The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

EUROPEAN
SCIENCE
FOUNDATION

MedCLIVAR

ENEA

2165-1

International MedCLIVAR-ICTP-ENEA Summer School on the Mediterranean Climate System and Regional Climate Change

13 - 22 September 2010

Ocean Obs: Mediterranean circulation and thermohaline functioning during the instrumental period

Vassilis Zervakis
University of the Aegean
GREECE

Lecture notes on

"**Ocean Obs: Mediterranean circulation and thermohaline functioning during the instrumental period**"

Vassilis Zervakis
University of the Aegean
Dept. of Marine Sciences

Abstract.
The Mediterranean is a textbook-example of a concentration basin, i.e. a basin feeding the global ocean with dense water. While the details of its circulation are still being revealed, its basic thermohaline functioning has been known since the early stages of modern oceanography. While initially it was thought to be in steady state, very significant changes have been revealed in the last 25 years. Due to the relatively small residence time of the water in it (less than 100 years), the Mediterranean is considered a miniature ocean, ideal to observe and study processes affecting the variability of thermohaline circulation. Here, we will review the progress of our knowledge for the Mediterranean circulation, and describe the variability recorded through the instrumental records. In order to do that effectively, we will provide some introduction regarding basic oceanographic notions, principles and tools, like the potential temperature and density, water types and masses, and the θ/S diagram.

Introduction.
Before examining the Mediterranean circulation and thermohaline functioning, one has to clarify what parameters constitute the forcing factors in this circulation. As all students of physical sciences know, the dynamics of matter in human-scale phenomena are described by the three laws introduced by Isaac Newton in the 18^{th} century. In short, Newton stated that i) in the absence of forces acting upon it, the matter tends to maintain its kinematic condition, ii) that the change of momentum of matter is proportional to the force acting upon it, and iii) that for each force……..
Thus, the only property of matter that relates forces to kinematic changes is mass:

$$\vec{F} = \frac{d(m\vec{u})}{dt} \text{ (Newton's second law).}$$

When examining the dynamics of fluids instead of particles, we use a form of the above equation that is divided by volume. This form of the equation, known as the Navier-Stokes equation, relates the acceleration of water particles to the net forces acting *per unit* volume of water:

$$\frac{d\vec{u}}{dt} = \frac{\vec{F}}{\rho}.$$

Thus, when referring to fluids, the only thermodynamic property that is directly related to motion is density.
The above introduction to our subject is given in order to clarify that *no other thermodynamic property can directly affect the dynamics of sea-water*.

Oceanographic observations
One would expect that the study of oceanic circulation would require the recording of ocean currents, thus the use of current meters. However, the size of the domain, as well as the great frequency range of oceanic motions (from seconds to decades) woud require the deployment of hundreds or thousand of current meters for several decades.

Alternatively, the θ/S diagram has proven a much more efficient way to study *not directly circulation (currents), but oceanic motion* (the dispersion of water types and masses throughout the various oceanic basins). The fact that the global ocean is an *overmixed* basin (salts remain diluted much longer than the typical time-scale of ocean circulation) results to the constant consistency of sea-salt (Marcet's principle), which also permits the introduction of the *salinity* (concentration of inorganic salts in sea-water by weight, symbolized by S). As the sea-water is a solution of ions (charged atoms), it conducts electricity. The capacity to conduct electricity (called conductivity) is a function of the sea-water temperature and pressure, as well as salt concentration (salinity).

$$C = C(S, T, p)$$

It is possible to solve the above equation for S and compute salinity through the measurement of in-situ temperature T, electric conductivity C and pressure p:

$$S = S(C, T, p)$$

Typically, an electronic platform carrying conductivity, temperature and pressure sensors (called CTD) is lowered to the water from a research vessel, and profiles of these properties are obtained. Combination of the above lead to the computation of salinity and density profiles.

The tools of the trade: potential temperature, density and the θ/S diagram

The sea-water density is itself determined by three thermodynamic properties, the sea-water temperature, salinity (the salt-content, measured as grams of salts in each kilogram of seawater) and pressure. The relation of density to the above parameters is called the equation of state of sea-water:

$$\rho = \rho(S, T, p),$$

where ρ stands for density, S for salinity, T for temperature and p for pressure.
Due to the fact that ρ typically ranges between 1020 and 1070 kg m^{-3} in the sea, for brevity oceanographers have chosen to describe the density of seawater by using just the last two digits, and to that aim they have introduced the parameter σ, defined as:

$$\sigma_{S,T,p} = \rho(S, T, p) - 1000$$

Thus, $\sigma_{S,T,p}$ typically ranges between 20 and 70 kg m^{-3} in the sea, and the higher values are obtained due to the density increase attributed to compression at large depths.
The density of seawater increases proportionally with the increase of pressure, i.e. the increase of depth. Thus, the density of a descending water parcel increases due to the increase of pressure; accordingly, the density of an ascending water parcel would be decreasing along its ascent. Thus, if one would like to compare the density of two different water quantities, he would have to (virtually) bring them to the same pressure. One way, might be to bring them to the sea-surface. However, when the pressure exerted on a fluid parcel changes, it is both temperature and density that change. The temperature that a fluid parcel would have if it rose to the surface adiabatically is called potential temperature (and symbolized by θ), and the density at the surface is called potential density (and symbolized by σ_θ). So,

$$\theta = \theta(T, p)$$

$$\sigma_\theta = \rho(S, \theta, p = 0) - 1000$$

Another property of the ocean that allows us to introduce a tool for comparing water-masses is that there are no processes that can effectively change the potential temperature and the salinity of a water parcel once it has left the surface layer (where it is in contact with the atmosphere). Thus, below the surface,

$$\frac{D\theta}{Dt}=0, \qquad \frac{DS}{Dt}=0$$

This enables us to use the potential temperature and salinity of the water as identifiers of its source. If these quantities of a large homogeneous volume of seawater were determined at the surface, this volume is called a *water type*. As the above quantities can identify different water types in a region, it makes sense to represent all water samples in the θ-S space, i.e. on a θ/S diagram (figure 1).

Conservation of heat and salt suggest that when two water types mix, the temperature and salinity of the resulting body of water will be the mean temperature and salinity of the starting types (weighted by mass). Thus, the properties of the new body on a θ/S diagram will lie along a straight line connecting the two water types. This new body of water is called a *water mass*.

θ/S diagrams constitute primary tools in recognizing water types and masses in an oceanic region, thus the origins and long-term motion of the various water bodies, and they are the primary diagnostic analysis tools for studies of the thermohaline circulation.

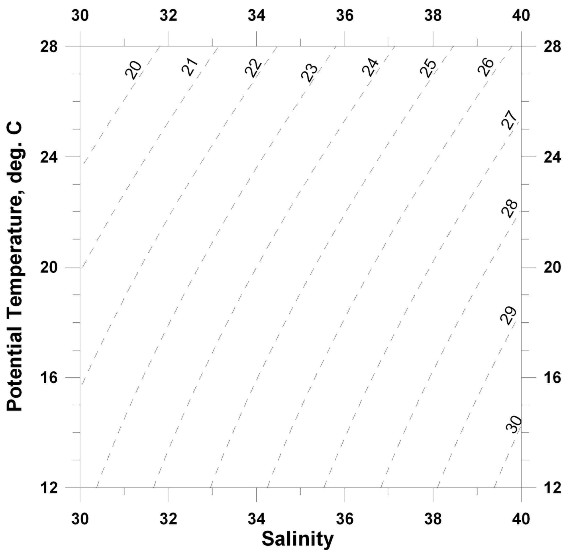

Figure 1. Basic θ/S diagram for oceanographic applications. Isopycnals (σθ) are shown as dashed lines

Semi-enclosed basins

Of special interest to oceanography are basins of smaller-than-the-ocean size that are connected with the ocean through a strait (usually accompanied with a topographic sill). The mean water-flux values through the air-sea interface (due to evaporation and precipitation) over the ocean and the semi-enclosed basin will be generally different due to the different geographic extent of the two. This difference will be affected when accounting for the riverine inputs to the coastal basin (and adding them to the water added through precipitation). Thus, in general, there are basins with a freshwater surplus and basins with freshwater deficit. In a basin with freshwater surplus, the oceanic water that enters the basin gets diluted and its density is reduced. Thus, at the connecting Strait, the inflowing water has a higher density than the outflow, and lies below it. This basin dilutes the oceanic water and hereafter will be referred to as a dilution basin (figure 2).

A basin with a freshwater deficit functions in the opposite way: The ocean water enters the basin through the surface layer in the connecting Strait; in the basin, it loses water to the atmosphere; its salinity, and thus, density rise, and dense water is produced, exiting to the ocean through the subsurface layer of the connecting strait figure 2).

Up to now, we have only considered the freshwater exchanges with the atmosphere, thus changes in salinity. However, a complete study of the thermohaline functioning of a basin requires also the study of heat exchanges, as temperature is the other factor affecting the density of the sea-water. It has been shown that while the Mediterranean long-term thermohaline functioning is dominated by the freshwater budget, the seasonal cycle is mainly controlled by the heat-fluxes.

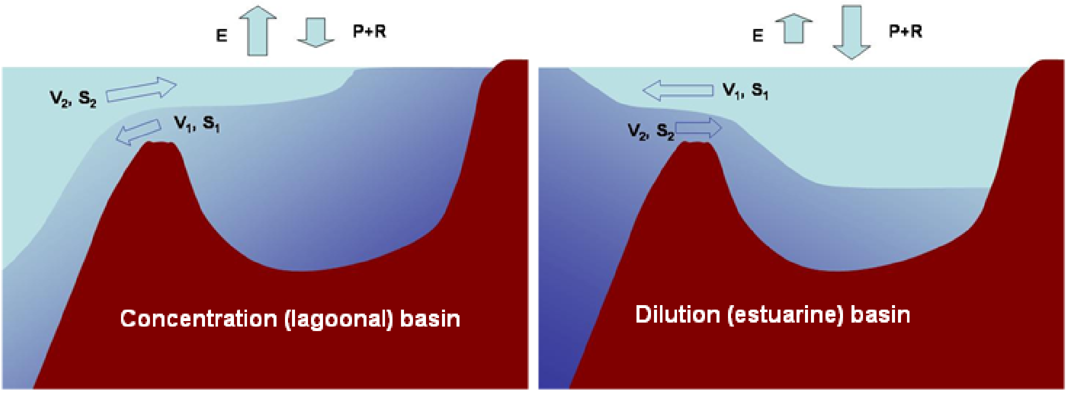

Figure 2. Thermohaline functioning of a concentration (left) and a dilution (right) basin. It should be noted that in the lagoon there is a lowering of the sea-surface, while in the estuary the sea-surface is higher than the ocean (not shown in this figure).

The era of innocence, or the steady state fallacy

If somebody was asked to describe the sea, one of the first choices would be "large". The large size of the ocean means that very large masses of water are involved, and thus there is a great inertia any attempt to change the kinematic condition of the ocean. This allows oceanographers, when analyzing the dynamics of the ocean, to always examine first of all the "steady state" condition (which usually, for large-scale phenomena, results to the description of geostrophy). Partly because of the perception of the stability of the Earth system (at least for human timescales), partly because of the difficulty and scarcity of measurements before the mid-1980s, oceanographers considered the intermediate and deep waters of the Mediterranean (as well as the whole ocean) as in steady state, thus having unchanging properties. As a result, oceanography professors used to require from their students to memorize temperature and salinity of deep water masses to the 2nd decimal digit!

What was considered "steady state" of the overturning circulation of the Mediterranean, was the result of a few large-scale cruises extending throughout the Mediterranean, and several more regional ones. It is unknown whether the little to no difference in the properties of the deep waters recorded in those cruises was indeed due to little variability, due to aliasing because of lack of frequent data, or due to incorrect measurements.

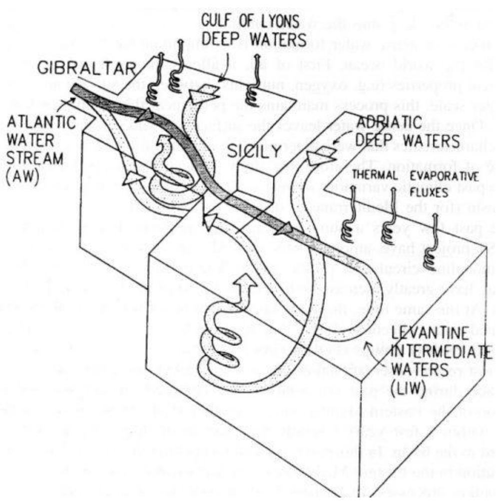

Figure 3. Schematic representation of the "steady-state" Mediterranean circulation (from Lascaraos et al., 1999).

As Lacombe pointed out at the publication that marked the end of this period, ***«The deep water of the Western Mediterranean has long been considered to have practically constant values of θ, S and σ_θ: between 1909/1910 (the Thor expedition) and the 1970 cruise of the Jean Charcot, the deep water, at more than 1800m depth, showed very little variation. The small changes which appeared through the***

years could be due in part to changes in instrumentation, analysis, and methods of sampling.»

One of the earliest cruises that shed light in the Mediterranean circulation was the Danish Oceanographic Expedition of 1910, which was followed by several cruises, mostly by French, Soviet and U.S. ships in extending from 1945 to 1970s. Most authors of the time converge to a "steady state" circulation summarized in the following figure 3 (Nielsen, 1912; Lacombe and Tchernia, 1958, 1960; Lacombe et al., 1958; Malanotte-Rizzoli and Hecht, 1988; Pollak, 1951; Plakhin, 1971, 1972; Lascaratos et al., 1999, Wüst, 1961). A little more light on the distribution of salinity that dictated the view of the thermohaline conveyor belts shown in figure 3 is presented in figure 4 (by Wüst, 1961):

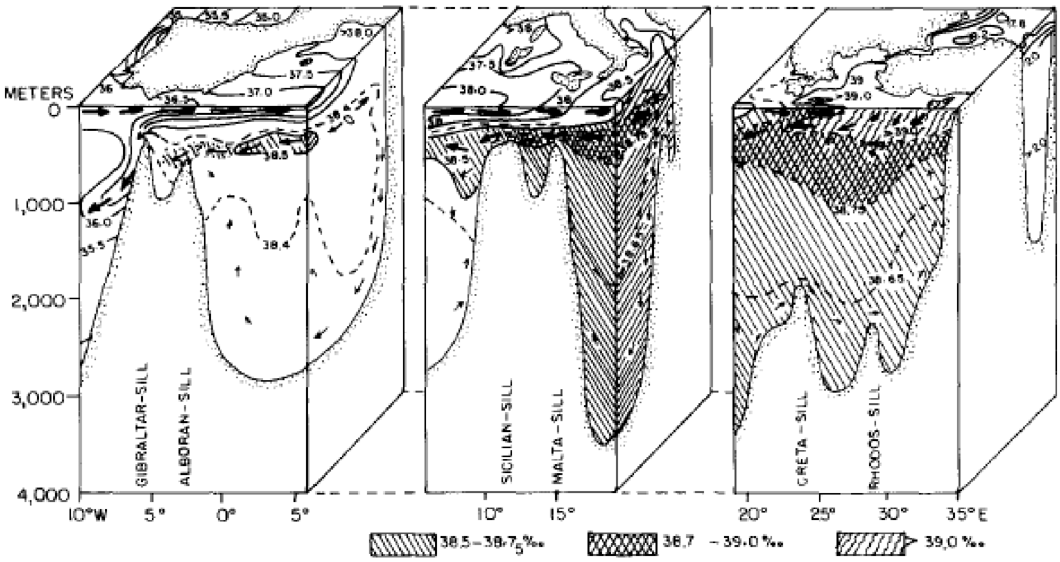

Figure 4. Schematic view of salinity distribution in the Mediterranean Sea (by Wüst, 1961)

As seen from both figures 3 and 4, the "steady state" thermohaline functioning of the Mediterranean can be described as follows: Atlantic water of relatively low salinity, (~36.5) enters the Mediterranean through the Gibraltar Strait as a inflowing surface current, and forms an eastward moving surface layer along the southern parts of the Alboran Sea. This water undergoes evaporation through its eastward path along the northern African coast (in what is known as the North African current), and gradually its salinity increases to about 38 at the Strait of Sicily. There, the north African current bifurcates, ad part of the Atlantic waters start a cyclonic flow around the western coasts of Italy to reach the south coast of France and east coast of Spain. The other branch of the Atlantic waters flows eastward, part of following a meandering eastward flow between sub-basin scale features of the Ionian and Levantine seas, called the mid-Mediterranean jet, while another part flows eastward through a coastal current. Both these currents carry Atlantic water (whose gradual evaporation has increased its salinity to more than 39!) to the Levantine Sea, where the circulation is dominated by a large cyclonic feature, the Rhodes Gyre. Both the increased salinity (i.e. high density) and the cyclonic circulation in the Rhodes Gyre are positive preconditioning factors for the formation of large quantities of dense waters under intense winter cooling and evaporation. Thus, the Levantine area is considered to be the source of the most voluminous water mass of the Mediterranean, filling the intermediate waters of the whole basin, the Levantine Intermediate Waters (LIW). The formation rate of LIW has been estimated to about 1 Sv (where 1 Sv = 10^6 m^3s^{-1}),

comparable to the inflow of Atlantic waters and the outflow of Mediterranean waters through Gibraltar (Lascaratos, 1993).
Surface waters that reach the northern extremities of the Mediterranean Sea (the Gulf of Lions, the Adriatic and the Aegean Sea) in the winter are exposed in extreme heat loss, their density increases and they descent, eventually feeding the deep and bottom layers of the western and eastern Mediterranean basins, as seen in figure 3. Almost all evidence (excluding Nielsen, 1912!) suggests that the deep water formation in the Aegean is significantly weaker than in the Adriatic (both in volume and density of the produced waters) and thus it is the Adriatic Deep Waters (ADW) that constitute the main source of Eastern Mediterranean Deep Waters (EMDW), while the waters originated in the Aegean (identified in the southern basins as Cretan Deep Water (CDW) form a thin layer that stabilizes at about 1000 m in the vicinity of the island of Crete. Thus, the main water types and masses of the Mediterranean are schematically shown on a θ/S diagram in figure 5. In constructing the figue, we have assumed that the only actual water types for the Mediterranean basin are the Atlantic Water (AW) as it inflows from the Atlantic, the Black Sea Waters (BSW) entering through the Dardanelles, the Levantine Intermediate Water (LIW), the Northern Adriatic Dense Water (NAdDW), the Adriatic Deep Water (ADW), and the North Aegean Deep Water (NAeDW) (the latter not shown in the figure). The rest of the water body is assumed to be consistent mainly of the following water masses: Eastern Mediterranean Deep Water (EMDW, a mixture of LIW and ADW), Western Intermediate Water and Tyrrhenian Deep water (WIW and TDW respectively, considered mixtures of LIW and WMDW, but also believed to be formed locally as types), and Cretan Deep Water (often considered a type, but with growing evidence that it is a mixture of NAeDW and LIW). The strength of the deep water formation in the Gulf of Lions and the Adriatic has been estimated to about 0.3 Sv.

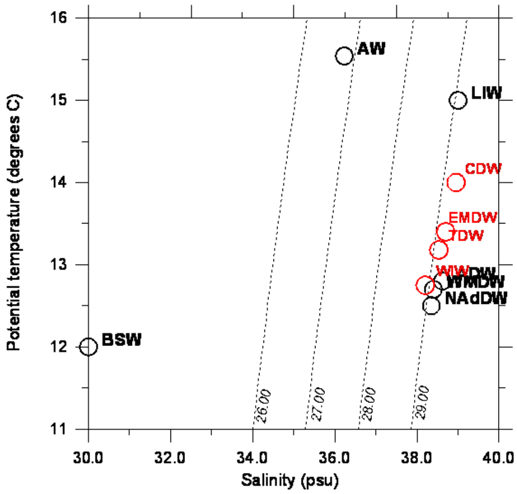

Figure 5. Major water types (in black) and masses (in red) of the Mediterranean Sea

Realizing change: The Western Mediterranean until 2004.
It was the introduction of the CTD platform in the 1970s, and the expansion of its use in the Mediterranean in the 1980s, that revealed the variability of the deep and intermediate waters in the basin. Lacombe et al. (1985), comparing data from cruises extending from 1909 until 1982, reported for the first time a significant rise in the temperature and salinity of the bottom layer of the Western Mediterranean. While the deep and bottom water properties remained constant between 1909 and 1970, cruises from 1972, 1973, 1981 and 1981 revealed a new, denser, growing bottom layer with variable properties, that seemed to have been produced through open-sea convection. It was the revelation that the deep layers of the Mediterranean Sea were subject to change.
In the following years, Lacombe et al.'s finds were repeatedly certified by several authors (Charnock, 1989; Bethoux et al., 1990; Bethoux and Gentili, 1996). Furthermore, Bethoux and Gentili (1999) showed that the rising trends of temperature

and salinity were linear, and the intermediate layers exhibited similar trends, but about twice higher in magnitude (figure 6).

These trends were certified later by climatological analyses over the whole Mediterranean (Painter and Tsimplis, 2003; Manca et al., 2004).

Based mostly on the above observation, Rohling and Bryden attributed the increase of WMDW θ, S values to similar recorded increases of LIW waters (1992). The salinity increase of LIW was attributed to the damming of the Nile and Eastern European rivers flowing into the Black Sea. This freshwater reduction was estimated to a decrease by 7% of E-P excess over the MED. Soon afterwards, Bethoux and Gentilli (1999) certified Rohling and Bryden's findings. They estimated that the warming trend amounted to an increase of heat flux by 1.5 Wm^{-2}, while the salinification trend amounted to a water deficit higher by 0.1 $m\ yr^{-1}$. They also attributed the water deficit mainly to riverine diversion, adding the Iberian river damming to the one of the Eastern Mediterranean / Black Sea mentioned before.

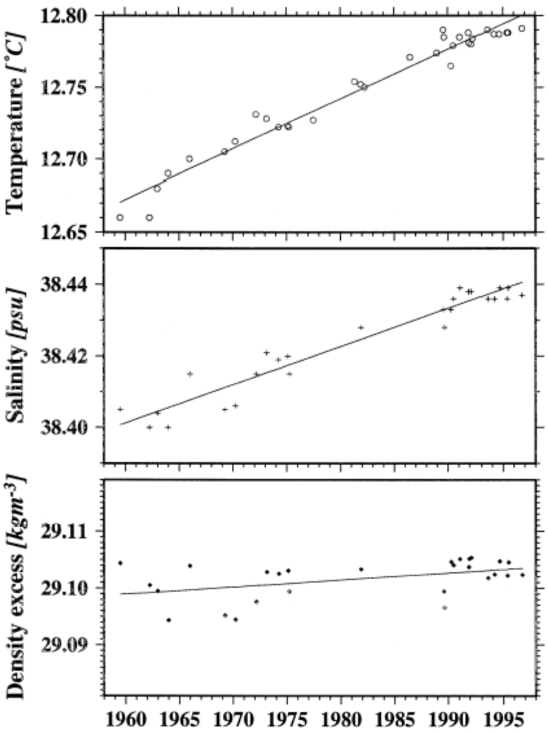

Figure 6. Linear rising temperature, salinity and density trends of the deep water of the Western Mediterranean (by Bethoux and Gentili, 1999).

In 2001, Tsimplis and Josey proposed that the variability of the evaporation – precipitation flux is related to that of the North-Atlantic Oscillation. They showed that the E-P rise in years of high NAO index is about four times higher than the river reduction in the Med, and they suggested that a series of positive NAO years must have contributed to the salinity inrease.

In 2004 Skliris and Lascaratos simulated the evolution of the Eastern Mediterranean after damming the rivers. Their results showed that the WMDW salinity increase during the last 40 years can be explained by about 50% from the salinity increase of the LIW (due to damming of Black Sea and Nile rivers).

Abrupt change: The Eastern Mediterranean Transient

While much was known about the evolution of the western Mediterranean Sea until the 1980s, there was a significant lack of information from the Eastern Mediterranean. This came to an end with the project POEM (Physical Oceanography of the Eastern Mediterranean), lasting between the mid-1980s to mid-1990s, incorporating essentially all the countries of the northern Mediterranean coasts and Israel. The preliminary results from POEM certified our basic knowledge about the thermohaline functioning of the Eastern Mediterranean has had been revealed by the scant observations up to that time: The major contributor to EMDW was the Adriatic, with the Aegean playing a secondary role as a dense water producer. Observations suggested that the Aegean Sea produced small amounts of water of relatively lower

density than the Adriatic, often exported through the Cretan Arc Straits in the form of lenses, forming a layer above the EMDW in the vicinity of Crete (Lascaratos, 1993; Theocharis et al., 1993).
Observations in the North Aegean obtained in the framework of POEM provided evidence of intense dense water formation (Theocharis and Georgopoulos, 1993), but the extent of the phenomenon was not realized until Roether et al. (1996) reported their findings from a comparison of hydrographic and tracer data from two zonal transects of the F.S. Meteor along the Eastern Mediterranean in 1987 and 1995 (figure 7).

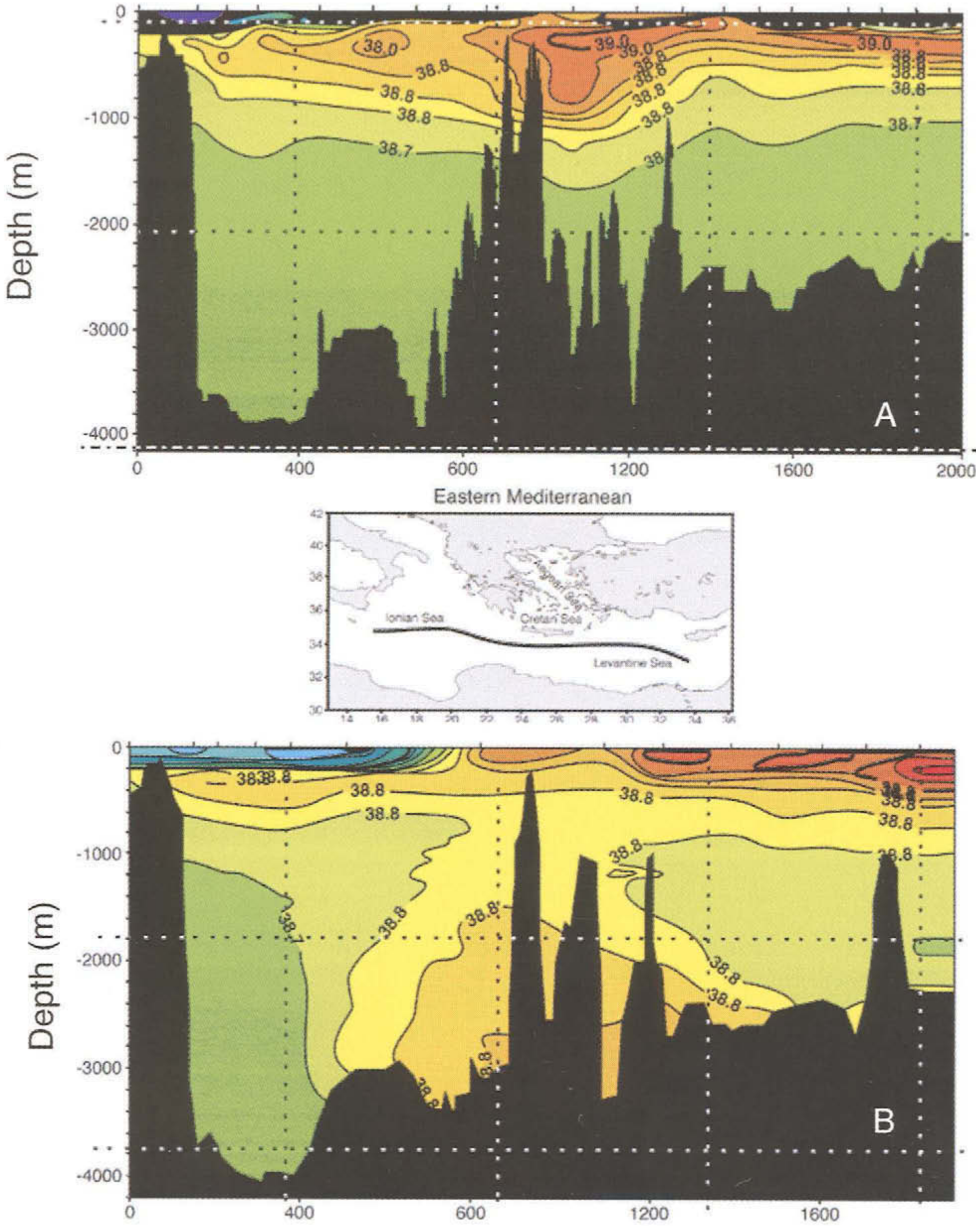

Figure 7. Salinity transects from the two cruises of the F.S. Meteor in the Eastern Mediterranean in 1987 (A) and 1995 (B). From Tsimplis et al., 2006, redrawn from Roether et al., 1996.

In the years the intervened between the two cruises, the bottom layers of the Eastern Mediterranean in the vicinity of Crete had been filled with warmer, saltier and denser water than the previous EMDW of Adriatic origin. The new water had obviously originated in the Aegean Sea, and was “pushing” the previous deep waters towards shallower depths. In a later analysis, Roether et al. (2007) estimated that the outflow

of CDW from the Cretan Arc amounted to about 3 Sv between 1992 and 1993, which is three times the inflow through Gibraltar!!!
Thus, during the early nineties, the Aegean Sea replaced the Adriatic as the major source of dense waters for the Eastern Mediterranean, in a dramatic shift rarely observed in any ocean, providing arguments for the characterization of the Mediterranean as a natural oceanic laboratory (figure 8).

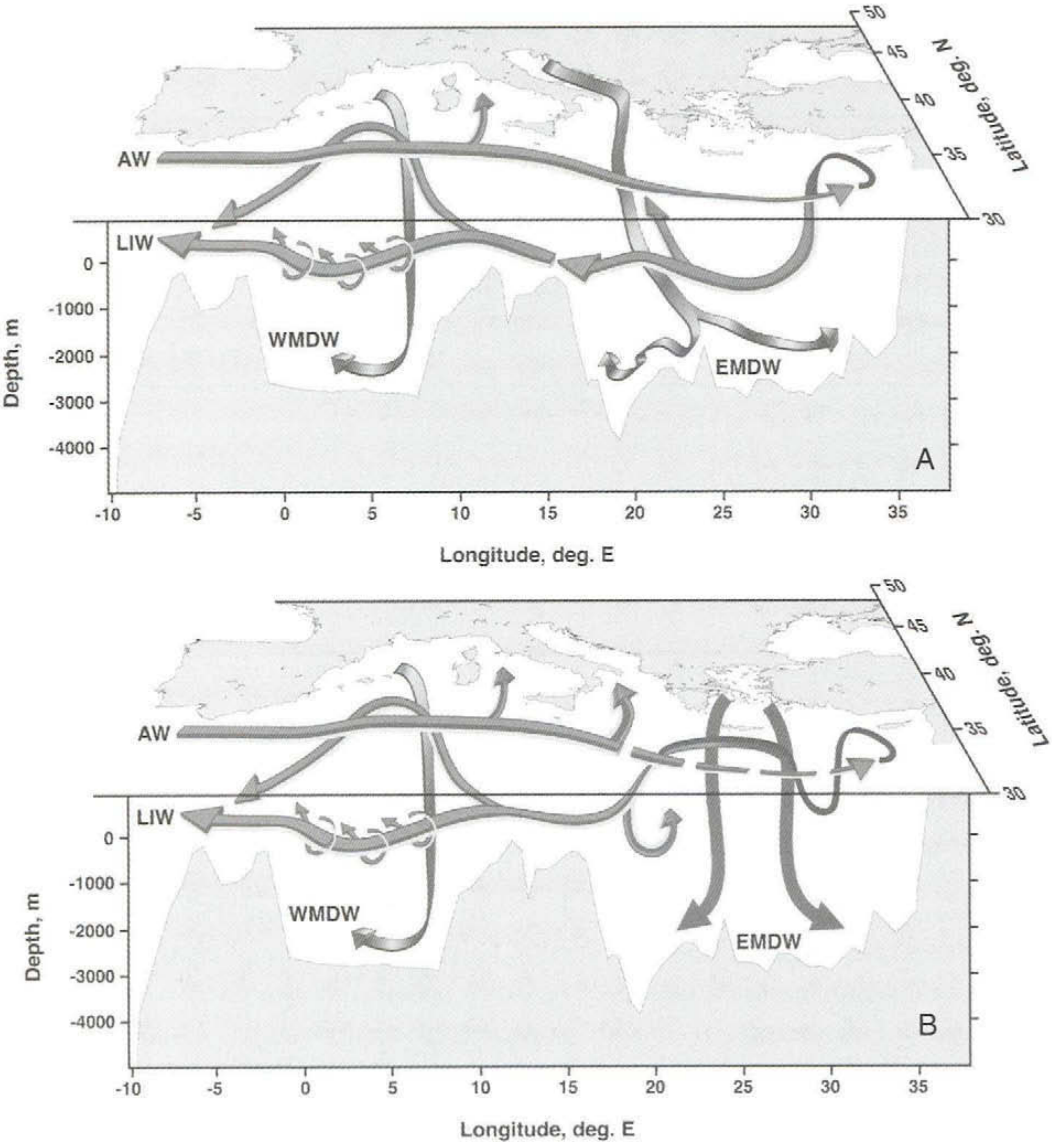

Figure 8. Traditional thermohaline functioning of the Mediterranean Sea (top), versus the functioning during the EMT (bottom). From Tsimplis et al., 2006.

Several mechanisms were proposed for the above change in overturning circulation, which was named the "Eastern Mediterranean Transient", or EMT event. A change of the wind pattern over the Eastern Mediterranean (Samuel et al., 1999) could be directly related to changes in the circulation in the Ionian (Malanotte-Rizzoli et al., 1997) which prevented Atlantic waters from entering the Levantine, thus raising the salinity in that basin. Local forcing over the Aegean Sea was definitely a contributor, as the early nineties was a period of excessive drought in the region (Lascaratos et al., 1999; Theocharis et al., 1999). Progressive erosion of the thermocline stratification in the Cretan Sea was also proposed (Boscolo and Bryden, 2001). A decrease of buoyancy input from the Black Sea through the Dardanelles would explain the huge amounts of dense waters formed in the North Aegean in 1987, and then again in 1992 and 1993 (Zervakis et al., 2000; Gertman et al. 2006). Not a single of the above mechanisms could explain the magnitude of the phenomenon, and all of them have been recorded; thus, it appears that all have contributed to the Eastern Mediterranean Transient. Maybe they were all parts of a greater response of the Eastern Mediterranean / Black Sea system to a greater-scale forcing. The relation of changes of surface properties of the Eastern Mediterranean to the North-Atlantic Oscillation has been investigated by Tsimplis and Rixen (2002), showing some correlation of positive NAO index to dry conditions over the Eastern Mediterranean. However, stronger correlations were found between the air-sea fluxes over the Easter Mediterranean / Black Sea system and the North Sea – Caspian climatic pattern (Gündüz and Özsoy, 2005).

After 1994-1995, the Cretan Sea stopped exporting large quantities of excessively dense waters, and the Adriatic has returned to become the major dense-water supplier for the Eastern Mediterranean (Klein et al., 2000). However, the properties of the dense new EMDW of Adriatic origin have changed, becoming more salty and warm than ever before (Hainbucher et al., 2006; Rubino and Hainbucher, 2007), a sign that the EMT maybe was just the first stage of longer-term changes in the functioning of the Eastern Mediterranean.

It's not over yet: The Western Mediterranean Transient.

The Eastern Mediterranean Transient, and the elevated salinities of the Levantine Intermediate Water, has not left the western basin unaffected. While, until 2004, there was no evidence of anomalous changes in the linear increase of temperature and salinity of the deep waters, the path of salinity anomalies propagating from the East to the West was being monitored. Gasparini et al (2005) have described the arrival of the EMT signal to Sicily Strait and the propagation of saltier, warmer water to the

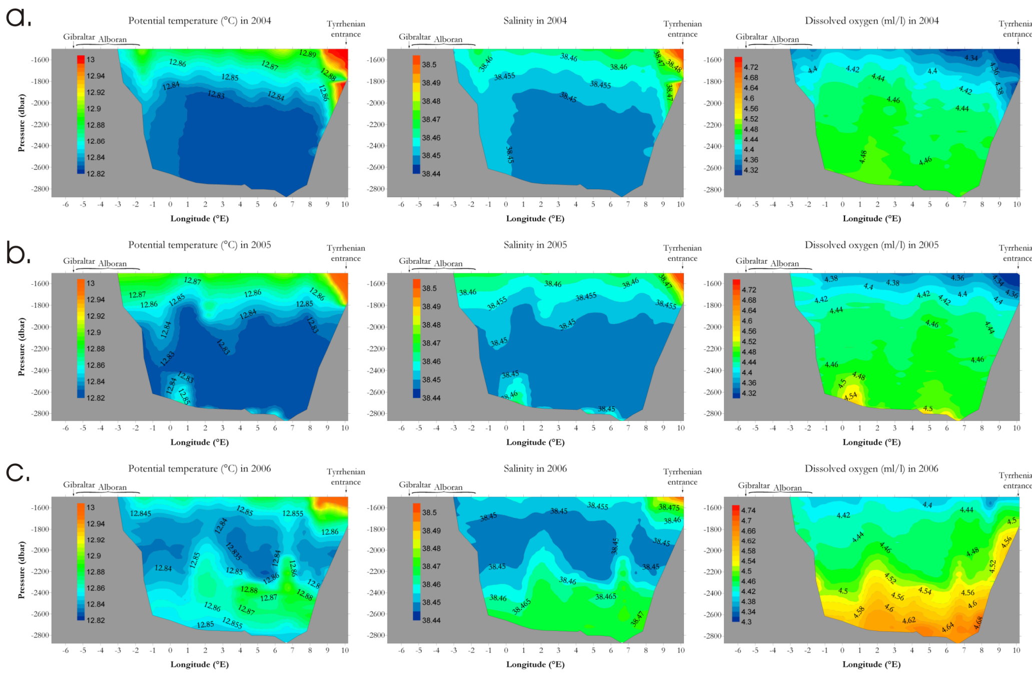

Figure 9. Vertical θ, S, and O2 distributions below 1500 m depth along a meridional transect from Gibraltar (to the left) to Sardinia (to the right) in (a) October 2004, (b) June 2005, and (c) October 2006. From Schröder et al., 2008.

Tyrrhenian basin. These data have been updated by Schröder et al. (2006), who have also shown that progressively saltier, warmer intermediate waters arrived in the Gulf of Lions, peaking in 2004. López-Jurado et al. (2005) observed an abrupt disruption of the warming and saltyfying trends in the deep waters around the Balearic islands. However, Schröder et al. (2008) have recorder a very similar event to the Eastern Mediterranean Transient, where in the years between 2004 and 2006 the old WMDW has been replaced by a new, warmer, saltier and significantly denser WMDW (figure 10) at a basin-wide phenomenon of equal magnitude and importance to the EMT, for which the name Western Mediterranean Transient has been proposed.

Observational initiatives

It is clear now that the Mediterranean has entered a stage of changes, not just gradual as they seemed to have been in the past, but rather abrupt. Furthermore, it appears that there are several inherent mechanism of the sea for the transport of heat and salt through different sub-basins, triggering various phenomena and changes in the thermohaline functioning. It has become obvious that the deep layers of the Mediterranean sea should be monitored for long-term variability (in extension to the currently operational oceanography initiatives).

One very important step towards that aim is the CIESM Hydrochanges initiative (http://www.ciesm.org/marine/programs/hydrochanges.htm). The initiative consists on coordinating several national actions towards the target of monitoring the deep basins of the Mediterranean through simple, low-cost instrumentation. The current Hydrochanges observational network is presented in figure 10.

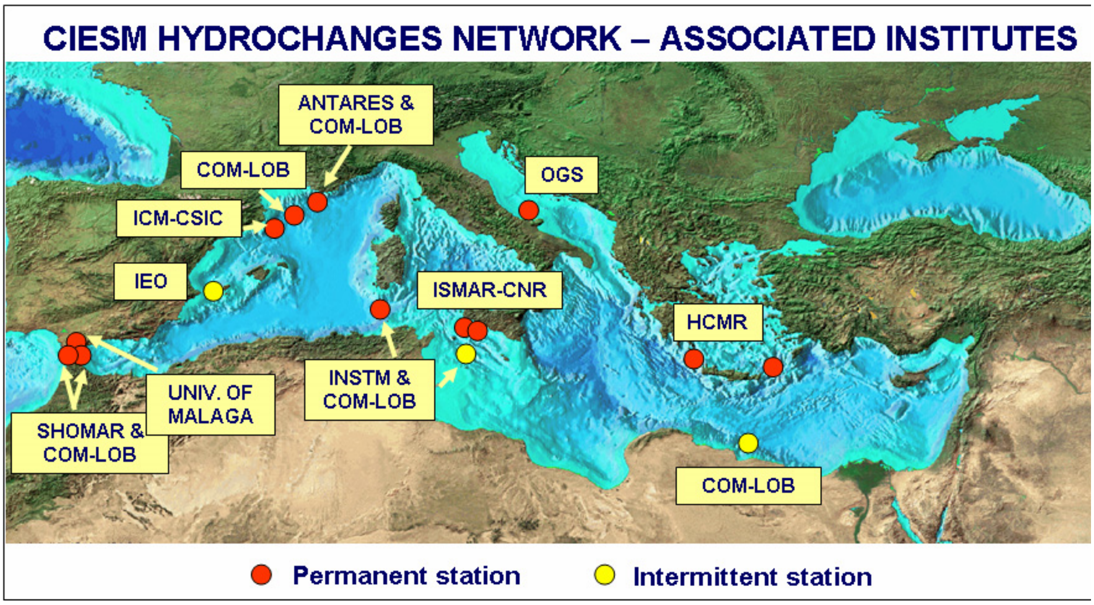

Figure 10. CIESM Hydrochanges network

Further to that initiative, it is possible to exploit new available technologies to assess and continuously monitor processes like volume exchange between basins (shipborne ADCPs on voluntarily observing vessels), satellite temperature and salinity measurements, HF radars at Straits, etc.

References

Bethoux, J.P. and Gentili, B., 1996. The Mediterranean climatic Sea, coastal and deep-sea signatures of and environmental changes. Journal of Marine Systems,7, 383-394.

Bethoux, J.P. and Gentili, B., 1999. Functioning of the Mediterranean Sea: past and present changes related to freshwater input and climate changes. Journal of Marine Systems 20, 33–47.

Bethoux, J.P., Gentili, B., Raunet, J. and Tailliez, D., 1990. Warming trend in the Western Mediterranean deep water. Nature, 347: 660-662.

Boscolo, R., and Bryden, H. L., 2001. Causes of long-term changes in Aegean Sea deep water. Oceanologica Acta, 24, 519-527.

Charnock, H., 1989. Temperature and Salinity Changes in the Deep Water of the Western Mediterranean Basin. 3rd POEM Scientific Workshop, Harvard, Cambridge, USA.

Della Vedova, B., Pellis, G., Camerlenghi, A., Foucher, J. P. and Harmegnies, F., 2003. Thermal history of deep-sea sediments as a record of recent changes in the deep circulation of the eastern Mediterranean. Journal of Geophysical Research, 108, C9, 8110, doi:10.1029/2002JC001402.

Gasparini, G. P., Ortona, A., Budillon, G., Astraldi, M., & Sansone, E., 2005. The effect of the Eastern Mediterranean transient on the hydpographic characteristics in the Strait of Sicily and in the Tyrrhenian sea. Deep-Sea Res. I, 52, 915-935.

Gertman, I.F., Pinardi, N., Popov, Y., Hecht, A., 2006. Aegean Sea water masses during the early stages of the Eastern Mediterranean Climatic Transient (1988–1990). Journal of Physical Oceanography 36 (9), 1841–1859.

Gündüz, M. and Özsoy, E., 2005. Effects of the North Sea Caspian pattern on surface fluxes of Euro-Asian-Mediterranean seas. Geophysical Research Letters, 32, L21701, doi:10.1029/2005GL024315.

Hainbucher, D., A. Rubino, and B. Klein (2006), Water mass characteristics in the deep layers of the western Ionian basin observed during May 2003. Geophys. Res. Lett., 33, L05608, doi:10.1029/2005GL025318.

Klein, B., Roether, W., Civitarese, G., Gačić, M., Manca, B.B., Ribera d'Alcala, M., 2000. Is the Adriatic returning to dominate production of Eastern Mediterranean Deep Water? Geophysical Research Letters 27, 3377–3380.

Lacombe H, Tchernia P. 1958. Température et salinité profondes en Méditeranée en période d' été (fin juin–octobre). Bulletin information comité central d' océanographie et d' étude des côtes, 10.

Lacombe H, Tchernia P. 1960. Quelques traits généraux de l'hydrologie Méditerranéene. Cahiers Océanographiques 20(8): 528–547.

Lacombe H, Tchernia P, Benoist G. 1958. Contribution à l' étude de la Mer Egée en période d' été. Bulletin d' Information de Comite Central d' Oceanographie et d' étude des Cotes X 8: 454–468.

Lacombe, H., Tchernia P. and Gamberoni, L., 1985. Variable Bottom Water in the Western Mediterranean Basin. Prog. Oeeanog. Vol. 14, pp. 319-338.

Lascaratos, A., 1999. Estimation of deep and intermediate water mass formation rates in the Mediterranean Sea. Deep-Sea Research I1, Vol. 40, No. 6, pp. 1327-1332.

Lascaratos, A., Roether, W., Nittis, K., Klein B., 1999. Recent changes in deep water formation and spreading in the eastern Mediterranean Sea: a review. Progress in Oceanography, 44, 5–36.

López-Jurado, J.-L., González-Pola, C. and Vélez-Belchí, P., 2005. Observation of an abrupt disruption of the long-term warming trend at the Balearic Sea, western Mediterranean Sea, in summer 2005. Geophysical Research Letters, VOL. 32, L24606, doi:10.1029/2005GL024430.

Malanotte-Rizzoli, P. and Hecht, A., 1988. Large-scale properties of the Eastern Mediterranean: a review. Oceanologica Acta, 11: 323-335.

Malanotte-Rizzoli, P., Manca, B. B., Ribera Dacala, M., Theocharis, A., Bergamasco, A., Bregant, D., Budillon, G., Civitarese, G., Georgopoulos, D., Michelato, A., Sansone, E., Scarazzato, P., and Souvermezoglou, E., 1997. A synthesis of the Ionian hydrography, circulation and water mass pathways during POEM— Phase I. Progress in Oceanography, 39, 153-204.

Manca, B., Burca, M., Giorgetti, A., Coatanoan, C, Garcia, M.-J., and lona, A., 2004. Physical and biochemical averaged vertical profiles in the Mediterranean regions: an important tool to trace the climatology of water masses and to vahdate incoming data from operational oceanography. Journal of Marine Systems, 48(1), 83-116.

Nielsen, J. N., 1912. Hydrography of the Mediterranean and adjacent waters. In Report of the Danish Oceanographic Expedition 1908–1910 to the Mediterranean and Adjacent Waters, Volume 1, Schmidt J (ed.). Andr. Fred Høst & Søn: Copenhagen; 72–191.

Painter, S. C, and TsimpHs, M. N., 2003. Temperature and salinity trends in the upper waters of the Mediterranean Sea as determined from the MED ATLAS dataset. Continental Shelf Research, 23, 1507-1522.

Plakhin, Ye. A., 1971. Formation of distinct deep water in the Mediterranean by convective mixing. Oceanology 11(4): 524–529.

Plakhin, Ye. A., 1972. Vertical winter circulation in the Mediterranean. Oceanology 12(3): 344–351.

Pollak, M. I., 1951. The sources of deep water in the eastern Mediterranean Sea. Journal of Marine Research 10: 128–152.

Roether, W., Manca, B.B., Klein, B., Bregant, D., Georgopoulos, D., Beitzel, V., Kovacˇevic´, V., Lucchetta, A., 1996. Recent changes in Eastern Mediterranean deep waters. Science 271, 333–335.

Roether, W., Klein, B., Manca, B. B., Theocharis, A. and Kioroglou, S., 2007. Transient Eastern Mediterranean deep waters in response to the massive dense-water output of the Aegean Sea in the 1990s. Progress in Oceanography, 74, 540–571.

Rohling, E. J., and Bryden, H. L., 1992. Man-induced salinity and temperature increases in Western Mediterranean deep water. Journal of Geophysical Research, 97, 11191-11198.

Rubino, A. and Hainbucher, D., 2007. A large abrupt change in the abyssal water masses of the eastern Mediterranean. Geophysical Research Letters, 34, L23607, doi:10.1029/2007GL031737.

Samuel, S. L., Haines, K., Josey, S. A., and Myers, P. G., 1999. Response of the Mediterranean Sea thermohahne circulation to observed changes in the winter wind stress field in the period 1980-93. J . Geophys. Res., 104, 5191-5210.

Schröder, K., Gasparini, G. P., Tangherlini, M. and Astraldi, M., 2004. Deep and intermediate water in the western Mediterranean under the influence of the Eastern Mediterranean Transient. Geophysical Research Letters, 33, L21607, doi:10.1029/2006GL027121.

Schröder, K., Ribotti, A., Borghini, M., Sorgente, R., Perilli, A. and Gasparini, G. P., 2008. An extensive western Mediterranean deep water renewal between 2004 and 2006. Geophysical Research Letters, 35, L18605, doi:10.1029/2008GL035146.

Theocharis, A. and Georgopoulos, D., 1993. Dense water formation over the Samothraki and Lemnos plateaux in the North Aegean Sea (Eastern Mediterranean Sea). Continental Shelf Research, l3(S-9), 919-939.

Theocharis, A, Georgopoulos, D., Lascaratos, A. and Nittis, K., 1993. Water masses and circulation in the Central region of the Eastern Mediterranean: Eastern Ionian, South Aegean and Northwest Levantine, 1986-1987. Deep Sea Research II, 40, 1121-1142.

Theocharis, A., Nittis, K., Kontoyiannis, H., Papageorgiou, E., and Balopoulos, E., 1999. Climatic changes in the Aegean Sea influence the Eastern Mediterranean thermohaline circulation. Geophys. Res. Lett., 26, 1617-1620.

Tsimplis, M. N., and Rixen, M., 2002. Sea level in the Mediterranean Sea: The contribution of temperature and salinity changes. Geophys. Res. Let., 29(3), art no. 2136

Wüst, G., 1961. On the vertical circulation of the Mediterranean Sea. J. Geophys. Res., 66: 3261-3271.

Zervakis, V., Georgopoulos, D., and Drakopoulos, P. G., 2000. The role of the North Aegean in triggering the recent Eastern Mediterranean climatic changes. J. Geophys. Res., 105,26103-26116