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The Eastern Mediterranean in the 80s and in the 90s: the big transition in the intermediate and deep circulations

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Abstract

We present definitive observational evidence that the startling change of the Eastern Mediterranean deep circulation observed in winter 1995 and documented by [Roether, W., Manca, B.B., Klein, B., Bregant, D., Georgopoulos, D., Beitzel, V., Kovacevich, V., Luchetta, A., 1996. Recent changes in the Eastern Mediterranean deep water. Science 271, 333–335.] actually started before October 1991. This change involved not only the deep water mass pathways but also the origin and pathways of the water mass spreading in the intermediate layer. We carry out the first unified analysis of the POEMBC-O91 data set, which shows that, differently from the previous decade of the 80s, the Cretan/Aegean Sea was in 1991 the 'driving' engine of the intermediate, transitional and deep layer circulations, with Cretan Intermediate Water (CIW), transitional water and Cretan Deep Water (CDW) spreading out from the Cretan Sea into the basin interior. The most important new results are: (a) the Levantine Intermediate Water (LIW) formed inside or at the periphery of

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the Rhodes gyre is blocked in its traditional westbound route on its density horizons $\sigma_\theta = 29.05$ and 29.10 kg/m^3 by a three-lobe strong anticyclonic structure in the Southern Levantine, which induces a substantial LIW recirculation in the Levantine basin itself; (b) the CIW exiting from the Western Cretan Arc Straits spreads into the Ionian interior on the $\sigma_\theta = 29.05$–29.10 kg/m^3 isopycnal surfaces, thus replacing the LIW confined in the Levantine basin. A branch of CIW flows eastward in the Cretan passage and is entrained by the Ierapetra anticyclone to flow again into the Cretan Sea through the Eastern Cretan Arc Straits; (c) on the horizons $\sigma_\theta = 29.15$ and 29.18 kg/m^3 a transitional water mass of Cretan origin, denser than CIW, and CDW are observed to spread out massively from the Cretan Arc Straits both into the Ionian and Levantine interiors. These isopycnal surfaces rise to much shallower depths in 1991 than in 1987, increasing the salt content of the intermediate, transitional and deep layers. This leads to a massive salt increase in the Ionian below 1200 m, clearly related to lateral advection of the new denser waters of Cretan/Aegean origin, thus contradicting the hypothesis of a vertical salt redistribution proposed by Roether et al.

Keywords: Transition; Eastern Mediterranean; Circulation

1. Introduction

During the last decade, the Eastern Mediterranean has been the subject of very intensive research coordinated by the international collaborative programme POEM (Physical Oceanography of the Eastern Mediterranean) sponsored by UNESCO, IOC and the sponsoring agencies of each participating country (Malanotte-Rizzoli and Robinson, 1988). Under this programme, a series of coordinated hydrographic surveys was carried out by the R/V of Greece–Israel–Italy and Turkey in the period 1985–1987, culminating in POEM-AS87 in which the German 'Meteor' conducted a basin-wide CTD and transient tracer survey (Roether and Schlitzer, 1991). The observational data set collected in these surveys was intercalibrated, pooled and distributed to all the participating scientists in a series of UNESCO sponsored workshops. The joint analysis and interpretation led first to a group paper summarizing the new findings that included extended modeling results (POEM Group, 1992). Successively, a special issue of Deep-Sea Research was devoted to this phase of POEM (Robinson and Malanotte-Rizzoli, 1993).

These studies definitively established the Eastern Mediterranean as being characterized by three predominant scales interacting in the general circulation pattern: the basin-scale, the sub-basin scale and the mesoscale.

The basin-scale thermohaline circulation is composed of two cells. The first one is the closed internal cell of the deep circulation comprising the Ionian and Levantine basins. In the period 1985–1987, this closed, deep thermohaline cell, the Eastern Mediterranean 'conveyor belt', was shown to be driven by the deep water of Southern Adriatic origin, which becomes the Eastern Mediterranean Deep Water (EMDW) reaching the Levantine basin with a renewal time of ~ 126 years (Roether and Schlitzer, 1991; Schlitzer et al., 1991; Roether et al., 1994). The external thermohaline cell involves the exchange of water between the Eastern and the Western Mediterranean and the North Atlantic ocean, with Atlantic Water (AW) entering into the Gibraltar Straits, moving eastward and spreading from the Sicily Straits throughout the Eastern Mediterranean as Modified Atlantic Water (MAW) confined in a surface layer ~200 m thick. Simultaneously, Levantine Intermediate Water (LIW) formed mainly in the northeastern Levantine flows westward in an intermediate layer between ~200 and ~600 m, finally exiting into the Northern Atlantic Ocean.

The building blocks of the Eastern Mediterranean upper thermocline circulation are sub-basin scale gyres and permanent, or quasi-permanent, cyclonic and anticyclonic structures interconnected by intense jets and meandering currents. Recently, the entire data set of the first phase of POEM has been revisited for the Ionian sea with an in-depth reanalysis that has led to important new findings (Malanotte-Rizzoli et al., 1997). These include the first detailed definition of the upper thermocline circulation in the Ionian sea, with the discovery of the strong Mid-Ionian Jet (MIJ) crossing the basin interior in north/south direction and then becoming the Mid-Mediterranean Jet (MMJ); and the first definition of the pathways of the LIW and of the EMDW.

In 1990, POEM evolved into POEM-BC (Biology and Chemistry) a fully interdisciplinary programme, with the major overall objective of establishing the phenomenology of the 90s for the chemical and biological parameters together with a reassessment of the phenomenology of the physical properties, contrasted to that of the 80s (POEM-Phase 1). The first interdisciplinary general survey of the entire basin was carried out in October 1991, POEMBC-O91, followed by a more restricted survey in March 1992 and a final overall survey by the R/V Meteor (Germany) in January 1995 with a second CTD and transient tracer basin-wide network of stations. The latter was part of the preconditioning phase of the LIW experiment followed by the successive phases of the LIW formation and spreading concentrated in the Northern Levantine during the following months, February through April 1995 (Malanotte-Rizzoli et al., 1996). The analysis of the data collected during the Meteor survey, including the transient tracer observations, revealed a very important change in the deep thermohaline circulation. Specifically, in 1987, the driving engine of the closed thermohaline cell was the Southern Adriatic, where deep convention leads to the formation of the Adriatic Deep Water (ADW) that, exiting from the Otranto Straits, becomes EMDW and spreads throughout the Eastern Levantine in the bottom layer. General upwelling to the intermediate transitional layer (below 1000 m) provides the return pathways to the Southern Adriatic closing the cell (Roether and Schlitzer, 1991). In winter 1995, the situation was completely different: the engine of the deep thermohaline circulation was the Aegean Sea, with denser water masses that, exiting from the Cretan Arc Straits, spread throughout the entire basin and push to the west in the Ionian Sea and to the east in the Levantine basin the less dense EMDW of Southern Adriatic origin (Roether et al., 1996).

We present here the first observational evidence that this dramatic change in the Eastern Mediterranean deep circulation actually started before 1991 and involved not only the deep water masses but the intermediate ones as well, specifically the origin and pathways of the water masses of the intermediate layer, i.e., the Cretan Intermediate Water (CIW), and the traditional LIW. This evidence is based on the first unified analysis of the POEMBC-O91 general survey, carried out in October 1991 jointly by the

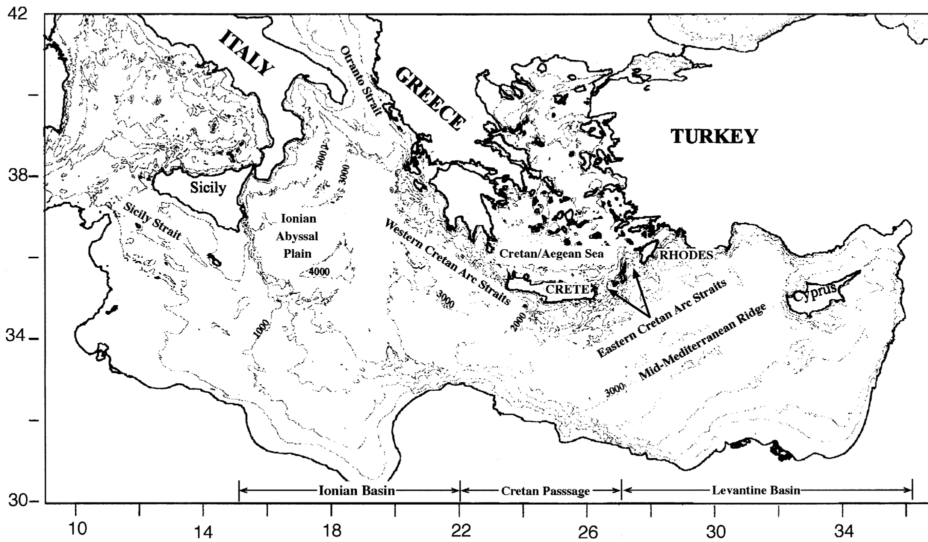


Fig. 1. Bathymetry of the Eastern Mediterranean Sea, showing the bottom topography in meters, the location of the major sub-basins, straits and passages.

R/V of Greece, Israel, Italy and Turkey. Fig. 1 shows the bathymetry and geography of the Eastern Mediterranean and Fig. 2 the overall network of hydrographic stations. The

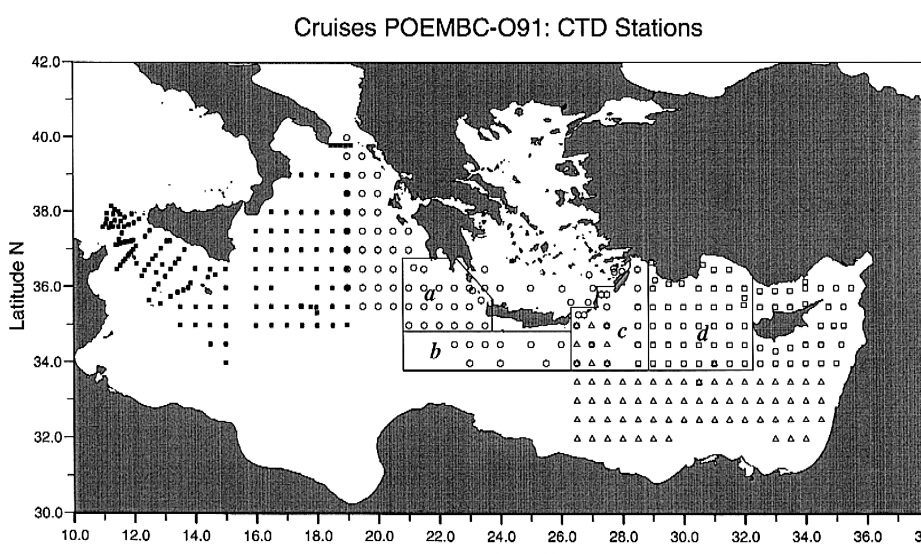


Fig. 2. Combined station network of the R/V of Greece (open circles), Israel (open triangles), Italy (black squares) and Turkey (open squares) surveys during POEMBC-O91. The four different regions are marked for which θ/S diagrams are constructed.

CTD casts carried out by Italy and Israel reached full depth, while the casts carried out by Greece and Turkey reached the maximum depth of 2000 and 1800 dbar, respectively. Two workshops were devoted to the intercalibration of the unified data set. The intercalibration confidence intervals were assessed as $\pm 0.02°C$ for temperature and 0.01 for salinity (POEM Scientific Report #10, 1996).

The analysis reveals first overall similarities in the upper thermocline circulation in the Ionian sea while important changes are evident in the Levantine basin. Specifically, this analysis shows a crucial difference between 1987 and 1991 in the intermediate and deep layers. In 1987, the LIW was formed in the proper Levantine basin, and entered the Ionian Sea through the Cretan passage south of Crete. A major branch proceeded directly to the Sicily Straits and successive branches were 'peeled-off' and veered northwards by the Ionian Anticyclones (IA) occupying the Ionian interior. This behavior was observed on all the isopycnal surfaces from 29.00 to 29.15 kg/m^3 (Malanotte-Rizzoli et al., 1997). On the other hand, as we show below, in 1991, all the water masses detected in the Ionian on the horizons 29.00 to 29.18 kg/m^3 are formed inside the Aegean Sea, and exiting from the Cretan Arc Straits, spread into the Ionian interior. A very strong three-lobe anticylonic structure is present in the Southern Levantine Basin, essentially blocking the traditional westward path of LIW.

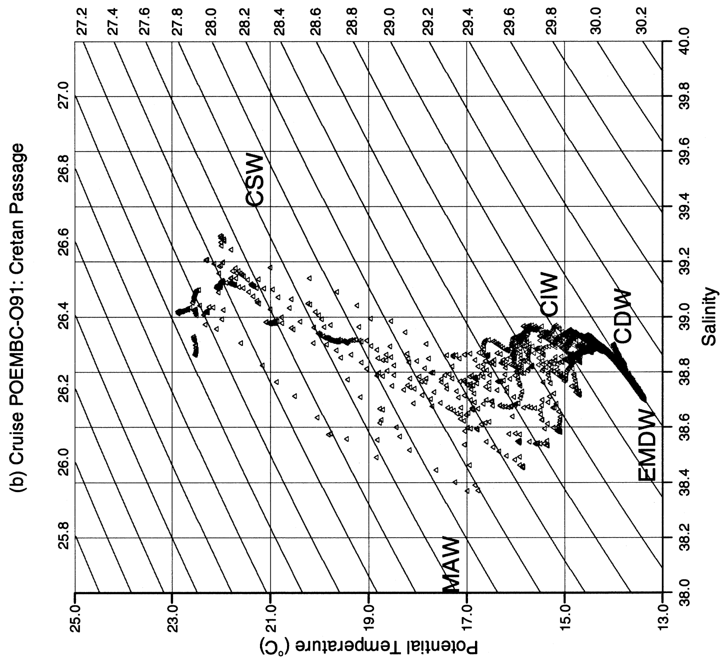
The paper is organized as follows. In Section 2, we discuss the water mass properties of the different regions of the basin in 1991 and their vertical distributions comparing them with the 1987 configuration. In Section 3, we discuss and compare the upper thermocline circulation patterns in 1991 vs. 1987, emphasizing similarities and differences. In Section 4, we document the change intervened between 1987 and 1991 in the intermediate and deep water mass pathways. We further discuss an interesting piece of evidence, i.e., the mixing and homogenization of the intermediate to deep layers of the Ionian interior, consistent with the hypothesis of a local inertial recirculation. Finally, in Section 5, we summarize the major novel results and conclusions of the present work.

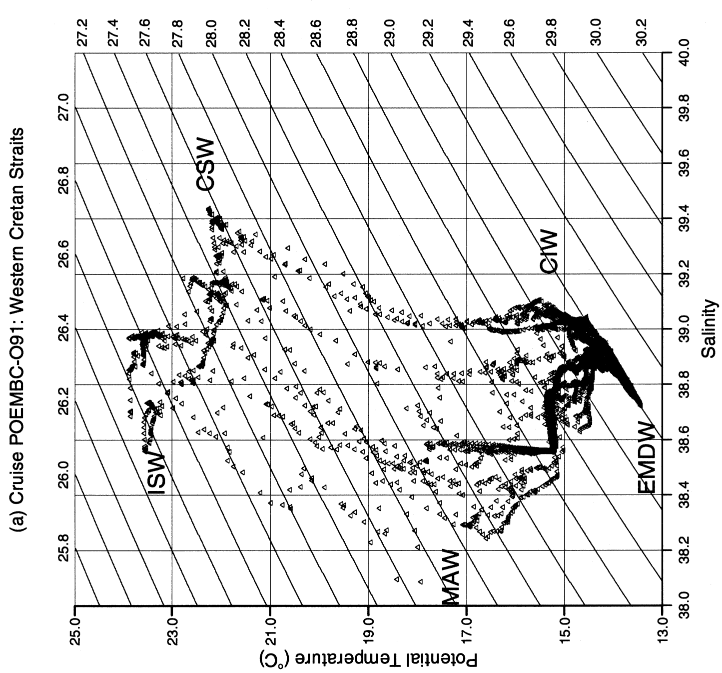
2. Water mass properties and vertical distributions

2.1. θ/S diagrams

To define the water mass properties and their major transformations during POEMBC-O91 we present potential temperature/salinity diagrams constructed separately for four different regions surrounding the Aegean Sea marked as a, b, c and d in Fig. 2, where the most important changes occurred with respect to POEM-AS87.

The first two diagrams are constructed for the western regions (a) and (b) of Fig. 2 characterized by an abundance of MAW and a subsurface salinity maximum. The diagrams are shown in Fig. 3a (Region a) and Fig. 3b (Region b) using the data for the Western Cretan Arc Straits and Cretan passage, respectively. Both regions are directly exposed to the Aegean water outflow. Water masses are marked in the diagrams. The water mass census in 1991 is very different from the 1987 situation, as the water masses


(b) Cruise POEMBC-O91: Cretan Passage
Potential Temperature (°C)
Salinity
CSW
CIW
CDW
EMDW
MAW


(a) Cruise POEMBC-O91: Western Cretan Straits
Potential Temperature (°C)
Salinity
ISW
CSW
CIW
EMDW
MAW

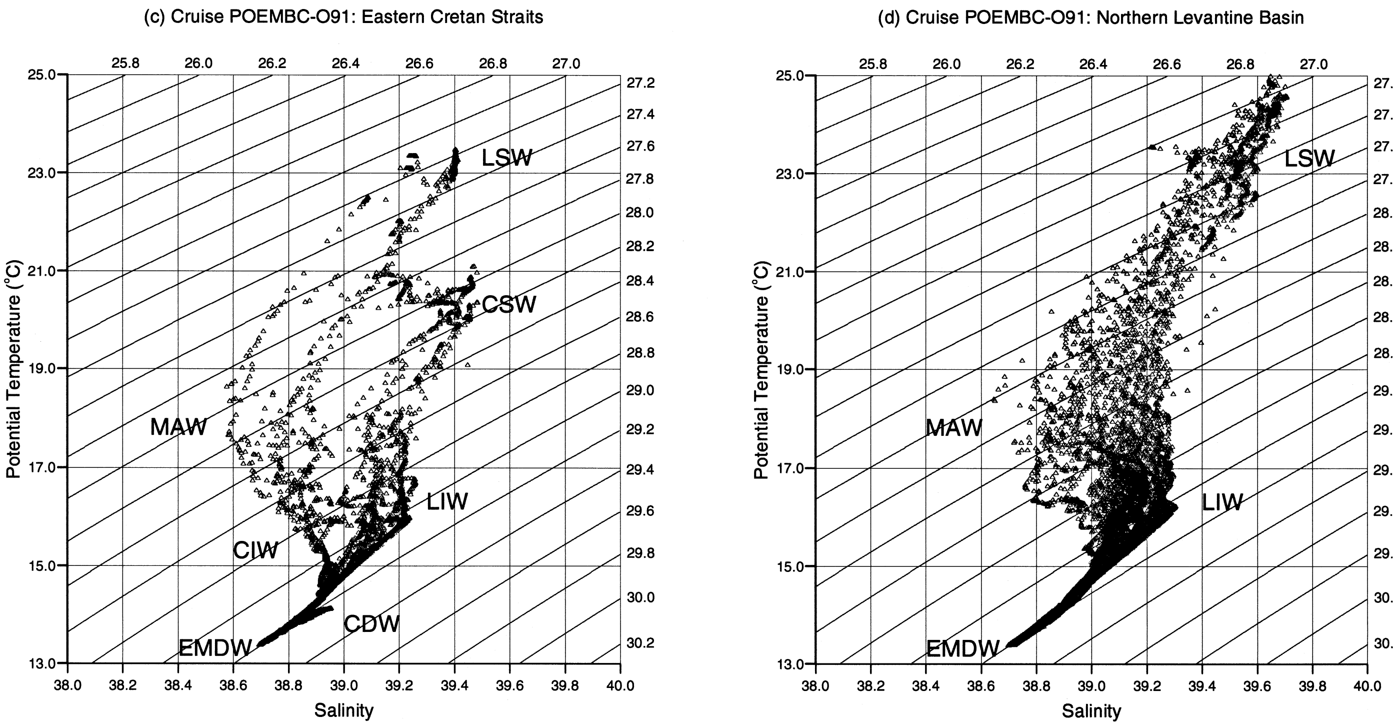


Fig. 3. Potential temperature–salinity relationships in the different regions of the Eastern Mediterranean shown in Fig. 2. (a) Western Cretan Straits, (b) Cretan passage, (c) Eastern Cretan Straits and (d) Northern Levantine Basin.

present in these regions are mostly of Cretan/Aegean sea origin. A new water mass classification is therefore required. The new water masses are the Cretan Surface Water (CSW), the CIW and the Cretan Deep Water (CDW). The Ionian Surface Water (ISW) occupies exclusively the surface layer of the Eastern Ionian. The CSW occupies a large area around the Western Cretan Arc Straits where it mixes with the ISW, warmer but less saline, in Region a of Fig. 2. The CSW can also be distinguished both in Regions a and b of Fig. 2. The MAW is detected by its salinity minimum ($S < 38.60$) in the subsurface layer, i.e., in the density range of $\sigma_\theta \cong 27.8$–28.8 kg m^{-3}. We point out that the MAW core inside the Sicily Strait has salinity values in the range 37.4–37.6 (practical salinity scale). It reaches the Eastern Ionian with $S \cong 38.3$–38.6 and undergoes a significant transformation in the Cretan passage reaching values in the range $S \cong 38.6$–38.8. Notice the disappearance of ISW from Region a, the Western Cretan Arc Straits, to Region b, the proper Cretan passage, by comparing the θ/S diagrams of Fig. 3a,b.

In the intermediate layer, i.e., in the potential density range $\sigma_\theta \cong 28.8$–29.15 kg m^{-3}, the maximum of salinity ($S > 38.90$) identifies CIW of Aegean origin. We use the term 'Intermediate' specifically with relationship to the depth the CIW occupies both inside the Aegean/Cretan sea (150–250 m) and outside in the Ionian sea (150–600 m), at the same depths as LIW, now replaced by this 'new' CIW. The CIW is less dense than the CDW and also less dense than the water of Aegean origin in the transitional layer (700–1200 m), sandwiched between CIW and CDW, which will be discussed in Section 4. The weak difference of the CIW properties from those of LIW may make it difficult to distinguish between them. However, the prevalent abundance of high salinity data points in the western Region a of Fig. 2 with respect to the Cretan passage (Region b) can be explained only by defining as the CIW core the larger pool of data points with $\theta \cong 14.5$–15.5°C and $S > 39.0$, while the proper LIW is found in Regions c and d. This interpretation is confirmed when examining the vertical distribution of properties in Section 2.2 and the horizontal distributions in Section 4.

Finally, the tail in the θ–S diagrams of Fig. 3a,b with uniform core properties of $\theta \cong 13.5$°C, $S \cong 38.70$ and $\sigma_\theta \cong 29.18$–$29.20$ kg m^{-3} clearly shows the presence of EMDW. Dense water with $\sigma_\theta > 29.20$, but with a considerable inversion towards higher temperature and salinity, is identified as CDW which outflows from the Aegean Sea to the outer region of the Western Cretan Straits.

The second group of diagrams (Fig. 3c,d) is related to the data of the stations located outside the Eastern Cretan Strait, Region c of Fig. 2, and in the Northern Levantine Basin Region d of Fig. 2. Notice the appearance of Levantine Surface Water (LSW) in the upper layer (S-$>$ 39.2), warmer ($\theta \cong 23$–25°C) than the CSW, the latter being equally salty but cooler ($\theta \cong 19$–21°C). In the intermediate layer water with LIW properties characteristic of the formation site is found ($\theta \cong 16$–17°C, $S = 39.0$–39.3 and $\sigma_\theta \cong 28.80$–$29.10$ kg m^{-3}). Notice the simultaneous presence of CIW and LIW in the θ/S diagram of Fig. 3c, corresponding to Region c of Fig. 2. The CSW and CIW disappear in the diagram of Fig. 3d, the easternmost Region d of Fig. 2, where only LSW and LIW are present. The transition from the Ionian sea to the Levantine basin through the Cretan passage is therefore marked in 1991 by the presence of the water masses of Aegean Sea origin, i.e., CSW, CIW and CDW. The bottom layer, however, is consistently filled by the densest EMDW. The presence of CDW in Region d could not be detected as the Turkish casts reached the maximum depth of 1800 dbar.

2.2. Vertical distribution of properties

The major water masses present in the Eastern Mediterranean during POEM-BCO91 were identified in the θ/S diagrams of Fig. 3a,b,c,d, with the Aegean/Cretan sea being identified as the site of origin of CSW, CIW and CDW. Vertical distributions of temperature and salinity are now analyzed to identify the dispersion pathways of these water masses and to compare them with the corresponding distributions during POEM-AS87. The section considered is oriented along the open thermohaline cell circulation as defined by Schlitzer et al. (1991), i.e., a West–East latitudinal section crossing the whole basin from the Sicily Strait to the Levantine basin. It is located along the main path of the MAW in its eastward spreading in the upper layer (0–200 m) and along the LIW movement in the opposite direction in the intermediate layer (200–800 m). It has been constructed using the CTD stations located along the southernmost latitudinal border at 35°N in the Ionian and along 34°N and 33.5°N in the Cretan Passage and Levantine basin, respectively. We analyze a further section North–South oriented, from the African coast to the eastern tip of Crete. The position of the sections is shown in the inset corresponding to the vertical distribution of the hydrographic properties.

Fig. 4 shows the vertical distributions of potential temperature (upper panel) and salinity (lower panel) along the West–East section crossing the whole basin for POEMBC-O91. The upper layer of the water column shows the connection between the upper thermocline circulation and the water masses distribution. The most important features are: (i) the spreading of MAW through the Central Ionian; (ii) the maximum salinity LIW ($S \sim 39.00$) stored in the core of an intense anticyclonic region in the Western Levantine; (iii) a diluted salty tongue ($S \approx 38.85$) which protrudes westward reaching the Maltese escarpment in the Ionian and flows over the sill of the Sicily Strait into the Western Mediterranean. The analogous distributions for POEM-AS87 are shown in Fig. 5, potential temperature (upper panel) and salinity (lower panel). The most important difference between Figs. 4 and 5 is given by the presence of the two strong anticyclones in the Levantine basin in 1991 (Fig. 4), quite evident in the deepening of isotherms and isohalines, that modify the water mass pathways. The first of this anticyclones is located south of Crete and will be identified in Section 3 as the Ierapetra gyre. These anticyclonic regions were completely missing in 1987, characterized by the traditional westward spreading of LIW from the site of origin, the Northern Levantine, in the intermediate layer with the isohaline 38.80 reaching the Sicily Straits, Fig. 5, lower panel (Malanotte-Rizzoli et al., 1997). In 1991, the anticyclones trap LIW diverting it into an eastward recirculation inside the Levantine basin. CIW is observed to exit from the Western Cretan Arc Straits and to spread westward into the Ionian and eastward in the northern side of the Cretan passage (see Section 4). Thus, the salty diluted tongue with $S = 38.85$ that reaches the Sicily Straits in 1991, lower panel of Fig. 4, is probably old LIW originated in previous years, possibly mixed with the more saline CIW (see Fig. 3a). This interpretation is reinforced by the confinement of all the isohalines with $S \geq 38.90$ (new LIW) to the region occupied by the anticyclones in 1991

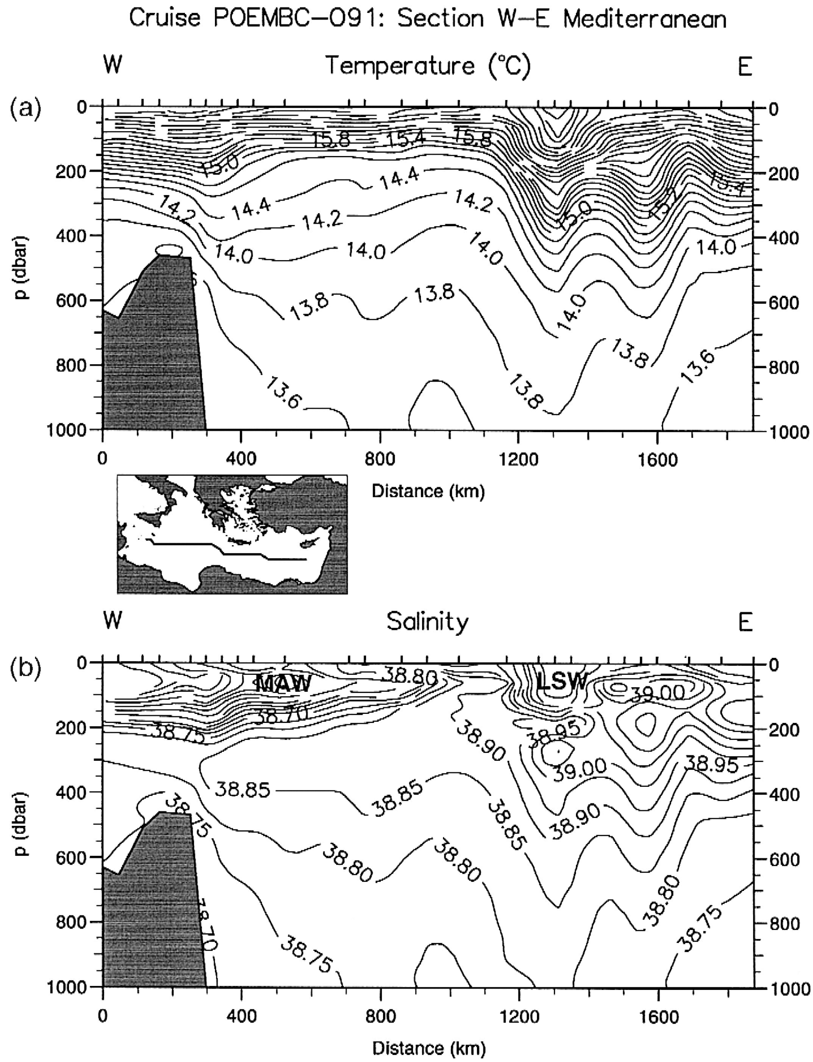


Fig. 4. Vertical distributions of properties down to 1000 dbar for the West–East section through the Eastern Mediterranean in 1991 (see inset map); (a) potential temperature and (b) salinity. The position of the stations is indicated by the ticks at the top.

(Fig. 4), while in 1987 the isohaline $S = 38.90$ extends much more westward (Fig. 5). This pattern will be definitively confirmed by the analysis of properties on isopycnal surfaces, Section 4. A further important feature is that in 1991, despite a major invasion of the Ionian Sea by the MAW occupying the upper 200 m layer, the MAW never reaches the Levantine basin, but is entrained inside the Ionian circulation, see the confinement inside the Ionian of the 38.70 isohaline and the front developed at the entrance of the Levantine basin occupied by the LSW, Fig. 4 lower panel. The different

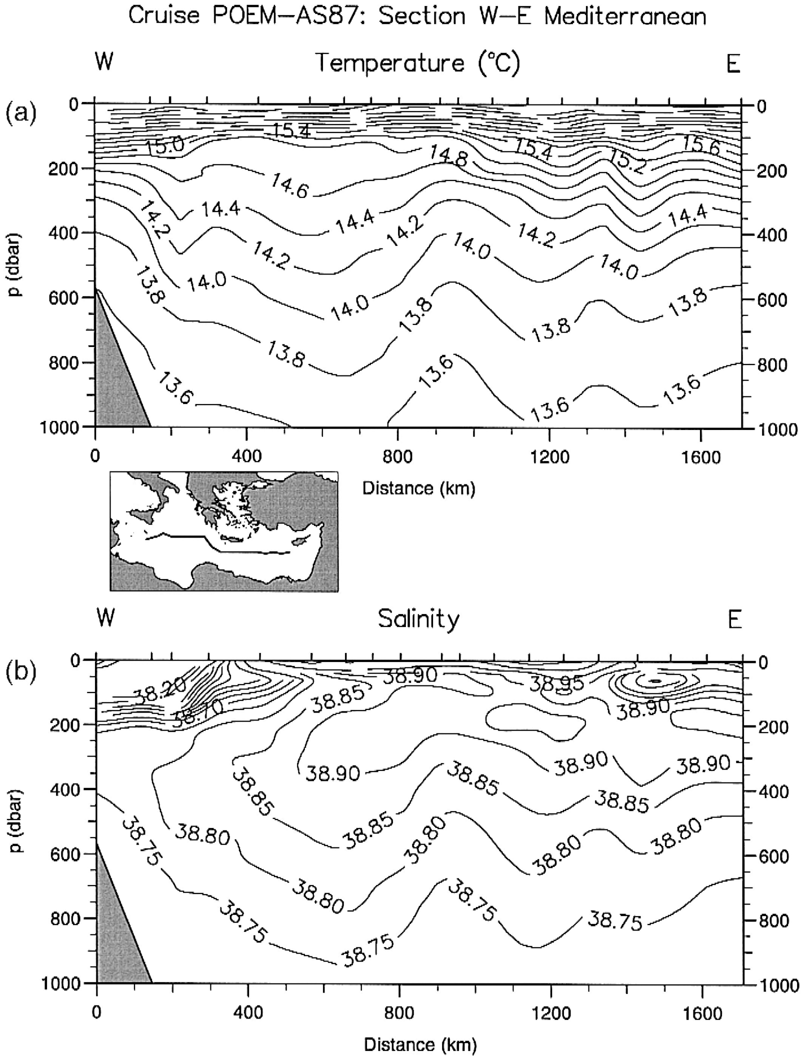


Fig. 5. As in Fig. 4, but for the survey in 1987.

penetration of MAW into the Ionian in 1987 and 1991 will be further discussed in Section 3.

Finally, in the POEMBC-O91 meridional section of Fig. 6, small packets of LIW core $(S \gtrsim 39.0)$ seem to be confined below the Ierapetra anticyclone following a westbound route in the southern side of the Cretan passage. The diluted patches $(S < 38.90)$ present south of the Ierapetra between 100 and 200 m (Fig. 6, lower panel) are probably patches of MAW spreading eastward. The upper layer of the central Cretan passage on the other side is occupied by a saltier water mass which will be shown to be

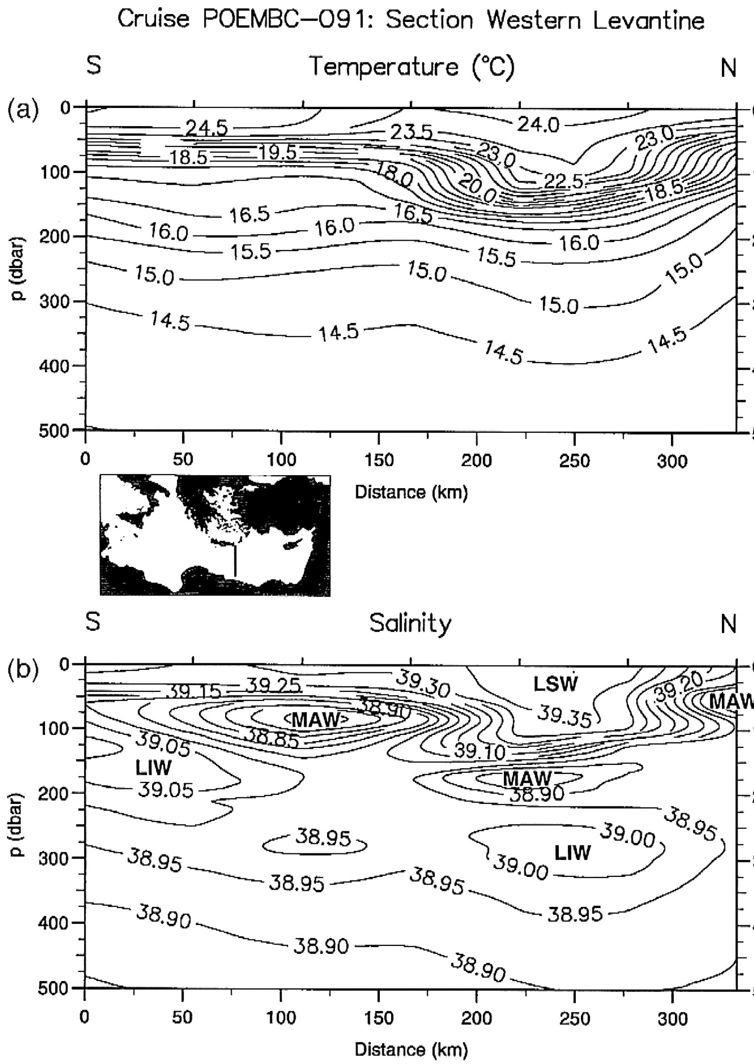


Fig. 6. Vertical distribution of properties down to 500 dbar for the meridional section on the Western Levantine basin, in 1991 (see inset map); (a) potential temperature and (b) salinity.

the LSW entrained by the Ierapetra gyre. These different water masses are marked in the lower panel of Fig. 6.

3. The upper thermocline circulations in 1991 and 1987

The first dynamic height anomaly map of 30 m with respect to 450 dynamic meters of the unified POEM-AS87 data set was carried out by Robinson et al. (1991) and is shown in Fig. 7a. Successively, the melding of the observations and model dynamics carried out by Robinson and Golnaraghi (1994) and the synthesis of observations reported in earlier POEM surveys (POEM Group, 1992; Ozsoy et al., 1992, 1993) has led to the schematic representation of the upper thermocline circulation shown in Fig. 7b. In the Levantine basin, a series of permanent and semipermanent structures can be unambiguously identified. Prominent features in the Levantine basin are the cyclonic Rhodes and West Cyprus gyres, the anticyclonic Mersa–Matruh gyre, the MMJ and the Shikmona eddy south of Cyprus.

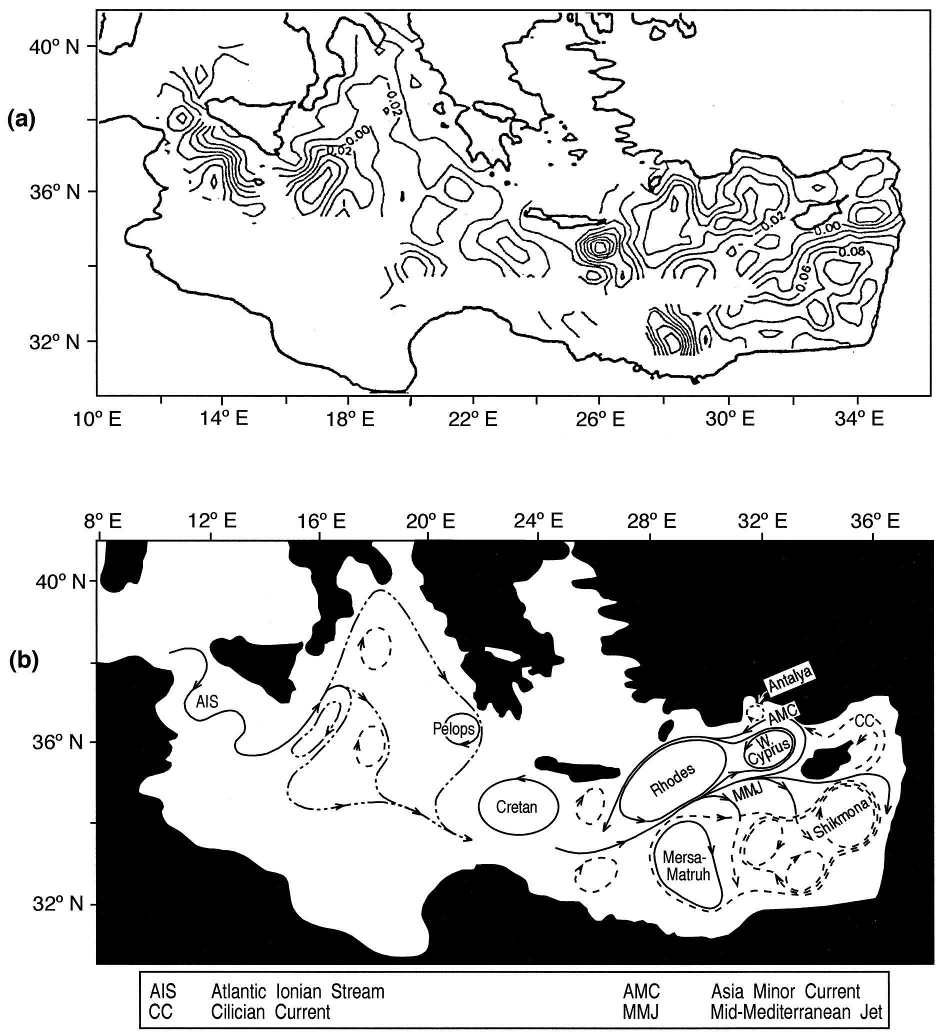


Fig. 7. (a) Dynamic height anomaly (dm) at 30 m with reference to 450 m during the POEM-AS87 survey (from Robinson et al., 1991); (b) schematic upper thermocline general circulation obtained melding the observations and model dynamics (from Robinson and Golnaraghi, 1994).

The upper thermocline circulation of the Ionian Sea on the other hand was not fully resolved by the above studies. Malanotte-Rizzoli et al. (1997) revisited the first phase of the POEM hydrographic data set with a thorough in-depth analysis. The upper thermocline circulation is shown in Fig. 8a (Fig. 18d of Malanotte-Rizzoli et al., 1997), i.e., the dynamic height anomaly of the surface with respect to 250 dbar. The path of LSW is marked in Fig. 8a.

The re-analysis of the complete 1986–87 data set has led to the scheme of the upper thermocline circulation in the Ionian Sea presented in Fig. 8b with nomenclature given for the major structures (from Malanotte-Rizzoli et al., their Fig. 24a). The major novel results that emerged from this study with respect to the previous knowledge can be summarized as follows.

(a) In the near surface layer, the MAW entering through the Sicily Straits is advected by the strong AIS, which forms a broad meandering jet in the Ionian Sea interior. The AIS–MAW jet bifurcates at ∼17°E, 37°N into two main branches. One branch turns directly south towards the African coast enclosing an overall anticyclonic area with multiple centers, the Ionian Anticyclones (IA), advecting MAW along its route.

(b) The second AIS branch protrudes into the northeastern Ionian advecting the MAW up to 39°N. It then turns southward to cross the entire Ionian Sea meridionally, thus forming the MIJ which advects southward the MAW on its right side and ISW on its left. It finally turns to the east at 20–22°E and enters the Cretan passage becoming the MMJ. North of it, LSW emerges from the Cretan passage, and is veered first by the Cretan cyclone (CC) south of Crete and successively anticyclonically around the Pelops gyre, then entering the Cretan Sea.

(c) The Cretan cyclone south of Crete is confined to the upper thermocline and disappears at ∼400 dbar.

(d) The Pelops anticyclone, differently from the schematic representation of Fig. 7b, is as intense as the Cretan cyclone, and is strongly barotropic below the upper 100 dbar layer, penetrating down to 800 dbar.

In Fig. 9a and b, we show the dynamic height anomaly of the surface with respect to 250 dbar and to 800 dbar, respectively, for the POEMBC-O91 survey. We emphasize the strong similarities between the two maps, clear evidence that the upper thermocline circulation is determined by the strong current and sub-basin gyres of the upper ∼250 m layer. Features that appear very intense both in Fig. 9a and b have a strong barotropic component and penetrate below the 250 dbar level. They will emerge quite strong in the dynamic height anomaly of the 250 and 400 dbar horizons with respect to 800 dbar, discussed in Section 4. Interesting similarities and differences emerge in the comparison between Fig. 9a,b for POEMBC-O91 and the previous Fig. 7a,b and Fig. 8a,b for POEM-AS87. We discuss them separately for the two sub-basins, the Ionian Sea and the Levantine basin communicating through the Cretan channel.

The comparison of Fig. 8a and Fig. 9a shows similar features in the upper thermocline circulation in the Ionian basin, as depicted by the scheme of Fig. 8b, but with the caveat that the currents and anticyclonic features are all intensified. The following changes may be recognized. (a) The AIS and MIJ are strong and more clearly defined in 1991 compared to 1987. The AIS meanders in the Sicily Strait and intrudes into the Ionian after the bifurcation at the southernmost tip of Sicily. It seems to enclose an

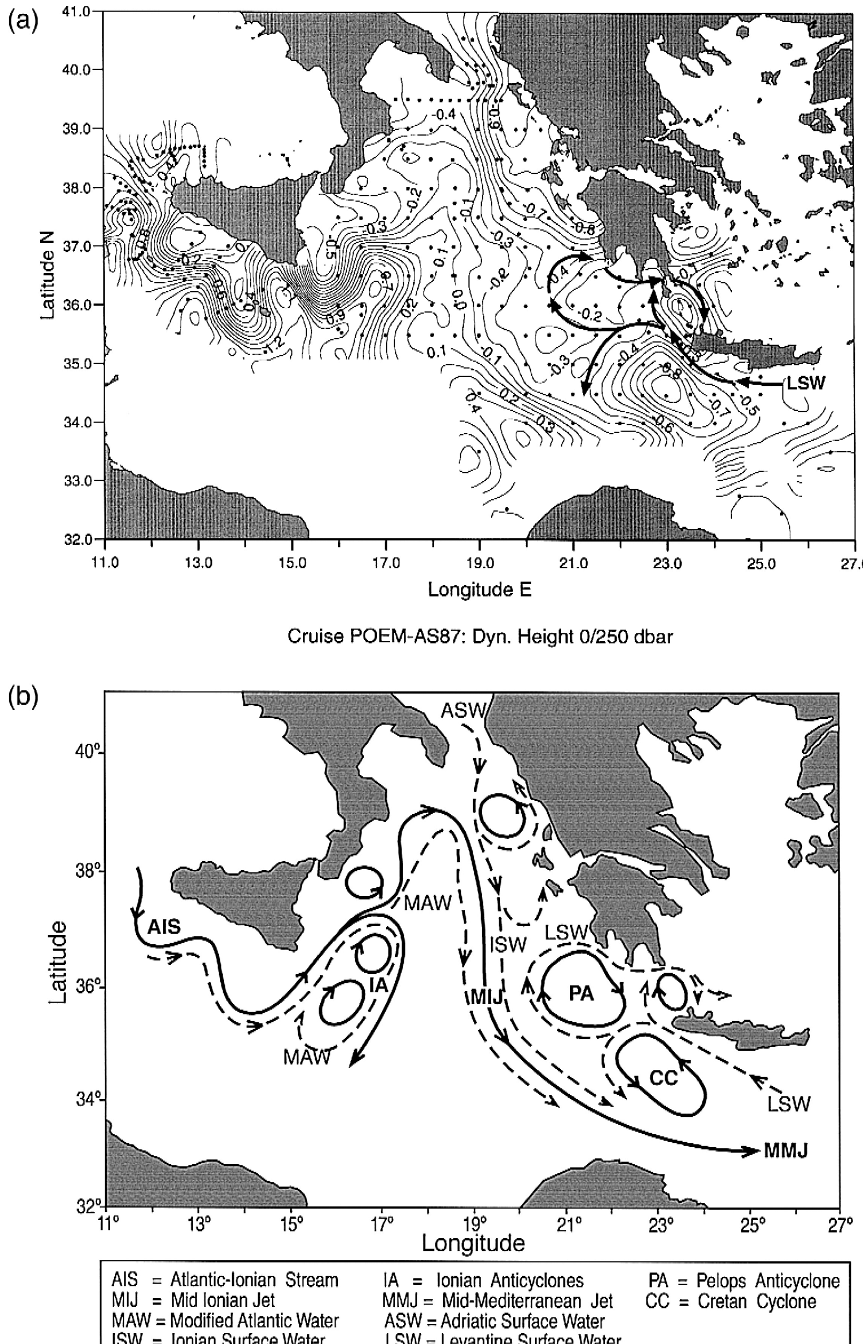
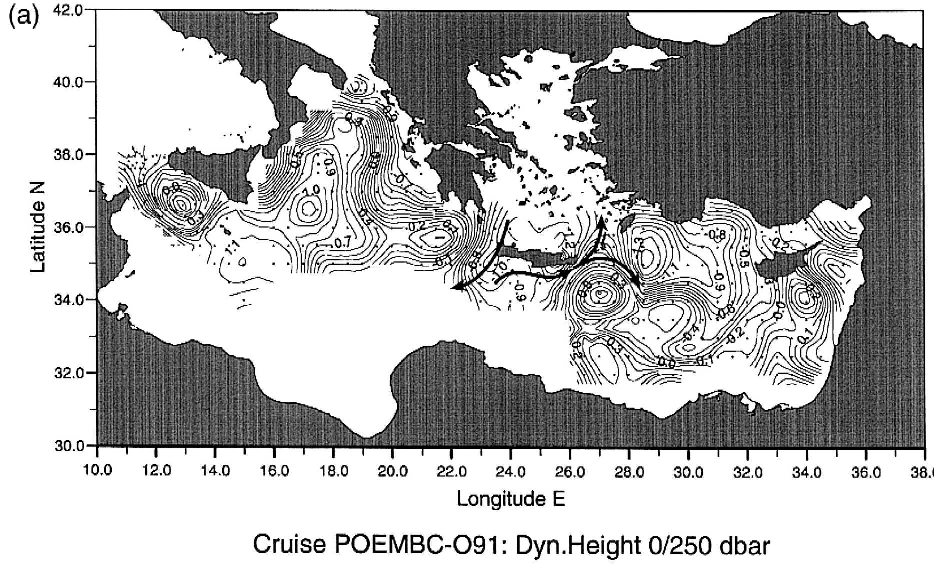


Fig. 8. (a) Dynamic height anomaly (m^2/s^2) of the surface with reference to 250 dbar for 1997 survey (from Malanotte-Rizzoli et al., 1997); (b) schematic representation of the upper thermocline general circulation in 1987 (from Malanotte-Rizzoli et al., 1997).



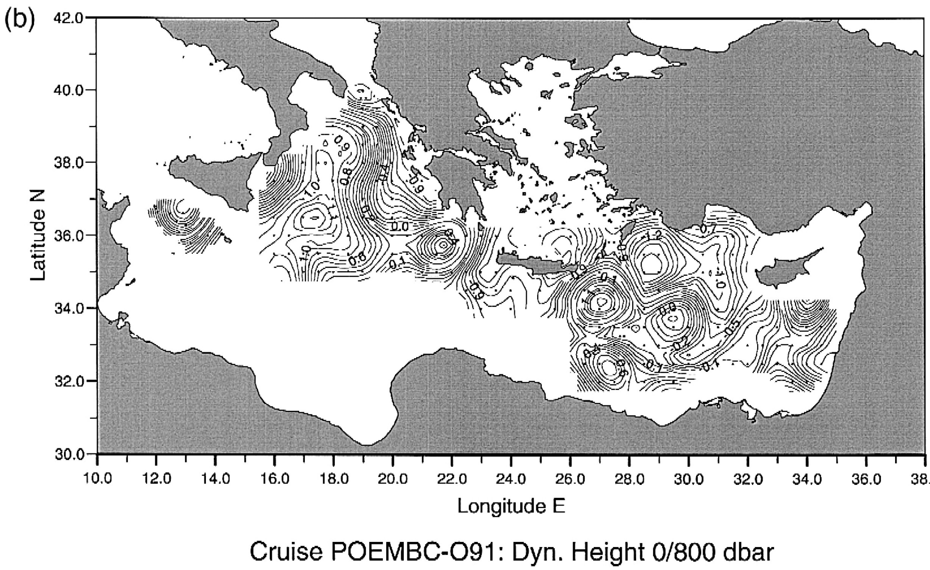


Fig. 9. (a) Dynamic height anomaly (m^2/s^2) of the surface with reference to 250 dbar in 1991; (b) dynamic height anomaly (m^2/s^2) of the surface with reference to 800 dbar.

anticyclonic gyre centered at 15°E, 35°N not resolved by the station network in 1987. The AIS jet protrudes into the northeastern Ionian and bifurcates again at 17°E, 38°N. One branch reaches the southern mouth of the Adriatic Sea, then turns to the south becoming the MIJ enclosing a broader anticyclonic region much more intense than in 1987. This anticyclonic region comprises the Ionian Anticyclones. (b) In 1991, the MIJ encircles the Pelops gyre advecting the ISW which merges with the CSW outflowing from the Western Cretan Arc Straits. (c) The Pelops anticyclone is also surface intensified, broader and stronger in 1991 with respect to 1987. (d) The Cretan cyclone, on the other hand, south and west of Crete is much smaller in 1991, with a weak signature that disappears completely in the dynamic height anomaly of the 250 dbar surface (Fig. 11a). Trajectories of surface drifters dropped in the Sicily Straits and at the conjunction with the Tyrrhenian Sea in the first half of the 90s and tracked by satellite confirm the presence of the strong northward meander of the AIS and the equally strong MIJ throughout the early 90s (Poulain, personal communication and Poulain, 1998).

Some features of the Levantine circulation, such as the northern cyclonic Rhodes gyre and the Shikmona eddy south of Cyprus, were similar in 1987 and 1991. However, some important differences emerge in the pathways of surface and subsurface water masses all around the Cretan Arc Straits and in the Levantine basin. In 1987, LSW entered the Cretan passage, proceeding westward around the Cretan cyclone and Pelops anticyclone and protruded into the Eastern Ionian, finally entering the Cretan Sea (Fig. 8a,b). In 1991, LSW is replaced by CSW that exits from the Cretan Sea and flows in the opposite direction, i.e., eastward south of Crete (Fig. 9a,b).

In the southwestern Levantine basin, a very important multi-lobe anticyclonic feature develops, which is in fact the major difference between 1987 and 1991 (Fig. 7a,b and Fig. 9a,b). Although multiple, coherent anticyclonic eddies were quite common in the Southern Levantine Basin in the preceding periods of POEM, the 1991 pattern differs significantly showing three anticyclones of relatively larger size that cover the entire southwestern Levantine basin. The two northern anticyclones were already revealed and discussed in Section 2.2 examining the vertical distributions of properties. A large coherent anticyclonic structure with multiple deep centers was identified as the Mersa–Matruh gyre in 1985 and 1986 (Ozsoy et al., 1989, 1991, 1993) when there was no evidence of the Ierapetra anticyclone. In 1987 (Robinson et al., 1991; Theocharis et al., 1993) and 1989 (Ozsoy et al., 1991, 1993), the Ierapetra could easily be identified. In 1991, these features appear larger in size, completely blocking the traditional LSW pathway, and preventing it from flowing westward in the Cretan Passage. Furthermore, in 1987 and 1989, the multiple anticyclonic centers in the region led to a convoluted path of the MMJ (also called Central Levantine Basin Current by Ozsoy et al., 1993) advecting MAW into the Levantine basin between the southern rim of the Rhodes gyre and the northern boundary of the Mersa–Matruh anticyclone. In 1991, CSW is advected eastward in the Cretan passage by a northern current that bifurcates at the southeast tip of Crete. One branch enters again the Cretan sea and a second one enters the Levantine basin passing between the northern border of the Ierapetra and the southern rim of the Rhodes gyre. The CSW pathways are marked in Fig. 9a. The present analysis of dynamic heights for POEMBC-O91 confirms the water mass structure and pathways inferred from the examination of the vertical distributions of (θ,S) discussed previously in Section 2.

The further major difference pointed out previously in Section 2 between 1991 and 1987 is the much greater volume of MAW present in the Ionian sea in 1991, which however, does not reach the easternmost Levantine. As the MAW is characterized by the minimum salinity compared to all the other water masses (Fig. 3), the MAW is clearly revealed by examining the patterns of salinity minimum in the upper 250 m layer for the two years. Fig. 10a,b shows such horizontal distributions for 1987 (10a) and 1991 (10b), respectively.

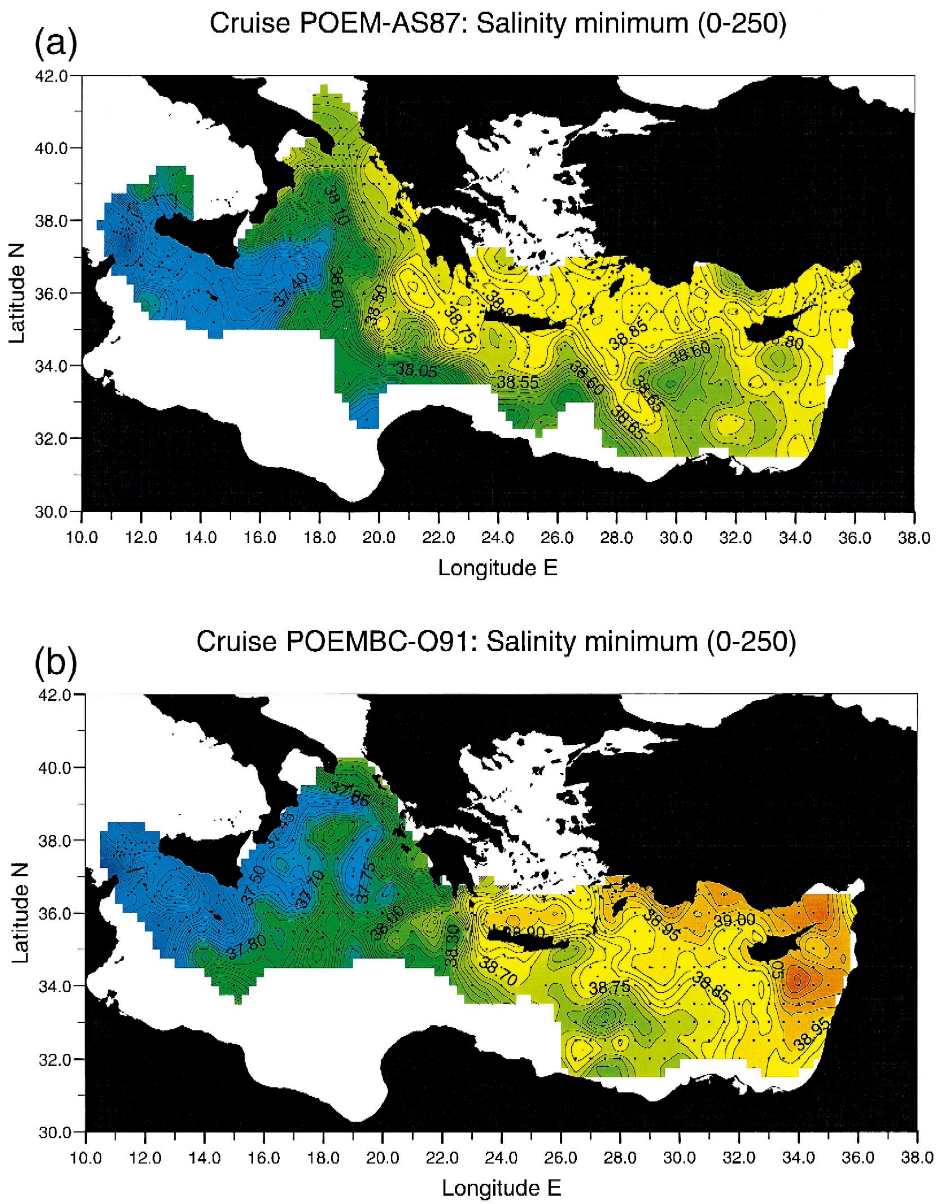


Fig. 10. Horizontal distribution of minimum of salinity in the upper layer (0–250 dbar), in 1987 (a) and 1991 (b). It is representative of the distribution of the MAW.

In 1987, the MAW advected through the Sicily Straits by the AIS into the Ionian interior remains confined in a narrow pool with $S < 38.00$ to the right of the MIJ (Fig. 10a), is advected southward by the MIJ, and then eastward through the Cretan passage in its southern side by the MMJ. The MMJ veers around the northern rim of the Mersa–Matruh anticyclone, and the MAW, which has undergone a continuous transformation becoming saltier from the Ionian value $S = 38.00$, reaches the southeastern Levantine where it forms a broad pool with $S = 38.60$. The entire Northern Levantine is occupied by saltier water, with $S \geq 38.85$, that spreads westward through the Cretan passage, entering the Eastern Ionian with $S \geq 38.75$.

In 1991, Fig. 10b, a much greater volume of MAW with $S < 38.00$ occupies the entire Ionian interior. The salinity front marked by the isohaline $S = 38.00$ reaches now 20–21°E. The MAW pool with $S \approx 38.30$, evident in the θ/S diagram of Fig. 3a, remains, however, confined to Region a of Fig. 2. Its path is in fact blocked by CSW with $S = 38.70$, that, exiting through the Western Cretan Arc Straits, spreads eastward through the Cretan passage into the northwestern Levantine. The CSW pathway had already been inferred from the examination of the surface dynamic heights of Fig. 9a,b. The salinity front marked by $S = 38.90$ defines the pool of LSW with $S > 39.00$ that occupies the northernmost and eastern parts of the Levantine basin. Thus, in 1991, the Ionian and Levantine basins are much more separated than in 1987 with respect to water masses movements in the upper thermocline layer. This is a further demonstration of the different sources of water masses in the two years, with the Cretan/Aegean sea playing a major role in 1991, as well as in the dynamical features characterizing the upper thermocline circulation.

4. Intermediate and deep layers

The most important differences between 1987 and 1991 are the origin and pathways of the intermediate and deep water masses. Fig. 11a,b shows, respectively, the dynamic height anomalies of the 250 and 400 dbar surfaces with respect to the 800 dbar level. The main features of the upper thermocline circulation have been filtered out leaving only the subsurface intensified and/or strongly barotropic structures.

The examination of Fig. 11a,b reveals a series of anticyclonic regions comprising multiple centers some of which were already evident in the upper circulation (Fig. 9a,b). First and foremost is the three-lobed anticyclone located in the same region of the Mersa–Matruh in the Southern Levantine, with the addition of the strong Ierapetra anticyclone and of a further intense anticyclonic center at 29–30°E and 33–34°N. North of this region, the Rhodes cyclonic gyre is quite evident, even though not particularly intense on this horizon. These Southern Levantine anticyclones quite clearly prevent any major westward spreading of the intermediate/deep water masses formed in the Northern Levantine.

In the Ionian sea, the strong Pelops anticyclone veers anticyclonically the CIW and CDW outflowing from the Western Cretan Straits. The entire northwestern Ionian is occupied by the Ionian Anticyclones, broader and stronger than in 1987.

In 1986–87, the major source of LIW was the Northern Levantine Basin. The salinity distribution on $\sigma_\theta = 29.05$ kg/m^3, that is, the typical horizon for LIW, is shown in

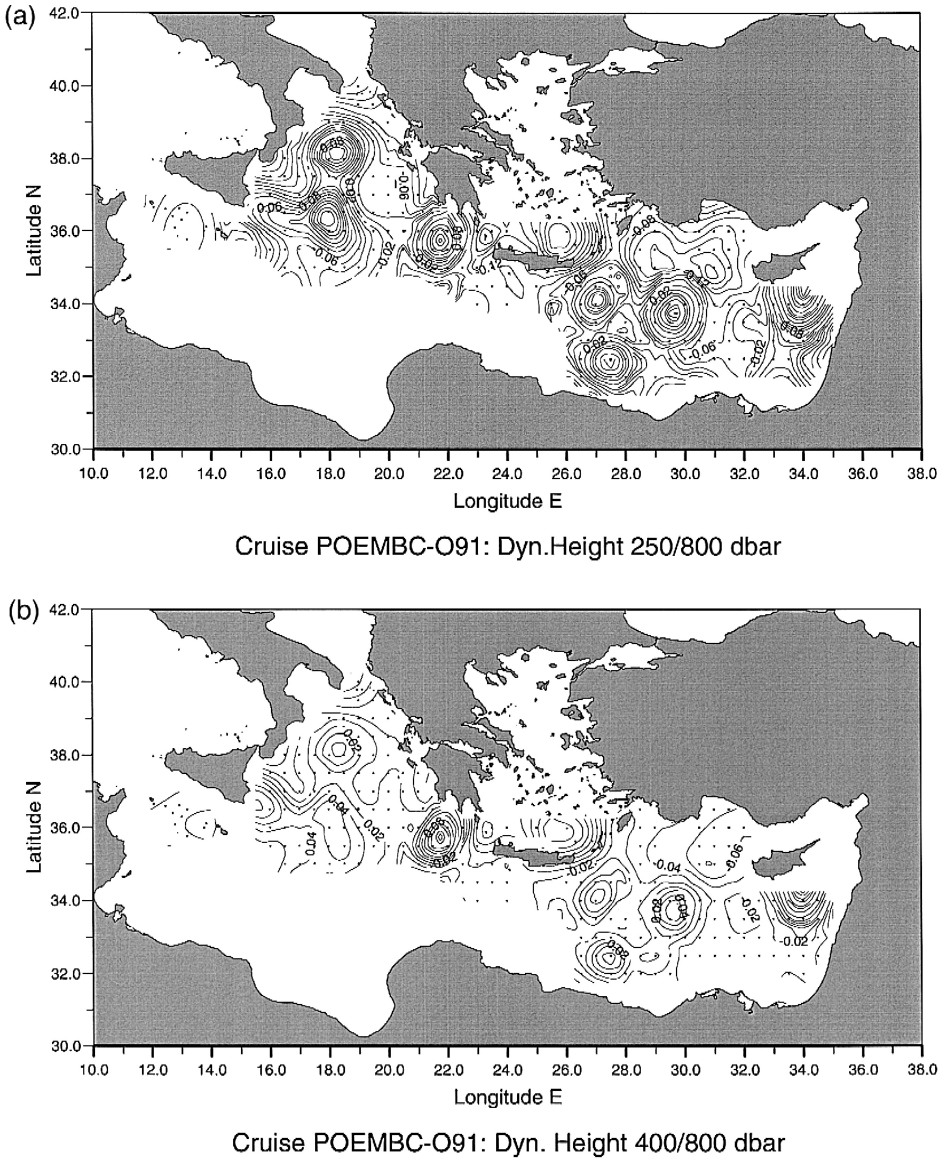
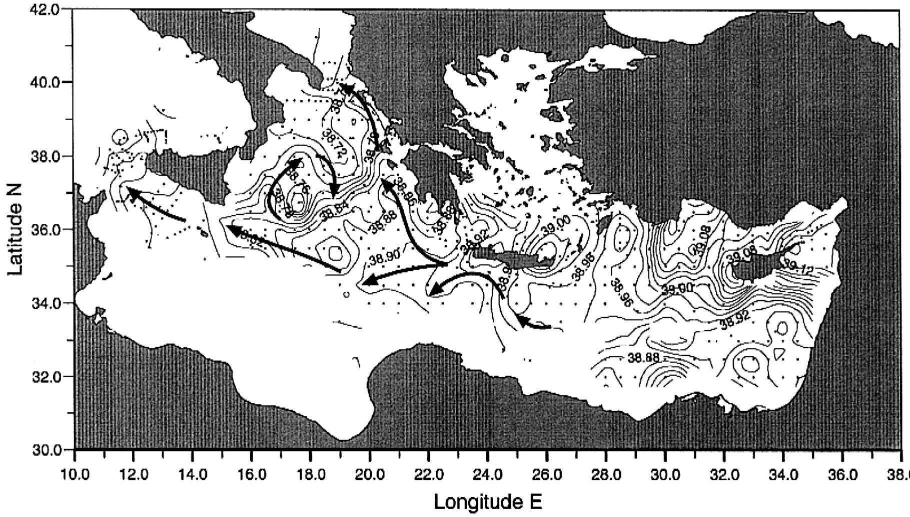


Fig. 11. Dynamic height anomaly (m^2/s^2) at 250 (a) and 400 (b) dbar with reference to 800 dbar.

Fig. 12 (Malanotte-Rizzoli et al., 1997). The LIW pathways are marked in Fig. 12. The formation region is clearly the Northern Levantine Basin, where the highest salinity values are reached, $S > 39.0$, at ≈ 200 m depth (isopycnal depth not shown). The LIW route in the Northern Levantine is not clearly determined by advection alone, but seems rather to be a balance between advection and diffusion. A tongue of high salinity water with $S \geq 39.00$ surrounds the northern source, but its southwestward spreading would be



Cruise POEM-AS87: Salinity at density=29.05 kg/m3

Fig. 12. Salinity distribution on the isopycnal surface 29.05 kg/m^3 in 1987.

inhibited by the Rhodes gyre circulation, which would veer LIW cyclonically around the Rhodes gyre center. Strong diffusion induced by mesoscale eddy activity may indeed mask the purely advective route. When entering the Cretan passage the LIW is entrained around the Cretan cyclone into the Ionian sea. Here, a branch is first entrained northward by the Pelops anticyclone and proceeds along the Greek coastline to the Otranto Strait. The major LIW pathway is towards the Sicily Straits, with a second entrainment around the Ionian Anticyclones.

The salinity distribution for POEMBC-091 on the isopycnal surface $\sigma_\theta = 29.05$ kg/m^3 is shown in Fig. 13. The salinity in the center of the Rhodes Gyre in 1991 is 39.02, much higher than the salinity of 38.92 in 1987. In 1991, the LIW follows very specific and different paths. Firstly, it is advected by the Asia Minor Current through the Rhodes Straits into the southeast Aegean sea. Successively, it partially exists into the northwestern Levantine basin through the Cretan Straits forming a well defined tongue that protrudes southward and is entrained cyclonically around the southern rim of the Rhodes Gyre. The LIW does not seem to move westward into the Cretan passage. This is evident from the meridional front that is formed between the salty new LIW in the Western Levantine and the less saline water mass with $S < 38.94$, probably ‘old LIW’ as discussed in Section 2.

In 1991, the CIW replaces the LIW in the Eastern Ionian. It has a salinity maximum of $S = 39.10$ inside the Cretan Sea, and a high salinity tongue protrudes from the Western Cretan Arc Straits. It is confined by the isohaline $S = 38.90$ in the southeastern Ionian. A secondary branch spreads eastward through the northern part of the Cretan passage. This CIW mixes with the above mentioned ‘old LIW’ and re-enters the Cretan sea east of Crete. The interior of the Ionian sea has a homogeneous salinity of about

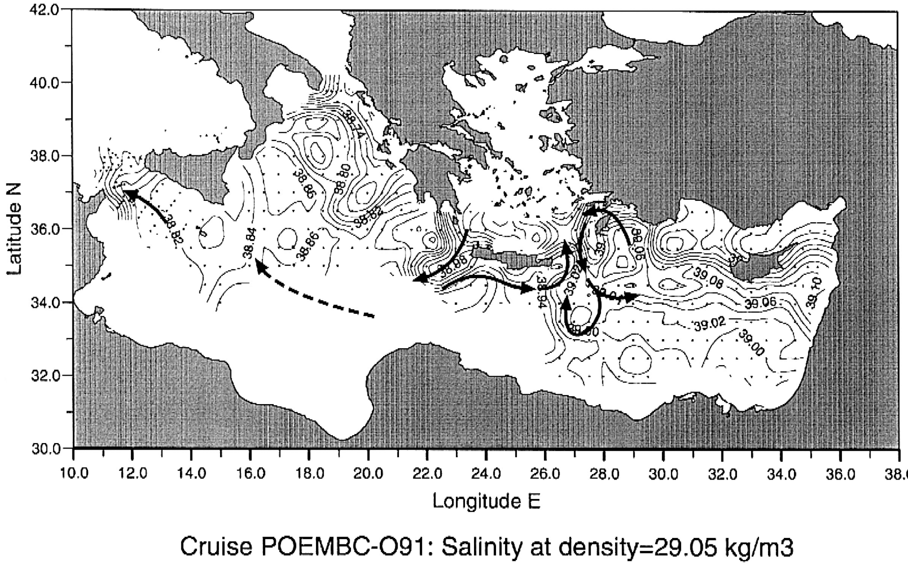


Fig. 13. Salinity distribution on the isopycnal surface 29.05 kg/m^3 in 1991.

$S = 38.86$. The minimum salinity core of $S = 38.78$ at 18°E and 38°N is due to the downwelling of MAW from the upper layer within the center of the very strong northern Ionian Anticyclone. In comparison to 1987, in 1991 the salinities on the isopycnal surface of $\sigma_\theta = 29.05$ kg/m^3 were higher by 0.15 in the Rhodes Gyre and in the north Cyprus region. The Ionian interior exhibits a reversal picture concerning the distribution of salinity at intermediate depths. In 1987, high salinity water (LIW), delimited by isohalines with $S > 38.80$, occupied the eastern and central parts of the Ionian forming a front at 37°N and showing the evident flow of LIW westward to the Sicily Straits (Fig. 12). In 1991, the large amount of saltier CIW ($S = 38.80$–39.10) induces the isohaline of 38.80 to protrude to 39°N. The flow path along the Greek coastlines towards the Otranto Strait is absent too, and the northeastern Ionian is instead occupied by a less saline water of Adriatic origin (Fig. 13). A meridional salinity front with $S = 38.84$ is also present at 16°E and apparently blocks any possible western route of CIW toward the Sicily Straits making the CIW to recirculate in the Ionian interior. The CIW pathways are marked in Fig. 13. A parallel increase in salinity is observed in the Sicily Strait ($S = 38.82$ in 1991 vs. $S = 38.78$ in 1987), even though the origin of the water mass outflowing from the Sicily Strait is not clearly revealed by the data set in 1991. The pathways and formation sites of the salty water masses identified on the isopycnal surface $\sigma_\theta = 29.05$ kg/m^3 also appear on the isopycnal horizons $\sigma_\theta = 29.00$ and 29.10 kg/m^3 with a fully similar pattern.

The salinity and depth of the isopycnal surface $\sigma_\theta = 29.15$ kg/m^3 for the POEM-AS87 and POEMBC-O91 are presented in Fig. 14a,b and Fig. 15a,b, respectively. In both years, a transitional water mass, below the LIW in 1987 and the CIW in 1991 and above the deepest EMDW, is formed within the Cretan Sea and spreads uniformly out from all

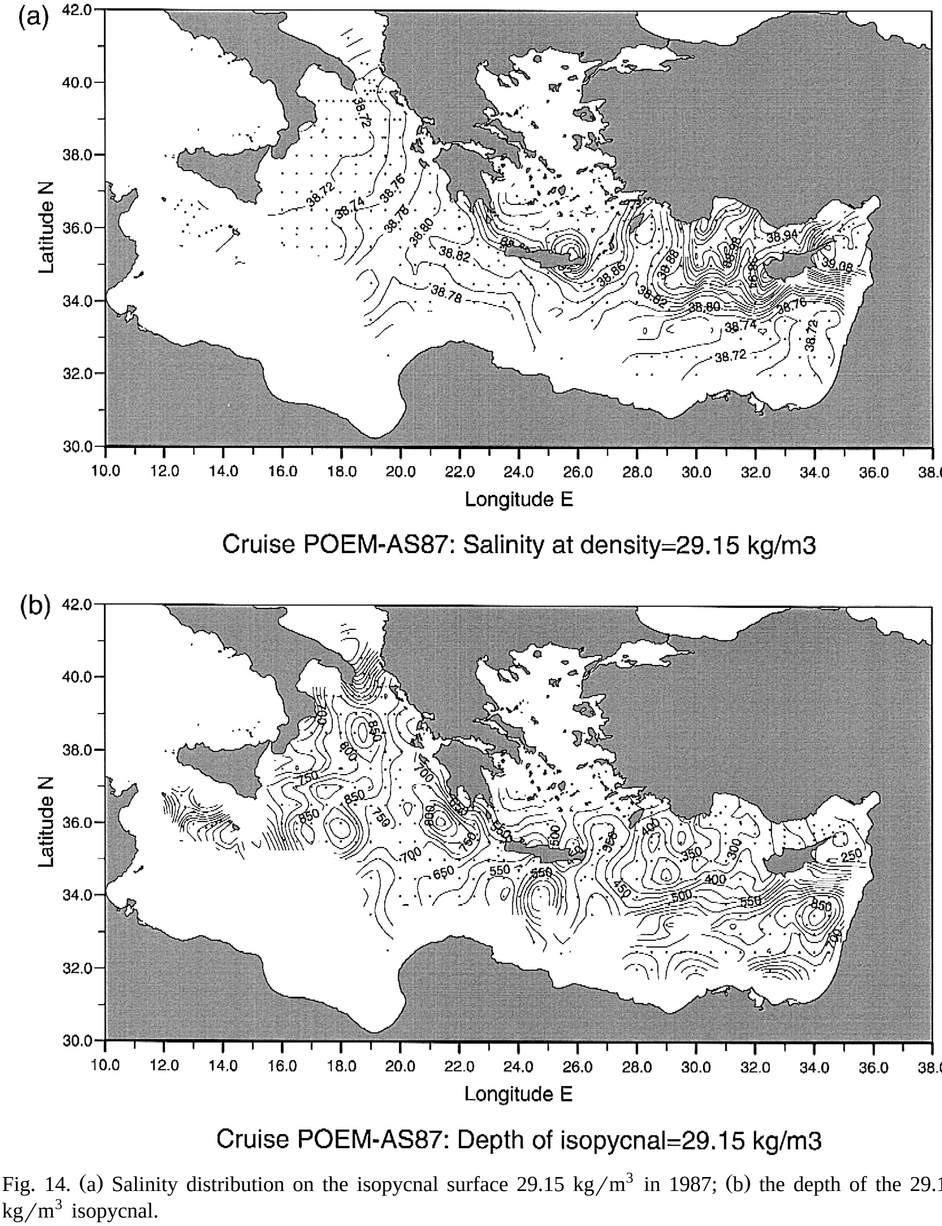


Fig. 14. (a) Salinity distribution on the isopycnal surface 29.15 kg/m^3 in 1987; (b) the depth of the 29.15 kg/m^3 isopycnal.

around the Cretan Arc Straits. Schlitzer et al. (1991) classified as 'intermediate' these transitional waters. According to the water mass classification given in Section 2.1, we define them as 'transitional' being sandwiched between the less dense CIW and the denser CDW. In 1987, a route is present of this transitional water towards the Ionian interior (Fig. 14a) at a depth of $\sim$800 m (Fig. 14b). The fresh water of Adriatic origin

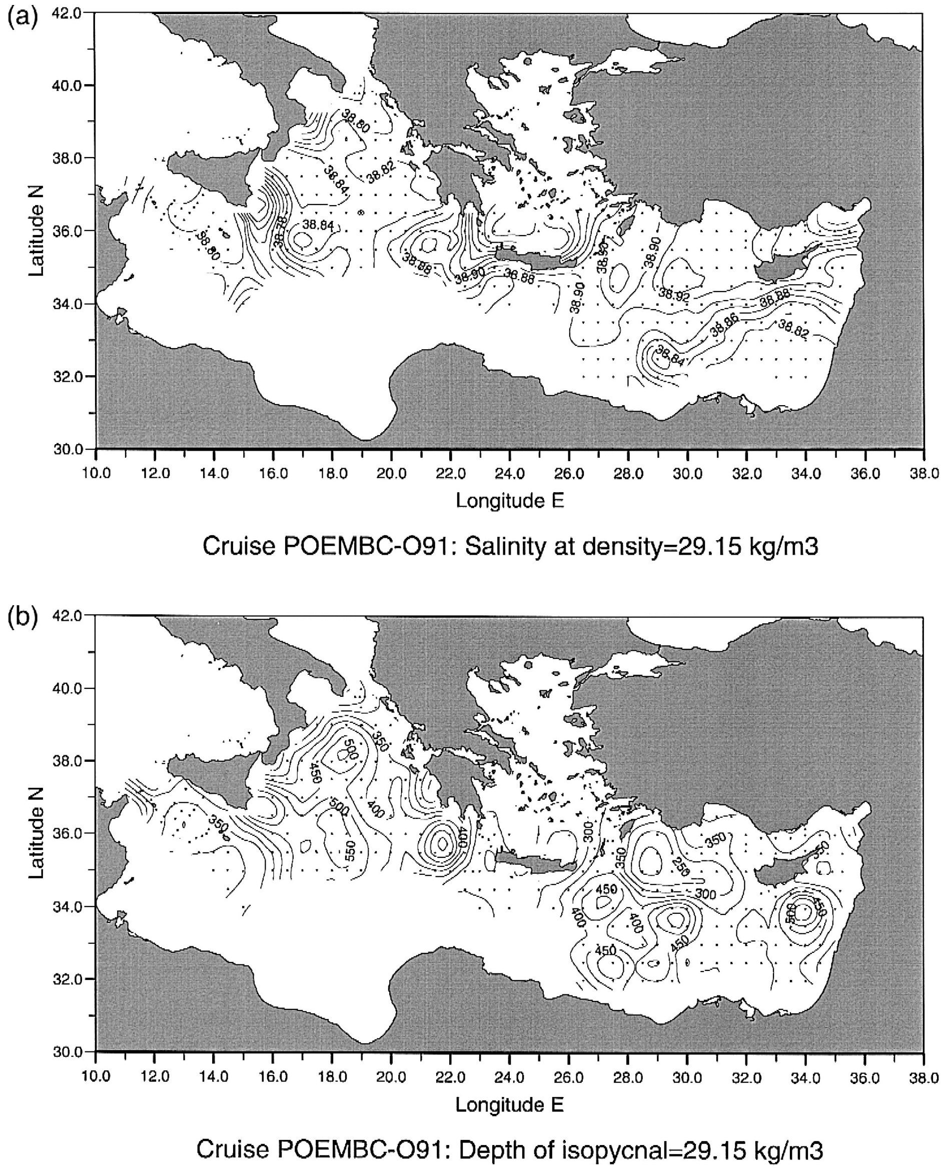


Fig. 15. As in Fig. 14, but for the isopycnal 29.15 kg/m^3 in 1991.

occupies the Western Ionian forming a pool marked by the isohaline $S = 38.72$. At the Sicily Straits, the sill depth shallower than 450 m prevents any major advective outflow of this water. In 1991, an anticyclonic recirculation of a homogeneous water mass with $S = 38.84$ is observed on this isopycnal horizon in the Ionian interior (Fig. 15a). At the Sicily Straits, the isopycnal 29.15 kg/m^3 is now much shallower, reaching the depth of 350m and hence able to cross significantly over the sill depth (Fig. 15b). Compared to

1987, the 1991 salinity distribution of Fig. 15a shows a more massive spreading of this transitional water mass out of the Cretan sea all around the Cretan Arc Straits, both on the western and the eastern sides.

A salinity increase in 1991 with respect to 1987 is quite evident on this surface. The transitional water exiting from the Cretan Strait in 1991 has a salinity of $S = 38.90$ as compared to $S = 38.82$ in 1987. In 1987, the Ionian interior salinity progressively

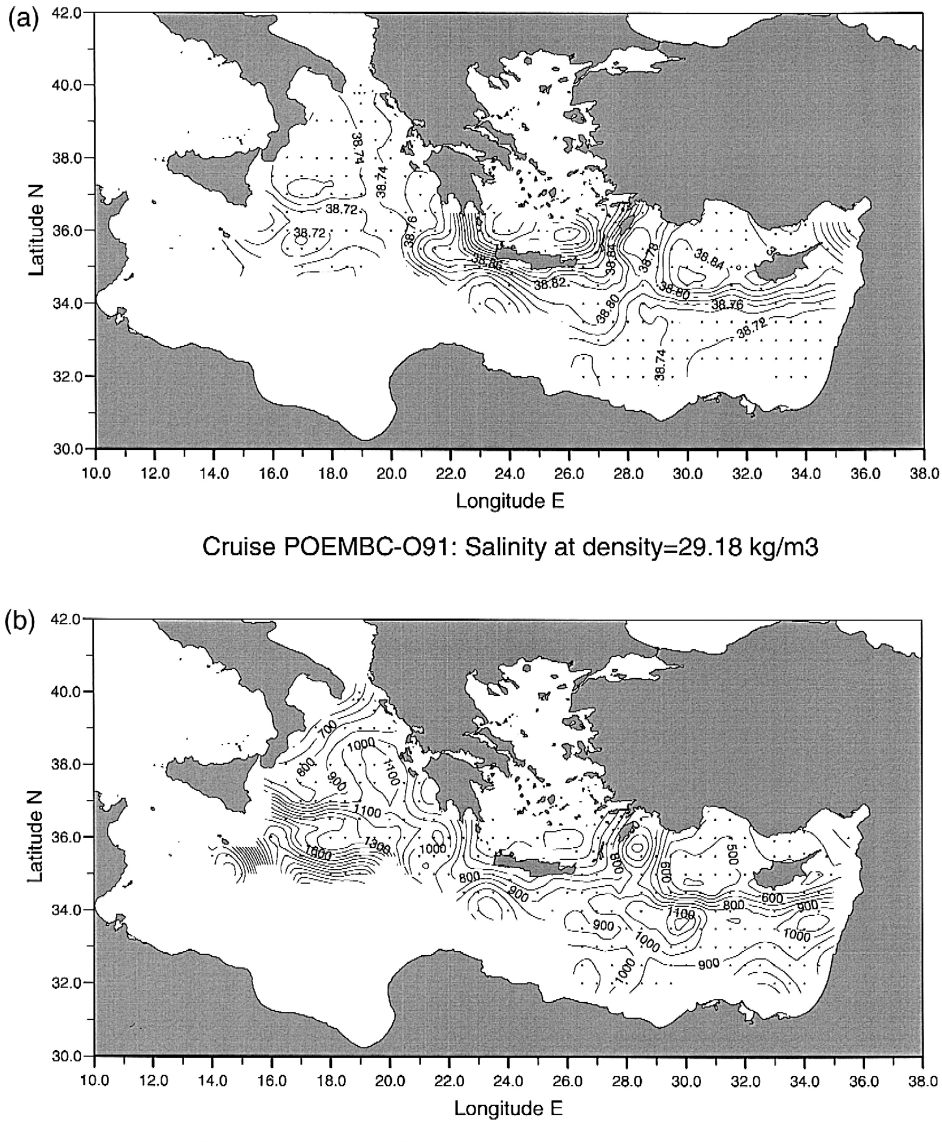


Fig. 16. As in Fig. 15, but for the isopycnal 29.18 kg/m^3 in 1991.

decreases from 38.80 to 38.72 towards the west, while in 1991 it is homogenized at $S = 38.84$. The Levantine basin salinity is also higher in 1991, especially in the southeastern region by about a difference of 0.1. In 1991, the isopycnal surface rises to a much shallower depth than in 1987, compare Fig. 14b and Fig. 15b. In the Levantine basin, the average rise in depth is of about 100 m. In the Ionian it is much greater, the isopycnal rising to 400–500 m depth in 1991 vs. the depth of 750–850 m in 1987.

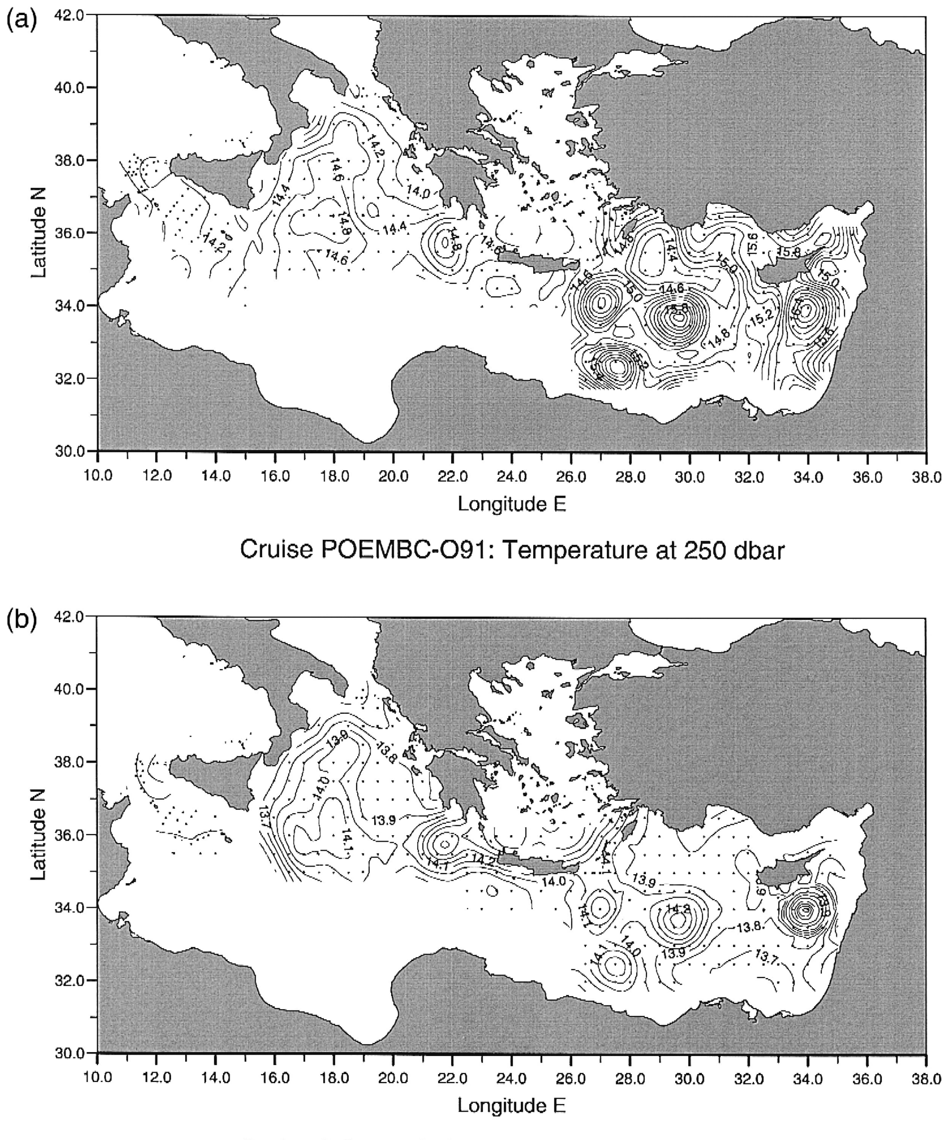


Fig. 17. Horizontal distributions of potential temperature (°C) at 250 dbar (a), 500 dbar (b) and 800 dbar (c).

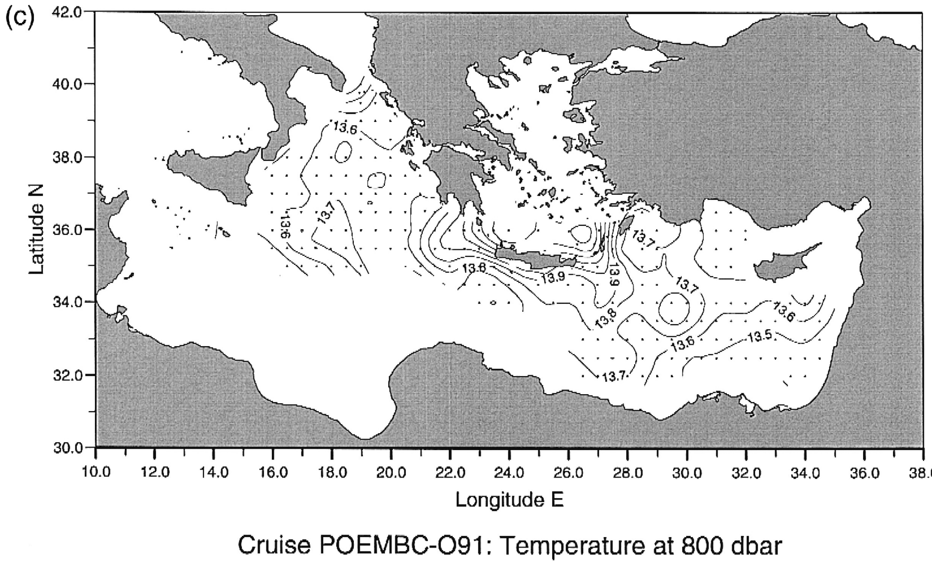


Fig. 17 (continued).

Finally, the salinity distribution on the denser 29.18 isopycnal surface and its depth are shown in Fig. 16a and b, respectively. This distribution cannot be depicted for the 1987 survey as the density of the EMDW was of about 29.17 kg/m^3 (Schlitzer et al., 1991) in the majority of the CTD data sets reaching the bottom in the Levantine basin. Fig. 16a shows a pattern similar to the 29.15 kg/m^3 isopycnal surface of Fig. 15a but even more intensified. The CDW flows out as a massive volume from the Cretan sea through all the Cretan Arc Straits where it is found at a depth of about 800–900 m (Fig. 16b). This isopycnal surface reaches the much greater depth of about 1600 m in the Ionian interior, again characterized by a homogeneous salinity of about $S = 38.72$ in the deep layer. This implies that in 1991 the EMDW in the deep Ionian interior is denser than in 1987 and it is pushed to the west where it still occupies the bottom layer.

The salinity distributions in the intermediate, transitional and deep isopycnal surfaces, from $\sigma_\theta = 29.00$ to $\sigma_\theta = 29.18$ kg/m^3 clearly show that the Ionian interior broad anticyclonic region is occupied by a well homogenized water mass. In Fig. 17a,b,c, we show the temperature patterns at 250, 500 and 800 dbar, respectively, as further confirmation of this homogenization. At 250 dbar, the Ionian interior has temperature values in the range 14.6 to 14.8°C; at 500 dbar in the range 13.9 to 14.1°C; at 800 dbar in the range 13.6–13.7. The presence of this homogeneous water mass is consistent with the hypothesis of a local inertial recirculation and the theories of Rhines and Young (1982a,b). The presence of the strong, multi-lobed anticyclonic region in the Ionian interior in the intermediate and deep layers indicates in fact advection of local waters in a closed circulation pattern. Mesoscale eddies are then a very efficient mixing mechanism to erode tracer gradients and homogenize the water mass. In 1991, the Ionian basin is thus the Eastern Mediterranean equivalent of the homogenized closed recirculation pools observed in the intermediate levels of the North Atlantic subtropical gyre.

Roether et al. (1996) presented evidence of an abrupt salinity increase in the Aegean sea starting in 1987 and advanced the hypothesis of a vertical salt redistribution within the Eastern Mediterranean induced by a change in the upper circulation, bringing into the Aegean/Cretan sea water masses from the Eastern Levantine with high salinity. We want now to assess the consistence of our results with this hypothesis. On all the horizons $\sigma_\theta = 29.00–29.05–29.10$ kg/m^3 (salinity distribution on $\sigma_\theta = 29.05$ kg/m^3 shown in Fig. 13) the LIW present inthe northeastern Levantine, which in 1991 is very salty, $S = 39.15–39.20$, is pushed by the Asia Minor current directly into the Aegean/Cretan sea through the Rhodes Straits. Even though a branch of it exits again into the Levantine through the Eastern Cretan Straits, it is very probable that part of this salty LIW reaches the Cretan Sea interior. The further results of the previous isopycnal analysis show that: (a) there is an overall increase in salinity in the intermediate/transitional layers occupied, respectively by CIW and by the transitional water mass of Cretan origin. This salinity increase is especially marked on the 29.15 kg/m^3 isopycnal surface; (b) the 29.15 surface rises in the Ionian to 500 m depth in 1991, bringing higher salinity waters into this layer; (c) all these saltier water masses were formed in the Cretan/Aegean sea and they spread out from the Western Cretan Arc Straits invading the Ionian interior.

We have finally evaluated the salt budgets of the Ionian sea for 1987 and 1991. Specifically, we have considered the square region limited by 35.5 to 38°N in latitude and by 16 to 19°E in longitude (called region 3 in the work of Malanotte-Rizzoli et al., 1997), which was equally covered in 1987 and 1991 with 0.5 degree station networks. The water column was divided in four layers: 0–250 m, 250–800 m, 800–1200 m, 1200–bottom. Salinity multiplied by the in situ density was integrated over each layer to obtain the salt content in kg/m^3 at each station. The following Table 1 shows the concentrations of the different quantities for the two years.

The decrease of salt in 1991 in the surface layer is clearly due to the much more massive invasion of MAW that occupies a much broader region in the Ionian interior, see Fig. 10b. This salt decrease is, however, more than compensated by the salt increase in the intermediate, transitional and deep layers. The salt increase of $+2.65 \times 10^{12}$ kg in the intermediate layer, 250–800 m, is clearly due to the rising to 500 m of the 29.15 isopycnal surface. The massive salt increase of $+8.19 \times 10^{12}$ kg/m^3 in the bottom layer below 1200 m is due to the protrusion of the 29.18 isopycnal carrying salty CDW. Table 1 shows the hypothesis of Roether et al. (1996) of a vertical salt redistribution could have occurred at most in the upper 1200 m. The massive salt increase below 1200 m shows instead the importance of lateral advection of the new denser waters of Cretan

Table 1

Depth (m)	S, in 1987 (kg m^{-3})	S, in 1991 (kg m^{-3})	ΔS (kg m^{-3})	Volume (10^{12} m^3)	Salt (10^{12} kg)
0–250	39.592	39.450	−0.142	31.7	−4.50
250–800	39.901	39.939	0.038	69.7	+2.65
800–1200	39.835	39.864	0.029	50.7	+1.47
1200–bottom	39.790	39.827	0.037	221.3	+8.19

origin. The above scenario is consistent with the preconditioning of the Cretan/Aegean sea through the invasion of salty LIW from the Northern Levantine. Under the winter average conditions of cold, dry Ephesian winds blowing from the mainland, the newly formed water mass will be denser, thus convection cells may become very vigorous and reach the 800–1000 dbar level. The entire Cretan/Southern Aegean may then become filled with a mixture of progressively denser water masses, i.e., CIW, intermediate water and CDW, respectively, which would then spill out the Cretan Arc Straits sills and spread into the Eastern Mediterranean interior. The above scenario is also supported by the recent analysis of monthly wind stress field over the Mediterranean for 1980–1993 and related modeling study of Samuel et al. (1998). They carry out two major circulation experiments, the first one forced by the wind stress climatology for the period 1980–1987 and the second one for the period 1988–1993. In the second simulation, there is a collapse in ADW formation, and in contrast there is increased exchange of LIW at the Cretan Straits and enhanced CDW production. Thus, the change to the Cretan/Aegean sea as the driving engine of the Eastern Mediterranean thermohaline circulation may have been induced by the changes in winter wind stress between the two periods.

5. Conclusions

We present in this paper definitive observational evidence that the dramatic change observed in Winter 1995 by Roether et al. (1996) to have occurred in the deep thermohaline circulation actually started before October 1991. The first unified analysis of the POEMBC-O91 data set is here carried out, the survey covering the entire Eastern Mediterranean, Fig. 1. This analysis clearly shows that in 1991 the Cretan/Aegean sea was the ‘driving’ engine of the intermediate, transitional and deep layer circulations with CIW, intermediate water of Cretan origin and CDW spreading out from the Cretan Sea into the basin interior. The major novel specific results of this analysis can be summarized as follows.

(a) In 1987, the intermediate layer circulation, 250 to 600 dbar, was characterized by the westbound pathway of ‘traditional’ LIW, formed in the Northern Levantine, which spread towards the Sicily Straits through the Cretan Channel and the Ionian interior. A second major route produced by the veering by the Pelops anticyclone, was northward bound along the Greek coastline to the Otranto Straits. This circulation pattern was consistently found on the isopycnal surfaces $\sigma_\theta = 29.00$, 29.05 and 29.10 kg/m^3, characterizing the LIW range. In 1991, CIW formed inside the Cretan/Aegean sea substitutes for LIW, exiting from the Western Cretan Arc Straits and spreading into the Ionian in a well-defined tongue that reaches the basin interior on $\sigma_\theta = 29.05$ and 29.10 kg/m^3. A branch of this CIW flows eastward in the northern side of the Cretan passage and enters the Cretan sea again through the Eastern Straits, Fig. 13. The salty water reaching the Sicily Straits (Fig. 4) seems to be a mixture of LIW present in the Cretan passage from previous winters with recently formed CIW.

(b) The salty LIW formed on these horizons in the Northern Levantine was diverted in 1991 from spreading westwards by the presence of a multi-centered strong anticyclonic region in the Southern Levantine. The sub-gyres were the very intense Ierapetra and Mersa–Matruh anticyclones, while a third sub-gyre, not present in 1987, was centered at 29–30°E and 33–34°N, Fig. 11a,b. This latter anticyclone induces a local LIW cyclonic recirculation around the southern rim of the Rhodes Gyre, while the Ierapetra anticyclone entrains the CIW spreading eastward in the Cretan channel directly into the Cretan sea.

(c) On the horizon $\sigma_\theta = 29.15$ kg/m^3, a transitional water mass is found also of Cretan/Aegean origin, which spreads out from the entire Cretan Arc Straits into both the Ionian and Levantine interiors. This is observed in both 1987 and 1991, but the intrusion is much more massive in 1991.

(d) In the deep layer, specifically on the horizon $\sigma_\theta = 29.18$ kg/m^3, a further dramatic change is evident. In 1987, the deep water mass, EMDW, was formed in the Southern Adriatic as ADW, spread out from the Otranto Strait into the entire Eastern Mediterranean (Roether and Schlitzer, 1991). In 1991, again the Cretan/Aegean Sea becomes the source of the deep water, CDW, spreading out uniformly from the Cretan Arc Straits to occupy the entire basin interior.

(e) The transitional and deep water masses on $\sigma_\theta = 29.15$ and 29.18 kg/m^3, respectively, both of Cretan/Aegean origin, rise to much shallower depths in 1991 than in 1987. The horizon 29.18 kg/m^3 is observed at $\sim$1000 m in the Levantine reaching the maximum depth of 1600 m in the Ionian. This implies that old and slightly denser EMDW of Southern Adriatic origin is pushed to the west and down to the near bottom layer by the CDW. The horizon 29.15 kg/m^3 on the other side rises to 500 m depth in the Ionian, being much shallower (100 m) in the Levantine basin. These changes imply a lateral advection of salt confirmed by the salt budget analysis.

(f) In the intermediate/deep Ionian interior, the broad region of the Ionian Anticyclones is occupied by a water mass well homogenized both in salinity and temperature, in all the intermediate/transitional and deep horizons. This homogenization is consistent with a local inertial recirculation in which tracer gradients are eroded by mesoscale eddy mixing processes.

(g) Finally, the upper thermocline circulation in the Ionian sea is quite similar both in 1987 and 1991, the major differences being that in 1991, the anticyclonic sub-basin gyres are all broader and stronger and that the MAW intrusion is much more massive reaching into the basin interior, Fig. 10b. The striking novelty in the upper thermocline circulation is found in the Southern Levantine and is due to the presence of the multi-lobe anticyclonic area that penetrates barotropically to the deep layer.

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