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Thermohaline properties in the Eastern Mediterranean in the last three decades: is the basin returning to the pre-EMT situation?

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Abstract

We present temperature, salinity and oxygen data collected during the M84/3 and P414 cruises in April and June 2011 on a basin-wide scale to determine the ongoing oceanographic characteristics in the Eastern Mediterranean (EM). The east–west transect through the EM sampled during the M84/3 cruise together with data gained on previous cruises over the period 1987–2011 are analysed in terms of regional aspects of the evolution of water mass properties and heat and salt content variation. The present state of the EM basin is also evaluated in the context of the evolution of the Eastern Mediterranean Transient (EMT). From this analysis we can infer that the state of the basin is still far from achieving the pre-EMT conditions. Indeed, the 2011 oceanographic conditions of the deep layer of the central Ionian lie between the thermohaline characteristics of the EMT and the pre-EMT phase, indicating a possible slow return towards the latter. In addition, the thermohaline properties of the Adriatic Deep Water are still in line (warmer and saltier) as when it restarted to produce dense waters after the EMT. Special attention is given to the variability of thermohaline properties of the Levantine Intermediate Water and Adriatic Deep Water in three main areas: the Cretan, the central Levantine and the central Ionian Seas. Finally, this study evidences the relationships among the hydrological property distributions of the upper-layer in the Levantine basin and the circulation regime in the Ionian.

1 Introduction

The circulation of the Eastern Mediterranean (EM) is deeply influenced by several driving forces, from strong topographic and coastal influences to internal dynamical processes. As a result, a complexity of patterns interacting with the thermohaline cell at a different temporal scales yields in three predominant scales: the basin scale, the sub-basin scale and the mesoscale (Robinson et al., 1991).

The basin scale thermohaline circulation of the EM is formed by two cells: the closed internal cell of the deep circulation encompassing the Ionian and the Levantine Sea, which represents the Eastern Mediterranean conveyor belt, and the external thermohaline cell involving the exchange of water between the Eastern and the Western Mediterranean (Lascaratos et al., 1999). The first one, mainly driven by the Adriatic Deep Water (AdDW) which eventually becomes the Eastern Mediterranean Deep Water (EMDW) is characterized by a renewal time of approximately 126 yr (Roether and Schlitzer, 1991). Indeed, the major source of the deep waters of the EM has long been considered to be the Adriatic Sea. It was conjectured the existence of an almost perfectly repeating cycle in water mass characteristics and formation rates during a long period (Nielsen, 1912; Wüst, 1961; Hopkins, 1978, 1985; Malanotte-Rizzoli et al., 1999; Roether and Well, 2001; Roether et al., 2007). Evidence, however, reveal that also the Aegean Sea has been occasionally a minor contributor to the deep and bottom waters of the EM (Lascaratos et al., 1999) even before the occurrence of the Eastern Mediterranean Transient (EMT) when it became the main contributor of dense water for the EM for several years (between 1990 and 1997 approximately).

A coherent complex of the sub-basin-scale cyclonic and anticyclonic gyres, permanent and/or quasi-permanent, populates the EM interconnected by jets and meandering currents. Several studies, including Robinson et al. (1991, 2001) and Malanotte-Rizzoli et al. (1997), stressed that these features have a quite high variability that consists in shifts of their centres, deformation and oscillation of the gyre boundaries, meandering of currents and the location and number of current branching. In particular, the southern Levantine basin is populated by separate multiple centers Mersa-Matruh and Shikmona anticyclonic gyres. The North Ionian Gyre (NIG) influences the Atlantic Water (AW) pathway that cyclically diverges from its way towards the Levantine basin meandering into the interior of the Ionian Sea. The Cretan cyclonic and the Pelops anticyclonic gyres are other important structures that influence the dynamics of the Ionian Sea.

During the last decades dramatic changes were recorded in the circulation of the EM. On late 1980s/early 90s the Eastern Mediterranean conveyor belt underwent a major climate shift known as the EMT (Roether et al., 1996, 2007; Theocharis et al., 2002), during which dense waters of Aegean origin replaced the AdDW in the abyssal layers of the EM. The structure of the Aegean Sea (namely, the Cretan Sea) water column changed as exceptionally dense and salty water of local origin started to fill the deep Cretan Basin and to overflow the sills of the Cretan Arc straits. Observations conducted in 1987, 1991 and 1995 have indeed indicated a reduced transport of Atlantic water into the Levantine basin, where the salinity increased. This fact altered the circulation pattern of the Levantine Intermediate Water (LIW) from the formation site into the Ionian Sea (Klein et al., 1999; Malanotte-Rizzoli et al., 1999). These drastic changes and the major contribution of dense water continued for a period of 7–8 yr. Due to its high density ($\sigma_\theta > 29.35\,\mathrm{kg\,m^{-3}}$), the Cretan Deep Water (CDW) continued to fill the deepest parts of the Levantine and Ionian basins and uplifting the resident and older deep and bottom waters of Adriatic origin (Schlitzer et al., 1991; Roether et al., 1996; Malanotte-Rizzoli et al., 1997). CDW appeared to be a very important (or unique) source of the new type of EMDW, the AdDW not being dense enough to spread over the bottom layer of the EM.

Hydrographic measurements obtained in 2003 indicate a new ventilation of the deep layers in the Adriatic and Ionian Seas (see Hainbucher et al., 2006; Manca et al., 2006; Cardin et al., 2011), but only after 2005, following a salinity increase linked with the EM water influence at intermediate levels, the necessary preconditioning factors for deep convection in the southern Adriatic Pit (SAP) and for the formation of water dense enough to spread below the bottom water of EM origin were re-established. As a result, bottom waters encountered in the abyssal layers of the Ionian basin became warmer and saltier between 2003 and 2007 (Rubino and Hainbucher, 2007). This implies a rather direct but delayed link between characteristics of the intermediate layer of the southern Adriatic and abyssal waters of the Ionian Sea (Bensi et al., 2013).

In the central Mediterranean area (Ionian and Adriatic Seas), the two thermohaline cells of the EM interact, generating an important natural source of decadal variability for the entire Mediterranean Sea. The mechanism of this interaction, recently discovered by Gačić et al. (2010), called Adriatic–Ionian Bimodal Oscillating System (BiOS) is briefly summarised here. Associated with the Ionian cyclonic or anticyclonic circulation, the alternate advection into the Adriatic of saltier water from the Aegean/Levantine basis or fresher water of Atlantic origin modifies the thermohaline properties of the Adriatic. These modifications induce redistribution of water masses in the Ionian capable of sustaining the reversals of the upper layer circulation (Gačić et al., 2010). The relationship between water masses of the Adriatic, Ionian and Aegean Seas is very complex, especially because the density of the abyssal water masses are laying very closely together and the source water masses of the Adriatic and Aegean Sea interact with each other influencing their composition and causing nowadays a large variability for water mass formation and stratification in the EM. Recently, the role of BiOS in the decadal variations of salinity has been extended to the Levantine basin (Gačić et al., 2011) and to the Western Mediterranean (Gačić et al., 2013).

The aim of this paper is to study the evolution of the thermohaline properties of the EM during the last two-three decades. To achieve this goal, vertical distributions of temperature and salinity sampled during 6 repeated surveys carried out in different oceanographic stages of the EMT were analysed. We focus our attention on the pathways and property evolution of the AdDW, the EMDW, and the LIW, and compared them to the large-scale oceanographic characteristics emerged from the M84/3 and the POS414 data (April and June 2011, respectively) in 2011. Special attention is given to two areas: the central Ionian and the central Levantine, in order to highlight the evolution of the deep layer and relate it with the changes occurred throughout the water column in the Cretan Sea. This study complements the work of Hainbucher et al. (2013) where an extensive analysis of the water properties during 2011 is done. In contrast to this paper, they investigate properties along a section covering the whole Mediterranean Sea with the aim, among others, to exposure differences between the western and eastern Mediterranean basins. Data and methods are reviewed in Sect. 2, an extensive analysis of the 2011 oceanographic characteristics by means of different transects is presented and discussed in Sect. 3 while the long-term variability is discussed in Sect. 4, and the work summarized in Sect. 5.

2 Data and methods

2.1 M84/3 and POS414 cruise data set

The hydrographic data analysed in this study were collected in the framework of two German initiatives: (i) the *Meteor* M84/3 cruise (April 2011) was set-up to follow the demands and requirements of repeating hydrography as specified by the GO-SHIP group (http://www.go-ship.org/), i.e. with a comprehensive set of physical and chemical parameters measured to the highest standards. The aim of the cruise was to cover the quasi-zonal section through the Mediterranean Sea, covering the main basins of the Mediterranean Sea, with dense sampling of physical and chemical parameters throughout the whole water column; (ii) the *Poseidon* P414 (June 2011) cruise whose primarily goal was to identify the routes and entrainment rates of the AdDW into the Ionian Sea, so as to study the spatial and temporal variability of the spreading and mixing of the EMDW (Fig. 1a).

The data set is made of two main components: the continuous profiles from the Conductivity-Temperature-Depth (CTD), and the discrete data from the water samples. It contains information from 61 hydrographic stations sampled during the April cruise (M84/3) (more information in Tanhua et al., 2013) and 33 full depth standard hydrographic stations sampled in June 2011 during the POS414 cruise. A SeaBird SBE911plus CTD-O_2 probe equipped with dual sensors of temperature, salinity and dissolved oxygen was employed attached to a SeaBird carousel 24 (12) bottle water sampler during the M84/3 (P414) together with an altimeter. Additionally, a fluorometer sensor was installed on the CTD during the M84/3 cruise and a digital reversing thermometer was attached to the probe for quality check. At almost all stations, water samples for dissolved oxygen were taken at different depths throughout the whole water column. The oxygen samples were analysed on board using a Winkler potentiometric method. From three depth levels, depending on the vertical profile of the stations, water samples were taken also for calibration purposes of the salinity values and they were analyzed onboard using a Guildline Autosal Salinometer. Data were processed applying the Seabird software and a Matlab post-processing package. Spikes were removed from all data by applying the instrumental and climatological range criteria backed up by visual checks. Profiles were then averaged every 1 dbar. The overall accuracies are within 0.002 °C for temperature and 0.003 for salinity.

2.2 Long-term variability

Vertical distributions of hydrographic data in the EM were considered to determine the long-term variability in the area since 1985. Therefore, two different approaches were applied to determine it:

1. vertical distributions of temperature and salinity from the quasi-zonal section crossing the EM, from the Sicily Strait to the Levantine basin are analysed by means of repeated surveys. Data from cruises carried out in 1987 (Nellen et al., 1996), 1995 (Hemleben et al., 1996), 1999 (Pätzold et al., 2000), 2001 (Hemleben et al., 2003) and 2008 (Moutin et al., 2011) were considered, being the only available for a trans-basin section. All these cruises were carried out as part of some collaborative investigations of the EM, like POEM (Physical Oceanography of the Eastern Mediterranean) research program, EMTEC (Eastern Mediterranean Transient and Ecosystem monitoring) designed to monitor the status and evolution of the water masses structures and dynamics in the EM, and BOUM (Biogeochemistry from the Oligotrophic to the Ultraoligotrophic Mediterranean) experiment. The long-term variability of the water mass structure in the EM is analysed on the basis

of single profiles located in two areas: western Ionian [17–19° E/34.5–36° N] and central Levantine [29–31.5° E/33–35° N] (Fig. 1).

2. The temporal evolution of the water mass structure in the Cretan Sea is analysed on the basis of thermohaline parameters collected within the area depicted in Fig. 1 between 1985 and 2012. Part of the data comes from the MEDATLAS database (see Maillard et al., 2002 and Manca et al., 2004 for a detailed description of the dataset) while others were collected in the framework of European and German National projects. Profiles obtained between 2006 and 2012 were provided by the Hellenic Centre of Marine Research – HCMR sampled during the E1M3A observatory maintenance cruises.

For all datasets derived parameters such as potential temperature, salinity and potential density were obtained from each original in-situ temperature and conductivity profile. Hereinafter the temperature indicates the potential temperature (θ), the salinities are reported according the practical salinity scale, the density indicates the potential density excess (σ_θ) and the oxygen corresponds to dissolved oxygen.

3 2011 thermohaline conditions

The Absolute Dynamic Topography (ADT) of the EM referred to April 2011 obtained at the Live Access Server of the AVISO web portal (http://las.aviso.oceanobs.com/las/getUI.do) shows the major circulation features in the upper thermocline (Fig. 1b). A coherent complex of sub-basin-scale cyclonic and anticyclonic gyres, permanent and/or quasi-permanent, well-developed, interconnected by jets and meandering currents may be recognized. Part of the stations sampled during the cruise is positioned at the edges of structures that are influential for the definition of the water masses pathway.

The vertical distribution of temperature and salinity from the quasi-zonal section crossing the EM, from the Sicily Strait to the Levantine basin is shown in Fig. 2. In

April 2011, the easternmost part of the transect, i.e. the Levantine basin, was characterised by the presence of the Levantine Surface Water (LSW), which occupied the first 50 dbar showing high temperature ($\theta > 18\,^{\circ}$C) and salinity ($S > 39.15$). Two anticyclones are evident in Fig. 2 from the deepening of the isoterms and isopycnals that modified the water mass pathway limited to the area of influence of the Shikmona anticyclonic gyre (see Fig. 1 for the position of the gyre). Beneath this layer, a core of the LIW with a salinity maximum of 39.24 (St. 292) protruded westward (Fig. 2b), occupying the 150–350 dbar layer. Cretan Sea Water characterised by $S > 39.20$ and $\theta > 17.50\,^{\circ}$C) flowed out from the Cretan Sea (St. 297) through the eastern Cretan Arc spreading into the Levantine Sea, and breaking the main LSW/LIW tongue with the outcrops of the isohalines. Small packets of LIW core ($S > 39.10$) seem to be confined below the Ierapetra (Mersa-Matruh) anticyclone, that the transect stations touched only marginally.

The westernmost part of the surface layer was mainly occupied by the AW being very reduced spatially (upper 130 dbar), entrained inside the Ionian circulation and confined by the 38.80 isohaline. AW propagated eastward along the pathway observed from the dynamic heights (ADT, Fig. 1b). Hence, from the analysis of Figs. 1b and 2 we can deduce: (i) the flow veered due to the action of an intense anticyclonic mesoscale structure centred over the deepest area of the Ionian (at ∼ 19° E–36° N) of which we sampled the edge with the three first stations (St. 305, 303, 302); roundabout the flow shows a cyclonic circulation. Thus, the less salty patch ($S < 38.80$) visible at St. 305 and St. 303 can be attributed to the AW influence. Indeed, its intrusion into the Levantine is very variable and may depend on the circulation present in the Ionian (Gačić et al., 2010). In 2011, the NIG circulation was just reversing to cyclonic, as shown from the sequence of yearly averaged ADT pictures in Fig. 2 in Gačić et al. (2014). Hence in 2008, the AW meander was still protruding northward up to 39° N, whilst in 2009 and 2010 it was already weaken and disorganized. Finally in 2011, the small cyclones already present in the northernmost part of the Ionian progressively developed in a larger and more coherent cyclonic gyre. The main effect of about five years of anticyclonic regime of the NIG (2006–2010), when the AW meandered in the northernmost part of the Ionian Sea, was a general increase of salinity in the Levantine basin (see the long-term analysis and discussion in Sect. 4).

The deep layer below 2500 dbar (Fig. 2) was divided in two parts by Herodotus Trough (see its location in Fig. 1a): a large part of the Ionian basin was dominated by waters of Adriatic origin, the AdDW, still representing the coldest and freshest dense water mass of the area with relative minima in temperature ($\theta < 13.48\,^{\circ}$C), and salinity ($S < 38.73$), and corresponding maxima in oxygen (max value of about 204 μmol kg^{-1}). At this time of the cruise, 2011, this water mass had $\sigma_\theta \approx 29.20\,\mathrm{kg\,m^{-3}}$ and can be associated to the newly formed EMDW. The signal of the AdDW flowing out the Otranto Strait was also found in profiles measured in the northernmost part of the Ionian, as will be shown later. The deepest part (below 2000 dbar) of the Levantine basin was filled by waters with similar σ_θ but slightly warmer and saltier, ($\theta > 13.6\,^{\circ}$C, $S > 38.78$) than the AdDW found in the northern Ionian, and with lower oxygen levels (between 185 and 190 μmol kg^{-1}) (see Fig. 2c).

The Cretan Sea Water that flowed from the Kasos Strait showed salinity higher than ~ 39.15 occupying the first 250 dbar and protruding like a tongue into the Levantine (Fig. 3). However, its area of influence remained mainly confined in the north part of the EMR; south of this area it encountered the AW at the surface layer, while it mixed with the LIW in the intermediate one. Very dense waters characterized the deep layer of the Cretan Sea that remained "isolated" by virtue of the presence of the sill. Notably, the densest water was found in the Cretan Sea at St. 288 ($\sigma_0 > 29.30\,\mathrm{kg\,m^{-3}}$, $\sigma_2 \approx 37.93\,\mathrm{kg\,m^{-3}}$, $\theta \approx 13.95\,^{\circ}$C, and $S \approx 39.06$, Hainbucher et al., 2013, 2014), and attributed to the CDW. However, this water remained blocked in the Cretan Sea filling the bottom layer below 1000 dbar, as seen at St. 289, likely due to limited amount of water that was not enough to overflow the sill of the Kasos Strait and reach other abyssal parts of the EM.

The T-S diagram (Fig. 3d) shows a double salinity inversion throughout the water column, feature that can be used to track the signal of the abundant dense water formed during the EMT, as pointed out by Roether et al. (2007). The intermediate minimum can be found close to 470 dbar and a maximum near 500 dbar at St. 289 (purple) located over the sill. Below that maximum temperature and salinity decreased steadily down to the bottom and AdDW was present in the area close to St. 296 located at the Cretan Arc out of the Cretan Sea.

From its formation area towards west, the LIW pathway was directly influenced by the NIG and by the anticyclonic vortex present around 35.5° N/19.0° E that trapped low salinity waters in its centre as seen in Fig. 1b and Fig. 3. There, the LIW bifurcates: one branch flows westward directly to the Sicily Channel, while and a second one flows northwards along the eastern shelf-break of the Ionian. To describe the LIW pathway into the northern Ionian and into the Adriatic, temperature, salinity and density meridional transects are presented in Fig. 4. The LIW seems to be influenced both by the Cretan cyclone as shown by the doming of the isohalines and by the Pelops anticyclone and by the water exiting the Cretan Sea through the Antikithira Strait (right part of the panels). The southernmost stations of the transects depict the presence of the AW on the first 100 dbar, while the rest of the stations show the LIW spreading northward into the Ionian basin as a warm ($\theta \sim 15.0\,^{\circ}\mathrm{C}$), and saltier (salinity maximum ranging from 38.8 and 39) tongue of water. At the time of the cruise (April–June) the LIW core ($S \geq 39.0$) did not enter the Adriatic through the Strait of Otranto, or only water with salinity lower than 38.80 was advected over the Otranto sill, occupying the LIW horizon in the Adriatic. The deep layer (> 800 dbar) of the southern Adriatic (not shown) was filled with AdDW ($\theta \approx 13.07\,^{\circ}\mathrm{C}$, $S \approx 38.73$, $\sigma_\theta \approx 29.275\,\mathrm{kg\,m^{-3}}$). Yet, only a portion of AdDW overflowed the Otranto sill (depth ~ 850 dbar), cascading along the Ionian continental margin towards the deep layer of the central Ionian.

The western meridional (N–S) section (Fig. 5) links the southern Adriatic and Ionian Seas along the Italian coast, ending at the western edge of the quasi-zonal transect crossing the EM. This field distribution complements the information inferred from the previous Fig. 4, indicating that the LIW did not enter the Adriatic, while the cyclonic circulation observed is coherent with the ADT distribution in Fig. 1b. High salinity waters characterized the intermediate layer spreading from east to west in a cyclonic circulation with the core of the LIW located between 200 and 300 dbar, whereas low salinity waters were confined to the surface layer almost along the whole section evidenced from the northern part of transect B and C depicted in Figs. 4 and 5. The latter shows also two cores of high salinity: the first located at St. M309 and the second at St. M305 catching a less diluted signal of the LIW spreading westward from the Levantine. Beneath the LIW, low salinity waters (38.72) with relative large oxygen content (198 µmol kg^{-1}) filled the deepest part of the central Ionian. They can be attributed to a relative fresh and recently ventilated water of Adriatic origin. The oxygen minimum layer was located in the layer 1000–1300 dbar, with values around 180 µmol kg^{-1} as this layer was scarcely renewed.

Maps of salinity distributions (Fig. 6a) at 20 dbar and at the isopycnal surface of $\sigma_\theta = 29.05\,\mathrm{kg\,m^{-3}}$ (Fig. 6b), i.e. the typical horizon of the LIW (Malanotte-Rizzoli et al., 1997) provide firstly evidence of the major water masses occupying the basin from the Sicily Channel to the Cretan Passage and their circulation patterns. The AW entered the Ionian Sea from the Sicily Channel and protruded towards east and north occupying an extended portion of the west half of the Ionian basin. A front ranging from 38.45° N to 38.60° N separated low salinity waters of Atlantic origin from high ones attributed to the Ionian Surface Waters (ISW). Indeed, this pattern confirms what already seen in the salinity vertical distribution (Fig. 2), i.e AW was trapped in the anticyclone located at 19° E. Bifurcated pathways of LIW are recognizable from the salinity distribution at 29.05 $\mathrm{kg\,m^{-3}}$ (Fig. 6b): (i) the tongue defined by $S \sim 39.0$–39.05 spread directly from the Cretan Passage towards the Sicily Channel; (ii) another branch of LIW was embedded in the NIG, and extended north of the Peloponnesus peninsula along the eastern border of the Ionian basin. On its way towards west and northwest the LIW mixed with the surrounding waters decreasing its salinity. This feature is particularly enhanced in the branch directed towards the Sicily Channel, probably due to the mixing induced by the anticyclone located at 19° E.

4 Long-term variability in the Eastern Mediterranean

The long-term variability along the quasi-zonal section, from the Sicily Strait to the Levantine basin, is discussed here through the analysis of the vertical distributions of temperature and salinity sampled during 6 repeated surveys carried out in different oceanographic stages of the EMT: 1987 during the pre-EMT phase; in 1995 when the EMT was in full swing; in 1999 at the end of the EMT. Finally, data from cruises carried out in 2008 and 2011 help to depict the more recent oceanographic situation. Figures 7 and 8 show the vertical distributions of temperature and salinity respectively. For a detailed discussion on the major findings from the cruises carried out in 1987, 1995 and 1999, the reader is referred to the works by Klein et al. (1999), Malanotte-Rizzoli et al. (1999), Manca et al. (2003), Roether et al. (2007). A similar approach was used by Touratier and Goyet (2011) to determine the distributions of properties (θ, S, Oxygen) along a transect west-east in the EM but considering all stations (from Medar/Medatlas II database) within a band of 200 km for the three stages of the EMT and a for years 2000–2001.

Data from the 1987 M5/6 cruise permit to study the hydrographic conditions prior to the EMT in the Ionian and Levantine basins, when the AdDW was clearly the main contributor to the EMDW (Fig. 8a). This distribution is considered as a reference for the climatological state of the EM (Schlitzer et al., 1991). Indeed, the deep western and central Ionian showed a temperature of 13.30 °C and salinities lower than 38.68. On the other hand, observations conducted during the EMT phase, in 1995 and 1999 (Figs. 7 and 8, b and c, respectively) revealed the presence of Aegean waters outside the Cretan Passage with large salinity and temperature values, lying at the deepest layer of the EM. Enhanced salinity and temperature relative to 1987 (values higher than 38.84 and 13.60 °C) were ubiquitous already in early 1995 (Roether et al., 2007), except the western Ionian deep layer that was still occupied by low salinity and temperature waters ($S < 38.68$, $\theta < 13.30$ °C). In 1995 waters of Aegean origin at the Cretan Passage were clearly recognizable by a dome of the ventilated bottom waters associated with $\theta > 14.0\,^{\circ}\mathrm{C}$ and $S > 38.78$. An analogous distribution was found in 1999 (see Theocharis et al., 2002; Manca et al., 2003) at the Cretan Arc and at the easternmost part of the Levantine basin (Figs. 7d and 8d), blocked by the bathymetry constraint of the Herodotus Trough. On the other hand, in the same years, signs of new EMDW of Adriatic origin were already evident in the western continental slope of the Ionian Sea, i.e. indicating that a major change occurred between 1999 and 2003 in the abyssal part of the Ionian basin, where AdDW returned to be the principal contributor to the EMDW (Hainbucher et al., 2006; Manca et al., 2006; Rubino and Hainbucher, 2007; Bensi et al., 2013). In 2008 (Figs. 7e and 8e) only the Levantine basin was still under the influence of the warm and saline CDW overflowed during the EMT, whilst the EMDW that resided in the Ionian abyssal layer was influenced by more recent AdDW with modified properties being warmer and saltier ($\theta = 13.40\,^{\circ}\mathrm{C}$, $S = 38.72$) than in the past. These results are consistent with the tendency toward the warming of and salinification of the AdDW pointed out by Rubino and Hainbucher (2007) and seen also in 2011 (Figs. 7f and 8f), when in general temperature and salinity in the abyssal layer ($\theta \approx 13.40\,^{\circ}\mathrm{C}$, $S \approx 38.75$) depicted almost everywhere a continuous relaxation of the EMT since the early 1990s.

The decadal variability of the average thermohaline properties of the upper layer (0–500 m) in the Levantine basin is shown by the oceanographic results reported in Figs. 7 and 8. The relationship with the AW pathway influenced by the circulation regime in the Ionian Sea is particularly noteworthy. The salinity of the upper layer (0–400 m) in the Levantine basin (Fig. 8) appears to oscillate on multiannual/decadal scale, according to the BiOS regime. A relative minimum in salinity was evident in 1987 (Fig. 8a), followed by an increase in 1995. Note that at the end of 1980's, the Atlantic Ionian Stream (AIS) in the Ionian was intensifying, advecting anticyclonically the AW up to 39° N (Malanotte-Rizzoli et al., 1997). This happened after a period during which the NIG circulation was presumably cyclonic, as inferred from the sea surface temperature distributions presented by Marullo et al. (1997). Indeed, those analyses supported the hypothesis of the presence of a cyclonic circulation in the Ionian Sea until 1989.

Both circulation regimes seem to have occurred simultaneously, but in different parts of the Ionian, since in the second half of the 1980s the NIG was presumably reversing from cyclonic to anticyclonic (Civitarese et al., 2010). The anticyclonic period lasted until 1996, therefore the two salinity distributions of 1987 and 1995 (Fig. 8a and b, respectively) represent the two limits of a period during which the salinity progressively increased. In 1997, the NIG reversed again to a cyclonic regime, allowing a more intense advection of AW toward the Levantine basin. Accordingly, salinity distributions in 1999 (Fig. 8c) and in 2001 (Fig. 8d) show a relative decrease due to the dilution inferred by the AW in the easternmost part of the Mediterranean Sea. Again, the NIG switch to anticyclone in 2006 caused a progressive increase of salinity in the upper layer of the Levantine basin, as shown by the vertical distribution in 2008 and 2011 (Fig. 8e and f, respectively). Though the upper layer salinity patterns could also be partly affected by seasonal and/or local factors, and assuming the sections representativeness of the thermohaline properties of the entire basin, the salinity distributions presented in Fig. 8 fall in the BiOS scheme, that set the conditions for the decadal oscillation of salinity in the layer occupied by the AW and the LIW, i.e. by the two water masses involved in the open thermohaline cell of the entire Mediterranean Sea.

The massive production and outflow of dense water of Aegean origin was one of the principal components of the EMT. Roether et al. (2007) highlighted the temporal evolution of density in the eastern Cretan Sea from 1986 to 2001. To observe the evolution of the thermohaline properties of the water column in the Cretan Sea this period, a Hovmöller time diagram of in situ temperature, salinity and density for the period 1986–2011 (Fig. 9) was obtained considering all those CTD profiles sampled in the area indicated in Fig. 1a and Fig. 9d. Special attention was given to the density of $\sigma_\theta = 29.20\,\mathrm{kg\,m^{-3}}$ ($\sigma_2 = 37.78\,\mathrm{kg\,m^{-3}}$) being the maximum density recorded in 1987 at the reference level of 1300 dbar in the proximity of the Kasos Strait, and considered the threshold density for filling the deep layers of the EM. The 900 dbar level highlighted in Fig. 9 is considered the outflow level for a certain water to exit above the Kasos sill. Finally, the 500 dbar level characterised the intermediate layer. Our data confirm what hypothesised by Roether et al. (2007) regarding the evolution of the Cretan waters thermohaline properties post-EMT at the outflow level, i.e. that the slow decrease of the 29.20 kg m^{-3} isopycnal will maintain density levels exceeding pre-EMT values for several years. Actually, in the last couple of years (after 2010) the layer with density higher than 29.20 kg m^{-3} increased its thickness of about 200 m, reaching about 700 m depth.

While during the EMT the Cretan basin was filled up to about 400 dbar with water of density more than 29.20 kg m^{-3}, producing a large volume of dense water, the fact that after 2000 (post-EMT phase) water at 500 dbar did not exceeded 29.15 kg m^{-3} (37.74 kg m^{-3}) is an indication of a strong reduction of the volume of threshold density. Salinity distribution shows that since 2005 the salinity in the intermediate level has increased reaching absolute maximum values for the considered period (more than 39.1 in 2011). Nevertheless, this salinity increase was accompanied by a parallel increase of temperature, that prevented effective convection able to produce water enough dense to accumulate in the deep Cretan basin, and finally to outflow over the Cretan straits sill. With the present hydrological situation, only a series of two or more severe winters would produce suitable conditions for another EMT-like event.

The spatial and temporal evolution of the water mass structure is analysed also through the comparison of vertical profiles of temperature and salinity within two areas: central Ionian and central Levantine (see Fig. 10a and b for vertical profiles and Fig. 1 for the location of the areas). This analysis includes those data from cruises already discussed in the previous paragraph. The inset graphs enhance the oceanographic characteristics for the deep layer below 1500 dbar. Salinity and temperature profiles for both areas (Fig. 10a and b, zoomed areas) are mostly indicative of changes in the water mass structure related to the EMT. In 1987, the central Levantine shows below 2500 dbar a vertical homogeneity in temperature and salinity in the ranges of ≈ 13.34 °C and ≈ 38.66, respectively. In 1991, it is possible to recognise a slight increase of salinity from about 500 dbar down to the bottom. In 1995, the salinity increase was remarkable, especially below 2300 dbar where it jumped from 38.71 to about 38.84

because of the new dense Cretan Sea Outflow Water (CSOW) (Roether et al., 1996). The CSOW signature was tracked until 2007, when the salinity began to decrease. Meanwhile, in the central Ionian the salinity continued to increase, suggesting that the spreading of the earlier CSOW from the Cretan Arc area towards the Ionian was still active. In 2011, temperature and salinity deep profiles in the Levantine were positioned between 1987 and 2001, confirming that the signature of CSOW was still present in the deep layers of the Basin. In 2011, the presence of AdDW in the Ionian was recognizable from the deep temperature and salinity deep profiles, though with characteristics rather different if compared to the situation before the EMT.

5 Conclusion

In April and June 2011, two oceanographic cruises were carried out in the framework of two German initiatives: the *Meteor* cruise M84/3 (April 2011) and the *Poseidon* cruise P414 (June 2011). The main scope of these cruises were to cover a quasi-zonal section trough the Mediterranean Sea and to add information about the evolution of the EMT as well as about the thermohaline variability of the main water masses which characterize the basin. In this study, we focus our attention on the EM, on the pathways and property evolution of the AdDW, the EMDW, and the LIW. We also present a long-term comparison of the evolution of the oceanographic properties along a quasi-zonal section in the EM during the last three decades.

The 2011 oceanographic conditions highlighted high salinities waters in the formation area of the LIW in the easternmost part of the Levantine. This water propagated westward and dispersed into the southern Ionian towards the Strait of Sicily. It also protruded towards the Adriatic Sea, though by the time of the cruise this water did not cross the Otranto Strait turning cyclonically and flowing southward along the Italian coast. Yet, Bensi et al. (2013) indicated a sudden increase in salinity in the intermediate layers in the central and southern Adriatic during the late fall of 2011 confirming the inflow of salty waters into the Adriatic Sea.

Our results, which represent the most updated analysis for the whole EM, revealed also that the thermohaline properties in the study area are still far from those observed in the pre-EMT phase (1987). The analysis of the three areas i.e. Cretan Sea, central Levantine and central Ionian revealed the imprints of the EMT still present in the deep layers.

The salinities of the upper waters potentially contributing to dense water formation in the Cretan Sea increased after 2005 reaching absolute maximum values of 39.1 in 2011 (Fig. 9), which is a major prerequisite to bring about the EMT-like event. However, this salinity increase was complemented with an increase of temperature, which prevented the formation of relative highly density water through deep convection, able to overflow the Cretan Straits sill. At the same time, density values are still high as those in 1992 meaning that dense Aegean outflow is yet to subside to pre-EMT conditions.

The signature of the salinity maximum at the LIW horizon in 2008 is present in the Levantine and observed in the central Ionian in 2011 on its way towards the Sicily Channel and/or the northern Ionian. The westernmost part, i.e. the Ionian abyss, experienced the effect of a post-EMT phase which started approximately in 2003, characterized by the intrusion of newly formed AdDW completely different from the recent past, inasmuch warmer and saltier. The 2011 oceanographic conditions of the deep layer of the central Ionian, however, lie between the thermohaline characteristics of the EMT and the pre-EMT phase, indicating a possible slow return towards the latter. Moreover, the formation of dense AdDW waters with different characteristics from those observed in the previous 9 yr, less saline and colder, as a result of the harsh winter in 2012 reported by Bensi et al. (2013), could induce in the next future to a noticeable variability in the structure of the abyssal layers of the Ionian basin.

This study evidences the relationships among the hydrological property distributions of the upper-layer in the Levantine basin and the circulation regime in the Ionian. The NIG operates as a sort of roundabout that constrains the AW to travel different pathways according to the decadal variability of the circulation way. Since the crucial role of the LIW in the preconditioning of the deep water formation areas in the entire

Mediterranean Sea, the resulting salinity fluctuations, evidenced by the easternmost salinity distributions, transfer the decadal variability of the Ionian upper-layer circulation to the effectiveness of the deep water formation processes and to the characteristics of the deep and intermediate thermohaline cells. Nevertheless, the sensitiveness of this large thermohaline system to the sea-atmosphere heat transfer is noteworthy, as evidenced in our analysis of the Cretan Sea density evolution, and shown by Gačić et al. (2014) for what concern the NIG circulation regime. Future studies should pay attention in relating the climate changes with the complex interactions occurring within the thermohaline cells in the Mediterranean.

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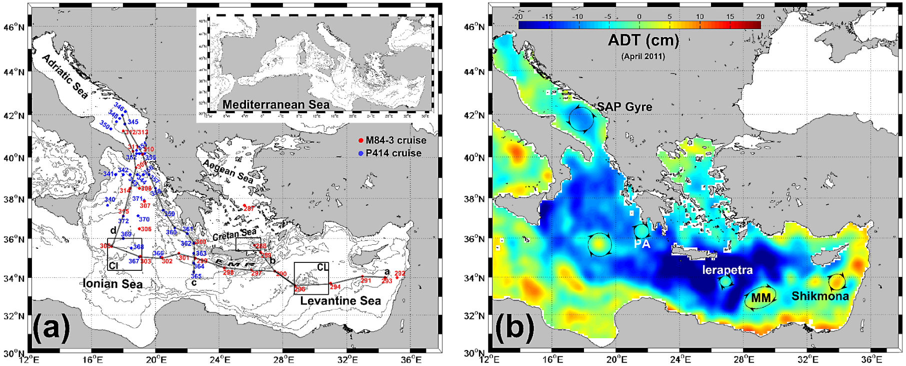

CI = Central Ionian CL = Central Levatine EMR = Eastern Med. Ridge

ADT = Absolute Dynamic Topography
PA = Pelops Anticyclone

SAP = Southern Adriatic Pit
MM = Mersa Matruh Gyre

Fig. 1. (a) CTD stations sampled in the Eastern Mediterranean Sea and Adriatic Sea during the M843 (red) and POS414 (blue) cruises and areas selected for the long-term analysis are depicted. Sections discussed in the text are identified. **(b)** Monthly Absolute Dynamic Topography (ADT) map of the Eastern Mediterranean for April 2011. Principal structures are highlighted in the map.

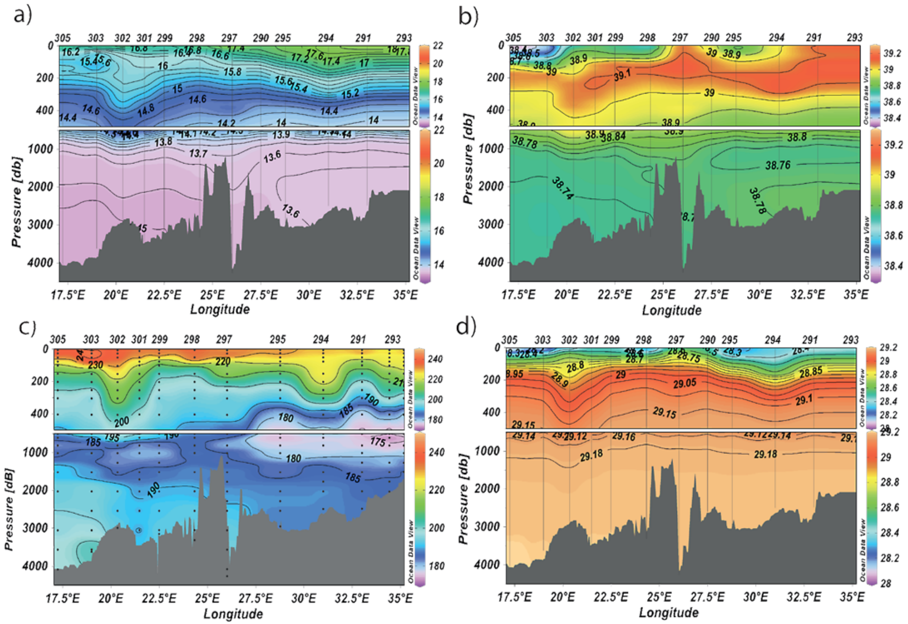

Fig. 2. Water properties along a quasi-zonal section west-east (marked as A in Fig. 1): **(a)** temperature (°C), **(b)** salinity, **(c)** oxygen (µmol kg^{-1}), **(d)** density (kg m^{-3}). The upper panel highlights the first 500 dbar.

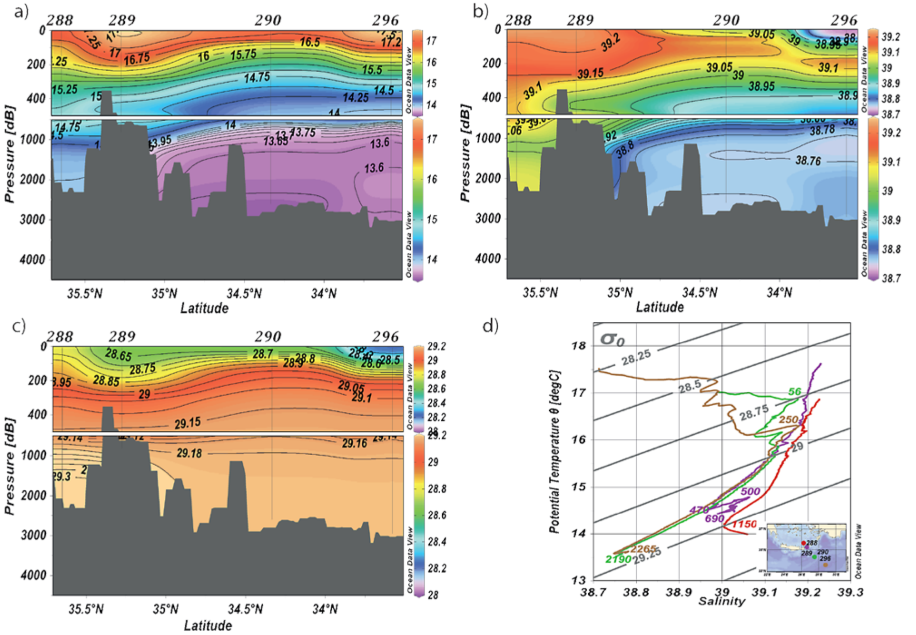

Fig. 3. Water properties along the transect crossing the Kasos Strait (marked as b in Fig. 1a): **(a)** temperature (°C), **(b)** salinity, **(c)** density (kg m^{-3}), **(d)** *T*-*S* diagram of stations considered on the transect. Positions of salinity inversions along the water column are indicated in dbar in the diagram and coloured similar to the station profile. The upper panels of **(a)**, **(b)** and **(c)** highlight the first 500 dbar.

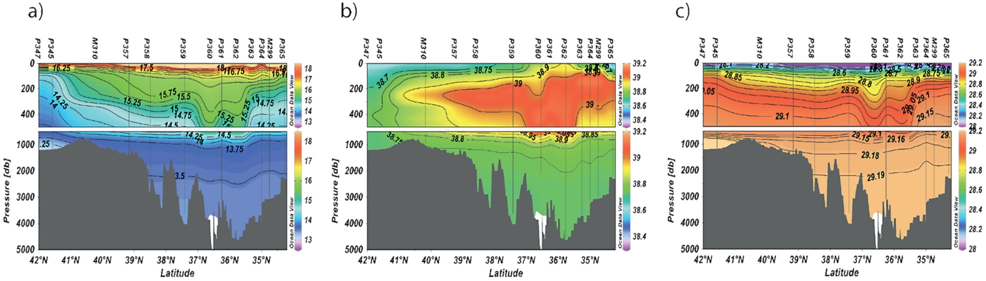

Fig. 4. Water properties following the traditional path of the saline core water towards the Adriatic Sea (marked as c in Fig. 1): **(a)** temperature (°C), **(b)** salinity, **(c)** density (kg m^{-3}). The upper panels highlight the first 500 dbar. *Poseidon* stations are identified by letter P, while *Meteor* by letter M.

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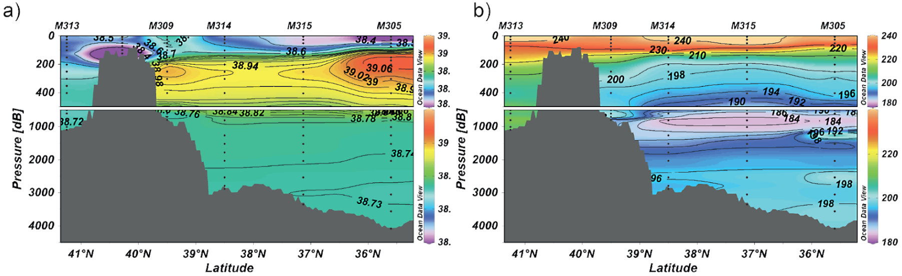

Fig. 5. Water properties along the longitudinal section (N–S) in the western Ionian (marked as d in Fig. 1): **(a)** salinity, **(b)** oxygen (µmol kg^{-1}). The upper panels highlight the first 500 dbar.

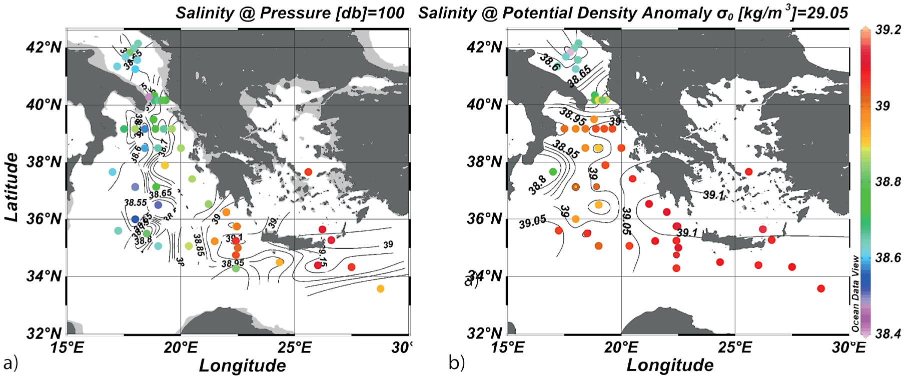

Fig. 6. Salinity distribution at 20 dbar **(a)** and on 29.05 kg m^{-3} isopycnal **(b)**.

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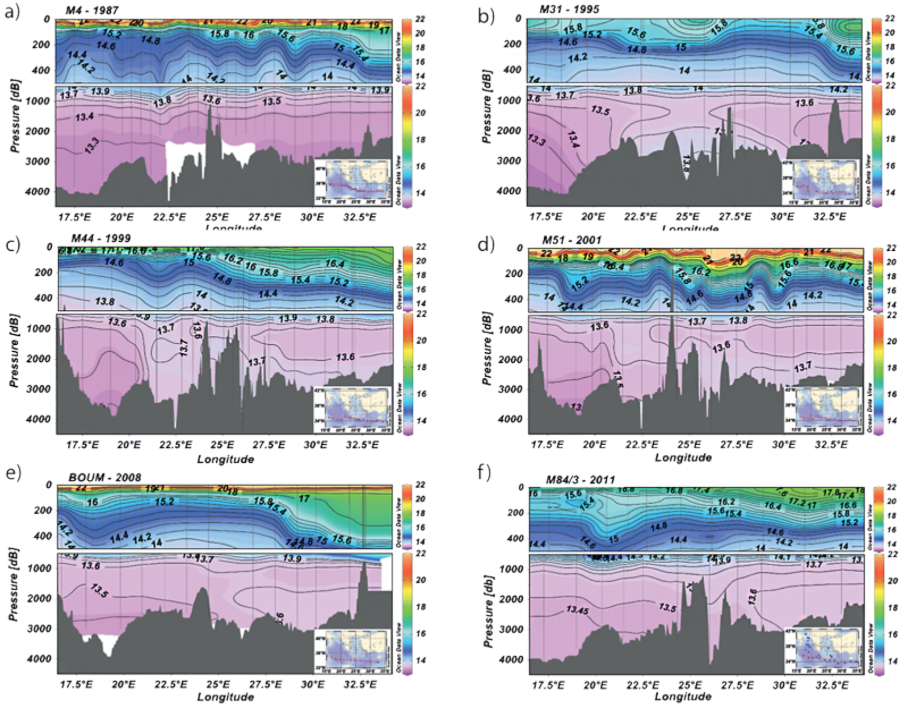

Fig. 7. Sections of temperature (°C) (see inset map) in **(a)** 1987 (*Meteor* M5/6), **(b)** 1995 (*Meteor* M31), **(c)** 1999 (*Meteor* M44), **(d)** 2001 (*Meteor* M71), **(e)** 2008 (Boum), and **(f)** 2011 (*Meteor* M84/3). The upper panels highlight the first 500 dbar.

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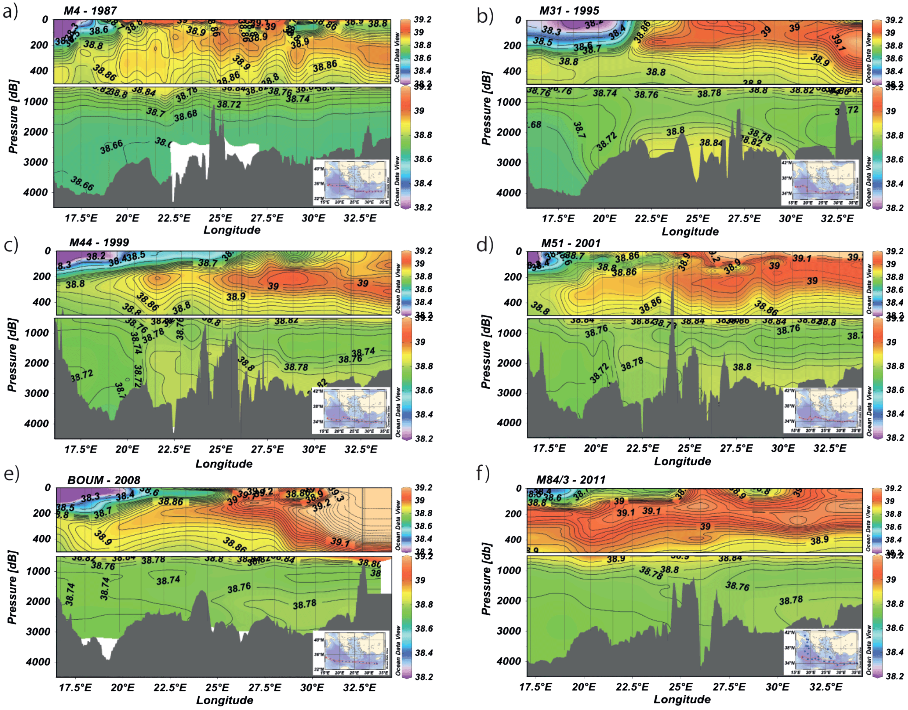

Fig. 8. Sections of Salinity (see inset map) in **(a)** 1987 (*Meteor* M5/6), **(b)** 1995 (*Meteor* M31), **(c)** 1999 (*Meteor* M44), **(d)** 2001 (*Meteor* M71), **(e)** 2008 (Boum), and **(f)** 2011 (*Meteor* M84/3). The upper panels highlight the first 500 dbar.

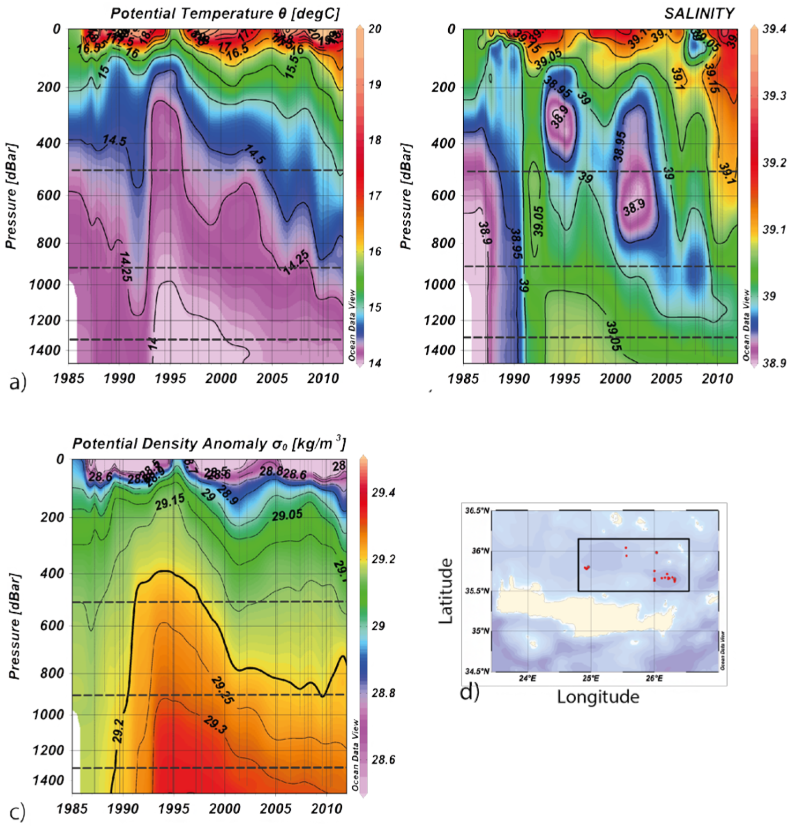

Fig. 9. Hovmöller time diagram of the in situ temperature, salinity and density for the period 1986–2011 for the Cretan Sea. *Y* axis are stretched at the top part.

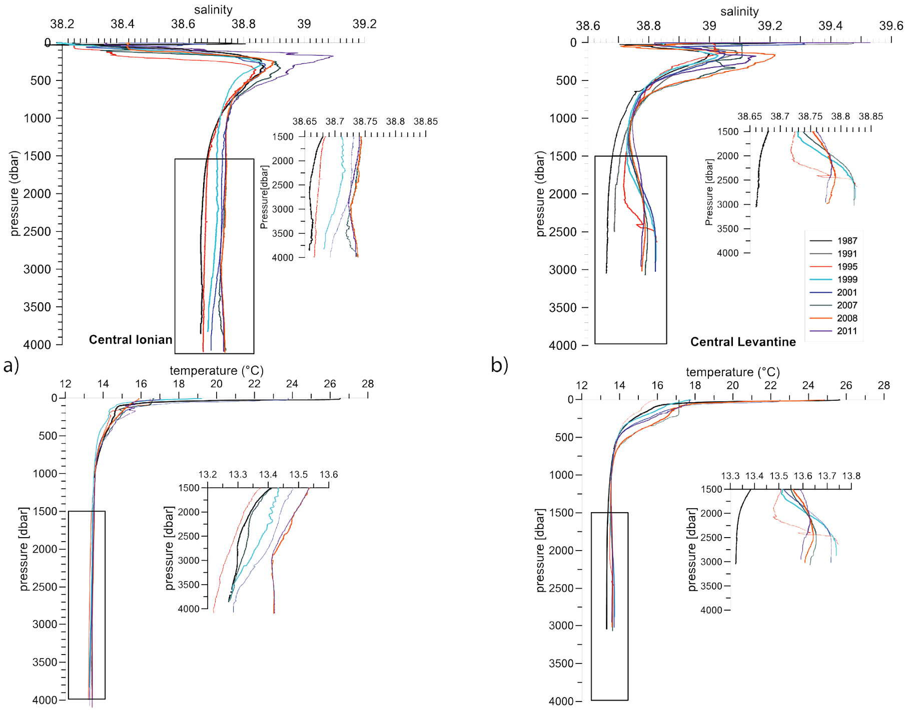

Fig. 10. Vertical profiles of temperature (°C) and salinity in the central Levantine **(a)** and central Ionian **(b)**. For graphical purposes salinity scale has the same unit length but ranging from 38.6 to 39.6 for the central Levantine range, while from 38.2 to 39.2 for the central Ionian. Position of the boxes is shown in Fig. 1.

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