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. â€œDynamics of Mediterranean deep watersâ€. by. Font J., BÃ©ranger K., Bryden H., Budillon G., Fuda J.L., GaÄiÄ‡ M., Gascard J.C., Packard T., Puig P., Roether W., Salat J., Salusti E., Schroeder K., Theocharis A. and H. van Haren. This synthesis was written by all participants of the workshop under the coordination of Jordi. Font.Â DYNAMICS OF MEDITERRANEAN DEEP WATERS - Malta, 27-30 May 2009 I - Executive Summary of CIESM Workshop 38 â€œDynamics of Mediterranean deep watersâ€ by Font J., BÃ©ranger K., Bryden H., Budillon G., Fuda J.L., GaÄiÄ‡ M., Gascard J.C., Packard T., Puig P., Roether W., Salat J., Salusti E., Schroeder K., Theocharis A. and H. van Haren This synthesis was written by all. 2014. Executive Summary pp. 7 - 20 in CIESM Workshop Monograph nÂ°46 [F. Briand, ed.] Marine litter in the Mediterranean and Black Seas, 180 p., CIESM Publisher, Monaco. 7.Â New methods for the unbiased estimation of mortality rates and the effects on the population dynamics of many affected species are urgently needed. Combined studies including telemetry, dynamics of currents, biological traits, migration patterns, species spatial distribution have to be integrated in a holistic approach to tackle marine litter effects.