Aegean Sea Water Masses during the Early Stages of the Eastern Mediterranean Climatic Transient (1988–90)

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ABSTRACT

The Aegean water masses and circulation structure are studied via two large-scale surveys performed during the late winters of 1988 and 1990 by the R/V *Yakov Gakkel* of the former Soviet Union. The analysis of these data sheds light on the mechanisms of water mass formation in the Aegean Sea that triggered the outflow of Cretan Deep Water (CDW) from the Cretan Sea into the abyssal basins of the eastern Mediterranean Sea (the so-called Eastern Mediterranean Transient). It is found that the central Aegean Basin is the site of the formation of Aegean Intermediate Water, which slides southward and, depending on their density, renews either the intermediate or the deep water of the Cretan Sea. During the winter of 1988, the Cretan Sea waters were renewed mainly at intermediate levels, while during the winter of 1990 it was mainly the volume of CDW that increased. This Aegean water mass redistribution and formation process in 1990 differed from that in 1988 in two major aspects: (i) during the winter of 1990 the position of the front between the Black Sea Water and the Levantine Surface Water was displaced farther north than during the winter of 1988 and (ii) heavier waters were formed in 1990 as a result of enhanced lateral advection of salty Levantine Surface Water that enriched the intermediate waters with salt. In 1990 the 29.2 isopycnal rose to the surface of the central basin and a large volume of CDW filled the Cretan Basin. It is found that, already in 1988, the 29.2 isopycnal surface, which we assume is the lowest density of the CDW, was shallower than the Kassos Strait sill and thus CDW egressed into the Eastern Mediterranean.

1. Introduction

During the last 15 years of the twentieth century, observations have revealed that the Aegean Sea could be a source of Eastern Mediterranean Deep Water, even a larger one than the most abundant source known to be located in the southern Adriatic Sea (Roether et al. 1996; Klein et al. 1999; Lascaratos et al. 1999).

A comprehensive analysis of the southern Aegean Sea (Sea of Crete; Fig. 1) hydrological data and atmospheric conditions over the eastern Mediterranean Sea (Theocharis et al. 1999b; Lascaratos et al. 1999) suggests that a massive overflow of deep water, the so-called Cretan Deep Water (CDW), began in 1989, from the Cretan Sea into the eastern Mediterranean. The estimated rate of overflow for the period from 1989 to 1995 was about 1.2 Sv (Sv $\equiv 10^6$ m^3 s^{-1}), which is 4 times the estimated typical outflow from the Adriatic Sea (Roether et al. 1996; Lascaratos et al. 1999). Numerical models also succeeded in simulating the start of CDW overflow from the southern Aegean Sea in 1989

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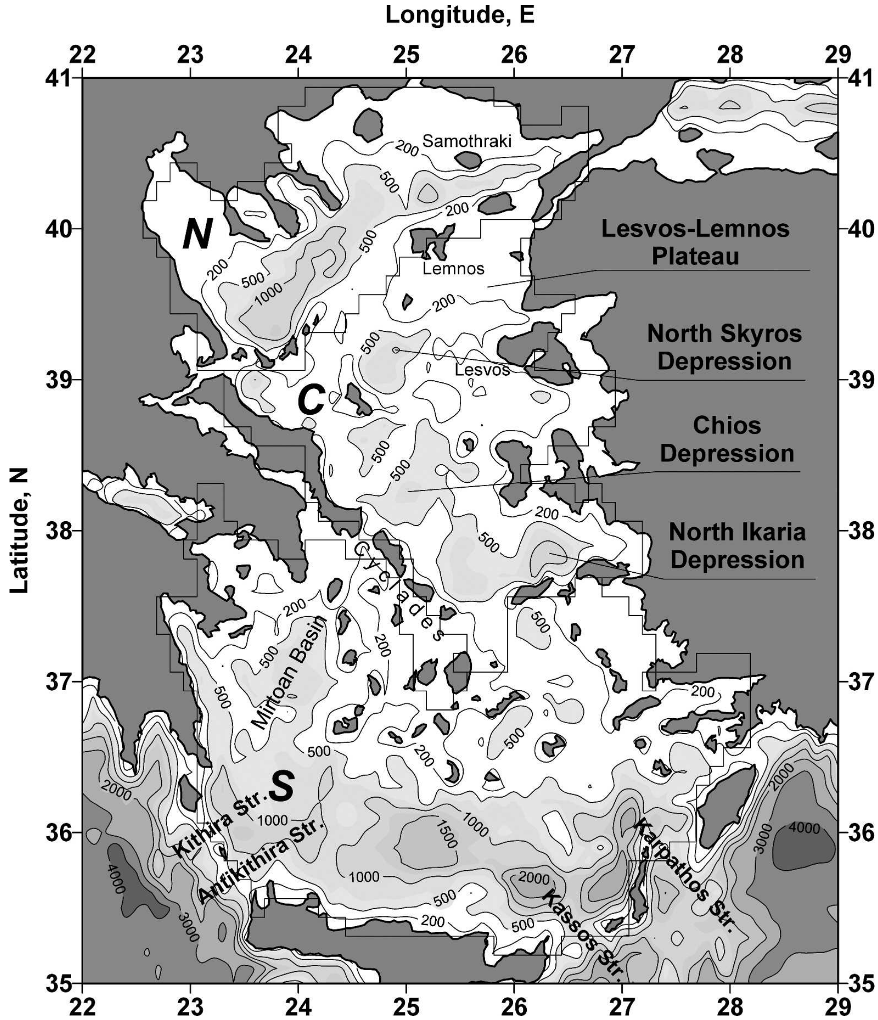

FIG. 1. Aegean Sea topography. The black line is the boundary of the (1/8)° grid used for the objective interpolation of the temperature and salinity fields; N: northern basin; C: central basin; S: southern basin or Sea of Crete.

(Lascaratos et al. 1999; Wu et al. 2000; Demirov and Pinardi 2002).

Theocharis et al. (1999b) conclude that the outflow from the Aegean Sea was forced by the increase of deep-water density ($\sigma_\theta > 29.20$) in the southern Aegean and by the subsequent rise of the isopycnal surface 29.20 above the sills of the Cretan Arc straits. According to them, during the earlier stage of the Eastern Mediterranean Transient (EMT), before the severe winters of 1992 and 1993, the density rise was induced by an increase in the salinity of the deep waters, probably connected to abnormally arid periods in the Aegean Sea region, and to the enhanced salinity of Levantine surface water (LSW) advected into the Aegean Sea. The enhanced salinity of the LSW is connected to the blocking of Atlantic water exchange between the Ionian and the Levantine basins (Malanotte-Rizzoli et al. 1999).

It is important to note that we have not found in the literature any evidence of deep-water convection events in the Cretan Sea before 1992. Even during the very cold winter of 1987 the convection there was limited to 700 m (Zodiatis 1991b). Observations during the transient event (Theocharis et al. 1999b; Gertman et al. 1990) and afterward (Theocharis et al. 1999a) show that the densest waters of the Cretan Sea are found near the bottom in the western part of the sea, where they arrive via slope convection from the shelf regions of the Cycladic Plateau (the central Aegean Sea in Fig. 1). However, the precise site where waters with CDW properties are produced and stored is unknown. According to Zervakis et al. (2000) these waters originate in the

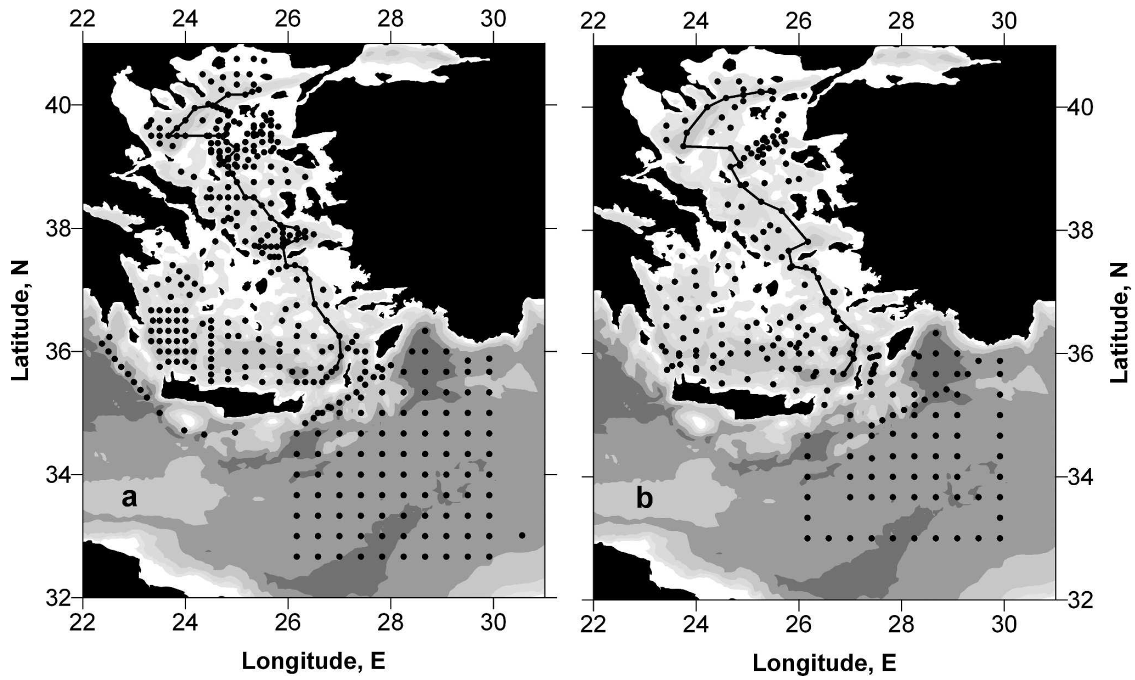

FIG. 2. The R/V *Yakov Gakkel* surveys of the Aegean Sea: (a) Cruise 31, 22 Feb–25 Apr 1988; (b) Cruise 36, 24 Jan–4 Mar 1990. Lines depict trans–Aegean Sea sections shown on Figs. 5 and 8.

north Aegean Sea (Fig. 1). Their investigation suggests that the formation of very high density waters in the northern Aegean is triggered by a combination of two factors: a dry and cold winter and a low water outflow from the Black Sea. The newly formed high-density waters sink to the bottom of the northern Aegean and push up the previous high-density bottom water, which then proceeds southward, reaching and filling the Cretan Sea. Eventually, the high-density Cretan Sea waters spill out into the eastern Mediterranean Sea.

Recently, a detailed investigation of the Aegean Sea water formation processes during EMT was accomplished using a three-dimensional numerical ocean model by Nittis et al. (2003). The authors concluded that the main water mass formation sites are the northern part of the central basin and the Cycladic Plateau. Open sea convection is found to be the main mechanism of dense water formation in the Aegean Sea. The authors validated their results using the only available basinwide winter survey carried out by R/V *Aegaeo* in February–April 1987. The authors stressed the absence of observations on the Lesvos–Lemnos Plateau to confirm the model dense water formation in this area.

We attempt to enhance the understanding of the Aegean Sea water mass formation by analyzing the data from two Russian cruises carried out by R/V *Yakov Gakkel* during the late winters of 1988 and 1990 (Gakkel-31 and Gakkel-36, respectively). These cruises are unique since each of them covers the entire Aegean Sea with a relatively dense net of stations (Fig. 2) during a relatively short time (less than one month). Moreover, these winter cruises took place between the two extreme events of deep-water formation in the Aegean Sea [1987 and 1992, according to Theocharis et al. (1999b), Lascaratos et al. (1999), and Nittis et al. 2003]. Thus, the present paper will describe events occurring between 1987 and 1992 in the Aegean Sea, in an attempt to elucidate the start of the EMT.

Preliminary results of these cruises were published (Gertman et al. 1990). At the time, the EMT was not recognized. Now, for the first time, we define the water mass structure of the entire Aegean Sea during winter 1988 and 1990; that is, we elucidate the formation and distribution of the Aegean waters during the early stages of the EMT.

In section 2 we describe the dataset and the methods of data analysis, in section 3 we define major Aegean Sea winter water masses, and in sections 4 and 5 we describe the water mass structure in 1988 and 1990, respectively. In section 6 we discuss the main results, and we conclude in section 7.

2. Data description and data processing

Gakkel-31 carried out a total of 367 casts, covering the central basin from 22 to 28 February 1988, the northern basin from 28 February to 12 March 1988, the southern basin (the Cretan Sea) from 13 to 24 March 1988, and the northwestern part of the Levantine basin from 24 March to 17 April 1988. An additional 50 casts were carried out again in the central basin from 17 to 25 April 1988 (Fig. 2a). Gakkel-36 carried out a total of 187 casts covering the northern basin from 24 to 26 January 1990, the central basin from 26 to 28 January 1990, the southern basin from 1 to 8 February 1990, and the northwestern part of the Levantine basin from 9 to 26 February 1990. An additional 43 casts were carried out again in the central and northern basin from 27 February to 4 March 1990 (Fig. 2b). The temperatures and the salinities were measured by a Russian-made CTD. Available vertical resolution of the casts was 10 dbar in the layer from 0 to 400 dbar, 50 dbar in the layer from 400 to 1000 dbar, and 100 dbar below 1000 dbar. Owing to the CTD cable limitation, no measurements were obtained below 2000 dbar. Distance from the deepest measurement to the bottom varied from 10 dbar for shallow casts to about 4% of the depth for deep casts. Later intercalibrations with measurements carried out by well-known CTDs, like Neil Brown and Sea Bird, indicated that the accuracy of the Russian CTD was on the order of $\pm 0.03°C$ for temperature and ± 0.03 for salinity (Hecht and Gertman 2001). This resulted in an accuracy of ± 0.03 kg m^{-3} in density.

The temperatures and densities discussed in the present paper are all potential temperatures and potential densities. For mapping and for the statistical volume analysis all casts were interpolated linearly with a 10-dbar vertical step and for each level the data were objectively analyzed for each cruise. The objective analysis scheme is described in the appendix. It was modified to exclude correlations between casts separated by islands or bottom topography. For the interpolation we use a ⅛° grid already used by Demirov and Pinardi (2002) in modeling the EMT. The Aegean Sea boundaries and average depths are shown in Fig. 1. All calculations and figures were made using the field values with an estimated error variance less than 30% to be very conservative. This means that the extrapolated data were not used in the water-mass volume analysis presented below.

The volumetric statistical analysis is based on methods introduced by Cochrane (1958), Montgomery (1958), and Pollak (1958). In general, the differences between the various analysis schemes pertained to the determination method of the sea's elementary volumes, which are used to compute the distribution function of water volumes in the temperature–salinity (θ–S) space (e.g., Mamaev 1975; Worthington 1981). According to Cochrane (1958) an ideal statistical volumetric analysis requires uniformly spaced sets of temperature and salinity data from the surface down to the bottom. To simulate this ideal state we use the gridded fields of temperature and salinity produced by the objective analysis. The volume of the Aegean Sea resulting from our approximation (Fig. 1) turns out to be 71 369 km^3, which is reasonably close to the one presented by Hopkins (1978), 74×10^3 km^3, or by Zervakis et al. (2000), 75×10^3 km^3. Because we did not use extrapolations, the objective analysis filled only 95% of the nodes for the 1988 data and 93% of the nodes for the 1990 data of the entire Aegean Sea grid. To compare the water mass volumes between the two periods we normalized the results with the nodes available for each cruise of the Aegean Sea.

Figures 3a and 6a depict the distribution of water volumes in θ–S space for the entire range of observed temperatures and salinities. Figures 3b and 6b (large-scale sections of Figs. 3a and 6a) allow one to study the details of the largest water mass volumes. The water volume for every θ–S cell (0.06°C $\times$ 0.06) is indicated by an arbitrary color scale. Thus the least value on that scale, light green, indicates that the volume is between 0.0001% and 0.001% of the volume of the Aegean Sea (i.e., 7–70 km^3). The largest value on that scale, purple, indicates that the volume is between 5% and 6% of the Aegean Sea (i.e., 3500–4200 km^3). For instance, Black Sea water (BSW) (salinities less than 38.7) occupy a large area in θ–S space but the color index shows that their volume is minimal, just 4.5% of the Aegean Sea (Table 1). In Figs. 3b and 6b the numbers within the cells are the average depths of the water volumes. In these figures we indicate the arbitrary boundaries assigned to the various water masses. For surface waters these boundaries are relevant only in winter, while for deeper waters they might be more general since the deeper waters do not change from season to season. These boundaries were used for the calculation of water-mass average parameters presented in Table 1.

The statistical analysis of the winter water masses of the Aegean Sea (Figs. 3 and 6) and the space distribution of their parameters (Figs. 4, 5 and 7, 8) will guide us in defining the dominant water masses. Figures 4d and 7d, showing dynamic topography at the sea surface relative to 200 dbar, will help us to estimate large-scale features of the Aegean Sea circulation. Obviously, in a sea with such a complicated topography the actual conditions are far from fulfilling geostrophic balance conditions. However, for understanding the mechanisms of water mass spreading, the dynamic topography provides very useful additional information to the space distribution of water mass parameters. It is also obvious

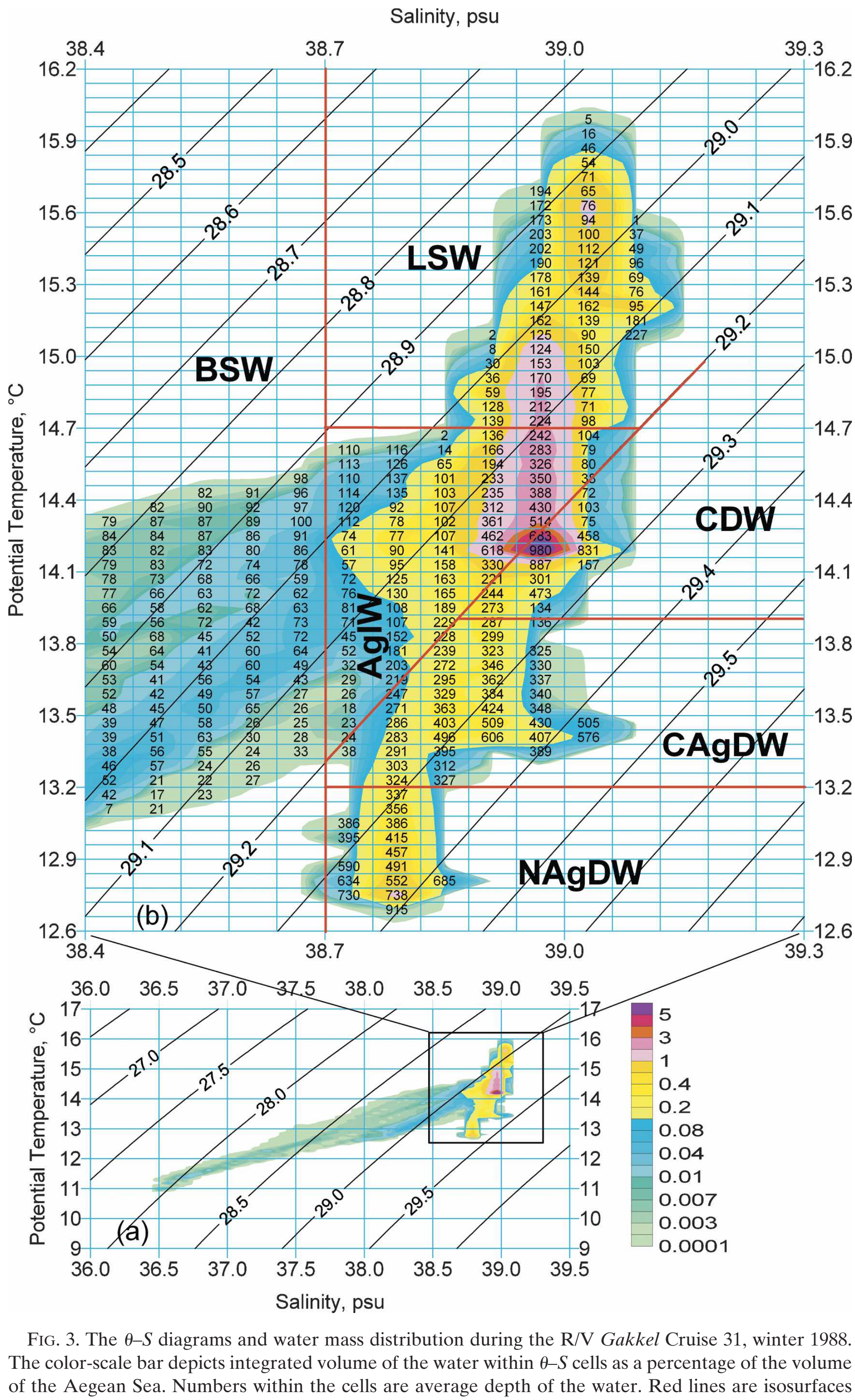

FIG. 3. The θ–S diagrams and water mass distribution during the R/V *Gakkel* Cruise 31, winter 1988. The color-scale bar depicts integrated volume of the water within θ–S cells as a percentage of the volume of the Aegean Sea. Numbers within the cells are average depth of the water. Red lines are isosurfaces indicating the boundaries between water masses. Water mass definitions are in the text.

TABLE 1. The Aegean Sea water parameters derived from volume statistical θ–S water analysis.

Water mass	Volume km^3	Volume %	Mean temperature (°C)	Mean salinity
Winter 1988				
BSW	3216	4.5	13.13	38.12
LSW	20 820	29.2	15.12	38.99
AgIW	28 724	40.2	14.39	38.93
CDW	10 032	14.1	14.18	38.97
NAgDW	3658	5.1	12.91	38.78
CAgDW	4919	6.9	13.56	38.87
Total	71 369	100.0		
Winter 1990				
BSW	2131	3.0	13.22	38.16
LSW	11 677	16.4	15.11	39.08
AgIW	32 949	46.2	14.43	38.95
CDW	15 582	21.8	14.20	38.98
NAgDW	3095	4.3	13.04	38.84
CAgDW	5934	8.3	13.63	38.90
Total	71 369	100.0		

that the 200-m depth can hardly be accepted as a no-motion level in the Aegean Sea. According to model simulation of the Aegean Sea winter circulation, this circulation is quite energetic at 100-m depth and weakens significantly at the 300-m level (Kourafalou and Barbopoulos 2003). We calculate dynamic topography relative to 200 dbar in order to elucidate the circulation over a wide area, ignoring unavoidable errors in the magnitude of currents. In the following text, when we refer to data and/or results during 1988 or 1990, we mean the late winter of 1988 or of 1990, respectively.

3. Water mass definitions

To calculate water mass parameters by volume statistical analysis we need to choose the upper and lower limits in temperature, salinity, and density fields for each water mass. The θ–S diagrams (Figs. 3 and 6), as well as the spatial distributions of temperature and salinity (Figs. 4, 5 and 7, 8) show that, despite significant changes in the distribution of water masses between the two late winters 1988 and 1990, we can define one set of limits for both winters.

The most conspicuous boundary ($S = 38.7$) is that for winter BSW. For salinities larger than 38.7, the θ–S diagrams (Figs. 3 and 6) show that the cell volumes increase significantly. The horizontal salinity distribution maps (Figs. 4 and 7), as well as the trans-Aegean vertical sections (Figs. 5 and 8), show that the isohaline 38.7 is the outer boundary of the winter Black Sea waters haline front. The other surface winter water type is LSW, which is distinguished by high salinity and temperature. There are high-salinity water masses below the LSW, but the LSW has a higher temperature (higher than 14.7°C) and hence its density is lower than 29.1. Thus, the isothermal surface $\theta = 14.7°C$ is the outer boundary of the LSW horizontal and vertical distributions (Figs. 4, 5 and 7, 8). Vertically the 14.7°C isotherm is at the upper boundary of the winter thermocline.

Since we are describing winter conditions, the LSW is a thick layer that would normally include the Levantine Intermediate Water (LIW) formed in the Rhodes gyre, or along the northern or eastern shelves of the Levantine basin (Ovchinnikov et al. 1976; Malanotte-Rizzoli and Hecht 1988). Instead, the intermediate waters of the Aegean, which are colder than LIW, are of local origin, and we name them Aegean Intermediate Water (AgIW). Regarding the AgIW we believe that its water mass properties are maintained throughout the year.

To separate AgIW from other water masses formed during the transformation and mixing of BSW and LSW, we use three isosurfaces (Figs. 3b and 7b): the isohaline surface $S = 38.7$, which separates AgIW from BSW; the isothermal surface $\theta = 14.7°C$, which separates AgIW from LSW and the isopycnal surface $\sigma_\theta = 29.2$, which separates AgIW from all deep-water masses located below the AgIW in all three basins, the north, central, and south Aegean (Figs. 5 and 8).

Deep-water masses, lying below the AgIW in the north and central Aegean, are stored in depressions, separated by sills that impede water exchanges between the depressions. Therefore, water temperature and salinity limits are quite obvious (Figs. 5 and 8). The salinities of all of the deep-water masses are more than 38.7. To separate North Aegean Deep Water (NAgDW), the coldest deep water, we use the isothermal surface $\theta = 13.2°C$. Deep-water masses with temperatures between 13.2° and 13.9°C can only be found in the central basin depressions (Figs. 5 and 8), but to separate the Central Aegean Deep Water (CAgDW) from AgIW we use the $\sigma_\theta = 29.20$ isopycnal surface as an upper-water density limit. Deep-water masses of the Cretan Basin (CDW) have temperatures higher than 13.9°C and, again, in order to distinguish between them and the AgIW we use the $\sigma_\theta = 29.20$ isopycnal surface as the lowest value for the density.

4. Aegean Sea water masses during 1988 (Gakkel-31)

In this section we examine the Aegean Sea water masses during 1988 as observed during the Gakkel-31 cruise. We determine representative quantitative water mass parameters for winter to be compared in the next section with those of 1990, as observed during the Gakkel-36 cruise.

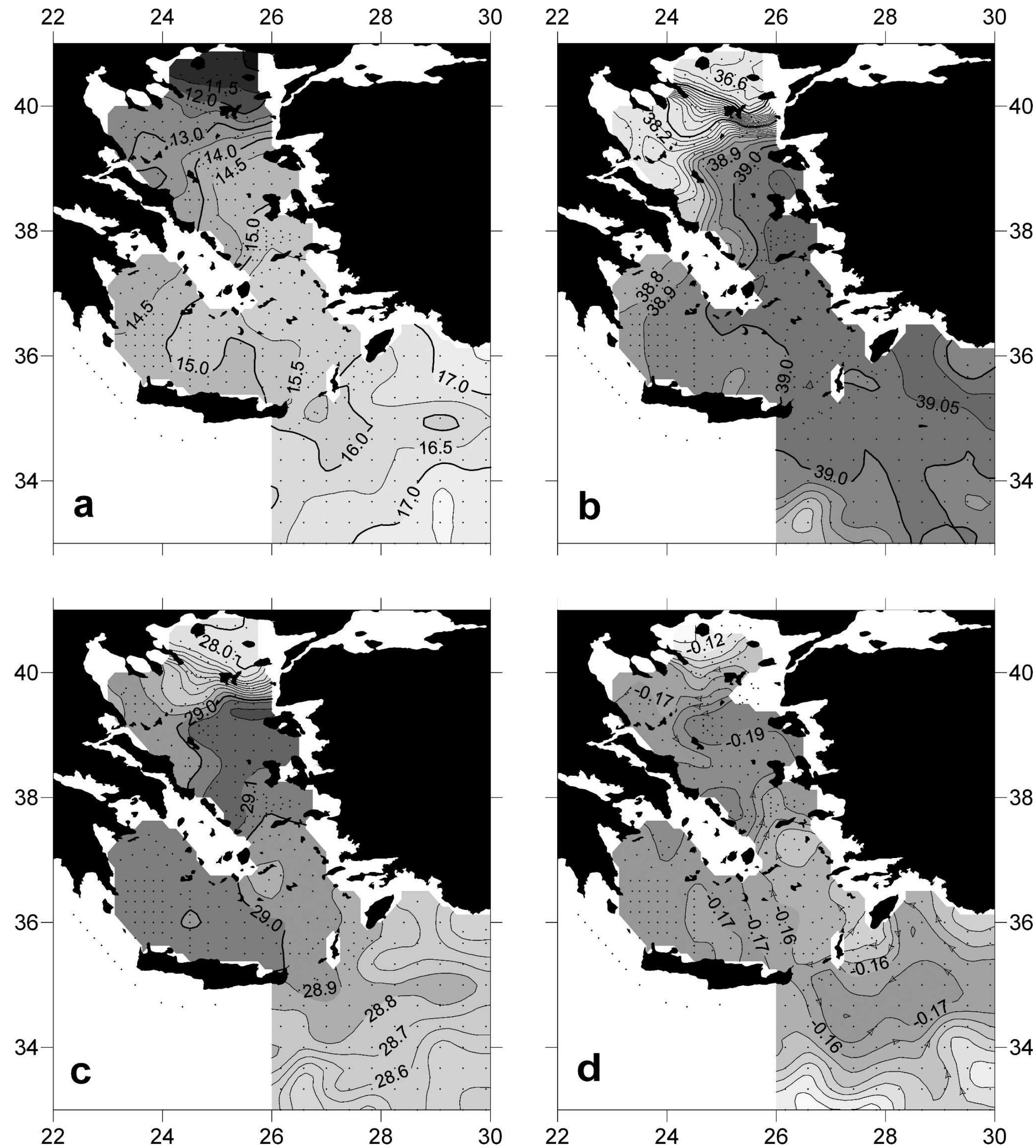

FIG. 4. Horizontal distribution of (a) potential temperature, (b) salinity, (c) density in the surface layer, and (d) dynamic topography in dynamic meters (0/200 dbar), during the R/V *Gakkel* Cruise 31, winter 1988.

a. Surface-water masses

The BSW enters the Aegean Sea via the Dardanelles with salinities of about 24–28 (Unluata et al. 1990). Unfortunately our data do not cover the region north of the western end of the Dardanelles. The lowest salinities (36.0–36.5) during 1988 were found on the northern shelf of the north basin (Fig. 4b). This water flows cyclonically (Fig. 4d) and eventually covers the entire northern basin, as well as the western part of the central basin. Modified BSW continues to spread, in the surface layer, from the central basin into the western side of the southern basin. The dynamic topography (Fig. 4d) reflects the general cyclonic movement of BSW in the north basin and its penetration into the western part of the central basin. This picture agrees well with results of winter high-resolution simulations by Kourafalou and Barbopoulos (2003) for the north part of Aegean Sea. Recent field current measurements by drifters (Kourafalou et al. 2003) reveal very complex

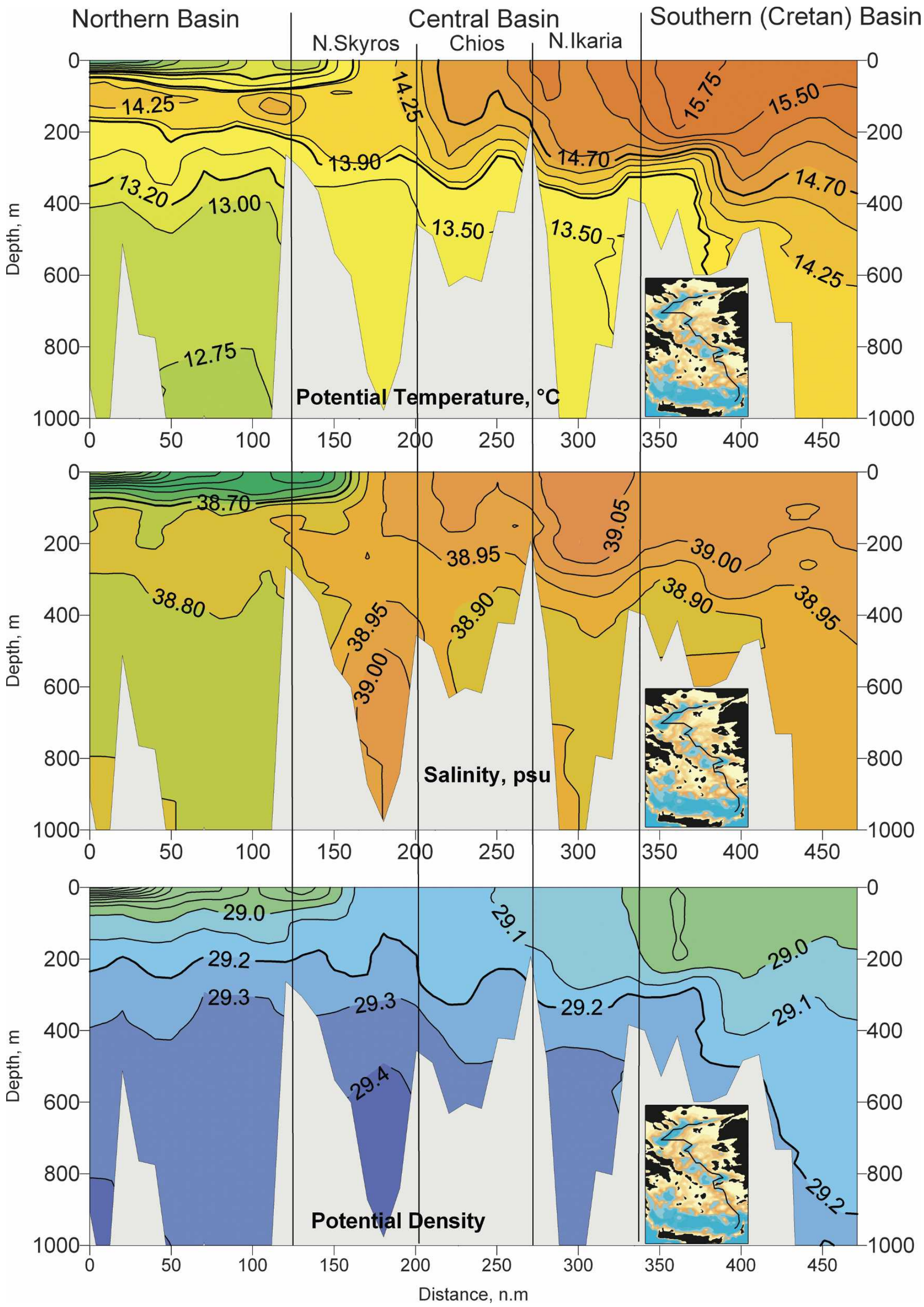

FIG. 5. Vertical distribution of potential temperature, salinity, and potential density along a trans–Aegean Sea section during the R/V *Gakkel* Cruise 31, winter 1988.

flow patterns in the north and central basins, but they also confirm the presence of a general cyclonic circulation in the northern basin and a cyclonic eddy above the North Skyros Depression. Moreover, these measurements clearly show the propagation of BSW from the central basin to the southern basin via the straits of the Cycladic archipelago.

BSW cools down rapidly since they form a relatively thin (30–80 m) and stable layer. Owing to its low salinity, the density of 98% of the BSW is lower than 29.1. Thus, the northern basin is covered by a cool, low-salinity, low-density layer, which does not allow deep winter mixing. The water volume of BSW is only 4.5% of the entire volume of the Aegean Sea (Table 1). Thus,

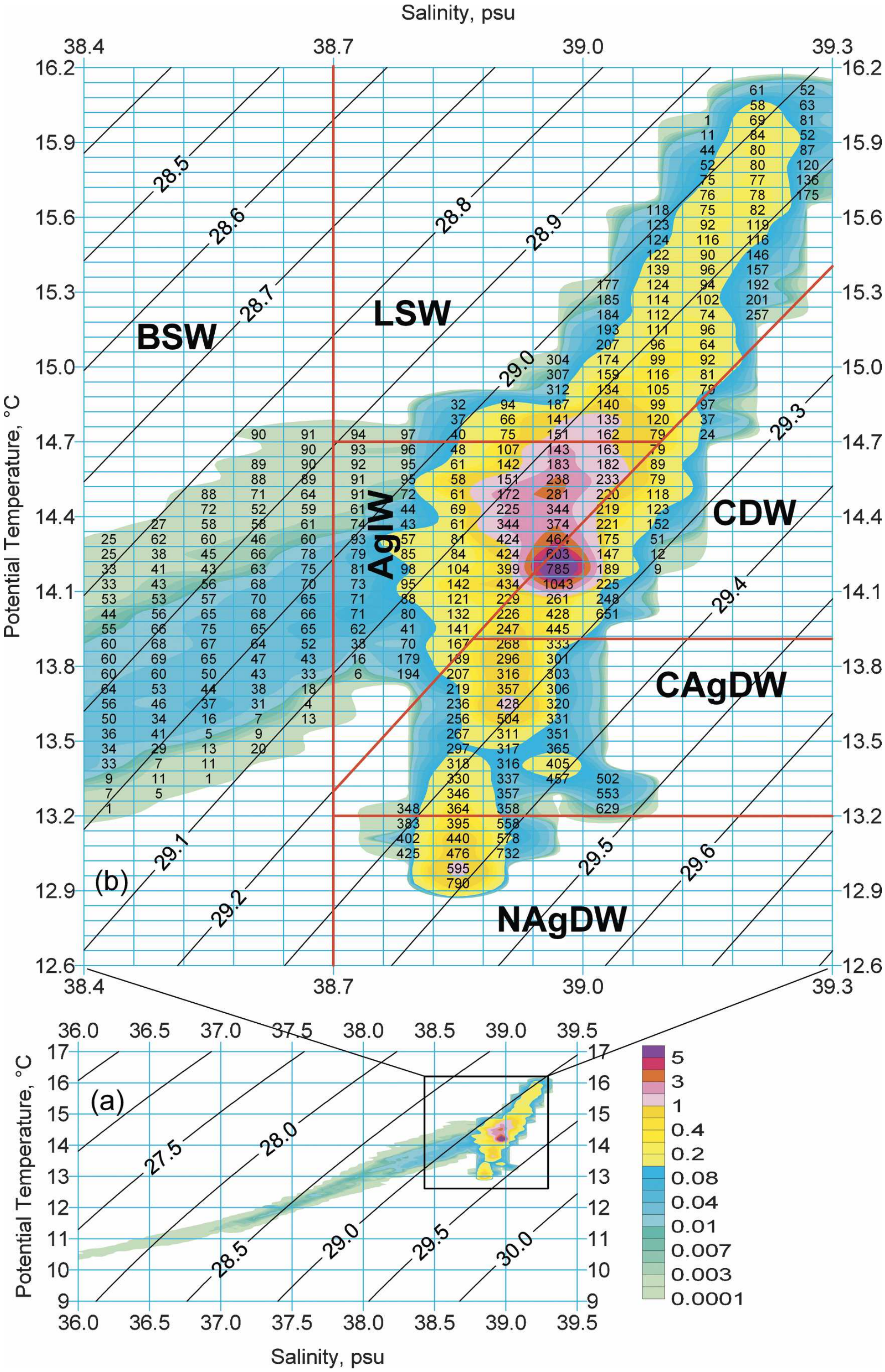

FIG. 6. The θ–S diagrams and water mass distribution during the R/V *Gakkel* Cruise 36, winter 1990. The color-scale bar depicts integrated volume of the water within θ–S cells as a percentage of the volume of the Aegean Sea. Numbers within cells are average depth of the water. Red lines are isosurfaces indicating the boundaries between water masses. Water mass definitions are in the text.

the parameters of BSW could change rapidly, subject to changes in atmospheric conditions. In particular, synoptic wind changes can lead to significant fluctuations in the position of the southern boundary of the BSW front on the Lesvos–Lemnos Plateau (Gertman et al. 1990; Zodiatis and Balopoulos 1993; Zodiatis 1994; Zervakis and Georgopoulos 2002) and to the rate of water mass formation over the shelf.

In the southern basin, the distribution of water temperature, salinity, and density (Figs. 4, 5) indicates that in 1988 large quantities of warm saline LSW were penetrating into the Aegean via the eastern straits of the Cretan Arc as a thick, 200–300 m, layer. This water originates from the north periphery of the Rhodes cyclonic gyre (Fig. 4d) where it has salinities of more than 39.05 (Fig. 4b). Dynamic topography (Fig. 4d) shows that LSW can penetrate the Aegean Sea mainly via the two straits around Rhodes Island and, to a lesser degree, via the Strait of Kassos. This agrees well with the winter circulation pattern produced in climatological runs by an eddy-resolving model (Korres and Lascaratos 2003). A major difference between the climatological pattern and the circulation during 1988 was observed in the southern basin where the simulations (Fig. 15a in Korres and Lascaratos 2003) show westward propagation of LSW, cyclonic circulation within the northwestern part of the Cretan basin (i.e., the Mirtoan basin), and finally exit through Kithira–Antikithira Straits. In 1988 LSW occupies about one-half of the surface area of the Cretan basin but general propagation was northward (Fig. 4d). In the central basin, this water spreads up to the Lesvos Island. LSW is well mixed by winter convection and is bounded by a sharp thermocline. Over the Lesvos–Lemnos Plateau (Fig. 1) LSW transforms extensively, first because of cooling and after that mixing with BSW. The volume of the LSW is about 6 times the volume of the BSW (Table 1); therefore, all of the derived water masses have temperatures and salinities closer to LSW.

The surface water of the central basin is the densest of the Aegean Sea surface waters (29.1–29.2). On the Lesvos–Lemnos Plateau this water type extends to the bottom. Thus, there is a front between the northern basin surface water and that of the central basin.

b. *Intermediate-water masses*

Vertical sections through the main Aegean Sea basins and depressions (Fig. 5) show that the AgIW could be found everywhere below the surface water. The isopycnal surface 29.20, which we defined as the highest-limit density isopycnal for the AgIW, has an asymmetric domelike structure with its maximum elevation above the North Skyros Depression (Fig. 5). The domelike water structure is connected with cyclonic circulation in this region (Fig. 4d). The southern slope of the dome is steeper that the northern slope. Above the maximum elevation of the dome the water masses are quite homogenous. The dense surface water of the northern part of the central Aegean basin downwells and spreads isopycnically as intermediate water below the surface water and above the deep-water masses. The volume of AgIW is 40% of the Aegean Sea volume, and thus is the largest Aegean Sea water mass.

Average temperature and salinity of AgIW are 14.39°C and 38.93. Note that, in θ–S space (Fig. 3), the salinity distribution of the AgIW is asymmetrical. Since about 73% of the AgIW volume is located in the Cretan basin, where it is quite homogeneous, most of the salinity is between 38.9 and 39.0. The central basin AgIW has the same temperature and salinity as the Cretan basin AgIW. This suggests that most of the AgIW is ventilated in the region of cyclonic circulation in the central basin. The northern basin AgIW temperature and salinity are lower than in the central basin because the northern basin AgIW is formed on the northern periphery of the central basin cyclonic gyre and also because they transform during their spreading from the central basin because of mixing with the above-lying BSW (Zervakis and Georgopoulos 2002).

c. *Deep-water masses*

The north and central Aegean deep-water masses are located in depressions (700–1300 m) separated by sills (200–500 m: Fig. 1).

During 1988, the coldest Aegean deep water was NAgDW. It had a maximum volume in the θ–S interval 12.72°–12.78°C and 38.76–38.82 at an average depth of about 740 m (Fig. 3). These values coincide with those found by Zervakis et al. (2000) in the same depression just after the intense storm of 3–13 March 1987. As pointed out by Theocharis and Georgopoulos (1993), one week before the storm, the parameters of the NAgDW were typical of the pre-EMT state—that is, 13.2°–13.3°C, 38.80–38.85, and 29.27–29.32. Therefore we argue that NAgDW was renovated during the 1987 winter storm and then preserved at least until the winter of 1988/89.

The deep water of the central basin, CAgDW, was warmer and saltier than NAgDW (Fig. 3b). While the NAgDW is relatively homogeneous, the salinity interval of the CAgDW is wider. This is related to the presence of separated depressions within the central basin (Fig. 1) and a different position of the depressions relative to the main source location of the deep waters, the

Lesvos–Lemnos Plateau. The water masses from the North Skyros Depression (Fig. 5) are colder and saltier (θ–S interval 13.38°–13.44°C, 38.94–39.06 at a depth of about 500 m) than water masses from the Chios and North Ikaria Depression (θ–S interval of 13.44–13.50°C, 38.82–38.88 at a depth of about 500 m). Because of bottom topography, the North Skyros Depression traps the densest waters formed on the Lesvos–Lemnos Plateau. During the winter of 1988 the density of the deep water in the North Skyros Depression was about 29.42. Such dense water was observed there for the first time in the summer of 1987 (Zervakis et al. 2000). Apparently renovation also took place during the storm of 3–13 March 1987.

During 1988, the largest Aegean deep-water mass was that of the southern (or Cretan) basin. It is important to note that March 1987 was the first time that the water with density more than 29.20 was found in the Mirtoan basin (Theocharis et al. 1999b). Just one year later, in 1988, we show that the CDW volume reached 14.1% of the Aegean Sea (Table 1). The distribution of the integrated volumes peaks sharply within the θ–S interval 14.16°–14.28°C and 38.94–39.00 at a depth of 700–1000 m (Fig. 3). Relative to 1987 (Zervakis et al. 2000) the temperature of the CDW did not change significantly, but salinity increased by about 0.05.

The surface layer salinity distribution during 1988 (Fig. 4b) indicates that two regions of the Aegean could be the potential sources of the CDW. One is the western Cretan basin where the salinity varies from 38.9 to 39.0. The other one is the region of cyclonic circulation within the central Aegean basin. The stable stratification in the upper layer of the Cretan basin during winter 1988 as well as during winter 1987 (Theocharis et al. 1999b) indicates that CDW were advected there but not generated by open sea convection in the Cretan basin. The most obvious region from which the CDW is advected appears to be the Cycladic Plateau (Gertman et al. 1990; Zervakis et al. 2000). However, observations carried out during the summer of 1987 (Zodiatis 1991a; Theocharis et al. 1999b) show that the CDW volume increased even throughout the summer when the warm and shallow Cycladic Plateau shelf cannot be a source of deep waters. The only other possibility for a summer increase of the CDW volume is advection of deep waters from the central Aegean basin through the wide and deep passage east of the Cyclades. We believe it is possible that during the winter of 1987, dense waters accumulated in the central basin and during the following summer, they spread to the Cretan basin through the trenches in the wide passage between the Cyclades and Asia Minor.

5. Aegean Sea water masses during 1990 (Gakkel-36)

In this section we analyze the water masses and their thermohaline structure during 1990 and compare them with those observed during 1988.

a. Surface-water masses

In 1990, relative to 1988, the important change in the distribution of BSW was the northward movement of the frontal zone between BSW and LSW (Fig. 7b). During 1988 the frontal zone position was slightly north of Lesvos (Fig. 4b), while during 1990 more than one-half of the shallow Lesvos–Lemnos Plateau was occupied by waters with a salinity of about 38.95–39.10. These waters originating from the Levantine basin lost their enthalpy without dilution with BSW and north of Lesvos reached a density larger than 29.20 (Fig. 7c). Apparently, waters denser than AgIW formed on the broad area of the Lesvos–Lemnos Plateau. Note that the volume of the LSW during 1990 was about 60% of the volume of the LSW during 1988 (Table 1). The diminished volume of the LSW could be attributed partly to decrease in the area covered by the Gakkel-36 survey, in particular near the Asia Minor coast. An additional reason is that, according to the dynamic topography of winter 1990 (Fig. 7d), after entering the Cretan basin, the LSW turns north more sharply than was observed during the late winter of 1988. However, while the volume of the LSW decreased, its average salinity increased from 38.99 in 1988 to 39.08 in 1990 (Table 1). Lascaratos et al. (1999) attributed the Aegean Sea surface salinity increase to the dry period of 1989–90. We suggest two additional factors that were not discussed in the numerical simulations of the EMT (Nittis et al. 2003; Demirov and Pinardi 2002). The first is the propagation of LSW after the Cretan Arc straits northward instead of the climatic westward propagation (Korres and Lascaratos 2003). The second is an increase in the salinity between 1988 and 1990 on the northern periphery of the Rhodes gyre (Fig. 7b). This increase in the salinity of the LSW is a complex process that could be due to the severe winter of 1987 (Hecht and Gertman 2001) and/or to the circulation pattern described by Malanotte-Rizzoli et al. (1999).

Our calculations also show an increase in the average salinity of BSW from 38.12 to 38.16 (Table 1). These changes however are too small to reach any conclusion regarding their causes; that is, changes in atmospheric forcing and/or amount of water influx from the Dardanelles.

The northward movement of the front between the BSW and the LSW, together with the increase of LSW salinity, leads to an intensification of the of AgIW and

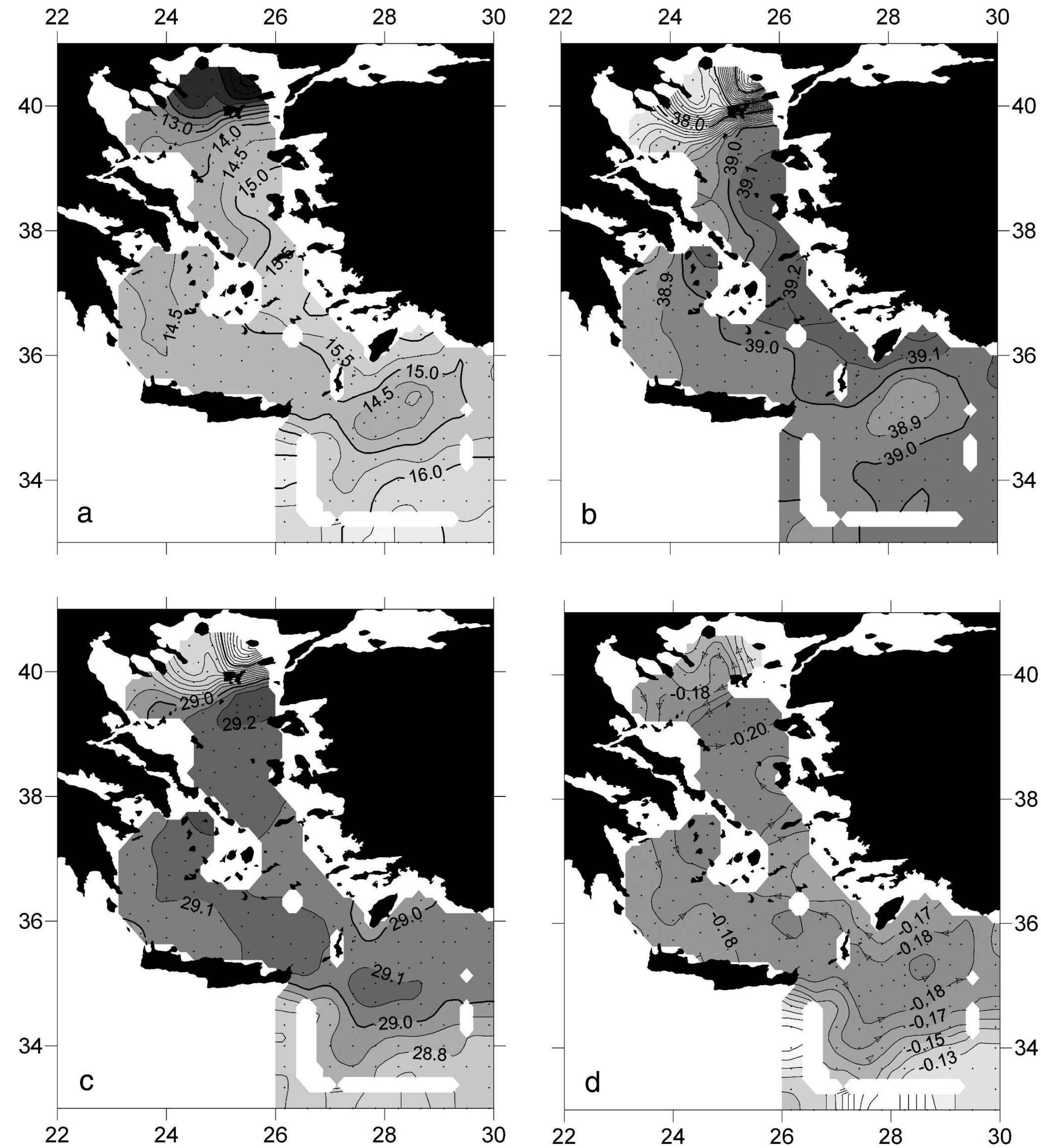

FIG. 7. Horizontal distribution of (a) potential temperature, (b) salinity, (c) density in the surface layer, and (d) dynamic topography in dynamic meters (0/200 dbar) during the R/V *Gakkel* Cruise 36, winter 1990.

CDW formation processes. In other words, these factors also lead to the intensification of the Aegean Sea "conveyor belt"—the process that transforms the LSW ingressing into the Aegean Sea into outflowing higher-density waters that spread into the deep layers of the eastern Mediterranean.

b. Intermediate-water masses

During 1990, the area occupied by the high-density (i.e., $29.1 < \sigma_\theta < 29.2$) surface layer in the central basin and Cretan basin (Fig. 7c) was much larger than the one in 1988 (Fig. 4c). The mixed layer, with a water density of about 29.15–29.18, reached a depth of 400–500 m (Fig. 6). All of these indicate that, in contrast to 1988, AgIW was formed not only within the central basin but also in the Cretan basin.

The θ–S parameters of AgIW did not change significantly, but their volume in 1990 increased by about 15% relative to the volume in 1988 (Table 1, Fig. 6). Moreover, during the period between the cruises the

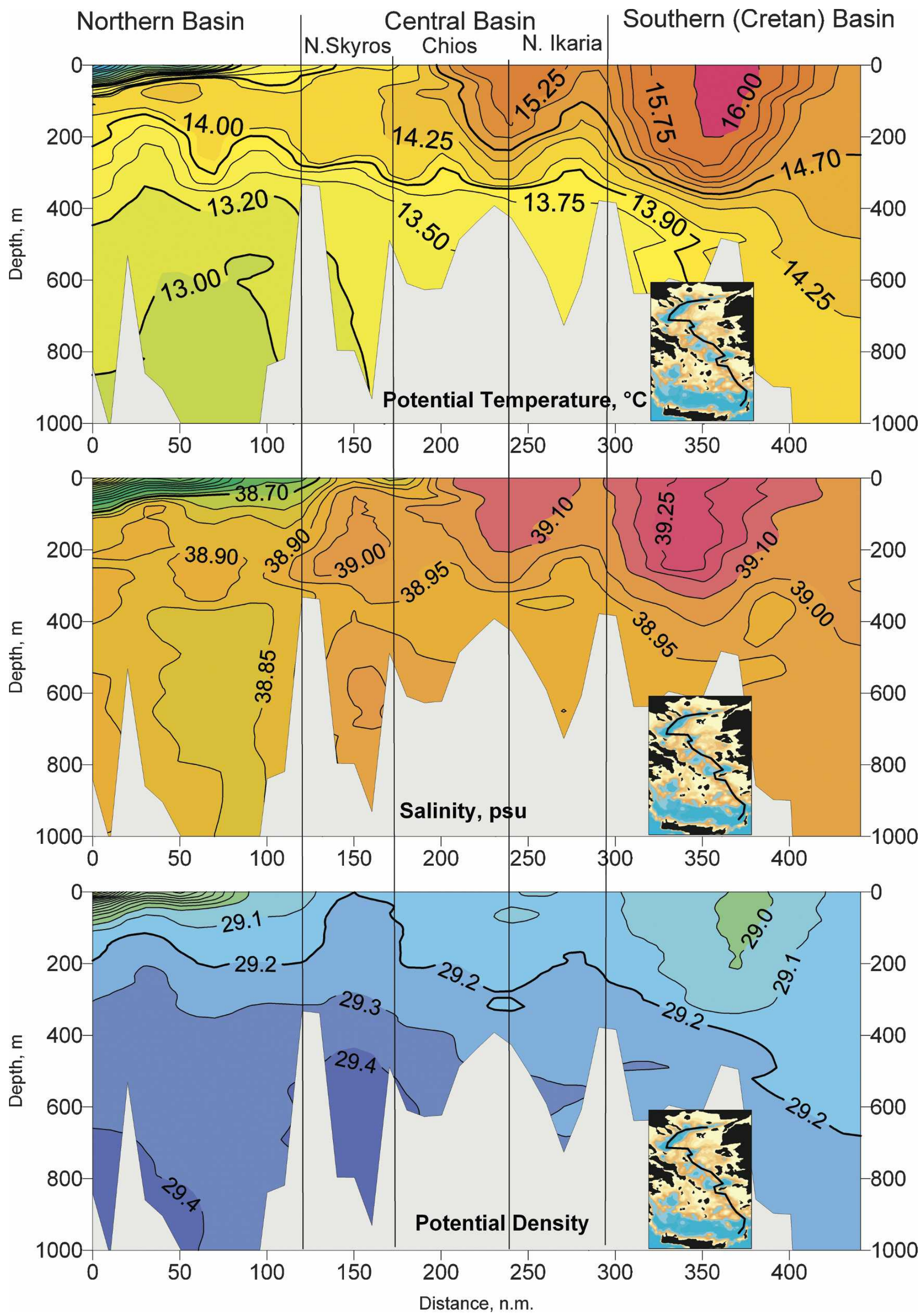

FIG. 8. Vertical distribution of potential temperature, salinity, and potential density along a trans–Aegean Sea section during the R/V *Gakkel* Cruise 36, winter 1990.

volume of the deep waters in the central basin and Cretan basin has increased and, consequently, has pushed the AgIW layer upward (Fig. 8). During 1990, the bulk of AgIW, with a salinity of about 38.94–39.00, was found at a depth of 140–370 m (Figs. 6, 8) versus a depth of 240–430 m (Figs. 3, 5) during 1988. The surfacing of the AgIW layer relative to the depth of the main straits of the Cretan Arc (Kassos, 400–1000 m; Karpathos, 500–800 m; Antikithira and Kithira, 200–700 m) indicates that the outflow of AgIW into the Ionian Sea and the Levantine basin has intensified in 1990. A significant part of these waters, with a density higher than 29.17 is heavy enough to sink to the bottom outside the Aegean Sea.

c. Deep-water masses

Generally speaking, in 1990 all the deep waters enhanced their density because of an increase in the salinity despite a parallel increase in the temperature (Table 1). The density of the NAgDW reached a maximum value of 29.44 (versus 29.42 during late winter 1988). Average temperature and salinity of the NAgDW reached values of 13.04°C and 38.84 (versus 12.91°C and 38.78 during 1988; Table 1). Similar to 1988, the renovation of NAgDW by direct vertical mixing was not possible because the entire north Aegean Basin was covered by BSW with a density of less than 29.0 (Figs. 7c and 8).

During 1990, the volume distribution of the CAgDW reflects a bimodality (Fig. 6) related to the different characteristics of deep waters in the various depressions (Fig. 8). The first mode, the bulk of the CAgDW, consists of waters from the Chios and North Ikaria Depressions (θ–S interval of 13.68°–13.74°C, 38.88–38.94 psu in 1990 about the same as in 1988). The second mode consists of waters from the North Skyros Depression. From the distributions of the water parameters in the upper layer of the north and central basins (Figs. 7 and 8) we can infer that the North Skyros Depression was filled by slope convection of dense waters from the Lesvos–Lemnos Plateau. However, the data used to build the winter 1990 θ–S diagram and space distributions (Fig. 6, 7, and 8), do not include the observations obtained during the last phase of the Gakkel-36 cruise (see section 2). Additional illustrative data from the last phase of the cruise (1–3 March) are shown in Fig. 9 along a vertical section crossing the plateau. As one can see, between the two cruise phases, that is, from the middle of February to the beginning of March 1990, the density of the water above the Lesvos–Lemnos Plateau reached 29.30–29.40 and the bottom layer, on the slope from the plateau to the North Skyros Depression, contained water with a density of 29.50. These observations strongly indicate that slope convection occurred from the Lesvos–Lemnos Plateau into the North Skyros Depression (Fig. 9).

The intensification of the Aegean Sea conveyor belt during the period between the two cruises is also reflected in the increase in the volume of CDW by about 1.5 times (Table 1). The maximum integrated volumes remained within the same θ–S interval as in 1988, the average θ–S parameters of CDW increased only by 0.02°C and 0.01 but even these small differences, which are less than the accuracy of the measurements, appear

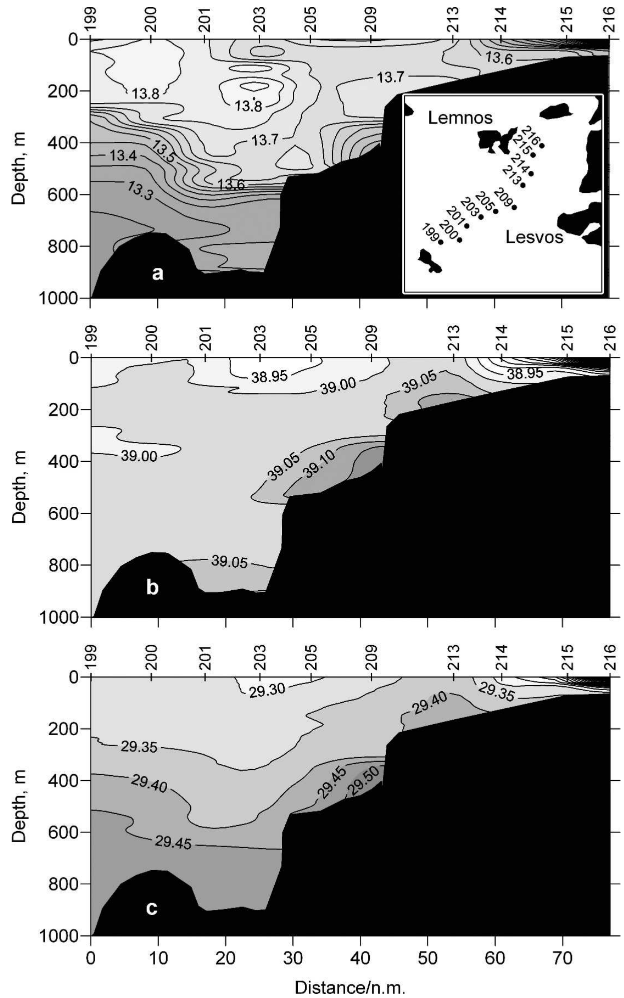

FIG. 9. Vertical distribution of (a) potential temperature, (b) salinity, and (c) potential density along a section from Lemnos–Lesvos Plateau to North Skyros Depression during 1–3 Mar 1990.

to be significant because they are the result of averaging the observations of 100 casts. The isopycnal surface of 29.20, which we defined as the minimum density for CDW, rose in all three basins of the Aegean Sea (Fig. 10c). In the central basin, the site of the domelike structure did not change between the two winters; however, in 1990, the peak of the dome rose to a shallower level (cf. Figs. 5c and 8c). This domelike structure of the isopycnal surfaces in the interval 29.20–29.25 (Fig. 8) indicates the path of the newly formed CDW from the Lesvos–Lemnos Plateau to the deep layers of the Cretan basin. In contrast to 1988, CDW penetrated the Cretan basin not only through the trenches connecting the central Aegean and the Cretan basin, but also on a wide front above the bottom of the Eastern Cycladic Plateau (Fig. 10).

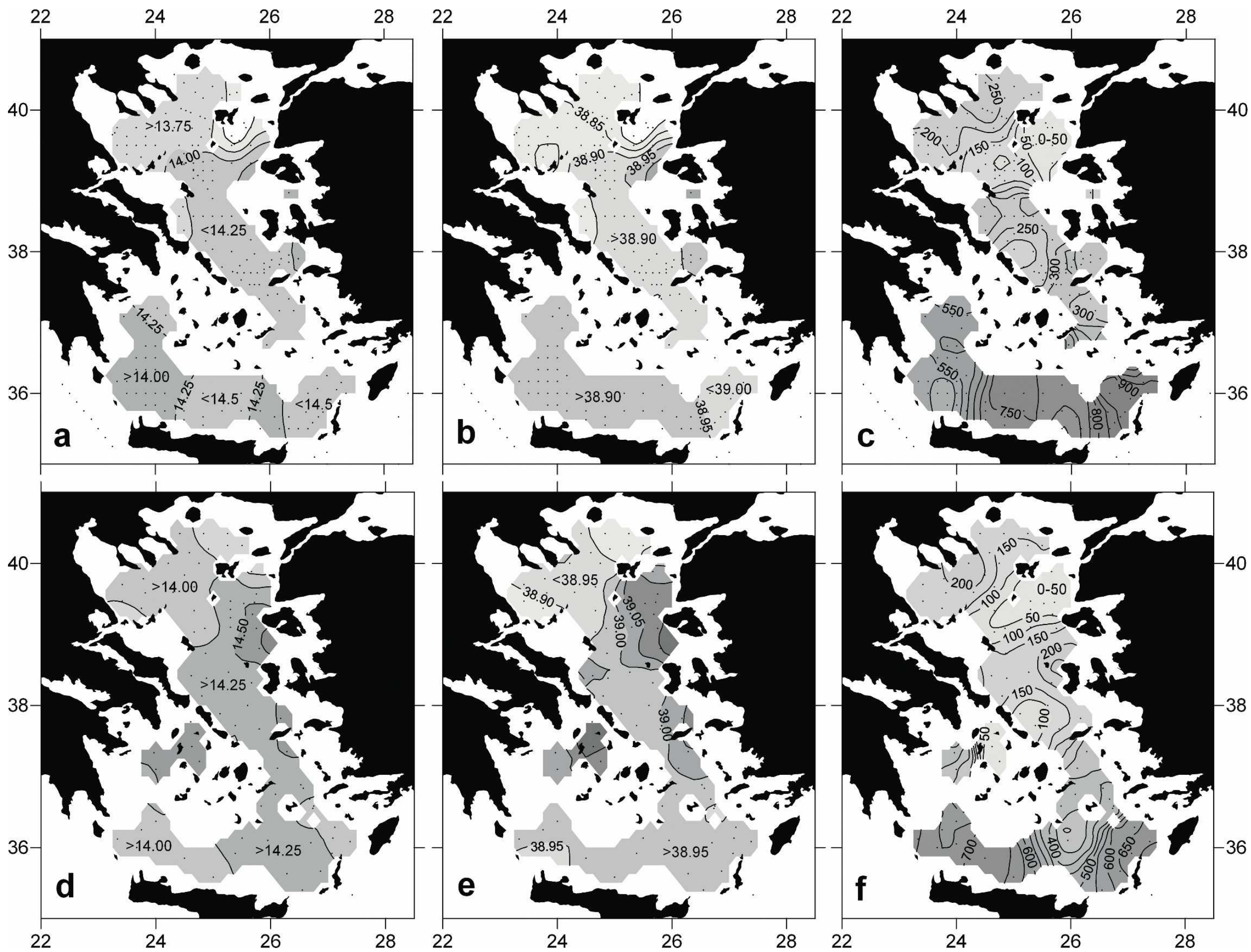

FIG. 10. (c), (f) Depth of the 29.20 isopycnal surface, and (a), (d) the distribution of potential temperature and (b), (e) salinity on this isopycnal surface. (top) Winter 1988; (bottom) winter 1990.

6. Discussion

The filling of the Cretan Basin with water denser than 29.20 started during the severe winter of 1987 (Theocharis et al. 1999b). The winters of 1988 and 1990 were not cooler than usual (Lascaratos et al. 1999; Wu et al. 2000) but the volume of CDW increased. During 1988 the volume of CDW reached 14.1% (10 932 km^3) of the Aegean Sea and during 1990 it increased to 22% (15 587 km^3). The mechanism that produced such a large volume of dense water is not simple. In the deep part of the Cretan Basin, direct convective mixing to the bottom was not observed, even during the severe winter of 1987 (Zodiatis 1991b). During the winters of 1988–90 the convection does not penetrate deeper than 700 m and, even then, the upper mixed layer was warmer than the CDW. The detailed numerical simulations of Nittis et al. (2003) show that deep mixing took place in the western Cretan Basin during late winter 1987, that it was very limited in the central basin in the winter of 1988, and that during the winters of 1989 and 1990 (excluding the north basin) it was quite similar to that during the extreme winter of 1987. The increase in the CDW volume was attributed mainly to open-sea convective processes rather than to dense shelf water formation. Indeed, the model results indicated the presence of water with a density larger than 29.1 on the southern part of the Lesvos–Lemnos Plateau during the winter of 1987 but not during the winters of 1988 and 1990 as instead it was observed in the Gakkel-31 and -36 cruises. A possible reason for these discrepancies is the underestimation of the LSW volume (or the salinity) incoming into the Aegean. This problem is mentioned by the authors of the simulations (Nittis et al. 2003).

Another possible reason stems from the fact that the models allow the BSW to reach too far south on the Lesvos–Lemnos Plateau and thus diminish the water formation on the plateau. Observed winter fields of salinity during the Gakkel cruises (Figs. 4b and 7b), as well as those presented by Theocharis and Georgopoulos (1993) and by Zodiatis (1994), suggest that the BSW turns north immediately upon exiting the Dardanelles and do not flow around Lemnos Island as, instead, models try to do (Kourafalou and Barbopoulos 2003; Korres and Lascaratos 2003).

The geographical position of the central basin defines its crucial role in the Aegean Sea water mass formation. We have shown that warm and saline water, the LSW, moves northward from the Levantine basin (15.5°–16.5°C, 39.10–39.20 during the late winters of 1988–1990) along the Asia Minor coast. On its way to the central basin, the LSW becomes cooler and it arrives in the northern part of the central basin where more acute transformations are occurring.

We have shown that waters with a density of 29.3–29.5 fill the depressions of the northern and the central basins: we show evidence of slope convection from the Lemnos–Lesvos Plateau to the North Skyros Depression. We also have shown that, between 1988 and 1990, water with a density of 29.2–29.3 occupy the intermediate layers of the northern and central basins and spread into the Cretan basin where they sink down the slopes to the bottom. Waters with a density of 29.1–29.2 spread mostly as intermediate waters in all three basins. These intermediate waters form the most important part of the Aegean Sea conveyor belt. In oceanographic literature this water is usually named intermediate water of Levantine origin, or Levantine Intermediate Water. In this paper we name it Aegean Intermediate Water because it forms within the Aegean Sea and not within the Levantine basin proper as LIW does.

Our analysis (Table 1) shows that between 1988 and 1990 the volume of CDW has increased because of the intensive formation of this type of water in the northern central basin. The path which AgIW and CDW take from the region of the cyclonic gyre in the central basin to the Cretan basin follows the bottom topography and the structure of isopycnal surfaces.

Figure 10 synthesizes the differences between 1988 and 1990 representing the water masses on the 29.2 isopycnal surface and its depth. The exposed area with a water density of more than 29.2 above the Lemnos–Lesvos Plateau increased significantly from the winter of 1988 to the winter of 1990. Simultaneously there is an increase of the salinity and the temperature of the AgIW located above this isopycnal. The CDW below the 29.2 isopycnal is shallower in 1990 versus 1988, indicating a volume increase of CDW. Both the AgIW and CDW spread isopycnically south into the Cretan basin. They spread across the northeastern side of the Cretan Sea (Fig. 10) as well as via the Cycladic Straits into the western part of the Cretan basin. The Cycladic Straits are shallower, and water mass exchanges through them can be significantly less then through the wide eastern passage between the central basin and the Cretan basin. Apparently AgIW and CDW could form over the Cycladic Plateau itself but, judging from general propagation of the LSW in a northward direction, this plateau could not be as productive as the Lesvos–Lemnos Plateau.

The rate of water mass formation of CDW over the Lesvos–Lemnos Plateau and its θ–S parameters are defined by the parameters of the incoming LSW and by the rate of buoyancy loss at the sea surface. Another very important factor, which defines water mass formation rates, is the lateral advection of buoyancy due to the waters of Black Sea origin. During winter the position and horizontal gradients of the frontal zone vary significantly as they are determined by the wind pattern over the Aegean Sea (Gertman et al. 1990; Zodiatis and Balopoulos 1993; Zodiatis 1994). During 1988, the Lesvos–Lemnos Plateau was covered mainly by BSW (see the position of the salinity front in Fig. 4b) and the Aegean Sea conveyor belt produced mainly AgIW. During 1990 the frontal zone has moved significantly northward, and saltier and denser waters were formed over the plateau (Fig. 7). Since the BSW is much lighter and occupies a relatively thin layer, the front between BSW and LSW is not only determined by the volume of the waters ingressing through the Dardanelles but significantly more by the local wind stress curl and heat loss.

In a comprehensive analysis of the EMT, Lascaratos et al. (1999) propose two reasons for the increase of the salinity in the upper layer of the Aegean Sea and the subsequent increase in the rate of AgIW and CDW formation during the years 1989–90. The first one is a lack of precipitation over the Aegean Sea. The second one is a redistribution of salinity within the eastern Mediterranean due to development of a multilobe anticyclonic circulation in the southwestern Levantine basin (Malanotte-Rizzoli et al. 1999). This pattern impeded the penetration of less saline Atlantic water into the Levantine basin and prevented the outflow of high-salinity Levantine Intermediate Water into the Ionian Sea. Thus a long-term increase in the salinity of the Levantine basin was initiated, resulting in an increase in the salinity of LSW entering the Aegean Sea. The changes registered in the surface salinity field of the 1988 (Fig. 4b) and 1990 winters (Fig. 7b) support the second hypothesis. In all of the regions penetrated by the LSW, there was a stable increase in the sea surface salinity of about 0.15–0.20. The maximum increase in the sea surface salinity was observed in the central basin in the region of northwestward movement of the frontal zone between the LSW and the BSW.

7. Summary and conclusions

The dense grid of stations, carried out by R/V *Yakov Gakkel* during two winter surveys (February–March 1988 and January–February 1990), allowed the detailed description of the three-dimensional field of temperature and salinity, density, and dynamic height as well as the statistical analysis of the principal water masses of the Aegean Sea (Table 1) for these two winters. Integral parameters of the principal water masses during the beginning stage of the EMT were computed by statistical volumetric analysis.

We identify two surface water masses: the saltiest one (LSW) of Levantine origin and the freshest one (BSW) of Black Sea origin. All other principal water masses of the Aegean Sea are generated locally from those two surface water masses by local meteorological conditions and by mixing.

It is found that the central basin and the Lesvos–Lemnos Plateau, in particular, are the main regions of water mass formation and transformation. The rate of new water mass formation and their θ–S characteristics are determined by the θ–S characteristics of the LSW and the BSW as well as by the position of the front between them.

Thus, dense waters are formed when the LSW is situated over the Lesvos–Lemnos Plateau and cooling is relatively intense. Whether these waters fill the depression of the central basin, to become CAgDW, or the depression of the northern basin, to become NAgDW, depends strongly on the position of the front with respect to the slope of the bottom. Moreover, the central basin appears to be a constant source of AgIW with relatively narrow θ–S and density range (13.5°–14.8°C, 38.8–39.0, 29.1–29.2). These waters accumulate in the central basin depressions and spread into the Cretan basin.

The volume of the BSW in the Aegean Sea is the smallest. However, because of its low salinity this water type plays an important role as a regulator of the intensity of water mass formation in the northern central basin. During 1988, BSW occupied most of the Lesvos–Lemnos Plateau (Fig. 4), and the central basin produced mostly AgIW. During 1990, the BSW–LSW frontal zone was farther to the north (Fig. 7), and the Lesvos–Lemnos Plateau produced water with CDW characteristics (Fig. 9). Nevertheless, the main contributor to the formation rate of CDW is the increase in

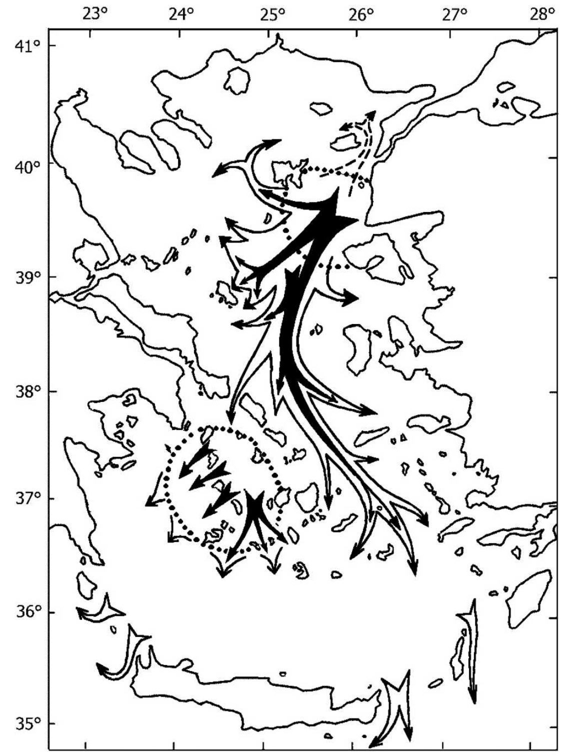

FIG. 11. Regions of intermediate water and deep-water formation (dotted areas) and propagation pathways in the Aegean Sea.

the LSW salinity from 1988 to 1990. This confirms the conclusion of Malanotte-Rizzoli et al. (1999) that the redistribution of the salinity in the eastern Mediterranean played a significant role in the first stages of anomalous CDW formation in the Aegean Sea. However, the intense cooling during the winter of 1987 (Theocharis et al. 1999b) cannot be excluded also as an important concomitant effect to determine the start of the EMT. This only factor has been shown by numerical simulations (Wu et al. 2000) to be capable to produce CDW that can exit the Cretan Sea in 1989, as expected.

The distribution of θ–S parameters on the isopycnal surface of 29.20 (Fig. 10) shows that the AgIW and CDW propagate from central basin to the Cretan basin below the LSW through the wide area between the Cycladic Plateau and Asia Minor. During 1988 only the AgIW spread to the Cretan basin (Fig. 5), while during 1990 CDW replaced most of the AgIW (Fig. 8). In Fig. 11 we illustrate the major pathways of intermediate and deep waters deduced by our investigation. The most plausible areas of Aegean dense water formation are indicated to be over the Lemons–Lesvos Plateau and the Cycladic Plateau or in the northwestern Cretan Sea.

In the Cretan basin, during 1988, the depth of the isopycnal surface of 29.20 was between 600 and 900 m (Fig. 10). During 1990, it shoaled to about 400–600 m, and during the summer of that year intense egression of dense waters into the eastern Mediterranean was observed (Popov 1991). Therefore, CDW already began overflowing the sills of the Kassos (1000 m) and Antikithira (500 m) Straits during the winter of 1988. Preliminary "collecting" of the Aegean waters in the Iera–Petra anticyclone during 1987 was documented by Schlitzer et al. (1991). Wu et al. (2000) attempted to model this outflow and they found that Kassos Strait is the first one to show outflowing CDW. However, they assume that there are no changes in the salinity advection from the Levantine basin and, therefore, in order to simulate the EMT they had to assume an unrealistically strong cooling over the north and central Aegean basin. Other numerical simulations of the EMT clearly show that Kassos Strait is the first one to be penetrated by the CDW outflow (Lascaratos et al. 1999; Demirov and Pinardi 2002). These simulations, based on realistic weather conditions, brought about an increase in the salinity of the Levantine basin, which served as a preconditioning phase to the intensive production of CDW and the EMT.

Our investigation shows that, during the 1988–90 period, the CDW was formed by a concomitant effect of typical atmospheric cooling and subsequent enrichment of salt by LSW advection into the central Aegean basin. The CDW slides southward into the Cretan basin, filling it (see also Theocharis et al. 1999b) and then egresses into the eastern Mediterranean. The whole process of CDW formation and outflow was reinforced by the early 1990s cooling events as described by Lascaratos et al. (1999) and by Josey (2003). However, it is clear from the 1988–90 surveys presented here that waters with θ–S characteristics similar to CDW were already overflowing Kassos Strait in 1988, probably because of the winter cooling event of 1987 (Theocharis et al. 1999a). It is then possible that the overall strength of the EMT and its long-term evolution are connected to a concomitant effect of successive cooling events and lateral salt enrichment processes.

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APPENDIX

Objective Analysis Method

The objective analysis used in this study is taken from the original work of Bretherton et al. (1976) and adapted to mesoscale oceanic flow fields by Carter and Robinson (1987). This technique allows to map on a regular grid N irregularly distributed stations, say φ_s, $s = 1, N$.

Given that the regular grid is at $\mathbf{x} = (x_i, y_i)$ then the best estimate of the field $\theta_\mathbf{x}$ in the least squares sense is

$$\theta_\mathbf{x} = \tilde{\theta} + \sum_{r=1}^{N} \mathbf{C}_{rx}\left[\sum_{s=1}^{N} \mathbf{A}_{rs}^{-1}(\varphi_s - \tilde{\theta})\right],$$

where $\tilde{\theta}$ is the mean value taken to be equal to the mean of the observations used to estimate the field. The correlation matrices $\mathbf{C}_{rs}$ and $\mathbf{A}_{rs}$ are written as

$$\mathbf{A}_{rs} = \mathbf{F}(\mathbf{x}_r - \mathbf{x}_s) + \mathbf{E}\delta_{rs} \quad \text{and}$$

$$\mathbf{C}_{rs} = \mathbf{F}(\mathbf{x}_r - \mathbf{x}_s).$$

Here, $\mathbf{E}$ is the initial expected error given as a percentage of the field variance and the correlation function $\mathbf{F}$ has been chosen homogeneous and isotropic; that is,

$$F(r) = \left(1 - \frac{r^2}{a^2}\right)e^{-r^2/2b^2},$$

where $r^2 = x^2 + y^2$ and $a = 80$ km and $b = 60$ km. Such values are chosen starting from the work of Nittis et al. (1993) where correlation functions were calculated from observations in the Ionian Sea, scaling the correlation by the relative size of the Rossby radius of deformation of the two regions. It is within the assumption of this least squares problem that correlation functions are homogeneous in space; that is, they do not depend on the particular grid point computed. This is why we cannot use this least squares solution to consider the spatial nonhomogeneity of the interpolation around non–simply connected domains. Within the assumption that the flow field around the island is within a coastal boundary layer not resolved by our measurements, and knowing the large differences between water masses on the two sides of several islands, we constrained the data from one side of the islands not to influence the other side interpolation. In addition, we have forced the objective analysis not to consider data across sills separating troughs.

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