# Distribution of the thermohaline characteristics in the Aegean Sea related to water mass formation processes (2005–2006 winter surveys)

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[1] Aiming at portraying the Aegean's water mass structure and identifying Dense Water Formation processes, two winter cruises were conducted in 2005–2006, across the plateaus and depressions of the Aegean Sea. The most prominent feature of the water mass distribution in the basin is a distinct "X-shape" of the Θ-S characteristics, suggesting a complicated coupling of the major Aegean sub-basins. The surface and deep waters are relatively decoupled with diverse origin characteristics, while the intermediate layers act as connectors of the main thermohaline cells. The Central Aegean seems to play a key role due to formation processes of water masses with densities equal and/or higher than 29.2 kg/m$^3$, that take place in the sub-basin and disperses in the North Aegean. On the other hand, the South Aegean appears greatly influenced by the Eastern Mediterranean circulation and water mass distribution, especially under the Eastern Mediterranean Transient status. The Transitional Mediterranean Water monitored in the post-EMT period and characterized by low temperature at 14.2°C, low salinity at 38.92 and low dissolved oxygen at 3.97 ml/l, with its core around 750 m and above the saline (39.06) Cretan Deep Water, altered significantly the South Aegean structure. The pre-EMT thermohaline pattern of the Central and South Aegean deep layers were similar, while the bottom density of the Central basin was higher than that in the South Aegean. Thus, it is possible that the deep waters of the Central Aegean acted as a dense water reserve supply for the deeper part of the Southern basin.

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## 1. Introduction

[2] In late 1980s and early 1990s the Aegean Sea drew the attention of the oceanographic community, due to the dramatic shift of the Eastern Mediterranean thermohaline circulation pattern. The abrupt changes in the Eastern Mediterranean Deep Water (EMDW) posed a series of questions on the stability of the regional thermohaline circulation. Since then, several authors oriented their work in the Eastern Mediterranean Transient (EMT) event, emphasizing the dynamical implication of the Aegean Sea as a substantial source of regional deep waters [*Roether et al.*, 1996, 2007; *Theocharis et al.*, 1999b, 2002; *Klein et al.*, 1999; *Lascaratos et al.*, 1999; *Samuel et al.*, 1999; *Malanotte-Rizzoli et al.*, 1999; *Zervakis et al.*, 2000; *Wu et al.*, 2000; *Boscolo and Bryden*, 2001; *Tsimplis and Josey*, 2001; *Stratford and Haines*, 2002; *Tsimplis and Rixen*, 2002; *Nittis et al.*, 2003].

[3] In the beginning of the 20th century oceanographic studies focused in the dense waters masses of the Aegean. In a process first proposed by *Nielsen* [1912] North Aegean Dense Water (NAgDW), "a uniform cold and heavy layer from surface to bottom north of Cyclades plateau," could flow toward the South Aegean and possibly contribute to the EMDW. However, *Schott* [1915] re-analyzing Nielsen's data confirmed his argument but disputed the fact that this is a dominant process. Furthermore, *Pollak* [1951], *Wüst* [1961] and later *Hopkins* [1978, 1985] minimized even more the role of the Aegean Sea as a Dense Water Formation (DWF) area, as well as a contributor to the EMDW compared with the Adriatic Sea. Under the same rationale *Plakhin* [1971, 1972] did not comment of the Aegean being a contributor to the EMDW, but made a step forward describing a thermohaline cell triggered from DWF in Chios and Cretan basins. *Lacombe and Tchernia* [1958] and *Miller* [1974] did not change the suggested marginal character of the Aegean Sea with respect to DWF. The only dissonance comes from *El-Gindy and El-Din* [1986], using cruise data from 1948 to 1972, suggesting that just outside the Cretan

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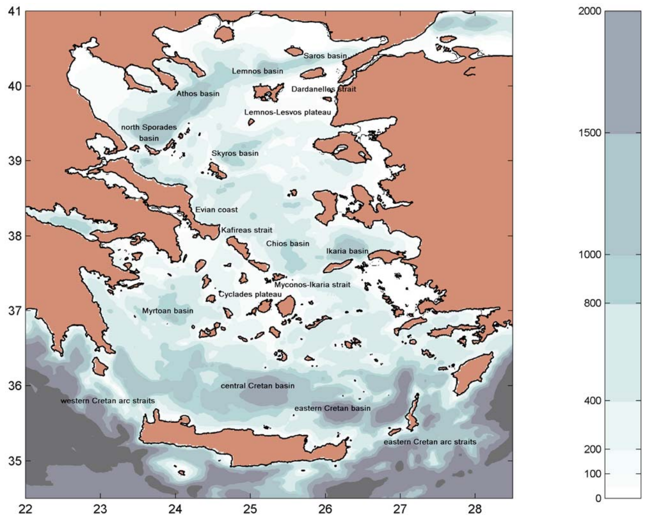


**Figure 1.** Aegean bathymetry and major features (basins, plateaus and straits).

arc straits 40% of the EMDW originated from the Cretan Deep Water (CDW). The general consensus of the majority of the authors in the pre-EMT period, leads to the hypothesis that the Aegean produces occasionally insignificant amounts of dense waters. On the other hand, in the light of new evidence, it becomes increasingly more likely that the Aegean Sea's location and atmospheric forcing make the basin an advantageous DWF area.

[4] The Aegean Sea is a semi-enclosed basin characterized by an alteration of shelves, sills and bottom depressions. It is a semi-enclosed basin located in the northeastern Mediterranean (one of the four major basins of Eastern Mediterranean Sea), covering an area of 180000 km$^2$. It is connected to the Marmara and Black Seas through the Dardanelles Strait in its northern part and connected to the Levantine and Ionian Seas through several straits at the southern end. The total volume of the Aegean Sea is about 75000 km$^3$ with an average depth of 415 m accounting for the presence of extensive plateaus. Its topography is very complicated, with over 3000 islands and islets and, in consequence, introducing fragments of continental shelf areas divided by numerous bottom depressions between them. The deepest basins include the North Aegean trough, encompassing the north Sporades, Athos, Lemnos and Saros basins, with maximum depths up to 1500 m, the Skyros, Chios and Ikaria basins in the Central Aegean with maximum depth of 1100 m, bounded to the south by the broad Cyclades plateau and sills with depths less than 350 m, and finally, the much bigger Cretan basin in South Aegean, with maximum depth of 2500 m (Figure 1).

[5] The dominant winds are primarily from the north, bringing cold and dry air through the Balkan Peninsula [*May*, 1982], contributing to substantial heat fluxes for surface buoyancy loss. The annual amount of evaporation over the Aegean is around 1.3–1.5 m/yr [*Jakovides et al.*, 1989; *da Silva et al.*, 1994; *Drakopoulos et al.*, 1998] and exceeds the sum of precipitation and river runoff 0.5 m/yr and 0.11 m/yr, respectively [*Poulos et al.*, 1997], while the annual upward net heat flux is estimated at 26 W/m$^2$ [*Poulos et al.*, 1997]. The latter implies that the Aegean Sea, on an average loses heat through its surface. A biased method to classify a basin as a concentration or dilution is to examine its density relative to the density of an adjacent basin [*Hopkins*, 1978]. *Zervakis et al.* [2004] suggested that the Aegean should be classified as a concentration basin, based on the density distribution below the sills.

[6] The Aegean's water masses and stratification are subject to strong variability at various timescales [*Zervakis et al.*, 2004; *Skliris et al.*, 2007], intense circulation patterns [*Korres et al.*, 2002; *Olson et al.*, 2007], water mass formation [*Velaoras and Lascaratos*, 2005, 2010; *Gertman et al.*, 2006; *Vervatis et al.*, 2009] and strong forcing of both wind and thermohaline character [*Theocharis et al.*, 1999b; *Sofianos et al.*, 2005]. The combination of this forcing with the complex sub-basin circulation and mesoscale eddy field render a complicated picture of the regional dynamics. All observational studies [*Gertman et al.*, 1990; *Ovchinnikov et al.*, 1990; *Theocharis and Georgopoulos*, 1993; *Theocharis et al.*, 1999b; *Zervakis et al.*, 2000; *Olson et al.*, 2007] and numerical simulations [*Wu et al.*, 2000; *Korres et al.*, 2002; *Nittis et al.*, 2003; *Sofianos et al.*, 2005], point out a general cyclonic circulation in the Aegean Sea, while an anticyclonic pattern dominates the northeastern corner of the basin [*Sofianos et al.*, 2005]. However, the most active dynamic features are the mesoscale cyclonic and anticyclonic eddies, which can extend to several Rossby radii of deformation (around $O$(10 km)). Some of these features appear to be permanent (i.e., cyclonic eddy in south Chios basin, anticyclonic circulation in Lemnos basin), while others have a transient character and yet the mechanisms responsible for the formation and decay of these features are not clear [*Olson et al.*, 2007].

[7] The main water masses and their distribution can be summarized as follows. The most characteristic feature of the stratification pattern in the North Aegean is the surface brackish Black Sea Water (BSW) outflowing from the Dardanelles Strait. The BSW forms a front with the intrusion of the much saltier Levantine Surface Water (LSW) entering the Aegean through the eastern Cretan arc straits. The intermediate layers of the North-Central Aegean are occupied by Levantine Water (LW) of Levantine origin and/or the locally formed Aegean Intermediate Water (AgIW) [*Gertman et al.*, 2006]. The Levantine Intermediate Water (LIW) entering through the eastern Cretan arc straits follows a northward path along the Turkish coast to be modified by the aforementioned LW. Over the Lemnos-Lesvos plateau the LW and/or the AgIW get sub-ducted below the BSW thermohaline front. The vertical structure of the North Aegean is comprised of a 20–70 m modified BSW surface layer, of an intermediate LW and/or AgIW layer down to 400 m and of the locally formed NAgDW [*Zervakis et al.*, 2003, 2004; *Velaoras and Lascaratos*, 2005]. After experiencing strong mixing in the North-Central Aegean, and being modulated by the presence of mesoscale eddies [*Zodiatis*, 1994], the water masses appear at the western side of the South Aegean, along the Evian coast and through the Kafireas strait, with significantly lower salinities than the ambient surface water masses. A less saline water mass present in the sub-surface layers of the South Aegean is the Modified Atlantic Water (MAW). At intermediate depths, the annually ventilated Cretan Intermediate Water (CIW), a water mass more saline than the LIW, has often been

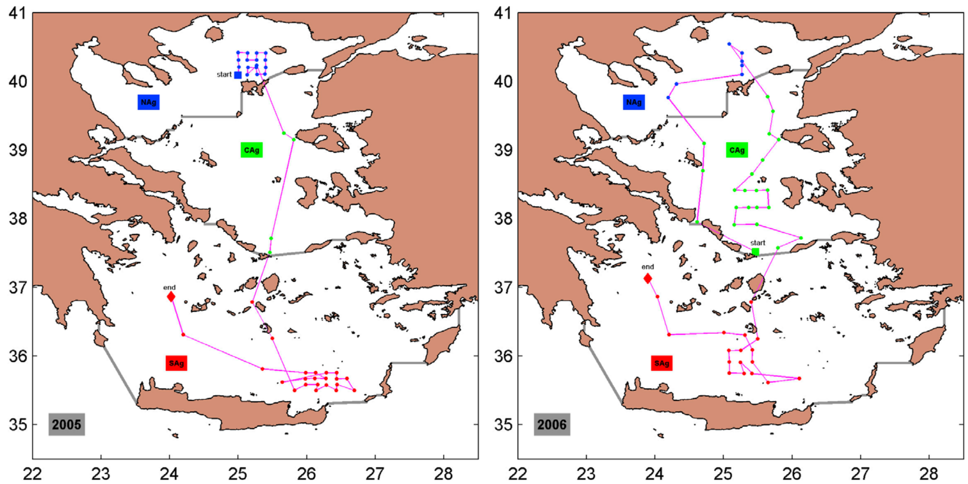


**Figure 2.** Hydrographic CTD stations during the winter cruises of 2005 and 2006; magenta line denotes cruise trajectory; first cruise station (start): square dot; last cruise station (end): diamond dot; North Aegean (NAg): blue dots; Central Aegean (CAg): green dots; South Aegean (SAg): red dots; gray lines: straits boundaries of the three major Aegean sub-basins [*Gertman et al.*, 2006].

monitored above the core of Transitional Mediterranean Water (TMW), a product formed by the mixture of LIW and EMDW outside the Cretan arc. In the early 1980s, the deep layers of the Cretan Sea were occupied by a homogenous water mass similar to the TMW and there was no signal of CDW type [*Zervakis et al.*, 2000].

[8] Observations after the early 1990s revealed a dramatically different structure of the Cretan Seawater column. During the EMT event, extremely dense and saline waters of local origin, started filling the deep Cretan basin and overflowing through the sills of the Cretan arc straits [*Roether et al.*, 1996; *Kontoyiannis et al.*, 1999; *Theocharis et al.*, 1999a, 1999b]. Due to its high density, the CDW displaced water from the deepest parts of the Levantine and Ionian basins of the Eastern Mediterranean, and as a consequence the TMW masses intruded the Cretan basin. During the EMT, the hydrography of the Cretan Sea included a distinctive deep water mass close to the bottom of the basin (800–2500 dbar), possibly formed by convection in the open sea and/or in the surrounding shelf areas [*Theocharis et al.*, 1999b; *Lykousis et al.*, 2002]. This structure was not static but seemed to undergo considerable changes during the same period. Following the EMT, the CDW volume in the Cretan Sea has decreased, most probably due to changes in the DWF processes [*Theocharis et al.*, 2006; *Sofianos et al.*, 2007; *Vervatis et al.*, 2009].

[9] Aiming at portraying the stratification of the Aegean's sub-basins, as well as locating possible areas of DWF processes, two cruises were conducted during the winters of 2005 and 2006 and the basic findings are described in this paper. In section 2 we provide a brief description of the cruises and the data collected. In section 3 the basic Θ-S characteristics of the water masses during both winters are reviewed and the hydrographic structure observed in the major concavities of the Aegean is presented. Additionally, in section 4 DWF structures are presented, under the scope of potential sub-basin coupling mechanisms. Finally, in section 5 in order to quantify the variability of the water mass structure, related to the EMT and its phases, an intercomparison analysis is carried out.

## 2. Data and Methods

[10] Two cruises were carried out on board the R/V *Aegaeo*, from 1 to 10 March 2005 and from 3 to 13 February 2006. During the first cruise a total of 44 hydrographic CTD stations were occupied while a total of 47 stations were recorded in the second cruise (Figure 2). The majority of the stations were concentrated in the deep concavities in order to identify the dense water characteristics along the main north-south axis of the Aegean Sea and locate possible areas of DWF. A small number of stations where occupied on this axis across the Aegean's plateaus, in order to identify possible shelf convection processes and to monitor exchanges between sub-basins.

[11] The profiles of temperature, salinity (conductivity), and dissolved oxygen concentration were collected using a Sea-Bird CTD with a General Oceanics rosette, including 12 Niskin Bottles for the oxygen and salinity calibration. The data set acquired was quality controlled, the dissolved oxygen concentration was calculated with the Winkler method [*Carpenter*, 1965] and the data set was filtered and sub-sampled at 1 dbar vertical resolution. For safety reasons the maximum depth of each profile was approximately 10 dbar shallower than the stations sea bottom. All the temperature and densities discussed in the present paper are potential temperatures and potential densities, respectively. In section 5, in order to compare the stratification of the Aegean Sea in different phases of the EMT event, a data set covering the winter of 1987 [*Malanotte-Rizzoli and Robinson*, 1988] has been analyzed together with the data sets of the 2005 and 2006 winter cruises. From the aforementioned data sets an averaged profile has been computed for each Aegean sub-basin. Finally, a data set (MEDATLAS II) was used for analysis of the Aegean deep

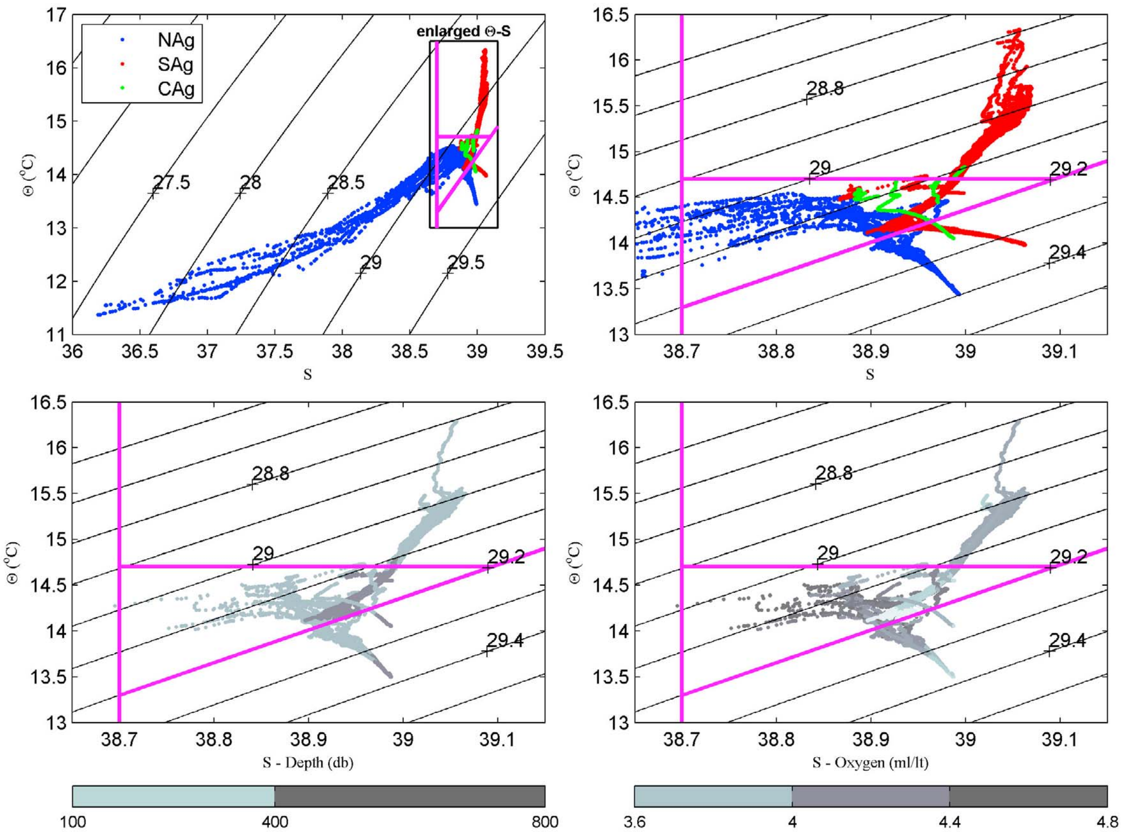


**Figure 3.** Θ-S diagram; winter 2005; North Aegean (NAg): blue dotes; Central Aegean (CAg): green dots; South Aegean (SAg): red dots; Gray-color bars: intermediate depths (db) and oxygen concentrations (ml/lt). Θ/S/$\sigma_\Theta$ boundaries (magenta lines): NAg surface layers (S < 38.7), SAg surface layers (Θ > 14.7°C), Aegean dense waters ($\sigma_\Theta$ > 29.2 kg/m$^3$) [*Gertman et al.*, 2006].

water properties evolution, during the EMT [*MEDAR Group*, 2002].

## 3. Cruises Hydrographic Observations

### 3.1. Θ-S Characteristics of the Aegean Sea

[12] The temperature and salinity characteristics measured during the first cruise, in winter 2005, are depicted in Figure 3. The projected data in a Θ-S diagram revealed a diversity of the surface and deep layers between the North (blue dots) and South (red dots) Aegean. The Θ-S characteristics present a distinct "X-shape." At the surface, the low salinity BSW layer and a warm LSW feature are observed, whereas in the deep layers, locally formed dense water masses of the NAgDW and CDW are found. The same Θ-S pattern is also observed in the second cruise in winter of 2006 (Figure 4). Differences between the two years data sets are mainly due to surface variability of the intruded BSW and LSW masses and different locations of sampling (e.g., Lemnos/Athos basins in North Aegean, Skyros/Chios basins in Central Aegean, central/eastern Cretan basins in South Aegean). Spatial differences in the deep layers across the Aegean sub-basins, indicates DWF variability and/or different Θ-S modification rates inside the depressions [*Zervakis et al.*, 2003, 2009].

[13] In Figures 3 and 4 the magenta triangle, following *Gertman et al.* [2006], represents intermediate layers of the Aegean, leaving outside the surface and deep waters. The "X-shape" of the Θ-S diagram implicitly suggests a transition in properties inside the magenta triangle where the North and South Aegean Θ-S characteristics converge in the Central Aegean, as clearly depicted in both cruises in Figures 3 and 4 (green dots, upper panels). The Θ-S trace indicates possible DWF, since high dissolved oxygen concentrations higher than 4.8 ml/L prevail from the surface down to depths of 400 m (Figures 3 and 4, lower panels). In general, relatively high dissolved oxygen concentrations were recorded in intermediate depths across all three Aegean sub-basins.

### 3.2. Stratification and Circulation

[14] In the North Aegean, observations on a dense grid of CTD stations from 2005 winter survey, illustrate the water mass structure of Lemnos basin. A SW-NE transect reveals a strongly stratified water column in the region (Figure 5). The most prominent water mass feature, characteristic of the circulation pattern and exchange with the Dardanelles Strait is the BSW intrusion, with surface temperature minimum 11.5°C, salinity 36.2 and density 27.5 kg/m$^3$, in a wedge like layer with depth changing from 100 m in the NE to 20 m in the SW ends of section. This salinity minimum is combined with the dissolved oxygen concentration maximum of the intruding water. The BSW intrusion from the Dardanelles Strait into Lemnos basin is divided in two basic branches

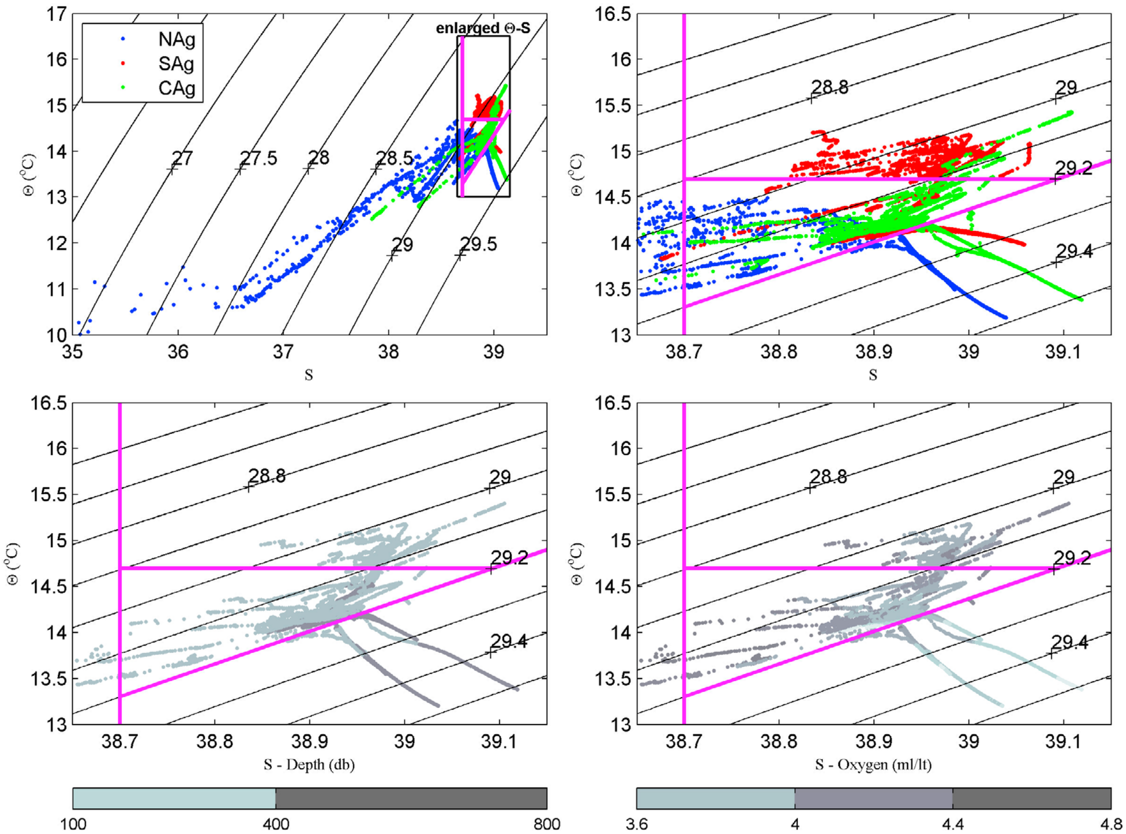


**Figure 4.** Θ-S diagram; winter 2006; North Aegean (NAg): blue dotes; Central Aegean (CAg): green dots; South Aegean (SAg): red dots; Gray-color bars: intermediate depths (db) and oxygen concentrations (ml/lt). Θ/S/$\sigma_\Theta$ boundaries (magenta lines): NAg surface layers (S < 38.7), SAg surface layers (Θ > 14.7°C), Aegean dense waters ($\sigma_\Theta$ > 29.2 kg/m$^3$) [*Gertman et al.*, 2006].

around the island of Lemnos, depicted also with surface drifters [*Olson et al.*, 2007]. The first is westward through Saint Eustratius strait and the second is northward through Lemnos strait. The second branch influences more the surface layers of Lemnos basin since the BSW extends to greater depths (Figure 5). Below the surface layer, a warmer and more saline layer centered at intermediate depths, extends down to 400 m in Lemnos basin (Figure 5, Θ/S panels). This denser water mass cannot be formed locally due to presence of the BSW insulator layer at the surface [*Zervakis et al.*, 2003, 2004; *Velaoras and Lascaratos*, 2005; *Gertman et al.*, 2006] and is most probably advected from the Central Aegean. This water mass (Figure 5, Θ panel) is a mixture of LW and/or AgIW formed locally in the Central Aegean (discussed in section 4), with varying values of temperature 13.9–14.4°C, salinity 38.7–39 and density 29–29.2 kg/m$^3$. In greater depths, below the main sill level, to the bottom of Lemnos basin the dissolved oxygen concentration decreases to 3.7 ml/l. The very low oxygen concentration of the deep waters inside Lemnos basin indicates possible trapping of "old" dense water from the early stages of the EMT. At the time of the cruises in the deepest parts of Lemnos basin, below 1000 m, the density was around 29.4 kg/m$^3$ gaining buoyancy in comparison with the first stages of the EMT [*Zervakis et al.*, 2003, 2009].

[15] In the Central Aegean the locally formed water masses, as well as the water masses of Black Sea and Levantine origin, undergo strong mixing while being modulated by the presence of mesoscale eddies [*Zodiatis*, 1994]. The modified water masses follow the general cyclonic circulation of the Aegean, exiting the Central Aegean via two main paths to the South Aegean: a surface path through Kafireas strait with Θ-S characteristics of 13°C, salinity at 38.1 and 28.8 kg/m$^3$ and a surface/intermediate path through Myconos-Ikaria strait. The latter exchange between the Central and South Aegean is monitored from three stations across the strait (Figure 6). Warm and saline waters of Levantine origin (maximum values at 15.4°C and salinity at 39.1, Figure 6, Θ/S panels), enter the Central Aegean at the east end of the strait with densities of 29 kg/m$^3$ (Figure 6, $\sigma_\Theta$/$O_2$ panels), whereas cool and less saline AgIW egress from surface/intermediate depths at the west side of the strait (minimum values at 13.8°C and salinity at 38.7, Figure 6, Θ/S panels) with slightly increased densities of 29.1 kg/m$^3$ (Figure 6, $\sigma_\Theta$/$O_2$ panels).

[16] The vertical water mass structure of the South Aegean follows a post-EMT typical three layer pattern consisting of a surface, an intermediate and a deep layer, but in contrast with the North Aegean the stratification is much weaker (surface density 29 kg/m$^3$; 1000 m density 29.18 kg/m$^3$). However, none of the layers resemble the Θ-S characteristics of the North Aegean. This can be explained mainly by the very strong influence from the adjacent basins. In Figure 7, a NW-SE transect during the winter close to

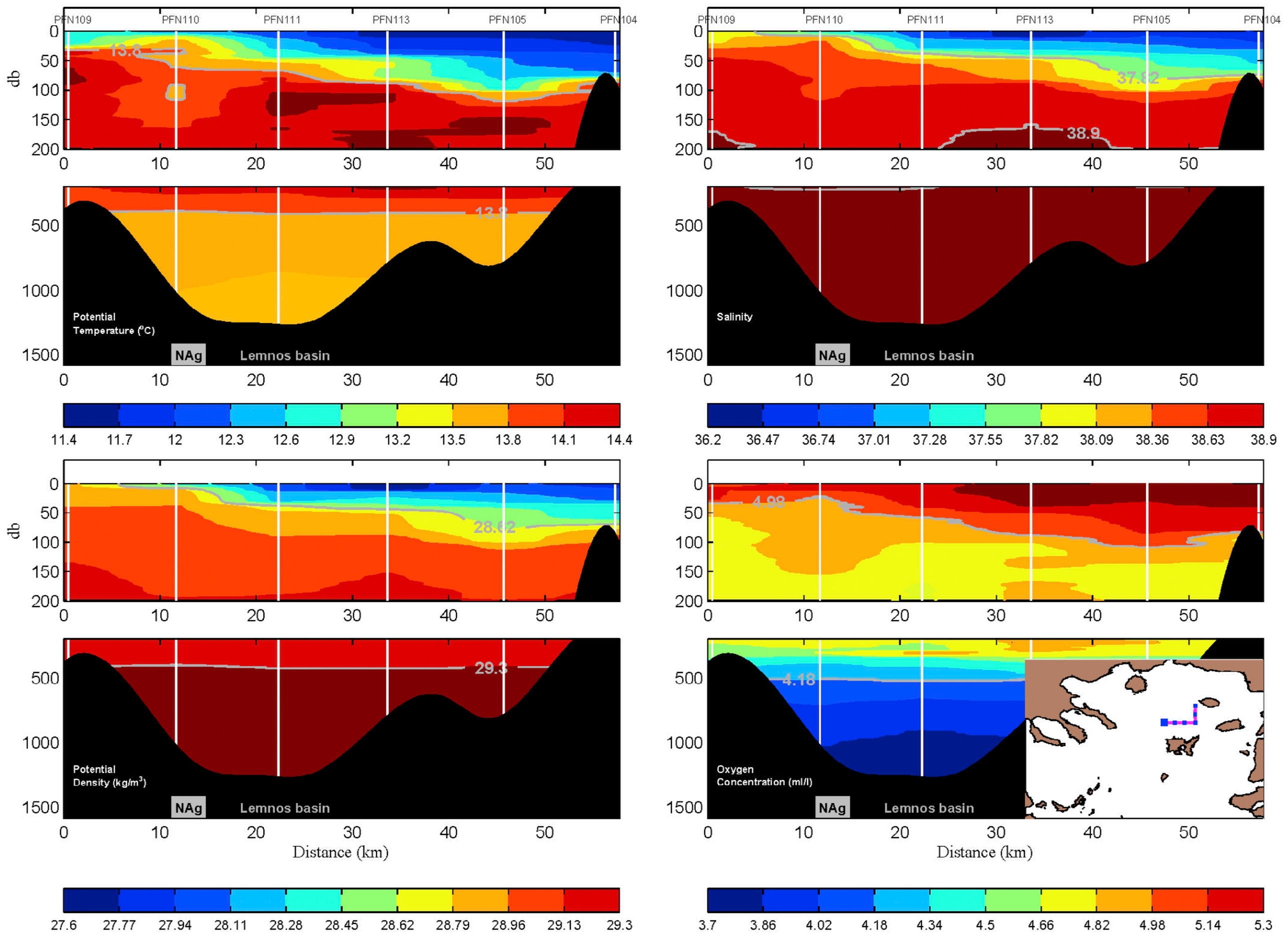


**Figure 5.** Transects of Θ (°C), S, $\sigma_\Theta$ (kg/m$^3$) and oxygen concentration (ml/lt), of 6 CTD stations in the winter of 2005 at Lemnos basin in the North Aegean (NAg); inside map blue large dot denote initial station, following a SW-NE direction of the magenta section (small blue dots); top axis indicating the code names of the stations during the cruise; lower axis are in distance (km) from the initial station; major seabed features: Lemnos basin.

Kassos strait, depicts the strong influence of Levantine region to South Aegean. In contrast with Lemnos basin where the surface stratification is dominated by the shallow (20–100 m thickness) BSW layer, the South Aegean Mixed Layer Depth (MLD) extends to 200 m (Figure 7). The horizontal temperature gradient, ascribed to a permanent cyclone in the eastern Cretan Sea [*Balopoulos et al.*, 1999; *Theocharis et al.*, 1999b; *Kontoyiannis et al.*, 1999; *Tsimplis et al.*, 1999; *Georgopoulos et al.*, 2000], is dominating the region (Figure 7, Θ/S panels).

[17] The South Aegean intermediate layers consisted of several intrusive and locally formed water masses. A mixture of LIW and locally formed Cretan Intermediate Water (CIW) lies between 200 and 500 m (Figure 7, Θ/S panels, intermittent core of 14.6°C and salinity at 38.98). A second very distinct intermediate layer in the Cretan Sea is the TMW, a mixture of LIW and old EMDW with its core around 750 m, which enters from the adjacent Levantine basin through Kassos strait at the sill depth. The TMW Θ-S core characteristics are low temperature 14.2°C, relatively low salinity 38.92 and low dissolved oxygen concentrations 3.97 ml/l (Figure 7) and had never been recorded inside the Aegean in the pre-EMT period. In the first stages of the EMT, the TMW was present in the Cretan Sea in intermediate layers of about 300 m [*Theocharis et al.*, 2006; *Sofianos et al.*, 2007; *Vervatis et al.*, 2009]. Since 1995 the EMT event started to decay confirming its transitional character. As a consequence, the TMW core was continuously deepening, due to the deflation and outflow of the CDW from the Cretan to Levantine basin through Kassos strait. At the time of the cruises, the CDW horizon has dropped in depths greater than the Kassos sill. The deep layers of Cretan basin are filled by CDW, locally formed in the Aegean Sea, with properties of 14°C, salinity of 39.06, 29.32 kg/m$^3$ and dissolved oxygen concentration of 4.2 ml/l, which is larger than the overlying TMW.

## 4. DWF Processes

[18] Although the North Aegean is a dilution basin (winter surface densities of 28 kg/m$^3$ influenced by the presence of BSW), the deep layers are filled up to the sills with very dense waters (29.4 kg/m$^3$ below a depth of 1000 m). Several authors in recent studies [*Zervakis et al.*, 2000, 2003; *Tragou et al.*, 2003; *Nittis et al.*, 2003] suggested that the northern Aegean can act in some exceptionally rare cases as a concentration basin, under extremely cold and dry winter

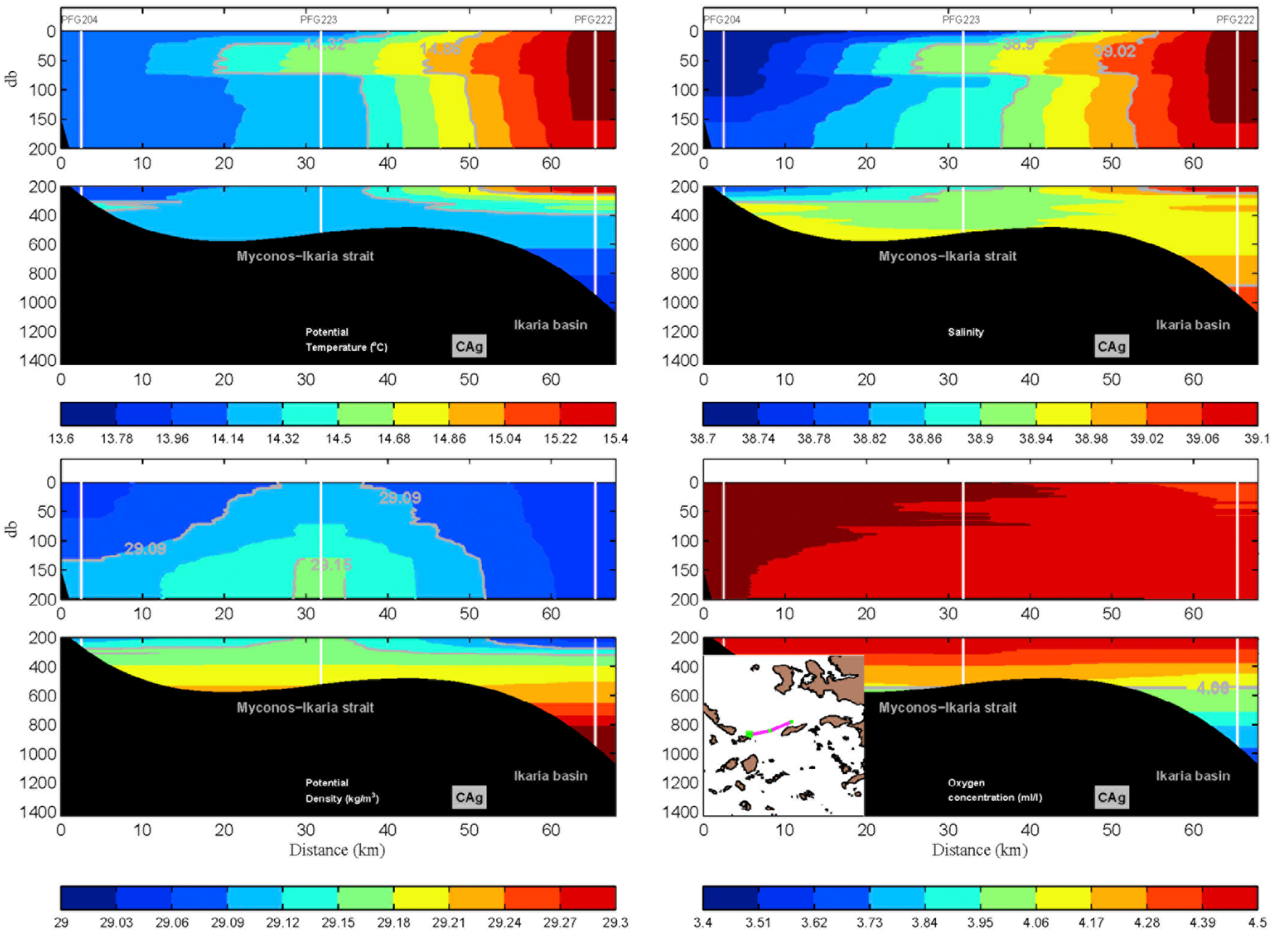


**Figure 6.** Transects of $\Theta$ (°C), S, $\sigma_\Theta$ (kg/m$^3$) and oxygen concentration (ml/lt), of 3 CTD stations in the winter of 2006 at the north edge of the Myconos-Ikaria strait in the Central Aegean (CAg); inside map green large dot denote initial station, following a W-E direction of the magenta section (small green dots); top axis indicating the code names of the stations during the cruise; lower axis are in distance (km) from the initial station; major seabed features: Myconos-Ikaria strait, Ikaria basin.

events such as the EMT. Under this scope two basic scientific questions arise: Are the Aegean sub-basins decoupled or is there a connecting mechanism? Is the Aegean circulation controlled by intrusions from adjacent basins or by local processes?

[19] Investigating the role of the Central Aegean in DWF processes, a number of stations were occupied during the cruise of 2006 in Skyros, Chios and Ikaria deep basins, aiming at capturing open ocean convection events and shelf convection in Lemnos-Lesvos plateau. In Figures 8 and 9 both eastward and westward transects are depicted, respectively, introducing a winter snapshot of the North-Central Aegean. The most outstanding feature in both transects is the surface isopycnal layers of 29.1 kg/m$^3$ and 29.2 kg/m$^3$ over almost the entire Central Aegean (Figures 8 and 9, $\sigma_\Theta$ panel). The physical mechanism which makes this area favorable for DWF is the combination of extreme saline LSW, loss of buoyancy through intense winter cooling, along its northward travel over the depressions and plateaus of the Central Aegean and finally transformed to the locally formed AgIW. This buoyancy loss mechanism is enhanced by the trapping of water in the permanent and semi-permanent cyclonic features in the region (Chios and Skyros cyclones) over the deep sub-basins [*Lykousis et al.*, 2002; *Olson et al.*, 2007]. Both deep water and shelf convection processes across the Lemnos-Lesvos plateau are believed to contribute to DWF in the region. During the 2006 cruise the DWF processes extended to intermediate depths around 400 m. The densest surface waters masses observed above Lemnos-Lesvos plateau at 29.3 kg/m$^3$, while in Chios and Skyros depressions the surface density was measured at 29.2 kg/m$^3$.

[20] Evidence of previous occurrences of DWF in the region is revealed by the deep stagnant layers in Figures 8 and 9. In Skyros and Athos basins, a strong EMT signal seems to be preserved since the late 1980s period, evidenced by extreme dense waters trapped in the bottom depressions. In Figure 9 the EMT signature is emphasized with low dissolved oxygen at 3.4 ml/l, low temperatures at 13°C and salinities at 39.05, resulting to high densities of 29.4 kg/m$^3$. *Zervakis et al.* [2003, 2009] suggested a slow renewing of the deep waters in both Skyros and Athos basins, due to an internal wave braking mechanism.

[21] Intrusive water masses from adjacent basins, such as the Levantine and Black Seas can play significant roles in the Aegean Sea processes. The fact that two different water

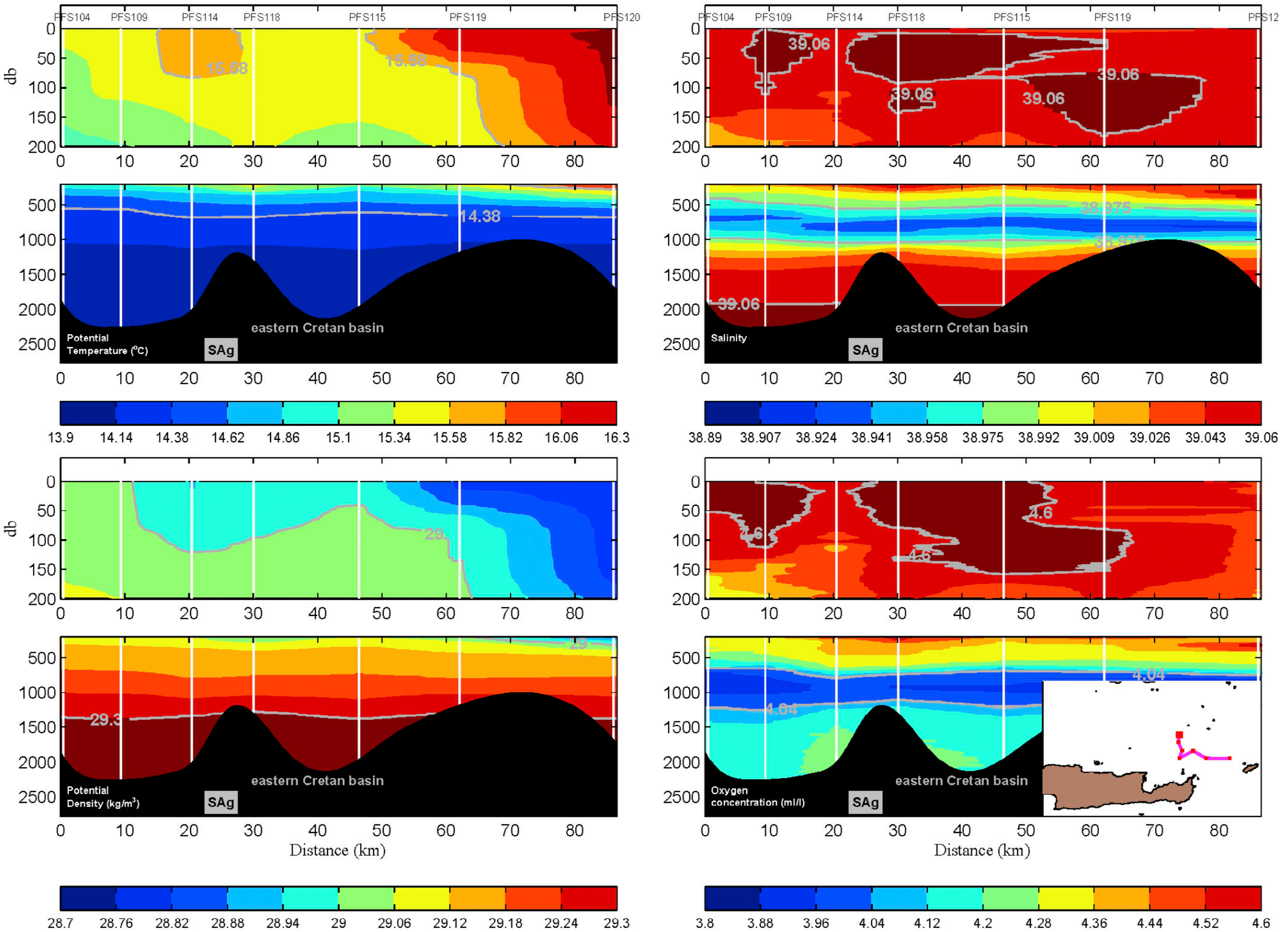


**Figure 7.** Transects of Θ (°C), S, $\sigma_\Theta$ (kg/m$^3$) and oxygen concentration (ml/lt), of 7 CTD stations in the winter of 2005 at eastern Cretan basin in the South Aegean (SAg); inside map red large dot denote initial station, following a NW-SE direction of the magenta section (small red dots); top axis indicating the code names of the stations during the cruise; lower axis are in distance (km) from the initial station; major seabed features: eastern Cretan basin.

masses (with very diverse temperature, salinity and density characteristics) are intruding from the south and north ends of the basin does not allow the development of a simple thermohaline cell. The BSW, with very low density, is covering big parts of the north region of the Aegean acting as an insulator and preventing DWF processes [*Zervakis et al.*, 2004]. Coupling between the basins is achieved through intermediate (and possibly deep) water mass formation processes in the central part of the basin, creating a rather complicated thermohaline cell. A replenishing mechanism of intermediate layers is introduced, through buoyancy loss of the saline LSW. A mixture of LW and/or locally formed AgIW recirculates at intermediate depths across the Aegean. Convection was monitored in Chios basin during the winter of 2006 (Figure 10), enhanced by the permanent Chios cyclone [*Sofianos et al.*, 2005; *Olson et al.*, 2007]. Dense water masses formed in Chios basin are observed to be spreading isopycnally at 400 m. The Θ-S characteristics of the dense water masses at intermediate depths of Chios basin (Figure 10, Θ/S panels) are also found in the North Aegean (Figures 5, 8 and 9, Θ panel) and in the western side of the Myconos-Ikaria strait (Figure 6), flowing into the South Aegean. The deep layers in different basins are decoupled from each other due to very irregular seabed topography.

## 5. Pre/Post-EMT State

[22] The stratification monitored during 2005 and 2006 cruises should be discussed in the framework of the EMT climatic shift. The question is: how typical is this late-post EMT pattern? In order to answer the latter question, a pre-EMT reference year, namely data from a 1987 cruise [*Malanotte-Rizzoli and Robinson*, 1988], is compared to the winter cruises of 2005 and 2006 (Figure 11, 1987–2005–2006 map panels). *Zervakis et al.* [2000] presented a synoptic log of the winter survey in the beginning of the EMT during 1987. A severe buoyancy loss took place in mid-March [*Lagouvardos et al.*, 1998] a few days before the stations depicted at Lemnos and Chios basin (Figure 11, 1987 map panel, blue/green dots). Therefore, no significant EMT signal was yet detected at that time in the deep layers. The stations in the Cretan basin (Figure 11, 1987 map panel, red dots) chronologically are placed in late-March, but the EMT signal monitored at least two months later in late-April. Conse-

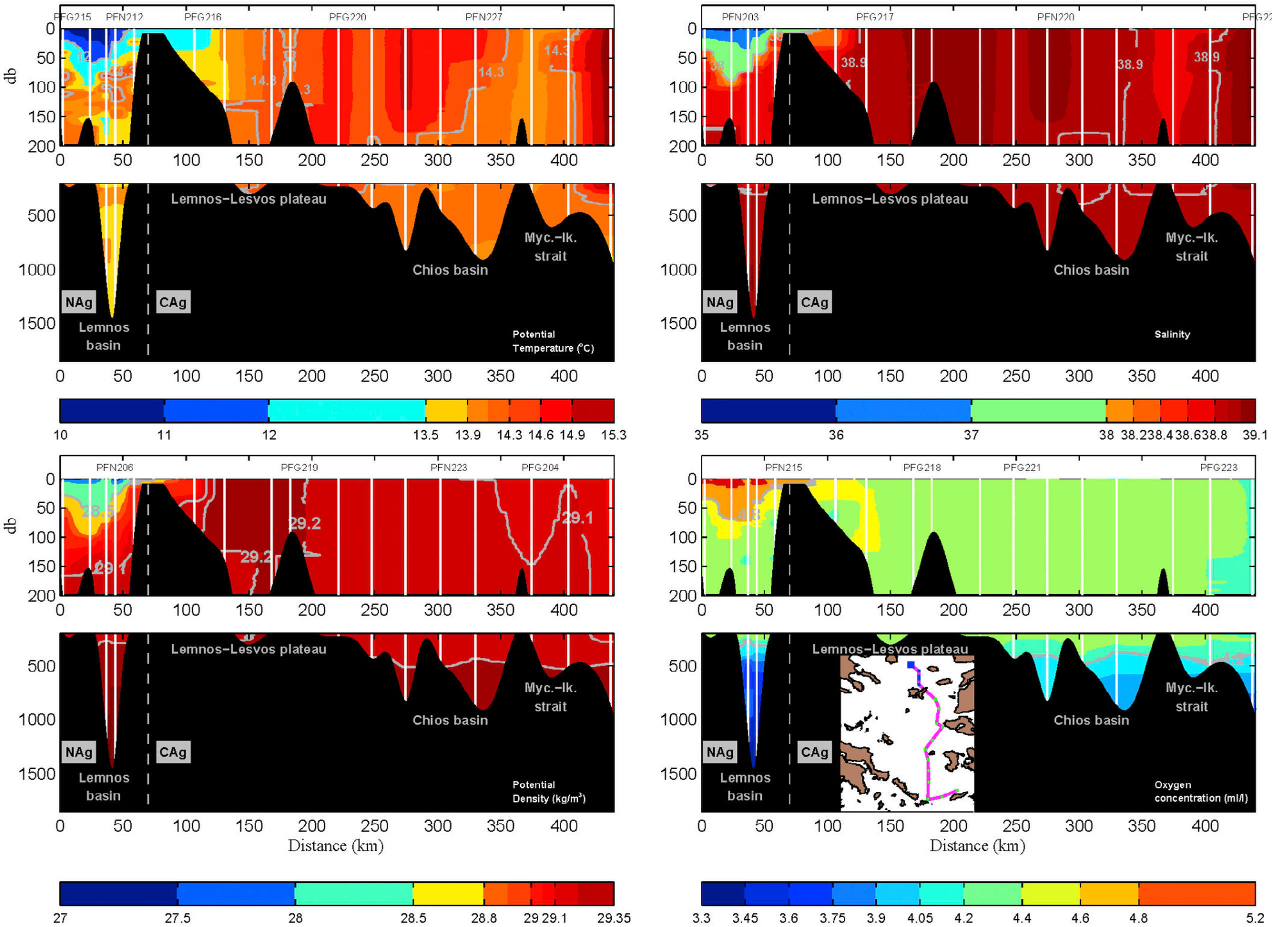


**Figure 8.** Transects of Θ (°C), S, $\sigma_\Theta$ (kg/m$^3$) and oxygen concentration (ml/lt), of 17 CTD stations in the winter of 2006 at the eastern side of the North-Central Aegean (NAg-CAg); vertical dashed gray line in seabed divides NAg-CAg regions; inside map blue large dot denote initial station, following a N-S direction of the magenta section (small blue-green dots for NAg-CAg, respectively); top axis indicating the code names of the stations during the cruise; lower axis are in distance (km) from the initial station; major seabed features: Lemnos basin, Lemnos-Lesvos plateau, Chios basin, Myconos-Ikaria strait.

quently, the 1987 mid/late-winter profiles are considered to be representative of the pre-EMT state of the Aegean.

[23] In Figure 11 (Θ/S/$\sigma_\Theta$ panels for the North-Central-South Aegean), an average winter profile is depicted, of the thermohaline properties during the three years (1987, 2005 and 2006). The North Aegean profiles reveal a three-layer stratification (Figure 11, top row Θ/S/$\sigma_\Theta$ panels). Surface BSW intrusion enhances the stratification, whereas LW and/or AgIW replenish the intermediate layers. In the deep layers NAgDW is trapped in the depressions. During 1987 the North Aegean surface waters appear to be more saline, probably due to reduction of the BSW inflow [*Zervakis et al.*, 2000] and/or to intrusion of larger amounts of LSW/LIW [*Malanotte-Rizzoli et al.*, 1999]. At the time of the cruises, the typical North Aegean Θ-S characteristics significantly changed, as the colder and less saline intermediate/deep layers altered in more saline water masses (Figure 11). Between the cruises, in late post-EMT state, the deep layers of Lemnos basin indicate a small buoyancy gain due to a possible internal wave breaking [*Zervakis et al.*, 2003, 2009]. This mechanism introduces a slow evolution of the North Aegean deep layers in the post-EMT period, in contrast to the uplifting mechanism of the deep layers ventilation during the EMT period.

[24] The South-Central Aegean exhibits a completely different structure during the pre/post-EMT periods. A two-layer stratification in both areas during the pre-EMT period changed in a compound mode during the EMT phase. In Central Aegean warm and saline surface water masses existed on top of cold and less saline trapped deep layers (Figure 11, middle row Θ/S/$\sigma_\Theta$ panels). During the winter cruises of 2005 and 2006 a much weaker stratification was observed, resulting to an almost uniform dense water column in 2006 of 29.15–29.2 kg/m$^3$ (Figure 11, middle row $\sigma_\Theta$ panel). The DWF processes described in section 4, replenish the intermediate layers of the Aegean sub-basins. The evolution of the deep layer characteristics during the EMT is presented in Figure 12, where the average deep (below 600 m, extracted from MEDATLAS II database) temperature, salinity and density was computed form data obtained during cruises from 1986 to 2006 [*MEDAR Group*, 2002]. Because the pre-EMT temperature/salinity patterns of the deep layers of the Central and South Aegean basins were similar (Figure 11, middle and bottom rows Θ/S/$\sigma_\Theta$ panels, 1987; Figure 12), and the bottom

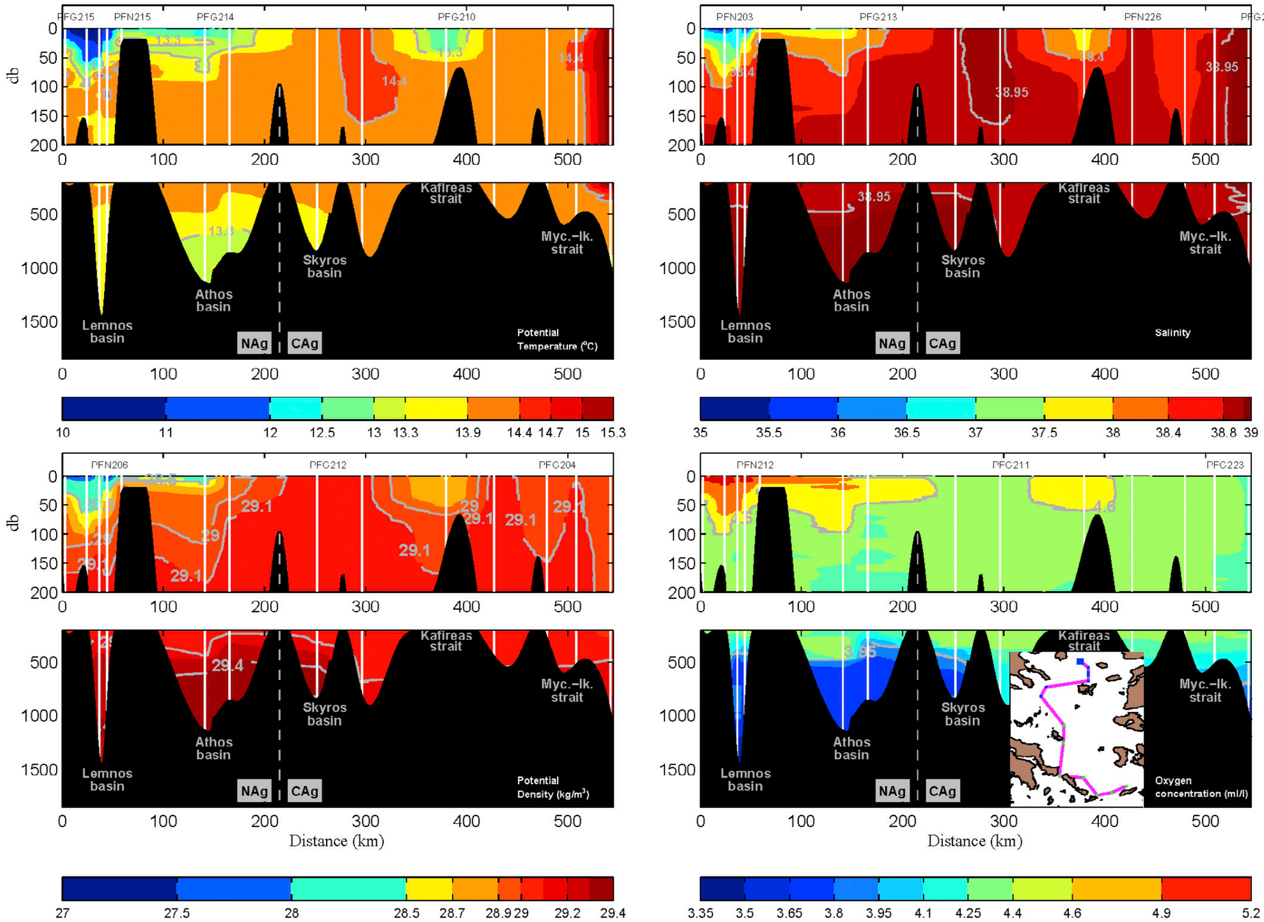


**Figure 9.** Transects of Θ (°C), S, $\sigma_\Theta$ (kg/m$^3$) and oxygen concentration (ml/lt), of 14 CTD stations in the winter of 2006 at the western side of the North-Central Aegean (NAg-CAg); vertical dashed gray line in seabed divides NAg-CAg regions; inside map blue large dot denote initial station, following a N-S direction of the magenta section (small blue-green dots for NAg-CAg, respectively); top axis indicating the code names of the stations during the cruise; lower axis are in distance (km) from the initial station; major seabed features: Lemnos basin, Athos basin, Skyros basin, Kafireas strait, Myconos-Ikaria strait.

density of the Central basin was higher than that in the South Aegean at that time, it seems likely that the deep waters of the Central basin acted as a reserve supply of dense water for the deeper part of the Southern basin. In fact, while salinity increased at deep layers in both basins, it was compensated by a temperature increase that resulted in a decrease of deep water density in the Central Aegean, while there was a marked increase of density in the Southern Aegean deep waters compared to pre-EMT stratification (Figure 11, middle and bottom rows Θ/S/$\sigma_\Theta$ panels; Figure 12). Furthermore, the coupling of the Central-South Aegean deep layers is complicated, due to entrainment phenomena, underlined from the greater densities in Chios than in Cretan basin, during the first stages of the EMT (Figure 12).

[25] The very complicated topography of the Aegean Sea can also play a role in the evolution of deep water characteristics. The topographic differences between the North and Central Aegean, highlighted by the hypsographic diagrams in Figure 13, can explain the density differences in the deep layers. Lemnos and Athos basins are very abrupt with a wide, shallow shelf and contrasting deep depression, favorable for replenishment by abrupt pulses of DWF on shelf regions such as the Lemnos-Lesvos plateau. The Chios basin is more like a V-shaped basin with gradual depth change (Figure 13), and easier to replace deep water masses by thermohaline circulation cell. However, in Central Aegean in Skyros basin the seabed topography is similar with the North Aegean Athos and Lemnos basins (Figure 13), and the deep water thermohaline properties deviate from those in Chios basin (Figures 4 and 9). This effect of topography on deep water mass renewal can explain the density differences between the depressions in the North and Central Aegean. Although temperature, salinity and density increased during the EMT in all northern deep basins, the density of the Central Aegean appears lower in the post-EMT, where renewal processes are favored by the local topography.

[26] The EMT signal inside the Cretan Sea has recently declined [*Theocharis et al.*, 2006; *Sofianos et al.*, 2007; *Vervatis et al.*, 2009] confirming its transitional character. However, it is still remaining strong enough to obscure a

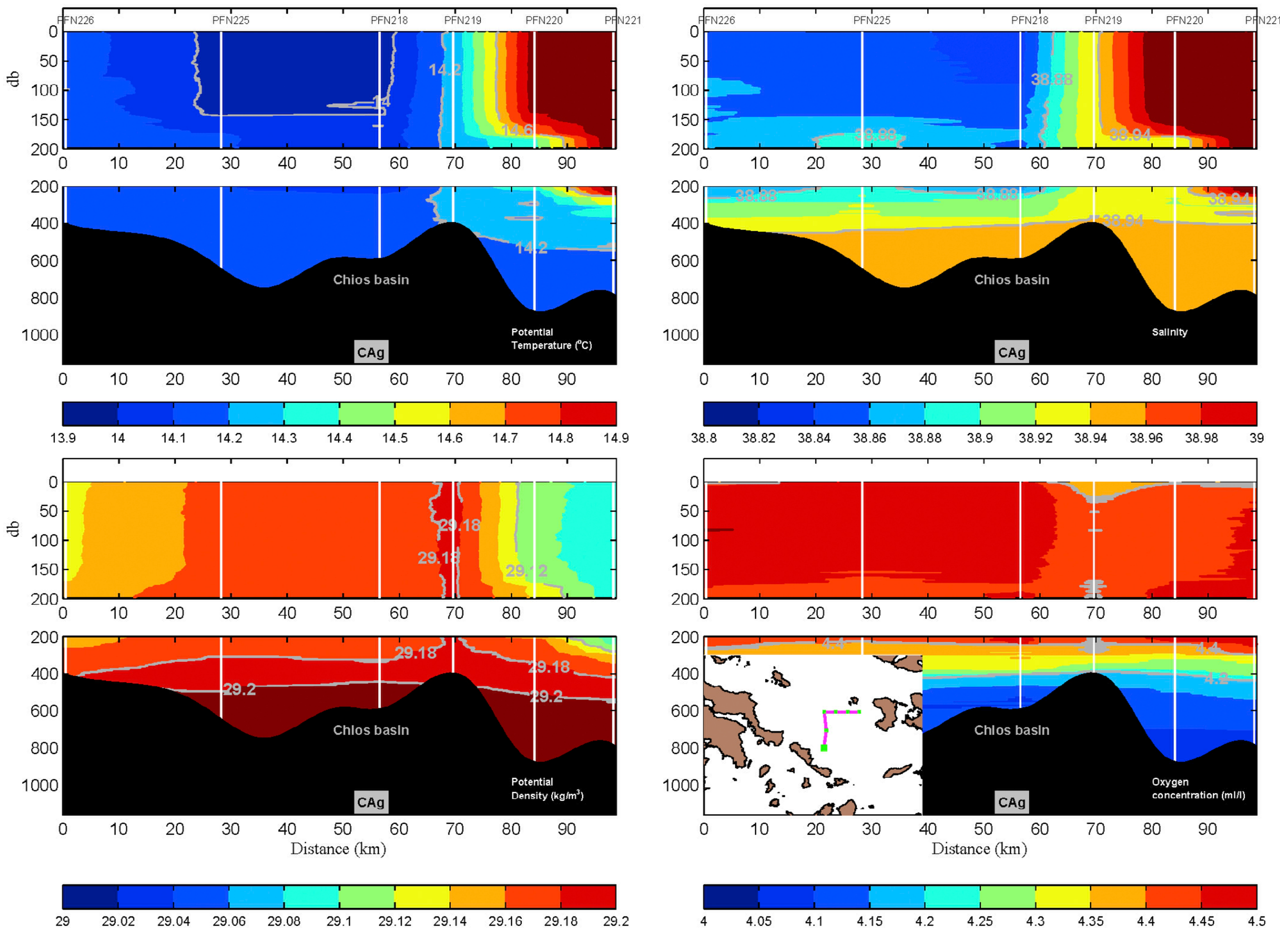


**Figure 10.** Transects of Θ (°C), S, $\sigma_\Theta$ (kg/m$^3$) and oxygen concentration (ml/lt), of 6 CTD stations in the winter of 2006 at Chios basin in the Central Aegean (CAg); inside map green large dot denote initial station, following a SW-NE direction of the magenta section (small green dots); top axis indicating the code names of the stations during the cruise; lower axis are in distance (km) from the initial station; major seabed features: Chios basin.

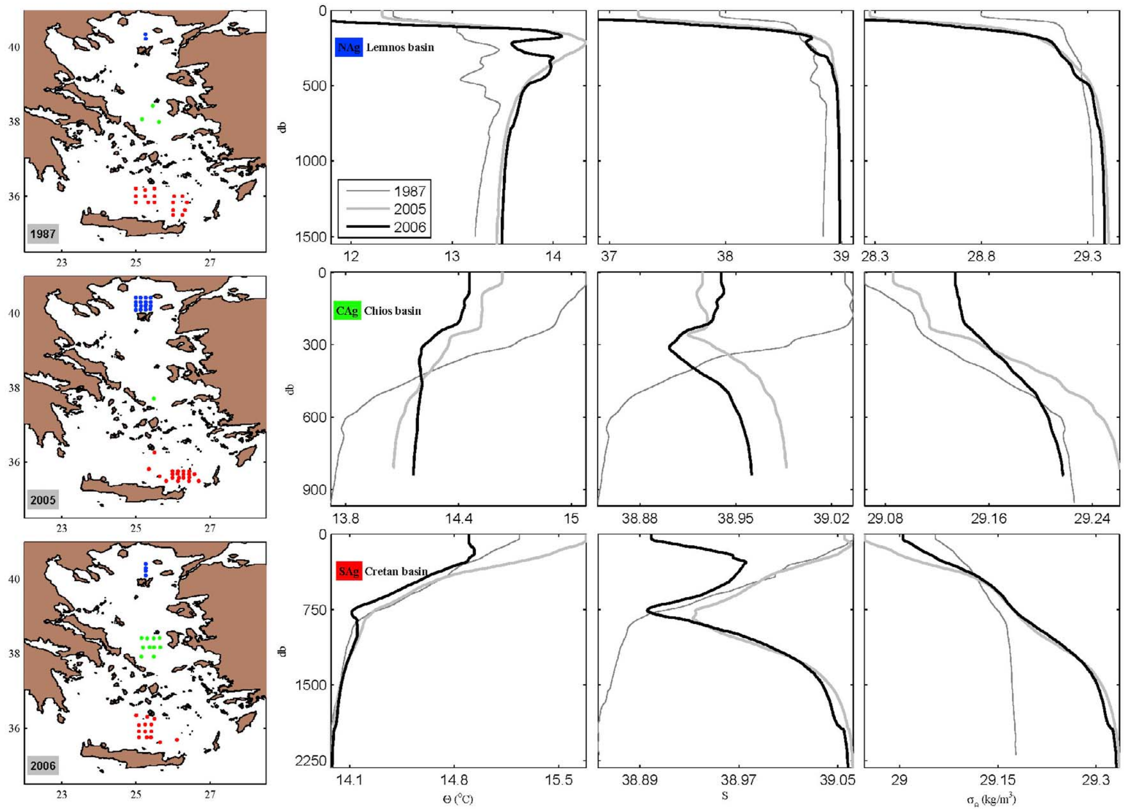


**Figure 11.** Map panels: Aegean Sea winter hydrographic stations for the years 1987 (pre-EMT), 2005 and 2006 (post-EMT); North Aegean (NAg): blue dots at Lemnos basin; Central Aegean (CAg): green dots at Chios basin; South Aegean (SAg): red dots at central-eastern Cretan basin. $\Theta$/S/$\sigma_\Theta$ panels: Averaged profiles of $\Theta$ (°C), S and $\sigma_\Theta$ (kg/m$^3$), for all three major sub-basins.

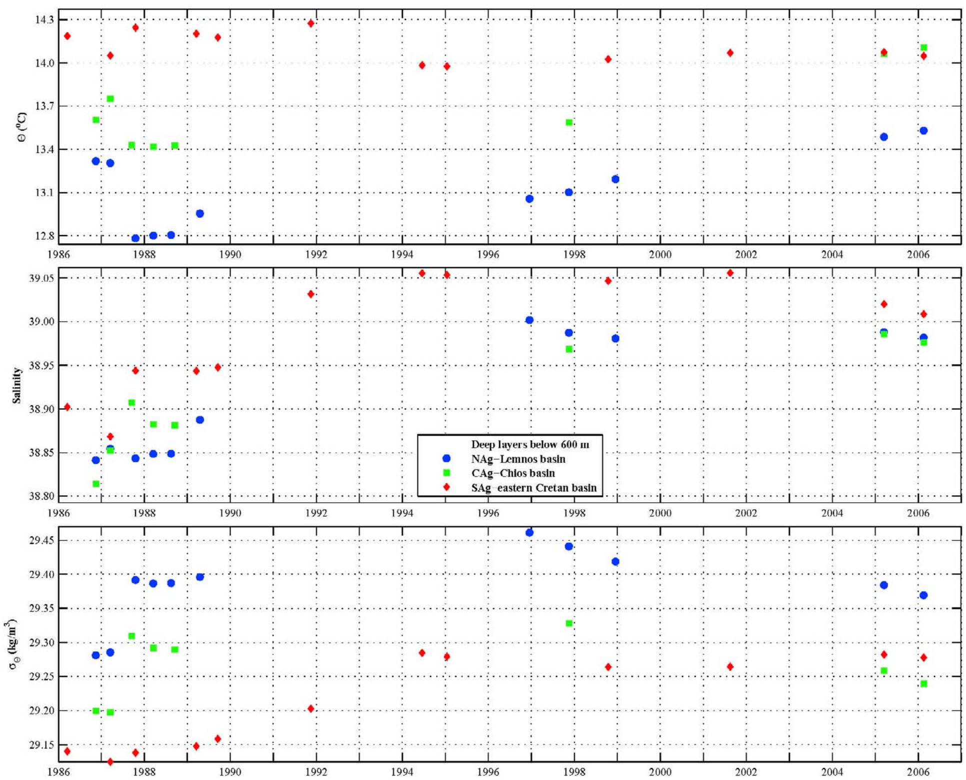


**Figure 12.** Θ/S/$\sigma_\Theta$ properties of the Aegean deep layers (averaged data below 600 m) during the pre/post-EMT period (1986–2006). Lemnos (North Aegean-NAg, blue circles), Chios (Central Aegean-CAg, green squares) and eastern Cretan (South Aegean-SAg, red diamonds) sub-basins.

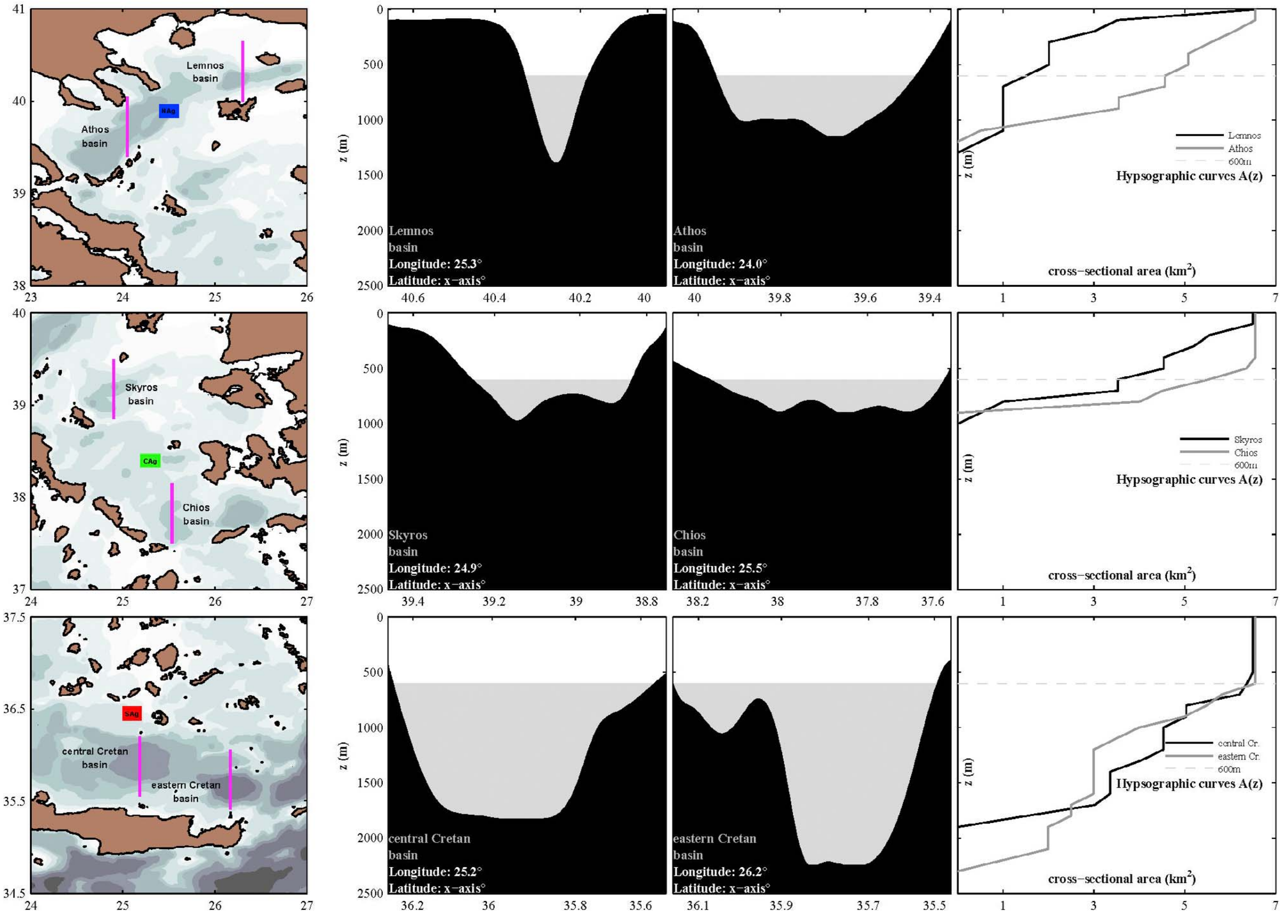


**Figure 13.** Hypsographic curves A(z) (km$^2$) of cross-sectional areas as a function of depth z (m). Meridional cross-sectional areas (magenta lines inside maps): Lemnos and Athos basins in North Aegean (NAg), Skyros and Chios basins in Central Aegean (CAg), central Cretan and eastern Cretan basins in South Aegean (SAg). Gray areas in transects and gray dashed line in hypsographic diagrams denote the deepest layers of the basins (below 600 m).

clear understanding of the dynamics of the Aegean, since the CDW remains extremely dense (29.32–29.34 kg/m$^3$ below 2000 m) and because the TMW evolution masks the signals of the change in intermediate layers.

## 6. Summary and Discussion

[27] Two winter cruises in the late post-EMT period were conducted during the winter season of 2005 and 2006 aiming at depicting the distribution of the thermohaline properties and possible DWF processes in the Aegean Sea. Previous studies highlighted the dramatic changes that took place in the region during the EMT [*Gertman et al.*, 1990, 2006; *Roether et al.*, 1996, 2007]. With respect to the last decade observational studies [*Balopoulos et al.*, 1999; *Kontoyiannis et al.*, 1999; *Tsimplis et al.*, 1999; *Theocharis et al.*, 1999a, 1999b; *Georgopoulos et al.*, 2000; *Zervakis et al.*, 2000, 2003, 2004; *Lykousis et al.*, 2002], the cruises designed to portray the water mass changes in the deep basins of the North and South Aegean. The decoupled surface and deep water masses, unveiled an intermediate conveyor belt coupling the Aegean sub-basins. A distinct "X-shape" Θ-S emphasizes that the intermediate layers connects the basins through a main thermohaline cell. Occasional deep water formation processes replenish the deep layers while the intermediate waters serve in their preconditioning.

[28] Intrusive water masses from adjacent basins, such as the Levantine and Black Seas influence the surface variability of the region, masking local effects. The deep layers of the three major bottom depressions of the Aegean Sea are decoupled from each other due to the very irregular seabed topography. Intermediate layers are replenished through buoyancy loss of the saline LSW. Both open ocean (Chios and Skyros basins) and shelf convection (Lemnos-Lesvos plateau) DWF processes were monitored in the Central Aegean. Intermediate dense waters were formed locally as a mixture of LW and local waters, recirculating at intermediate depths across the North-Central Aegean. On the other hand, the South Aegean appears greatly influenced by the Eastern Mediterranean general circulation and water mass distribution, especially under the EMT status. The South Aegean intermediate layers with a core at 750 m are influenced by the TMW intrusion in the Cretan Sea, a mixture of

the LIW and the old EMDW entering at sill depth of the Kassos strait from the adjacent Levantine basin.

[29] In order to quantify the variability of the water mass properties related to the EMT and its phases, a pre-EMT reference year, 1987, was selected to be compared with data from the winter cruises of 2005 and 2006. During the winter of 1987, relatively fresh and less dense waters are monitored in the deep layers. The BSW from the Dardanelles and the LSW/LIW intrusion from the Cretan arc straits governed the Aegean surface layers. However, this status changed dramatically during the EMT, due to the abrupt displacement of the deep Aegean waters, together with the significant TMW intrusion. In the post-EMT period, the TMW layer has similar characteristics with the dense water masses in pre-EMT period [*Zervakis et al.*, 2000]. Furthermore, those properties are very much alike to the Central Aegean DWF properties monitored in the two recent winter cruises during 2005 and 2006. Therefore, the DWF processes in the Central Aegean could not only trigger the intermediate conveyor belt, but also act as an EMT relaxation mechanism inside the Aegean.

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