JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. C11, PAGES 26,103–26,116, NOVEMBER 15, 2000

The role of the North Aegean in triggering the recent Eastern Mediterranean climatic changes

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Abstract. Drastic changes have occurred in the vertical structure of the deep waters of the eastern Mediterranean in the early 1990s, as dense water of Aegean origin has displaced lighter waters of Adriatic origin at the bottom of the deep basins. This work suggests that the initiation of this process took place in the North Aegean in the winter of 1986/1987 and was intensified by another formation event in 1992/1993. The available observations from the North Aegean support such a scenario. Furthermore, we propose that the outflow of Black Sea waters into the Aegean through the Dardanelles could act as an insulator of the deeper layer from the atmosphere, thus absorbing a large part of the heat and salt exchange; despite this fact, the existence of the densest bottom water of the Mediterranean in the North Aegean, and the continuation of density increase for a large period of time, suggests that it is a region of formation, thus that the insulation layer may at times be penetrated. We suggest that reduced Black Sea outflow into the North Aegean could facilitate dense water formation during the passage of cold atmospheric fronts in the winter.

1. Introduction

The eastern Mediterranean Sea has undergone dramatic changes in the last decade. Before the early 1990s, the Adriatic Sea was the single source of the dense waters occupying the bottom layers of the Eastern Mediterranean [*Pollak*, 1951; *Malanotte-Rizzoli and Hecht,* 1988; *Schlitzer et al.*, 1991]. During the early 1990s the Aegean Sea has replaced the Adriatic as the source of the waters occupying the deepest layers of the Levantine and Ionian basins [*Roether et al.*, 1996; *Malanotte-Rizzoli et al.*, 1996; *Lascaratos et al.,* 1999] (Figure 1). Until 1987 the deeper layers of the Cretan Sea were filled with a largely homogeneous water mass [*Theocharis et al.*, 1999a], that also characterized the Ionian and Levantine basins at the same depths. Its characteristics suggest that it was a transitional water body between Levantine Intermediate Water (LIW) and Eastern Mediterranean Deep Water (EMDW) [*Pollak*, 1951]; for this reason, researchers of the eastern Mediterranean hydrography have been referring to it as Transition Mediterranean Water (TMW) [*Balopoulos et al.,* 1999; *Theocharis et al.*, 1999b]. In 1987, very dense water has appeared at the bottom of the Cretan Sea (the southernmost basin of the Aegean Sea), and by 1992 it had filled the basin, outflowing to the eastern Mediterranean through the straits of the Cretan Arc [*Theocharis et al.*, 1999a]. The water density in the Cretan Sea exceeded the historically recorded maximum of σ_θ = 29.20 for the first time in 1987 and has exceeded values of 29.40 between 1992 and 1995 [*Theocharis et al.*, 1999a]. This water, the Cretan Deep Water (CDW), has been considered to be locally formed in the Cretan Sea and the shallow shelves of the surrounding islandic groups, especially the Cyclades islands [*Theocharis et al.*, 1999b].

Paper number 2000JC900131.
0148-0227/00/2000JC900131$09.00

As early as in 1912, Nielsen [1912, p. 141] proposed that the North Aegean could be a contributor to the deep waters of the eastern Mediterranean:

> We have seen further, that a uniform layer of water from surface to bottom occurs in the southern part of the Adriatic and in the Aegean Sea north of the Cyclades -possibly also in the deep water north of Crete- and that this layer is colder and heavier than the masses of water, which are found at the same level in the Levant and Ionian Sea. These masses of water will then move towards the south, in the extent to which the depths permit, and after reaching the Ionian Sea and Levant will flow down its northern slopes to the greatest depths.

Nielsen's suggestion was challenged by a series of investigators, who argued that the contribution of the Aegean to the bottom waters of the eastern Mediterranean was minimal and that the major contributor was the Adriatic [*Pollak*, 1951; *Malanotte-Rizzoli and Hecht,* 1988]. Once attention returned to the Aegean as a source of waters feeding the bottom layers of the eastern Mediterranean, the role of the North Aegean and its interaction with the south came again under consideration. In a numerical modeling study, *Wu et al.* [2000] were able to generate a pulse of very dense water in the North Aegean by lowering by 2^0C the relaxation sea surface temperature during February, for seven consecutive years. This water slowly propagated southwards, with the signal taking about 2 years to reach from the North to the South Aegean. The anomalously dense water filled the basins of the Cretan Sea and overflowed to the Ionian and Levantine basins through the straits of the Cretan Arc. However, in order to achieve enough buoyancy loss form the North Aegean, *Wu et al.* [2000] used unrealistically low sea surface temperature for excessively long time and ignored the

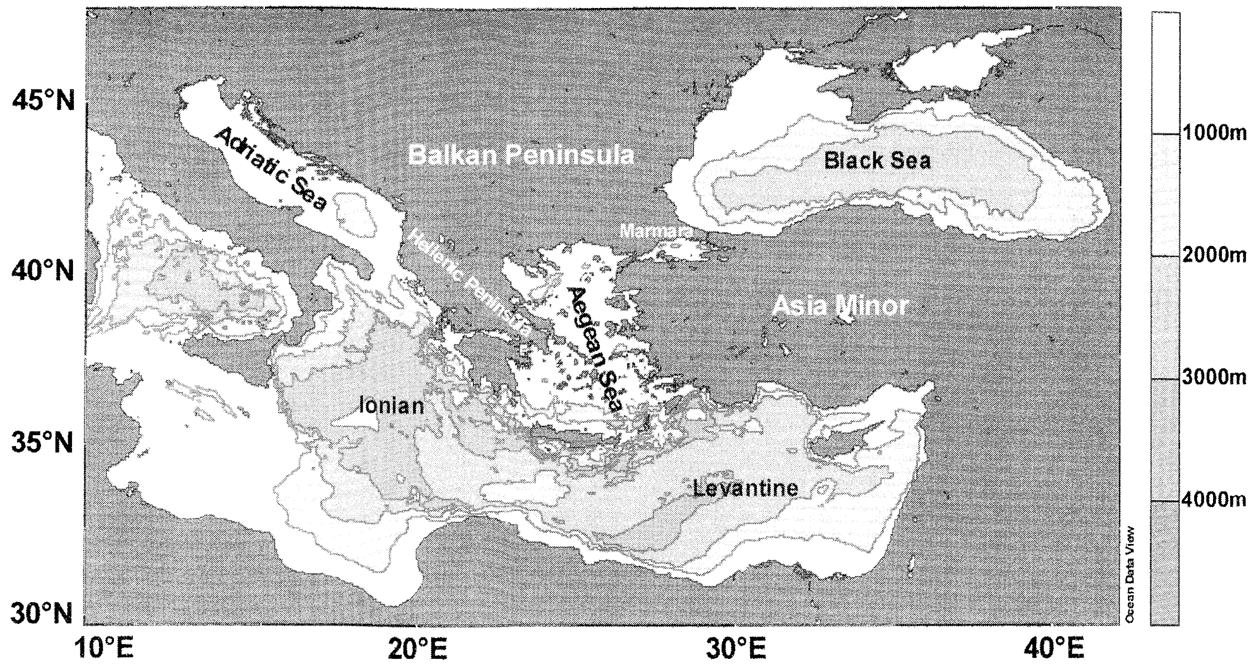

Figure 1. The Mediterranean and Black Seas. The locations of the various subbasins of the Eastern Mediterranean (Levantine, Ionian, Aegean, and Adriatic) are shown.

variability of the buoyancy flux into the North Aegean by the Dardanelles outflow.

This work is a contribution to the effort to understand the processes that led to the replacement of Adriatic origin waters by Cretan Sea waters in the deep layers of the eastern Mediterranean. We aim to examine the significance of the North Aegean, of the inflow of Black Sea waters through the Dardanelles, and indirectly, of the water surplus of the Black Sea to the preconditioning for dense water formation, especially for the incident during 1986-1993. The essence of this work lies in addressing two questions: (1) Under what circumstances are North Aegean dense waters produced? and (2) Do they contribute to the appearance of Dense Cretan Water?

In order to answer these questions, we provide first a description of the bottom morphology of the Aegean Sea. The next section deals with the way that the combination of the bottom relief and the fresh and brackish water inflows into the North Aegean determine the vertical structure of the water column in the region. Having described the "current" state of the North Aegean water column, we will describe the evolution of the pycnocline in each subbasin as it is revealed through the limited observations that exist in the area. A special section will be devoted to the examination of the possible interaction between the North and South Aegean deep waters, using θ/S diagrams as the tool of choice. Having examined the evolution of the North Aegean pycnocline through time and the interaction of the North and South Aegean deep waters, we direct our attention to the conditions favorable for dense water formation in the North Aegean. For this purpose we examine the buoyancy flux through the air-sea interface of the North Aegean; special attention is paid to the way that the Black Sea inflow through the Dardanelles may be affecting the buoyancy loss process and thus the dense water formation in the region. Finally, we summarize our analysis.

2. North Aegean Sea

2.1. Seabed Morphology

The Aegean Sea is one of the two seas (the other being the Adriatic) occupying the northern part of the eastern Mediterranean basin (Figure 1). It is an area of convergence of three major tectonic plates, the Asian, European and African, and that could be the cause of the great variability of its shores and bottom relief (Figure 2a). Geographically, it is divided into the South, Central, and North Aegean, and it turns out that this division can be extended also to the hydrographic characteristics of the subbasins of the sea.

The South Aegean (extending between 35^0N and 37^0N) consists mainly of the Cretan and the shallow shelf of the Cyclades Plateau, along with the Myrtoan Sea at the NW part of the region (Figure 2a). The Central Aegean consists of the northern shelf of the Cyclades islands and the Chios and Ikaria basins and extends between 37^0N and 38^0 40′ N. Finally, the North Aegean (lying north of 38^0 40′ N) is characterized by an alternation of deep trenches and troughs, shallow shelves, and sills. In general, the deep basins of the North Aegean are oriented in a SW-NE direction (Figure 2b). The North Sporades and Athos basins, reaching depths of 1468 and 1149 m, respectively, are separated by a 500 m deep sill from the 1550 m deep Lemnos basin. All three of them form the North Aegean Trough (Figures 2a and 2b) and are separated by a 350 m sill from the North Skyros basin and from the broader Chios basin, lying to their south.

2.2. Fresh-Brackish Water Inflow

The major characteristic of the North Aegean, which dictates its main differences from the rest of the Aegean and the eastern Mediterranean, is that it is a region where highly saline waters of Levantine and South - Central Aegean origin get diluted by the inflow of Black Sea waters from the Dardanelles and river runoff from the Greek and Turkish

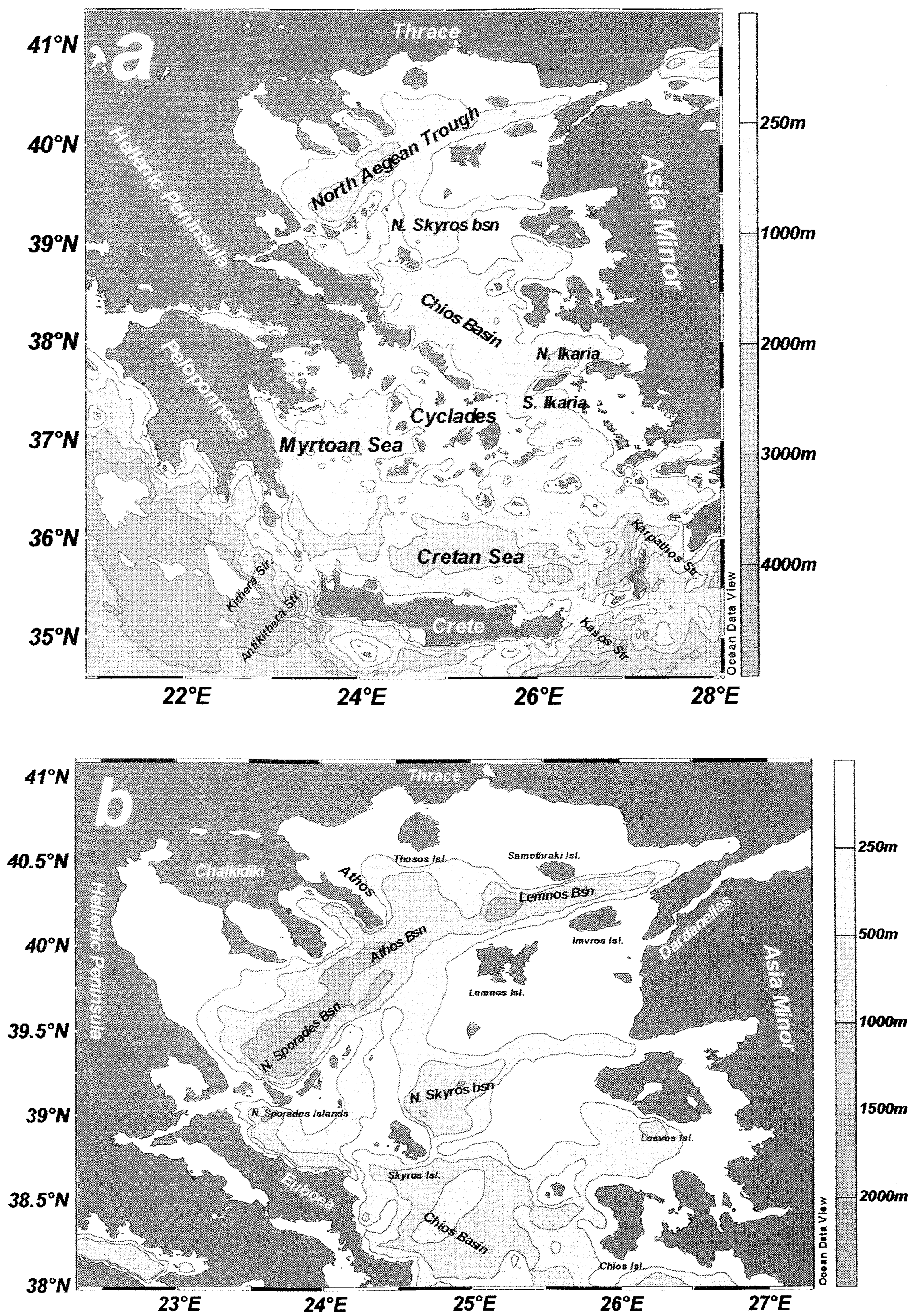

Figure 2. (a) The major basins of the Aegean Sea. (b) The various subbasins of the North Aegean, as well as names of the various geographic features of the area.

mainland. The brackish surface layer outflowing from the Dardanelles into the Aegean carries between 100 and 1300 $km^3 yr^{-1}$ [*Ünlüata et al.*, 1990; *Vlasenko et al.*, 1996], in comparison to the river run-off, which has been estimated to approximately 20 $km^3 yr^{-1}$ [*Therianos*, 1974; *Poulos et al.*, 1997]. Furthermore, the river runoff exhibits its maximum value in the period February - May, while the Dardanelles reach their maximum outflow in late spring.

The Dardanelles' surface current toward the Aegean has a salinity of 24-28 practical salinity units (psu) inside the straits [*Ünlüata et al.*, 1990] and is equivalent to an annual rainfall of 1.7 m yr^{-1} over the whole Aegean Sea [*Drakopoulos et al.*, 1998] the equivalent rainfall estimate over just the North Aegean Sea would be much higher.

2.3. Water-Mass Characteristics of the North Aegean

The morphology of the seabed, as well as the presence of fresh and brackish water, dictate the structure of the North Aegean water column. A typical winter θ/S profile from the region (as of 1997) is shown in Figure 3. Three major water masses can be identified in the region: The Black Sea Water (BSW), exiting the Dardanelles with a salinity less than 30 psu, forms a surface layer of less than 40 m thickness. This layer of BSW is characterized by its very low salinity in relation to the Aegean waters, but also very often (especially in winter) by the lower temperatures that characterize the inflowing water mass. The BSW layer undergoes modification of its characteristics by air-sea interaction and vertical diffusion through mixing with the underlying waters, and gradually reaches a salinity of 38 psu in the region of the Sporades islands (Figure 4). However, its very low salinity by far determines its density, and as a result the underlying, highly saline and denser waters of Levantine origin are effectively isolated from the atmosphere by a thin layer of very light BSW.

The depth range below 50 m and above the depths of the sills that separate the North from the South Aegean (which is about 400 m) is occupied by water whose θ/S characteristics suggest Levantine origin (LIW). It is the depth range where communication of the various basins of the North and the South Aegean is not restricted by bottom topography.

Finally, below 400 m, the presence of saline and extraordinarily dense waters, with slightly different hydrological characteristics per basin, suggest local formation and limited communication between the basins [*Georgopoulos*, 2000]. The waters occupying the deepest layers of the various North Aegean suppressions are hereinafter all referred to with the name North Aegean Deep Waters (DW), in spite of the fact that they often possess significantly different θ/S characteristics per basin. The fact that usually the North Skyros basin, almost devoid of the insulating "lid" (Figure 4), is found to have the densest and saltiest DW, enforces the argument for the isolating role of the superficial BSW layer to deep water formation processes, and suggests that the BSW water contributes to the formation of a less saline, colder deep water at the northern basins, as we will see in section 4.

The total volume of the surface layer (upper 50 m) in the whole North Aegean, as defined in Figure 2, is 3.1×10^{12} m^3, the intermediate layer (50-400 m) is 1.04×10^{13} m^3, and the

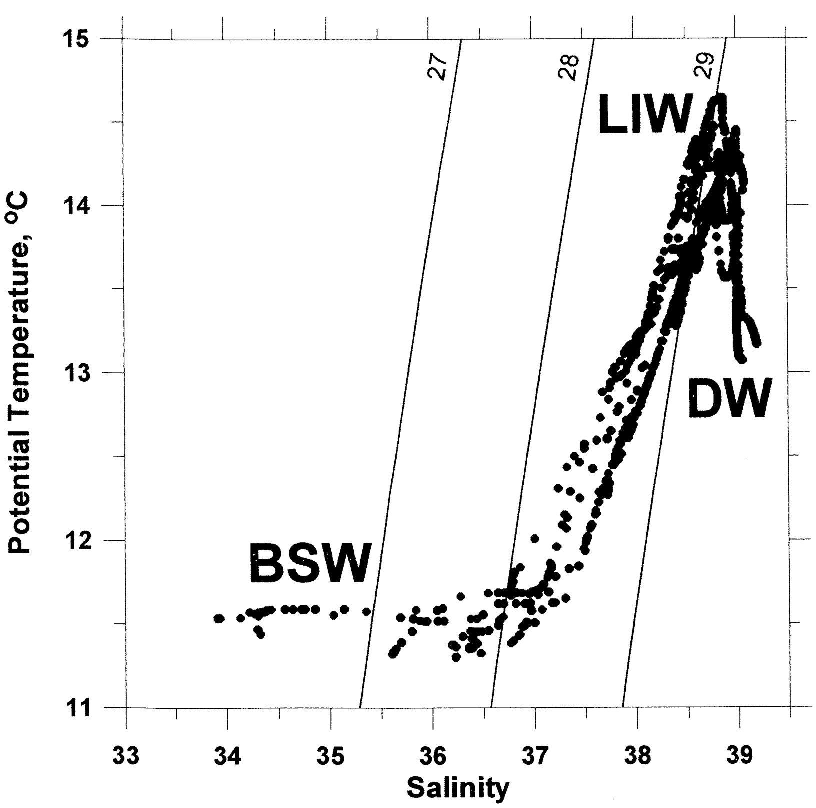

Figure 3. Representative winter North Aegean θ/S diagram. The data are from the March 1997 cruise of the R/V Aegaeo in the region, in the framework of the MTP-II project MATER. Modified Black Sea Waters (BSW), waters of Levantine origin (LIW), and North Aegean deep waters (DW) are identified. Note the bifurcation of the deep water signature, identifying the different θ/S properties at two distinct basins.

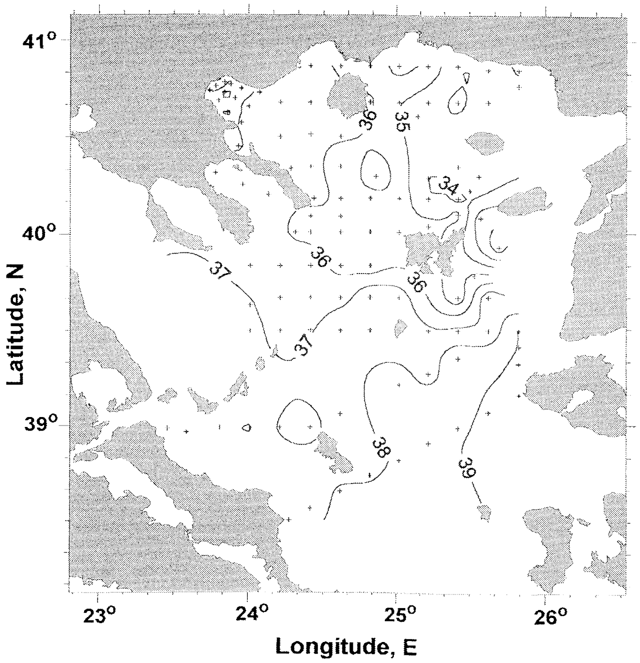

Figure 4. Surface salinity in the North Aegean in May 1997.

deep waters 3.85×10^{12} m^3. For comparison the volumes of the North, Central, and South Aegean basins, as defined in Figure 2, are about 1.7×10^{13}, 1.4×10^{13}, and 4.4×10^{13} m^3, respectively.

3. Interannual Evolution of the North Aegean pycnocline

The North Aegean Sea has not always had the same characteristics as the ones revealed in Figure 3. The whole basin has a rather small volume (1.7×10^{13} m^3) and thus presents low inertia to external forcing. Unfortunately, this area attracted rather low oceanographic interest before the mid-1980s, and as a result, a very limited number of observations from the region are available. The first good quality measurements in the region were taken by R/V *Atlantis* (1948) and R/V *Calypso* (1955); later, the R.R.S. *Shackleton* (1978) performed a survey in the NW Aegean. The Physical Oceanography of the Eastern Mediterranean (POEM) project gave a considerable boost to the oceanographic research of the region [*Malanotte-Rizzoli and Robinson*, 1988]. Thus there is a significant number of observations from 1986 until 1989, although they become more scarce between 1989 and 1990, when POEM's interest is focused more in the South Aegean and Levantine basins. Two fisheries cruises that took place in November 1992 and in May 1993 provide valuable information from that time, since no physical oceanography cruises were performed in the region from 1990 until 1997. The next period of intensive monitoring of the North Aegean is 1997-1998, when two research projects funnded by the European Union (EU), MTP-II MATER and INTERREG-1 "Interregional Pollution in the North Aegean" allowed the National Center for Marine Research (NCMR) to do several extensive surveys in the region.

The evolution of the pycnocline in four different subbasins of the North Aegean is displayed in Figure 5a. Unfortunately, there are large periods of time that correspond to a complete lack of data from the deep subbasins of the region, thus there is no way to make a safe statement about deep water formation events during those times. The recorded evolution of the pycnocline is presented despite the lack of data, in order to introduce the reader to the level of variability of density in the North Aegean before the dramatic change of hydrological characteristics initiated in the mid-1980s. Our following analysis is not based on pre-1986 data; the latter are used just for the sake of comparison to post-1986 conditions. Note that despite the lack of data, we can conclude with rather good certainty that the depths of the isopycnals at all four different basins have remained relatively constant throughout the 1950-1980 period.

Between 1948 and the early 1990s, there is a general slow tendency of the isopycnals to "sink." This trend is equivalent to a decrease in the density of the bottom waters, observed especially at North Skyros and Athos basins, where data exist. This trend suggests that the slow, gradual effect of vertical diffusion processes (like internal wave-induced mixing) is to decrease the density of the bottom waters by mixing them with the lighter waters of the intermediate layer above 400 m [*Georgopoulos et al.*, 1998]. Some bottom water formation has taken place at Athos and North Sporades basins, most probably between the years 1948 and 1953, but lack of data hinders any analysis.

Between 1971 and 1986 we observe a rise of the deep isopycnals by about 200 m. Lack of data hinders the analysis at most basins, but sampling for three continuous years in the early 1970s in the North Skyros Basin reveals that bottom water formation took place there sometime between 1970 and 1974. We believe that it is reasonable to assume that the formation was the result of a large-scale atmospheric forcing to which every subbasin of the North Aegean responded similarly. After the forcing of the early 1970s, no major formation seems to have taken place in the North Skyros basin, as the isopycnals remain at the same depths until the winter of 1986.

The period 1986-1990 is very well resolved relatively to previous times, due to the availability of NCMR's R/V *Aegaeo* and the POEM project. This fact is fortunate, because it was also the period of very dense water formation. The high temporal resolution of the data permits us a better examination of the pycnocline evolution between 1986-1998 (Figure 5b). In detail, the severest formation appears to have taken place in the basins of Lemnos and North Skyros, a somewhat striking observation, as these basins are the most distant from each other. Waters of σ_θ exceeding 29.40 appear in the deep layers of both these basins in the summer of 1987. The θ/S characteristics of these bottom waters are distinct, suggesting different formation sites and possibly processes (see next section). Formation at the two other sites seems to be slower.

Another striking fact is that the deep waters of Lemnos basin gain buoyancy progressively after the 1987 event, until 1990, while the density of the deep waters of the neighboring Athos basin slowly increases. The latter takes place despite the fact that a sill reaching 500 m separates the Lemnos basin from the Athos and North Sporades basins, a fact suggesting that simple lateral advection could not mix the two water masses. A more complicated mechanism, maybe vertical diffusion in combination with lateral advection could be responsible for the changes observed.

The next period of available data in all four sites is the winter of 1997. The isopycnals are once again found to have

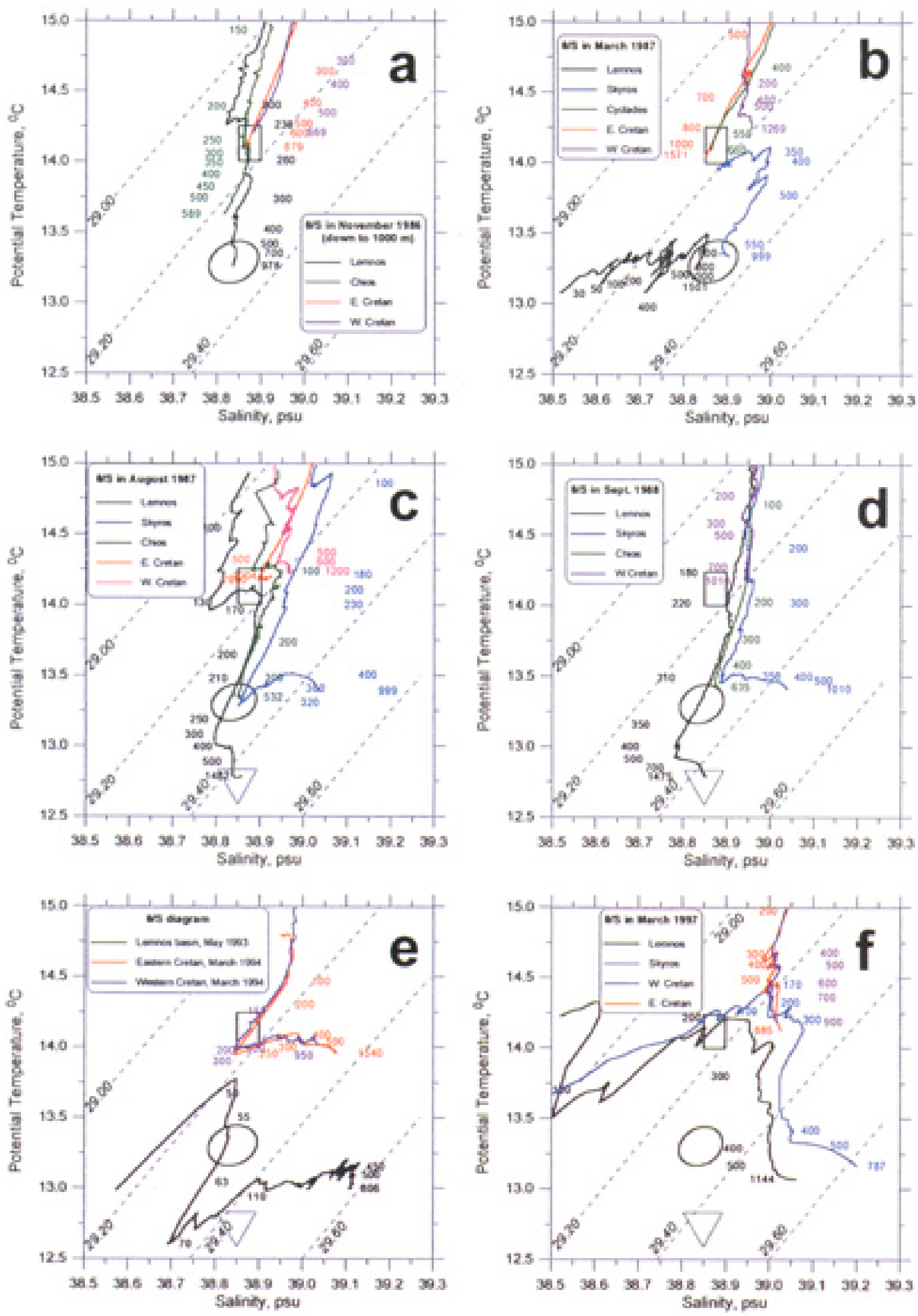

Plate 1. The evolution of the deep waters of various Aegean Sea subbasins along a meridional direction, as revealed by successive θ/*S* diagrams. Displayed are the hydrographic conditions in (a) November 1986, (b) March 1987, (c) August 1987, (d) September 1988, (e) May 1993/March 1994, and (f) March 1997. The numbers denote depth; color coding is used to identify stations. The square and the ellipse denote the θ/*S* values of the deep waters of the South and North Aegean, respectively, before the summer of 1987, while the triangle the θ/*S* values of the North Aegean deep waters formed in winter 1992-1993.

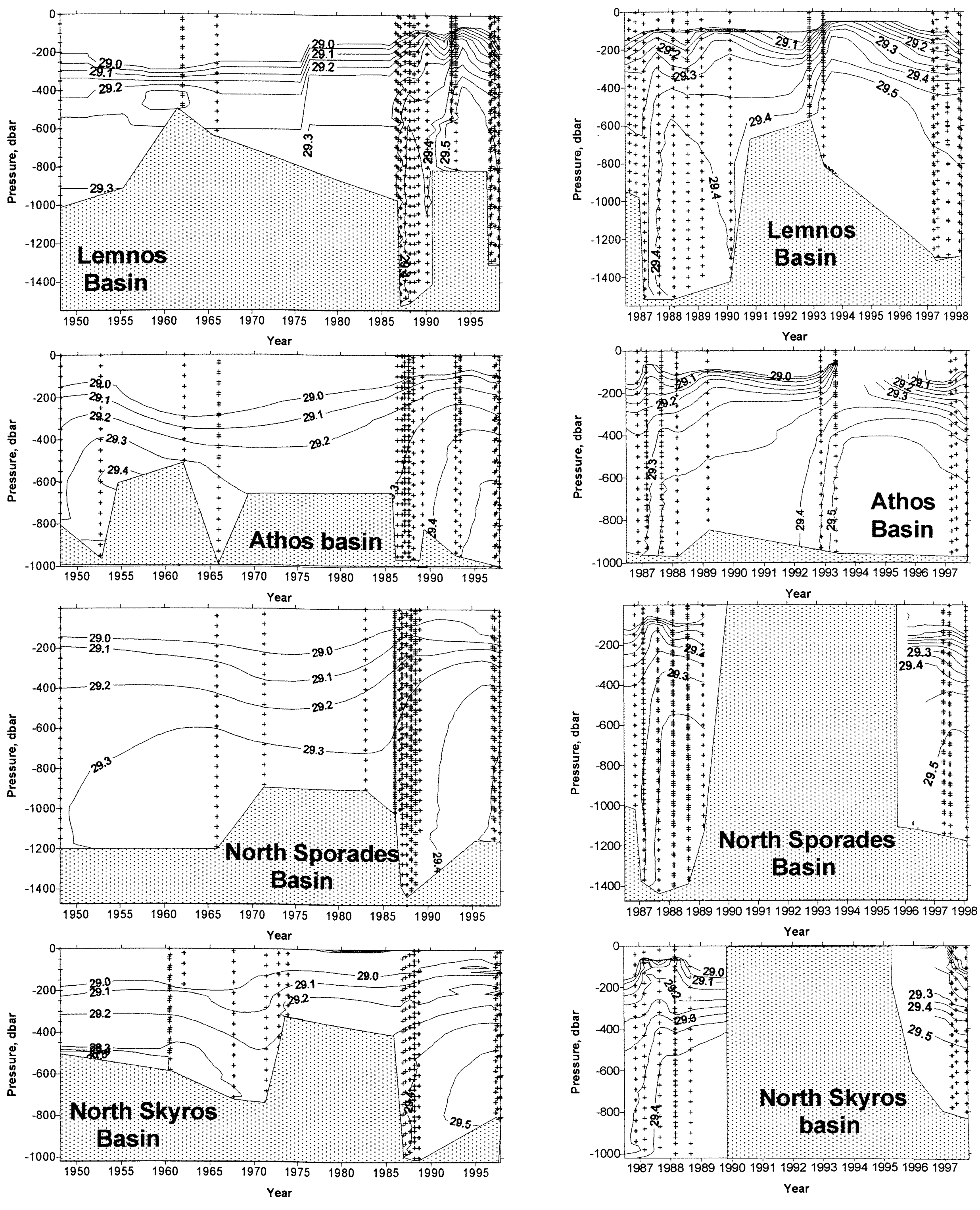

Figure 5. (a) The evolution of the pycnocline at four basins of the North Aegean in the last 50 years. Isopycnals are plotted every 0.1 kg m^{-3}. (b) A zoom in the evolution in the decade between 1987 and 1998, with isopycnals every 0.05 kg m^{-3}.

risen by 100-500 m since 1990, depending on the site, suggesting that significant bottom water formation took place sometime in between. Two NCMR fisheries cruises that took place in November 1992 and May 1993 in the basins of Lemnos and Athos point to that particular winter as the period of bottom water formation. The validity and accuracy of this data set has been tested by comparison to Hellenic Navy Hydrographic Service measurements from that period. New bottom water of σ_θ exceeding 29.50 fills the Lemnos basin, up to the 500 m level, and all the previous bottom water is pushed to intermediate depths (see next section). After that time and until 1998, vertical diffusion acts again to feed buoyancy to the deep waters of Lemnos basin (V. Zervakis et al., manuscript in preparation, 2000). A similar scenario may be possible for all the other three subbasins of the North Aegean; however, the lack of data between 1990 and 1997 provides with the only certain conclusion that bottom water was formed some time between 1990 and 1997.

4. Interaction of the North and South Aegean Seas

The interaction between the deep waters of the North and the South Aegean basins has been under question. As a series of shallow shelves and sills separate the deeper basins of the two regions, the direct communication of the deep (under 400 m depth) waters is impossible. This argument is further enforced by the fact that the θ/S characteristics of the deep waters of the two seas are different; as mentioned in the previous chapter, the North Aegean waters barely exceeded $\sigma_\theta = 29.40$ before the mid-1980s. At the same time the Cretan Deep Water was always lighter than $\sigma_\theta = 29.20$.

In order to examine the possible interaction between the North and South Aegean seas, we selected the θ/S diagram as the proper tool. Five distinct regions of the Aegean were selected and data from these regions overlaid on the same θ/S diagram to examine the fate of different water masses at different parts of the sea. The different regions are outlined in Figure 6. The evolution of the θ/S characteristics of the deep waters of various Aegean Sea subbasins is described in Plate 1.

4. 1. November 1986

The situation in November 1986, before the major formation event of winter 1986-1987, is shown in Plate 1a. Data from four stations are shown, in Lemnos and Chios basins and East and West Cretan Sea. During this cruise, the profiles reach only 1000 m, but as at a later cruise the water column was quite homogeneous below that depth, we consider the measurement quite representative of deeper layers. We have placed an ellipse and a square on the θ/S diagram, to denote the position on such a diagram of the deep North and deep South Aegean waters, respectively, in fall 1986. The θ/S properties of the deep waters of the Cretan Sea (square) in fall 1986 are not different than the waters occupying the same depths outside the Aegean, that is, Transition Mediterranean Water. Of special interest is that the intermediate water (at a depth range of 230-260 m) from the Lemnos basin falls within the square, that is, has the same properties as the deep waters of the Cretan Sea. Similar water is found between 240 and 350 m at the Chios basin.

Thus the intermediate layers of the North Aegean contain the same water as the deep and bottom Cretan Sea. This importance of the latter lies in the fact that every winter the mixed layer of the North Aegean at the Chios and North Skyros basins (where there is no BSW isolation layer at the surface) reaches down to 200-300 m [*Georgopoulos*, 2000]. Thus, there is evidence that the intermediate water of the North Aegean and the deep Cretan Waters before 1987 belong to the same water type, and furthermore, that the oxygenation of the Cretan Deep Water (in the pre-1987 condition) was possible through wintertime convective mixing in the North Skyros and Chios basins annually.

4. 2. March 1987

The data presented here were collected throughout February-April 1987; a major factor in extending the duration of the oceanographic cruise was the bad meteorological

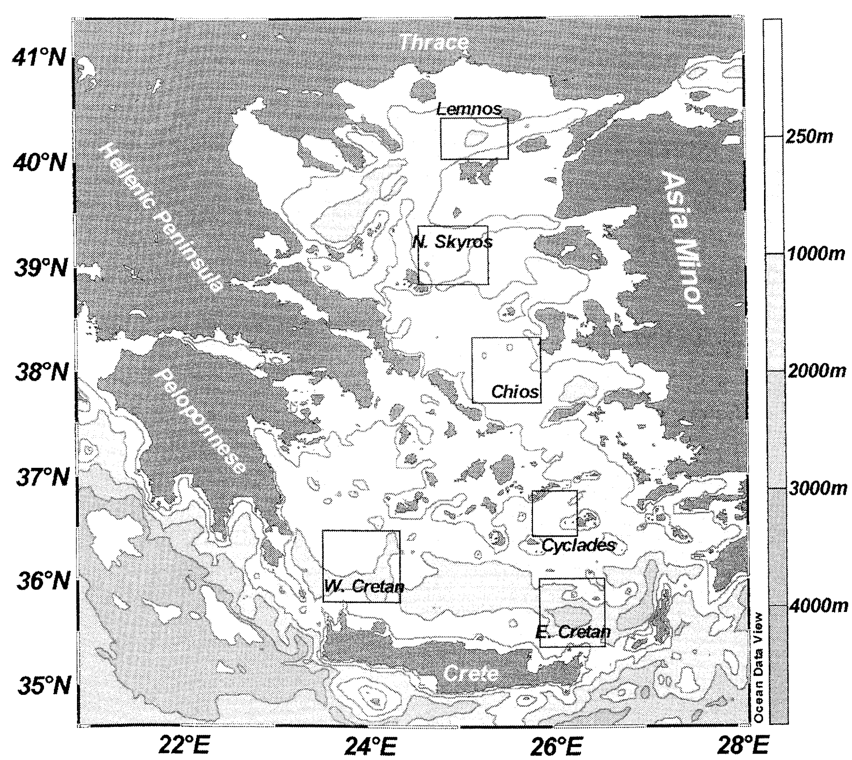

Figure 6. The five different sites of the Aegean selected to examine the communication of North and South basins. Displayed are the subbasins of Lemnos, North Skyros, Chios, Cyclades, East Cretan, and West Cretan.

conditions of winter 1987. The R/V *Aegaeo* after departure from Piraeus harbor sailed to the north and proceeded to conduct hydrographic work in the North Aegean. Bad weather caused a daylong delay in a harbor of northern Greece, and then the sampling continued while sailing southward along the eastern Aegean. An atmospheric cold front propagating over Greece forced the ship to remain in harbor at Chios Island for 15 days before continuing the survey. The cold front was severe both in its intensity and duration (March 3-13, 1987), and has been extensively described by *Lagouvardos et al.* [1998]. Cold-air damming along the eastern coast of continental Greece caused the heaviest snowfall of the century; the meteorological station at Lemnos airport reported extremely strong winds (of the order of 25 m s^{-1}) and low air temperatures (-4^{0}C) on the island. The analysis by *Lagouvardos et al.* [1998] has shown that the extreme conditions prevailed mostly in the North Aegean Sea, and this is attributed largely on the cold-air damming phenomenon.

The observations of the R/V *Aegaeo* in the North Aegean Sea, despite having been collected before the passage of the severe atmospheric front described above, have revealed that (1) production of waters of relatively high density had already taken place along the shallow shelves of the region, and (2) the surface waters were characterized by very high salinities [*Georgopoulos et al.*, 1992; *Theocharis and Georgopoulos*, 1993]. The high salinity of the surface could be attributed either to the erosion of the surface layer by convection processes and vertical mixing due to bad weather, or to a significant decrease of the Black Sea water outflow through the Dardanelles, or a combination of the two.

In March 1987, before the atmospheric forcing of March 3-13, the deep waters of Lemnos basin and the Eastern Cretan Sea have not changed significantly yet (Plate 1b). The intermediate layers exhibit more pronounced changes: the temperature of the upper and intermediate layers in Lemnos basin has fallen significantly, exhibiting intrusions down to 500 m, while the properties of the deep waters have remained the same as in November 1986 [*Georgopoulos et al.*, 1992; *Theocharis and Georgopoulos*, 1993]. Very high salinities were recorded at all depths above 550 m in Skyros basin in late February 1987. The absence of data from 1986 restricts any comparisons in Skyros basin. The dominant cyclonic circulation over the Aegean could carry the very dense waters recorded at Skyros basin toward the Cyclades plateau, where further increase in density would take place due to air-sea exchanges throughout the extremely cold event of March 3-13. Evidence for that is the presence of excessively dense water (σ_θ=29.40 psu) recorded at a single station over the Cyclades plateau in mid-March [*Georgopoulos*, 2000], directly after the passage of the atmospheric front. The new, dense bottom water in the western Cretan Sea was recorded in late April 1987, 2 months after the Skyros observation. The respective positions in the θ/S diagram of the surface and intermediate waters at Skyros and the bottom waters at Western Cretan, support the scenario described above. On the contrary, the selected Cyclades and Eastern Cretan stations do not exhibit any significant changes over the previous condition. The position of the Cyclades station, near the southeastern limits of the Cyclades plateau, was selected based on the morphology of the 250 m isobath. A very significant change appears at a station located at the westernmost part of the Cretan Sea, sampled on April 25th: waters deeper than 200 m appear denser than before: especially below 500 m, there is a very significant salinity increase, with σ_θ reaching for the first time 29.20 (a more detailed description on the changes observed in the Cretan Sea by *Theocharis et al.* [1999a]). It is noteworthy that stations of the Western Cretan Sea sampled during the second half of March do not exhibit this change; instead, their hydrographic properties were identical to those of the Eastern Cretan, sampled only during March. Thus anomalously dense water appears at the bottom of the Western Cretan Sea for the first time in April 1987, for which time we have no data in the Eastern Cretan Sea.

4. 3. August 1987

The oceanic consequences of the severely cold and windy conditions during the March 1987 atmospheric front passage [*Lagouvardos et al.*, 1998] were revealed by a cruise of R/V *Aegaeo* in August 1987. Newly formed bottom water, of density (σ_θ) that exceeded 29.40, raised the old bottom waters to 210-250 m depth in Lemnos basin, and to 290-340 m in North Skyros basin (Plate 1c). The very high density of the new deep water in Skyros basin is mostly due to a salinity increase over the preexisting deep water, while the change in Lemnos basin is attributed more to a drop in temperature. Here we should note that historically, the deep waters of the North Skyros Basin exhibit higher salinity than the sub-basins of the North Aegean trough. This difference is attributed to the different water formation locations [*Georgopoulos*, 2000]. North Skyros basin deep water is formed mostly over the extended shelf area between the islands of Lemnos and Lesvos. This area is (due to the cyclonic circulation of the Aegean) devoid of Black Sea Waters, and thus formation is easier and the resulting waters exhibit high salinity. By contrast, Lemnos basin waters are formed on the shelf of Thrace, which is characterized by low salinities at the surface layer. Formation of very dense water is significantly harder, and when it takes place, the resulting salinity of the deep water is smaller than at North Skyros Basin [*Georgopoulos*, 2000].

At the same time the previous Cretan Deep Water is now found above 750 m depth in the Cretan Sea, while water of similar θ/S characteristics to the latter is traced in the Lemnos basin at a depth of 140-160 m. The signature of the dense water replacing the old Cretan Deep Water at the bottom of the Cretan Sea continues to be more pronounced in the West Cretan Sea, where the volume of the water exceeding σ_θ = 29.20 has increased considerably [*Theocharis et al.*, 1999a]. A very important clue toward tracing the pathways of the dense water signal is given by the water at the Chios station, which now exhibits θ/S characteristics identical to those of pre-March 1987 North Aegean Dense Waters (compare Plate 1c with Plate 1a and 1b). Thus we suggest that the latter, having been uplifted by the newly produced, denser water in the North Aegean, propagates southward. Note that the water that fills the bottom of the Western Cretan Sea has the same θ/S values as water found at 100-150 m at the Chios station.

We cannot make a precise estimate of the total volume of new dense water produced in the North Aegean; however, we can estimate a lower limit, as we know that the new, dense North Aegean deep water reached depths shallower than 300 m, which corresponds to a minimum production of a volume of 5.4×10^{12} m^3. It is probable that a greater quantity was produced but overflowed over the sills toward the south. By comparison the new CDW that filled the depths greater than 1000 m in the Cretan Sea had a volume of 4.5×10^{12} m^3.

4. 4. September 1988

By September 1988 the situation has not changed dramatically; vertical diffusion has homogenized somewhat the waters, and as a result the θ/S diagram appears much smoother (Plate 1d). The old North Aegean Deep Waters have sunk a bit relative to August 1987, now found at 310-340 m in Lemnos basin; however, this difference is not very dramatic and could be attributed to dynamic causes. The waters found at the deep layers of the North Aegean have not changed considerably since August 1987, a fact suggesting that deep water formation has not occurred since. The θ/S properties of the waters at the Chios station suggest that they consist a mixture of the pre-1987 North Aegean deep water and the intermediate waters of Levantine or Cretan origin.

4. 5. May 1993 to August 1994

Due to a lack of projects in the region at the time, there are not much data available in the North Aegean in the early 1990s. Two fisheries cruises took place in November 1992 and May 1993, and these suggest that a very strong deep-water formation event took place in the winter of 1992-1993 in the North Aegean (Plate 1e). Very saline dense water has filled the Lemnos basin, raising the North Aegean Bottom Water produced in 1987 to 80-100 m. In the same basin, water of θ/S characteristics similar to pre-1987 DW is found at 55-61 m, while water similar to pre-1987 Cretan Deep Water (with characteristics identical to TMW, but cooler by 1^0C) is found at 50 m. In the early to mid-1990s, the volume of the post-1987 Cretan Deep Water reached its maximum, and as a result it overflowed the sills of the Cretan Arc to fill the bottom basins of the Levantine and the Ionian [*Roether et al.*, 1996; *Theocharis et al.*, 1999a; *Kontoyiannis et al.*, 1999; *Tsimplis et al.*, 1999]. To conserve mass in the Cretan Sea, the inflow of TMW into the Cretan Sea was increased, and thus the layer of TMW has a very pronounced signal. The signature of this layer extends throughout the Aegean and is upwelled to a depth of 50 m in the North Aegean (Plate 1e). Here, we should point out the following: there are no North Skyros data available from that period. However, our experience as well as data presented here (Plate 1c and 1d) suggests that dense waters formed there are saltier and denser than DW of the Lemnos basin. This is also supported by the argument laid out earlier in this chapter, describing the effect that the surface layer of BSW (or its absence) may have on the DW formed in the Lemnos basin (or the North Skyros basin, respectively). Furthermore, Plate 1f presents further evidence that the water formed in 1992-1993 was denser and saltier in North Skyros basin than in Lemnos basin.

The newly formed DW of Lemnos basin reaches up to the level of the sills separating the various basins (350-400 m). Thus, assuming that all basins in the North Aegean responded similarly, we can set a lowest estimate for the new dense water production, by converting the minimum depth at which new waters are encountered to respective volumes based on the bottom topography. In the North Aegean the new, saline deep water reached 100 m depth, which corresponds to a production of 1.2×10^{13} m^3. It is not possible to estimate the maximum DW produced in that event, as water may have overflowed and dispersed toward the west and south.

Unfortunately, there were no hydrographic cruises in the South Aegean in 1993. The Cretan Sea data presented in Plate 1e were collected in the framework of the MTP-I project "PELAGOS" in 1994. In the Cretan Sea a new Cretan Deep Water, much denser than the previous, is detected below the TMW, owing its high density to its increased salinity relative to the TMW (and CDW of 1986) water. It is not clear to us whether this water has been locally formed in the Cretan Sea by direct interaction of the surface waters with the atmosphere or is a result of a more complicated process that includes the propagation of very dense water from the North Aegean southward and its modification through mixing and air-sea interaction in the shallow shelves of the Cyclades islands. Its position on the θ/S diagram does not exclude the possibility that it could be a mixture of local LIW with newly formed DW from the North Aegean that overflowed through the sills and propagated southward, with possible modification over the Cyclades plateau. The minimum volume of the new CDW observed in the South Aegean is about 2.5×10^{13} m^3.

4. 6. March 1997

Finally, in the framework of the MTP-II MATER project we were able to record the hydrographic conditions in the basins of Lemnos, North Skyros, and the Cretan Sea in March 1997 (Plate 1f). As has been already mentioned in the previous section, no significant deep water formation took place between 1994 and 1997. As a result, the process of CDW outflowing through the straits of the Cretan Arc has relaxed, and the associated inflow of TMW into the Cretan Sea has been reduced. Vertical diffusion has worked effectively over 3 years to almost erase the signal of TMW from both the North and South Aegean, being now much more effective than the lateral advection of this water. Early signs of this process have been recognized at previous works in the Cretan Sea [*Georgopoulos et al.*, 2000].

Note the much higher salinity and density of the deep waters of the North Skyros basin, relative to the deep waters of the Lemnos basin. Most records suggest that this is most commonly the case, reflecting the effect that the insulating layer of the superficial BSW may have on the bottom water formation processes at the basins of Lemnos, Athos and North Sporades [*Georgopoulos,* 2000]. Also noteworthy is the observed decrease of the maximum density of every single basin (both Cretan Sea and North Aegean), reflecting the homogenization of the deep, isolated from lateral advection part of the water column due to vertical diffusion, a scenario examined elsewhere (V. Zervakis et al., manuscript in preparation, 2000).

Summarizing, this section reveals a path of interaction between the North and South Aegean deep waters that has not been described in depth previously, despite the fact that a preliminary analysis of 1987-1988 observations has arrived at similar conclusions [*Gertman et al.,* 1990]. The production of very dense waters in the North Aegean causes the rise of the old DW to depths higher than the sills hindering the north-south communication. At such depths the old DW is expected to move toward the south, following the dominating cyclonic large-scale circulation of the Aegean. The old DW, however, is denser than the deep waters of the southern basins, and on its way south (being modified by mixing) it will sink below the deep waters of the next basin to the South. The latter will rise to intermediate levels, move to the south and replace the bottom waters of the next basin, and so on, until the signal reaches the Cretan Sea and new deep waters fill the bottom layer of this basin, raising the old Cretan Deep Water to shallower depths. It is a process we like to call hereinafter "the domino effect." One can include the

Levantine and Ionian basins in the domino effect, as, there too, the bottom waters were risen to shallower depths by denser water formed in another basin, in this case the Cretan Sea. Above, we have shown evidence that this process has probably taken place in the Aegean twice since the 1970s. Evidence exists that the production in 1987 and 1992-1993 may have exceeded the volume of just the deep basins of the North Aegean. The uplifting of dense water to intermediate-upper depths will contribute to the easier initiation of dense water formation at other regions the next year, etc.

Furthermore, the massive dense water production in the North Aegean triggers a thermohaline conveyor belt in the Aegean Sea, where highly saline water of CIW/LIW characteristics propagates at intermediate depths toward the North Aegean in order to balance the outflow of dense water toward the south. This effect increases the salinity of the intermediate layers of the North Aegean, and preconditions it for the production of dense waters of even higher salinity. Evidence for this is the highly structured water column during periods of high production.

During relaxation periods, when no large quantity of bottom water is produced in the North Aegean, the interaction of the North and South Aegean bottom waters is interrupted. Then vertical diffusion becomes the dominant process in the deep waters of each basin, homogenizing the layer below 300-400 m, the depth of free advection over the sills.

5. Buoyancy Fluxes

The thermohaline circulation of the Aegean is driven by the buoyancy fluxes through the surface and that advected through the Dardanelles strait. Following *Gill* [1982], we define the buoyancy flux as

$$B=-c_w^{-1} g\alpha Q_T+g\beta S(E-P)$$

where c_w is the specific heat of water, g is the acceleration of gravity, α and β are the expansion and contraction coefficients due to thermal and saline contributions in the seawater equation of state, respectively, Q_T is the net heat flux through the surface, E is the evaporation, and P is the precipitation.

In order to evaluate this formula we have used the Comprehensive Ocean-Atmosphere Data Set (COADS) spanning the period from 1980 to 1995. The net heat flux was estimated in a manner similar to that presented by *Garrett et al.* [1993] and *Poulos et al.* [1997]. The solar shortwave radiation influx was obtained by the formula of *Reed* [1977] and scaled down to match the *in situ* data observed in the meteorological station of Athalassa in Cyprus. For the long wave radiation the bulk formula by *Bigniami et al.* [1995] which is tuned for the Mediterranean Sea was employed. The thermal expansion coefficient was evaluated from COADS sea surface temperature and the saline contraction coefficient from the climatology of local sea surface salinity. Heat fluxes were estimated for the whole Mediterranean basin, and thus it was assured that the long-term budget was close to the observed one (~ -7 W m^{-2}) [*Bethoux*, 1979]. In this way we exploited the restrictions of the budget imposed by the semienclosed nature of the basin in order to significantly reduce the inherent uncertainties involved in the use of bulk formulae. For precipitation we used monthly records collected by the Hellenic Meteorological Service in six relevant coastal and insular weather stations. The equivalent freshwater influx from the Black Sea was estimated using the Bosphorus volume transport based on the output of a box model of the Black Sea developed by the Ukrainian Hydrometeorological Research Institute [*Simov et al.,* 1999; Y. Golubev and Z. Golubeva, personal communication, 1999] and extrapolating to Dardanelles outflow [*Ünlüata et al.,* 1990]. The advected waters were spread over all the North Aegean COADS squares and transformed in precipitation equivalent following the approach of *Drakopoulos et al.* [1998]. This spreading in various squares was accomplished using a weighting factor for each square, deduced from the climatology of the vertical salinity distribution in the area. As an indication, the corresponding surface freshwater inflow can exceed 2.0 m yr^{-1}, that is, over 4 times larger than the mean value of precipitation in the area (~0.5 m yr^{-1}). Although we are confident that the above estimated buoyancy fluxes in the Aegean do not deviate significantly from reality, it should be noted here that we are interested not as much in the absolute values of the air-sea exchange, but rather in its interannual variability.

In Figure 7a the net buoyancy flux in the North Aegean after the seasonal cycle has been removed is depicted. As it is evident (apart from the uncertainties involved in the data and bulk formulae), in the long term, there is almost always buoyancy loss from the surface. Although the *E-P* term in the North Aegean adds buoyancy, its contribution is an order of magnitude smaller than that of the heating term. A striking feature of the interannual variability during that period is that during 1986-1987 and 1991-1993 (shaded areas) in Figure 7, there is excessive buoyancy loss from the surface. During these periods, as stated above, there was observed deep water formation.

However, the question that arises is whether the insulating effect of the brackish Black Sea Waters can be overwhelmed by surface buoyancy loss of that magnitude. In other words, what is the potential of the North Aegean surface layer of brackish water to serve as an absorber of air-sea energy and mass exchanges and thus to moderate the atmospheric potential for dense water formation in the region.

Plakhin [1972, p.346] addressed the same problem when trying to identify regions of dense water formation in the Mediterranean:

> As we know, low-salinity Black Sea water carried out through the Bosphorus and the Dardanelles, can traced in the surface layer of the Aegean Sea. The low density of the surface layer interferes with the development of vertical circulation. To overcome this "barrier", a considerable drop in temperature is required, and consequently, a considerable loss from the surface. As we can see from the curve, 21 kcal cm^{-2} (897.23 MJ m^{-2}) are required for convection to penetrate to a depth of 200 m, 18 kcal cm^{-2} (753.62 MJ m^{-2}) are spent in the northern part of the Algerian-Provence basin for mixing to a depth of 2000 m.

So *Plakhin* [1972] testifies that the BSW waters play an important role as an insulator in the North Aegean. However, we showed above that massive dense water formation indeed took place between 1986 and 1994 in the North Aegean basins, despite the surface layer. So we arrive to the question asked at the beginning, that is, under what circumstances does massive dense water formation take place in the North Aegean?

In order to address this question we introduce a simple conceptual model. Let there be a two-layer fluid, representing the upper water column of the North Aegean.

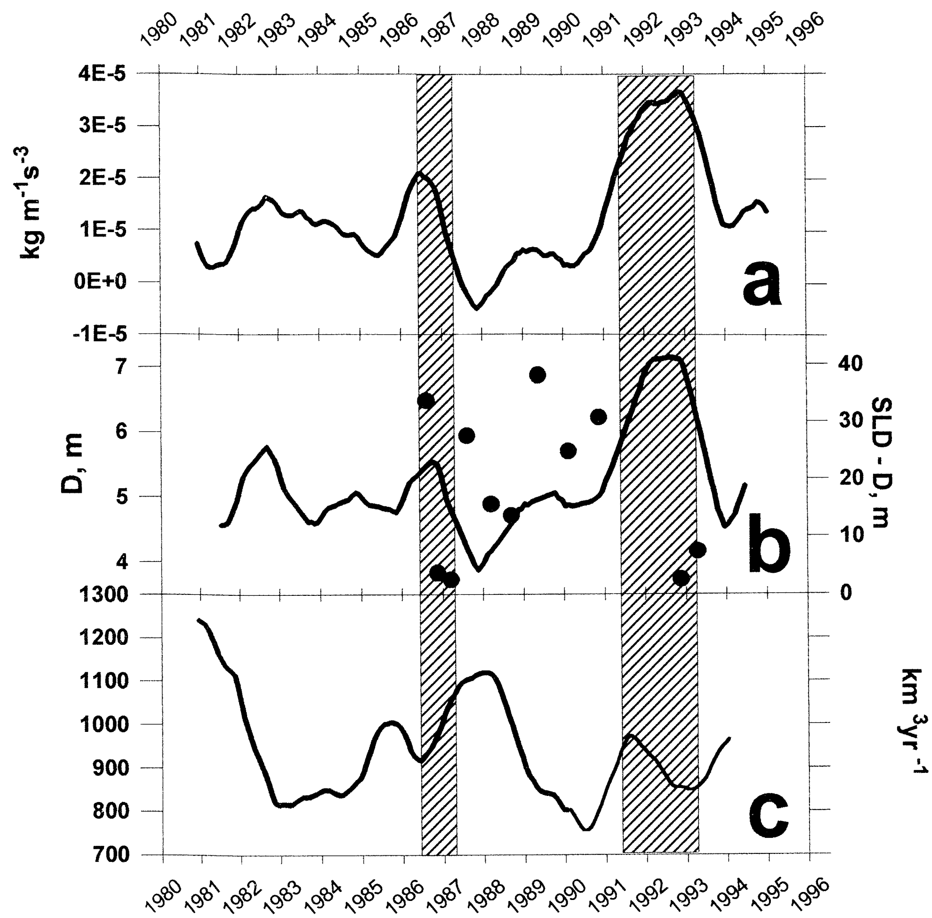

Figure 7. (a) The total buoyancy flux from the North Aegean. (b) The maximum monthly depth of neutralization D is plotted as a solid line, and the difference between observed surface layer thickness and D as solid circles. (c) The estimated Dardanelles outflow. The shaded areas denote the times of observed formation in the North Aegean. Read 4E-5 as 4×10^{-5}.

The top layer is assumed to have an initial salinity $S = 35$ psu and a temperature 12^0C (typical values for the surface layer of the winter) and the lower layer a salinity $S = 39$ psu and a temperature 15^0C. The corresponding initial density difference between the two layers is $\Delta\sigma_\theta = 2.47$ kg m^{-3}, which converted to buoyancy corresponds to a difference of $\Delta b = 24.23$ kg m^{-2} s^{-2}. As the salinity of the lower layer was close to 38.9 psu in the 1980s, we estimated that a change of 0.1 psu in its salinity would cause a change of the buoyancy difference between the two layers by only 0.3%. The two layers have such distinct properties that small changes in their characteristics do not affect much the outcome, that is, that there is a very strong buoyancy difference between the two layers. In order for the process of deep water formation to initiate, the surface layer will have to attain the same density as the lower layer, thus it will have to gain density through buoyancy loss to the atmosphere.

Let b be the buoyancy of the surface layer. Then

$$\frac{\partial b}{\partial t} + u_h \cdot \nabla b = -w \frac{\partial b}{\partial z}. \qquad (1)$$

Integrating with depth from the bottom of the surface layer at $z = D$ to the surface at $z = 0$, and assuming that the thickness D of the surface layer remains constant in time, and that the buoyancy flux through the bottom is insignificant, we get

$$D\left\{\frac{\partial b}{\partial t} + u_h \cdot \nabla b\right\} = B(t), \qquad (2)$$

The most difficult parameter to estimate is the advection term, that is, the second term on the right-hand side. We decided to follow the method used by *Williams* [1987] to estimate the advection term. Given that the interannual variability of the buoyancy air-sea flux is much smaller than the magnitude of the seasonal cycle [*Garrett et al.*, 1993], we can integrate (2) over a year to obtain

$$\langle u_h \cdot \nabla b \rangle = \frac{1}{DT}\int_0^T B(t)\,dt. \qquad (3)$$

Thus, assuming that the advection term is fairly constant throughout a year, we can introduce (3) into (2) and integrate from time t_1 to t_2, to get

$$D\,\Delta b = \int_{t_1}^{t_2} B(t)\,dt - \frac{(t_2 - t_1)}{T}\int_0^T B(t)\,dt. \qquad (4)$$

The second term of the right-hand side is not really constant with time: The $u_h \cdot \nabla b$ within the North Aegean is mostly driven by the seasonal variability of the Dardanelles outflow, which is of the order of a third of the average outflow (Y. Golubev and Z. Golubeva, unpublished data, 1998). Thus we expect the error of the second term of the right-hand side to be of the same order. Moreover, the annual integral of vertical buoyancy flux is of the same order as the month-to-month variability, thus the second term on the right-hand side is an order of magnitude smaller than the first. As a consequence, the error in (4) associated with the assumption that the advection term is constant in time is expected to be small, considering that we are interested in relative variability and not absolute values.

Equation (4) allows us to estimate the maximum thickness of an idealized surface layer that would lose its excess buoyancy to the atmosphere and the surroundings over time $t_2 - t_1$. Comparing this thickness D to the observed North Aegean surface layer depths, we can have a first estimate of times when the surface layer did not provide enough insulation to the underlying layers, and when deep water formation was facilitated.

Equation (4) was evaluated using the buoyancy flux estimated earlier; however, now the advection term (contribution of Black Sea outflow) has been estimated using (3), and $B(t)$ represents the time series of vertical buoyancy flux through the air-sea interface. We will use $\Delta t = t_2 - t_1 = 1$ month, thus our estimate of D will be a monthly neutralization depth, that is, the maximum thickness of a surface layer with properties as described above, that under the observed vertical buoyancy fluxes would lose within a month its excess buoyancy relative to the underlying layer. The seasonal neutralization depth would be approximately the sum of three monthly neutralization depths.

The results with the seasonal signal removed are presented in Figure 7b. We see that during the formation periods the fluxes have indeed more potential to break the insulating shell, as their effect penetrates deeper into the sea each month. The solid dots represent the difference of the available observations of surface layer depth (SLD) minus the monthly neutralization depth. We realize that this estimate has large errors associated with it, as mesoscale variability, wind-induced vertical mixing, etc., can introduce considerable noise to it. However, the minima of SLD-D suggest that indeed during dense water formation periods the surface layer could lose its insulating buoyancy more easily than other periods by exchanging heat and mass with the atmosphere. The time series of thickness D can be compared to the time series of the Black Sea outflow into the Mediterranean (Figure 7c) [*Altman et al.*, 1991; *Simov et al.*, 1999; Y. Golubev and Z. Golubeva, unpublished data, 1998]). According to that, during the formation periods the outflow appears to be reduced, which supports the above estimates of surface layer thickness. Note that reduced Dardanelles outflow is estimated also for the winter 1982-1983, but that the buoyancy loss over the North Aegean at the time does not exhibit a peak as strong as the two formation periods mentioned above.

6. Discussion

This work is a contribution toward the comprehension of the processes involved in the large-scale changes observed in the deep waters of the eastern Mediterranean in the early 1990s. Observations from the Aegean Sea suggest that the changes were initiated in the North Aegean by an overturning of the water column that took place after an extreme cold event during March 1987. Waters of extremely high density were produced, reaching the bottom of the North Aegean deep basins, thus raising the old bottom waters to depths where they could be transported toward the south. The signal of these changes eventually reached the Cretan Sea, with similar effects, and the restructuring of the water column caused denser, more saline waters to move toward the North Aegean, thus feeding the cycle.

In the winter, very cold and dry north winds from the Balkan peninsula blow over the North Aegean. As a result, local maxima of heat and buoyancy fluxes appear in the region, which has the potential to be a permanent source of deep water formation, as a Balkan analogous to the Gulf of Lions. However, the existence of a shallow layer of brackish water, having its origins in the Dardanelles outflow, consumes a large fraction of the air-sea exchange, thus acting as an insulator for the underlaid, denser saline waters of Levantine origin. The low temperature of the surface water further reduces the amount of heat loss to the atmosphere during the extreme cold events.

Thus the deep water formation process in the North Aegean does not depend only on the atmospheric conditions over the region but on the thickness and hydrographic characteristics of the surface layer of BSW in the region as well. The thickness and properties of this layer is directly related to the Dardanelles outflow, which serves to balance the freshwater budget of the Black Sea.

The large southeastward flowing rivers of central and eastern Europe play a dominant role in establishing a water surplus in the Black Sea, as they exceed precipitation in the region by 1 order of magnitude (Y. Golubev and Z. Golubeva, unpublished data, 1998). Thus this paper suggests that meteorological conditions over central and eastern Europe and the Black Sea could be an important factor in whether extreme cold events over the Aegean Sea would result to bottom water formation or not. Having established the role that the North Aegean overturning plays in the production of dense water and its advection southward, we propose that there is a link between the climatic conditions over the central/eastern Europe and Black Sea and the eastern Mediterranean deep water renewal processes. Further modeling and observational work could help the definition of such a link.

Assuming that indeed reduced water surplus in the Black Sea facilitates dense water formation in the North Aegean, and based on trends to reduce the fresh water inflow to the Black Sea, we can expect that episodes like the massive formation events of 1987 and 1993 can be repeated in the future. The reason is that there is a man-induced trend of reduction of the water surplus in the Black Sea; it is not very easy to clearly quantify the trend, due to natural interannual variability, like the drought of the early 1990s over the eastern Mediterranean, which coincided with low precipitation over the central/eastern Europe regions. However, significant anthropogenic changes have been under way: a large-scale water management and hydroenergy project from the Soviet era starting in the early 1950s was completed in the early 1970s, reducing the inflow of fresh water in the Black Sea from the rivers Don, Kuban, Dnieper and Dniester by 24.6%. This reduction reached 44.7% by 1985, intensified by enhanced agricultural consumption for irrigation, reclamation of wet and acid lands, etc. [*Gustafson*, 1980] and was expected to reach 63% by the year 2000, if everything went according to the Soviet water management plans [*Tolmazin*, 1985]. Changes of the vertical structure in the Black Sea, suggesting a reduction in the volume of the top layer of brackish water, have been recorded since, suggesting that the river flow reduction could be important in the water budget of the sea [*Murray et al.*, 1989]. Assuming the man-induced reduction of fresh water inflow into the Black Sea continued, we would expect that the bottom water formation processes in the North Aegean would become a more common phenomenon.

However, this has not been the case. The Black Sea level has been rising ever since 1992, and this trend shows both in

TOPEX/Poseidon data (E. Peneva et al., unpublished data, 1999), tidal gauge records [*Tsimplis and Baker*, 2000], and in the Black Sea box model we mentioned above. Whether this is due to human intervention or to natural variability is not entirely clear; however, the scenario of the link between Black Sea Water surplus and the formation of excessively dense waters in the North Aegean can still be supported, as no significant quantities of dense water have been formed since 1993.

Acknowledgments. We wish to thank Yuri Golubev and Zoya Golubeva for the provision of their data on the Black Sea water budget evolution. Also, we are grateful to Savvas Christianides for providing the data from the 1992-1993 fisheries cruises. This work has been supported by the European Commission DG-XII, Marine Science and Technology MTP-II MATER project, contract no PL950401. The maps of the Aegean Sea were produced using Reiner Schlitzer's software Ocean Data View 4.0 (http:/www.awi-bremerhaven.de/GEO/ODV, 2000).

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(Received March 22, 1999; revised May 22, 2000; accepted June 19, 2000.)