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The circulation of the Mediterranean Sea: a historical review of experimental investigations

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The Mediterranean Sea is an enclosed basin composed of two similar basins and different sub-basins. It is a concentration basin, where evaporation exceeds precipitation. In the surface layer there is an inflow of Atlantic water which is modified along its path to the Eastern basin. This transformation occurs through surface heat loss and evaporation specifically in the Levantine basin. The Mediterranean is furthermore the site of water mass formation processes, which can be studied experimentally because of their easy accessibility. There are two main reasons why the Mediterranean is important. The first one is the impact of the Mediterranean on the global thermohaline circulation, the second reason is that the Mediterranean basin can be considered as Laborartory for investigating processes occurring on the global scale of the world ocean. In this paper we want to provide a short historical review of the evolving knowledge of the Mediterranean circulation that has emerged from experimental investigations over the last decades. We start by describing the old picture of the basin circulation which had stationary, smooth large scale patterns. Then we show the major experiments that led to the discovery of the sub-basin scale circulation and its mesoscale features. We conclude with the dynamical discovery of EMT in the 1990s and the most exciting ongoing new research programmes.

Keywords: Mediterranean Sea; THC Thermo Haline Circulation; EMT East Mediterranean Transient; POEM; MedCLIVAR

1. Introduction: why the Mediterranean?

The Mediterranean Sea is an enclosed basin connected to the Atlantic ocean by the narrow and shallow Strait of Gibraltar (width ∼13 km; sill depth ∼300 m) (Figure 1). It is composed of two similar basins, the Western and Eastern ones, connected by the Strait of Sicily. In each of them a number of sub-basins are presently characterized by a rugged topography, especially in the Eastern part. The Mediterranean Sea is a concentration basin, where evaporation exceeds precipitation. At Gibraltar there is inflow of Atlantic water in the surface layer with temperature $T = 15^\circ C$ and salinity $S = 36.2$ psu which becomes Modified Atlantic Water (MAW) along its path to the Eastern basin. In the bottom layer there is outflow of Mediterranean water, the Levantine Intermediate Water (LIW) with $T = 13.5^\circ C$ and $S = 38.4$ psu. The transformation of MAW into LIW occurs through surface heat loss and evaporation specifically in the Levantine basin. The result is...
that the Mediterranean has an overall mean heat loss in the range of 3–7 W/m². For a thorough review of these properties see Tsimplis et al. [1].

Why is the Mediterranean important? There are two main reasons. The first one is the impact of the Mediterranean on the global thermohaline circulation which originates in the polar convecting cells of the Northern Atlantic Ocean (Labrador and Greenland seas) where North Atlantic Deep Water (NADW) is formed. In fact the salty North Atlantic Upper Deep Water is the one spreading out at Gibraltar and forming a characteristic tongue that spreads into the eastern and northern Atlantic interior at \(\sim1000–1500\) m depth. This is the LIW discussed above, which has a direct advective path to the polar seas [2] as well as an indirect effect by progressive mixing with North Atlantic Central Waters [3].

The second reason is that the Mediterranean can be considered as a Laboratory Basin for investigating process occurring on the global scale of the world ocean. Being relatively small, the Mediterranean is a test basin for general circulation studies.

The Mediterranean Sea thermohaline circulation is characterized by different vertical cells. The first one is an open thermohaline cell comprising both basins, with the MAW spreading from Gibraltar to the Eastern part, being transformed into LIW in the Levantine basin through cells convecting to mid-depth, of which the most studied is the Rhodes gyre, and finally returning to Gibraltar and exiting there in the bottom layer to spread into the Northern Atlantic interior [4,5]. More importantly, the Eastern Mediterranean is characterized by a closed thermohaline cell, the basin ‘conveyor belt’ analogous to the global one originating in the polar Atlantic. In the Eastern Mediterranean the source driving the cell has been traditionally the Southern Adriatic. But the eastern basin is sufficiently small, with a short deep residence time of \(\sim100\) years [6], that transition to a different equilibrium was found in the 1990s, with the driving source of the deep water shifting to the South Aegean Sea, what has become know in the literature as the Eastern Mediterranean Transient (EMT). Furthermore, in the 1980s the existence of multiple scales of motion that define the general circulation was discovered, in particular the sub-basin scale that characterizes the upper thermocline circulation in each sub-basin and the ubiquitous, energetic mesoscale of the eddy field.
The Mediterranean is furthermore the site of water mass formation processes which can be studied experimentally because of their easy accessibility. The Western Mediterranean Deep Water is formed in the Gulf of Lyons in the northwestern corner, and was the object of an extensive observational campaign, the MEDOC experiment in the early 1970s. The deep convection in the Southern Adriatic has been known since the pioneering work of Pollack [7], and the Southern Adriatic Deep Water spreading out in the bottom layer from the Otranto Strait forms the Eastern Mediterranean Deep Water, which is a component of the closed thermohaline cell. Finally, as already mentioned above, intermediate convection in the Levantine basin, and in the 1990s in the Southern Aegean, leads to the formation of LIW and intermediate Cretan Water respectively. For a thorough recent review of these properties see Tsimplis et al. [1].

Another important mechanism of Dense Shelf Water Cascades is recently studied by the scientific community. That process in the global oceans play a crucial role in Earth’s long-term climate [8]. Indeed, these processes are complementary to the open ocean convection ones, both constituting the main mechanism for ventilation of the deep oceans, and are also relevant to carbon export and burial impacting deep-sea ecosystems, as well as to sediment transport affecting sea floor morphology. In the Mediterranean both type of dense water formations happen, offshore (convection, typically in the Gulf of Lions, and Southern Adriatic) and on the shelf (cascading, again in the Gulf of Lions and in the Adriatic).

In this paper we want to provide a short historical review of the evolving knowledge of the Mediterranean circulation. In the last decades theoretical and modeling studies of the dominant dynamical mechanisms responsible for the wind-driven and thermohaline circulations, as well as for water mass formation and transformations, have increasingly appeared in the literature. A thorough review of these theoretical interpretations and modeling results is beyond the scope of the present paper. We limit ourselves to provide a review of the evolving understanding of the Mediterranean properties that has emerged from the experimental investigations over the last decades. This experimental knowledge is the basic source of information giving the necessary foundations to any theoretical investigation. Thus in Section 2 we describe the old picture of the basin circulation which presented a stationary, smooth large scale patterns. Then in Section 3 we discuss the 1980s and 1990s, with the execution of major experiments in both the Western and Eastern basins that led to the discovery of the sub-basin scale and the mesoscale. We devote Section 4 to the EMT which constituted a major observational and dynamical discovery in the 1990s. Finally, in Section 5, we give a short discussion of the most exciting ongoing new research programs.

2. The old picture: the stationary ocean

The first general surveys of the Mediterranean go back to Nielsen [9] who pioneered the Mediterranean oceanography and produced the first overall scheme of the circulation. The surface pattern of currents in summer is given in Figure 2. Ovchinnikov and Fedoseyev in 1965 [10] and Ovchinnikov in 1966 [11] carried out a geostrophic analysis producing the surface circulation in winter shown in Figure 3, very similar to that of Figure 2. The circulation features are defined by broad currents, smoothly evolving and forming a continuous pattern from the western to the eastern basins. This is clearly the picture of a linear, stationary ocean.
The pioneering work by Wust in 1961 [12] explored the water mass formation and their evolution using the core method to infer the mean steady circulation. Wust also discovered the open thermohaline cell of the Mediterranean discussed in the introduction, shown in Figure 4. In Wust’s words ‘... the vertical circulation offers by the transformation of the Atlantic water type to the Mediterranean a unique example of interaction between the atmosphere and the ocean’. The core method defines the main axis of propagation of the water types. Evident in Figure 4 is the entering Atlantic Water, the intermediate convection in the eastern basin and the returning tongue of LIW outflowing at Gibraltar. Wust also presented a three-dimensional picture of the Mediterranean thermohaline circulation, given in Figure 5, in which the deep waters are formed in the northwestern part of the Western Mediterranean (Gulf of Lyons) and in the Southern Adriatic Sea in the Eastern Mediterranean, and from their sources they spread in the bottom layers.

These patterns remained the unchallenged description of the Mediterranean circulation until the discovery of more localized circulation features, delimited by the various sub-basins, and of the mesoscale eddy field which started in the 1980s.
Starting in the early 1980s a series of major experiments started both in the Western and Eastern basins. The first was the Western Mediterranean Circulation Experiment, amply discussed in La Violette et al. [13]. After that, the most comprehensive series of observational studies in the Western Mediterranean has been carried out in [14–16] and has been extensively reviewed in [17]. Millot’s picture of the western circulation emphasizes the crucial role of eddies in modifying the mean climatological circulation and mixing properties into the interior of the different sub-basins, which include the Tyrrenian,
Ligurian and Alborean Seas (Figure 1). These mesoscale eddies have scales ranging from 10ths to 100ths of kilometers. An example is given in Figure 6a which shows the circulation of the MAW and of the Winter Intermediate Water (WIW) in the upper layer. These eddies have a strong barotropic component, and they appear also very strong in the intermediate layers, where the pathways of the LIW and Tyrrenhenian Dense Water (TDW) can be traced as shown in Figure 6b. The eddies penetrate into the bottom layer equally intense, where the TDW and WMDW spread, Figure 6c.

More recent studies of the Western Mediterranean behaviour adopted a basin wide approaches [18], even that they do not use a dedicated oceanographic survey. Other studies, on the contrary, are detailed but consider only distinctive events as the winter dense water formation processes occurring in the Gulf of Lions and in the Ligurian Sea have been extensively studied, both experimentally and through models [19,20]. Besides these, several authors have described the circulation and the fluxes, using both geostrophic calculations and direct measurements from shipborne, moored or lowered ADCPs [21–25]. One of the most comprehensive work on water exchanges across the whole western basin is given by Béthoux [26], who made a quantitative estimation of the mean water fluxes in different areas of the Mediterranean, on the basis of the water and salt budgets across the sea surface and various regions in the sea.

In the last years, in Schroeder et al. [27], a large portion of the WMED has been investigated during the oceanographic campaign MEDOCC05 (spring 2005), in order to enhance the description of the pathways and the properties of the water masses involved in the circulation of the basin. They analyzed in situ observations to study the circulation of the WMED during April–May 2005, by means of an inverse box model (IBM). The method resolve the geostrophic flow of the ocean on the basis of property conservation and has been firstly described by Wunsch [28–32]. Pinot and Ganachaud [21] and Vetrano et al. [25] applied it successfully to the Balearic Sea and the Central Mediterranean Sea (CMED), respectively, thus providing the first applications to the Mediterranean Sea. The geostrophic velocities and water fluxes across transects, obtained with the IBM, were compared with vessel-mounted ADCP measurements and with a GCM, see Figure 9, p. 961 in Schroeder et al. [27].

The comparison with the directly measured velocity field shows differences between the geostrophic computation, and the instantaneous view of the motion, the latter including a geostrophic small-scale and wind-induced motions. The comparison looks better with a well-validated and robust numerical model, the GCM-OPA model MED16, that provides a high spatial resolution circulation field, complementing the geostrophic computation, which is actually a snapshot of the spring 2005 situation. The inverse solution, the direct current measurements and the GCM simulation agree in reproducing large-scale features of the WMED circulation (i.e. the Algerian Current, the Atlantic Ionian Stream, the Northern Current, and the cyclonic circulations in the Gulf of Lions, in the Balearic Sea, in the Algerian basin and in the Tyrrenhenian Sea). As expected, mesoscale features are mostly visible in the velocity field provided by the instantaneous current measurements with the shipborne ADCP and in the high-resolution GCM simulation. Some of the mesoscale features are present in the inverse solution as well, mainly in the Algerian Sea and in the Algero-Provenceal basin. Circulation patterns in critical areas seem better simulated by the GCM then by the IBM, for instance the AW stream through the Sicily Strait, the LIW flow from the EMED through the same transect and through the eastern edge of the Sardinia–Sicily passage, and the northward flow through the Corsica Channel.
Figure 6. (a) Western Mediterranean circulation in the upper layer (modified from [17]). (b) Western Mediterranean circulation in the intermediate layer (modified from [17]). (c) Western Mediterranean circulation in the bottom layer (modified from [17]).
The comparison of the transport estimates obtained by IBM and GCM displays quantitative discrepancies with the geostrophic ones, while the directions of the principal and well-known current features agree very well with the inverse solution and previous observations. One of the most evident geostrophic structure was the Algerian Current. Interesting to note that transport estimates from Schroeder et al. [26] papers are in close agreement with the classical estimate, which refers to the 1970s conditions. This finding induces to evidence how, in spite of the sensitivity of the hydrographic properties, mean transport values appear stable.

In the last work Schroeder et al. [33] show evidence also of a recent sudden change in the deep layer structure, heat and salt contents of the western Mediterranean, that may be related to two different effects, acting at two different scales (see Figure 3, p. L18605, [33]). A decadal salt and heat accumulation at intermediate levels, induced by the arrival of the EMT signal as described in Gasparini et al. [34] and Schroder et al. [35] was observed. Along with this long-term modification of the water column, a particularly severe weather conditions as described in López-Jurado et al. [36] were responsible for the extensive DWF in winter 2004/2005. The rapid change in deep water properties in the WMED as a response to a dramatic event in the EMED, one decade earlier, is an example of instabilities in the thermo-haline circulation and how different sub-basins interact with each other.

There are quite a lot of open questions with regard to the new WMDW characteristics. Further investigations are needed and above all, it will be necessary to assess the effect on the Mediterranean Outflow Water (MOW) toward the Atlantic Ocean and when this will be visible. Stommel et al. [37] showed that water from about 700 to 1000 m depth may participate directly in the outflow, while Kinder and Parrilla [38] pointed out that there is a presence of WMDW on the Atlantic side of the Strait. Data collected in 2004, 2005 and 2006 suggests that, starting from 2005, almost the whole WMED is filling up with these particular water masses, significantly accelerating the ventilation of the deep WMED. Considering that in the EMED the Eastern Mediterranean Transient (EMT) discussed in the next session IV, produced an uplifting of the old Eastern Mediterranean Deep Water (EMDW) of about 500 m, see [39], what we are observing now in the WMED seems to be significant as well (300 m displacement of the resident WMDW in 2 years on average).

In the Eastern Mediterranean a multi-national collaborative effort started in 1984 under the support of UNESCO and IOC. This was the Physical Oceanography of the Eastern Mediterranean (POEM) program (1984–1987) which evolved into POEM-BC, with biological and chemical components (1991–1995). Five general surveys were carried out under POEM with oceanographic vessels from Italy-Greece-Turkey-Israel and Germany in POEM-V. Three further general surveys were carried out under POEM-BC [40,41]. The POEM surveys were fully reanalyzed in the 1990s leading to the schematic of the upper thermocline circulation shown in Figure 7a, which clearly identifies the sub-basin scale gyres largely topographically controlled [42]. This reanalysis allowed also to identify the major pathways of the LIW on the density surfaces 29.0–29.10 kg/m³. The salinity and the current pathway on the isopycnal surface of 29.05 kg/m³ is shown in Figure 7b.

Figure 7a identifies the major features of the upper thermocline circulation in the Ionian Sea. First, the Atlantic Ionian Stream (AIS) is seen entering the straits of Sicily transporting MAW into the eastern basin becoming the Mid Ionian Jet (MIJ). The latter one forms a strong meander protruding well into the northern Ionian before turning southeastward. A broad anticyclonic area, comprising multiple centers, the Ionian
Figure 7. (a) Upper thermocline circulation reanalysis (modified from [42]). (b) Reanalysis of salinity distribution and currents pathway along the isopycnal 29.05 kg/m$^3$ (modified from [42]). (c) Schematic upper thermocline general circulation obtained melding the observations and model dynamics (modified from [41]).
Anticyclones (IA), is present in the interior. In its eastward pathway, the MIJ becomes the Mod Mediterranean Jet (MMJ) that enters the Cretan channel. Outside the Western Greek straits, important permanent sub-basin features are present, i.e. the Pelops Anticyclone, strongly barotropic south of the Peloponnesus peninsula; and the Cretan Cyclone, confined to the upper thermocline, south of Crete.

The schematic of the upper thermocline circulation in the Levantine basin is depicted in Figure 7c [41]. The MMJ proceeds northeastward in the Levantine basin strongly controlled by the Mid Mediterranean ridge. It separates the strong Mersa-Matruh Anticyclone in the south from the Rhodes gyre in the North. The permanent, strongly barotropic Ierapetra anticyclone is observed just south of Crete. The MMJ bifurcates south of Cyprus. One branch flows southward comprising a series of anticyclonic centers of which the Shikmona eddy is the most permanent one. The second branch flows northward and around the Cyprus Island becoming the Asia Minor Current that high the Turkish coast north of the West Cyprus anticyclone. All these upper thermocline sub-basin gyres have been consistently found in the POEM and POEM-BC general surveys.

The ubiquitous, energetic eddy field of the Eastern Mediterranean was also discovered during POEM, with dominant scales rather smaller than in the Western Mediterranean. The Eastern eddies cover scales ranging from a few to ~50 km. Figure 7c shows the mesoscale temperature cross-section along the composite section in the lower right panel during POEM-87, evidencing the small interior baroclinic eddies [41].

The mesoscale eddy field has been also investigating through satellite altimetry. One example is given in Figure 8 [43] showing the rms sea level anomaly (upper panel) and the geostrophic velocity variance evaluated from altimetry (lower panel). The latter one especially evidences regions of very high eddy energy in different sub-basins of the entire Mediterranean.

Between 1987 and 1995 a profound change occurred in the Eastern basin which revolutionized its knowledge and the dynamical understanding of its circulation. This change is the object of the next section.

4. The Eastern Mediterranean Transient (EMT)

It has been known since a long time that the deep and bottom waters of the Eastern Mediterranean are formed in the Southern Adriatic with the Adriatic Deep Water (ADW) flowing into the abyssal depths of the Ionian Sea [7]. In modern terminology, the closed thermohaline cell of the basin is driven by the Southern Adriatic deep convection and related water mass formation. This is in fact what was found in POEM-V, in which the average flow rate from the Adriatic was estimated to be ~0.3 Sv of EMDW, with a renewal time of the deep and bottom waters of ~125 years [44].

The finding of POEM-BC III in 1995 was therefore altogether startling. The ‘engine’ of the closed thermohaline cell switched to the Southern Aegean/Cretan Sea with Cretan Intermediate Water (CIW) and Cretan Deep Water (CDW) spreading out through the Cretan Arc Straits while simultaneously pushing to the west and lifting the less dense EMDW of Adriatic origin. Figure 9 [45] provides this startling evidence. The two upper panels give the CFC-12 distribution along sections crossing the basin and shown in the inserts. The top panel shows the distribution in 1987, with the clear bottom maximum of CFC-12 hugging the deep continental slope of the western Ionian, following the bottom isobaths after exiting from the Adriatic Sea. In 1995, middle panel, the situation is
completely different. The deep CFC-12 maximum spreads out from the depths of the Levantine basin into the Eastern Ionian. The bottom panel confirms this spreading of Cretan waters into the abyssal layers of the Eastern Mediterranean showing the salinity pattern at 2200 m depth.

A further startling discovery was that this shift of the source of the deep/bottom waters was already occurring in 1991, and therefore started in the transition from the 1980s to the 1990s. The in-depth analysis of the survey POEM-BC I of 1991 showed in fact that the Cretan Sea was the source of intermediate and deep waters with CIW and CDW spreading into the Ionian in their respective layers, as shown in Figure 10 from [46]. Tsimplis [1] provides an excellent review of the EMT. First studies suggested that the deep water formation occurred only in the Cretan Sea [39,45,47,48]. Zervakis et al. [50] proposed an alternative mechanism, with the reduction of Black Sea Freshwater into the Northern

Figure 8. (a) The rms sea level anomaly using satellite altimetry, cycles 2–75 (modified from [43]). Units are centimeters. (b) Geostrophic velocity variance using satellite altimetry, cycles 2–75 (modified from [43]). Units are centimeters.
Figure 9. (a) CFC12 vertical distribution during September 1987 along the section shown in the insert (modified from [45]). Units are in pmol/kg. (b) CFC12 vertical distribution during January 1995 along the section shown in the insert (modified from [45]). Units are in pmol/kg. (c) Salinity distribution at 2200 m depth during January/February 1995 (modified from [45]).
Aegean suggesting that the deep water formation first started there and then overflowed into the southern Aegean Sea. A two steps scenario was proposed by [39,48]. The 1987 situation constitutes the background condition before the start of the EMT. Deep waters within the Cretan basin became first saltier (1987–1991) and then saltier and cooler (1991–1995) and this changes led to the EMT. Figure 11 from [1] shows the two schemes of the Eastern Mediterranean closed thermohaline cell before the EMT (upper panel) and during the EMT (lower panel).

Different dynamical scenarios were proposed. We report here the only one related to changes in the large-scale basin circulations, both in the atmosphere and the ocean. Samuel et al. [51] showed that the period of increase dense-water formation over the Aegean coincided with changes in the mean winds between the 1980s and the 1990s and hence in the wind-driven circulation. Malanotte-Rizzoli et al. [46] and the LIWEX Group [52] showed that in both years a gyre developed in the Ionian Sea deflecting the MAW to the Northern Ionian. Simultaneously, a strong wind-driven anticyclonic region with three centers developed from the surface to the bottom in the southern Levantine east of Crete blocking the LIW from flowing westward and forcing its recirculation into the Cretan Sea through the Eastern Cretan Arc straits. The intrusion of LIW preconditioned the surface and intermediate Cretan waters leading to the formation of CIW and CDW by surface cooling which spread out from the Western Cretan Straits towards the Sicily strait both in 1991 and 1995. Alternative mechanisms, linked to more local phenomena such as the damming of the Nile, were proposed by Boscolo and Bryden [53] and Skleris and Lascaratos [54]. Tsimplis and Josey [55], instead, proposed as leading mechanism North Atlantic Oscillation (NAO)-induced changes in evaporation/precipitation fluxes over the basin. The relaxation of the EMT to the previous traditional scenario with the origin of deep waters going back to the Southern Adriatic seems to have occurred in the mid of 1997 [56]. In the latter work and in Gacic et al. [57] it is shown that the relaxation of the EMT is associated with a complete reversal of the Ionian upper layer circulation from anticyclonic to cyclonic, produced not by wind-vorticity input but rather by baroclinic vorticity production. The final provoking possibility is that multiple equilibria of the Eastern Mediterranean thermohaline cell do exist of which the EMT constitutes one state.
The paramount importance of global warming which the latest IPCC (Intergovernmental Panel for Climate Change) Report [58] has shown to be unequivocal, has had an enormous impact on the earth sciences, showing that the earth system cannot be investigated only by looking at its individual components but at their coupled interactions and feedbacks (Atmosphere, Hydrosphere, Cryosphere and Biosphere as a whole). New programs oriented to the investigation of climate have been developed and the related studies are growing at an exponential rate. One of such programs is the NOAA-sponsored CLIVAR (Climate Variability and Predictability) project of the World Climate Research Programme. In 2004 a new component of it was endorsed by the CLIVAR International Steering Committee, the Mediterranean Climate Variability Programme or MedCLIVAR.

Figure 11. Mediterranean Sea Thermohaline Circulation Scheme (modified from [1]). Note the Eastern Mediterranean behaviour before (upper panel) and during (bottom panel) the Eastern Mediterranean Transient (EMT).
Because of its latitude the Mediterranean Sea is located in a transitional zone, where mid-latitude and tropical variability are both important and in competition [59,60]. Thus the northern part of the Mediterranean region presents a Maritime West Coastal Climate while the southern part is characterized by a Subtropical Desert Climate. Furthermore, the Mediterranean Climate is exposed to the South Asian Monsoon in summer and the Siberian high pressure system in winter. The southern part of the region is mostly under the influence of the descending branch of the Hadley cell, while the northern part is more linked to the mid-latitude variability. An important consequence is that the analysis of the Mediterranean climate could be used to identify changes in the intensity and extension of global scale climate patterns, such as the Northern Atlantic Oscillation (NAO), the El Nino-Southern Oscillation (ENSO) and the monsoons. Moreover it is important to consider the role of the Mediterranean Sea as a heat reservoir and a source of moisture for surrounding land areas. The Mediterranean Sea is also a source of energy and latent heat for cyclone development [61] in analogy to the hurricanes ‘feeding’ from the Sargasso Sea and its effect on the Meridional Overturning Circulation (MOC) of the Atlantic Ocean.

For all these and further reasons not discussed here, the Mediterranean coupled atmosphere-ocean system can be considered as a laboratory basin for climate studies relevant not only for the region but also at global scale.

References

[1] M.N. Tsimplis, V. Zervakis, S.A. Josey, E.L. Peneva, M.V. Struglia, E.V. Stanev, A. Theocharis, P. Lionello, P. Malanotte-Rizzioli, V. Artale, E. Tragou, and T. Oguz, in Changes in the Oceanography of the Mediterranean Sea and their Link to Climate Variability, in Mediterranean Climate Variability, Vol. 4, P. Lionello, P. Malanotte-Rizzioli, and R. Boscolo, eds., Developments in Earth & Environmental Sciences, Elsevier, 2006, pp. 227–282.

[2] J.L. Reid, On the total geostrophic circulation of the North Atlantic Ocean: flow patterns, tracers and transports, Prog. Oceanogr. 33 (1994), pp. 1–92.

[3] M.S. Lozier, W.B. Owens, and R.G. Curry, The climatology of the Northern Atlantic, Prog. Oceanog. 36 (1995), pp. 1–44.

[4] Robinson and Golnaraghi, The physical and dynamical oceanography of the Mediterranean sea, in Ocean Precesses in Climate Dynamics: Global and Mediterranean Examples, Vol. 419, P. Malanotte-Rizzioli and A.R. Robinson, eds., Kluwer Academic Publishers, The Netherlands, 1994, pp. 225–306.

[5] P. Malanotte-Rizzioli, Modeling the general circulation of the Mediterranean, in Ocean Processes, in Climate Dynamics: Global and Mediterranean Examples, Vol. 419, P. Malanotte-Rizzioli and A.R. Robinson, eds., Kluwer Academic Publishers, The Netherlands, 1994, pp. 307–321.

[6] W. Roether, V. Roussenov, and R. Well, A tracer study of the thermohaline circulation of the Eastern Mediterranean, in Ocean Processes in Climate Dynamics: Global and Mediterranean Examples, Vol. 419, P. Malanotte-Rizzioli and A.R. Robinson, eds., Kluwer Academic Publishers, The Netherlands, 1994, pp. 371–394.

[7] M.I. Pollak, The sources of deep water in the Eastern Mediterranean sea, J. Mar. Res. 10 (1951), pp. 128–152.

[8] M. Canals, R. Danovaro, S. Heussner, V. Lykousis, P. Puig, F. Trincardi, A.M. Calafat, X. Durrieu de Madron, A. Palanques, and A. Sánchez-Vidal, Cascades in Mediterranean Submarine Grand Canyons, Oceanography. 22 (1) (2009), pp. 26–43.

[9] J.N. Nielsen, Hydrography of the Mediterranean and Adjacent Waters in Report of the Danish Oceanographic Expedition 1908–1910 to the Mediterranean and Adjacent Waters, Copenhagen. I (1912), pp. 72–191.
[10] I.M. Ovchinnikov and A.F. Fedoseyev, The Horizontal Circulation of the Water of the Mediterranean Sea during the Summer and Winter Seasons, in Basic Features of the Geological Structure, Hydrological Regime and Biology of the Mediterranean, L.M. Fomin, ed., Translation of the Institute for Modern Languages for the USN Oceanography Office, 1965, pp. 185–201.
[11] L.M. Ovchinnikov, Circulation in the surface and intermediate layers of the Mediterranean, Oceanology. 6 (1966), pp. 48–59.
[12] G. Wust, On the vertical circulation of the Mediterranean Sea, J. Geophys. Res. 66 (1961), pp. 3261–3271.
[13] P. La Violette, The Western Mediterranean Circulation Experiment (WMCE): Introduction, J. Geophys. Res. 95 (1990), pp. 1511–1514.
[14] C. Millot, Circulation in the Western Mediterranean Sea, Oceanol. Acta. 10 (1987a), p. 143.
[15] C. Millot, The circulation of the Levantine Intermediate Water in the Algerian Basin, J. Geophys. Res. 92 (1987), p. 8265.
[16] C. Millot, Mesoscale and seasonal variabilities of the circulation in the Western Mediterranean, Dyn. Atmos. Oceans. 15 (1991), pp. 179–215.
[17] C. Millot, Circulation in the Western Mediterranean Sea, J. Mar. Systems. 20 (1999), pp. 423–444.
[18] C. Millot and I. Taupier-Letage, Circulation in the Mediterranean Sea, Handbook Environ. Chem. 5 (K) (2005), pp. 29–66.
[19] J.P. Béthoux, X. Durrieu de Madron, F. Nyyfeler, and D. Tailliez, Deep water in the western Mediterranean: peculiar 1999 and 2000 characteristics, shelf formation hypothesis, variability since 1970 and geochemical inferences, J. Mar. Sys. 33–34 (2002), pp. 117–131.
[20] C. Dufau-Julliand, P. Marsaleix, A. Petrenko, I. Dekeyser, Three-dimensional modeling of the Gulf of Lion’s hydrodynamics (north-west Mediterranean) during January 1999 (MOOGLI3 Experiment) and late winter 1999: Western Mediterranean Intermediate Water’s (WIW’s) formation and its cascading over the shelf break, J. Geophys. Res.-Oceans 109 Art. No. C11002 (2004).
[21] J.-M. Pinot and A. Ganachaud, The role of winter intermediate waters in the spring-summer circulation of the Balearic Sea 1. Hydrography and inverse box modeling, J. Geophys. Res. 104 (1999), pp. 29843–29864.
[22] M. Rhein, U. Send, B. Klein, and G. Krahmann, Interbasin deep water exchange in the western Mediterranean, J. Geophys. Res. 104 (C10) (1999), pp. 23495–23508.
[23] C. Bouzinac, J. Font, and C. Millot, Hydrology and currents observed in the channel of Sardinia during the PRMO-I experiment from November 1993 to October 1994, J. Mar. Sys. 20 (1999), pp. 333–355.
[24] R. Onken and J. Sellschopp, Water masses and circulation between the eastern Algerian Basin and the Strait of Sicily in October 1996, Oceanol. Acta. 24 (2) (2001), pp. 151–166.
[25] A. Vetrano, G.P. Gasparini, R. Molcard, and M. Astraldi, Water flux estimates in the central Mediterranean Sea from an inverse box model, J. Geophys. Res. 109 (2004), p. C01019.
[26] J.P. Béthoux, Mean water fluxes across sections in the Mediterranean Sea, evaluated on the basis of water and salt budgets and of observed salinities, Oceanol. Acta. 3 (1) (1980), pp. 79–88.
[27] K. Schroeder, V. Taillandier, A. Vetrano, and G.P. Gasparini, The circulation of the Western Mediterranean Sea in spring 2005 as inferred from observations and from model outputs, Deep Sea Res. Part I. 55 (2008), pp. 947–965.
[28] C. Wunsch and J.-F. Minster, Methods for box models and ocean circulation tracers: Mathematical programming and non-linear inverse theory, J. Geophys. Res. 87 (1982), pp. 5647–5662.
[29] C. Wunsch, An eclectic Atlantic Ocean circulation model. Part I: The meridional flux of heat, J. Phys. Oceanogr. 14 (1984), pp. 1712–1733.
[30] A.M. Macdonald and C. Wunsch, An estimate of global ocean circulation and heat fluxes, Nature. 382 (1996), pp. 436–439.
[31] J.C. De Munck, *A comparison of methods to determine mass transports from hydrographic measurements*, Am. Meteorol. Soc. 27 (1997), pp. 1635–1653.

[32] A. Ganachaud and C. Wunsch, *The oceanic meridional overturning circulation, mixing, bottom water formation and heat transport*, Nature. 408 (2000), pp. 453–457.

[33] K. Schroeder, Ribotti, Borghini, Sorgente, Perilli, G.P. Gasparini, *An extensive western Mediterranean deep water renewal between 2004 and 2006*, Geophys. Res. Lett. 35, L18605, doi:10.1029/2008GL035146, (2008b).

[34] G.P. Gasparini, A. Ortona, G. Budillon, M. Astraldi, and E. Sansone, *The effect of the Eastern Mediterranean Transient on the hydro-graphic characteristics in the Strait of Sicily and in the Tyrrenian Sea*, Deep-Sea Res. Part I – Oceanographic Res. Papers. 52 (6) (2005), pp. 915–935.

[35] K. Schroder, G.P. Gasparini, M. Tangherlini and M. Astraldi, *Deep and intermediate water in the western Mediterranean under the influence of the Eastern Mediterranean Transient*, Geophys. Res. Lett. 33 (2006), L21607, 10.1029/2006GL027121.

[36] J.-L. Lopez-Jurado, C. Gonzalez-Pola and P. Ve`lez-Belchi, *Observation of an abrupt disruption of the long-term warming trend at the Balearic Sea, western Mediterranean Sea, in summer 2005*, Geophys. Res. Lett. 32 (2005), L24606, 10.1029/2005GL024430.

[37] H. Stommel, H. Bryden, and P. Mangelsdorf, *Does some of the Mediterranean outflow come from great depth?*, Pure Appl. Geophys. 105 (1973), pp. 879–889.

[38] T.H. Kinder and G. Parrilla, *Yes, some of the Mediterranean out-flow does come from great depth*, J. Geophys. Res., 92 (C3) (1987), pp. 2901–2906.

[39] A. Lascaratos, W. Roether, K. Nittis, and B. Klein, *Recent changes in deep water formation and spreading in the Mediterranean Sea: a review*, Progr. Oceanogr. 44 (1999), p. 36.

[40] A.R. Robinson, M. Golnaraghi, N. Leslie, A. Artegiani, A. Hecht, E. Lazzone, A. Michelato, E. Sansone, A. Theocharis, and U. Unluata, *Structure and Variability of the Eastern Mediterranean general circulation*, Dyn. Atmos. Oceans. 15 (1991), pp. 215–240.

[41] A.R. Robinson and M. Golnaraghi, *The physical and dynamical oceanography of the Mediterranean Sea in Ocean processes, in Climate dynamics: Global and Mediterranean Examples*, Vol. 419, P. Malanotte-Rizzoli and A.R. Robinson, eds., Kluwer Academic Publishers, The Netherlands, 1993, pp. 255–306.

[42] P. Malanotte-Rizzoli, B. Manca, M. Ribera d’Alcala’, A. Theocharis, A. Bergamasco, D. Bregant, G. Budillon, G. Civitaressi, D. Georgopoulos, A. Michelato, E. Sansone, P. Scarazzato, and E. Souvermezoglou, *A synthesis of the Ionian hydrography, circulation and water mass pathways during POEM-Phase I*, Progr. Oceanogr. 39 (1997), pp. 153–204.

[43] G. Larnicol, P.Y. LeTraon, N. Ayoub, and P. DeMey, *Mean sea level and surface circulation variability of the Mediterranean Sea from 2 years of TOPEX/Poseidon altimetry*, J. Geophys. Res. 100 (1995), pp. 25, 163–25, 177.

[44] W. Roether and R. Schlitzer, *Eastern Mediterranean deep water renewal on the basis of chlorouroluoromethane and tritium data*, Dyn. Atmos. Oceans. 15 (1991), pp. 333–354.

[45] W. Roether, B. Manca, B. Klein, D. Bregant, D. Georgopoulos, V. Beitzel, V. Kovacevic, and A. Luchetta, *Recent changes in Eastern Mediterranean deep waters*, Science. 271 (1006), pp. 333–335.

[46] P. Malanotte-Rizzoli, B. Manca, M. Ribera d’Alcala’, A. Theocharis, S. Brenner, G. Budillon, and E. Ozsoy, *The Eastern Mediterranean in the 80s and the 90s: the big transition in the intermediate and deep circulations*, Dyn. Atmos. Oceans. 29 (1999), pp. 365–395.

[47] B. Klein, W. Roether, B. Manca, D. Bregant, V. Bitzel, V. Kovacevic, and A. Luchetta, *The large deep water transient in the Eastern Mediterranean*, Deep-Sea Res. 46 (1999), pp. 371–414.

[48] A. Theocharis, K. Nittis, H. Kontoyiannis, E. Papageorgiou, and E. Balopoulos, *Climatic changes in the Aegean Sea influence in the Eastern Mediterranean thermohaline circulation*, Geophys. Res. Lett. 26 (1999), pp. 1617–1620.

[49] V. Zervakis, D. Georgopoulos, and P.G. Drakopoulos, *The role of the North Aegean in triggering the recent Eastern Mediterranean climatic changes*, J. Geophys. Res. 105 (2000), pp. 103–26, 116.
[50] S.L. Samuel, K. Haines, S.A. Josey, and P.G. Myers, *Response of the Mediterranean Sea thermohaline circulation to observed changes in the winter wind stress fielding the period 1980–93*, J. Geophys. Res. 104 (1999), pp. 5191–5210.

[51] LIWEX Group, *The Levantine Intermediate Water Experiment (LIWEX) group: Levantine basin, a laboratory for multiple water mass formation processes*, J. Geophys. Res. 198, doi:10.1029/2002JC001643, (2003).

[52] R. Boscolo and H.L. Bryden, *Causes of long-term changes in Aegean Sea deep water*, Oceanol. Acta. 24 (2001), pp. 519–527.

[53] N. Skliris and A. Lascaratos, *Impacts of the Nile river damming on the thermohaline circulation and water mass characteristics of the Mediterranean sea*, J. Mar. Systems. 52 (2004), pp. 121–143.

[54] M.N. Tsimplis and S.A Josey, *Forcing of the Mediterranean Sea by atmospheric oscillations over the North Atlantic*, Geophys. Res. Lett. 28 (2001), pp. 803–806.

[55] G.L.E. Borzelli, M. Gacic, V. Cardin and G. Civitarese, *Eastern Mediterranean Transient and reversal of the Ionian Sea circulation*, Geophys. Res. Lett. 36, Doi: 101029/2009GL039261, (2009).

[56] M. Gacic, G. Civitarese, G.L.E. Borzelli, V. Cardin and S. Yarui, *Can deep water thermohaline properties shape the upper-layer circulation? The Adriatic-Ionian example*, Science (2009), submitted.

[57] IPCC (Intergovernmental Panel for Climate Change), in *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Core Writing Team, R.K. Pachauri and A. Reisinger, eds., IPCC, Geneva, Switzerland, 2007, p. 104.

[58] P. Alpert, S.O. Krichak, H. Shafir, D. Haim, and I. Osetinsky, *Climatic trends to extremes employing regional modeling and statistical interpretation over the E Mediterranean*, Glob Planet Change. 63 (2008), pp. 163–170.

[59] R.M. Trigo, E. Xoplaki and E., Zorita, *Relationship between variability in the Mediterranean region and mid-latitude variability*, in: Mediterranean Climate Variability, Elsevier B. V., 2006, pp. 179–226.

[60] P., Lionello, U. Boldrin and F. Giorgi, *Future changes in cyclone climatology over Europe as inferred from a regional climate simulation*, Clim. Dyn. DOI: 10.1007/s00382-007-0315-0, (2007)