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.

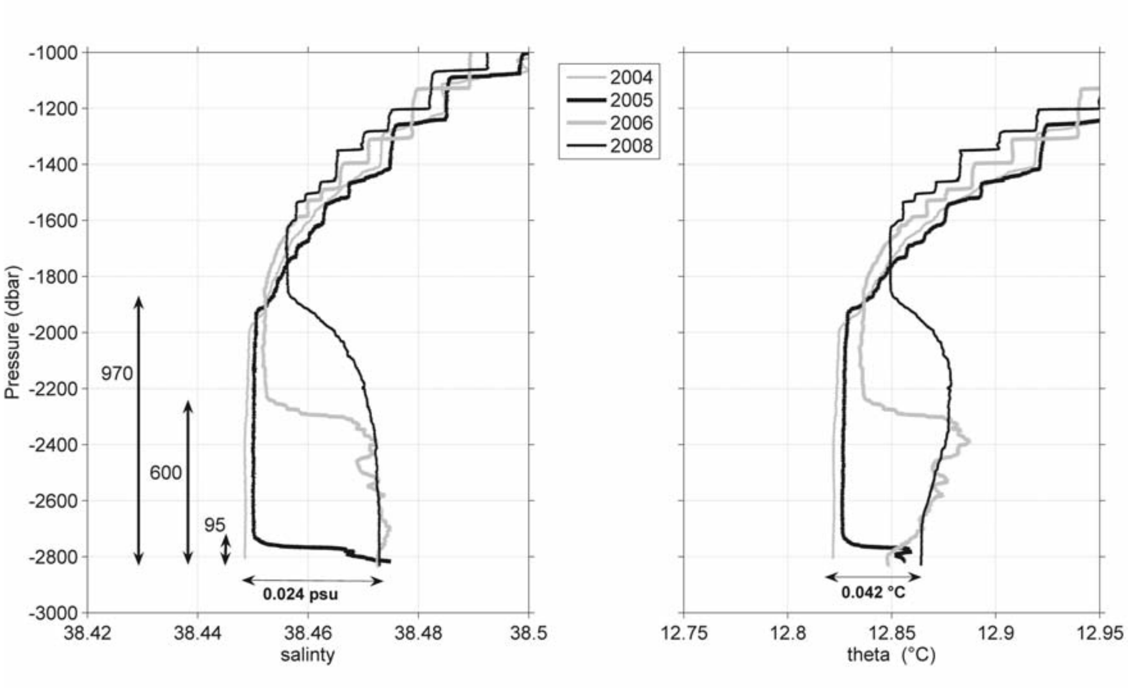

Figure 1. Vertical profiles of salinity (left) and potential temperature (right) measured at an example station in the Algerian basin (5 °E, 38 °N) in October 2004 (gray thin), June 2005 (black thick), October 2006 (gray thick) and November 2008 (black thin). The vertical arrows indicate the thickness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

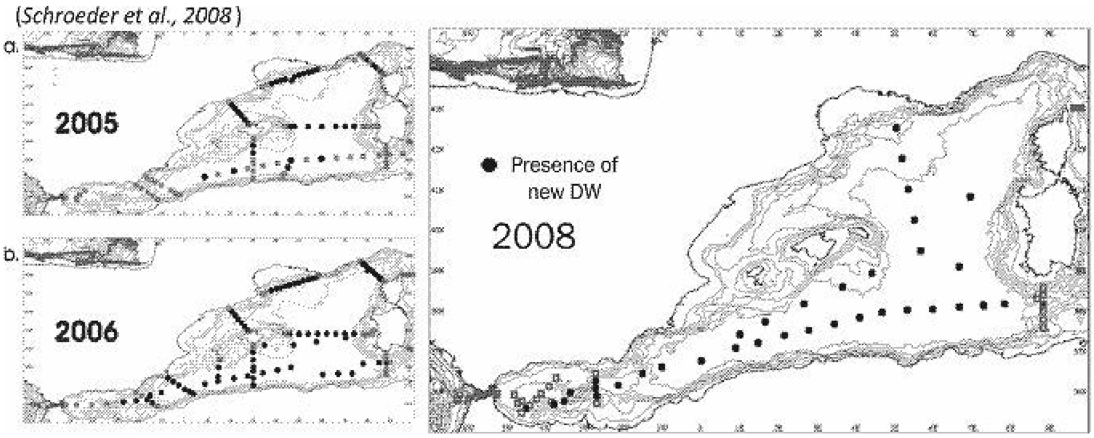

Figure 2. Spreading of the new WMDW (black dots) during 2005, 2006 (from Schroeder *et al.*, 2008b) and 2008. The distinction criterion between stations with (without) new deep water was the presence (absence) of the “hook” in the theta-S diagram with a significant increase of dissolved oxygen.

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.

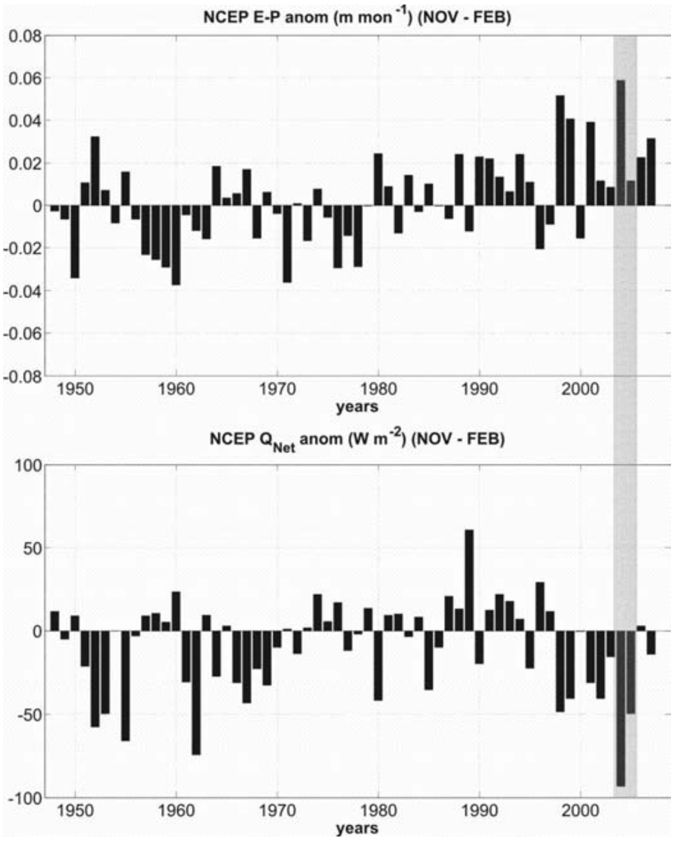

Figure 3. Winter (NDJF) net evaporation anomalies and net heat fluxes anomalies from 1948 to 2008, from NCAR-NCEP over the NW-MED.

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.).

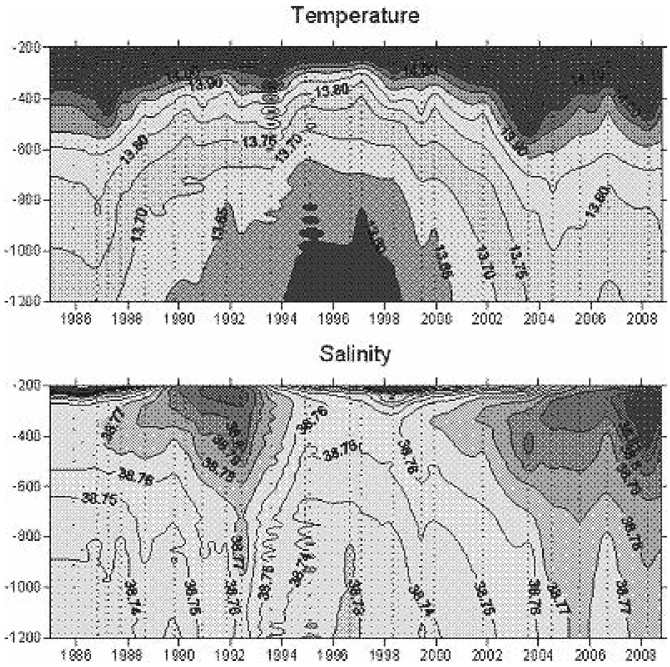

Figure 4. Temporal evolution of potential temperature and salinity in the central Strait of Sicily between 200 m and 1,200 m. In 2008 the highest temperature and salinity values since 1985 have been recorded.

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 Mediterranean 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).

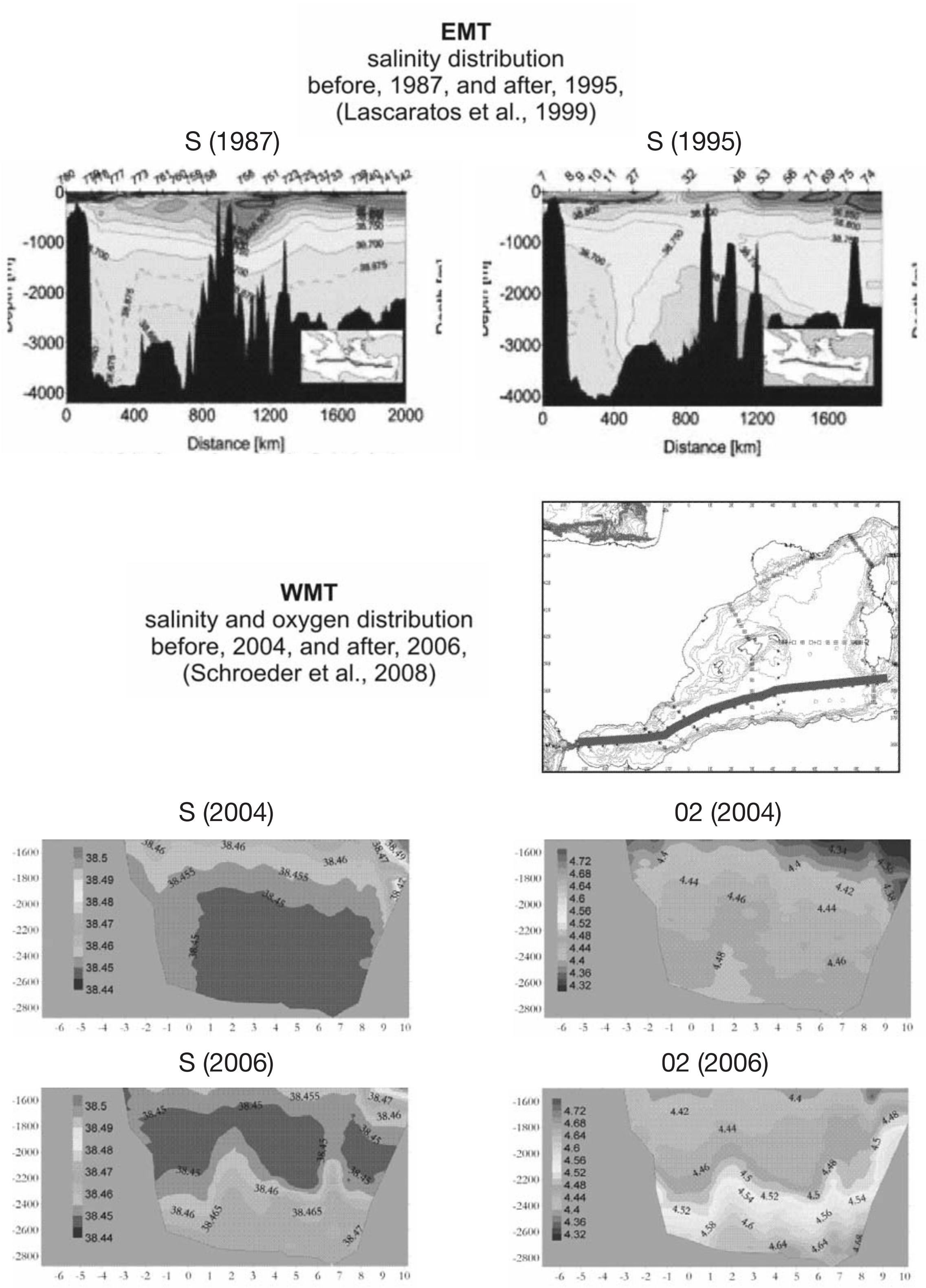

Figure 5. Comparison between observations of the EMT in the eastern basin and recent observations in the western basin.

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 $\Delta S = 0.016$ 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.

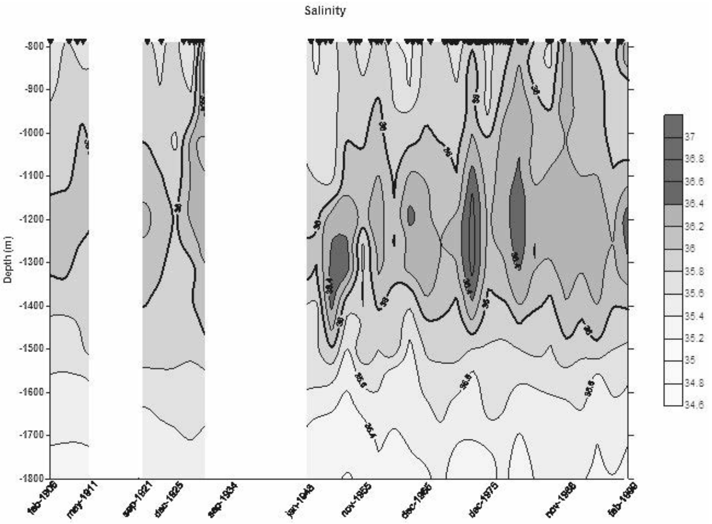
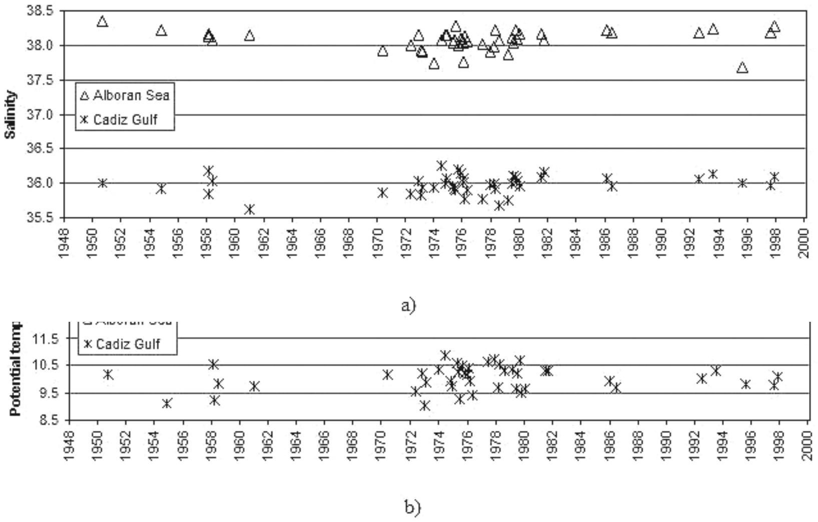


Figure 1. Properties of MW in the Gulf of Cadiz, depth versus time: monthly mean of salinity. Superimposed triangles show temporal distribution of monthly mean profiles.



a)

b)

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.

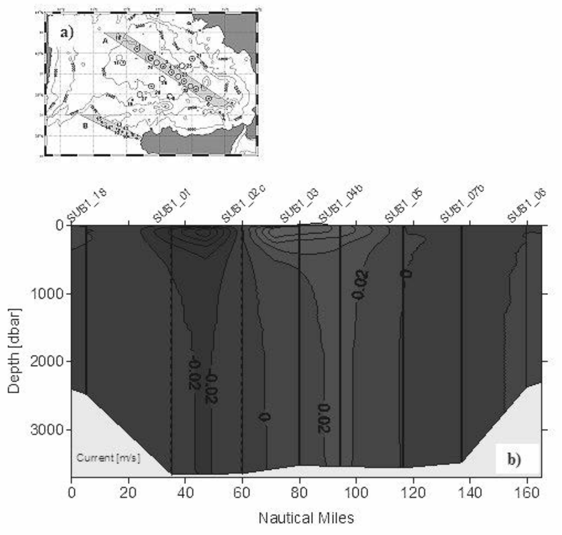


Figure 3. a) cast positions during CIESM-SUB1 (points, July 2005) and CIESM-SUB2 (circles, December 2005) cruises in the Tyrrhenian Sea; b) vertical section of geostrophic currents, the reference level was taken at 50 m depth imposing the velocity measured by the LADCP.

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.

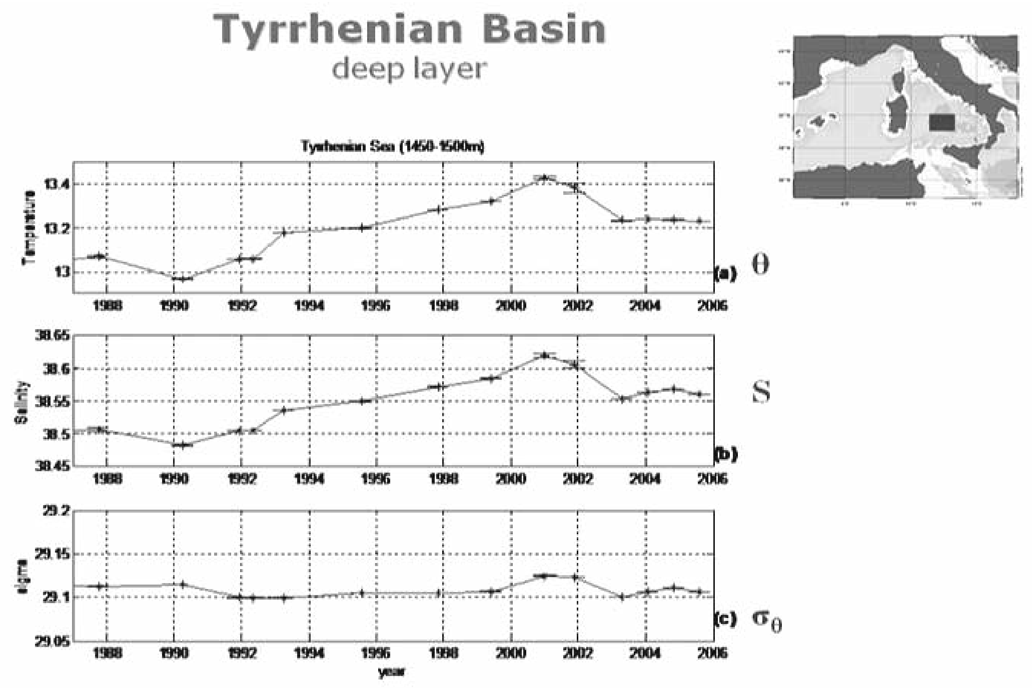


Figure 4. Temporal evolution of potential temperature (θ), salinity (S), and potential density (σ_θ) in the deep layers of the Tyrrhenian Sea (update from Gasparini *et al.*, 2005 with the data collected during the CIESM-SUB1 and CIESM-SUB2 cruises).

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.

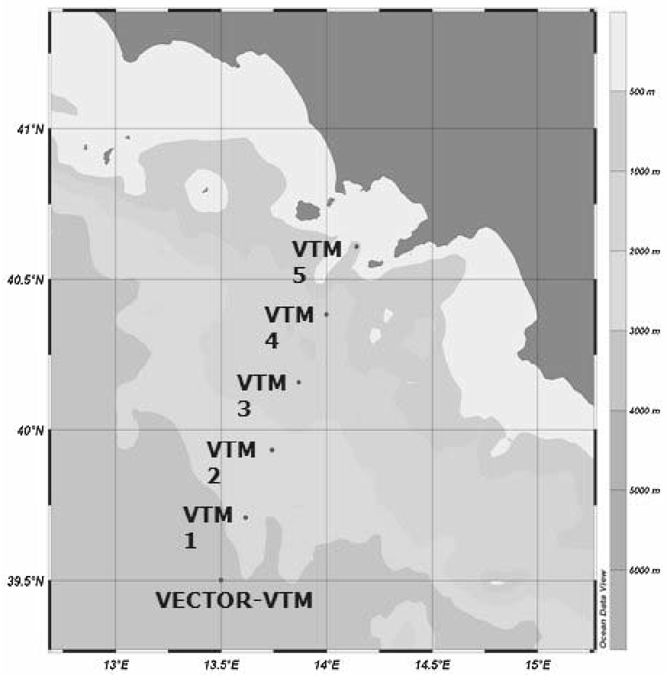


Figure 5. Vector project, sampling locations in the southern Tyrrhenian Sea.

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) µmol kg^{-1} at station VTM (both in July and averaged in the different seasons) and 2577 (± 1) µmol 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.