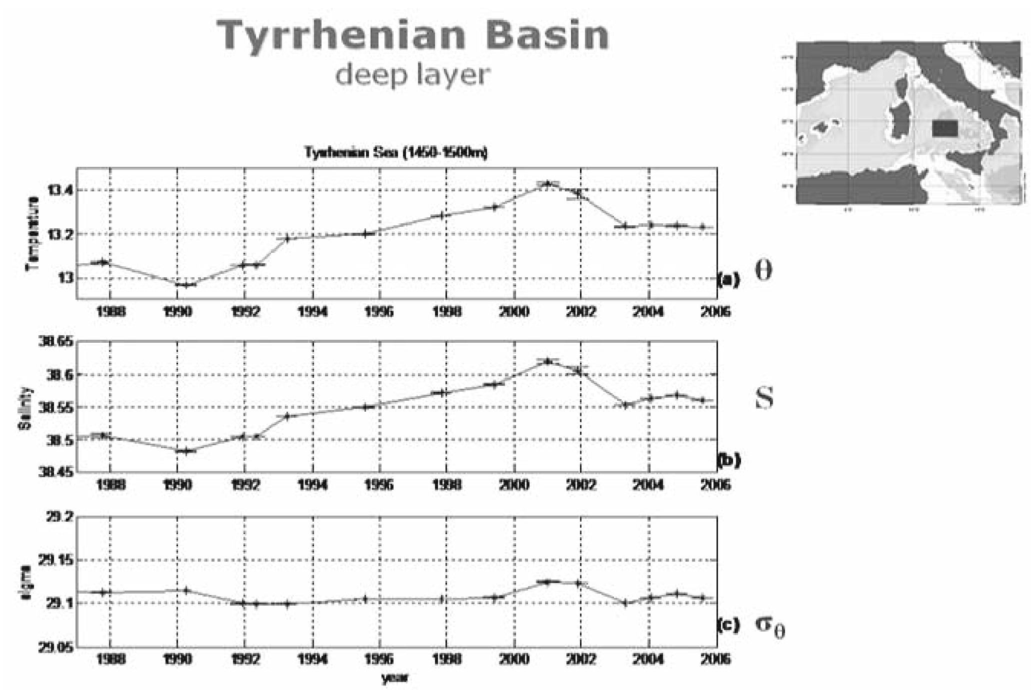

Figure 4. Temporal evolution of potential temperature (θ), salinity (S), and potential density (σ_θ) in the deep layers of the Tyrrhenian Sea (update from Gasparini *et al.*, 2005 with the data collected during the CIESM-SUB1 and CIESM-SUB2 cruises).

The available observations also allow us to establish that the EMT reached the Tyrrhenian entrance between April and May 1992 because of a huge, impulsive amount of salt and cold water mass. The impact of the EMT on the western basin is maximum during the 1992-1994 period, when a great portion of the Strait outflow sinks into the deep Tyrrhenian basin, probably reaching its greatest depths. This behavior is in good agreement with the different phases of the EMT and with changes observed in the eastern basin (Malanotte-Rizzoli *et al.*, 1999; Lascaratos *et al.*, 1999; Theocharis *et al.*, 1999a; Klein *et al.*, 2004). More specifically the results confirm that the EMT began well before the winter of 1991-1992, likely in 1989.

In 2006-2008 the Italian VECTOR Project (VulnErability of the Italian coastal area and marine Ecosystems to Climatic changes and Their rOle in the Mediterranean caRbon cycles) was carried out, involving most researchers interested in studying the significant effects of climate change on the Mediterranean marine environment and the role of this basin on the planetary CO_2 cycle.

The general objective of one of the project work packages (WP 8 Carpel) was to study the role of the Mediterranean Sea pelagic regions on the carbon cycle; in particular, a branch of WP8 was devoted to study the Southern Tyrrhenian Sea. The status of the Mediterranean Sea in the global carbon cycle has been a subject of interest for a number of years, nevertheless little is known, for instance, about its role as a source or a sink for the atmospheric CO_2. The difficulty lies in the poor sampling of the Mediterranean for the parameters of the carbonate system, i.e. pH, total alkalinity (TA), total inorganic carbon (TCO_2) and the partial pressure of CO_2 (pCO_2). The few published measurements are essentially from the western Mediterranean and they indicate that it can be considered a sink of organic carbon from and a source of inorganic carbon to the Atlantic Ocean (Dafner *et al.*, 2001).

Samples from the Southern Tyrrhenian Sea, collected at VTM station and along the section extending from there to the Gulf of Naples (see Figure 5), allowed us to have the first dataset of the inorganic carbon parameters from this area, as no measurements had been previously collected, apart one station sampled during the French Prosope cruise (Rivaro, pers. comm.). Moreover we could evaluate the seasonal variations of the inorganic carbon system over the period studied (November 2006-February 2008). In particular, TA and pH were measured in the sea water samples, while pCO_2 was calculated from TA and pH data.

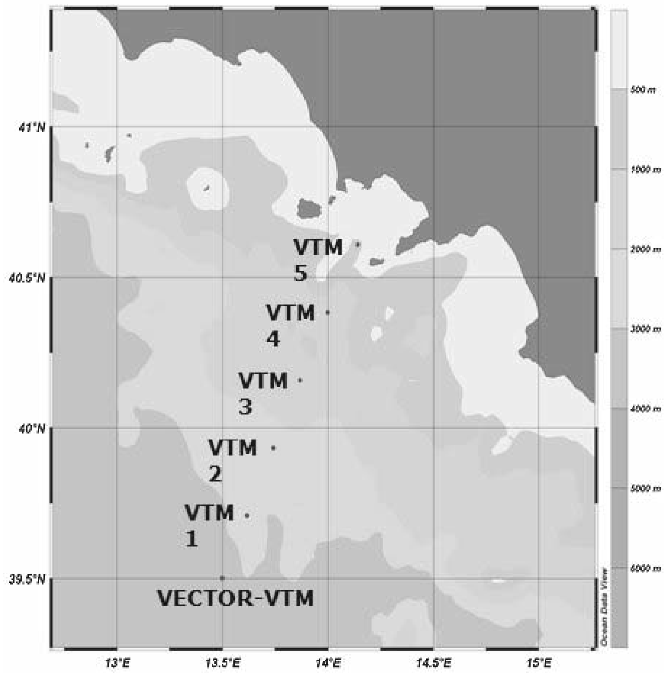

Figure 5. Vector project, sampling locations in the southern Tyrrhenian Sea.

The general relationship between total alkalinity and salinity was TA = 96.62 S - 1139.1 µmol kg^{-1} (Pearson's $r^2 = 0.979$, n = 320) in agreement with that found for the Western Mediterranean Sea. Moreover, no seasonal deviation in this relationship was observed. Thus, it appears that TA can be considered to first order to be conservative in the Southern Tyrrhenian Sea. The Tyrrhenian Sea is a three-layer system; the top layer (0-200 m) is occupied by the Modified Atlantic Water (MAW), the intermediate layer (200-700 m) is occupied by a mixture of intermediate waters, which especially before the 1990s (Gasparini *et al.*, 2005), was dominated by the Levantine Intermediate Water (LIW). Finally, the deep layer, is occupied by the Tyrrhenian Deep Water (TDW). TA average and the relative standard deviation values measured at top, intermediate and deep layer along the section in the five surveys are presented in Table 1.

Table 1. Total Alkalinity (TA) measured in the water column in the Southern Tyrrhenian Sea (see Figure 5 for the station locations).

		TM1 Nov. 2006	TM2 Feb. 2007	TM3 Apr. 2007	TM4 Jul. 2007	TM5 Feb. 2008
Station VTM	0 - 200 m	2560 ± 19	2552 ± 27	2547 ± 26	2550 ± 33	2549 ± 21
	200 - 700 m	2605 ± 2	2603 ± 3	2598 ± 2	2600 ± 3	2598 ± 1
	700 m - bottom	2588 ± 6	2588 ± 6	2584 ± 4	2586 ± 4	2585 ± 5
Section VTM-VTM5	0 - 200 m	2556 ± 16	2543 ± 23	2535 ± 25	2531 ± 30	2544 ± 22
	200 - 700 m	2603 ± 4	2603 ± 8	2600 ± 4	2600 ± 4	2598 ± 1
	700 m - bottom	2591 ± 6	2590 ± 10	2588 ± 6	2589 ± 7	2586 ± 6

The conservative behaviour of TA allowed us to identify from a chemical point of view the presence of the mentioned water masses. In particular MAW was characterized by the lowest TA values and by a higher dispersion of data depending on salinity variability, while the LIW core at about 400-500 m coincided with TA maxima. The deep layer corresponding to TDW showed statistically different results from the others and it was characterized by relatively high TA values.

No seasonal statistically significant variation in the water column was found during the period studied, with average and standard deviation of the entire data set in each layer being comparable to those of each cruise. Therefore, the occurrence of a proper total alkalinity concentration in the main Mediterranean water masses suggests that it could be used as signature of the physical structure of the water column, together with the other physical and chemical parameters.

A recent paper (Ribera *et al.*, 2008) reported that the Southern Tyrrhenian Sea displays an homogeneous distribution of nutrient with similarities between the seasons, with a profile more of eastern than western Mediterranean basin type and different from those of the northwestern and of the Algero – Provencal areas. Another study reported that TA measured in the deep layer in the south of the Tyrrhenian Sea during the Prosope cruise was higher than in deep water at the Dyfamed site, suggesting that Tyrrhenian deep water contributes to the Ligurian – Provencal Basin deep water (Copin-Montégut and Bégovic, 2002). Our data confirm this hypothesis, with TA in the deep layer being 2585 (± 4) $\mu mol\ kg^{-1}$ at station VTM (both in July and averaged in the different seasons) and 2577 (± 1) $\mu mol\ kg^{-1}$ at one station sampled in the Ligurian Basin. Temporal variability of pCO_2 was evaluated at VTM station. The lowest pCO_2(13°C) were recorded in February 2007 and 2008 (305 ppm), when the highest values of pH and of chlorophyll-a were measured, confirming that biological activity was driving the inorganic carbon equilibrium during the early spring blooms.

CONCLUSION

The need to monitor the thermohaline changes in the Mediterranean Sea is obvious; at the same time the revisit of historical information (as MEDAR/MEDATLAS II) is a fundamental step in long term studies.

Surface monitoring of the ocean properties in turn can provide insights into the ocean interior. A network of meteorological buoys tactically distributed in the locations where the deep convection takes places and the satellite derived variables (SST, altimetry, ocean color, wind stress, etc.) could assess the interannual variability of these processes and they can also provide useful information for the initialization and validation of the atmospheric and oceanic models.

Thermohaline and fluxes time series at fixed points (as already called for in CIESM Monograph 16 (2002) (<http://www.ciesm.org/marine/programs/hydrochanges.htm>) as well as CTD/LADCP/CFC transect trough relevant sections are needed to monitor the interior of the basins; ARGO float deployment could be also an important implementation of these observations.

The Tyrrhenian Sea cannot be considered just as a marginal basin of the western Mediterranean (as already pointed out by Millot, 1999); in particular, the recent evidence provided by Millot *et al.* (2006), suggests that the TDW plays a crucial role in the deep circulation of the western basin, but is also currently a major ingredient in the export of Mediterranean waters into the Atlantic. This global character attached to a dense water formed in the Tyrrhenian calls for a continuous monitoring of its formation and spreading, which will have to be contextualized in the framework of climate change, as well as of global, regional and local telecommunication patterns. The existing moorings have to be kept in place and enhanced for at least a few decades, others be deployed, and regular hydrological and biogeochemical activities should be carried out in the basin, as well as the studies of the atmospheric forcing at the surface, since the Tyrrhenian may well represent a privileged observation point for the entire Mediterranean.

Nevertheless, as the Mediterranean Sea is one of the few places in the world where deep convection and water mass formation takes place, it can represent in selected areas and seasons a strong marine sequestration of anthropogenic CO_2. The anthropogenic carbon cannot be measured directly, but since the global chlorofluorocarbons (CFC) temporal evolution is similar to that of CO_2, CFC distribution is particularly interesting for the study of anthropogenic carbon invasion in the oceans. This approach, followed successfully in the Ross Sea (Antarctica) (Sandrini *et al.*, 2007), will be important for studying the Mediterranean Sea too.

Mediterranean deep convection and ocean general circulation. Intercomparison with Nordic Seas.

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Open ocean deep convection is a very peculiar phenomenon only occurring in dedicated and restricted regions of the World Ocean. One of these regions is the North Western Mediterranean Sea (Gulf of Lions).

The Subpolar Oceans of the Atlantic sector (Weddell Sea, Greenland Sea and Labrador Sea) are also well known regions for open ocean deep convection and it is interesting to compare them with the Mediterranean Sea.

In this presentation we will describe the deep convection processes as observed in the Mediterranean Sea during the mid 70s, the mid 80s and the mid 90s and the coupling between open ocean deep convection and the general ocean circulation. We will also describe how the deep waters, formed and transformed in the North West Mediterranean Sea, circulate and propagate across the entire domain and how much of these deep waters participate to the Mediterranean deep overflow at the Strait of Gibraltar.

Then we will describe similar situations in the Nordic Seas (Greenland, Labrador Seas) and make some intercomparisons between the overflows at Gibraltar and at the Denmark Strait respectively.

It is important to determine how the open ocean deep convection might contribute (or not) to the large scale thermohaline circulation or the meridional overturning circulation. Is the Mediterranean a good case for explaining the relationship between Open Ocean deep convection and the global thermohaline circulation ?

Other important elements concern (1) the formation of intermediate waters, (2) the formation of dense water in shallow seas, (3) interior mixing processes and (4) sill dynamics and hydraulic control.

Mechanisms for deep water formation. Open ocean deep convection. Baroclinic instability.

In 1975 during the so called "MEDOC" experiments, a submesoscale eddy embedded in a deep water formation region was discovered. That revealed the importance of baroclinic instability involved in the open ocean deep convection processes. This was also observed in the Labrador Sea in 1976 and 1978. More recently (2004), 30 years after the Medoc experiment, long lived submesoscale eddies were observed in the deep convective area of the Greenland Sea. It is quite important to understand the role of these eddies in deep water formation since the eddy core is entirely composed of newly formed Western Mediterranean deep waters. We are arguing that similar processes occur in the Aegean Sea.

Mechanisms for mode water formation. Mesoscale eddies.

In 2000 during the so called “POMME” experiment a mesoscale eddy was observed in the North East Atlantic. The anticyclonic eddy core, very oxygenated, was composed of a mode water resulting from intermediate depth winter convection occurring in the North East Atlantic. This eddy looks very much like the so called “Tourbillon” eddy observed in the Bay of Biscay during the 80s. It is also quite important to understand the role of these eddies in the formation of mode waters, i.e. waters characterised by a minimum of absolute potential vorticity. Relative potential vorticity was nearly -f. We believe that similar processes occur in the Levantine basin of the Eastern Mediterranean Sea and contribute to the formation of the Levantine intermediate water in winter.

Mechanisms for large scale circulation. Wind driven versus density driven ocean circulation.

It is quite important to distinguish between the wind driven and the thermohaline driven circulation although it is very hard since the two components of the general ocean circulation are coupled by non linear interaction. Do we need deep or intermediate convection leading to the formation of deep or mode waters to create a thermohaline circulation? Should we make a distinction between thermohaline circulation and meridional overturning circulation? What is the respective role of buoyancy controlled by atmospheric forcing and internal mixing in large scale circulation? One of the best case studies concerns the Nordic Seas. It is interesting to compare Nordic Seas with the Mediterranean Sea in this respect. Contrary to what is commonly believed, the Mediterranean Sea is not a perfect example for describing the global thermohaline circulation as its east to west predominant geographical distribution and topography leads several basins to be separated by shallow sills. However the Nordic Seas offer more ressemblance due to similar kinds of geographical basins distribution separated by shallow sills.

Mechanisms for thermohaline circulation (meridional overturning circulation). Topography control versus Interior mixing processes.

For the Nordic Seas and as for the Mediterranean Sea as well, the general circulation is partly controlled or at least dependant on sill dynamics. The deep western boundary current in the North Atlantic is largely due to the dynamics generated at the sill between Iceland and Greenland and through the Faeroe-Scotland channel where a lot of energy is converted from gravity into potential energy. Dense water formed in shallow waters by freezing, sea-ice and brines production, are expending and propagating far away from the source region as internal plumes reaching the abyssal plain. This is also true for the Mediterranean Sea in the Adriatic and in some other continental shelf regions where evaporation dominates in winter. We have to distinguish very clearly hydraulic plumes from internal plumes such as described by J. Marshall and F. Schott (1999). The long lasting hydraulic plumes are really and efficiently transporting dense water masses from the shelves to the abyssal plain or even deep and dense waters overflowing through shallow straits. The internal plumes are much more ephemeral and contribute mainly to internal mixing rather than transport.

Where does the new Mediterranean deep water go?

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Abstract

Deep water formation in the western Mediterranean Sea occurs sporadically in late winter in the Gulf of Lions. In both 2005 and 2006, new saltier, denser deep waters were formed over wide areas of the northwest Mediterranean (Smith *et al.*, 2008) and these new deep waters have filled most of the western basin by autumn 2008 (Schroeder *et al.*, this volume). What happens to these new deep waters? Where do they go? Studying the long-term evolution of the deep water distribution and the evolution of its properties should provide insight on the circulation, mixing and ventilation of the deep water.

Problem

The Mediterranean Sea is a semi-enclosed basin where the Gibraltar sill with a depth of about 300 m depth isolates the deep Mediterranean from direct horizontal exchange with the open ocean. Deep water formation in the northwest Mediterranean has been observed during some winters (but not all winters) since the 1969 MEDOC experiment. What happens to these new deep waters? We might imagine three forms of evolution of new deep waters.

First the formation of deep water in the northwest Mediterranean might remain locally contained so that it remains in place to be repenetrated by deep convection in following severe winters to form slightly different deep waters with a persistent high oxygen signature representing recent ventilation. The spreading of the 2005-2006 deep waters throughout the western basin would appear to rule out such local containment of new deep waters.

Second, given that new deep water formed locally in the Gulf of Lions does spread laterally at depth, the new deep water might spread laterally along isopycnals so as, for example, sit above last year's denser wintertime deep water but below the deep water formed five years earlier. Identifying such layering could be difficult unless the different vintages of deep water have distinct temperature-salinity characteristics or clear evidence of constant density layers separated by a pycnocline. Mixing of course would erode such layers but a topical problem is to identify the processes and time scales on which mixing occurs. For the abyssal global ocean, tides are thought to provide much of the mixing (Munk and Wunsch, 1998), though tides are notably small within the Mediterranean Sea.

Third, there might be direct aspiration of the new deep water up and over the Gibraltar sill. Stommel *et al.* (1973) suggested that the high velocities of the Mediterranean outflow in the Strait of Gibraltar can provide a Bernoulli suction that enables deep water in the Mediterranean to flow up and over the sill, out into the Atlantic (Figure 1). Laboratory experiments with stratification representative of the Mediterranean water below sill depth by Whitehead (1985) suggested that waters as deep as 1,000 m behind the sill could be drawn up and over the sill. Kinder and Parrilla (1989) actually observed relatively pure western Mediterranean deep water west of the Gibraltar sill, confirming that the direct aspiration of deep water does occur, at least during strong spring tidal flows.

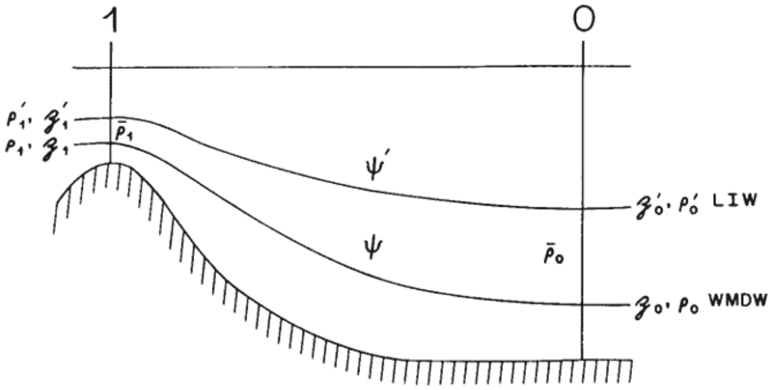

Figure 1. A schematic diagram of Bernoulli aspiration in the Strait of Gibraltar and Alboran Sea (from Kinder and Bryden, 1990). A zonal section is shown with the upper streamline representing Levantine Intermediate Water (LIW which can outflow directly) and the lower streamline representing Western Mediterranean Deep Water (WMDW which must be 'sucked' over the sill from depth). If the speed along the upper streamline is great enough, the lower streamline will be able to rise above the depth of the sill.

Considering the second and third forms of evolution of new deep waters, we might speculate that there is a competition between direct aspiration of the deep waters and slow mixing of the deep water properties. The slow mixing downward of heat and salt (from the Levantine Intermediate Water above) gradually decreases the density of the deep waters (Wust, 1961) while new recently formed deep water replenishes the bottom layers. Thus, the deep waters may be stratified by age with older, more mixed waters sitting above younger less mixed deep waters. When the oldest, mixed deep water reaches the top of the deep water layer, it would then flow out through the Strait of Gibraltar into the Atlantic. On the other hand, direct aspiration without any mixing would imply that new deep water injected at depth raises the older, less dense deep waters upward and the least dense deep water formed last year or 20 years ago is then able to flow over the Gibraltar sill into the Atlantic (Figure 2). In this case, the deep waters would be stratified by the density of the deep waters when they are formed regardless of age. The distinguishing characteristic between these two scenarios is how much mixing there is in the deep water where there is little stratification. How long can we identify a newly formed deep water type before it is mixed away into a continuous temperature-salinity-density stratification?

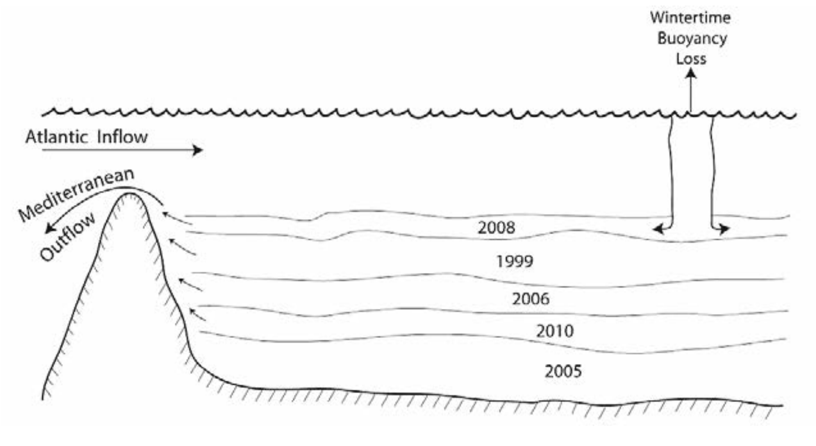

Figure 2. Schematic diagram of possible distribution of western Mediterranean deep water vintages. The deep waters are stratified according to their density. In this scenario, the deep waters formed in 2005 are the densest, those formed in 2008 are the least dense, and the vintages formed in 1999, 2006 and 2010 have intermediate densities; and no deep waters were formed in 2000-2004, 2007 or 2009.

PRESENT SITUATION

The deep waters recently formed during 2005 and 2006 were saltier, warmer and denser than previous deep waters. They have spread out away from the Gulf of Lions and now sit as bottom waters throughout the western basin with a noticeable halocline, thermocline and pycnocline separating them from the older deep waters. It appears possible that we can now define the depth of this interface between new and older waters to make an estimate of the volume of new deep water formed during 2005 and 2006. And spatial variations in the depth of the interface should provide clues as to how this deep water is circulating. Is the interface banked up against the boundaries marking a cyclonic or anti-cyclonic circulation? Does the deep interface shoal westward as the deep water moves toward the exit at Gibraltar? Is the new deep water piling up behind the Gibraltar or Sicily sills?

Observing the temporal evolution of the interface between new and old deep waters should shed light on the mixing processes. Does the interface mix away more quickly over rough topography and remain more constant over abyssal plains? How long will the new and older deep waters remain distinct?

Direct outflow of deep water does appear to occur shortly after wintertime deep water formation. Garrett *et al.* (1990) suggested that new deep water would raise the interface between Atlantic and Mediterranean waters behind the Gibraltar sill, changing the hydraulic control condition and leading to increased outflow (and inflow) in springtime. Indeed Garcia Lafuente *et al.* (2007) have observed pulses of colder outflow waters at the Spartel sill a few months after the deep water formation events of 2005 and 2006. Millot (2009) has shown that it is possible to monitor the different types of intermediate and deep waters exiting the Strait of Gibraltar with strategically placed moored instruments. Examination of the properties of the deep waters as they approach the Gibraltar sill could determine whether they represent direct aspiration of the new deep water or an increased outflow of the upper, least dense deep waters that have been raised up as a result of the new deep water formed.

There are regular Argo profiles of temperature and salinity down to depths of 1,500 m and greater (Figure 3) and systematic hydrographic surveys of the western Mediterranean, both of which could be exploited to examine the evolution of new deep waters formed in 2005 and 2006. Are Argo salinities sufficiently accurate to define the interface between the new deep waters of 2005-06 and the older deep waters? Do the Argo profiles go deep enough to find the interface? Are there enough deep Argo profiles to map out the depth of the interface? The systematic surveys of the western Mediterranean clearly define the mid basin distribution of the 2005-06 deep waters (Schroeder *et al.*, this volume). But can they define the distributions near the boundary to identify the direction of the deep geostrophic flows? Is there any evidence for uplift of the interface as the new (and old) deep waters approach the Gibraltar sill?

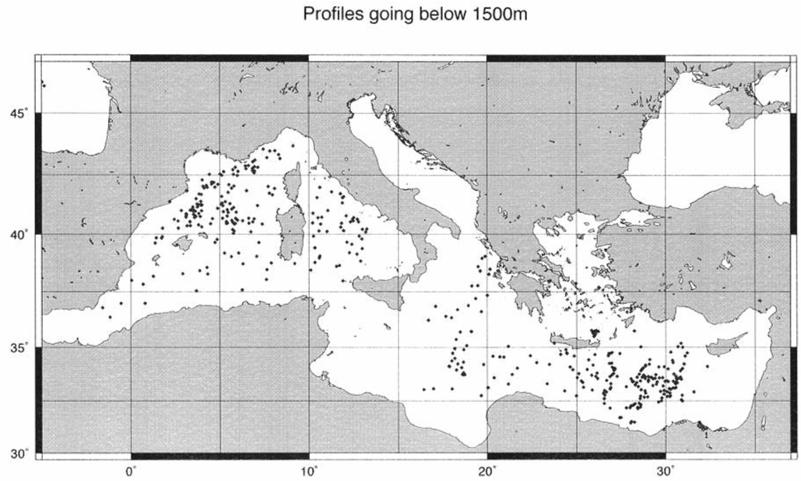

Figure 3. Location of Argo profiles extending deeper than 1,500 m (as of mid April 2009).

In terms of new wintertime deep water formation events, recent experience suggests that gliders deployed in the Gulf of Lions during January-March are capable of defining the depth and salinity and temperature characteristics of deep winter mixed layers and hence the properties of any western Mediterranean deep water formed each winter. Glider profiles used in an interactive mode with shore-based scientists may also be capable of defining the spatial distribution of deep convection as well as the horizontal and vertical scales of plumes and chimneys associated with the deep wintertime mixed layers.

Summary

With Mediterranean waters becoming progressively saltier and denser over time, we have a unique opportunity to observe how wintertime deep water formation affects the overall Mediterranean circulation. For severe winters, new bottom waters will be formed as in 2005 and 2006 and their evolution can be tracked, underpinning and raising up older deep waters. For less severe winters, deep waters of intermediate density may be formed into layers that spread laterally within the pre-existing deep water stratification. Mixing in these intermediate layers away from the bottom may be weaker than in the bottom waters in contact with topographic features. We have the instruments and scientific and technical capabilities (Argo floats, gliders, systematic surveys) to identify where new Mediterranean deep water goes. Defining the evolution of new deep waters over a number of years will provide unique insights into the circulation and mixing of deep waters which are pertinent to the global abyssal circulation as well as to the deep Mediterranean circulation.

Adriatic Sea dense water formation: local influences and interaction with the Eastern Mediterranean

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Adriatic Sea, the most important source of the Eastern Mediterranean Deep Water, is characterized by a strong interannual and decadal variability of either the quantity of the water formed or of its thermohaline properties. The bottom water in the Adriatic (Adriatic Dense Water – AdDW) is formed through an open-ocean deep convection (Figure 1) in the south Adriatic Pit (Gačić *et al.*, 2002). Its thermohaline properties are determined by the intermediate layer salt content of the water coming from the Ionian (Levantine and/or Aegean origin) or Modified Atlantic Water, by the contribution from the Northern Adriatic and by the air-sea heat fluxes that are dictated by the local climatic conditions. Interannual variability of the amount of AdDW water formed has been studied from the intensity of the bottom outflow in the Strait of Otranto and associated with variations of the winter air-sea heat fluxes (Manca *et al.*, 2002b). This outflow and then presumably the volume of the bottom water formed can vary from one year to another by more than three times (Figure 2), reaching maximum values of around 0.4 Sv (10^6 m^3/s). This represents about 40% of the total outflowing water volume rate. In addition, the thermohaline properties of the vertically mixed water column in the South Adriatic Pit are subject to prominent decadal variations that are then essential in determining the density of the outflowing AdDW. This density subsequently determines the horizon occupied by that water in the Ionian Sea. Moreover, the sudden change in the Eastern Mediterranean deep circulation that occured in the mid 1990s (also called Eastern Mediterranean Transient – EMT), further influenced the density difference between the AdDW exiting the Ionian and the bottom water in that area (Klein *et al.*, 1999). More specifically, during this sudden deep circulation change the Aegean Sea became bottom water source of the entire Eastern Mediterranean substituting the Adriatic Sea (Roether *et al.*, 2007). This change occurred for two reasons: on one hand the Adriatic was producing less dense waters, while at the same time the Aegean was becoming a source of extremely dense waters.

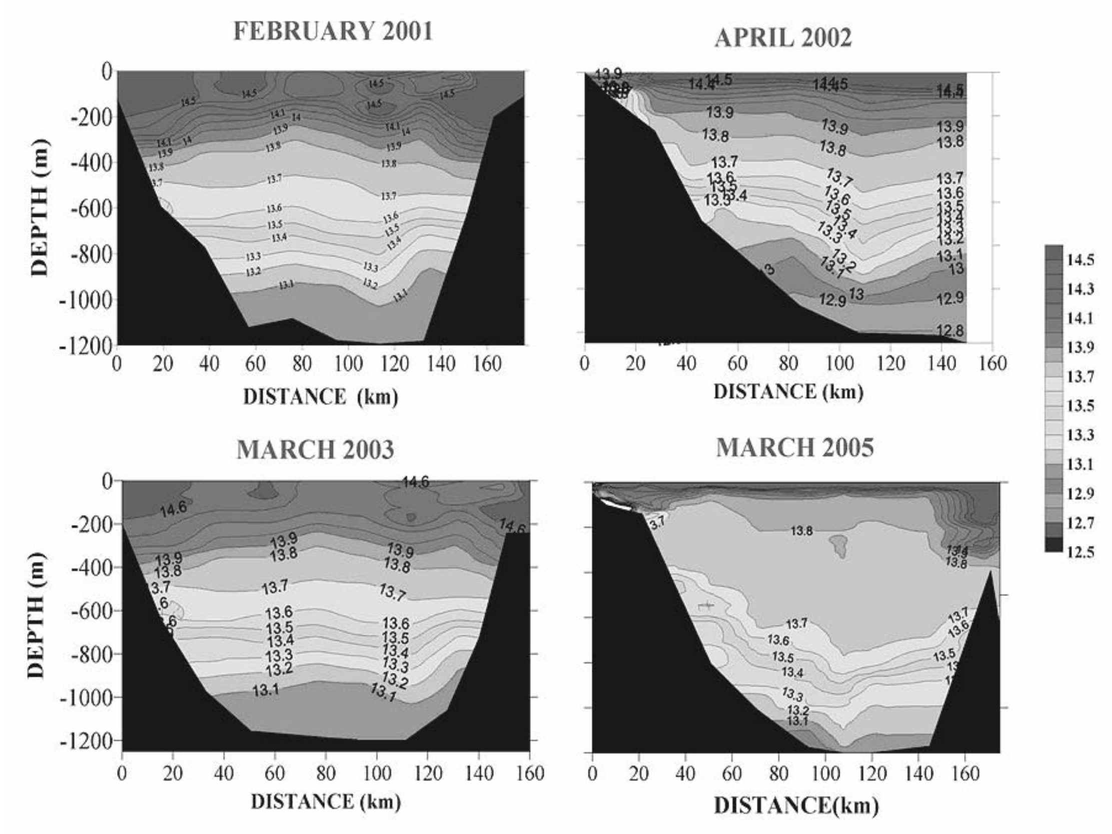

Figure 1. Vertical temperature distribution along a transect in the South Adriatic Pit.

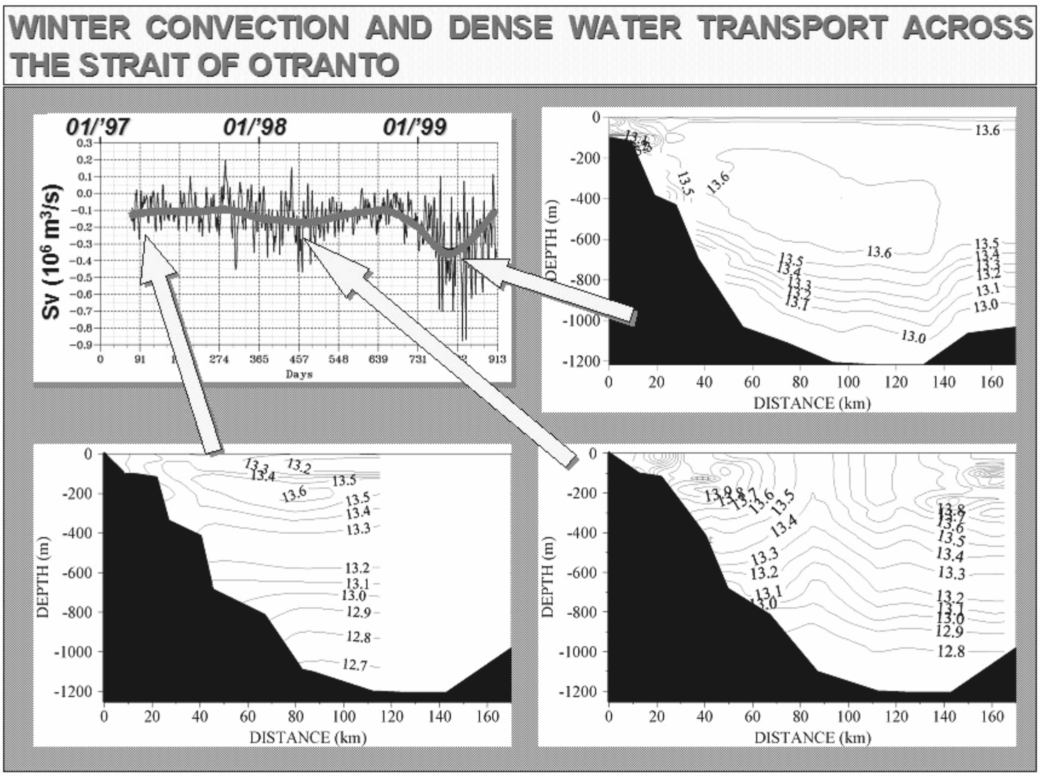

Figure 2. Interannual variability of the AdDW outflow through the Strait of Otranto. Vertical temperature distributions at a transect across the South Adriatic Pit in a post-convection phase in different years are also shown.

The spreading of the Aegean dense waters, denser than the Adriatic deep waters, in the abyssal part of the Ionian caused an inversion of the bottom pressure gradients and very likely, the inversion of the basin-wide surface circulation (Borzelli *et al.*, 2009). This inversion consists in the passage of the circulation pattern from anticyclonic to cyclonic (Figure 3). Due to this circulation change the inflowing water in the Adriatic originates from the Aegean and Levantine, which means that the Adriatic becomes affected by waters of higher salt content and the buoyancy content decreases. The results of such changes are an increase in the salinity of the Adriatic dense water and also of the intensity of deep convection. Therefore, the Adriatic Sea, due to this circulation inversion, is very likely experiencing an intensification of the deep water production and becoming again the main source of the EMDW.

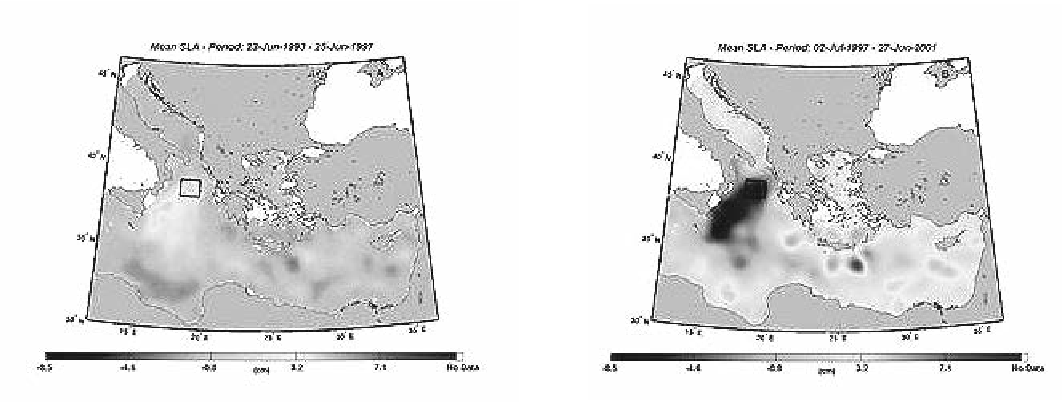

Figure 3.

The inversion in the surface circulation pattern in the Ionian is associated with the vertical movements of interfaces; during the anticyclonic phase the interfaces are deeper than during the cyclonic one and such differences can reach several hundreds meters (Figure 4). Consequently the waters entering the Adriatic from the Ionian have different biogeochemical properties in function of the surface circulation pattern. During the anticyclonic phase along the perimeter of the circulation structure the upwelling takes place and thus the water entering the Adriatic brings large amounts of nutrients. Vice versa the cyclonic gyre is characterized by downwelling along its perimeter and thus the water inflowing the Adriatic is rather poor in nutrient content. The biogeochemical properties of the South Adriatic sea water are therefore a function of the Ionian upper-layer circulation, i.e. the circulation in the water column shallower than the

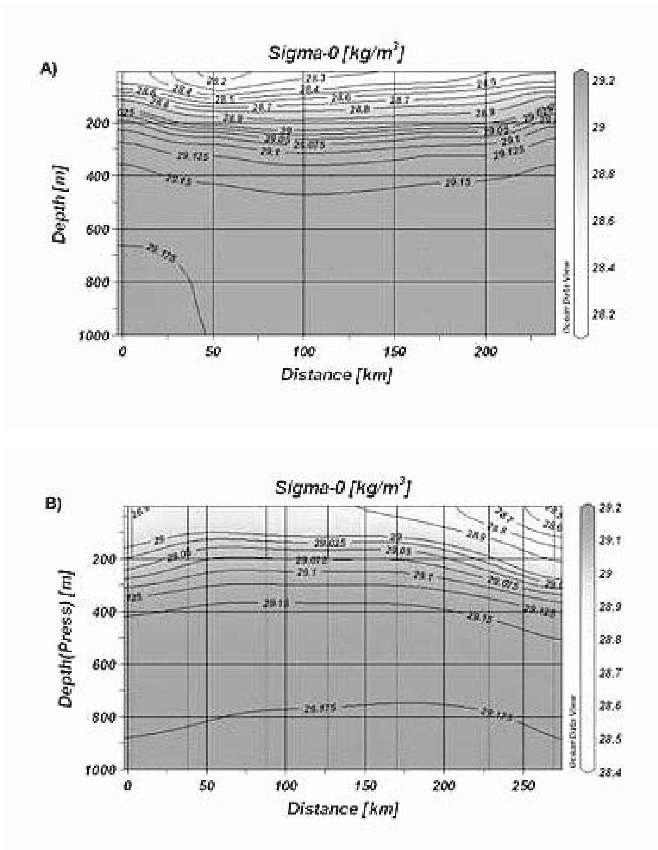

Figure 4.

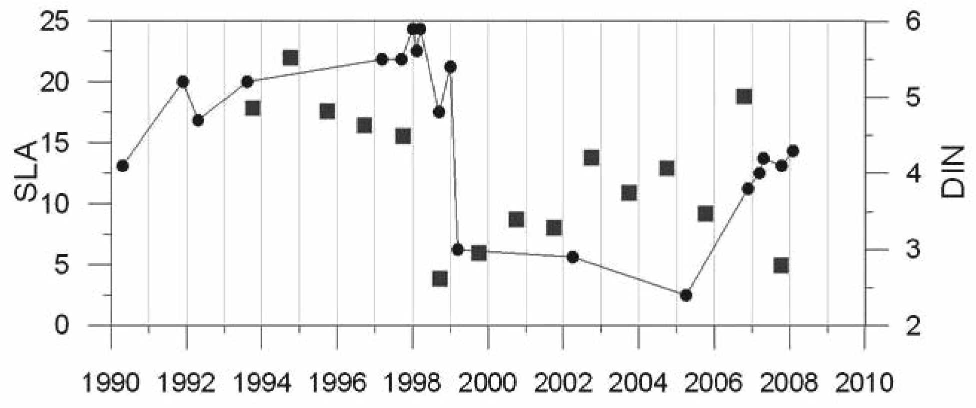

Figure 5. Interannual variations of Sea Level Anomalies (SLA – cm) and dissolved inorganic nitrate DIN (µmol/l).

Otranto Strait depth (700 m) – see Figure 5. Nutrient content change integrated over the entire water column can double on decadal time scale, however it seems that these changes do not have important impacts on ecological status of the basin (Civitarese and Gačić, 2001). This is probably due to the fact that in the high-nutrient inflow regime, the vertical stability of the water column is higher and the intensity of the winter convection is weaker.

Local slantwise convection and deep inertial motions near a dense water formation area

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Abstract

We discuss observations from the lower half of the 2,800-m deep part western basin of the Mediterranean Sea. Moored and shipborne CTD-data indicate relatively large variations in water mass properties and stability that are associated with, but not directly caused by, dense-water formation to the north of the site. These large variations are apparently dominated by local convection induced by small-scale eddies and propagation of inertial waves in stratified and homogeneous layers. Hereby the horizontal component of Coriolis parameter is important, governing slantwise, tilted convective mixing. This mixing is across some 200-400 m thick layers, a thickness beyond the typical vertical buoyancy scale relevant for double diffusion. The marginally stable deep waters are found as spicy as near-surface waters.

1. Introduction

Cold and dry northwesterlies, blowing in winter in the western basin of the Mediterranean Sea between Pyrenees and Alps, make surface waters denser in the shallow Gulf of Lions and the deeper Provençal subbasin (including the Ligurian Sea) (Figure 1). Offshore convection in the subbasin (Schott and Leaman, 1991) has always been assumed (e.g., Millot, 1999) to be more efficient than cascading from the former, even when observations over shelf and slope show intense cascading, such as during the 2004-2005 winter (Canals *et al.*, 2006). During that winter, huge amounts of dense waters were thus formed in both areas before spreading in the deeper part of the Provençal subbasin (Font *et al.*, 2007), the Algerian subbasin and the entire basin. Here, we discuss some aspects of such newly formed deep waters away from their formation areas, and we contrast them with local internal mixing.

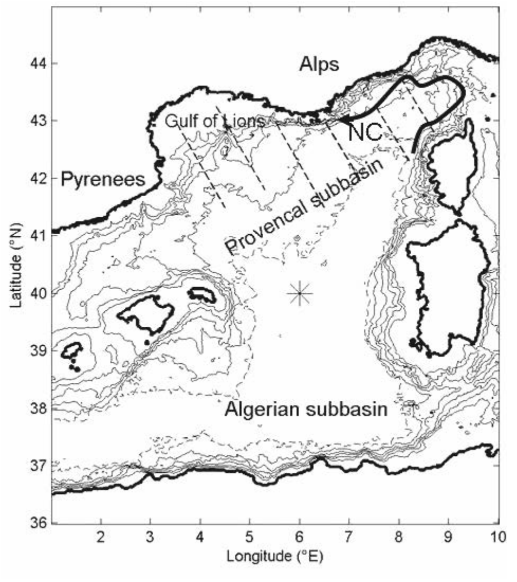

Figure 1. Western Mediterranean Sea with observational site *. Depth contours every 500 m, for [500, 2,500] m and 2,750 m contour. Hatched: area of dense-water formation.

Stratified shear flows are considered stable as long as the isopycnals slope less to the horizontal than lines of constant momentum. However, as transport is easiest along isopycnals, a stable shear flow allows free convection along weakly slanted isopycnals (McIntyre, 1970), (Figure 2a). Such convection may be found for example, across fronts and boundary currents (Ruddick, 1992). It occurs in rather thin (1-10 m) weakly stratified layers, in otherwise strong stratification. These layers, in which double diffusive fingering may develop, are very weakly (a few degrees) tilted to the horizontal. They are similar to ones found in the present Mediterranean data between about 300 and 1,200 m, but we do not consider them here. Different are the (100 m) thick layers at large depths discussed below.

In such large weakly stratified layers, another form of slantwise convection may develop. In any convective area, mixing will initially occur vertically, with velocities of several 10^{-2} m s^{-1} (Schott and Leaman, 1991) in the direction of gravity (Figure 2b; dash-dotted line). After some time (1/f), the vertical plumes will become affected by the rotation of the earth Ω, due to the high aspect ratio by its horizontal component $f_h=2\Omega\cos\varphi$, φ the latitude, besides the more familiar inertial frequency $f=2\Omega\sin\varphi$. Except at the pole, this will result in a tilting over angle $(\pi/2-\varphi)$ with gravity (vertical, z) of a convective tube, so that constant density layers become aligned with constant momentum surface M along Ω (Figure 2b solid line): [planetary] slantwise [vertical] (Straneo *et al.*, 2002) or 'tilted' (Sheremet, 2004) convection. If stratification is larger than that due to alignment along Ω, it will be stable in a slantwise convective sense (Figure 2b dotted line). The minimum stratification N_{min} for which planetary slantwise convection just about cannot occur is estimated at $N_{min}=2f_h$ or $4f_h$, depending on the stability model used, for all φ except near the equator $|\varphi|<2°$ (van Haren, 2008). Note that this convective mixing does not necessarily commence near the sea surface but also in its interior, i.e. in weakly stratified layers capped by well-stratified ones.

Convection involves wide ranges of space and time scales, with horizontal velocities up to 0.5 m s^{-1} near the bottom (Millot and Monaco, 1984). There it forms Western Mediterranean Deep Water (WMDW) involving relatively warm and salty waters originating from the eastern basin such as Levantine Intermediate Water (LIW) and Tyrrhenian Dense Water (TDW) that are warmer, saltier and less dense than WMDW. Waters cascading from the shelf are initially fresher and cooler, but they markedly mix with the previous ones over the slope since in a basin all waters are driven by horizontal density gradients along the isobaths counterclockwise, due to the earth rotation (Millot, 1999). The consequent heterogeneity of hydrological characteristics that must thus be expected in and close to a dense water formation area, originating near the surface, is intensified in the deep when densest waters reach the bottom, before mixing progressively along their route and being finally uplifted by and mixed with more recent and denser water. Another spreading from the convection area is associated with horizontally small-scale (1-10 km) sub-surface eddies (Testor and Gascard, 2003). In the vicinity of dense water formation areas, a marked heterogeneity of dynamical characteristics is therefore also expected.

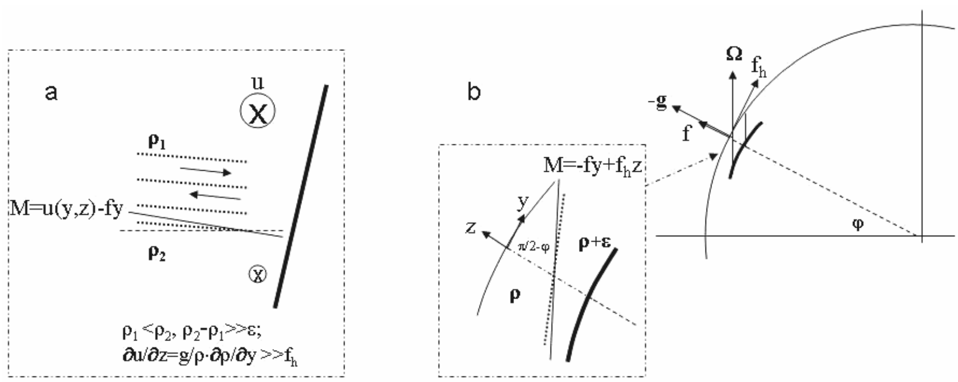

Figure 2. a) Sketch of slanted horizontal advection in strong stratification. Isopycnals tilt in baroclinic shear flows up to momentum M inclination from the horizontal. b) Sketch of planetary slantwise vertical convection in weak stratification when surfaces of constant density align with surfaces of constant M (solid line), instead of vertical (gravity; dash-dotted) or more "horizontal" as in stable stronger stratification (dotted).

2. Observations

A mooring equipped with six single-point current meters immersed between 1,685 m and 2,720 m, was operational at 49°0′ N, 6°0′ E (H=2,760 m) from 13/04/2005 to 12/02/2006 (Figure 1). During the deployment/recovery cruises, three to five SeaBird-911 CTD-profiles were obtained near the mooring in a yoyo-fashion within a 3-4-hour delay.

These profiles show substantial variations in hydrographic properties during each cruise and between the two cruises (Figure 3). Comparable with observations in the Algerian subbasin, where an 800-m thick homogeneous layer is observed below 2,000 m (van Haren and Millot, 2004), a slightly less thick density anomaly σ-homogeneous layer is observed here (1,700-2,400 m in 2005, 1,600-2,100 m in 2006, Figure 3a). In 2005 in particular, this σ-homogeneous layer can be markedly heterogeneous in both temperature T and salinity S (Figure 3b,c), while a relatively thick near-bottom stratified layer is found, in 2006. Note that our observations are from February 2006, before a major dense water formation period in March 2006. Our observations are similar to recent observations from the Algerian Basin (Schroeder *et al.*, this volume). The σ-homogeneous layer is significantly older (oxygen content about 75% saturation, Figure 3d) than the more turbid (Figure 3e) and ‘stratified’ layer below (80%). The homogeneous layer is uplifted by more recent, less homogeneous, and denser waters that circulate in the area. These more recent waters feed the deeper layer of the Algerian subbasin (Millot, 2009), but also mix rapidly with layers above, as may be inferred from the transmissometer data (Figure 3e).

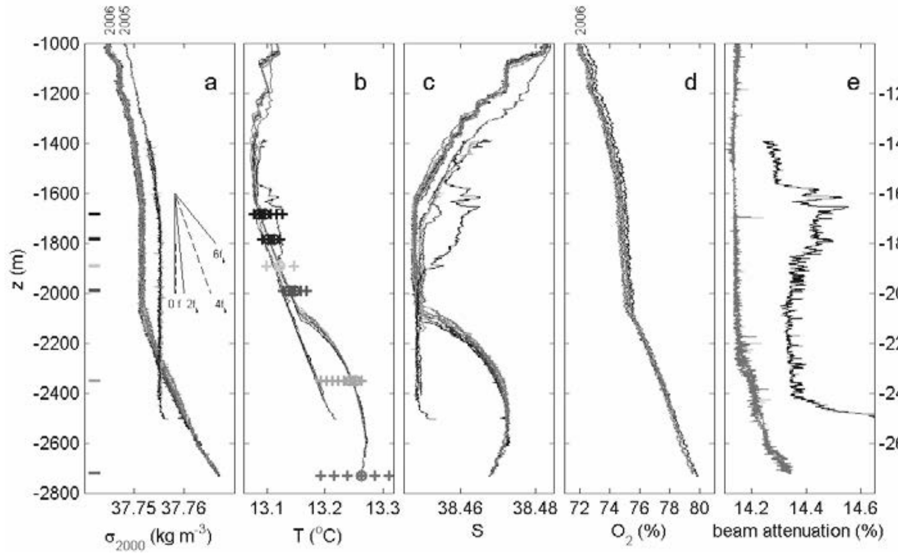

Figure 3. CTD-4 h yoyo-data from April 2005 (all down- and up-casts shown; deepest: 2,500 m) and February 2006 (less variable data; upcasts and only one downcast). Data are not off-set deliberately. a) Potential density anomaly (to 2,000 dbar), including particular slopes and immersions of moored instruments. b) *In situ* temperature. During the first day moored data are indicated by +, during the last 10 days by o. c) Practical salinity. d) Oxygen saturation, 2006 only. e) Beam attenuation for two profiles, one from each year (arbitrary units).

The 1,600-2,100 m homogeneous layer in 2006 is concentrated in a small θ-S-portion (Figure 4a) and probably corresponds to those values that, in 2005, were the coolest and freshest ones in the lower part of the σ-homogeneous layer: they indicate relatively old WMDW that might have transited through the Algerian subbasin. The deeper 2006-stratified layer shows water formed in the north during the 2004-2005 winter, which can be considered as new WMDW influenced by LIW and TDW, either markedly, near T- and S- intermediate maxima, or slightly, near T- and S- minima near the bottom.

The most eye-catching T and S variations in our CTD profiles (notably 2005 profiles, Figure 3) occur in both the upper stratified layer (above 1,700 m) and the σ-homogeneous (1,700-2,100 m) one, apparently not affected by the transition in density. This is also seen in the transmissometer data, also in 2006 at great depth. It implies density compensation that might be different at different depths. The stratified layer above the large σ-homogeneous layer has buoyancy frequencies $N \approx 2f_h$ in both 2005 and 2006. We find $N \approx 4f_h$ below 2,400 m in 2005 and 2,050 m in 2006. Both N-values are equal to minimum values for stability along Ω (van Haren, 2008). This σ-compensated heterogeneity in θ and S observed in the deep resembles the one commonly observed in the surface mixed layer (Rudnick and Ferrari, 1999). There it is attributed to horizontal shear dispersion, slumping and mixing resulting in a density ratio $R=\alpha\Delta\theta/\beta\Delta S=1$, α and β denoting expansion coefficients of heat and salt, respectively.

We find R=1 (Turner angle $Tu_\theta=90°$) between 1,000 m and the top of the homogeneous layer near 1,600 m in 2006, even down to 2,000 m within that layer in 2005. R=1 contrasts with R=2 that is typically found in the stratified layers of the global ocean, below the surface mixed layer all the way to the bottom (Schmitt, 1999). In our data, the situation is relatively complex below 2,000 m in 2005 and between 1,600 and 2,400 m in 2006 (-inf < R < 1). Here, R→2 only deeper than 2,600 m in 2006. R=1 is a result of density compensation in which θ-S correlations provide water that has large 'spice τ' (Veronis, 1972). Our R=1 data evidence slantwise convection. Sheremet (2004) who interpreted similarly spicy data collected by Pickart *et al*. (2002) in convective near-surface Labrador Sea waters.

The water column is marginally stable with clear suggestions for double-diffusive (DD) convection and Rayleigh-Turner instability (Figure 4b). This can be inferred from the 2005-profile between 1,400 and 1,950 m, i.e. from the upper stratified layer well into the large σ-homogeneous layer, and from the 2006-profile above 1,600 m, i.e. within the upper stratified layer. Likewise, the 2006-profile indicates a diffusive unstable layer between 2,000 and 2,400 m, i.e. in both σ-homogeneous and lower stratified layers, some stability between 2,400 and 2,500 m, and some weak DD-instability or salt-finger regime below 2,600 m associated with R=2. In this layer enhanced beam attenuation is observed (Figure 3e). As a result, the expectation that σ-homogeneous layers are unstable and stratified layers are stable in a static sense is not found true from our data.

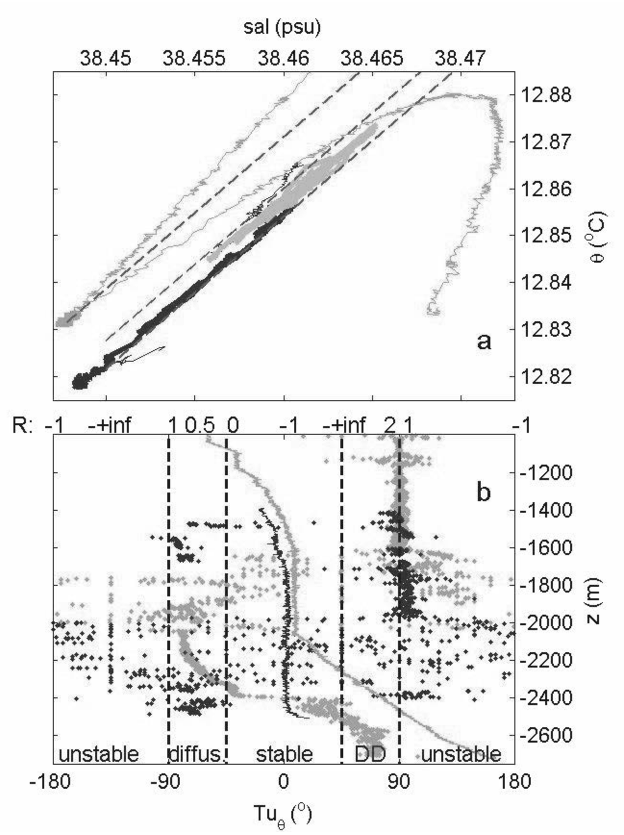

Figure 4. Stability and mixing from CTD-4 h yoyo-data. a) Representative potential temperature θ-salinity diagrams from 2005 and 2006. Thick portions of both diagrams correspond to the large σ-homogeneous layer while the light 2005-portion corresponds with 1,550-1,700 m section of upper stratified layer. Dashed lines indicate constant density anomalies referenced to 2,000 dbar. b) Density R and Turner angle $Tu_\theta=\tan^{-1}((\alpha\Delta\theta-\beta\Delta S)/(\alpha\Delta\theta+\beta\Delta S))$ (Ruddick, 1983; McDougall *et al.*, 1988) for profiles in a). For reference, their density profiles from Figure 3a are given (arbitrary scale).

The T-variability with depth and time (Figure 3b) is consistent with moored T and current C variability with time (Figure 5). The entire time series basically indicates two different periods before and after days 260-270. The first period shows large T, C small-scale eddy fluctuations, while the second is quieter but still showing significant T-, C-variations, the latter dominated at f. C is markedly barotropic in both σ-homogeneous and -stratified layers as well as during both periods. Such overall features indicate either that the general circulation in the study area suddenly changed during days 260-270, first rapidly advecting at on average 0.07 m s^{-1} an eddy field (0.3-0.45 m s^{-1}) then slowing down markedly, or that some kind of large-scale front permanently separated an active zone from a much quieter one, the front having passed over the mooring during days 260-270.

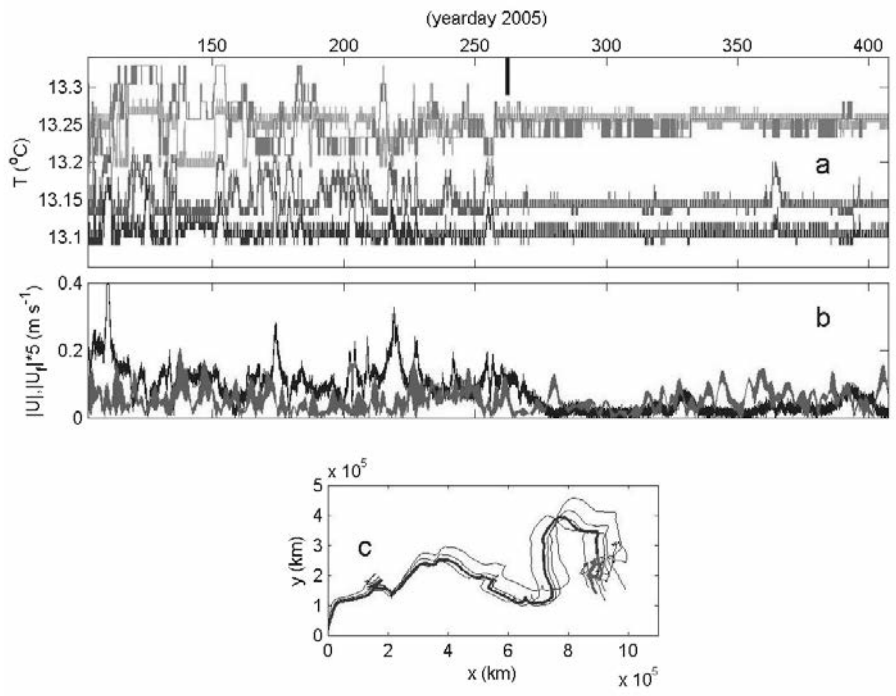

Figure 5. a) Some T time series (yearday 0.5=12 UTC, 1 January 2005 and days in 2006 are +365) using color-shading of instruments' depths in Figure 3a. T-data are calibrated using 2006-CTD. b) Total current amplitude at 1,700 m (black) and band-pass filtered inertial |C|*5 at 2,700 m (light-tone).

Variations in deep dynamical characteristics occur over depth ranges (100-1,000 m) where stratification is weak. Small-scale eddies may create local vertical convection just like meso-scale eddies (van Haren *et al.*, 2006), although after the times of dense water formation and over a much longer period at a particular site. One must also consider inertio-gravity waves (IGW) that can transit between stratified and homogeneous layers (100 m) thick (van Haren and Millot, 2004). At f IGW always pass the transition between such different layers without attenuation, regardless of their orientation in the horizontal plane. In homogeneous layers, IGW vertical velocities, notably w(f), show ratios w/(u, v) of 0.1-1, occasionally even >1 (van Haren and Millot, 2005), which thus create convective plumes like small-scale eddies but having inertial periodicity. What remains to be quantified is the rapidity of mixing, or how long particular dense water formation can be traced.

Interactions between open-sea convection and shelf cascading dense waters in the formation of the Western Mediterranean Deep Water

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Abstract

Sea-atmosphere interactions play an important role on the oceanographic processes at various spatial and temporal scales. In the Mediterranean Sea, several regions are key spots of intense air-sea interactions which affect considerably the heat and water budgets. An example of this is the wintertime formation of dense water through interaction with the atmosphere, and further sinking by convection or cascading. The Gulf of Lions is one of the regions in the Mediterranean where massive dense water formation occurs because of cooling and evaporation of surface waters during winter-time. Concurrent with the well known open-sea convection process over the MEDOC region, coastal surface waters over the wide shelf of the Gulf of Lions also become denser than the underlying waters and cascade downslope until reaching their equilibrium depth. Through this climate-driven phenomenon, dense shelf waters carrying large quantities of particles in suspension are rapidly advected hundreds of meters deep, mainly through submarine canyons. Recent observations within the frame of several research initiatives conducted in the north-western Mediterranean indicate that major dense shelf water cascades from the Gulf of Lions have a direct effect on the Western Mediterranean Deep Water (WMDW) thermohaline properties and are responsible for the formation of a thick and persistent bottom nepheloid layer (BNL) that spreads throughout the western Mediterranean basin and scales in thickness with the WMDW anomaly created during sever winters like those of 1999 and 2005.

Introduction

Dense shelf water cascading (DSWC) is a global climate-driven oceanographic phenomenon common not only on high latitude continental margins, but also on mid latitude and tropical margins (Ivanov *et al.*, 2004). DSWC is a specific type of buoyancy-driven current, in which dense water formed by cooling, evaporation or freezing in the surface layer over the continental shelf descends down the continental slope to a greater depth. The general DSWC concept was formulated by Fritjof Nansen (1906), who made the first direct measurements over the Rockall Bank in the North Atlantic Ocean (Nansen, 1913). The term "cascading" was introduced later by Cooper and Vaux (1949), but the same phenomenon is also referred as "shelf/slope convection".

Cascades of DSW can last for several weeks and the associated strong currents can induce erosion and resuspension of surface sediments in the outer shelf/upper slope and generate bottom nepheloid layers (i.e. layers of water that contains significant amounts of suspended sediment). Such layers can be detached at intermediate levels when the mixture of water and particles reach their equilibrium depth, or if the density is large enough, evolve into a thick bottom nepheloid layer that can reach the lower continental slope and basin (Figure 1). This cascading mechanism contrasts with the typical offshore convection, since only the latter brings dense "blue water" free of particles to the basin.

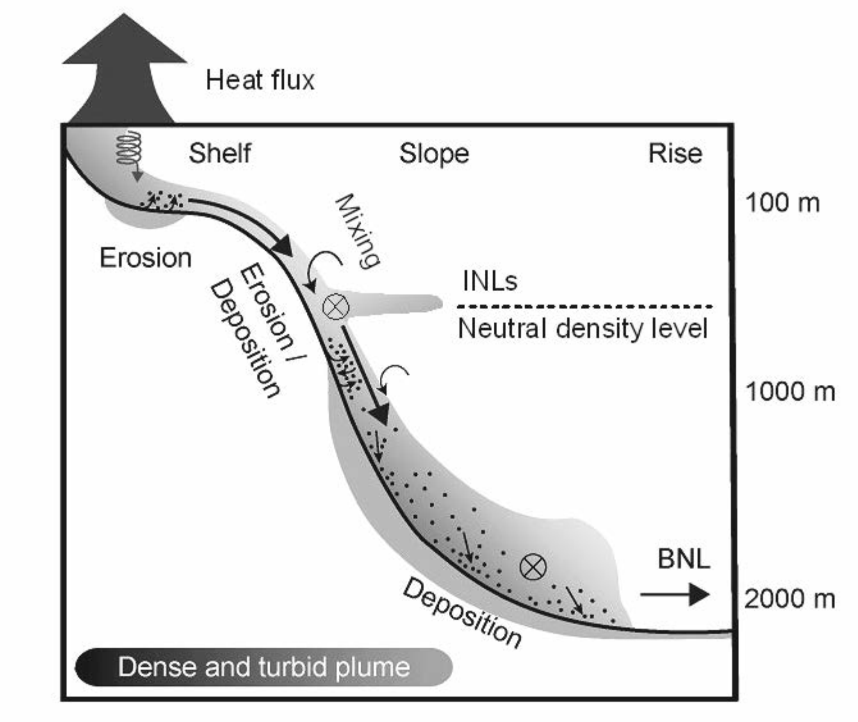

Figure 1. Schematic diagram of the DSWC mechanism illustrating the formation of intermediate nepheloid layers (INLs), when water and particle detachments occur at the neutral density levels, and of a thick bottom nepheloid layer (BNL) when dense shelf waters reach the basin [adapted from Fohrmann *et al.* (1998)].

Winter heat losses and evaporation induced by persistent, cold and dry northerly winds affecting the Gulf of Lions cause densification and mixing of coastal waters. Despite the buoyancy gain induced by freshwater inputs, once denser than surrounding waters, surface waters over the shelf sink, overflow the shelf edge, and cascade downslope until they reach their equilibrium depth, which changes from year to year (Millot, 1990; Durrieu de Madron *et al*., 2005). The first evidence of DSWC in the Gulf of Lions was found in 1953 by Bougis and Ruivo (1954), who identified the formation of dense waters along the southwestern shelf and their cascading into the Lacaze-Duthiers submarine canyon. Further DSWC events in the same area were also observed in 1969 by Fieux (1974) and in 1971 by Person (1974), who traced dense shelf waters down to 800 and 350 m depth, respectively. Further evidence was gained during winter 1995 by Lapouyade and Durrieu de Madron (2001) at the same location; they observed a cascade at its final stage with a large tongue of cold water escaping the shelf and reaching its neutral density level around 170 m depth. More recently, a fine spatial resolution hydrographic survey performed in 2004 along the axis of the Cap Creus Canyon (Durrieu de Madron *et al*., 2005) showed a cold and less salty filament, attached to the seabed, down to 350 m. The section exhibits a transitional case, as the leading edge has not reached the neutral density level, between 400 and 500 m. In both cases, the advection of turbid shelf waters produces a turbidity maximum associated to the dense water tongue.

In all cases, temperature is the sole driver of cascading. At the initial stages, when dense waters escape the shelf and spread around the shelf break depth (150-200 m), they contribute to the formation of the Winter Intermediate Water (WIW), with typical properties T = 12.5°C, S = 38.0 (Dufau-Julliand *et al*., 2004). In the case when dense shelf waters cascade to deeper levels, they eventually mix with the warmer and saltier Levantine Intermediate Water (LIW) layer (T = 13.2°C, S = 38.5) that extends between 200 and 1,000 m depth or eventually with the underlying WMDW.

The monitoring of temperature, current and downward particle fluxes conducted since 1993 in the lower part of the Planier and Lacaze-Duthiers submarine canyons by the "Centre de Formation et de Recherche sur l'Environnement Marin" of Perpignan (CEFREM) revealed an inter-annual variation of the DSWC intensity in the Gulf of Lions (see Heussner *et al.*, 2006 and Canals *et al.*, 2006 for details). Based on these time series Béthoux *et al.* (2002) inferred that during the abnormally cold 1999 winter, the intense shelf cascading episode traced at 1,000 m on the continental slope, with down-slope velocities up to 60 cm s^{-1}, contributed to the renewal of the bottom waters of the western Mediterranean basin. Previous severe winters with anomalous dense water formation (i.e. those with major cascading events reaching the basin) were identified by these authors after the analysis of historical hydrographic data and presumably took place in winter 1971, 1980 and 1988, therefore occurring at subdecadal intervals.

Further time series observations in the Gulf of Lions were conducted under the frame of the EuroSTRATAFORM project, during which seven submarine canyon heads were monitored simultaneously in winter 2004. These results revealed that the preferential cyclonic circulation of the coastal current and the narrowing of the shelf at the southwestern end of the Gulf cause most of the water and sediment transport during DSWC events to occur through the Cap de Creus submarine canyon (Palanques *et al*., 2006). Since then, the occurrence and effects of dense shelf water cascades from the Gulf of Lions have been continuously monitored at the Cap de Creus submarine canyon head, as a complement to the two long-term mooring deployments in the Planier and Lacaze-Duthiers submarine canyons at 1,000 m depth. The subsequent major DSWC event recorded by those instrumented moorings occurred during the abnormally dry, windy and cold winter 2005, when cascading was exceptionally intense, lasting for more than three months. Under these circumstances, dense shelf waters propagated along and across the continental slope (Font *et al*., 2007), reaching depths >2,000 m where they merged with dense waters formed off-shelf, in the MEDOC area, by a typical open-sea convection process (MEDOC group, 1970). The mixing of these two dense waters generated a thermohaline anomaly in the WMDW that spread throughout the entire north-western Mediterranean basin (López-Jurado *et al.*, 2005; Schroeder *et al*., 2006). The following major DSWC event occurred in winter 2006, which could be also traced down to 1,900 m depth by a large network of instrumented moorings deployed in the south-western end of the Gulf of Lions margin under the frame of the HERMES project (Sánchez-Vidal *et al*., 2008). This consecutive major DSWC event presumably contributed to the modification and spreading of the "new" WMDW generated after winter 2005 and 2006 characterized by Schroeder *et al*. (2008).

The aim of this contribution is to provide evidence of the contribution of DSWC to the changes in the WMDW after the strong winters 2005 and 2006, and to revisit the role that the winter 1999 DSWC event played in the thermohaline and turbidity anomalies in the WMDW, which resemble the 2005-2006 ones.

TIME SERIES OBSERVATIONS

As stated before, the occurrence and effects of dense shelf water cascades from the Gulf of Lions have been continuously monitored at the Cap de Creus submarine canyon head (300-500 m depth) since November 2003 under the frame of several research projects (Figure 2). This mooring has been maintained as a permanent observatory and is equipped with an Aanderaa RCM 9/11 doppler current meter with temperature, conductivity, pressure and turbidity sensors placed at 5 m above the bottom.

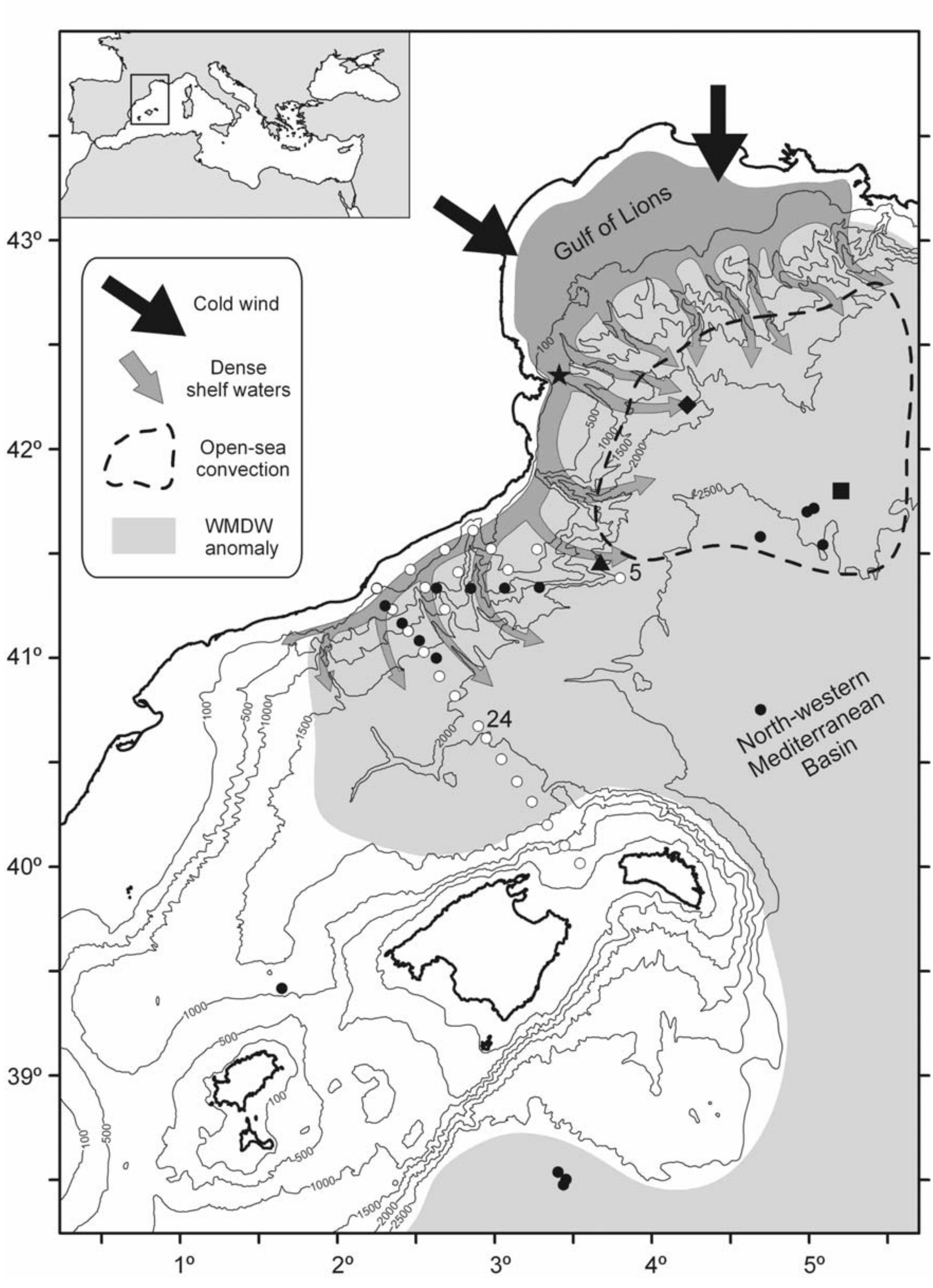

Figure 2. Bathymetric map of the north-western Mediterranean showing the pathway of the dense shelf water cascading mechanism extending from the Gulf of Lions along and across the Catalan continental slope, the open-sea convection region (MEDOC area) and the region affected by the thermohaline and turbidity anomaly observed in the WMDW during the 1999 and 2005 major cascading events. Black dots represent the CTD casts collected in winter 2005 and the white dots those collected in winter 1999. The location of the monitoring sites at the head (star) and mouth (diamond) of the Cap de Creus submarine canyon, at the basin (square) and at the Hydro Changes ICM location (triangle) is also shown.

Contemporary with the Cap de Creus time series observations, since October 2003 and as part of the HydroChanges (HC) pilot program launched by CIESM (<http://www.ciesm.org/marine/programs/hydrochanges.htm>; CIESM, 2002), the "Institut de Ciències del Mar of Barcelona" (ICM) has been maintaining an instrumented mooring in the lower Catalan continental slope (hereafter named HC-ICM), which has proved very valuable in identifying the interactions between open-sea convection and shelf cascading dense waters in the formation of the WMDW (see Font *et al*., 2007 for details). The HC-ICM mooring is located at 1,890 m depth, downstream from the Gulf of Lions margin and south of the Palamós submarine canyon (Figure 2). This location was chosen because it was previously used in 1993-94 for a study related to the spreading of the deep water formed in the NW Mediterranean (Send *et al.*, 1996), from where background information existed. The mooring is equipped with a SeaBird 37 model CTD recorder at 15 mab and an Aanderaa RCM 8 mechanical current meter at 11 mab, and since March 2007 an auxiliary Aanderaa RCM 11 doppler current meter equipped with a turbidity sensor has been installed on it.

Additionally, in the context of the research project EFLUBIO a moored instrumented array was installed in the North Balearic Basin at 2,350 m depth (5º 12'; 41º 48'; Figure 2) from November 2003 to April 2005. The array was equipped with an Aanderaa RCM 11 doppler current meter and a Technicap PPS 5/2 conical sediment trap with a 1 m^2 collecting area and 24 receiving cups. The current meter was placed 220 mab and the sediment trap 250 mab. The sediment trap collected 48 samples in the two consecutive deployments with a mooring turn-around in mid-September 2004. The trap collecting intervals ranged from 5 to 15 days, depending on the season, and the current meter sampling interval was set at 60 minutes.

In the same study area, and as part of the HERMES project, nine mooring lines were also deployed from October 2005 to October 2006 along the axes of the Lacaze-Duthiers and Cap de Creus submarine canyons at 300, 1,000, and 1,500 m depth, and on the adjacent southern open slope at 1,000 and 1,900 m depth. Each mooring was equipped with one sequential sampling (12 cups) PPS3 Technicap sediment trap (0.125 m^2 opening) at 30 mab and an Aanderaa RCM 9/11 doppler currentmeter with temperature, conductivity, pressure and turbidity sensors placed at 5 m above the bottom (mab). For the purpose of this contribution, only the time series from the mooring placed at 1,900 m depth along the Cap de Creus canyon axis (Figure 2) is used.

Figure 3 shows several time series obtained in the above-mentioned observational sites reflecting the changes in the thermohaline properties of the WMDW and the transfer of particles to the north-western Mediterranean basin. Data recorded during several consecutive winter deployments in the Cap de Creus submarine canyon head (300-500 m depth) have allowed monitoring and identifying the occurrence and magnitude of dense shelf water cascades from the Gulf of Lions (Figure 3a,b). Cascading events are easily recognizable since they are characterized by abrupt decreases in water temperature (below 12 ºC) associated with increases in current speed (up to 80 cm/s) and with increases of suspended sediment concentration (data not shown).

The time series of data recorded at the HC-ICM mooring indicated a clear difference between winters characterized by minor or major cascading events. The potential temperature (12.84-12.86 ºC) and salinity (38.45-38.46) values at 1,980 m depth in the lower Catalan continental slope (Figure 3c,d) were almost unchanged from October 2003 until the end of January 2005, indicating a stable water mass situation that corresponds to typical WMDW characteristics (θ 12.8-12.9, S 38.43-38.46, σ_θ 29.09-29.10), depending on the specific conditions that occurred during its formation in winter. However, from this last date, and simultaneously with the initiation of the major 2005 cascading event in the Cap de Creus Canyon, θ and S rapidly increased to 12.99 ºC and 38.50 respectively, and then for one month fluctuated between 12.90-12.95 ºC and around 38.49 (σ_θ = 29.11). Such increases were attributed by Font *et al.* (2007) to the arrival at the HC-ICM site of dense waters formed or pre-conditioned by the offshore convection process, which had a large contribution of an unusually warm and salty LIW/TDW. By early March 2005, potential temperature and salinity suddenly decreased by more than 0.2 ºC and 0.04, respectively, as a consequence of the arrival of colder and fresher dense shelf waters, which cascade from the Gulf of Lions to the lower Catalan continental slope (Font *et al.*, 2007). The signature of these dense shelf waters remained during one month in a range of low values (with peaks down to 12.51 ºC and

38.41, σ_θ = 29.14), lasting for almost as long as the continuous cascading was recorded within the Cap de Creus Canyon, and was followed by a period of gradual θ and S increase until reaching quite steady values of 12.88 ºC and 38.48 (σ_θ = 29.12) by mid June 2005. In late December 2005, potential temperature and salinity sharply increased by 0.06 ºC and 0.01 respectively, presumably as a consequence of the arrival of newly formed dense waters by winter offshore convection, and afterward, θ and S fluctuated between 12.82-12.95 ºC and 38.47-38.49 until mid March 2006. At that time, a sudden drop of 0.16 ºC and 0.04 took place, associated to the arrival of dense shelf waters to the HC-ICM site exported during the major 2006 cascading event. Similar to what occurred in the preceding year, the signature of the dense shelf waters could be detected at 1,890 m depth for more than a month, with minimum values of 12.66 and 38.43 (σ_θ = 29.13). Progressively, θ and S values reached the same "new" (i.e. after 2005) steady values of 12.88 and 38.48 (σ_θ = 29.12) by mid May 2006, although both variables showed after that date a subtle but persistent increasing trend with periodic fluctuations of several days. The HC-ICM mooring was recovered (and reinstalled again) in early March 2007 without showing any evidence of thermohaline changes in the WMDW associated to the several minor cascades that occurred in winter 2007.

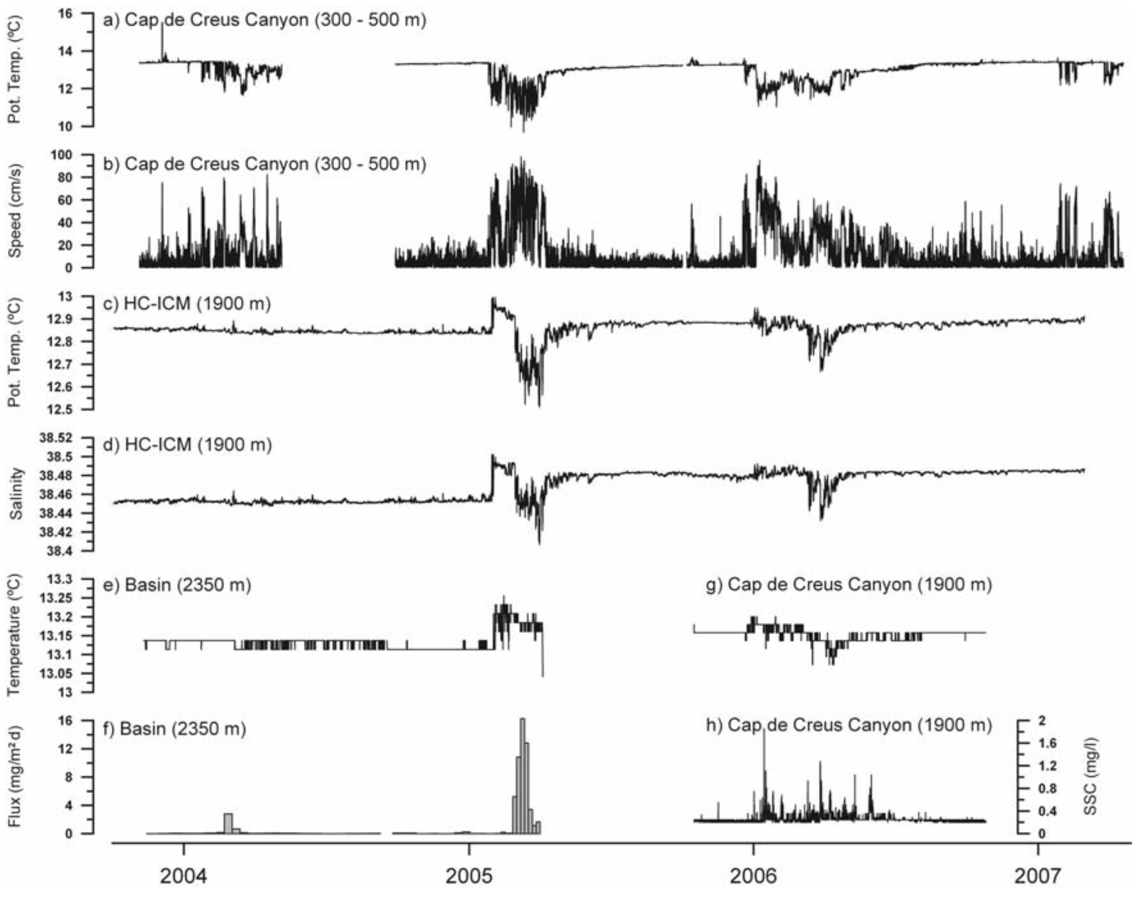

Figure 3. Time series observations from the north-western Mediterranean showing: a) potential temperature and b) current speed at the head of the Cap de Creus submarine canyon; c) potential temperature and d) salinity recorded at the HC-ICM site; e) *in situ* temperature and f) total mass fluxes collected at the basin site; and g) *in situ* temperature and h) suspended sediment concentrations recorded at the Cap de Creus canyon mouth.

At the basin site (2,400 m depth, 220 mab), *in situ* temperature recorded at 220 mab from November 2003 to February 2005 showed a similar temporal evolution pattern. It maintained a relatively constant value of 13.11-13.13 ºC and increased to 13.20-13.23 ºC between early February and early March 2005. Afterwards it decreased by about 0.05ºC, to 13.16-13.18 ºC, until early

April 2005, when a sudden drop to 13.04 ºC occurred just before the mooring recovery (Figure 3e). Based on these multiple observations on the effects of the major 2005 DSWC event, we can state that dense shelf waters head began to flow uninterruptedly down-slope along the Cap de Creus canyon towards greater depths on 24 February 2005. Five days later, DSWC mixed with offshore convection waters reached the ICM-HC site, producing a temperature drop of 0.2 ºC. This drop was smaller (0.05 ºC) at the basin site and occurred seven days later, indicating that the arriving of dense shelf waters to the basin was more mixed with offshore convection waters than at the Catalan deep slope. The arrival of DSWC at the basin site produced a particle flux increase of 2-3 orders of magnitude (up to 16.27 g/m^{2}d) from late February 2005 until at least the end of the deployment on early April 2005 (Figure 3f), indicating that this deep DSWC event transported a large particle load to the basin (Palanques *et al*., 2009).

At the Cap de Creus canyon mouth (1,900 m depth), during winter 2006, *in situ* temperature also exhibited the same temporal evolution recorded at the HC-ICM site (Figure 3g). It showed quasi steady values around 13.16 ºC from mid October to late December 2005, and afterwards it progressively increased to 13.20 ºC. By mid January 2006, a drop to 13.11 ºC (event also noticed in the HC-ICM record) coincided with a sharp peak of suspended sediment concentration (SSC) (Figure 3h). From that date onwards, temperature decreased progressively to 13.07 ºC until mid April 2006 (with an isolated drop by mid March 2006) and SSC displayed high values until late June 2006 at the time that *in situ* temperature progressively increased and stabilized again at values around 13.16 ºC.

CTD PROFILES

The sequence of changes recorded by these time series observations could be observed in numerous CTD casts collected immediately after the 2005 dense water formation period. During the EFLUBIO-2 cruise conducted from mid March to early April 2005 (see CTD casts position in Figure 2), the signal of the 2005 DSWC event and the formation of a thick BNL associated to the dense water plume spreading off the Gulf of Lions could be mapped and traced as far south as Barcelona.

Figure 4 shows the vertical profiles of SSC and σ_θ of a hydrographical transect across the Barcelona continental margin, from 300 m down to 1,700 m depth. On these profiles (as well as in others not shown) a thick BNL that scales in thickness with a dense water plume can be observed at all depths. This BNL becomes thicker with depth although the maximum concentrations reached close to the seafloor are similar and reach values around 0.6 mg/l (three times higher that the typical background levels).

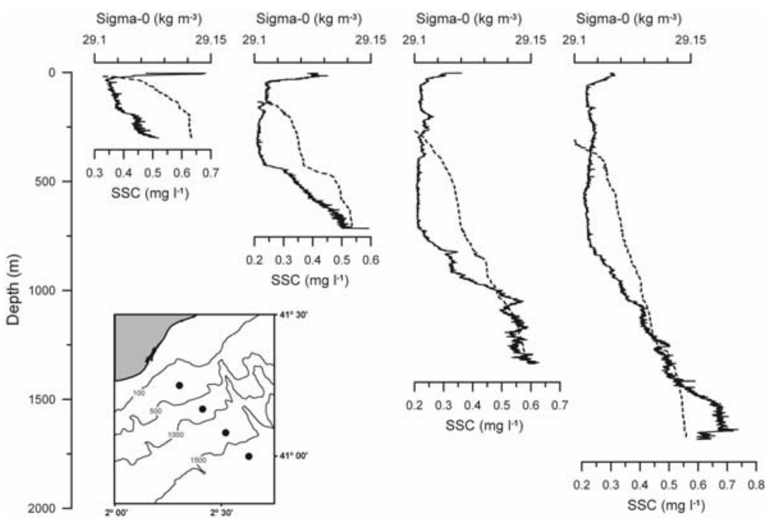

Figure 4. Vertical profiles of suspended sediment concentration (SSC) and σ_θ from a hydrographical transect conducted across the Barcelona continental margin, from 300 m down to 1,700 m depth on 24 March 2005. The inset map shows the detailed location of the CTD casts (see Figure 2 for a general situation).

These observations corroborate the results obtained by the deployed instruments and clearly illustrate the capacity of the major DSWC events in the Gulf of Lions to spread along and across the north-western Mediterranean margin and to carry large amounts of particles in suspension, along with dense shelf waters, towards the basing.

This BNL has been observed in deeper profiles collected during the same cruise (Figure 2), not only associated with the dense shelf waters, but with the positive thermohaline anomaly in the WMDW that spread throughout the entire north-western Mediterranean basin (López-Jurado *et al*., 2005; Schroeder *et al*., 2006).

The 1999 event

As stated before, the previous anomalous winter that affected the north-western Mediterranean and caused a major cascading event was in 1999. To asses the extent to which the CTD observations collected after the 2005 DSWC were unique or shared some similarities with the 1999 DSWC, data from the HIVERN-99 oceanographic cruise were re-examined. This cruise took place from late February to mid March 1999 (see CTD casts position in Figure 2) during which several deep CTDs and a detailed transect from Barcelona to Mallorca was conducted. To illustrate the interactions between open-sea convection and shelf cascading dense waters in the formation of the WMDW during winter 1999, the θ, S and SSC vertical profiles from two CTD casts have been plotted in Figure 5.

The CTD cast conducted closer to the Gulf of Lions (cast # 5) clearly captured the formation of dense waters by open sea convection since the θ and S vertical profiles were almost constant through the water column (12.89 ºC and 38.44) and free of particles in suspension. However, the near-bottom layer was occupied by a 600 m thick colder, fresher and more turbid water mass that corresponded to the arrival of dense shelf waters to the basin (see inset in Figure 5).

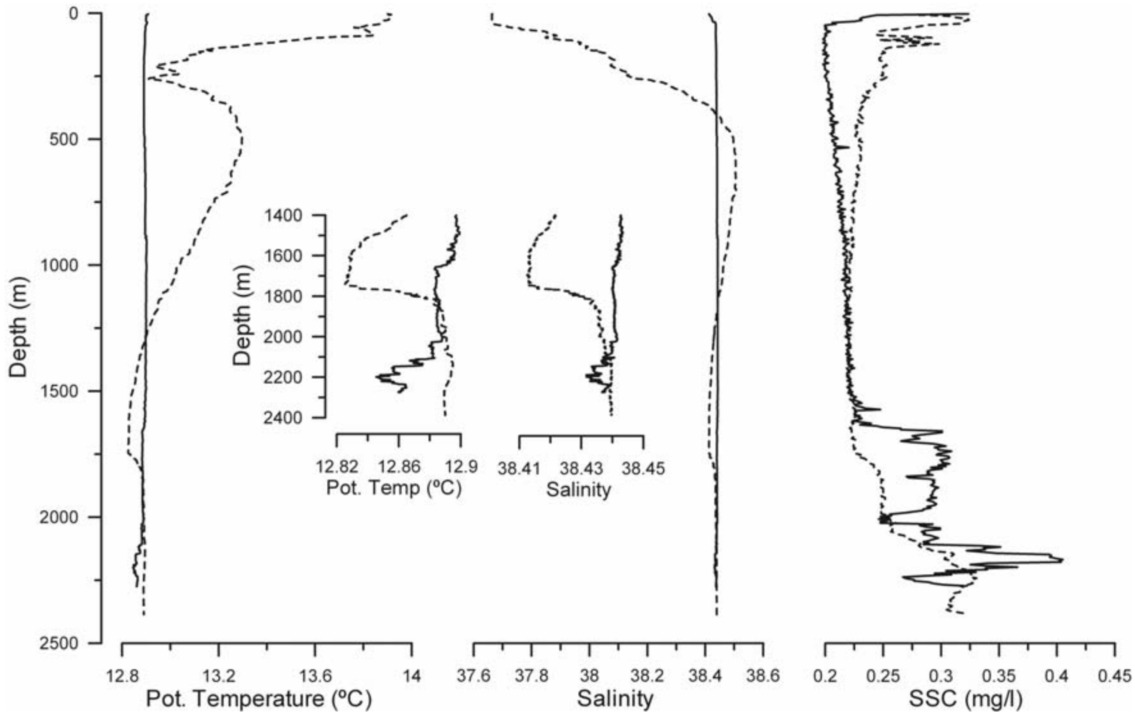

Figure 5. Vertical profiles of potential temperature, salinity and suspended sediment concentration from two deep CTD casts collected in the north-western Mediterranean on 21 February 1999 (cast # 5, solid line) and on 25 February 1999 (cast # 24, dashed line) illustrating the interaction between the cascading and convection dense waters generated during winter 1999. See Figure 2 for CTD positions.

Contrary to what was observed in winter 2005, the hydrographic transect from Barcelona to Mallorca did not show the formation of a thick BNL associated to the spreading of dense shelf waters towards the south, probably because of a limited extension of the dense water plume escaping from the Gulf of Lions at the time of the cruise. Nonetheless, the deepest profile in the middle of the Valencia valley (cast # 24) did show a well developed BNL (600 m thick) that scaled in thickness with a positive thermohaline anomaly similar to that observed in 2005 (Figure 5).

The comparison between these two deep CTD casts conducted in winter 1999 provide further evidence that the arrival of suspended particles to the basin during anomalous winters is associated to the occurrence of deep DSWC events, while the positive thermohaline anomaly is caused by the open sea convection process, since the high anomalous θ and S values for the WMDW in cast # 24 fall in the range of the dense convection waters observed in cast # 5 (i.e. 12.89 ºC and 38.44). Therefore, it seems that the mixing of the two dense water masses is responsible for the thermohaline (mainly convection) and turbidity (solely cascading) anomaly observed after winter 1999, as well after winters 2005 and 2006 (see Salat *et al.*, this volume for further details).

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Modelling water mass formation in the Gulf of Lions (Mediterranean Sea)

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Abstract

The inter-annual variability characteristics of the winter convection in the Gulf of Lions in the Mediterranean Sea are studied using a high resolution model. After a 15-year spinup, the model was forced by the European Centre for Medium-range Weather Forecast (ECMWF) analyses from 1998 to 2008. Deep convection (> 500 m) occurs in the MEDOC zone [40, 43.5 °N; 3, 7 °E south of the Gulf of Lions] in a quasi circular area of about 234 km diameter. While shallow deepening of the mixed layer to a depth of 400 m only is noticed in the Ligurian Sea and eastern Catalan sub-basins, convection is much deeper in the Gulf of Lions and reached the sea bottom in the winter of 2005. The location, the maximum depth, the duration and the formation rate of convection vary inter-annually. Compared to observations the hydrographic characteristics are slightly less dense by 0.01, mainly due to an offset in temperature of about 0.2°C. The spreading of the deep waters shows a cyclonic circulation. From the Gulf of Lions, the deep current flows southward along the eastern coast of Menorca. Then it splits in two directions, the first vein flows toward Gibraltar along the southern shelf of the Balearic Islands and the second vein toward the Gulf of Lions, where it interacts with mesoscale eddies and gyres.

1. Introduction

The Mediterranean Sea transforms the inflowing light Atlantic Water (AW) into denser and deeper Mediterranean waters as a result of the air-sea forcing. A change in the climate may have important consequences in the forcing and consequently for the basin circulation and hydrography. As the forcing of the thermohaline circulation is due to the sinking of dense water from the surface to intermediate or deep layers in a few specific areas, generating a pressure gradient between the Atlantic Ocean and the Mediterranean Sea, it is important to study the capability of numerical models to reproduce this dense water formation adequately.

Following the pioneering work of the Medoc Group (1970), a large number of studies have been dedicated to water mass formation in the Mediterranean Sea. An extensive summary of them was given by Madec *et al.* (1991a,b) and Marshall and Schott (1999) concerning the mechanism, and by Castellari *et al.* (2000) for the modeling. Typically, deep water formation has been observed in the Gulf of Lions (Mertens and Schott, 1998) with a strong inter-annual variability in response to change in atmospheric large scale features (Somot *et al.*, 2006).

Several factors participate in deep water formation. First, strong heat exchanges associated with high wind stress drive buoyancy loss and generate mixing and entrainment at the bottom of the mixed layer (Marshall and Schott, 1999). Another factor is the oceanic circulation, which plays an important role by forming a steady cyclonic structure preconditioning deep convection (Gascard, 1978). The steady cyclonic structure compels water parcels to stay at the same place near the center of this circulation and consequently to be subject to atmospheric forcing for a longer time. This preconditioning is important in the Gulf of Lions (Killworth, 1976). It contributes to the trapping of the oceanic structures and counter-acts the destabilizing effect of the baroclinic instability (Madec *et al.*, 1991a,b; 1996; Jones and Marshall, 1993).

The Western Mediterranean Deep Water (WMDW) forms in the Gulf of Lions in winter. The convection depth is highly variable, ranging from 800 m to the bottom (Medoc Group, 1970; Schott *et al.*, 1996; Millot, 1999; Testor and Gascard, 2003; Schroeder *et al.*, 2008b). WMDW formation occurs near 42°N-5°E, generally in February during a succession of strong convective events. If the formation area is well identified and quite steady from year to year due to geographical factors, the convection presents a strong inter-annual variation, depending on the strength of the atmospheric forcing (Thetis Group, 1994; Mertens and Schott, 1998). The potential density of the formed water is about 29.10, the potential temperature θ=12.85°C and the salinity S=38.45 (Leaman and Schott, 1991). According to recent observations (Medar Group, 2002; Petrenko *et al.*, 2005; Schroeder *et al.*, 2008b), the latter two parameters seem to have slightly increased during the last decade up to θ=12.93-13.01°C and S=38.56-38.57, due to warmer and saltier Levantine Intermediate Water (LIW) involved in the convection (Schroeder *et al.*, 2006) since the Eastern Mediterranean Transient (Roether *et al.*, 1996).

In the present paper, we try to document the inter-annual variability of the formation and dispersion of the WMDW in the Gulf of Lions for the last decade (1998-2008) from a high resolution simulation.

2. The numerical experiment

The Mediterranean model MED16 (Béranger *et al.*, 2004; 2005) has an horizontal resolution of about 5 km and extends from 11°W to 36°E and 30°N to 46°N. This numerical model is a version dedicated to the Mediterranean Sea of the primitive-equation numerical model Ocean PArallel (Madec *et al.*, 1997) with a rigid lid. The Atlantic Ocean was simulated as a box (37°, 40° N, 5°, 11° W) where the potential temperature and the salinity 3D fields are restored towards the seasonal climatology of Reynaud *et al.* (1998). In the Mediterranean Sea, the initial hydrographical seasonal conditions were provided by the MODB-4 winter climatology (Brankart and Brasseur, 1998). The model is forced by heat and freshwater fluxes and winds. During a spinup period of 11 years (January 1987 to February 1998) the MED16 model was forced by the ERA40 air sea fluxes (ECMWF re-analyses). Then the experiment was carried out from March 1998 until April 2008 by forcing MED16 with the fluxes and winds provided by the recent ECMWF analyses.

Several studies based on the same simulation have shown a good agreement with *in situ* observations collected for the period 1998-2002 (Béranger *et al*., submitted) and the satellite observations for the 10-year period studied (Herrmann *et al.*, 2009). The intermediate circulation (Taillandier *et al.*, 2006) and the deep circulation in the southwestern Mediterranean with the Algerian gyres and the Sardinian Eddies (Testor *et al.*, 2005a) are also in good agreement with *in situ* observations.

3. WMDW formation and spreading

The depth reached by convection in winter is diagnosed as the depth of the mixed layer which is defined as the depth at which the computed vertical diffusivity coefficient must be strongly increased to model the hydrostatic instability. An horizontal map representing the maximum of the convection depth reached at least once during the 10-year simulation at each grid point is displayed in Figure 1. It shows that convection deeper than 500 m occurred in a large area [40, 43 °N; 3, 7 °E] that we will call the MEDOC zone hereafter. This MEDOC zone corresponds to an horizontal area $\boldsymbol{A}^{T}$ equivalent to a circular area of radius of about 117 km. The bottom convection (>2,000 m) is centered in the middle of the MEDOC zone in a smaller area [41.4, 42.2 °N; 4, 5 °E] in agreement with the observations.

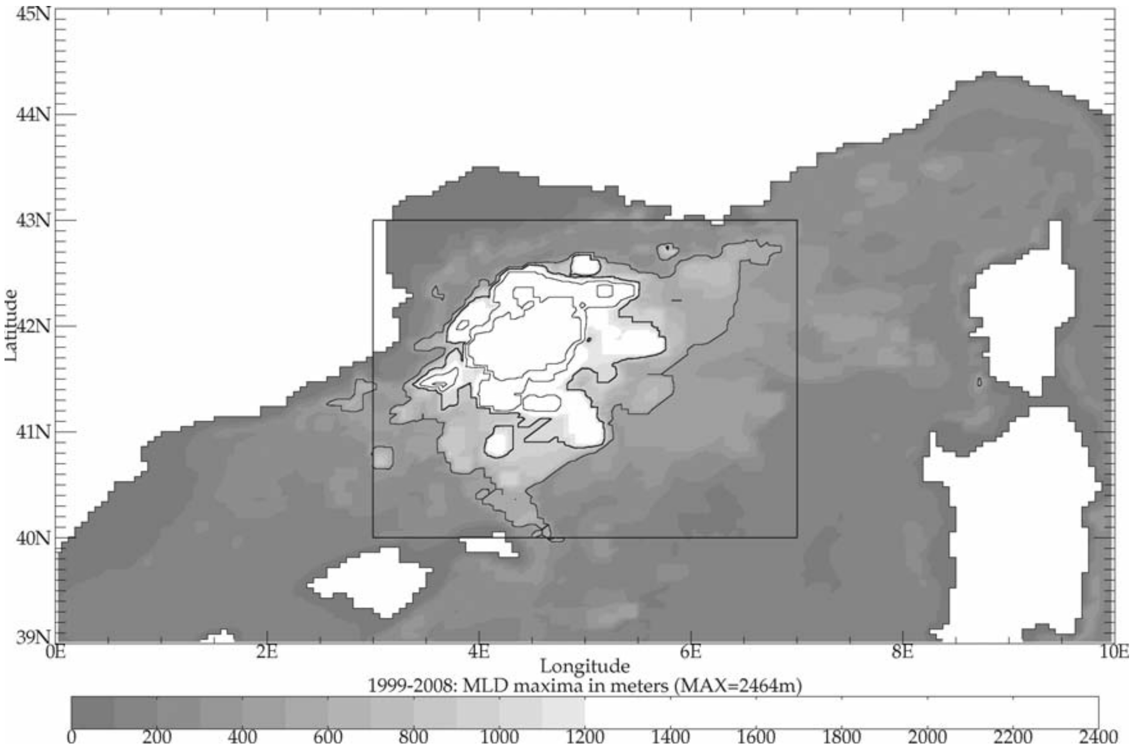

Figure 1. Map of the depth maximum $\boldsymbol{D}$ reached by the convection in the Gulf of Lions for the whole period 1998-2008. Contours are every 500 m. Depths larger than 500 m are inside the first contour line and correspond to the horizontal extent defined as $\boldsymbol{A}^{T}$ in the text. The MEDOC zone defined in the text is added as a box.

3.1 Open-sea mixing

Let us focus on the violent mixing phase of the deep water formation process described by the Medoc Group (1970) for the deep water formation process. A preliminary mixing (0-500 m, Figure 2) starts in mid-December up to mid-January during which the surface waters erode the Levantine Intermediate Water. It is followed in mid-February up to mid-March by the open-sea violent mixing during which the newly formed dense water sinks down to the sea bottom. During the 10-year simulation, the convection reached depths deeper than 500 m except for the years 2007 and 2008. The convection reached a depth deeper than 1,000 m in 1999, 2003, 2005 and 2006. The areas for which convection deeper than 500 m has occurred at least once during each winter are illustrated in Figure 3 by representing the maximum depth $\boldsymbol{D}$ reached by the convection during each winter. Mesoscale deep features are noticed in several places, for example around 41.9°N between 4° and 4.3°E during the winter of 1999 and around 5.1°E between 41.8°-42.5°N during the winter of 2003. Their positions vary with respect to the winter in latitude and longitude inside the MEDOC zone. The extent of the winter surface convection varies inter-annually and corresponds to surfaces of equivalent radius ranging between 20 km in 2002 up to 106 km in 2005 (Figure 4). The daily areas $\boldsymbol{A}$, for which convection deeper than 500 m has occurred at least once, are expressed as a percent of $\boldsymbol{A}^{T}$ and its evolution with respect to time is represented in Figure 2. That time-series shows two behaviors. Maximum values are noticed after a continuous increase of the surface for the winters of 1999, 2003 and 2005 while successive maxima separated by low surface values (restratification) are noticed for the other winters. The values ranged between 18 and 55% of $\boldsymbol{A}^{T}$ in 1999, 2003, 2005 and 2006 (when $\boldsymbol{D}$>1,000 m) to values lower than 11% in 2000, 2001, 2002 and 2004 (***D***<1,000 m). High (respectively low) values of the daily winter surfaces correspond to a maximum (respectively minimum) of the convection depth (Figure 2). The maximum value of these surfaces corresponds to 55% of ***A***, only highlighting the large variation in the location of the convection. The formation rate of WMDW is estimated as usual (Herrmann *et al.*, 2009) by computing the volume of newly formed waters divided by 1 year for the years for which convection is deeper than 500 m (Figure 4). This rate is maximum in 2005 with 1.28 Sv. The inter-annual variations of the formation rate are well correlated with those of the winter areas of deep convection (Figure 4), except in intensity, although the daily variations are well correlated (Figure 2, correlation coefficient of ~0.80).

High inter-annual variations are noticed in terms of horizontal extent, depth of the convection, location of the convection, duration of the convection and formation rate, during the 10-year simulation. The inter-annual cycle of the convection, mainly driven by the atmospheric forcing, seems to be in relative agreement with observations done during the so called *cold winters* in 1999, 2003, 2005 and 2006 (Petrenko *et al.*, 2005; Schroeder *et al.*, 2008b).

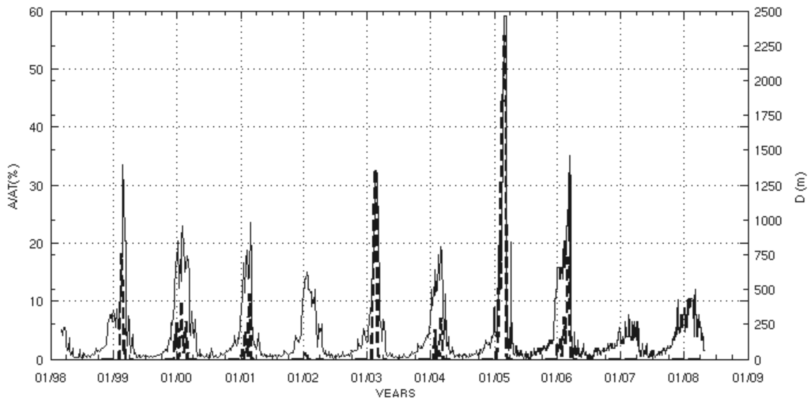

Figure 2. (Full line) Time-series of daily depth maxima ***D*** reached by the convection in the MEDOC zone during the 10-year simulation. (Dashed line) The daily extent of the convection (***A***) for which ***D*** > 500 m is expressed in percent of ***A***^{T}.

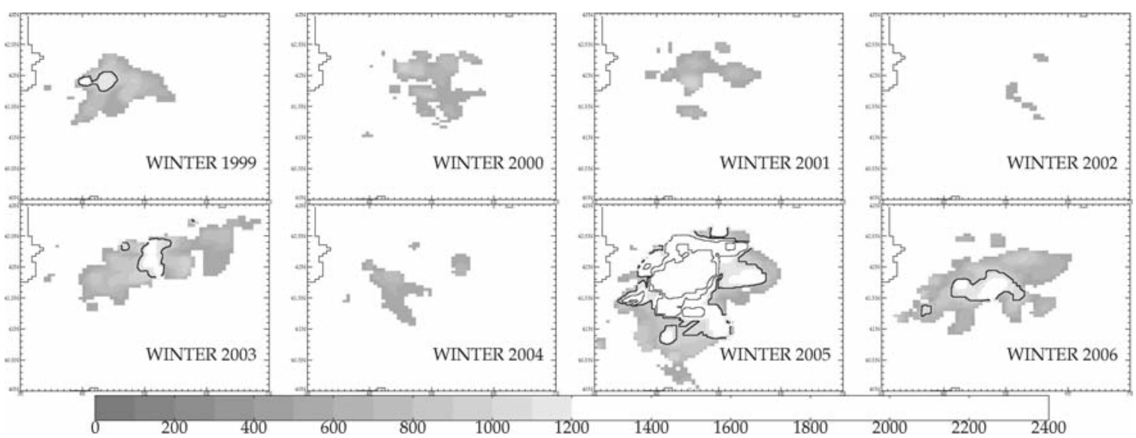

Figure 3. Maps of the depth maxima ***D*** reached by the convection for each winter in the MEDOC zone of Figure 1. It illustrates also the winter extent for convection reaching more than 500 m. Winters 2007 and 2008 are not plotted.

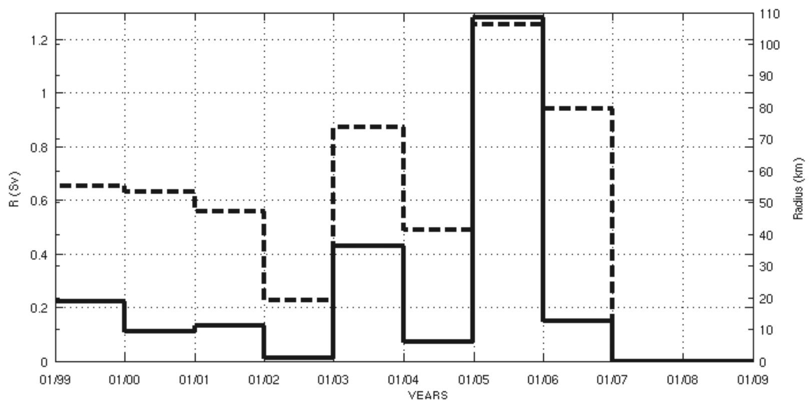

Figure 4. (Full line) Radius of winter extents (equal to a circular surface for ***D*** > 500 m) and (Dashed line) Formation rate ***R*** in Sverdrup (1 Sv=$10^6 m^3.s^{-1}$).

3.2 Characteristics of LIW and WMDW in the MEDOC zone

At the beginning of the simulation, in the MEDOC zone, the temperature of the Levantine Intermediate Water (LIW) and Western Mediterranean Deep Water (WMDW) are close to the model initial state, i.e. the climatology, due to the absence of convection deeper than 300 m during the spin up.

In the Channel of Sardinia, the hydrographic characteristics of the LIW core are θ ~13.90-14.30°C and S~38.65-80 at about 500 m depth and remain quasi constant during the 10 years of the simulation (not shown). In 1998 in the MEDOC zone, the LIW core is characterized by a potential temperature of θ ~13.90°C and a salinity of S~38.70 at about 400 m depth and the thickness of the LIW tongue (~200 m) is relatively shallow (Figure 5a). At this stage, the LIW was not yet diluted (due to the spin up) if we compare its hydrographic characteristics to those at the Strait of Sicily. During the ten years of the experiment, these characteristics increased regularly up to θ ~13.5-13.9°C and S~38.50-38.60 at a depth of about 400 m (Figure 5b,c). At the end of the experiment, after several winters for which relative deep convection events occurred, the LIW had been mixed with other water masses and its warm and salty signature was thus slightly decreased in the MEDOC zone. Concomitantly the thickness of the LIW vein has increased by 100 m with respect to the 1998 one (Figure 5b,c,d).

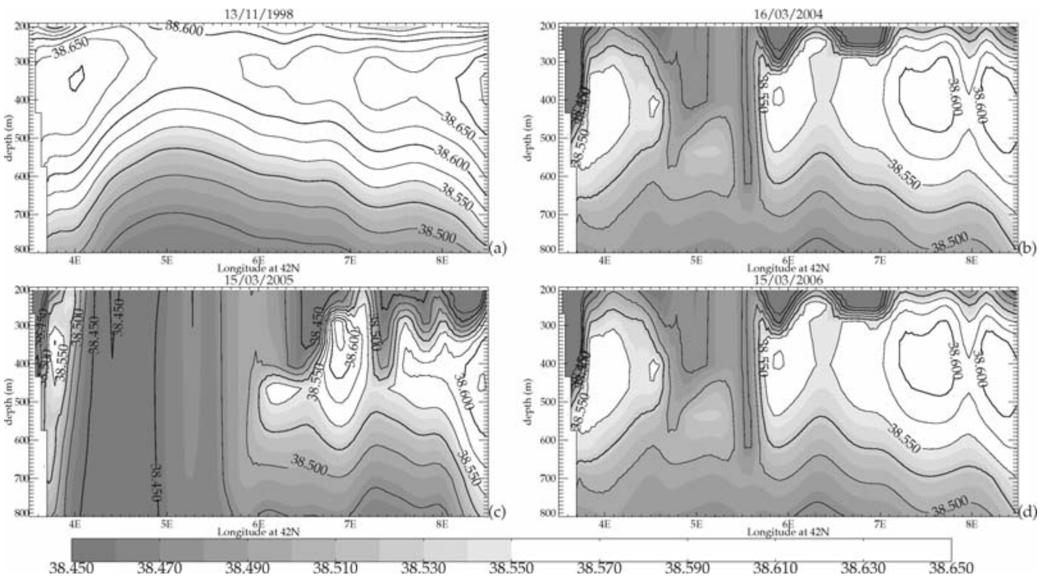

Figure 5. Vertical sections of salinity at 42°N in the MEDOC zone between 200 and 800 m for November 1998, March 2004, 2005 and 2006, showing the LIW characteristics and some convection events. Isohalines are every 0.025.

At the beginning of the simulation, in the MEDOC zone, the WMDW is characterized by a potential temperature θ ~12.71-12.92°C and a salinity S~38.405-38.450 from 1,000 m to the bottom (Figure 6a) with density ranging between 29.085 and 29.095. After several winters of relative deep convection (Figure 2), the WMDW signature has changed in the MEDOC zone. The newly formed WMDW in 2005 is characterized by potential temperature θ~12.78-12.9°C and salinity of S~38.42-38.45 (Figure 6b), with density ranging between 29.09 and 29.10. In 2006 and 2007, the WMDW has a density of 29.09 (Figure 6c,d).

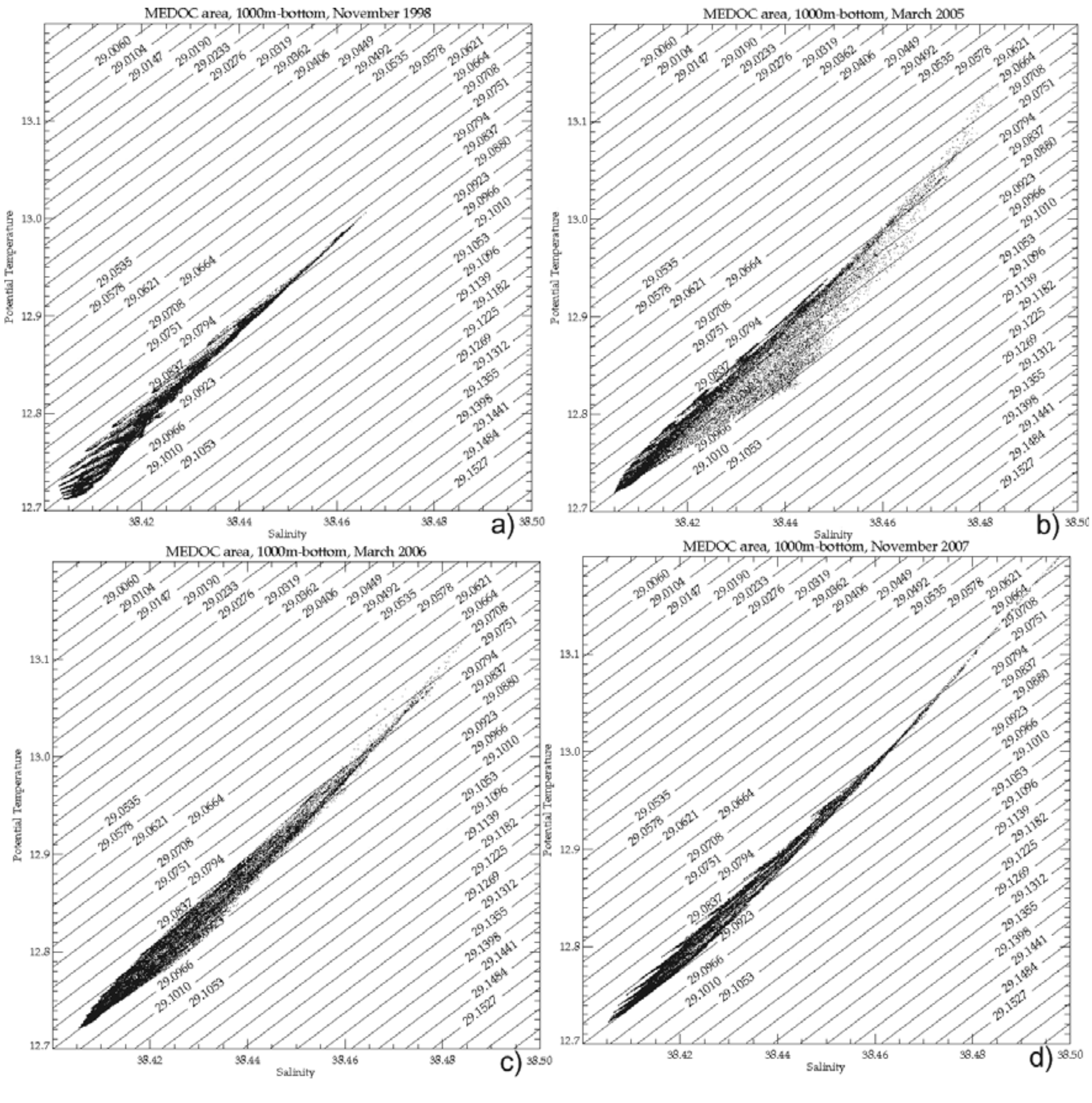

Figure 6. T,S diagram in the MEDOC zone between 1,000 m and the bottom in November 1998, March 2004, 2005 and 2006.

3.3 Spreading of LIW and WMDW

Let us now focus on the circulation on the density surfaces of 29.05 and 29.10 and the Bernoulli function in order to document the LIW and WMDW spreading described by the Medoc Group (1970) after the deep water formation process.

The intermediate circulation, which is associated with the flow of the LIW vein is shown in Figure 7. It represents the monthly mean of the LIW circulation in November 2004 above the 29.05 density surface, whose depths range between 300 and 550 m. The LIW vein flows northward the Sardinia coast as described by Millot (1999) and Béranger *et al.* (2005). It then forms a cyclonic vein streaming westward in the Gulf of Lionss. It flows southward at 4°E, then along the Majorcan continental shelf at 5°E. The LIW transport by eddies, as the anticyclonic Algerian eddies (Millot and Taupier-Letage, 2005) or the Sardinian eddies (Testor and Gascard, 2005) from the western Sardinian coast toward the interior basin, are also well reproduced in the simulation.

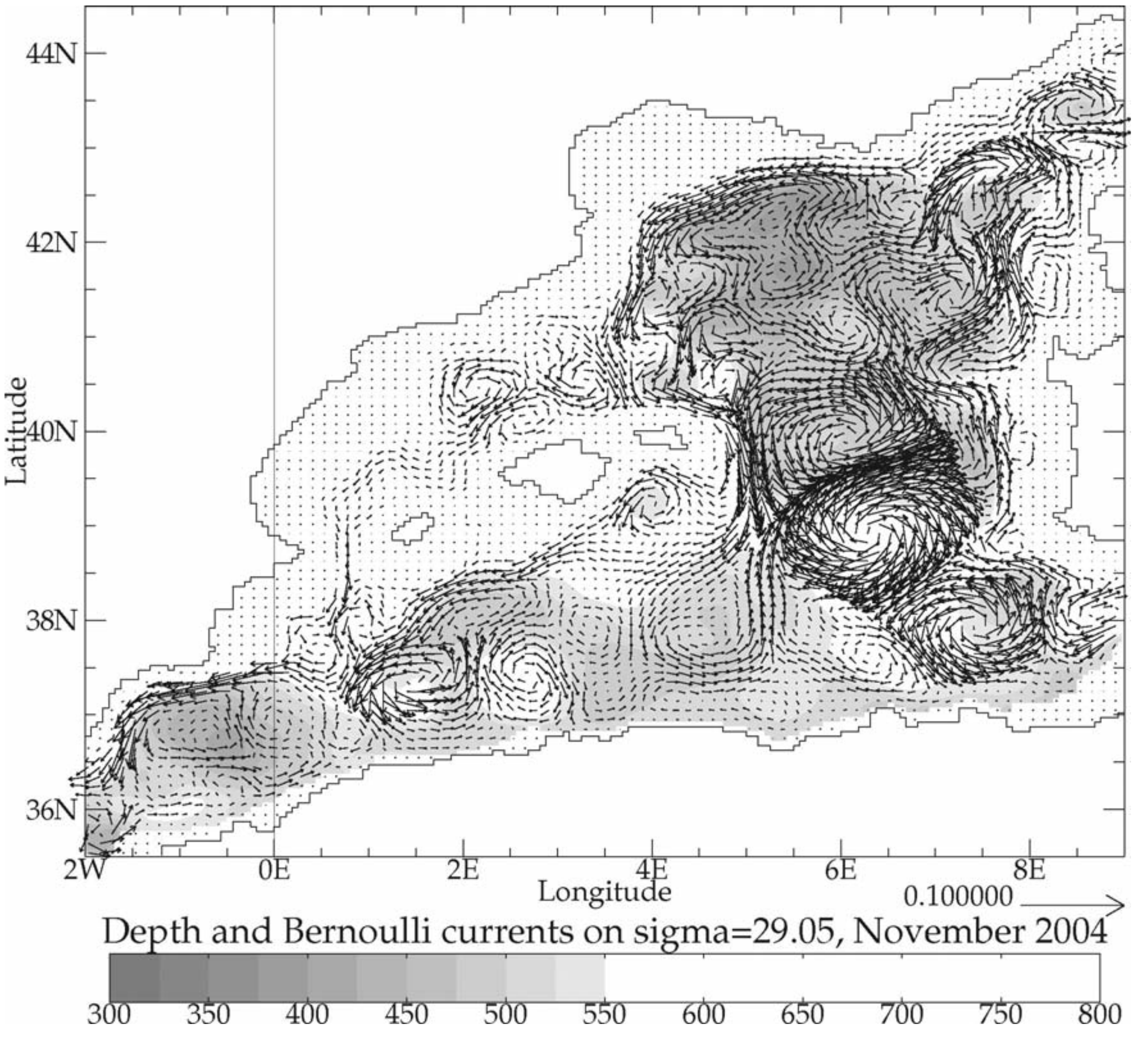

Figure 7. Depth and Bernoulli currents on the isopycne 29.05 in November 2004.

The main path of WMDW is illustrated in Figure 8, which shows the deep circulation in November 2007 above the 29.09 density surface, whose depth ranges between 1,500 and 1,900 m. It flows as a deep and shallow vein of 50 km width from the western part of the MEDOC zone toward the Algerian basin. It is trapped by the eastern continental shelf of Menorca and forms a boundary jet as described by Madec *et al.* (1996). Then it splits into two veins: the first vein turns westward and flows toward the Strait of Gibraltar following the southern shelf of the Balearic Islands. The second vein recirculates toward the Gulf of Lions trapped by the large deep cyclonic circulation affecting the western Mediterranean.

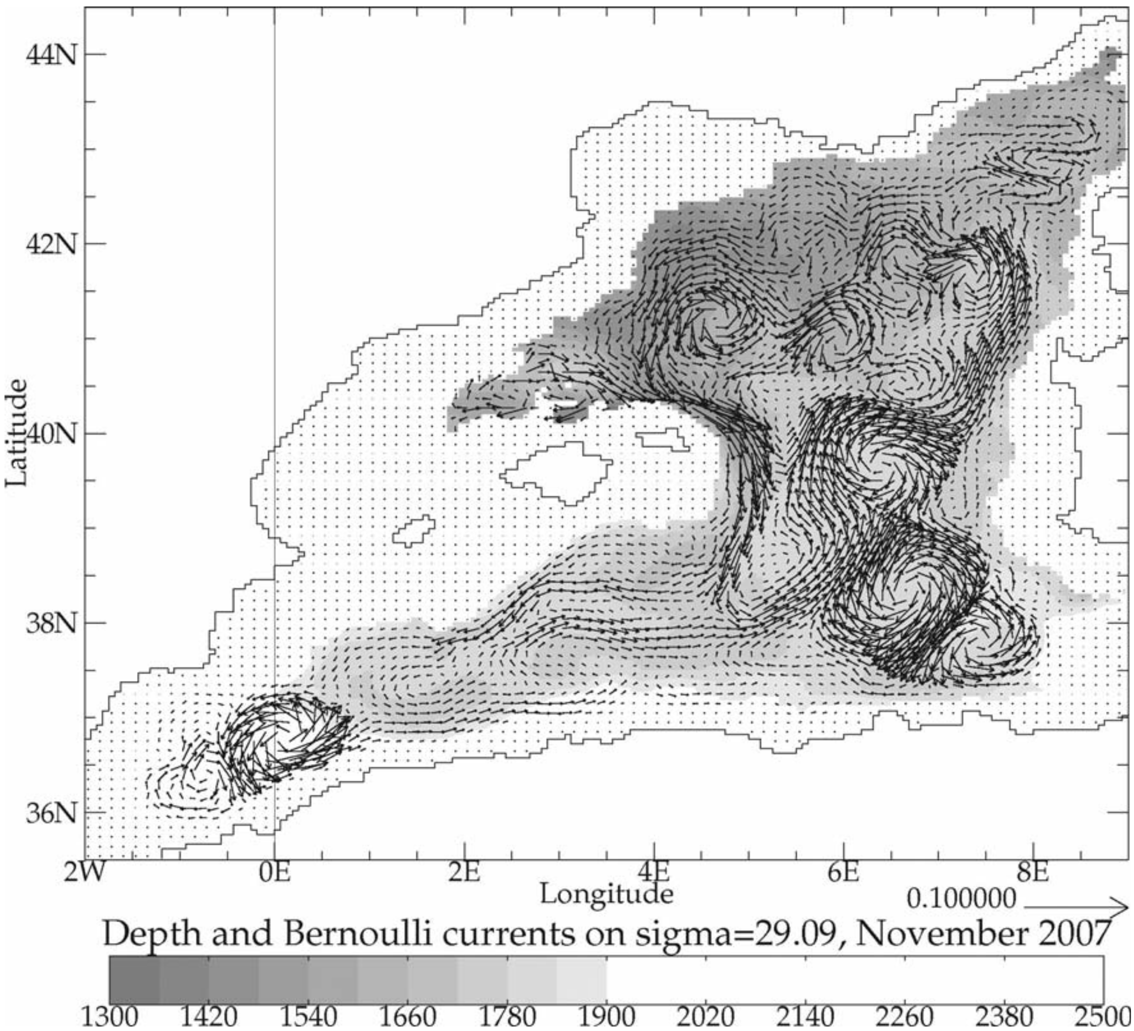

Figure 8. Depth and Bernoulli currents on the isopycne 29.09 in November 2007.

As for LIW, advection of WMDW is associated with eddy interactions, in particular in the Gulf of Lions where about four to five cyclonic eddies (~100 km diameter) are simulated in the fall. Such eddies bring waters from the MEDOC zone toward the eastern Catalan sub-basin and the Ligurian Sea where deep homogeneous density profiles have been reported (Smith *et al.*, 2008). The westward and southward circulation in the Gulf of Lions is enhanced in fall and sometimes in winter, forming a well identified boundary current flowing to the south and that can be increased by a cyclonic gyre centered at 41°N,4.5°E (its diameter varies between 100 and 300 km, not shown). In the simulation, the velocity of that deep coastal vein is ~5 cm.s^{-1} while the velocity of the cyclonic gyre can reach 10 cm.s^{-1}.

According to the simulation, the spreading of WMDW toward the interior basin and the Strait of Gibraltar seems to take a long time. The evolution of the main vein of WMDW along the eastern Majorcan coast is presented in Figure 9 by several vertical sections at 4.9°E. The signature of the WMDW vein at 40°N is more or less deep according to the season (more marked in the fall) and varies inter-annually. This vein brings waters formed at 42°N but also old deep waters coming from the center of the Gulf of Lions. It advects these old waters to the south and may recirculate them in the Gulf of Lions after the splitting into branches at 38N, 5E). These old waters are colder and saltier than the present waters. As a result, in the centers of the Gulf of Lions and of the Algerian basin, the mixing of water masses increased salinity by 0.005-0.01 and temperature by 0.01-0.02°C from 1998 (Figure 9a) to 2008 (Figure 9h) at the bottom of the sea (~2,800 m), although the newly formed deep waters did not really cascade on the bottom sea.

The amplitude of the inter-annual hydrographic drift in the Algerian basin bottom waters between 2004 and 2008 are lower in the model than in the observations, which give ~0.05°C in temperature and 0.02 in salinity from 2004 to 2006 (Schroeder *et al.*, 2008b). The spreading of the newly formed WMDW in the model takes about one year (from March 2005 to March 2006) to advect the old water mass characteristics from the MEDOC area into the deep layers of the Algerian basin. The model represents the spreading by dynamical effects by a deep current along Menorca and mesoscale eddy transport which acts on the whole water column and not by a simple static dilution effect.

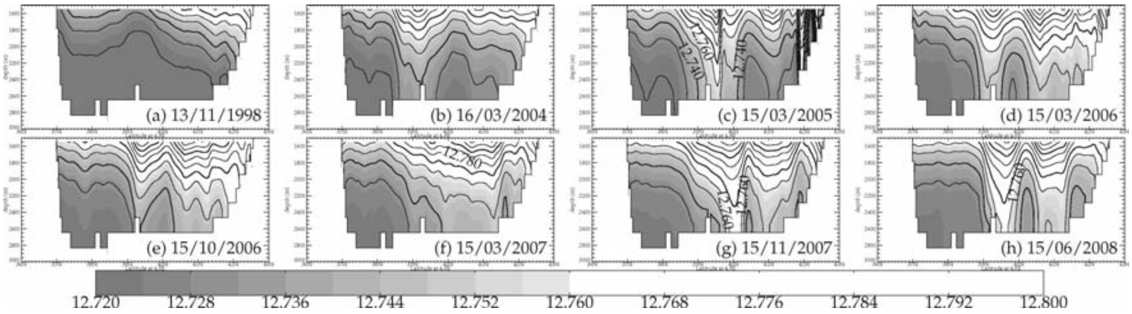

Figure 9. Vertical sections of potential temperature at 4.9°E in the western Mediterranean between 1,500 and 3,000 m in November 1998, March 2004 and 2005, March and October 2006, March and November 2007, and June 2008. Isotherms are every 0.01°C.

4. Conclusion

We have documented here the deep-water formation in the Gulf of Lions for the period 1998-2008 thanks to a high resolution ocean model. The MED16 simulation reproduces the convection fairly realistically with convection depths in statistical agreement with the observations analyzed by Mertens and Schott (1998). The convection presents a high frequency variability (succession of events lasting a few days) as reported by Gascard (1978) and described by Marshall and Schott (1999). The convection also presents a high spatial distribution in a relatively large area [40, 43 °N; 3, 7 °E] if we consider convection deeper than 500 m (~1,000 km^2) and in a smaller area [41.4, 42.2 °N; 4, 5 °E] if we consider convection deeper than 2,000 m (~ 100 km^2). The formation rate is maximal in 2005 when the convection reached the sea bottom, with a value of ~1.3 Sv, which is a very high value compared to the other years (three to five times higher than the previous values). It corresponds to an equivalent circular water column of 160 km diameter and 2,000 m depth centered about at 42°N-5°E. This value seems more realistic than those obtained with coarser resolution models like those of Castellari *et al.* (2000).

The LIW flows toward the north along the western Sardinian coast. It is associated with many westward filaments and detachment of anticyclonic eddies propagating westward in the basin interior. It then spreads in the basin interior following two main paths, one flowing up to Gibraltar and one recirculating towards the Gulf of Lions at the northern periphery of the western Algerian Gyre. The spreading from the MEDOC zone to the southern part of the western Mediterranean is estimated to take about one or two years and is mainly driven by the mesoscale dynamic like the Algerian eddies and the Sardinian eddies. Besides, in particular in fall, the anticyclonic eddy centered at 3°E in the Catalan sub-basin and the cyclonic eddy/gyre at 41°N,4.5°E in the Gulf of Lions, drive a strong deep southward boundary current along the eastern coast of Menorca, which transports LIW and WMDW. We can conclude that a very high resolution oceanic model is essential for correctly representing mesoscale advective eddies and filaments that play a major role in the water mass transports as argued by Testor and Gascard (2006).

Acknowledgments: this work was supported by the French Mercator project (<www.mercator-ocean.fr>) and by the Service Hydrographique et Océanographique de la Marine (SHOM). ECMWF analyses were made available by the European Centre for Medium-range Weather Forecasts (ECMWF). Computations were made at the Institut du Développement et des Ressources en Informatique Scientifique (IDRIS) from the Centre National de la Recherche Scientifique (CNRS).

Fueling Western Mediterranean deep metabolism by Deep Water formation and shelf-slope cascading : evidence from 1981

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Abstract

We focus here on microbial respiration and its potential enhancement by organic-carbon injection via Deep and Intermediate Water formation in the western Mediterranean Sea. Electron transport system (ETS) activities of the nanoplankton and microplankton in the intermediate and deep water from this area show unexpected enhancement. Since ETS is a proxy for respiration these measurements indicate elevated respiration in these waters. In addition, they suggest horizontal transport of organic-carbon rich water-masses. In the western Mediterranean Sea the metabolic rates below 1,500 m were greater than rates at the same depths in the Atlantic. When all the profiles were corrected to the same temperature and normalized by the metabolic rate at 200 m, the Western Mediterranean rates were greater than rates from the same depths in both the Atlantic and equatorial Pacific Oceans. They also exceeded rates predicted from sediment traps. Furthermore they were not consistent with organic matter being supplied via rapidly sinking particulate material. Instead, they may be supported by dissolved organic carbon (DOC) transported to depth by eddies (van Haren *et al.*, 2006), wintertime deepwater convection, or the type of wintertime cold-water cascading recently observed in the canyons on the Catalan-Occitan continental shelf and slope (Canals *et al.*, 2006; Font *et al.*, 2007).

Background

Respiration in the deep-sea (deep metabolism, (Craig, 1971)) is an important factor in understanding the ocean's role as a sink for CO_2, in determining the magnitude of the new production, and in understanding deep-sea ecology, food chains, and variations in fisheries yield. Deep-sea respiration helps to dampen the build-up of CO_2 in the atmosphere by converting DOC and POC originally produced in the surface waters to CO_2 and sequestering it in the deep water. Three types of mechanisms for transporting carbon from the sea-surface to the deep-sea are currently recognized: the soft-tissue pump (biological pump), the carbonate pump and the solubility pump. All involve vertical fluxes and normally do not include horizontal transport in the subsurface waters. Here, we consider horizontal carbon fluxes associated with the entrainment of dissolved organic carbon (DOC) and particulate organic carbon (POC) in sinking surface waters. These waters, after cooling, reach great depths by sinking in the open ocean or by cascading off shelves and down canyons. At depth they spread along isopycnal surfaces increasing, temporarily, the volume of Deep and Intermediate Waters. Injection of CO_2 into the seawater occurs when the entrained POC and DOC are oxidized via respiration, i.e.,

$$POC + DOC + O_2 \rightarrow CO_2 + H_2O.$$

The CO_2 is then distributed into the different species of the carbonate system, carbonic acid (H_2CO_3), bicarbonate, (HCO_3^-), and carbonate (CO_3^{2-}).

$$CO_{2\,(aq)} + H_2O \longleftrightarrow H_2CO_3 \longleftrightarrow HCO_3^- + H^+ \longleftrightarrow CO_3^{2-} + 2\,H^+$$

Since the residence time of the Mediterranean Deep Water is on the order of 22 years (Bethoux, 1980), this injected CO_2 is effectively removed from the atmosphere for this time period: the rate at which CO_2 is produced from POM in the deep sea is thought to balance the sinking rate of POM from the near-surface waters. This sinking rate, in turn, is thought to balance the rate of phytoplankton new production in the near-surface waters. So a measure of either one of these three rates serves as an estimate of the others as well as an estimate of the soft tissue pump. However, none of the three rates considers the horizontal flux of carbon. If the deep metabolism is enhanced by horizontal carbon inputs then both calculations of vertical carbon flux and new production will be exaggerated. Furthermore curvature of the depth functions of the metabolism, POC, and DOC will be decreased. In other words, the attenuation of these quantities with depth will be less than if the fuel source for deep metabolism was from vertical flux. Here we observe, in the measurements of ETS activity, evidence for attenuation in the vertical depth function of respiration in the Western Mediterranean and suggest that it is caused by horizontal injections of POC and DOC subsequent to deep water formation in the Gulf of Lions.

DATA

The method for measuring ETS activity and its relationship to vertical carbon flux and new Production are given in Packard and Christensen (2004); Packard and Codispoti (2007); and references within these papers. The basic idea behind the ETS measurement is as follows. The biological breakdown of organic matter ($C_6H1_2O_6$) produces CO_2, protons (H^+), and electrons (e^-). The ETS in biomembranes transports the protons and the electrons to oxygen while concurrently producing adenosine triphosphate (ATP, cellular energy currency). The ETS method uses a redox dye (INT), an electron acceptor, to quantitatively intercept the electrons moving along the membrane towards oxygen. Thus in the presence of INT, the cellular respiratory reactions, instead of reducing oxygen to water, reduce INT to a scarlet end product. The formation rate of this end product, a formazan, is easier to measure than is the consumption of oxygen and so it serves as a proxy for respiration. The biochemical meaning of ETS and ETS activity, the relationship of the ETS to metabolism and respiration, its oceanographic use in bacterioplankton, phytoplankton, zooplankton, the deep-sea, and the oceanic euphotic zone are discussed in Nelson and Cox (2005); Packard (1985a,b); Hernandez-Leon and Gomez (1996); del Giorgio and Williams (2005); Aristegui and Montero (1995). The ETS data used here are from Packard *et al.* (1988); Christensen *et al.* (1989); La Ferla *et al.* (2003).

RESPIRATION PROFILES

Vertical profiles of ETS activity from the Mediterranean Sea and the Atlantic and Pacific Oceans were converted into respiration profiles and plotted as rates of CO_2 production (Figure 1) as in Packard *et al.* (1988) and Packard and Christensen (2004).

The vertical plots of respiration for the Atlantic (Sargasso Sea) and the Pacific (central Northern gyre) oceans have a much more pronounced curvature than those from the Mediterranean Sea. The western Mediterranean has the least curvature. If the Atlantic and Pacific respiration profiles are representative of systems where deep-sea metabolism is fueled by vertical carbon flux and the Mediterranean profiles display less curvature, the difference should yield information about the extent of horizontal carbon flux at depth. To facilitate this comparison, the Mediterranean respiration profiles from Figure 1 were normalized to their 200 m value and compared to similarly normalized Atlantic and Pacific profiles (Figure 2).

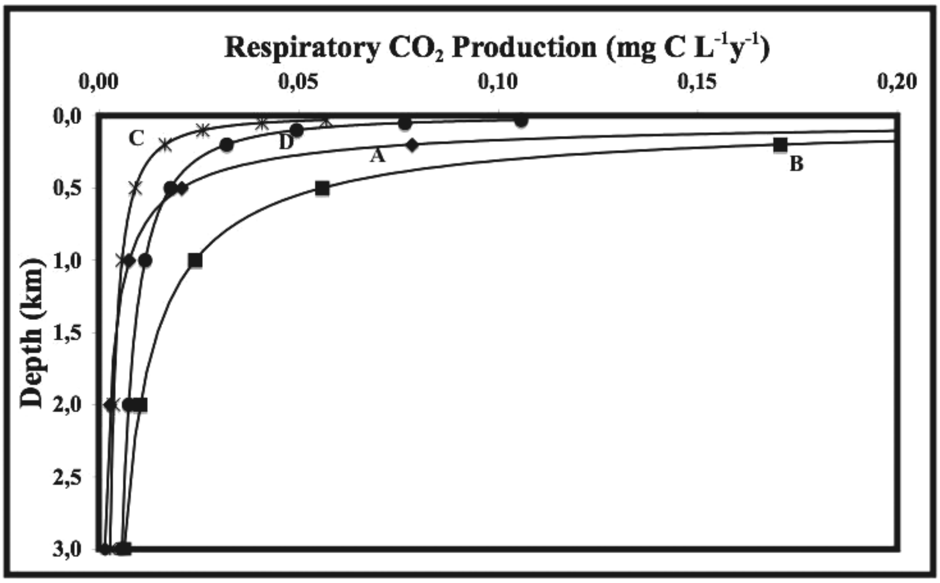

Figure 1. Vertical profiles of respiratory carbon production at *in situ* temperature in the: (A) Northern Sargasso Sea (Atlantic); (B) Central North Pacific Ocean; (C) W. Mediterranean Sea (MEDIPROD IV cruise); and (D) Central Mediterranean Sea. Units of respiration represent the mg C as CO_2 per liter that microorganisms and microzooplankton generate through their respiration in a year. This is stoichiometrically equal to the amount of organic carbon consumed by the same organisms in a year. Note the reduced curvature in the Mediterranean profiles.

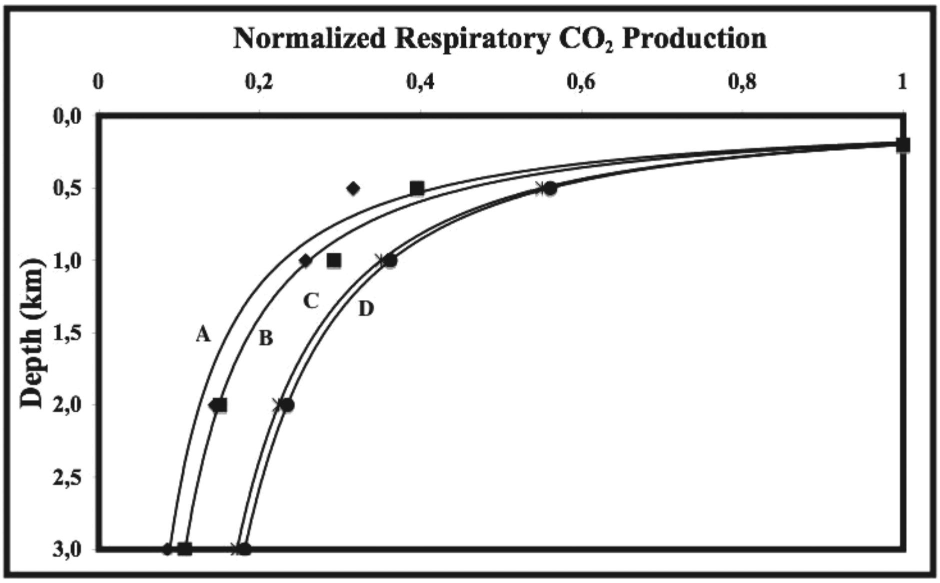

Figure 2. Vertical profiles from Figure1 recalculated with the Arrhenius equation for Mediterranean temperatures at equivalent ocean depths. These profiles have been normalized by their respiratory carbon consumption at 200 m so they are unitless. (A) Northern Sargasso Sea (Atlantic); (B) Central North Pacific Ocean; (C) W. Mediterranean Sea (MEDIPROD IV cruise); and (D) Central Mediterranean Sea. Note the relatively high respiration at the deeper depths in the Mediterranean profiles.

To eliminate the effect on the respiration of the different temperatures in the samples from the different deep waters, the Atlantic and the Pacific respirations have been corrected by the Arrhenius equation to respirations at Mediterranean temperatures for equivalent depths. Mediterranean Deep Water is about 10° C warmer that Atlantic and Pacific Deep Water so this correction shifts the deep-sea respiration up by about a factor of 2. Nevertheless, the respiration rates in the deep parts of the two Mediterranean profiles are relatively higher and the curvature of the profiles is lower than their counterparts in the Atlantic and Pacific. These differences suggest horizontal organic carbon input. They were measured in 1981, but likely represent conditions of today.

From these profiles there is no way to determine the seasonal, annual, or regional variability in the deep respiration. Neither can one determine whether the enhanced metabolism is derived from the open sea deep-water formation, eddy circulation, or from shelf cascading events. Modeling, at this stage of knowledge, cannot resolve these questions. An important step in their resolution would require deep respiration time-course profiles in the Gulf of Lions as well as seasonal and annual deep-sea respiration sections along the axis of deep-water flowing out of the Gulf of Lions. Still, this would not differentiate the impact of concurrent events of cascading and deep convective overturning in the open sea. For this, the development of biochemical water mass tracers using techniques such as peptide mass fingerprinting of proteins isolated by SDS-PAGE (Suginta, 2007), lipid fingerprinting by a combination of mass spectrometry, gas chromatography and nuclear magnetic resonance (De Souza *et al.*, 2006) or molecular biological analysis would be helpful.

The impact of open sea deep water formation and shelf cascading on deep-sea biology depends on the magnitude and frequency of these events. They should both accelerate the delivery and improve the quality of organic carbon being made available to the deep-sea biota. Accordingly they should enhance growth, respiration and biomass of the deep-sea populations of microbes, zooplankton and nekton. Fisheries harvesting deep-sea populations of fish, squid and shell-fish should note positive responses to these events after a suitable lag time. In other parts of the Western Mediterranean similar enhanced mesopelagic respiration has been found. In the Levantine Sea LaFerla and Azzaro (2001) attribute it to carbon injection from the Aegean Sea. In the Liguro-Provençal front Savenkoff *et al.* (1993) attributed it to vertical organic carbon transport in anticyclonic eddies (Meddies, Richardson *et al.*, 2000). In the NE Atlantic Ocean near the Canary Island (Hernandez-Leon *et al.*, 2001; Hernandez-Guerra *et al.*, 2005) lateral transport of organic carbon has been shown to account for between 30 and 60 % of the mesopelagic (100-1,000 m) respiration (Alonso-González *et al.*, 2009). It remains to be seen if the response of the fishery is in this order of magnitude.

The impact of these events on the biology of the near-surface waters should also be significant because the mixing that always co-occurs with deep-water formation will enrich the near-surface waters with inorganic nutrient salts (PO_4^{-3}, NO_3^-, and Si $(OH)_4$. Accordingly, as soon as the euphotic zone stabilizes, the phytoplankton will start to grow and a bloom will ensue. This will, in turn, enrich the epipelagic biota (microbes, zooplankton, and nekton) and fisheries dependent upon it.

EPILOGUE

Lateral transport of organic material in the deep-sea and its impact on deep metabolism now seems certain after the work of Christensen *et al.* (1989); Savenkoff *et al.* (1993); La Ferla and Azzaro (2001); Alonso-González *et al.* (2009). Furthermore, from different evidence this horizontal input was inferred in the works of Walsh (1991); Falkowski *et al.* (1994); Barth *et al.* (2002). The directionality of this flux changes the conceptual model upon which the decade-long JGOFS program was based, namely that the deep-metabolism was fueled by vertical carbon flux (Doney and Ducklow, 2006). Yet, as when Christensen *et al.* (1989) first alerted the scientific community of its potential role, these horizontal carbon inputs to the deep-sea have not been incorporated into current thinking about mesopelagic biota, metabolism, and food chains. Perhaps now, after the description of new mechanisms for injecting organic carbon into the deep sea involving cascading (Palanques *et al.*, 2009) and gyres (van Haren *et al.*, 2006), horizontal carbon fluxes in the deep-sea will be factored into research on mesopelagic biotic processes.

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Coherent abyssal eddies observed over the KM4 site from a single mooring in the Ionian Sea (Central Mediterranean Sea)

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On behalf of the NEMO collaboration.

Introduction

From July 2001 to March 2003 a deep sea mooring (two single-chain Aanderaa RCM 11 current meters at ~ 2,700 m and ~ 3,050 m depth) and three set of CTD casts (through March – August, 2002) measured deep marine currents, flowing over the site KM4 (36°19'N; 16°05'E), a flat abyssal plane in Central Mediterranean Sea (Figure 1) not far from the eastern rim of a trench marked by the 3,400 m isobath, directed toward North-North-West. This is the site of the NEMO experiment, i.e. the future deployment of an abyssal 'neutrino' telescope. This deep marine station is placed where "elementary" sub-nuclear particles, i.e., a flux of high energy neutrinos with dramatic high energy (up to 10^{14} eV) generated in an early moment of the Universe, are expected to be observed. Such neutrinos are part of the Cosmic Ray particles generated and accelerated in galactic and extragalactic sources (Riccobene *et al.*, 2007).

From year 1999 current meter and CTD data were collected in different location around this site. The early period (September - December 1999) has been analyzed by Manca *et al.* (2002a).

The new data analyzed in this work reveal that the region studied is strongly affected by mesoscale activity, a rather surprising feature not expected to be observed at such abyssal depths. We indeed found front dynamics and coherent eddies passing through the KM4 site which are also marked by temperature oscillation. An experimental method to better detect such eddies is also presented.

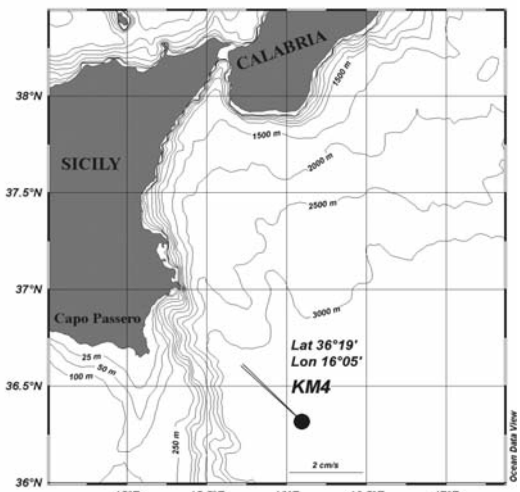

Figure 1. Geographical position of the KM4 site, with superimposed time-averaged velocity vectors for the current meters at 2,700 and 3,050 m depth. The mooring is at the eastern rim of a trench. Towards the East there is a flat area but direction of time-averaged velocity follows the 3,400 m isobath (Puig, pers. comm.).

Year 2001-2003 Temperature Data

From July 2001 to March 2003, CTD casts were made with an MK 317 Idronaut, lowered over the KM4 site till approaching the sea bottom within few meters (Figure 2). The MK 317 Idronaut data accuracy was: pressure = 0.5 db, temperature = 0.003 °C, conductivity = 0.003 mS/cm which are rather usual values. Both potential temperature θ_{2000} and salinity S show a linear stratification beneath 2,500 m depth. In particular, θ_{2000} decreases with depth by ~ 0.05°C in ~ 300 m depth and salinity S decreases by ~ 0.02. We compared our available casts with Rosette data, collected around KM4 site during the METEOR 2001 (October - November 2001; Roether *et al.*, 2007) and SINAPSI-4 cruises (March - April, 2002; Manca *et al.*, 2006). From these data, our CTD drifts were adjusted by lowering raw temperature of 0.02 °C and salinity of 0.005 since no reliable offset calibrations of NEMO CTD casts were carried out.

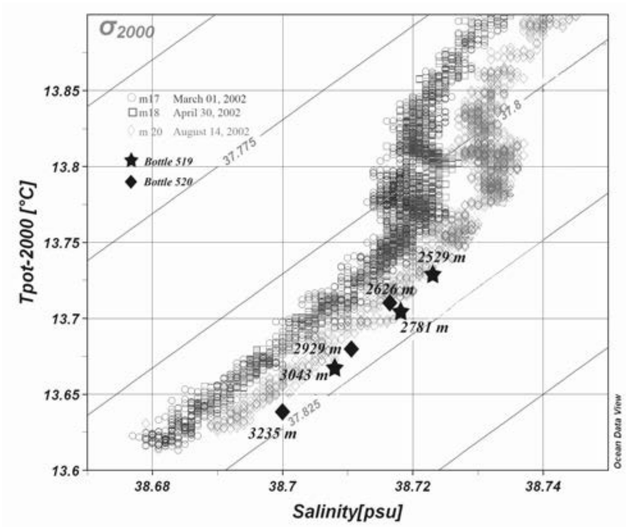

Figure 2. θ_{2000}/S of three CTD casts (m17, m18, and m20) over the KM4 site. The METEOR cruise Rosette B519 and B520 are also shown.

Temperature data were also obtained by the current meter mooring, a vertical chain equipped with two Aanderaa RCM 11 current meters set at ~2,700 m and ~3,050 m depth (Figure 3). The Aanderaa RCM 11 data accuracy was: temperature = 0.05°C; conductivity = 0.07 mS/cm. The raw data collected, taken every 1', were averaged every 30' directly from the current meter. The upper Aanderaa temperature is ~ 13.83± 0.05 °C, with some random 'one day' cold bursts. The deeper temperature sensor has a more disordered behaviour around 13.85 ± 0.05 °C, with some random "one day" warmer burst, till 13.91 °C. The depth averaged temperature data show that during the autumn 2002 the water column was ~ 0.015°C colder than the average, but no other seasonal trends are particularly evident.

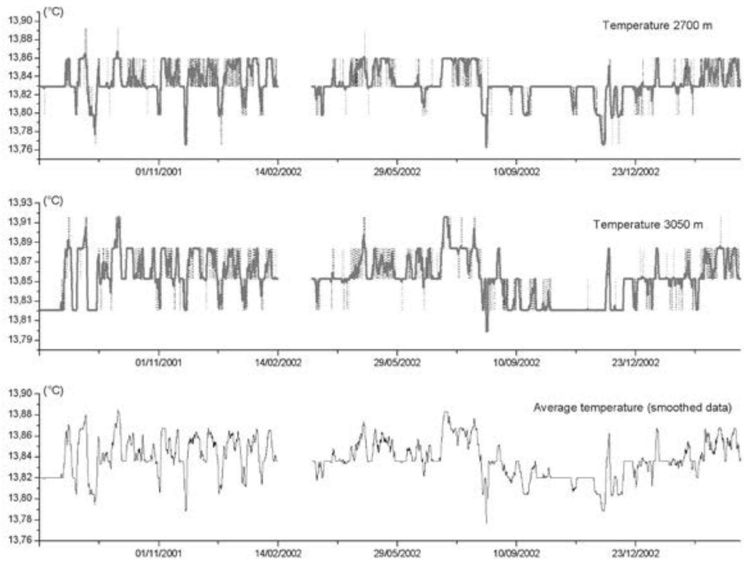

Figure 3. Time series of *in situ* temperature data: smoothed temperature data (bold line) for both current meters and their depth-averaged temperature at KM4 site (bottom). Here time is dd/mm/year.

Year 2001-2003 Current Meter Data

From the two Aanderaa RCM 11 current velocity data, we obtain a rather surprising scenario. Both current meters show similar velocities ~ 1.9 cm/s, essentially towards North-North-West (current meter accuracy is 0.3 cm/s), which directions form an angle of ~1˚12 (Figure 1). Accuracy for speed and direction are 0.3 cms^{-1}, and 5°, respectively. The maximum recorded raw velocity was ~ 12.6 cms^{-1}. Classical expectations for bottom currents in this region suggested a southward motion, due to the presence of Adriatic Deep Water outflow from the Otranto Strait. The unexpected behaviour which we found (i.e., a flow towards North-North-West) is probably due to a flow of Eastern Mediterranean Transient that re-circulates first westward through the Herodotus Trough in the southern Ionian Sea and then northward in the Eastern Mediterranean (Manca *et al.*, 2002a).

From current meter analysis, we found that the flow is strongly “barotropic” (i.e., depth independent) and that it does not show large fluctuations of the current directions (Figure 4), i.e., rather different features from those seen in other periods (Ursella, 2002; Gasparini, pers. comm.). However a possible front passage was noticed around December 2002 (Figure 4) also marked by a strong kinetic energy and a temperature rise of ~ 0.1 °C (not shown).

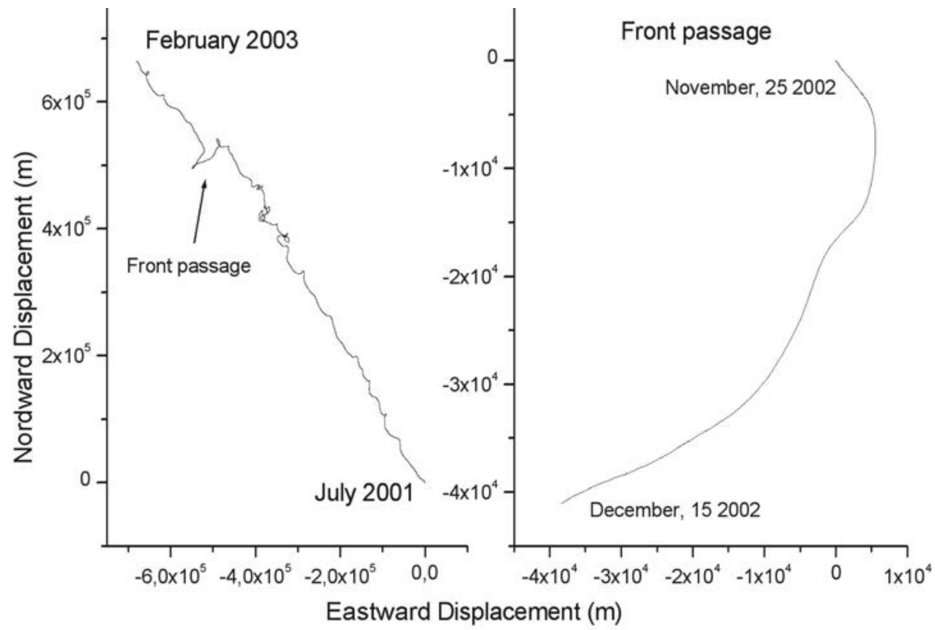

Figure 4. Progressive vectors of the low-pass filtered “barotropic” current data for the whole sampling time (left side) and for the high kinetic energy period around December, 10 2002 (right side).

Spectral analysis of the horizontal current reveals a mesoscale activity (~ 15 days) together with a tidal-inertial peak (~ 20 h) and other smaller tidal peaks as well. A weak “baroclinic” signal, mainly concentrated near the inertial range, was also found.

Time-averages of daily mean kinetic energy

$$\mathrm{MKE} = \frac{1}{2}\left[\overline{u}^2 + \overline{v}^2\right], \qquad (1a)$$

and the time-average of daily eddy kinetic energy

$$\mathrm{EKE} = \frac{1}{2}\left[\overline{(u')^2} + \overline{(v')^2}\right], \qquad (1b)$$

are shown for both current meters in Table 1. Here $u'(t) = u(t) - \overline{u}$, $v'(t) = v(t) - \overline{v}$ and the over-bar denotes the long-time average. Let us note that the EKE is larger than the MKE. This underlines that, even though the KM4 site is characterized by a near steady current, mesoscale nevertheless plays a relevant role.

Table 1. Mean characteristics of the currents at 2,700 and 3,050 m depth. Here $\bar{u}$ is the average North-South component and $\bar{v}$ is the average East-West component while $u' = u(t) - \bar{u}$ and $v' = v(t) - \bar{v}$ are the residual flow components.

Depth (m)	$\bar{u}$ (cm/s)	$\bar{v}$ (cm/s)	$\overline{(u')^2}$ (cm/s)^2	$\overline{(v')^2}$ (cm/s)^2	$\overline{u'v'}$ (cm/s)^2	MKE (cm/s)^2	EKE (cm/s)^2
2700	1.30	-1.37	4.21	4.93	-0.52	1.28	4.07
3050	1.34	-1.34	4.65	5.12	-0.77	1.29	4.89

To focus on these mesoscale signals, the velocities have been filtered with a 24-h Hanning filter, a good compromise between removing weak Mediterranean tides, inertial oscillations and internal waves while keeping mesoscale fluctuations. The stick diagram of daily filtered barotropic currents

$\vec{u}_B = \dfrac{\vec{u}_{2700} + \vec{u}_{3050}}{2}$ showed rotational events.

We analyse these events, without the confusing effect of the mean velocity, by changing reference into a new frame moving with the water velocity $\vec{u}$. In detail we studied both $\vec{u}^*(t)$, namely the velocity with the all-sampling average velocity removed, and $\vec{u}^{**}(t) = \vec{u}(t) - \vec{U}_r(t)$ (Figure 5) where $U_r(t)$ is the velocity averaged over 15 days, a time-scale suggested by energy spectra.

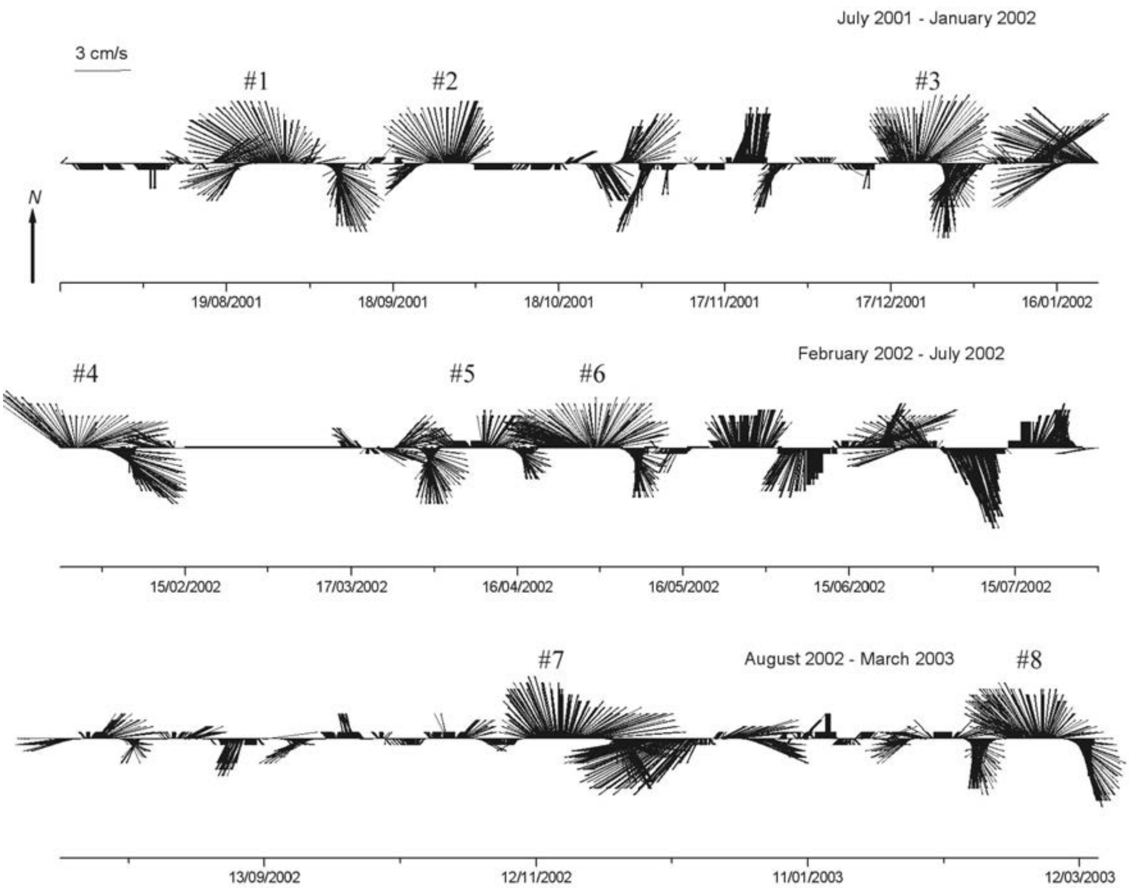

Figure 5. Stick diagram of the barotropic daily filtered current $\vec{u}^{**}(t)$, in the 15 days running average frame (see text) for the years 2001-2003. The eight eddies are shown and enumerated. Here time is synthetically dd/mm/year.

All this allowed us to identify eight energetic rotating events. In Figure 6 we show a detailed analysis of the first eddy (19/08/01 - 1/09/01) that has to be considered as a representative sample. In synthesis the eight events show

i) a temperature increase 0.06-0.01°C, with uncertainties ~ 0.02°C;

ii) almost close progressive vector diagrams;

iii) a transversal velocity, namely *v***, as large as ~ 3 cm/s, larger than the water velocity uncertainties.

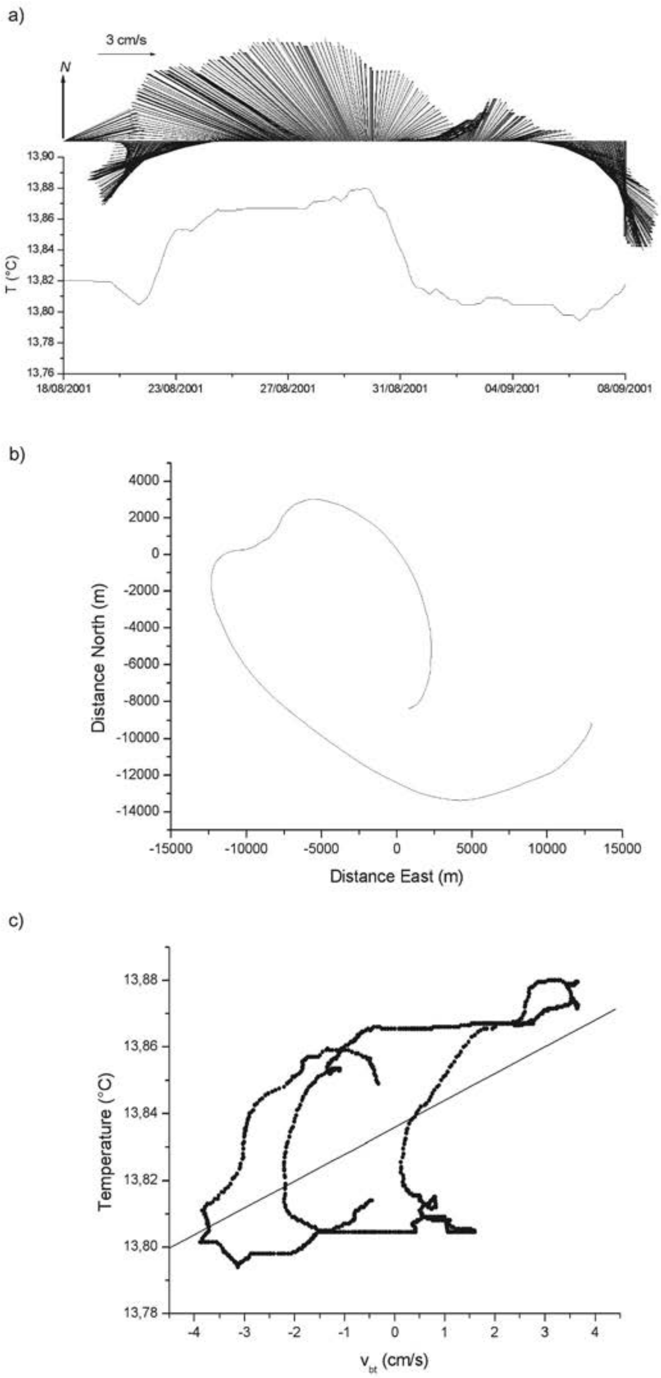

Figure 6. a) Stick diagram of $\vec{u}^{**}(t)$ for vortex #1 (19/08/01 - 1/09/01), superimposed with depth averaged temperature (time is synthetically dd/mm/year). b) Progressive vector of the "barotropic" low-pass filtered current in the moving frame and c) scatter plot of the cross-stream "barotropic" velocity component versus the average potential temperature. The solid line is the linear best fit.

No other events in the period studied meet the criteria described above. In this way, we were able to recognize eight coherent eddies of 15-20 km radius. Details of these eddies are shown in Table 2 in which one can observe that all these structures are marked by a warm core. It has to be added that somehow similar eddies have been found by OGS measurements in the Strait of Otranto (Ursella, 2002; Gačić *et al.*, this volume), stressing how a multi-current meter chain is of fundamental importance in detecting this kind of structure.

Table 2. Starting and crossing times of mesoscale signals passing over the KM4 site. Here *u* is the estimated barotropic water velocity of an eddy (Figure 12), and *u*/D is its vorticity. The rough diameter of the chord *D* is considered to have an error of ≈ 10%. $\Delta T_{adjacent}$ (°C) is the barotropic temperature increase of the eddy core compared with that of the adjacent ambient water, $\Delta T_{average}$ (°C) is the barotropic temperature increase of the eddy core compared with that of the long time average ambient water. In Appendix A we show that the standard deviation of these temperature increases are ~ 0.03 °C . Here time is synthetically dd/mm/year.

Starting time (dd/mm/year)	Crossing time (days)	*D* (km)	$\Delta T_{adjacent}$ (°C)	$\Delta T_{average}$ (°C)	*u* (cm/s)	Vorticity $u/D \times 10^{-5}$ (s^{-1})	Remarks
19/08/2001	12	20	0.06	0.04	5	0.3	warm core
20/09/2001	17	28	0.04	0.04	4	0.2	warm core
15/12/2001	20	33	?	0.02/-0.02	6	0.3	warm/cold core
24/01/2002	15	25	?	0.02/-0.02	4	0.1	warm/cold core
31/03/2002	17	28	?	0.01	2	0.1	warm core, eddy rather confuse
18/04/2002	20	33	0.06	0.05	3	0.2	warm core
1/11/2002	27	44	-0.03	-0.01	5	0.1	cold core, weak eddy velocity
19/02/2003	22	36	0.03	0.03	3	0.2	warm core

To analyze the origin of such eddies, the correlation Γ between local winds and deep current velocities has been carried out, giving rather low values, that is Γ ~ 0.2. Moreover, no reliable correlations of deep water velocity with atmospheric pressure gradients or satellite data of sea surface elevation was found. However, when an eddy passed over the KM4 site, the correlation between energy peaks and the barotropic temperature gave larger values Θ ~ 0.8.

About the characteristics of such eddies, we considered four possibilities, i.e., eddy rotating clockwise or anticlockwise, passing on the left or right side of a current meter (Figure 7). Comparing these hypothetical stick diagrams with those for *u*, *u** and *u*** (Figures 5 and 6) we obtain strong support to the idea that the observed eddies rotate anti-clockwise and were advected at the left of the current meter. This is also in agreement with a criterion of Lilly *et al.* (1999) that "the dominant signal of an advected eddy is expected to be in the normal velocity v_n, with v_n initially positive (negative) for a cyclone (anticyclone)".

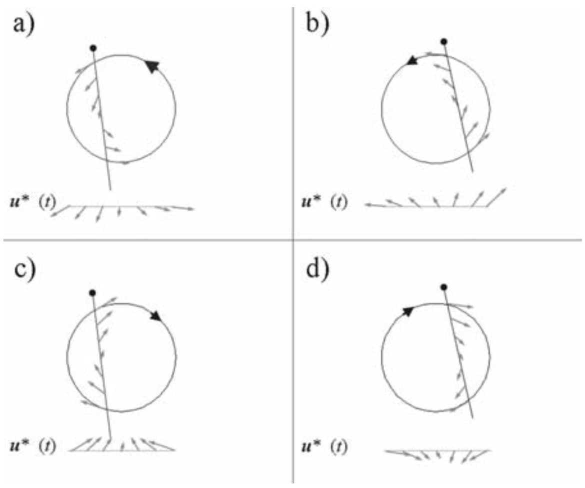

Figure 7. Qualitative drawing of four different cases: a) anti-clockwise eddy, passing on to the right of a current meter; b) anti-clockwise eddy, passing on to the left; c) clockwise eddy, passing on to the right; anti-clockwise eddy, passing on to the left. Stick diagrams as they appear in the current meter analysis are shown at the bottom of each scheme.

It may be relevant that Lilly *et al.* (1999) analysed data collected from a single current meter chain in the Labrador Sea and observed somehow similar eddies. From a nice analytic model of a symmetric vortex advected by a constant mean flow, they found that for idealized eddies the hodograph should be exactly closed, while this could not exactly happen for a realistic case, as neither happens for our progressive vector diagrams, in particular for our eddies # 2 and 7 in Figure 5.

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