

## **Hydrology and circulation in the North Aegean (eastern Mediterranean) throughout 1997 and 1998**

**V. ZERVAKIS and D. GEORGOPOULOS**

National Centre for Marine Research,  
Institute of Oceanography  
Agios Kosmas, Elliniko, 166 04 Athens, Greece

e-mail: zervakis@ncmr.gr

---

### **Abstract**

*The combination of two research projects offered us the opportunity to perform a comprehensive study of the seasonal evolution of the hydrological structure and the circulation of the North Aegean Sea, at the northern extremes of the eastern Mediterranean. The combination of brackish water inflow from the Dardanelles and the sea-bottom relief dictate the significant differences between the North and South Aegean water columns. The relatively warm and highly saline South Aegean waters enter the North Aegean through the dominant cyclonic circulation of the basin. In the North Aegean, three layers of distinct water masses of very different properties are observed: The 20-50 m thick surface layer is occupied mainly by Black Sea Water, modified on its way through the Bosphorus, the Sea of Marmara and the Dardanelles. Below the surface layer there is warm and highly saline water originating in the South Aegean and the Levantine, extending down to 350-400 m depth. Below this layer, the deeper-than-400 m basins of the North Aegean contain locally formed, very dense water with different  $\theta/S$  characteristics at each subbasin. The circulation is characterised by a series of permanent, semi-permanent and transient mesoscale features, overlaid on the general slow cyclonic circulation of the Aegean. The mesoscale activity, while not necessarily important in enhancing isopycnal mixing in the region, in combination with the very high stratification of the upper layers, however, increases the residence time of the water of the upper layers in the general area of the North Aegean. As a result, water having out-flowed from the Black Sea in the winter, forms a separate distinct layer in the region in spring (lying between "younger" BSW and the Levantine origin water), and is still traceable in the water column in late summer.*

**Keywords:** Circulation, Seasonal variability, Aegean Sea.

### **Introduction**

The Aegean Sea occupies one of the northern extremities of the eastern Mediterranean, the other being the Adriatic Sea. The area exhibits very strong gradients

along its North-South axis, which make it very interesting to oceanographers. While the South Aegean is filled with very warm and very saline oligotrophic water characteristic of the Eastern Mediterranean, the North Aegean is distinctly different. It is the region where cold, brackish

( $S \sim 29$  psu), and rather rich in biomass waters from the Dardanelles enter the Mediterranean, creating strong fronts with the warm, highly-saline ( $S > 38.5$  psu) and extremely oligotrophic waters of the Aegean (SIOKOU-FRANGOU *et al.*, 2002). Furthermore, the bottom layers of the North Aegean contain one of the densest waters of the world oceans, with densities exceeding  $\sigma_\theta = 29.50 \text{ kg m}^{-3}$  (ZERVAKIS *et al.*, 2000). The observed high densities of the North Aegean make it one of the principal dense water formation regions of the Mediterranean, together with the Adriatic, the Gulf of Lions and other parts of the Aegean Sea (NIELSEN, 1912; POLLAK, 1951; PLAKHIN, 1972; MALANOTTE-RIZZOLI & HECHT 1988; SCHLITZER *et al.*, 1991; LASCARATOS *et al.*, 1999; THEOCHARIS *et al.*, 1999a; ZERVAKIS *et al.*, 2000).

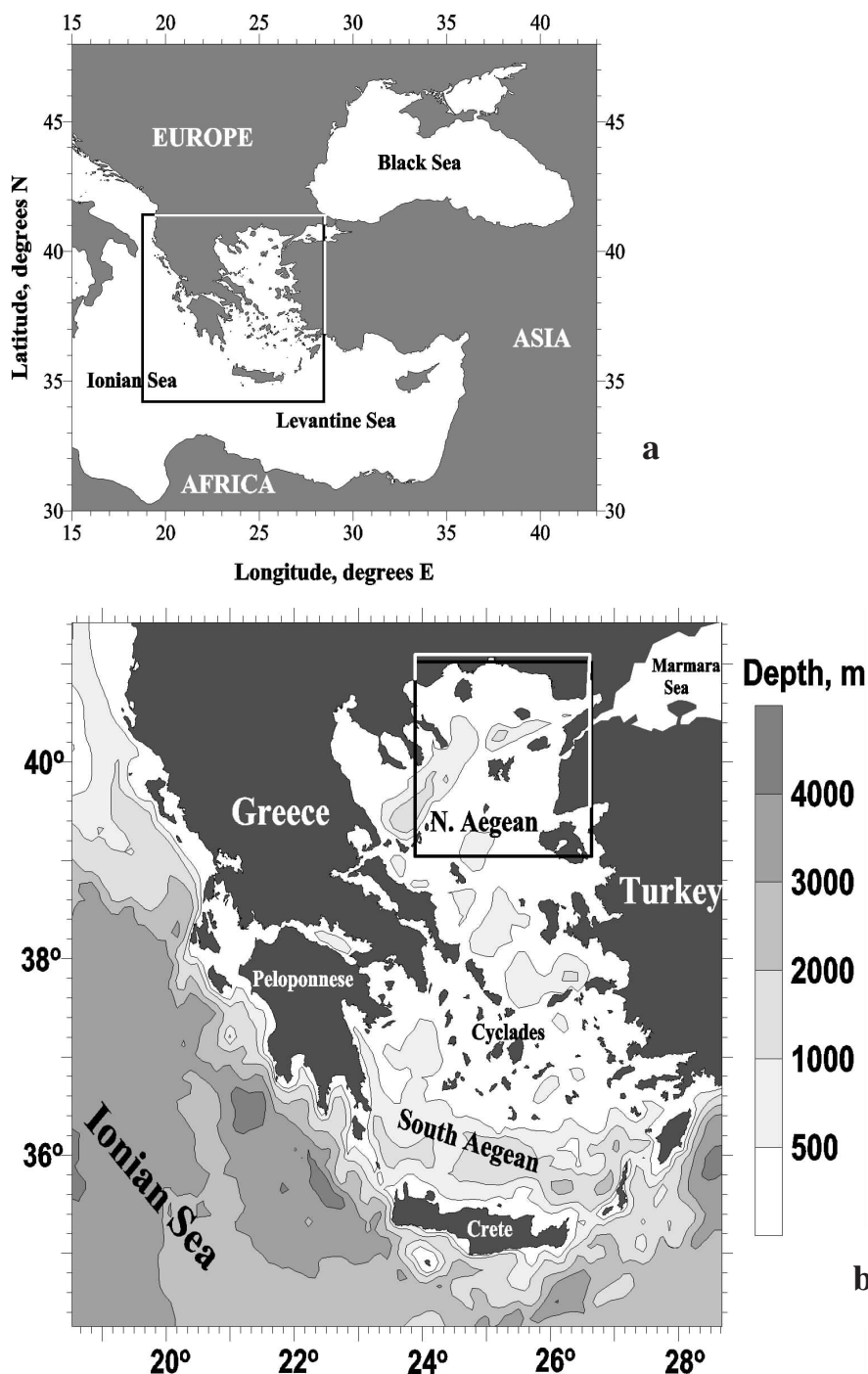
While extensive surveys have been carried out in the Gulf of Lions and in the Adriatic, not many studies have taken place in the northern part of the Aegean Sea. NIELSEN (1912) was the first to record the hydrology of the region, and to proceed to note its importance as a potential source of dense water. The R. V. *Atlantis* (1948) and R. V. *Calypso* (1955) provided good quality measurements in the region, while the R.R.S. *Shackleton* (1978) performed a survey in the N.W. Aegean. Based on the R/V *Calypso* data, LACOMBE *et al.* (1958) suggested the Gulf of Saros as one of the sources of the deep waters of the North Aegean trough, while PLAKHIN (1972) considered the Northern Aegean as one of the regions of potential deep water formation in the Mediterranean, together with the Gulf of Lions, the Adriatic and the Cretan Sea. More recently, THEOCHARIS & GEORGOPOULOS (1993) have witnessed dense water formation over the plateaux of Samothraki and Limnos.

While the question of deep water formation has been one of the major scientific questions in this area, the (related) exchange of waters between the North and the South Aegean has also been under debate: NIELSEN

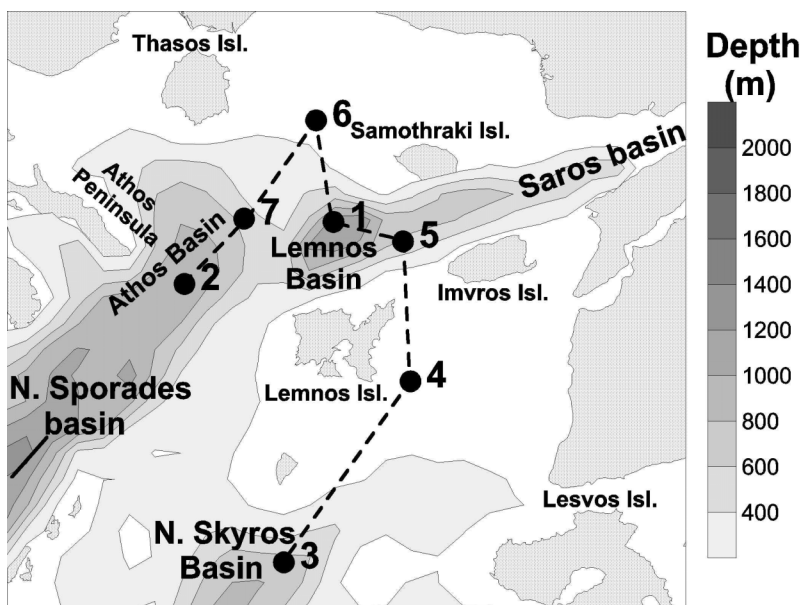
(1912) suggested that the transport of dense water from the North Aegean to the South Aegean and the Cretan Sea should be limited by the shallow sills and shelves separating the deep basins of the Archipelago. However, in a study based on  $\theta/S$  diagrams, EL-GINDY & EL-DIN (1986) suggested that the Cretan Deep Water consists of 50 % of North Aegean Deep Water. As for the waters shallower than 400 m, SULTAN (1981) proposed that the water masses of the intermediate layers of the North Aegean are advected into the area from the outside, i.e. from the Central and Southern parts of the Aegean Sea. More recently investigators have certified that the intermediate layers of the North Aegean are occupied by Levantine waters advected northwards along the west coast of Asia Minor by the dominant cyclonic circulation of the basin (THEOCHARIS & GEORGOPOULOS, 1993; ZODIATIS, 1994).

**Bottom topography.** The archipelago of the Cyclades islands, lying on a relatively shallow shelf (less than 300 m deep), separates the Aegean Sea into two distinct basins, the North and the South Aegean (Fig. 1b). The Cyclades plateau is not the only shallow shelf of the region; the North Aegean itself is characterised by an alternation of shallow sills and plateaux and deep sub-basins and troughs (Fig. 2). The most characteristic feature of the bottom relief is the North Aegean Trough, which is comprised of a series of sub-basins: the North Sporades, Athos, Lemnos and Saros Basins, from the SW to the NE. The North Sporades and Athos basins (1470 and 1150 m deep respectively) communicate with the 1550 m deep Lemnos basin through a 500 m deep sill. An approximately 350 m deep sill separates the North Aegean Trough from Chios basin, also consisting of several sub-basins, like the North Skyros basin. The communication between the North and South Aegean is limited to the top 350 m of the water column by the series of shallow sills separating the two basins (Figs 1b, 2).

**Water exchanges.** This sea exchanges waters with the Black Sea through the Dardanelles, and with the South Aegean and the greater



**Fig. 1:** (a) Geographic setting of the eastern Mediterranean. The box identifies the region shown on a larger scale in (b): Bathymetry of the Aegean Sea. The box identifies the region of interest, presented in Fig 2.



**Fig. 2:** Bottom relief, islands and coasts of the North Aegean Sea. Isobaths are plotted at 200 m intervals. The seven stations of the MTP-II MATER project are overlaid, along with the transect referred to later.

Levantine Basin through the passages between the Cyclades and the Turkish Coast. At the Dardanelles there is a two-layer flow, with very light waters of low salinity ( $< 29$  psu) forming a 20 m-thick surface layer flowing towards the Aegean, and highly saline, Levantine waters below them, flowing north-eastward towards the Black Sea (ÜNLÜATA *et al.*, 1990; BESIKTEPE *et al.*, 1993).

The Black Sea is the major, but not the only source of brackish water for the region; a series of small rivers contribute their small share. The annual contribution of the Dardanelles to the N. Aegean Sea water balance is of the order of  $300\text{--}1000 \text{ km}^3 \text{ year}^{-1}$  (ÜNLÜATA *et al.*, 1990; BESIKTEPE *et al.*, 1993), while the rivers do not exceed  $10 \text{ km}^3 \text{ year}^{-1}$  (THERIANOS, 1974). It is noteworthy that the inflow from the Dardanelles reaches its maximum in the summer, while that of the rivers does in the winter (POULOS *et al.*, 1997).

In this work we will describe the hydrography and circulation of the North Aegean as revealed through the National Centre for

Marine Research's (hereafter referred to as NCMR) expeditions in 1997 and 1998, focusing on the dispersion of Black Sea waters in the upper layers. The data-analysis methods will be described in the next chapter; then, a general description of the water masses will follow, and the role that the physical setting plays in determining the vertical structure of the water column. After a description of the general circulation as revealed by the water-mass analysis, a more detailed look at the seasonal evolution of the water column, and the circulation features of the region will follow. The seasonal variability of the position of the Dardanelles front, as well as its mobility in time scales of about 10 days are presented next, to finally conclude with the discussion of our results.

## Materials and Methods

The MTP-II project MATER, in combination with the project "Infrastructure development for the monitoring of inter-regional pollution in the North Aegean Sea"

(funded by the European Commission's 2<sup>nd</sup> Framework Program), offered us the opportunity to realise a comprehensive study of the hydrology and the circulation in the basin throughout 1997 and 1998. We were able to visit the region in March 1997 (two MATER-1 cruises), May 1997 (trans-boundary pollution cruise), September 1997 (two MATER-2 cruises), February-March 1998 (four MATER-3 cruises) and June 1998 (one trans-boundary pollution cruise). The above cruises are summarised in Table 1.

**Table 1**  
**Research Cruises.**

Cruise	From	To	CTD stations	CTD casts
MATER-1CH	22.03.1997	25.03.1997	7	17
MATER-1BG	28.03.1997	02.04.1997	7	26
Pollution-1	13.05.1197	23.05.1997	91	108
MATER-2BG	19.09.1997	24.09.1997	7	38
MATER-2CH	26.09.1997	01.10.1997	33	56
MATER-3WF	16.02.1998	22.02.1998	65	68
MATER-3BG	12.03.1998	19.03.1998	18	43
MATER-3PD	25.03.1998	30.03.1998	11	11
MATER-3CH	08.04.1998	10.04.1998	3	3
Pollution-2	15.06.1998	23.06.1998	112	115

Table 1 reveals that the sampling strategy varied between cruises: in some cruises (the ones most related to studying bio-geo-chemical cycles in the water column) the number of CTD casts greatly exceeded the number of CTD stations visited. In those cruises we were able to perform multiple CTD casts over the euphotic zone at each hydrographic station, thus obtaining a picture of the variability of the station over a few hours. This sampling strategy was planned in response to the needs of the MTP-II MATER project, where the study of the bio-geo-chemical cycles in the water column required a large volume of water samples at each station. The large number of CTD casts performed at each station every day (mostly within the euphotic zone) allows an estimation of the nature of the variability at

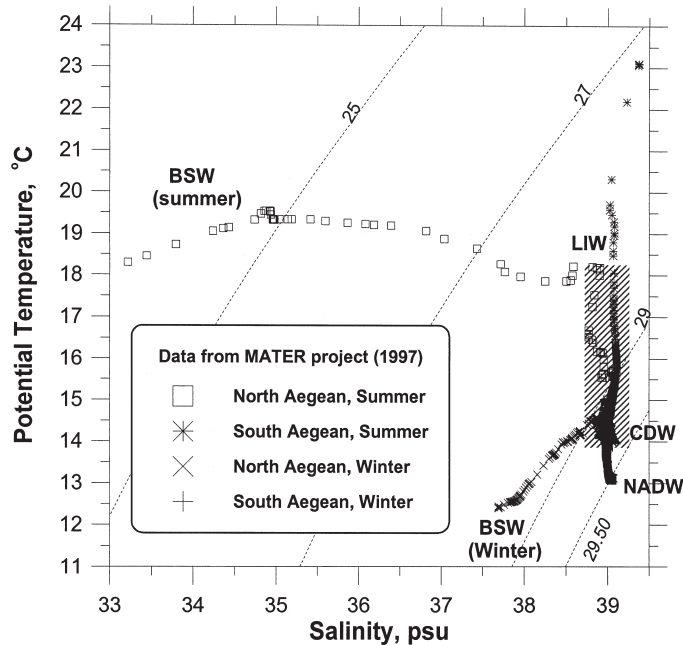
each station, however the tool of the  $\theta/S$  diagram has only limited powers regarding analysis of the circulation. In order to estimate the degree of variability at each station, we computed the average profile for each day, and the standard deviation of temperature, salinity and density at each depth.

Contrary to the MATER cruises, the cruises aimed at studies of the inter-regional pollution in the region covered a significant portion of the North Aegean with a large number of hydrographic stations. These cruises provided us with data sets adequate for detailed analysis of the circulation and dispersion of the water masses in the North Aegean.

## Results

**Water-masses.** The following water-mass analysis shows that the inflow of brackish, low density water in the North Aegean, as well as the bottom morphology of the region, to a large degree determine the structure of the water column, and the differences observed from the relatively vertically homogeneous South Aegean; the low-salinity modified BSW occupies the surface layers due to its low density, while the depths between 100 and 400 meters present the highest similarity to the South Aegean, due to the relatively unhindered communication of the two seas above 400 m. Below that depth, the North Aegean appears to be largely isolated from the South, and even the various sub-basins of the sea exhibit distinct characteristics. However, the waters filling the deeper-than-400 m depths at all basins are quite homogeneous vertically, and exhibit very high densities, with  $\sigma_\theta > 29.50 \text{ kg m}^{-3}$ .

Figure 3 displays a typical  $\theta/S$  diagram with data collected throughout the first two MATER cruises in the North and the South Aegean, in winter and summer 1997. The waters exiting from the Dardanelles (BSW) are identified by their very low salinity and, consequently, density. During winter the surface layer is colder than both the water



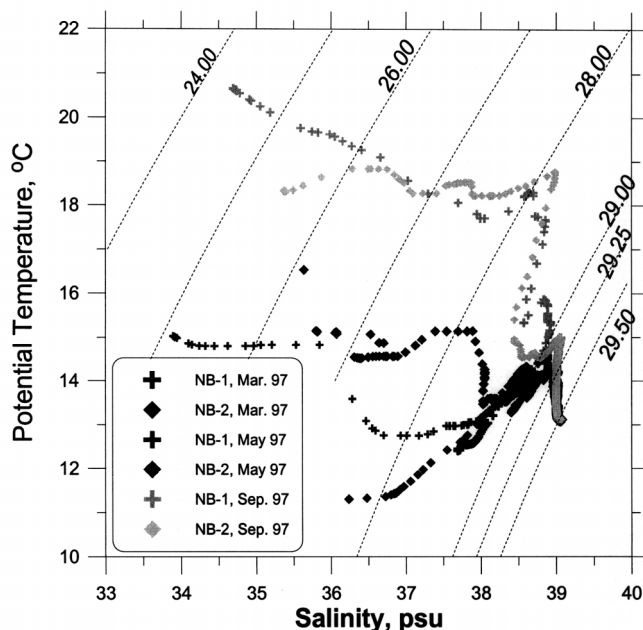
**Fig. 3:**  $\theta/S$  diagram from two typical stations from the North and South Aegean, for summer and winter 1997.

masses occupying deeper depths: the intermediate layer with waters with characteristics similar to Levantine Intermediate Water (LIW), and the deep layer with dense North Aegean Deep Water (NADW). In the summer the temperature of the surface layer rises to about 20 °C. In comparison to the highly salinity-stratified North Aegean, the stability of the water column in the South Aegean depends almost entirely on temperature. Due to the extended salinity axis, the intermediate Transition Mediterranean Waters (TMW, POLLAK, 1951; THEOCHARIS *et al.*, 1999b) of the Cretan Sea are barely identifiable in Figure 3. Also, due to the increased homogenization of the Cretan Sea in the winter, the winter curve is very hard to resolve. However, the large shaded area where the  $\theta/S$  curves of the two sub-basins meet, identify the layer between 50 and 350 m where waters of Levantine origin (LIW) enter the North Aegean, undergo some modification through diapycnal mixing with

the overlying and underlying layers, and return to the South Aegean. Of special interest are the very high densities of the deep waters, and that the density of the North Aegean bottom water exceeds by far the density of the bottom waters of the Cretan Sea.

**Seasonal evolution.** The seasonal evolution of the upper layers of the North Aegean emerges from Figure 4, a  $\theta/S$  diagram of casts from the stations MNB-1 and MNB-2 from successive cruises in March, May and September 1997. The surface waters in March are much colder than the rest of the water column. Of the two stations (MNB-1 and MNB-2) considered in Figure 4, the one closest to the Dardanelles (MNB-1) has a significantly smaller surface temperature (10.7 °C) and salinity (36.2 psu). Despite the lower temperature, the surface water at MNB-1 is significantly lighter than at MNB-2 ( $\sigma_\theta$  at 27.6 kg m<sup>-3</sup> versus 28.5 kg m<sup>-3</sup>), indicating the inflow of buoyancy in the North Aegean from the Dardanelles.





**Fig. 4:**  $\theta/S$  diagram from two typical stations (MNB-1 and MNB-2) from the North Aegean, for winter, spring and summer of 1997.

The re-stratification process in the North Aegean in May is partly due to local warming at the surface, partly due to the advection of buoyancy in the form of “younger”, relatively warm ( $15^{\circ}\text{C}$ ) and low salinity water from the Dardanelles. The new water forms a 20 m thick surface layer that lies over a 20-30 m thick “old”, cooler modified BSW layer that entered the region during winter; the latter layer retains its characteristics, as it remains isolated from the atmosphere by the surface layer. Traces of the “winter” BSW water can still be found in the  $\theta/S$  diagram of the September cruise. Thus, the increased buoyancy input through the Dardanelles in early summer results in increase of stratification and decrease of vertical diffusion in the North Aegean.

By integrating temperature over the top 100 m of the water column, we made an estimate of heat content in the surface layer. Between the end of March of 1997 and mid-September 1997, the surface layer gained heat at a rate of  $95 \pm 7 \text{ W m}^{-2}$ , while between

September 1997 and February 1998 there was a net heat loss at a rate of  $80 \pm 12 \text{ W m}^{-2}$ . Between February and March 1998 the net heat loss continued, thus throughout the year March 1997 - March 1998 there does not appear to have been any significant net heat change in the surface layer. The largest differences from the mean are found for both periods at stations 4 and 5, the ones closest to the Dardanelles. As we will show in later sections, the large differences from the mean are attributed mostly to the proximity of the stations to the sharp frontal feature associated with the Dardanelles outflow. Horizontal adjustments in the position of the front result in great changes in the hydrographic properties of the water recorded at these stations, depending on which side of the front they are.

**Circulation.** Previous studies (POULOS *et al.*, 1997; KRESTENITIS *et al.*, 1998), based mostly on satellite SST images, suggest that in summer the BSW surface layer, after exiting the Dardanelles, follows a south-westward

route, while in the winter it enters the Sea of Thrace by following a north-westward route through the strait between the islands of Imvros and Lemnos. This bi-modal behaviour has been attributed mostly to the forcing the northerly Etesian winds apply in the late summer on the BSW jet.

However, this scenario becomes more complicated when one examines the extent of the cold surface waters in the eastern Aegean, as revealed by summer satellite images. Their distribution and extent suggest, in agreement with previous studies (ZODIATIS, 1994), that the meridional gradient of the surface waters of the Aegean in the summer is caused by coastal upwelling along the western shores of Asia Minor, forced by the strong and steady Etesian winds. Furthermore, the BSW waters on the surface of the Marmara Sea undergo considerable heating before entering the Aegean, and thus their thermal signal is easily merged with the background of the Aegean warm waters; consequently, SST images prove useful in identifying upwelling regions, but not the BSW plume.

The salinity gradient between the Mediterranean and the Black Sea is too strong to be extinguished by evaporation or vertical mixing during the journey of BSW through the Turkish Straits and the Sea of Marmara; thus, salinity is a much better tracer of BSW, however not yet routinely monitored by satellite. Hydrographic cruises that took place in May 1997 and September 1998 in the framework of the 4<sup>th</sup>-Framework funded project "Infrastructure development for the monitoring of inter-regional pollution in the North Aegean Sea" provided the necessary information to study mesoscale features and the surface circulation in the North Aegean, and the dispersion of BSW at different seasons.

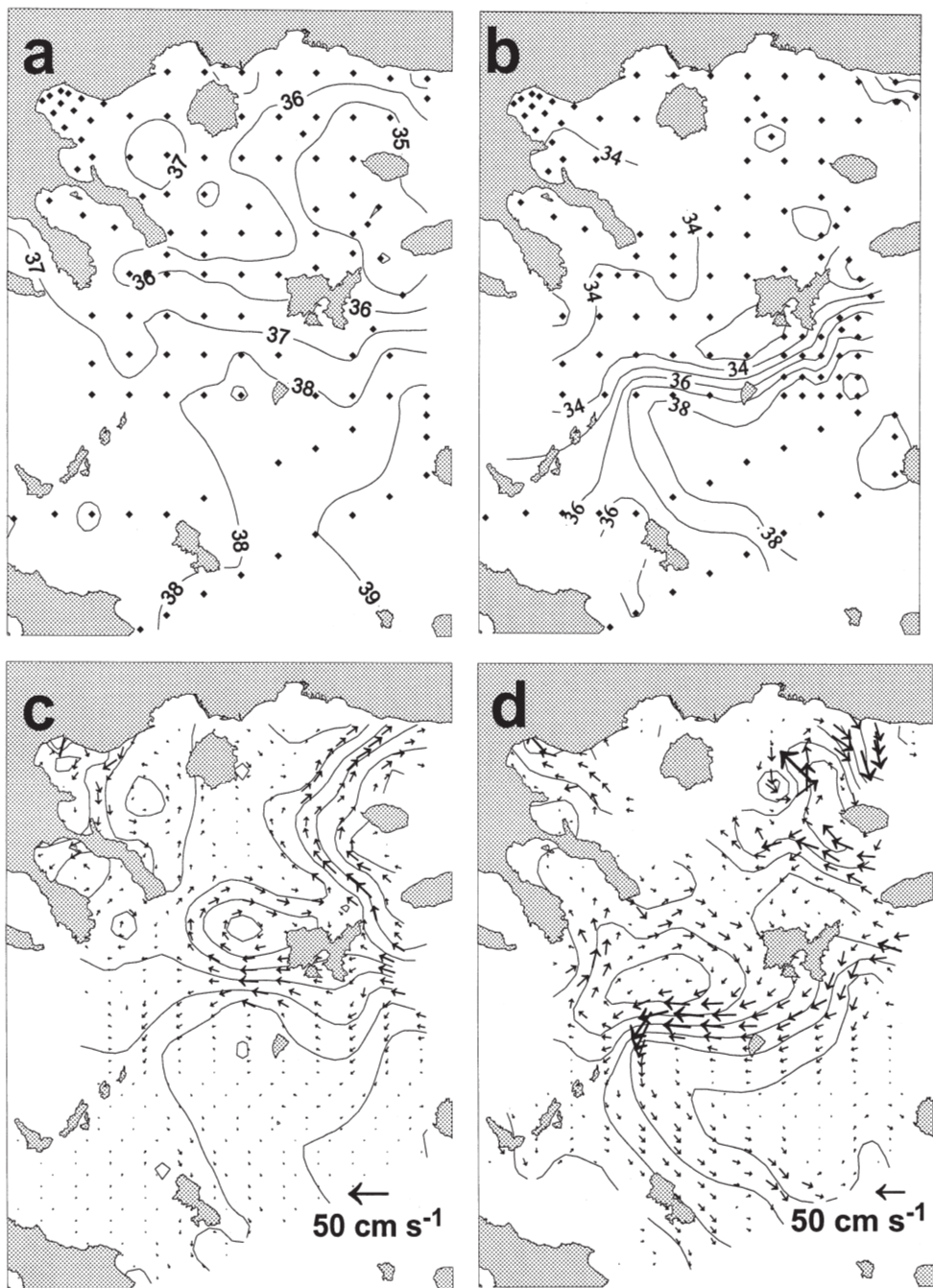
Surface Layer. The distribution of salinity at 10 dbar in (a) May 1997 and (b) September 1998 is shown in Figure 5. Note that the surface waters contain more salt in May, as they have mixed throughout winter with underlying highly saline waters of Levantine origin. The

strong front between BSW and LIW, identified by the  $S = 38$  psu isohaline, is at both times located south of Lemnos; however, a more significant quantity of brackish water follows a SW route in the summer, to reach the western shores of the Aegean and move cyclonically towards the South. In May, there is a tongue of water with salinity less than  $S = 36$  psu, that is arrested by the anticyclone east of Lemnos (Fig. 5c) and remains in the North Aegean. Most of the BSW is captured by the permanent anticyclone that dominates the eastern part of the Sea of Thrace, and flows around the island of Samothraki.

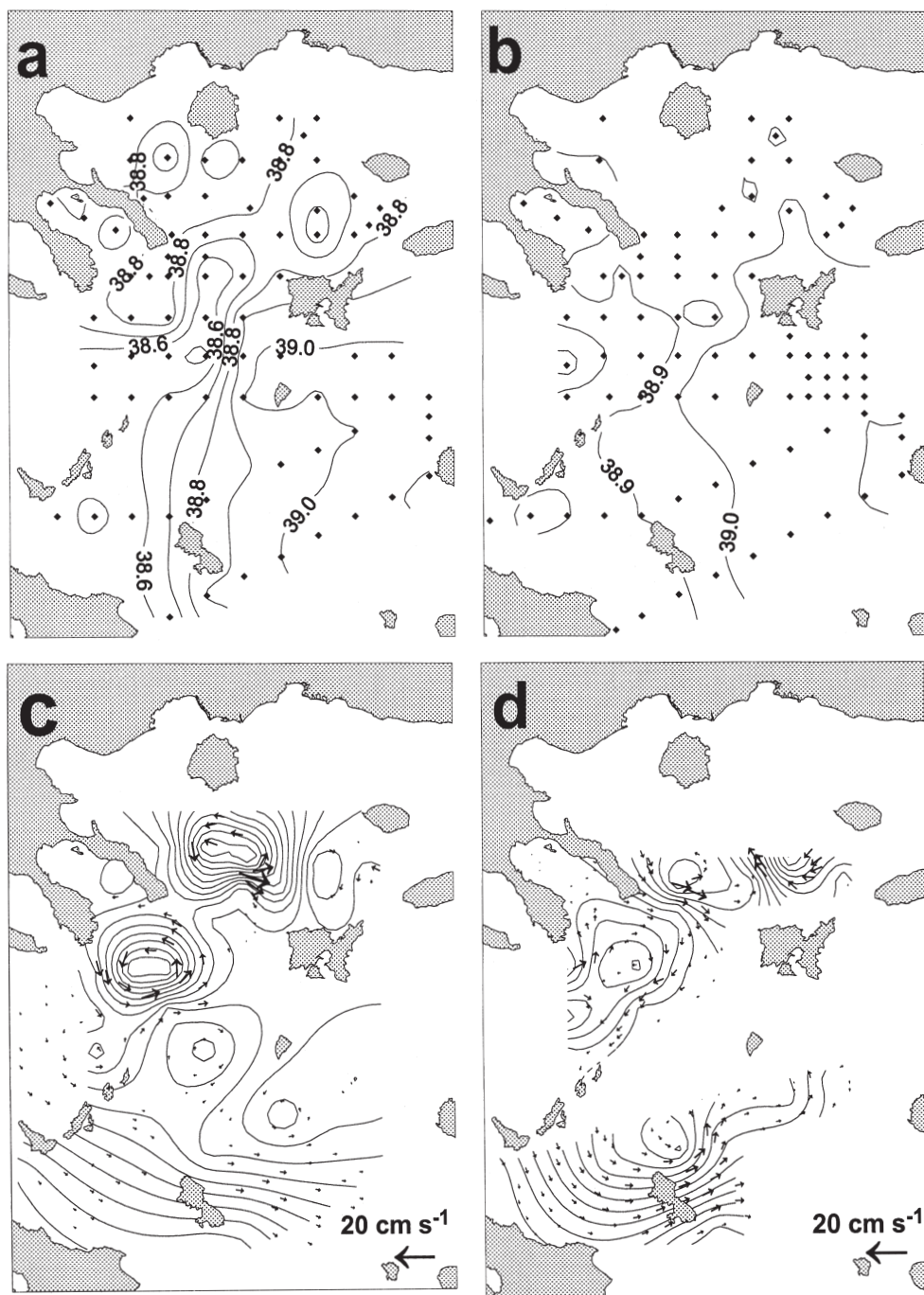
Figures 5c and 5d present the geostrophic current at 5 dbar relative to 50 dbar, and represent essentially -especially in the eastern parts of the sea, where vertical diffusion has not mixed the different layers- the motion of the BSW surface layer over the top of the LIW layer. A permanent feature at both times is the Samothraki anticyclone, formed by Dardanelles water flowing northwestward through the Lemnos-Imvros strait, and around the island of Samothraki. This anticyclone could be responsible for increasing the residence time of modified BSW in the North Aegean. In the summer however, as mentioned above, a significant quantity of BSW moves southwestward after exiting the Dardanelles (Fig. 5d), to eventually reach the western shores of the Aegean and turn to the south. The strong baroclinicity induced by the increased summer stratification causes the currents in the summer to be stronger. In May the currents at 5 dbar relative to 50 dbar varied at  $6 \pm 6$  cm s<sup>-1</sup>, with a maximum value at 51 cm s<sup>-1</sup>, while in September at  $14 \pm 11$  cm s<sup>-1</sup>, with a maximum value at 72 cm s<sup>-1</sup>.

Intermediate Layer. The distribution of salinity and geostrophic currents at the layer of water of Levantine origin is shown in Figure 6. The contours of salinity seem to suggest that a "tongue" of water of lower salinity enters the Sea of Thrace through the straits between Mount Athos and Lemnos in May. In reality, the tongue of lower salinity is attributed to the





**Fig. 5:** The distribution of salinity at 10 dbar in (a) May 1997 and (b) September 1998. Also, the geostrophic currents at 5 dbar relative to 50 dbar in May 1997 (c) and September 1998 (d) are shown. Figures c and d are reprinted from *Journal of Marine Systems*, Vol. 33-34, Lykousis *et al.*, “Major outputs of the recent multidisciplinary biogeochemical researches undertaken in the Aegean Sea”, pp.313-334, 2002, with permission from Elsevier Science.



**Fig. 6:** The distribution of salinity at 100 dbar in (a) May 1997 and (b) September 1998. Also, the geostrophic currents at 100 dbar relative to 400 dbar in May 1997 (c) and September 1998 (d) are shown. Interval of dynamic height contours is 0.2 cm.

vertical diffusion processes that mix the overlying relatively brackish BSW with the surrounding highly saline Levantine waters. The tongue traces the cyclonic route of the BSW exiting the Sea of Thrace, and at the same time being mixed downwards with saltier water. In September, there is no similar structure observed, and the distribution of salinity at 100 dbar corresponds to a meridional gradient. In both cases, the dominant cyclonic circulation and the intensity of the vertical diffusion processes determine the salinity distribution. The cyclonic circulation brings highly saline LIW towards the North Aegean along the western coast of Asia Minor. The salt content of the intermediate layer decreases by mixing with the low-salinity surface layer, and thus the waters returning towards the south along the eastern coast of continental Greece exhibit lower salinity.

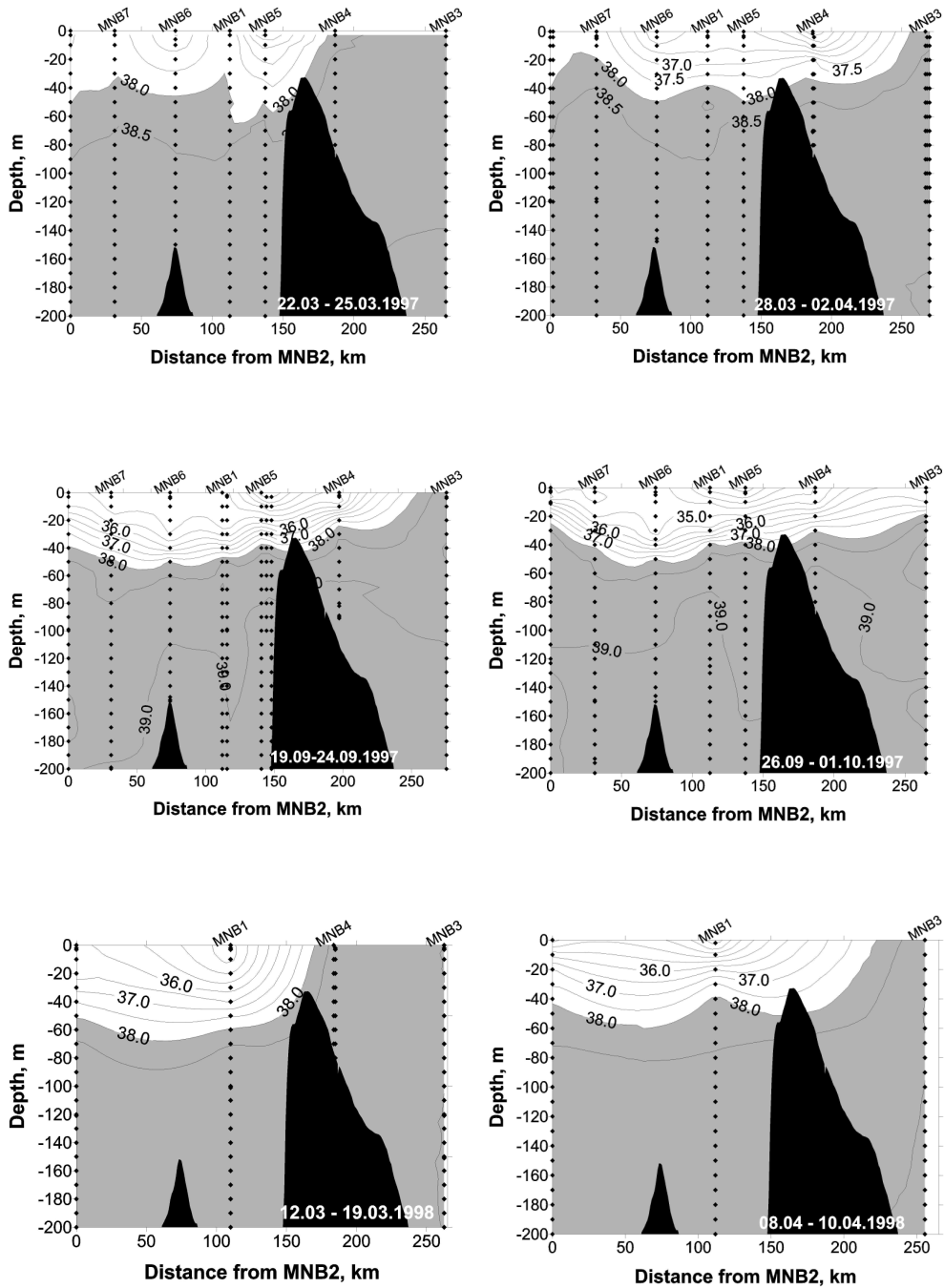
The vertical shear within that layer is much reduced relative to the surface layer, as the velocity difference between 100 and 400 dbar varies between  $3.3 \pm 2.6 \text{ cm s}^{-1}$  in May and  $3.2 \pm 1.8 \text{ cm s}^{-1}$  in September, with maximum values encountered at 18 and 13  $\text{cm s}^{-1}$  respectively. Note that the only permanent feature appears to be a cyclone to the east of Mount Athos, while the gyre south of Mount Athos has a cyclonic circulation in May, to be reversed in September. The circulation south of Lemnos and the Sporades appears to be a part of the greater cyclonic circulation of the Aegean.

**Local variability.** As already mentioned, the methodology followed in the majority of the MATER cruises was multiple CTD/Rosette casting over a single station each day. Furthermore, the nature of the experiment demanded a large number of scientists from different disciplines, more than the ship could accommodate. Thus, each cruise had to be divided into several legs; this enabled us to sample each station repeatedly throughout a day during each leg, and obtain an estimate of variability in the time scale of 5-10 days by

comparing the average profiles of different legs of a cruise.

Figure 7 is a presentation of the variability of the salinity field along the transect presented in Figure 2 (from station 2 to station 3) within the 7-15 day interval separating the two legs of each cruise, for all three MATER cruises, i.e. in March and September 1997, and in March-April 1998. Note that the halocline is much steeper in summer than in winter, due to a combination of higher Dardanelles outflow and increased stratification during summer, an expected result. Comparison of the salinity recorded in the deeper layers throughout the three cruises reveals that during March the 39 psu isohaline does not cross the Lemnos shelf into the Lemnos basin, but remains to the south of the shelf (is only recorded at station MNB3). On the contrary, we observe water of salinity exceeding 39 psu at depths shallower than 150 m at both legs of the September 1997 cruise. This is a clear indication that the waters intruding from the south Aegean at intermediate layers have a residence time smaller than one year in the Lemnos and Athos basins, as they exhibit a strong seasonal cycle reflecting the vertical homogenisation processes over the Lemnos plateau in the winter. The fact that the salinity in the intermediate layer of Lemnos and Athos basins increases in the summer to values exceeding 39 psu suggests that there is a continuous flow of south-Aegean water replenishing the intermediate layer of the North Aegean.

By defining the position of ventilation of the 38 psu isohaline as the position where the Dardanelles outflow front crosses the transect, we can examine the front's mobility on a time-scale of a few days. Examination of the top panel of Figure 7 reveals that the position of the front changes significantly in March 1997 within a week. While we have recorded waters of high salinity at station MNB4 during the first leg, suggesting that the Dardanelles outflow turned during the Northwest at that time, a week later station MNB4 exhibits waters of surface salinity about 34 psu, suggesting that



**Fig. 7:** The distribution of salinity along the transect from station MNB2 to station MNB3, as shown in figure 2. The two legs of the March 1997 cruise are shown at the top, the two legs of September 1997 in the middle, and the March 1998 legs at the bottom.



the plume of low-salinity waters can significantly change its position within time-scales of a few days. However, station MNB3 is characterized by highly-saline waters throughout the March 1997 cruise, a fact certifying that the route of the Dardanelles outflow during winter is towards the northwest after exiting the Straits.

This was not the case in September 1997, as low salinity waters are recorded at station MNB-3 during the second leg (September 26<sup>th</sup> – October 1<sup>st</sup> 1998). Again, there is high temporal variability of the front's position (as a week earlier station MNB-3 was characterized by highly-saline waters), but now the front lies to the southwest of Lemnos island, as expected from satellite images and related literature.

Bad weather during both legs of the March-April 1998 cruise did not allow sampling of all the hydrographic stations. Thus, the position of the front could not be very well determined during that time. This was not so much a problem during the first leg (March), due to the fact that we were able to sample the key station MNB4. The high surface salinity recorded at station 4 in March suggests that the front is positioned between the stations MNB1 and MNB4, and that the low-salinity waters flow towards the northwest through the Lemnos-Imvros Strait, as is the usual case in winter. Absence of data at station 4 during the second leg does not allow us to extract such a conclusion for April 1998.

## Discussion

This paper has been an attempt to update the information of the conditions in the North Aegean Sea, as revealed by data collected in the framework of the MTP-II MATER experiment. The results have confirmed that a very stratified water column, comprised of three water masses, characterizes the North Aegean: the surface layer of low-salinity and cool modified Black Sea Water, the inter-

mediate layer of warm and saline Levantine/South Aegean waters, and the deep layer of very dense North Aegean waters of local origin. The current analysis has certified past results that the front of the Dardanelles outflow can be highly mobile in time scales of the order of 10 days. This result is in agreement with the analysis of VLASENKO *et al.* (1996) suggesting that the position of the Dardanelles outflow is mostly responsive to changes in the wind-field. Furthermore, our observations on the seasonal variability of the position of the front point also to certify the conclusions of VLASENKO *et al.* (1996) on the relation of the front's position to the wind-field. We have observed (in agreement with ZODIATIS, 1994) that the front oscillates from a position to the southeast of Lemnos island in the summer to northeast of Lemnos in winter, a fact suggesting that the southward advection of the front can be attributed to the Etesian winds (northerlies) that dominate the late summer season.

Our analysis has revealed the role of the North Aegean as a dilution basin for the highly saline south Aegean waters that are advected here by the dominant cyclonic circulation. The observations suggest that there is a seasonal cycle of the intermediate water salinity, attributed to the inflow of more saline waters in the summer and less saline (due to vertical homogenisation over Lemnos plateau) in the winter. This seasonal cycle is also present in the geostrophic velocity fields recorded in the region, with the summer season being significantly more energetic than the winter. Semi-permanent and recurrent mesoscale features extend the residence time of the modified Black Sea waters in the region, thus further strengthening the highly stratified nature of the water column.

Until recently, the interest on the North Aegean has been focused on its character as a region of inflow of the mesotrophic Black Sea waters into the mostly oligotrophic Aegean. The recent production of very dense water there to be followed by the Eastern

Mediterranean Transient and the subsequent filling of the deepest basins of the Eastern Mediterranean has increased the interest in this marginal sea, and the dense water formation processes taking place there. The North Aegean has both a role as a dilution basin for the Aegean Sea (and possibly the Eastern Mediterranean) due to the low-salinity modified Black Sea waters inflowing in the region, but also possibly as a regulator of the thermohaline circulation of the Aegean Sea (ZERVAKIS *et al.*, 2000). We expect that due to its oceanographic and ecological importance, the North Aegean will remain one of the focuses of the oceanographic community of the Eastern Mediterranean in the years to come.

## Acknowledgments

This work was supported by the project “Establishment of infrastructure for the monitoring of interregional pollution in the North Aegean Sea”, funded through the INTERREG-I program of the National Ministry of Finance. We are greatly indebted to the captain, officers and crew of the R/V AEGAEON for their support.

## References

- BESIKTEPE, S., ÖSZOY, E. & ÜNLÜATA, Ü., 1993. Filling of the Marmara Sea by the Dardanelles lower layer inflow. *Deep-Sea Research*, 40, 9: 1815-1838.
- EL-GINDY, A. A. H., & EL-DIN, S. H. S., 1986. Water masses and circulation patterns in the deep layer of the Eastern Mediterranean. *Oceanologica Acta*, 9: 239-248.
- KRESTENITIS, Y. N. & BARBOPOULOS, K. A., 1998. Use of the satellite sea surface temperature (SST) data for the investigation of the Black Sea waters pathway in the North Aegean Sea. p. 84-86. In: *3<sup>rd</sup> MTP-II-MATER Workshop on the Variability of the Mediterranean Sea*, Rhodes, Greece, 15-17 October 1998.
- LACOMBE, H., TCHERNIA, P. & BENOIST, G., 1958. Contribution à l'étude hydrologique de la Mer Egée en période d'été. *Bulletin d'Information COEC*, 8: 454-468.
- LASCARATOS, A., ROETHER, W., NITTIS, K. & KLEIN, B., 1999. Recent changes in deep water formation and spreading in the eastern Mediterranean Sea. *Progress in Oceanography*, 44: 5-36.
- MALANOTTE-RIZZOLI, P. & HECHT, A., 1988. Large-scale properties of the eastern Mediterranean: A review. *Oceanologica Acta*, 11: 323-335.
- NIELSEN, J. N., 1912. Hydrography of the Mediterranean and Adjacent Waters. p. 72-191. In: *Report of the Danish Oceanographic Expedition 1908-1910 to the Mediterranean and Adjacent Waters*, Volume 1, Copenhagen.
- PLAKHIN, Y. A., 1972. Vertical winter circulation in the Mediterranean. *Oceanology*, 12: 344-351.
- POLLAK, M. I., 1951. The sources of the deep water in the eastern Mediterranean Sea. *Journal of Marine Research*, 10: 128-152.
- POULOS, S. E., DRAKOPOULOS, P. G. & COLLINS, M. B., 1997. Seasonal variability in sea surface oceanographic conditions in the Aegean Sea (Eastern Mediterranean): an overview. *Journal of Marine Systems*, 13: 225-244.
- SCHLITZER, R., ROETHER, W., OSTER, H., JUNGHANS, H.-G., HAUSMANN, M., JOHANNSEN, H. & MICHELATO, A., 1991. Chlorofluoromethane and oxygen in the eastern Mediterranean. *Deep Sea Research*, 38: 1531-1551.
- SIOKOU-FRANGOU, I., BIANCHI, M., CHRISTAKI, U., CHRISTOU, E., GIANNAKOUREN, A., GOTSIS, O., IGNATIADES, L., PAGOU, K., PITTA, P., PSARRA, S., SOUVERMEZOGLOU, E., VAN WAMBEKE, F. & ZERVAKIS, V., 2002. Carbon flow in the planktonic food web along a gradient of oligotrophy in the Aegean Sea (Mediterranean Sea). *Journal of Marine Systems*, 33-34: 335-353.
- SULTAN, S. A. R., 1981. Oceanographic studies of the Aegean Sea (Water masses and circulation). Ph. D. Thesis, University of Wales.
- THEOCHARIS, A. & GEORGOPOULOS, D., 1993. Dense water formation over the Samothraki and Lemnos Plateaux in the north Aegean Sea (Eastern Mediterranean Sea). *Continental Shelf Research*, 13, 8/9: 919-939.



- THEOCHARIS, A., NITTIS, K., KONTOYIANNIS, H., PAPAGEORGIOU, E. & BALOPOULOS, E., 1999a. Climatic changes in the Aegean Sea influence the eastern Mediterranean thermohaline circulation (1986-1997). *Geophysical Research Letters*, 26: 1617-1620.
- THEOCHARIS, A., BALOPOULOS, E., KIOROGLU, S., KONTOYIANNIS, H. & IONA, A., 1999b. A synthesis of the circulation and hydrography of South Aegean Sea and the Straits of the Cretan Arc. *Progress in Oceanography*, 44: 469-509.
- THERIANOS, A. D., 1974. The geographical distribution of river water supply in Greece. *Bulletin of the Geological Society of Greece*, 11: 2858 (in Greek).
- ÜNLÜATA, U., OGUZ, T., LATIF, M. A. & ÖSZOY, E., 1990. On the physical oceanography of the Turkish Straits. pp. 25-60. In: *The Physical Oceanography of Sea Straits*, edited by L. J. Pratt, Kluwer Academics, Norwell, Massachusetts.
- VLASENKO, V. I., STASHCHUK, N. M., IVANOV, V. A., NIKOLAENKO, E. G., USLU O. & BENLI, H., 1996. Influence of the water exchange through the Dardanelles on the thermohaline structure of the Aegean Sea. *Bulletin de l'Institut Océanographique, Monaco*, 17: 147 - 165.
- ZERVAKIS, V. & GEORGOPOULOS, D., 1998. High-frequency variability in the North Aegean Water column. p. 76-78. In: *3<sup>rd</sup> MTP-II-MATER Workshop on the Variability of the Mediterranean Sea*, Rhodes, Greece, 15-17 October 1998.
- ZERVAKIS, V., GEORGOPOULOS, D. & DRAKOPOULOS, P. G., 2000. The role of the North Aegean in triggering the recent Eastern Mediterranean climatic changes. *Journal of Geophysical Research*, 105, C11: 26103-26116.
- ZODIATIS, G., 1994. Advection of the Black Sea Water in the North Aegean Sea. *The Global Atmosphere and Ocean System*, 2: 41-60.

