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The large deep water transient in the Eastern Mediterranean

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Abstract

The recent changes in the thermohaline circulation of the Eastern Mediteranean caused by a transition from a system with a single source of deep water in the Adriatic to one with an additional source in the Aegean are described and assessed in detail. The name Cretan Sea Overflow Water (CSOW) is proposed for the new deep water mass. CSOW is warmer ($\theta > 13.6°C$) and more saline ($S > 38.80$) than the previously dominating Eastern Mediterranean Deep Water (EMDW), causing temperatures and salinities to rise towards the bottom. All major water masses of the Eastern Mediterranean, including the Levantine Intermediate Water (LIW), have been strongly affected by the change. The stronger inflow into the bottom layer caused by the discharge of CSOW into the Ionian and Levantine Basins induced compensatory flows further up in the water column, affecting the circulation at intermediate depth. In the northeastern Ionian Sea the saline intermediate layer consisting of Levantine Intermediate Water and Cretan Intermediate Water (CIW) is found to be less pronounced. The layer thickness has been reduced by factor of about two, concurrently with a reduction of the maximum salinity, reducing advection of saline waters into the Adriatic. As a consequence, a salinity decrease is observed in the Adriatic Deep Water. Outside the Aegean the upwelling of mid-depth waters reaches depths shallow enough so that these waters are advected into the Aegean and form a mid-depth salinity-minimum layer. Notable changes have been found in the nutrient distributions. On the basin-scale the nutrient levels in the upper water column have been elevated by the uplifting of nutrient-rich deeper waters. Nutrient-rich water is now found closer to the euphotic zone than previously, which might induce enhanced biological activity. The observed salinity redistribution, i.e. decreasing values in the upper 500–1400 m and

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increasing values in the bottom layer, suggests that at least part of the transition is due to an internal redistribution of salt. An initiation of the event by a local enhancement of salinity in the Aegean through a strong change in the fresh water flux is conceivable and is supported by observations.

1. Introduction

Early investigations of the Mediterranean Sea date from the beginning of the century (Nielsen, 1912). While the observational evidence gathered since then has helped to define general aspects of the circulation, important questions remain open due to a lack of data in critical regions and to complex dynamical structures. Intensive field research has been carried out in the eastern part of the Mediterranean in recent years during the multi-national cooperative research programs POEM (Physical Oceanography of the Eastern Mediterranean, Malanotte-Rizzoli and Robinson, 1988) and POEM-BC (Physical Oceanography of the Eastern Mediterranean-Biology and Chemistry, Malanotte-Rizzoli et al., 1996a) to obtain data in these critical regions and address open questions.

A long disputed issue has been the importance of the Aegean Sea for the thermohaline circulation and water mass characteristics of the Eastern Mediterranean (Pollack, 1951; Wüst, 1961; Miller, 1963; El-Gindy and El-Din, 1986; Malanotte-Rizzoli and Hecht, 1988). In the Aegean Sea as well as in the Adriatic, deep convection has been observed producing dense bottom waters in the respective basins. It has been generally accepted that the Adriatic was the major source of deep water production in the Eastern Mediterranean (Wüst, 1961), but it remained unclear to what extent the dense Aegean water was able to communicate with the outside. Efforts to define the deep circulation only on the basis of temperature and salinity observations have been restricted by the extreme vertical and horizontal homogeneity of waters below 1500 m (Wüst, 1961), i.e. Eastern Mediterranean Deep Water (EMDW). The limited quality of the historic data sets has posed another severe problem (El-Gindy and El-Din, 1986). A transient tracer survey in 1987 (as a part of the POEM program) shed much light on this issue (Schlitzer et al., 1991). The picture of the thermohaline circulation that emerged from these data attributed to the Aegean Sea only minor influences in the abyssal circulation and confirmed the Southern Adriatic as the primary source for the deep and bottom water of the Eastern Mediterranean (Schlitzer et al., 1991; Roether and Schlitzer, 1991). The tracer data showed clearly that the dense Adriatic deep water (ADW) at the bottom of Southern Adriatic was formed by deep convection. This water subsequently flowed over the sill of Otranto and downward into the Ionian Basin, entraining surrounding water in this process and acquiring T/S properties close to EMDW. The new waters added in the northwest Ionian Basin from the Adriatic source spread south and east in a near-bottom layer. We will refer to the new water in the following as "Adriatic Sea Overflow Water (ASOW)" to distinguish it from EMDW proper. Low concentrations of transient tracers between 1200 and 2600 m depth indicated the absence of direct ventilation for this part of the water column, so that renewal was restricted to upwelling from the bottom layer and vertical mixing with overlying waters. Signatures of Aegean waters were found outside the Cretan Arc, but it was evident from the oxygen and transient tracer signals that their influence was limited to intermediate depths. Schlitzer et al. (1991) proposed the name Cretan Intermediate Water (CIW) for the saline water mass found at depths of 500–1200 m below the Levantine Intermediate Water (LIW). Relatively high tritium concentrations and a strong tritium/salinity correlation demonstrated that outflowing Aegean Water resulted in a direct ventilation of the depth range below the LIW (Roether et al., 1997a). Convective renewal of the depth range attributed to CIW is in contrast to the earlier literature, in which this part of the water column has also been referred to as a "transition layer" (Wüst, 1961), implying that the renewal in this depth range was primarily due to vertical mixing between the uppermost EMDW and LIW.

In the upper water column, exchange of near-surface water masses between the Eastern and Western Mediterranean takes place via the rather shallow ($\sim$460 m) Sicily Strait. Modified Atlantic Water (MAW), characterised by a subsurface salinity minimum, flows into the Eastern Mediterranean in a surface layer about 200 m deep, while below it more saline LIW is exported into the Western Mediterranean, where its high salinity plays an essential role in the deep water formation (Medoc Group, 1970; Leaman and Schott, 1991). A direct communication between the abyssal waters in the two basins is not possible because of the shallow sill depth, but entrainment of waters below the LIW into the outflow is still an open question (Astraldi et al., 1996).

The formation area of LIW is another topic that is still under discussion. Malanotte-Rizzoli and Hecht (1988) concluded that the formation of LIW might not be restricted to an unique region (the Rhodes Gyre area) but might form simultaneously in more than one place. The southern Aegean and northern regions of the Levantine Basin are among the places that have been proposed as additional formation sites (Malanotte-Rizzoli and Hecht, 1988; Georgopoulos et al., 1989; Özsoy et al., 1993).

In recent years slow changes in the characteristics of the abyssal waters of the Western Mediterranean have been noted (Bethoux et al., 1990; Leaman and Schott, 1991). These have been attributed to man-induced changes in the fresh water budget of the Eastern Mediterranean, presumably through the damming of major rivers for agricultural purposes (Rohling and Bryden, 1992). Due to the crucial role of LIW in the formation of the abyssal water masses in both the Eastern Mediterranean (Ovchinnikov et al., 1985; Roether and Schlitzer, 1991) and Western Mediterranean, changes in the salinity of LIW can strongly affect the deep thermohaline circulation. Rohling and Bryden (1992) argued that increased LIW salinities are indeed responsible for the warmer temperatures of Western Mediterranean Deep Water (WMDW) found recently. Other changes in the Eastern Mediterranean have been noted as well. Sur et al. (1992) observed convection to 1000 m or more in the Rhodes Gyre area, where previously only intermediate convection leading to the formation of LIW had been noted. Hecht (1992) reported abrupt changes in the characteristics of LIW in the Levantine Basin in 1982.

Despite such variability, the Eastern Mediterranean was believed to be basically in a stable quasi-steady state. Surprisingly therefore, a recent hydrographic and tracer survey in 1995 revealed that the system was undergoing a major transition (Roether et al., 1996) in which the Aegean was playing a much more prominent role than previously. Due to enhanced salinities, the density of the Aegean water had increased sufficiently to allow the outflowing water to sink to the bottom. The near-bottom changes in temperature and salinity were extremely large, pointing to a major inflow into the bottom layer. A T/S census yielded a water volume of 2.3×10^{14} m^3 discharged from the Aegean by early 1995 (Roether et al., 1996), and salinity records from within the Aegean indicated a start of the event possibly as early as 1988. These two results together yield a volume transport of at least 1 Sv, i.e. for a 7-yr formation period of CSOW, which exceeds the accepted outflow from the Adriatic source (Roether and Schlitzer, 1991) by a factor of about three. Transient tracer concentrations suggested that most of the Aegean outflow was deposited at the bottom and only minor fractions went into the layers above 1000 m.

Although the changes in the bottom layer are most impressive, subtle changes could also be detected in the upper water column including the LIW layer (Roether et al., 1997b). It was noted that the spreading pattern of LIW in 1995 was distinctly different from that in 1987. LIW was absent in the central parts of the western Levantine Basin and the northern parts of the Cretan Passage in early 1995. The combined data sets from the POEM-BC LIW formation experiment in 1995 indeed showed that LIW was concentrated in the eastern Levantine Basin and the northern periphery of the Rhodes Gyre (Malanotte-Rizzoli et al., 1996a). But chlorofluorocarbon (CFC) concentrations indicated a lack of recent ventilation of the LIW in the eastern Levantine Basin and southwest of the Rhodes gyre (Roether et al., 1997b). CFC concentrations indicative of recent ventilation were only found in the Rhodes Gyre area and its northern periphery and throughout the Aegean. CFC concentration ages in the LIW were distinctly higher in 1995 than in 1987 showing that the additional upwelling associated with the intrusion of dense water at the bottom was continuous into the core of the LIW layer. A dilution of LIW of up to 30% by upwelling deeper water was calculated (Roether et al., 1997b). Additionally, the spreading of LIW into the northern Ionian Sea appeared to be blocked by a pronounced front west of Crete suggesting less transfer of LIW into the central Ionian Basin.

The purpose of the present paper is to provide a detailed description of the changes in water mass characteristics and circulation in the Eastern Mediterranean caused by the intense discharge of deep waters from the Aegean. The previous state is characterised by a large-scale survey in the Eastern Mediterranean in 1987 (METEOR cruise M5/6) and the new one by a similar survey in 1995 (METEOR cruise M31/1). The new state undoubtedly is a transient one, so that further changes have to be anticipated. Section 2 gives a brief overview of the data sets used and of the data handling. In Section 3 the changes in the deep and intermediate layers of the Eastern Mediterranean are described and discussed. Section 4 addresses implications of the additional production of deep water at a new formation site and of the new T/S characteristics.

2. Data sets and methods

The data defining the "new" state of the Eastern Mediterranean thermohaline circulation originate from a recent basin-scale survey in January/February 1995 (METEOR cruise M31, Fig. 1a). This cruise was performed in the context of the POEM-BC programme and included transient tracer measurements in addition to regular hydrographic work and nutrient sampling. A rosette water sampler was used in combination with a CTD to obtain the samples for the analysis of oxygen, nutrients and transient tracers. The CTD salinity was calibrated against salinity measurements performed onboard with a Guildline salinometer, to a precision of ± 0.002. A modified Winkler titration was used to determine the dissolved oxygen content giving a measurement precision of ± 0.7 μmol/l. Nutrients were measured using an auto-analyzer resulting in a measurement precision for silicate of about ± 0.02 μmol/l or 2%, whichever is greater. CFC measurements were performed by gas chromatography. The precision of the CFC-12 measurements was determined from replicate samples and amounted to $\pm$ 0.005 pmol/kg or 1%, whichever is greater (Bulsiewicz et al., 1998). The 1995 distributions are compared to those of a similar basin-scale survey in 1987 (METEOR cruise M5, Fig. 1b), characterising the previous "steady" state. Details on measurement techniques and quality of this data set can be found in Roether and Schlitzer (1991) and Schlitzer et al. (1991). Both surveys are far from eddy-resolving, and horizontal maps may therefore suffer from a lack of data; but vertical structures are properly resolved. Temperatures are given as potential temperatures (θ) throughout the text.

In the following sections, time information gained from the anthropogenic tracer CFC-12 will also be addressed. The atmospheric release of CFC-12 started in the 1930s and showed initially an exponential increase up to 1975, followed by a nearly linear increase afterwards. Since the late 1980s the increase has been slowing down, ranging between 5 and 1% per year between 1987 and 1995. The total increase of CFC-12 between 1987 and 1995 amounted to 18%. By air–sea gas exchange, the ocean mixed-layer is driven towards a solubility equilibrium with the atmospheric concentrations (Warner and Weiss, 1985). Non-vanishing concentrations in the ocean interior reflect addition of surface waters in recent decades. Because the equilibrium concentrations in the mixed layer depend on the temperature and salinity of the surface water, we will occasionally express the CFC-12 concentrations as an equivalent partial pressure in parts per trillion by volume (pptv), which removes this dependency.

3. Comparative description of the 1995 and 1987 data sets

After pointing out basic differences between the two surveys (Figs. 2–5), the 1995 situation is described in more detail in Figs. 6–10. Thereafter horizontal property maps from both surveys are discussed (Figs. 11–16).

One of the most prominent features of the deep water body in the Eastern Mediterranean in the past has been its extreme homogeneity. The waters below 2500 m

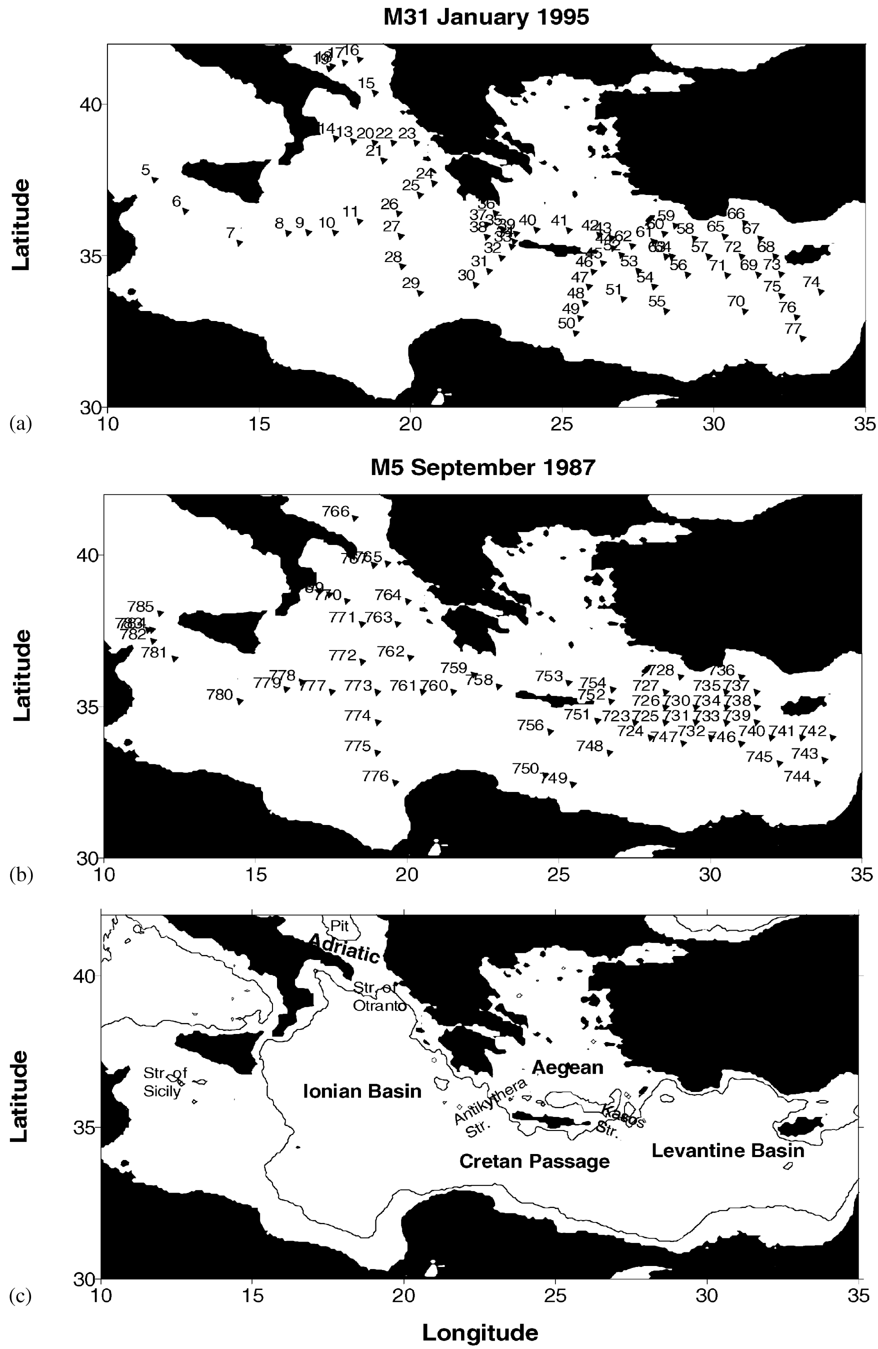


Fig. 1. Station map for Meteor cruise M31 in 1995(a), for Meteor cruise M5 in 1987 (b) and bathymetry of the Eastern Mediterranean including the 1000 m isobath (c). The names of major sub-basins and straits are noted in Fig. 1c. The southern part of the Aegean will be referred to as Cretan Sea.

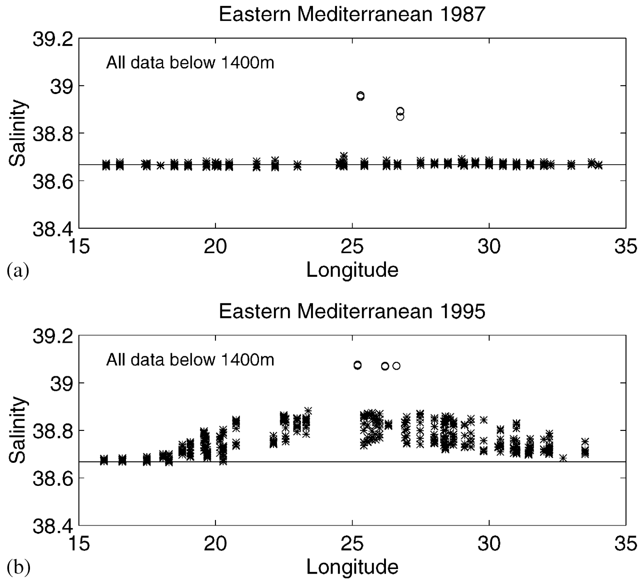


Fig. 2. (a) Deep water salinities (>1400 m depth) in the Eastern Mediterranean in 1987 based on bottle data from Meteor cruise M5. The solid line indicates a salinity of 38.668 and represents the definition of the bottom water as given by Schlitzer et al. (1991). (b) As (a) but for Meteor cruise M31 in 1995. Stations inside the Aegean are indicated by circles.

displayed nearly constant values of potential temperature (~13.3°C) and salinity (~38.663) throughout the basin (Schlitzer et al., 1991). In 1987 the deep water salinities (>1400 m; Fig. 2a) were both vertically and horizontally almost homogeneous. The only exceptions were data from within the deep parts of the Aegean Sea with salinities above 38.8, and a slightly larger spread of salinities in the longitude range 20–25°E in the Cretan Passage related to the presence of saline CIW (Schlitzer et al., 1991). By 1995 (Fig. 2b) the previous homogeneity of the deep water has been obliterated almost everywhere and deep water salinities have increased, exceeding 38.7 over large parts of the basin. Salinities from stations inside the Aegean have risen to about 39.1. Outside the Aegean, salinities increase towards the centre of the basin and are highest between 22°E and 27°E south of the Cretan Arc. The magnitude of change achieved in less than 8 yr by the outflow of very saline water from the Aegean is striking, considering that in the previous state the residence time of the water below 1400 m was estimated to be as long as 130 yr (Roether and Schlitzer, 1991).

In Fig. 3 the vertical distribution of temperature and salinity is presented along a zonal section between the Strait of Sicily and Cyprus. The high salinities depicted in Fig. 2b are visible as anomalously warm and salty waters in the bottom layer in and near the Cretan Passage (Fig. 3a and b). The waters added to the bottom layer are notably warmer (>0.3°C) and more saline (>0.2) than the surrounding waters. Especially in the Levantine Basin colder water is found lying above warmer water at

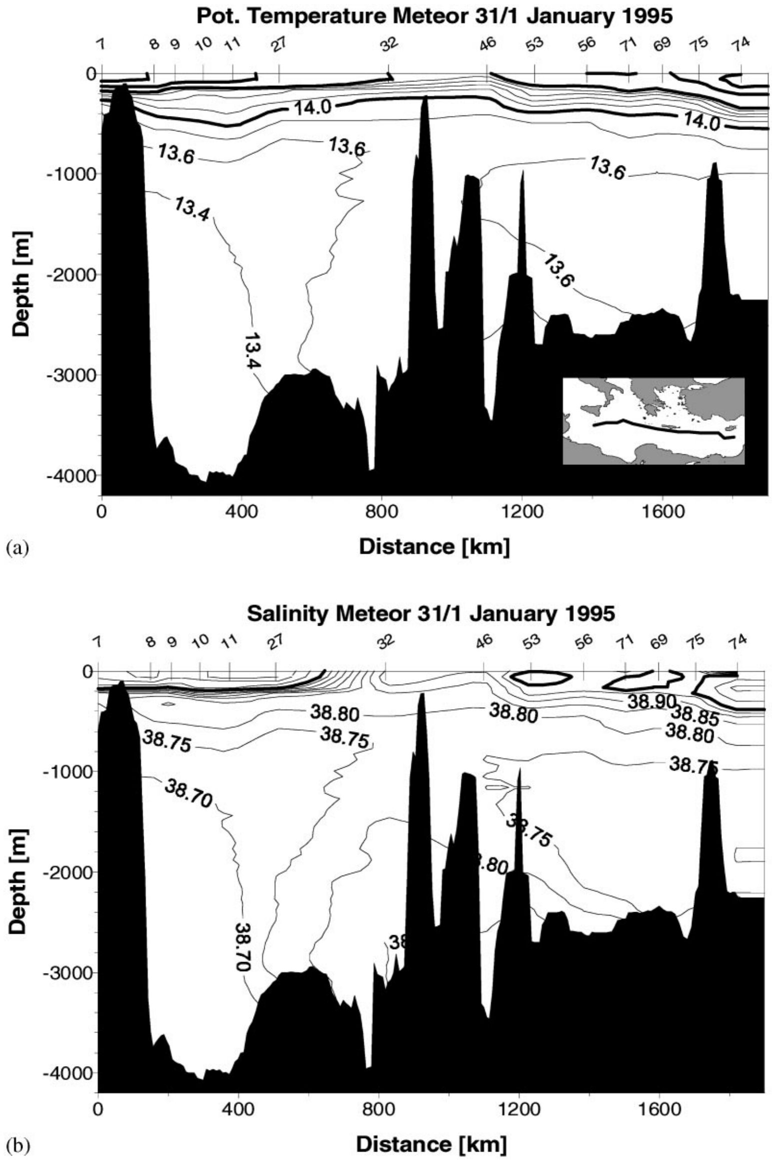


Fig. 3. Vertical section of pot. temperature (a) and salinity (b) between the Strait of Sicily and Cyprus. The orientation of the section is shown in the inset map.

the bottom, stability being obtained by a parallel change in salinity. ASOW derived from the Adriatic is still present as a water mass in the 1995 sections (Fig. 3a and b) but is limited to the western half of the Ionian basin. Its core can be found leaning on the continental slope in the west with properties of 13.22°C, and 38.668, i.e. typical for this region (Malanotte-Rizzoli et al., 1996b).

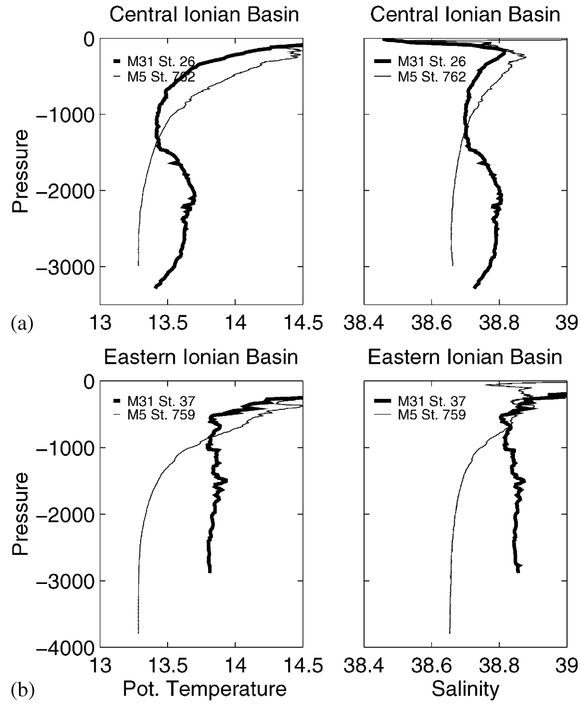


Fig. 4. Comparison of vertical profiles of pot. temperature (°C) and salinity from 1987 (thin line) and 1995 (solid line) in the central Ionian basin (a) and in the eastern Ionian Basin near Antikythera Strait (b). For station location, cf. Fig. 1.

A comparison of vertical profiles for stations at similar locations in the two surveys is given in Fig. 4. Stations 26 and 762 are located in the central Ionian Sea (Fig. 4a), while stations 37 and 759 are closer to the Greek coast near the entrance of the Antikythera Strait (Fig. 4b). It is evident that changes in the vertical structure are not restricted to the bottom layers, but that upper waters have also been effected. Changes in the water column above 1400 m are of sign opposite to those in the deeper part of the water column (Fig. 4a and b) but are lower in magnitude. Massive intrusions and fine structure are evident in the 1995 profiles, contrasting with those in 1987, which were very smooth below about 1200 m.

T/S diagrams (Fig. 5a and b) demonstrate that the source of the new type of dense waters can be located in the Aegean. The reason that the outflow from the Aegean reached the bottom is linked to the large increase of salinity in the Aegean (Fig. 5a). Bottom salinities increased from 38.995 to 39.076 between 1987 and 1995, while temperatures slightly decreased to 13.88°C. This resulted in an increase in bottom water densities from 29.20 to 29.37 kg/m^3. An increase in density is also found further up in the water column beyond the sill depth level (600–1000 m). In 1995 the density at sill depth was close to 29.22 kg/m^3, considerably exceeding those of waters outside the Aegean (29.16 kg/m^3). This excess apparently allowed the Aegean water to sink all

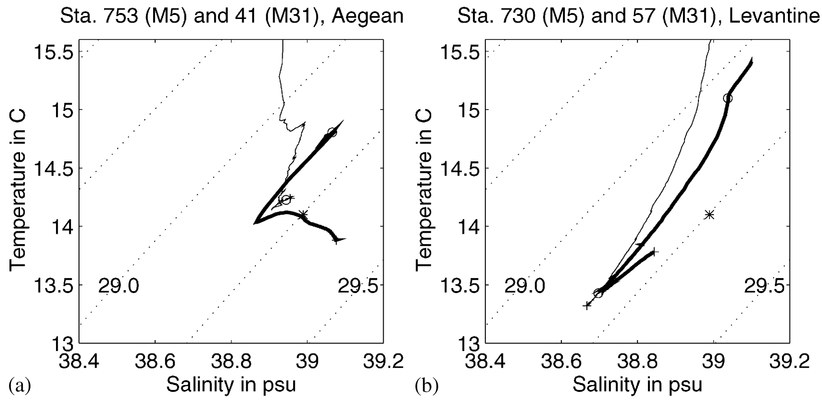


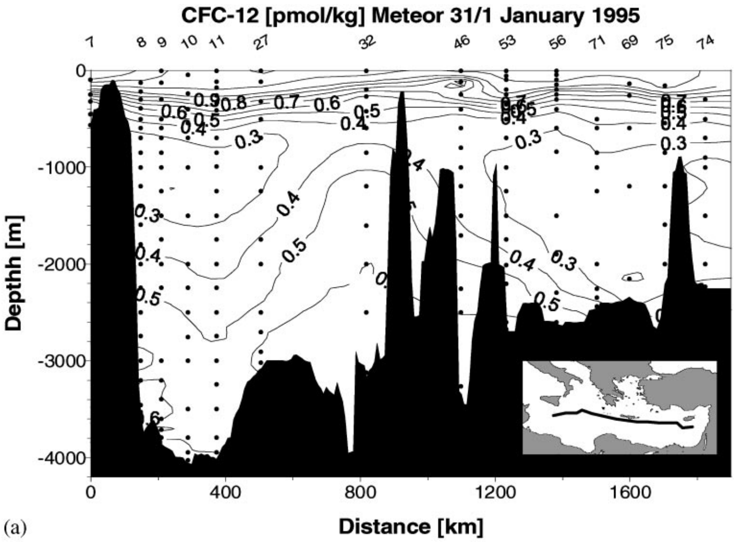
Fig. 5. Selected θ/S diagrams in the Aegean (a) and the Levantine Basin (b). Profiles from 1987 are given as thin lines, the 1995 profiles are represented as solid lines. Water mass properties found in 1995 at sill depth level (600–1000 m) in the passages through the Cretan Arc are indicated by the asterisk. Circles indicate a depth of 1200 m and bottom values are marked by crosses. For station location, cf. Fig. 1.

the way to the bottom and mix with the ambient deep water. In the former situation the density difference between the Aegean waters at sill depth and that outside was far smaller (~ 0.01) and only allowed penetration to intermediate depth, i.e. formation of CIW (Schlitzer et al., 1991).

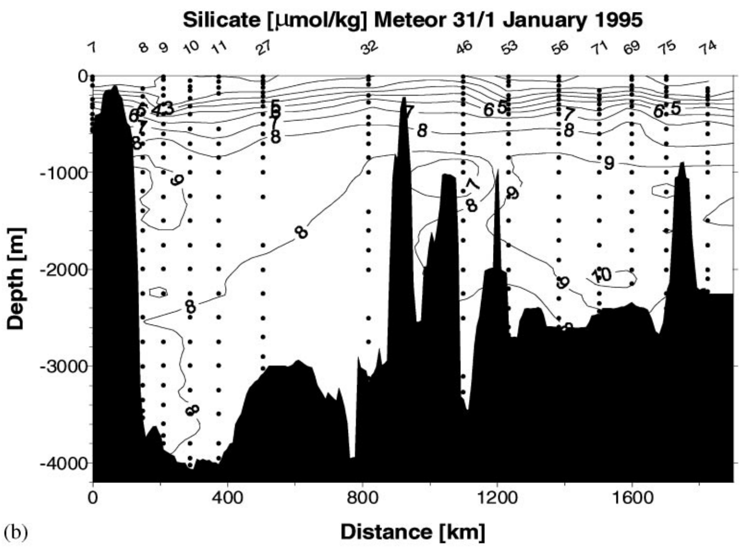
The intrusion of Aegean water to the bottom has altered the shape of the T/S curve, which now shows an inflection point near 1200 m (Fig. 5b). According to the characteristics of Aegean waters found at sill depth, shown in the diagram by an asterisk, it is obvious that the new bottom waters are a linear mixture of the overflowing waters with ambient EMDW (Fig. 5b). We propose the name Cretan Sea Overflow Water (CSOW) for the new water mass.

High CFC-12 concentrations (Fig. 6a) found around the Cretan Arc prove that the CSOW added to the bottom of the Ionian and Levantine Basin was recently ventilated. They also indicate relatively high volume transport, since CSOW has only been added recently into a low-CFC background. The second core of high CFC-12 concentration found at the base of the continental margin in the west is associated with the outflowing dense water from the Adriatic. CFC-12 concentrations in the ASOW have remained similar to those found in 1987 despite increasing atmospheric concentrations. The CFC-12 minimum layer at depth between 600 and 1400 m in the Ionian basin and between 600 m and 2000 m in the Levantine Basin has been found at shallower levels compared to the 1987 situation. This has been interpreted as an uplifting of older waters by intruding CSOW at the bottom (Roether et al., 1996).

The silicate distribution (Fig. 6b) shows a pattern similar to that of CFC-12, low silicate being representative of CSOW because of its recent contact with the surface. The addition of CSOW has reduced the deep silicate concentrations (>2000 m) below 8 μmol/kg at the eastern side of the Ionian Basin (Fig. 6b). In the previous situation



(a)



(b)

Fig. 6. Vertical distribution of CFC-12 (a), silicate (b) and oxygen (c) along the section shown in Fig. 3.

silicate concentrations above 9 µmol/kg were found in the deep water of the Ionian Basin (Miller et al., 1970). In the past highest silicate values (> 11 µmol/kg) were found in the eastern Levantine Basin (Krom et al., 1991, 1993), implying long residence times and poor ventilation. The discharge of CSOW into the Levantine Basin has lowered the silicate concentrations over the entire depth range. Maximum concentrations are still found in the eastern Levantine Basin (Fig. 6b) but have been reduced by 2 to about 9 µmol/kg.

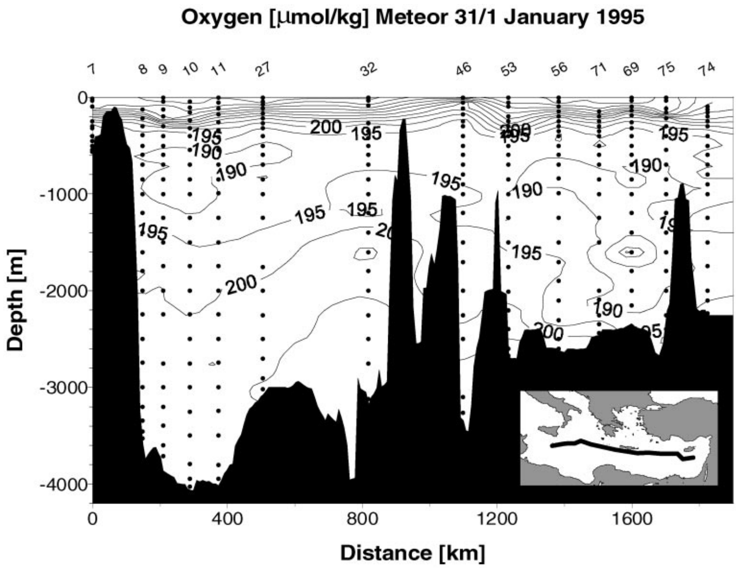


Fig. 6. (*continued*).

The deep layers of the Aegean are characterised by very high oxygen concentrations due to fast convective replenishment inside the Aegean. The change in oxygen content produced by the outflow of CSOW is therefore most pronounced (Fig. 6c). Around the Cretan Arc a broad oxygen maximum at the bottom (>205 μmol/kg) indicates the core of CSOW. The increase in oxygen concentrations is most prominent at the bottom, but throughout the water column an increase in oxygen is found in Ionian as well as in the Levantine Basin. The resulting higher background in the western Ionian even masks the signature of the ASOW. Oxygen concentrations as low as 177 μmol/kg in the eastern Levantine Basin (Schlitzer et al., 1991) had indicated long residence times of EMDW in the past. These concentrations have been elevated by more than 10 μmol/kg by the addition of CSOW.

Although the discharge of large amounts of CSOW has altered a considerable portion of the deep water in the Eastern Mediterranean, there was still a large reservoir of ADW detectable in the Southern Adriatic in 1995. The outflow of this dense water from the formation site in the southern Adriatic through the Strait of Otranto into the eastern Ionian Basin is depicted in Fig. 7. At the bottom of the South Adriatic Pit ADW can be identified through high CFC concentrations (Fig. 7b) and through its high oxygen content and low temperature (not shown). Its density in 1995 exceeds 29.25 kg/m^3 with potential temperatures of 12.57°C and salinities of 38.57. Near-bottom CFC-12 concentrations amount to 1.2 pmol/kg, which corresponds to 71% saturation with respect to the 1994 atmospheric concentrations (see insert in Fig. 7b). The upper 400 m of station 17 in the South Adriatic Pit displayed very homogeneous properties indicative of the onset of winter time convection in 1995. The ADW in

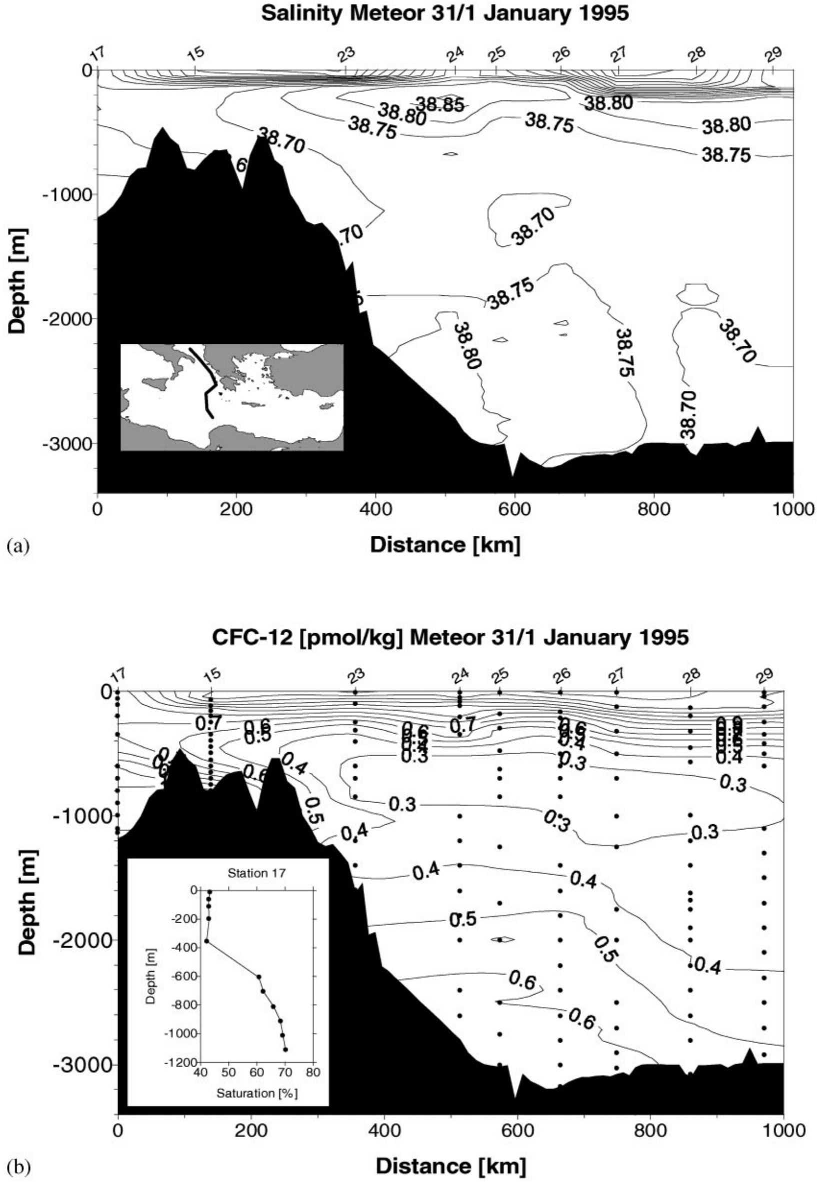


Fig. 7. Vertical section of salinity (a) and CFC-12 (b) following the ouflowing Adriatic Deep Water from the Southern Adriatic through the Strait of Otranto into the Ionian Basin. (see inset map in Fig. 7a). CFC-12 saturation levels corresponding to the atmospheric value in 1994 for station 17 in the South Adriatic Pit are displayed in the inset (b).

the deepest part of the South Adriatic Pit is not communicating directly with the outside. At sill depth ($\sim$800 m) pot. temperatures of less than 13.2°C and salinities less than 38.65 are observed, which apparently mix with surrounding waters and become progressively warmer and saltier as they spread into the Ionian. The main core of ASOW has been observed to turn west behind the Strait of Otranto (Bignamini et al., 1990; Malanotte-Rizzoli et al., 1996b) dynamically bound to follow the isobath contours along the Italian coast. In the past, the central and eastern Ionian abyssal plain was entirely occupied by homogenised EMDW with properties of 13.3°C, 38.663 (Schlitzer et al., 1991). In the 1995 survey, EMDW has mostly been replaced by mixtures with CSOW. The core of the newly added CSOW can be identified by the local temperature and salinity maximum below 2000 m with temperatures close to 13.6°C (not shown) and salinities greater than 38.75 (Fig. 7a). In the southern part of the section as well as very near the bottom at stations 28 and 29 remnants of EMDW, i.e. salinities <38.7, can be found.

Between 200 and 400 m depth a salinity maximum marks the advection of LIW into the Adriatic (Fig. 7a). Core values are as high as 38.8–38.85 in the central Ionian Sea and approximately 38.70 at the entrance of the Strait of Otranto; no clear gradient is distinguishable further into the Adriatic. Compared to the previous situation, the core salinities and layer thickness appear to be reduced, which will be discussed in more detail in Section 4. Outside the Adriatic the CFC-12 minimum layer (<0.3 pmol/kg; Fig. 7b) now extends from 400 to 1000 m. The addition of CSOW to the bottom layer has lifted the layer of old water sufficiently to become incorporated into the inflow into the Adriatic below the LIW. CFC-12 saturation levels in the upper 400 m of station 17 inside the Adriatic (insert in Fig. 7b) are as low as $\sim 43\%$ and increase toward the bottom. Since the source of CFC-12 is at the surface, such a saturation profile is conceivable only if the low-concentration waters at mid-depth have been entrained in the convection event.

The outflow of CSOW through Kasos Strait into the Levantine Basin is shown in Fig. 8. Like the South Adriatic Pit, the deepest part of the Aegean is blocked from a communication with the outside. Only waters above sill depth, located at about 1000 m depth (IBCM,1981), are in direct contact with the adjoining basin. The water flowing out of Kasos Strait is characterised by temperatures of 13.9°C and salinities of 38.95. It sinks immediately to the bottom and forms a warm, salty layer with high oxygen and CFC-12 concentration all along the bottom of the section (Fig. 8a and b).

The outflow of CSOW into the Levantine also alters the vertical structure of water masses adjacent to the Cretan Arc. Older EMDW, visible as a tongue of less saline (<38.8) water with low CFC-concentrations, apparently has been displaced upward. Also the CFC-12 minimum is now found near 1000 m depth (Fig. 8b), i.e. far shallower than previously (Roether et al., 1996). The upper part of this water reaches levels shallow enough to be incorporated into the inflow into the Aegean (Fig. 8a and b). It can also be noted that the salinity signature typical of LIW is absent in the central part of the section, where the "older" waters are intruding into the Aegean. This is shown in more detail in Fig. 8c–e, giving only the upper 1000 m of the same section. Two cores of high salinity, shaded in grey, can be identified at a depth of ~ 200 m at the northern and southern end of the section (Fig. 8d). The northern salinity maximum is only slightly stronger, but the different temperatures (Fig. 8c) result in widely separate densities of the two features. In the Aegean Sea (Sta. 43 and 44) the subsurface salinity

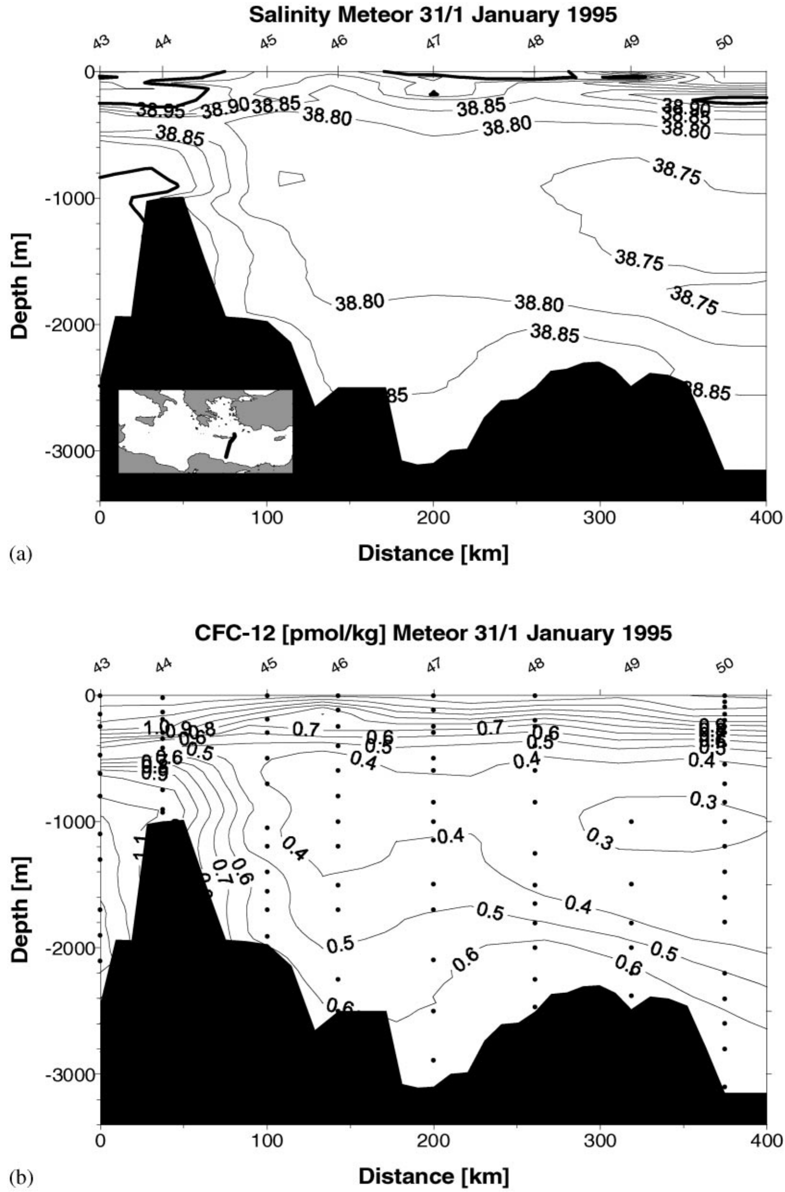


Fig. 8. Vertical section of salinity (a) and CFC-12 (b) following the outflow of dense water from the Aegean through Kasos Strait into the Levantine Basin (see inset map). The upper 1000 m of this section are shown enlarged for pot. temperature (c), salinity (d) and pot. density (e). Salinities in excess of 38.95 in (d) are indicated by shading.

maximum ($S > 39.05$) is associated with temperatures between 14.0 and 15°C and densities between 29.1 and 29.15 kg/m^3 (Fig. 8e). The southern counterpart corresponds to the classic definition of LIW (Wüst, 1961). It is associated with higher

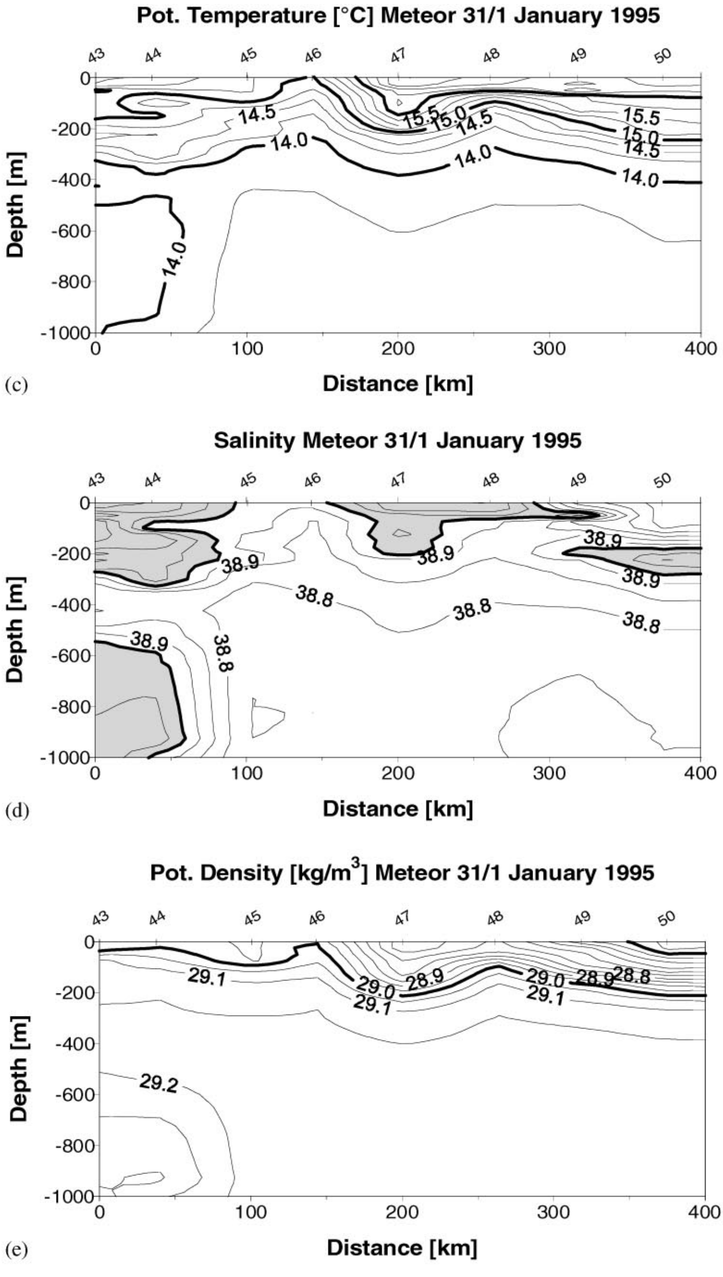


Fig. 8. (*continued*)

temperatures ($\theta > 15.3°C$) and a lower density 28.95–29.05 kg/m^3. Apparently the LIW is restricted to the southern part of the Cretan Passage and may be blocked from contact with the Cretan Arc. The isopycnal 29.1 kg/m^3 marks the bottom of the pycnocline and slopes downward from 100 m at the Cretan Arc to about 300 m in the south. The pronounced deepening of isopycnals in the middle of the section (Fig. 8e) is indicative of an anticyclonic motion presumably related to the Iera Petra gyre, in which very salty ($S > 38.9$) and warm Levantine Surface Water is recirculated (Theocharis et al., 1993).

The upper waters of the Aegean (Fig. 9) are characterised by high salinities, i.e. salinities between 39.0 and 39.1, down to 250 m (Fig. 9b), at relatively low temperatures ($\theta \sim 15.0°C$) (Fig. 9a). The outcropping of subsurface isopycnals at station 41 indicates that convection reached to intermediate depth (Fig. 9c). The surface characteristics of the water found at this location were $\theta = 14.8°C$, $S = 39.08$ and $\sigma_\theta = 29.14$ kg/m^3. This is close to the properties of the subsurface salinity maximum found at Kasos Strait (cf. Fig. 8). Although this water mass displays a subsurface salinity maximum, it should not be confused with LIW, since it is much denser than classic LIW and certainly formed in the Aegean. Formation of saline intermediate water in the southern parts of the Aegean Sea has been reported previously. Georgopoulos et al. (1989) observed the formation of a very saline water mass (>39.0) during late winter 1986 through intermediate convection, but because of much higher temperatures (>15.2°C) the feature was associated with a lower density (~29.02) compared to the present characteristics.

A tongue of less saline, poorly oxygenated water with low CFC-12 concentration at 300–500 m separates the surface layer from the saline, oxygen-rich bottom waters of the Aegean (Fig. 9b and d). The tongue at 300–500 m marks the "older" water, which is intruding into the Aegean from the east. The deep waters of the Aegean are remarkably close to surface characteristics in oxygen content and CFC-12 concentrations (Fig. 9d and e) indicating strong overturning and low residence times.

We now address the horizontal property maps from the two surveys. The surface distributions of salinity, CFC-12 and density for the 1995 cruise are given in Fig. 10a–c, density also serving as an indicator for the circulation in the upper thermocline. Modified Atlantic Water (MAW) with salinities of 37.8 (Fig. 10a) enters the Strait of Sicily, is transported to the east and leaves the strait at a modified salinity of 38.2. It turns north in the Ionian Basin, where it is encircled in the anticyclonic motion in the northern Ionian Basin (Fig. 10c). MAW forms a strong zonal front with the saltier water of Levantine origin at the eastern side of the Ionian basin (Fig. 10a). In the southeastern half of the Ionian Basin it joins the mid-Mediterranean Jet at 36°N flowing toward the Levantine Basin (Fig. 10c). There exists a complex dynamical structure of cyclonic and anticyclonic gyres in the Levantine basin (Robinson and Golnaraghi, 1994), which is not resolved by the spacing of the CTD stations available. Salinities in excess of 39.0 found in the Levantine Basin are typical for Levantine Surface Water (LSW), and similarly high salinities are also observed in the southern Aegean (Fig. 10a). CFC-12 values at the surface (Fig. 10b) are generally quite homogeneous except for two regions with significantly lower CFC-12 values, i.e. in the southern Adriatic and in the Rhodes Gyre area. In both areas surface concentrations of CFC-12 are evidently lowered by convection, which entrains lower-concentration waters from below. The surface density observed in the Rhodes Gyre (Fig. 10c) is as

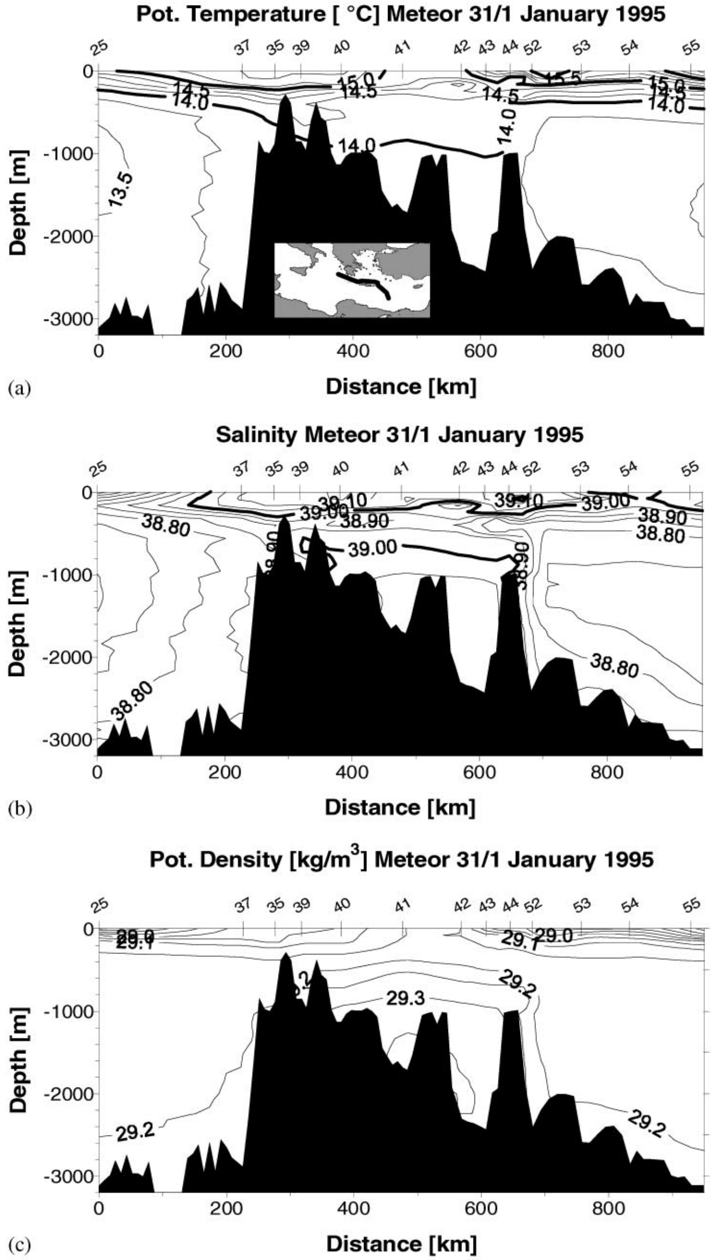
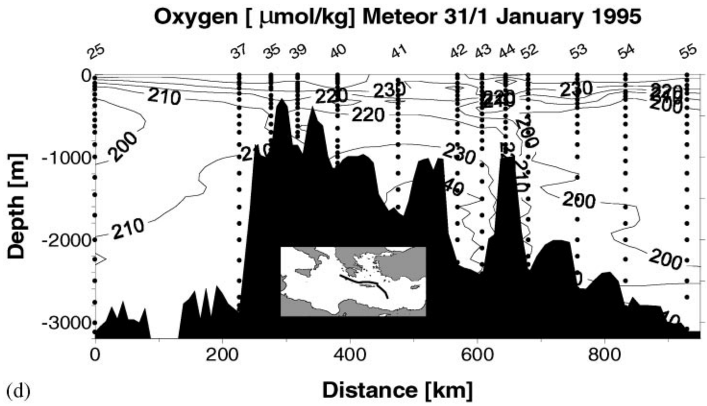
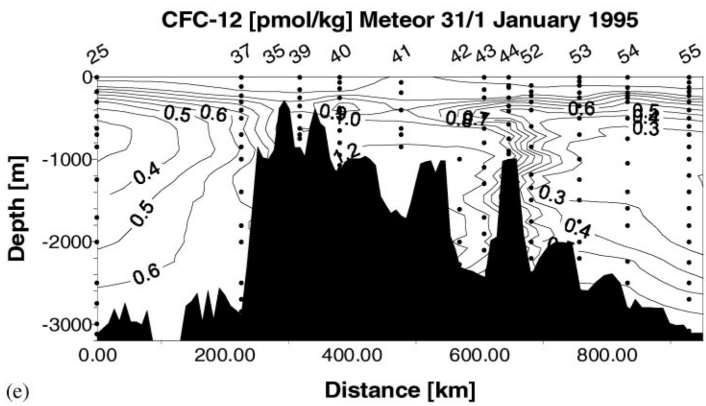


Fig. 9. Vertical section of pot. temperature (a), salinity (b), pot. density (c), oxygen (d) and CFC-12 (e) through the Aegean Sea (see inset map).



(d)



(e)

Fig. 9. (*continued*).

high as 29.16 kg/m^3 and exceeds the densities typical of LIW in the Levantine Basin by far. In the central Aegean outcropping of densities close to 29.14 kg/m^3 (cf. Fig. 9) is observed, which is also higher than found previously.

Property maps in 500 m depth, i.e. at the lower base of the LIW, for 1995 (Fig. 11a–f), respectively 1987 (Fig. 12a–f) demonstrate that changes in the vertical structure caused by the addition of CSOW at the bottom extends into shallow levels. While in the past this depth range was influenced by LIW and CIW, older waters prevail in the new situation. The uplifting of these waters from mid-depth to shallower levels is most evident in the Ionian basin, where temperatures and salinities have been reduced significantly (Fig. 11a and b) compared to the past (Fig. 12a and b), and a clear indication of westward spreading is missing in the present situation. In 1987 the 500 m level was still dominated by westward propagation of LIW in the Ionian basin, which is visible in the well established tongue centred at 36°N (Fig. 12a and b). The reduction in temperature and salinity is largest in the Ionian basin and south of

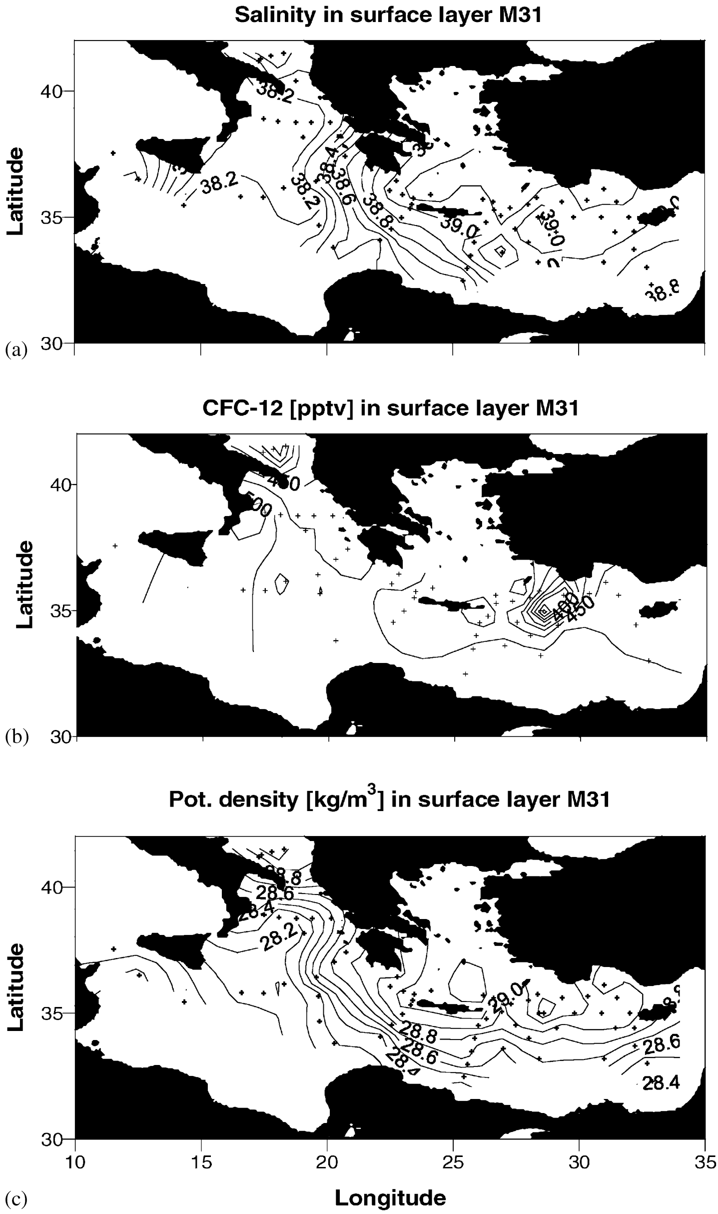


Fig. 10. Horizontal distributions of salinity (a), CFC-12 (b) and pot. density (c) in 1995 in the surface layer (10 m data). CFC-12 values are given as equivalent partial pressure.

Crete. The uplifting of mid-depth waters to shallower levels also results in a reduction of the oxygen concentrations and higher silicate levels (Figs. 11c, d, and 12c, d). The upward displacement of "older" water has furthermore lowered the CFC-12

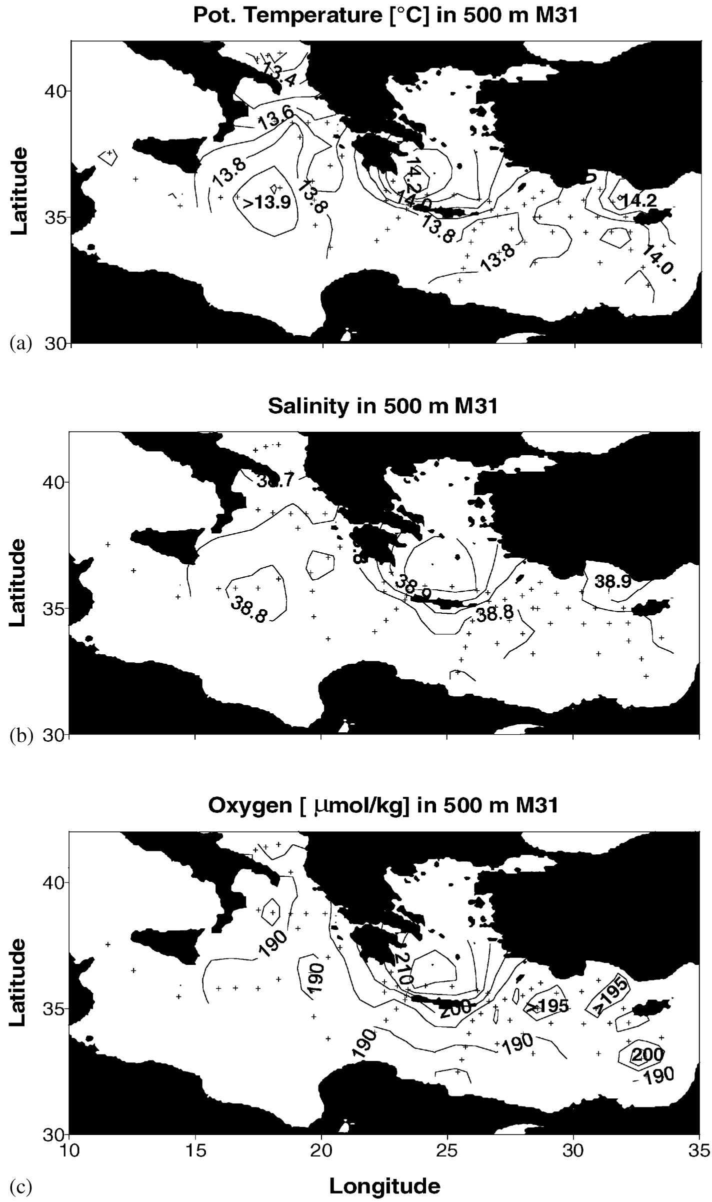


Fig. 11. Horizontal distributions of pot. temperature (a), salinity (b), oxygen (c), silicate (d), CFC-12 (e) and pot. density (f) in 1995 in 500 m depth. The layer represents the lower base of the LIW.

concentrations in the Ionian basin (Figs. 11e, and 12e). The sparseness of CFC data in the eastern Levantine in 1987 (Fig. 12e) makes patterns there unreliable.

The 1200 m level (Fig. 13) marks the transition towards the previously homogeneous deep water range. It is near this level that the 1995 profiles switch from a salinity

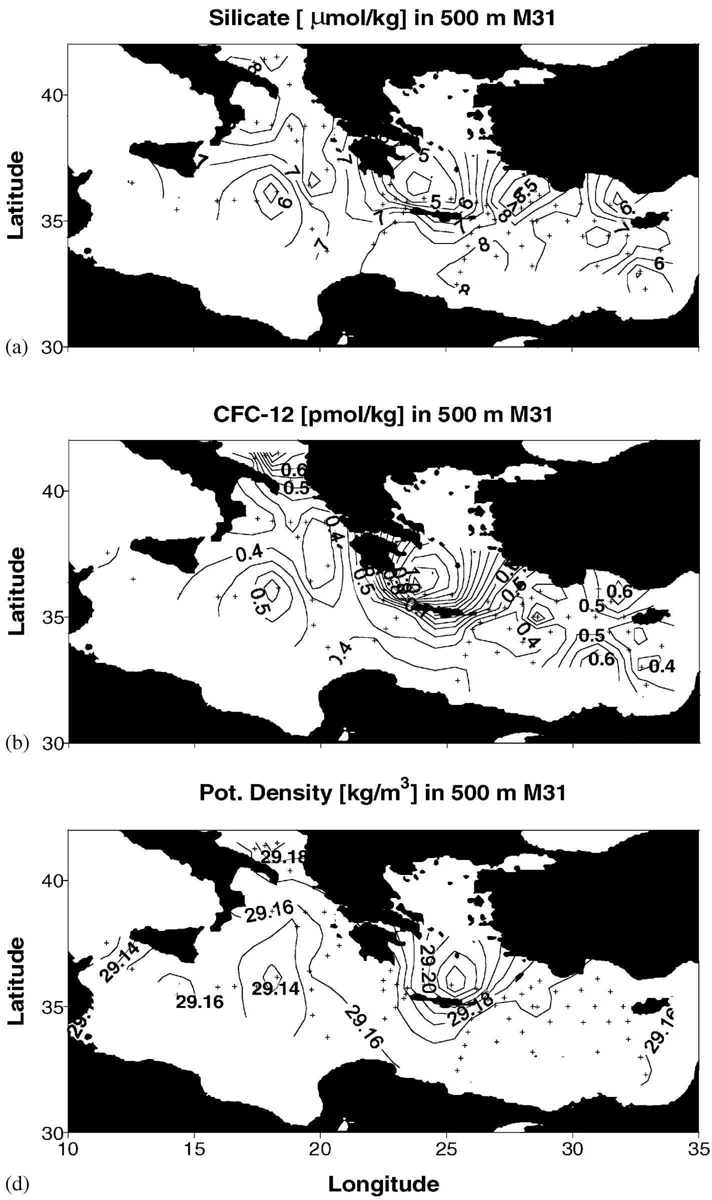


Fig. 11. (*continued*).

and temperature increase in the bottom layer to a salinity and temperature decrease further up (cf. Fig. 4). Profiles from both surveys nearly coincide at this level, and changes are therefore small. Isohalines show similar patterns in both surveys with maximum values found around the Cretan Arc. The 1987 salinity fields in 1200 m

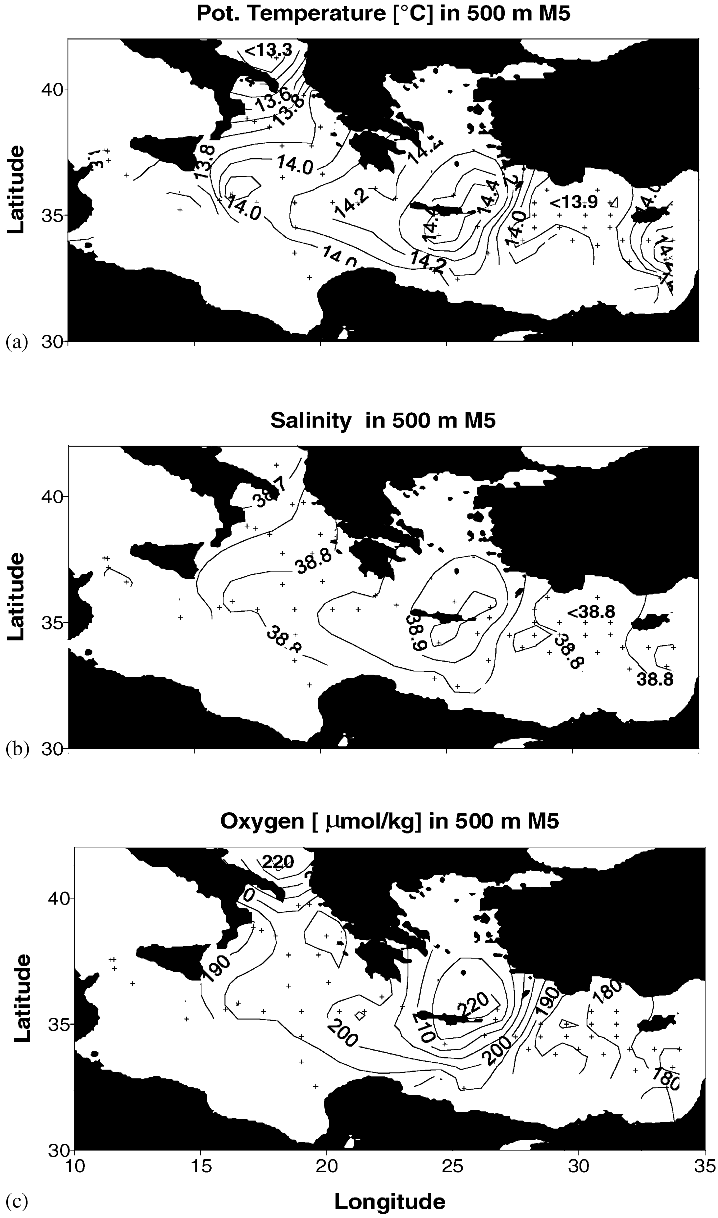


Fig. 12. As Fig. 11 but for 1987.

depth were still dominated by the influence of CIW. A lense of CIW observed south of Crete depressed isohalines enough to create the maximum salinity feature south of Crete (Fig. 13c), although the core of CIW is centred at shallower depth. The density of this feature was only slightly elevated above background levels (Fig. 13d). In 1995

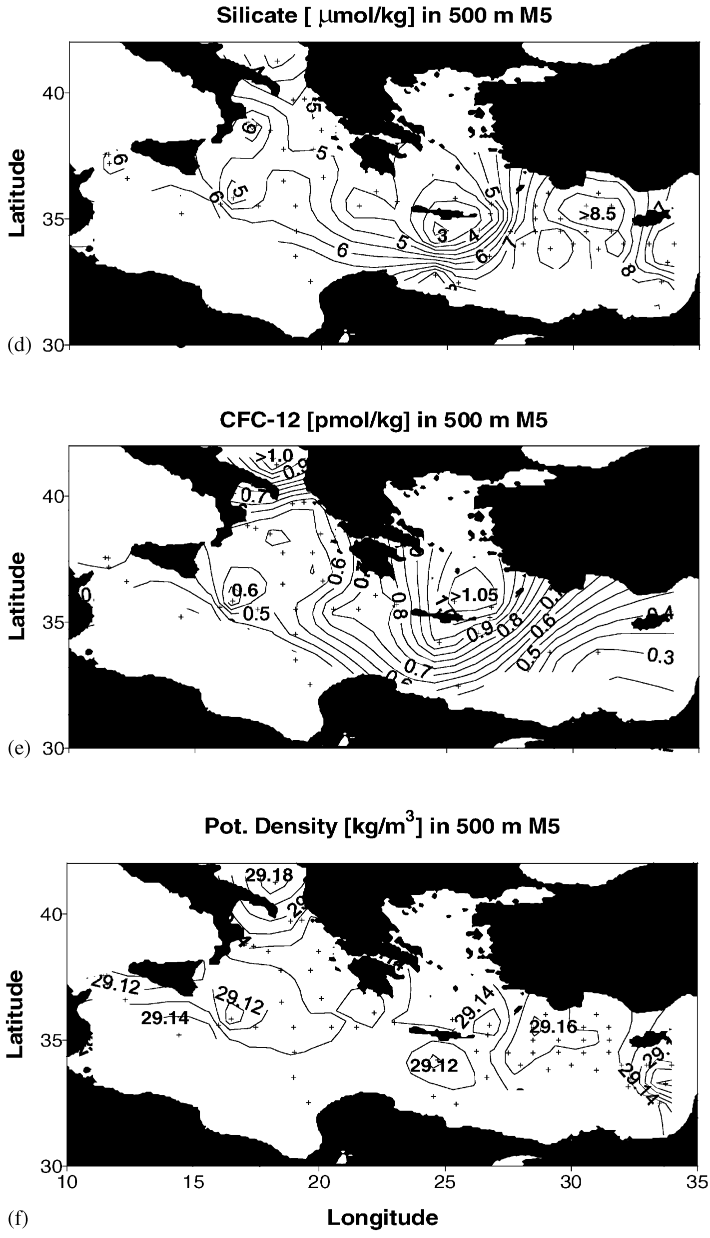


Fig. 12. (*continued*).

the salinity is higher everywhere on this horizon caused by the outflow of CSOW, and a stronger salinity gradient (Fig. 13a) and density (Fig. 13b) around the Aegean is produced.

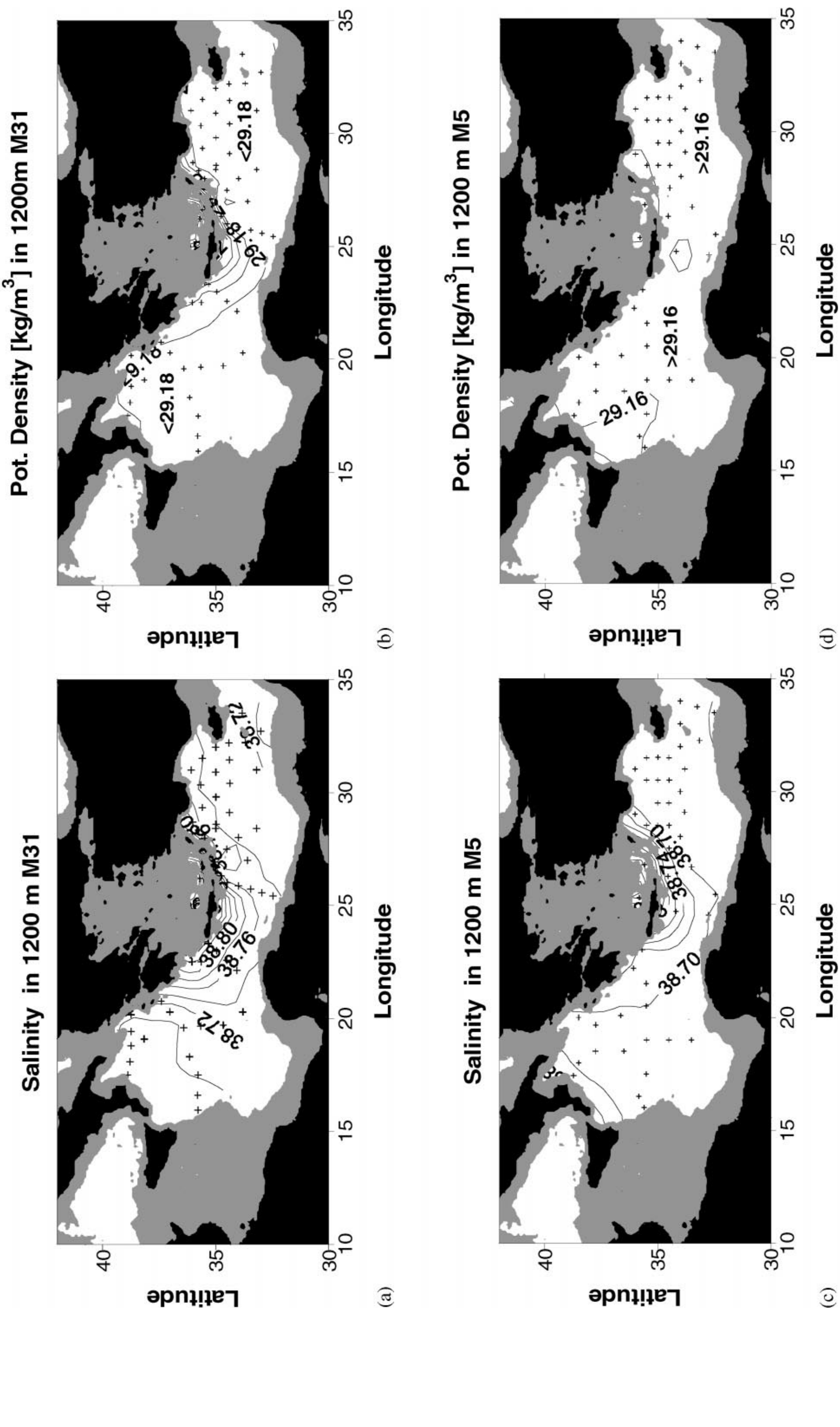


Fig. 13. Horizontal distributions of salinity and pot. density in 1200 m depth in 1995 (a, b) and in 1987 (c, d). Water depths less than 1200 m are indicated by shading.

The distributions shown in Figs. 14 and 15 represent the near bottom fields in the Eastern Mediterranean in 1995 and 1987 respectively. Water depths less than 800 m have been shaded to emphasise the fact that both the southern Adriatic and the southern Aegean are separated by shallow sills from the adjacent basins.

The addition of CSOW to the bottom has reversed the near-bottom vertical temperature and salinity gradients, causing these properties to increase towards the bottom. The horizontal gradients along the bottom are stronger than further up in the water column and display the most extreme characteristics of CSOW (Fig. 14a and b). At the eastern side of Crete the 13.8°C contour (Fig. 14a) makes a large excursion towards the south showing CSOW characteristics to extend all the way to the African coast, concurrently with high salinities. The large area influenced by CSOW could indicate that the major part of the CSOW has been discharged into the Levantine Basin through Kasos Strait before turning west under the influence of the Coriolis force. That a significant amount of CSOW must have been discharged into the Levantine Basin is consistent with the observed decrease in nutrient concentrations and increase in oxygen levels (cf. Fig. 6b and c) in the Levantine. But inflow into the eastern Ionian Basin through the Antikythera Strait is also noticeable from extrema in temperature and salinity just outside the strait (Fig. 14a and b). The influence of the colder and fresher ASOW is restricted to the western half of the Ionian Basin, apparently separated from the warmer and more saline CSOW by a strong front on the western side of Crete. Topographic steering by the Mediterranean Ridge might be responsible for this front. Della Vedova et al. (1997) in fact observed from heat-flow measurements in the sediment a propagation of a warming signal in the bottom in a southwestward direction from the Hellenic Trench outside Antikythera Strait towards the Sirte Abyssal Plain. In the past the influence of the cold and fresh ASOW could be detected beyond the Mediterranean Ridge as a tongue of lower temperatures (Fig. 15a) within the large reservoir of homogenised EMDW. The oxygen and CFC-12 distributions (Fig. 15c and e) showed more clearly that the core of ASOW followed the bottom topography in the western Ionian Basin forming a boundary current. Highest CFC-12 concentrations were found south of the Strait of Otranto and southeast of Sicily where the boundary current left the coast and turned into the central Ionian Basin (Fig. 15e). CSOW has raised the bottom CFC-12 concentrations considerably (Fig. 14e), which is especially evident in the Levantine Basin where concentrations previously were very low (Fig. 15e).

A summary of the observed water mass characteristics of the Intermediate Water, EMDW and CSOW in 1995 is given in Tables 1–3. Values of potential temperature, salinity and potential density have been averaged in 13 subareas (see Fig. 16). To give a consistent description of the 1995 situation, only data from METEOR cruise M31 have been used. Since the data set is not very large, most of the computations in the subareas are based on only a few stations and are therefore not robust in a statistical sense. The principal purpose of Tables 1–3 is to provide some estimates of water mass characteristics in the transition phase to which future observations can be compared. Mean values as well as the extreme core properties are given. Because of difficulties in defining uniform criteria for the water masses, we use slightly different ones for the

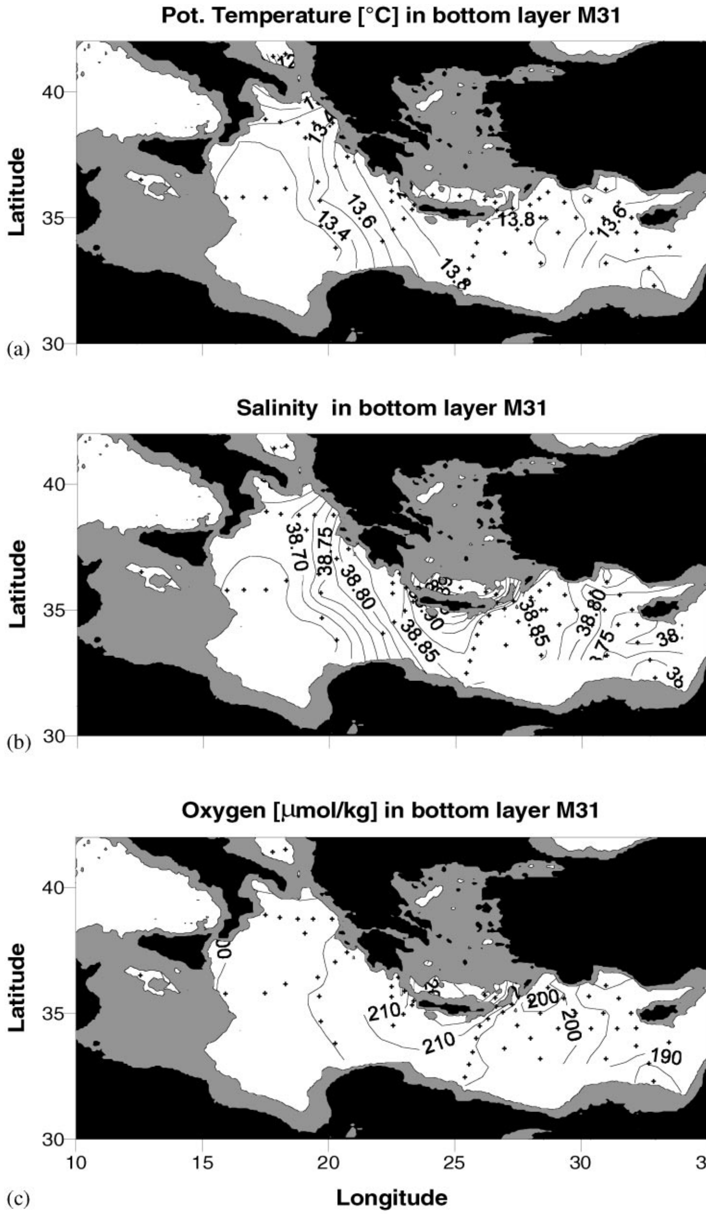


Fig. 14. Horizontal distributions of pot. temperature (a), salinity (b), oxygen (c), silicate (d), CFC-12 (e) and pot. density (f) in 1995 near to the bottom. Water depth less than 800 m has been represented by shading to indicate the topographic restraints to the flow posed by the shallow sills separating the Adriatic and Aegean Sea from the surrounding basins.

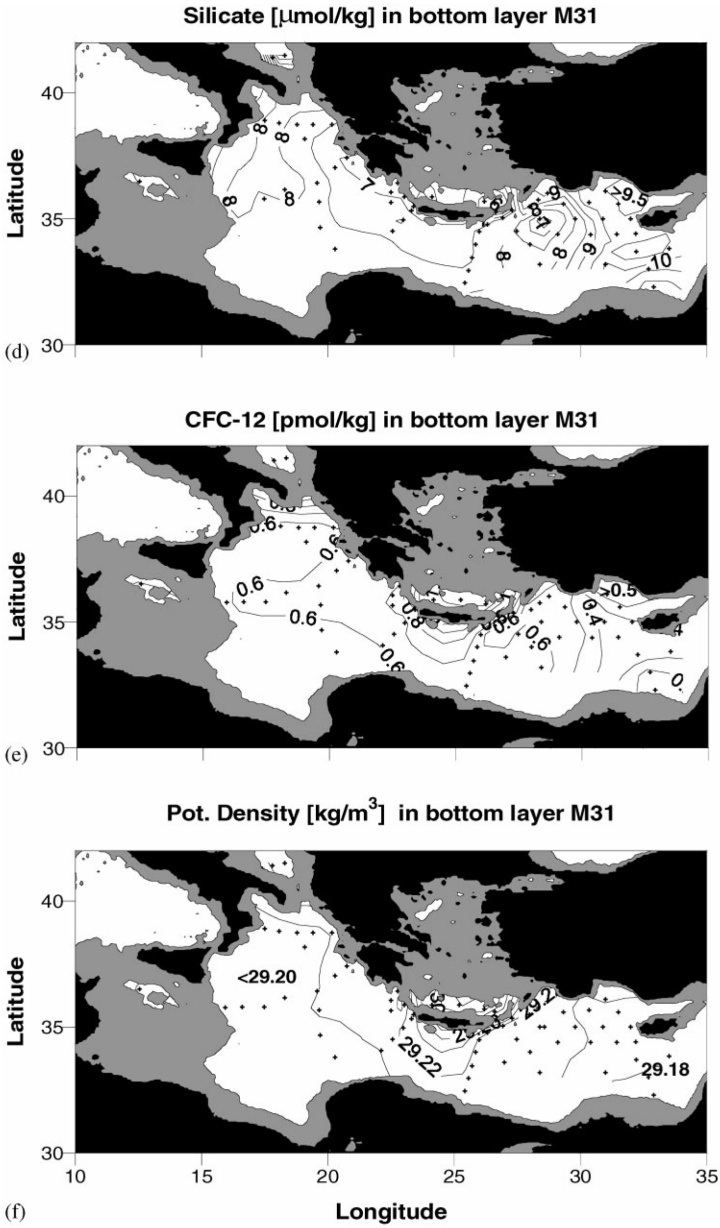


Fig. 14. (*continued*).

individual regions. The averaging was performed on coarsely smoothed CTD data with 1 dbar vertical resolution.

The Intermediate Water core properties (Table 1) show surprisingly high densities in the northern parts of the Levantine Basin. Only in the Western and Eastern

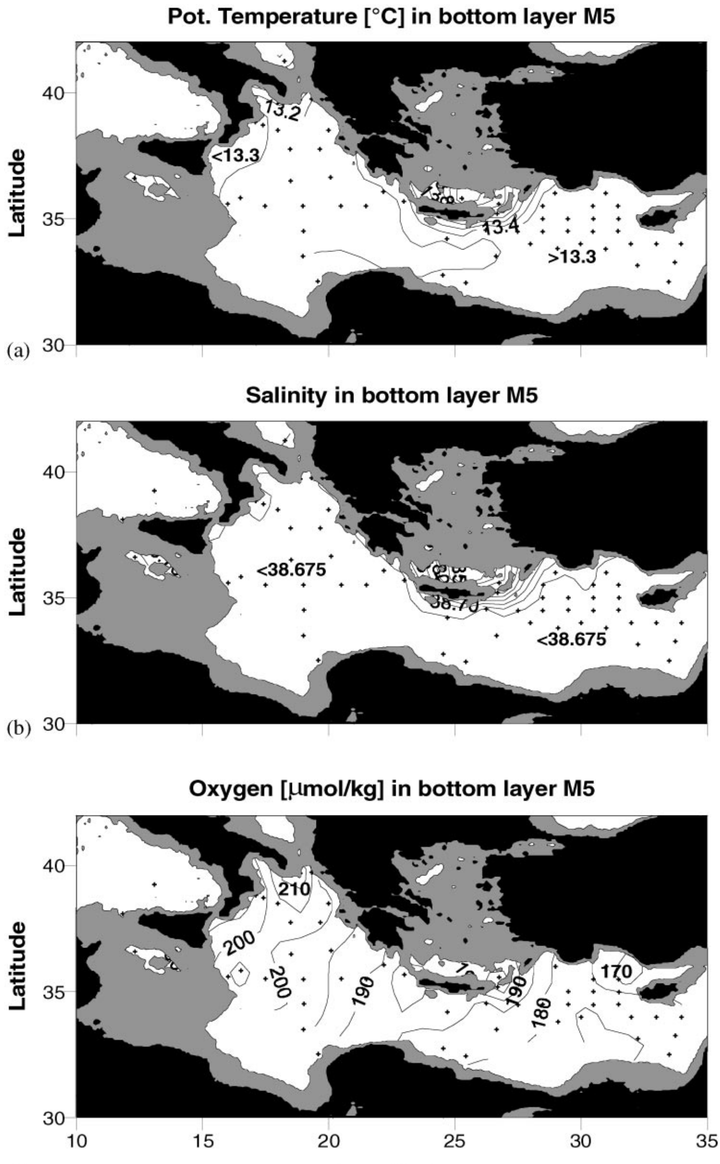


Fig. 15. As Fig. 14 but for 1987.

Levantine is the core density close to the “classic” LIW density between 28.9 and 29.0 kg/m^3, as defined by Wüst (1961). In the northern part of the Levantine (Rhodes Gyre and Antalya Basin) the salinity maximum is found at densities of about 29.14 kg/m^3, which clearly exceeds the “classic” LIW density. In the Aegean another

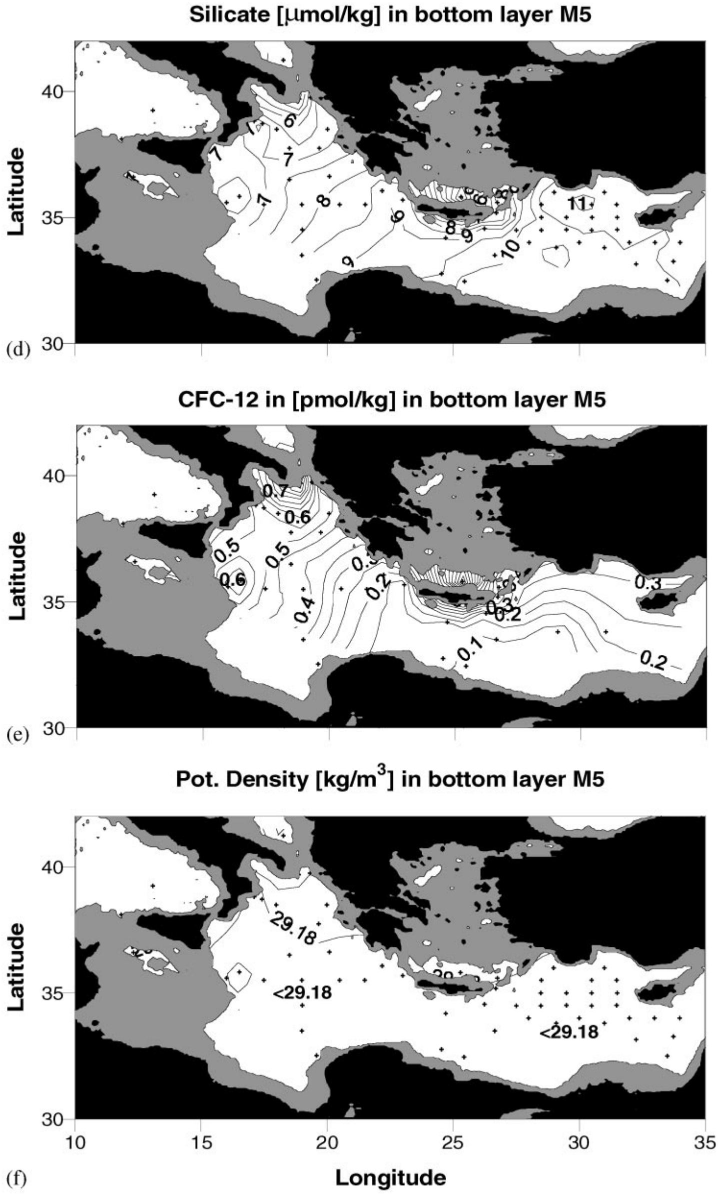


Fig. 15. (*continued*).

saltier intermediate water mass is formed again at rather high densities (29.14 kg/m^3). Both the Rhodes Gyre and the Aegean show high CFC-12 concentrations in the Intermediate Water range indicative of ventilation (Roether et al., 1997b). Lower CFC-12 concentrations are found to the south and the east (Western and Eastern

Table 1
Intermediate water core properties and pressure for the named regions of the Eastern Mediterranean. The water mass definitions used in the calculation are given in the first column (see also text). Pot. temperature in °C, salinity following the practical salinity scale, potential density in kg/m^3 and pressure in dbar. For definition of regions confer Fig. 16

Intermediate layer properties, 1995						
Region	θ	S	σ_θ	S_{max}	θ at S_{max}	P at S_{max}
Southern Adriatic ($S > 38.6$; $\sigma_\theta = 29.16$–29.18)	13.34	38.67	29.17	38.71	13.53	330
Northern Ionian ($S > 38.75$; $\sigma_\theta = 29.05$–29.15)	14.03	38.80	29.12	38.84	14.22	280
Western Ionian ($S > 38.80$)	14.14	38.83	29.12	38.86	14.29	310
Sicily Strait ($S > 38.70$; $\sigma_\theta < 29.15$)	13.78	38.73	29.12	38.79	14.24	240
Eastern Ionian ($S > 38.80$; $\sigma_\theta < 29.16$)	14.15	38.83	29.12	38.92	14.41	210
Kitherian Straits ($S > 38.90$; $\sigma_\theta = 29.10$–29.16)	14.54	38.95	29.13	39.04	14.94	250
Cretan Sea ($S > 39.0$; $\sigma_\theta = 29.10$–29.18)	14.84	39.06	29.14	39.14	15.26	80
W. Cretan Passage ($S > 38.85$; $\sigma_\theta = 29.0$–29.15)	14.70	38.92	29.06	39.02	15.25	230
E. Cretan Passage ($S > 38.90$; $\sigma_\theta = 29.0$–29.15)	14.81	38.95	29.06	39.06	15.31	220
W. Levantine ($S > 39.0$; $\sigma_\theta = 29.0$–29.15)	15.27	39.06	29.04	39.13	15.67	60
Rhodes gyre ($S > 38.85$; $\sigma_\theta = 29.10$–29.16)	14.39	38.93	29.14	39.04	14.96	70
Antalya Basin ($S > 39.0$; $\sigma_\theta = 29.10$–29.16)	14.84	39.04	29.13	39.08	14.95	270
Eastern Levantine ($S > 39.0$; $\sigma_\theta = 28.85$–29.15)	15.43	39.08	29.02	39.25	16.65	160

Table 2
Eastern Mediterranean Deep Water (EMDW) core properties and pressure for the named regions of the Eastern Mediterranean

EMDW properties, 1995						
Region (water mass definition)	θ	S	σ_θ	θ_{min}	S at θ_{min}	P at θ_{min}
Southern Adriatic[a] ($\sigma_\theta > 29.20$)	12.83	38.61	29.23	12.56	38.57	1140
Northern Ionian ($\theta < 13.40$; $S < 38.70$; $\sigma_\theta > 29.18$)	13.35	38.69	2918	13.29	38.68	2290
Western Ionian ($\theta < 13.40$; $S < 38.70$; $\sigma_\theta > 29.18$)	13.26	38.67	29.19	13.22	38.66	4110
Eastern Ionian ($\theta < 13.45$; $S < 38.72$; $\sigma_\theta > 29.18$)	13.35	38.69	29.18	13.26	38.67	3050
Kitherian Straits ($\sigma_\theta = 29.18$–29.20)	13.77	38.81	29.19	13.63	38.75	1230
Cretan Sea (TW) ($\sigma_\theta = 29.18$–29.20)	14.15	38.92	29.19	13.86	38.83	480
W. Cretan Passage ($\theta < 13.65$; $S < 38.75$; $\sigma_\theta > 29.15$)	13.58	38.75	29.18	13.50	38.74	2230
E. Cretan Passage ($\theta < 13.70$; $S < 38.78$; $\sigma_\theta > 29.15$)	13.61	38.75	29.18	13.52	38.73	1740
W. Levantine ($\theta < 13.70$; $S < 38.78$; $\sigma_\theta > 29.15$)	13.58	38.75	29.18	13.49	38.72	1770
Rhodes gyre ($\theta < 13.70$; $S < 38.78$;$\sigma_\theta > 29.16$)	13.59	38.75	29.18	13.45	38.71	1900
Antalya basin ($\theta < 13.70$; $S < 38.76$; $\sigma_\theta > 29.16$)	13.53	38.73	29.18	13.44	38.70	1790
Eastern Levantine ($\theta < 13.70$; $S < 38.74$; $\sigma_\theta > 29.16$)	13.48	38.71	29.17	13.37	38.68	1320

[a] The water mass formed in the Southern Adriatic is called ADW and is the source for newly ventilated EMDW. For units see Table 1. For definition of regions see Fig. 16.

Table 3
Cretan Sea Overflow Water (CSOW) core properties and pressure in the named regions of the Eastern Mediterranean. For units see Table 1. For definition of regions see Fig. 16

CSOW properties, 1995						
Region (water mass definition)	θ	S	σ_θ	$\sigma_{\theta max}$	S at $\sigma_{\theta max}$	P at $\sigma_{\theta max}$
Northern Ionian ($\theta > 13.4$; $S > 38.70$; $\sigma_\theta > 29.18$)	13.49	38.74	29.19	29.20	38.75	2900
Western Ionian	—	—	—	—	—	—
Eastern Ionian ($\theta > 13.5$; $S > 38.73$; $\sigma_\theta > 29.18$)	13.62	38.79	29.20	29.21	38.84	3050
Kitherian Straits ($\sigma_\theta > 29.20$)	13.80	38.85	29.21	29.22	38.85	4500
Cretan Sea ($\sigma_\theta > 29.20$)	14.01	39.04	29.31	29.37	39.08	1870
W. Cretan Passage ($\theta > 13.70$; $S > 38.80$; $\sigma_\theta > 29.18$)	13.75	38.84	29.21	29.22	38.85	3110
E. Cretan Passage ($\theta > 13.70$; $S > 38.80$; $\sigma_\theta > 29.18$)	13.79	38.84	29.21	29.22	38.87	3310
W. Levantine ($\sigma_\theta > 29.20$)	13.80	38.85	29.21	29.22	38.90	1250
Rhodes gyre ($\theta > 13.70$; $S > 38.80$;$\sigma_\theta > 29.18$)	13.75	38.83	29.20	29.22	38.86	2770
Antalya basin ($\sigma_\theta > 29.18$)	13.59	38.76	29.19	29.20	38.83	2570
Eastern Levantine ($\sigma_\theta > 29.18$)	13.56	38.75	29.19	29.20	38.80	2470

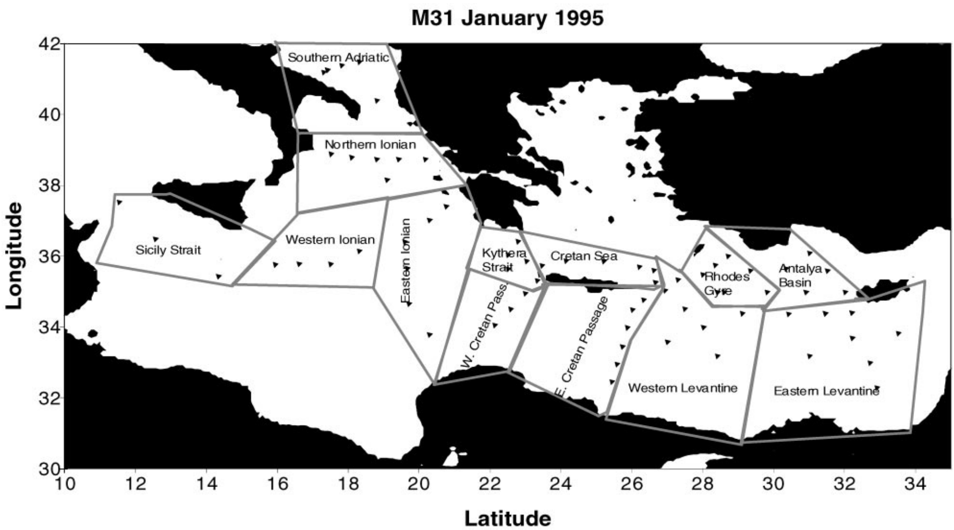


Fig. 16. Geographic subdivision of the Eastern Mediterranean into regions for which average water mass characteristics have been calculated (see Tables 1–3).

Levantine). The trend of increasing LIW densities into the Ionian Basin has already been noted by Wüst (1961) and has been attributed to mixing with adjoining waters, by which the Intermediate Water also loses salt. The densities of $\sim$29.12 kg/m^3 are in agreement with the "classic" definition.

In the southern Adriatic, ADW is formed with average properties of $\theta = 12.83$°C, $S = 38.61$ and $\sigma_\theta = 29.23$ kg/m^3 (Table 2). EMDW found in the Western Ionian is still closest to the values defined by Schlitzer et al. (1991) for the entire Eastern Mediterranean and indicates less contact with the outflowing CSOW. Towards the Cretan Passage and the Western Levantine the salinity increases due to mixing with CSOW. A decrease of salinities in the Antalya Basin and the Eastern Levantine suggest that the influence of CSOW is less dominant in these areas. In the Aegean the chosen density range is representative of the transition between the subsurface salinity maximum and the outflowing CSOW. An analogous transition water type has been defined outside the Aegean in the Antikythera Strait.

The most extreme properties in the deep layer outside the Aegean ($\theta = 13.80°C$, $S = 38.85$ and $\sigma_\theta = 29.21$ kg/m^3) are found around the Cretan Arc (Table 3) and are closest to the source properties of CSOW. The deep layer of the Cretan Sea is even more extreme, but most of these waters are below sill level. From its source CSOW spreads eastward into the Levantine Basin and westward into the Ionian Basin. As noted above, CSOW is more strongly diluted by EMDW in the northern part of the Levantine, where core properties show decreasing salinity and temperature. A similar dilution process is noted towards the west into the Ionian Basin, where properties of CSOW decrease because of mixing with ASOW.

4. Discussion

The observed changes of the T/S structure and the density field in the Eastern Mediterranean have interesting dynamical implications. The larger horizontal density gradients, especially in the deeper layers, must result in higher vertical shear in velocity and probably enhanced mixing. The outflow of dense water from the Aegean demands a compensation further up in the water column, which could lead to enhanced transport in the upper layers and modified advection pathways. Changes in the advection pathways of saline near-surface water masses could further stabilise or destabilise the Eastern Mediterranean thermohaline circulation due to the sensitivity of convection and the density of the end-product to the salinity of the contributing waters.

Two critical regions to examine changes in the advection of water masses are the Aegean and the southern Adriatic. Fig. 17a–d compares vertical profiles of salinity, CFC-12, pot. density and CFC-12 saturation for the South Adriatic Pit from both surveys. It is evident from the CFC-12 profiles (Fig. 17b) that in 1995 "old" water is advected into the Adriatic below the LIW, i.e. at depths between 300 and 600 m. The CFC-12 concentrations in this layer are lower than those in 1987 and can be explained only by advection. The source for these waters is to be found outside the Adriatic in the tracer-minimum layer (cf. Fig. 7b) representing upwelled mid-depth waters. In the past this horizon was influenced by the Aegean-derived CIW (Schlitzer et al., 1991; Roether and Schlitzer, 1991). From CFC and tritium budgets it has been claimed that the deep water formation in the Adriatic involved both LIW and CIW (Roether and Schlitzer, 1991), both with comparably high salinity. Since the Adriatic now apparently receives mid-depth waters in this horizon, which should have lower salinity than previously, the density of the ADW and consequently also of EMDW could be affected. However, a comparison of the 1995 and 1987 salinity profiles does not show

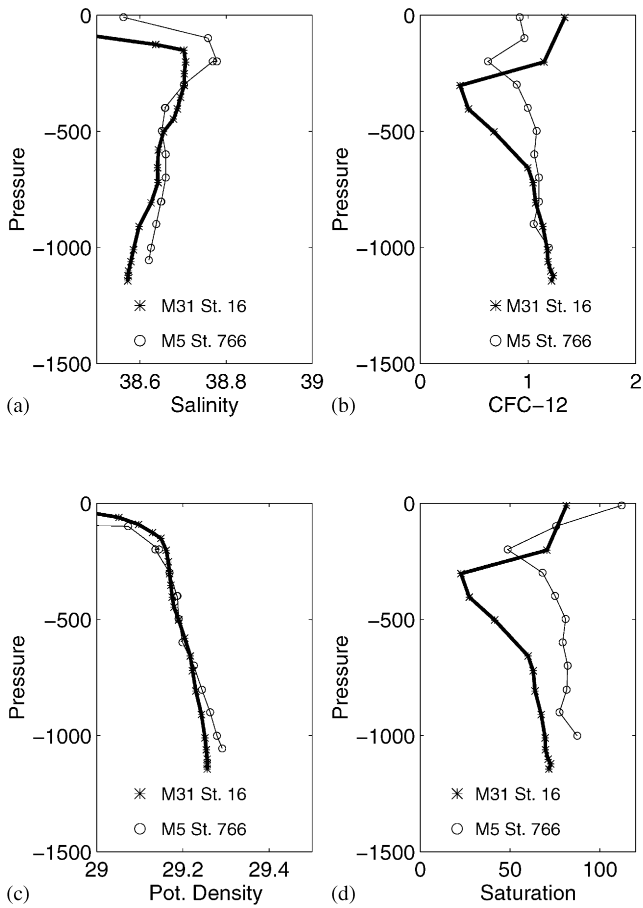


Fig. 17. Vertical profiles of salinity (a), CFC-12 in pmol/kg (b), pot. density in kg/m^3 (c) and CFC-12 saturation in % (d) in the South Adriatic Pit in 1987 (thin line) and 1995 (heavy line). For station location cf. Fig. 1.

advection of a less saline water mass in the CFC-12 minimum range. We ascribe this apparent discrepancy to the high spatial and temporal variability of T/S properties in the Adriatic (Zore-Armada, 1972), which makes individual station-to-station comparisons difficult.

CFC-12 concentrations concur in the deep water ($\sim$1000 m) (Fig. 17b), but due to increased atmospheric levels the CFC-12 saturation drops from 87% in 1987 to 73% in 1995 (Fig. 17d). A nearby profile (St. 17) had indicated that local convection was reaching to at least 400 m, and extremely low saturation values in the upper 400 m (cf. Fig. 7) could be explained only through entrainment of water from the CFC-12 minimum layer. One might therefore speculate that the reason for the reduced CFC concentrations in the South Adriatic Pit are already the result of the entrainment of the “old” water from the CFC minimum layer in the convection processes of previous

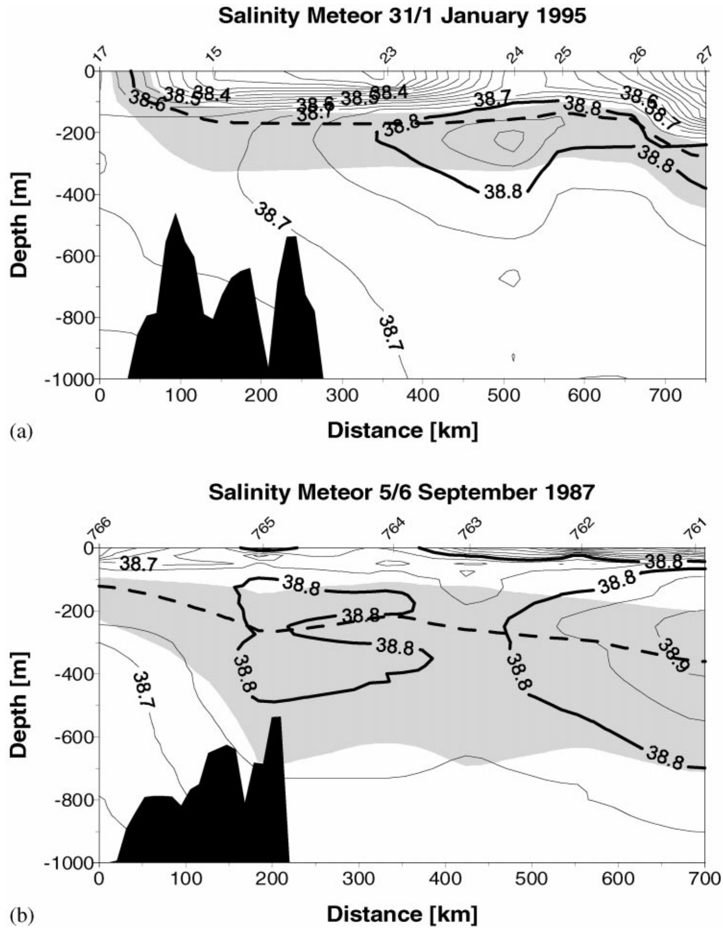


Fig. 18. Salinity section along the Greek coast into the Adriatic for 1995 (a) and 1987 (b). The 1995 section is in part identical with the full depth section in Fig. 7a. For section location cf. Figs. 1 and 7. Superimposed on the salinity sections are the distributions of a selected range of isopycnals. The area marked in grey represents the isopycnal range from 28.95 to 29.15. The heavy dashed lines marks the isopycnal 29.10.

years. But other possibilities for a lower concentration in the bottom layer are also conceivable, such as a reduction in deep water formation or variability of the under-saturation in the surface layer during formation. The deepest layers show a less saline and less dense variety of ADW in 1995 compared to 1987 (Fig. 17a and c), consistent with entrainment of "old" mid-depth water into the deep water.

A better view of a changed advection of salt into the Adriatic by LIW is provided by Fig. 18. The section follows the advection pathway of LIW along the Greek coast into the Adriatic (cf. Fig. 7). The 1987 salinity distribution (Fig. 18b) shows a strong presence of LIW with salinities in excess of 38.8 at the entrance of the Strait. Further upstream maximum salinities of 38.9 are identified. The 1995 section shows a much less well defined salinity maximum (Fig. 18a), and much lower salinities are found at the entrance of the strait. While in 1987 the maximum salinity was found along the 29.10 isopycnal, it has been shifted to higher densities in 1995. This could be due to the changes in the formation areas documented in Table 1. Also interesting is the overall reduction of the vertical extent of the salinity maximum layer, which has been reduced from ~500 m in 1987 to ~300 m to 1995. Fig. 18 supports a notion that the reduction in the amount of salt advected in the LIW and CIW range and the additional inflow of low-salinity mid-depth waters has led to decreased salinities observed in the South Adriatic Pit in 1995 (Fig. 17a).

A time record of changes in the South Adriatic Pit and the outflow characteristics in the Strait of Otranto was constructed from various Italian cruises and the two METEOR cruises. Fig. 19a shows T/S properties of ADW in Strait of Otranto and the associated potential density in Fig. 19b. Fig. 19a show distinctly varying characteristics, such as were noted previously (Zore-Amarda, 1972; Artegiani et al. 1993), which renders the detection of possible changes in the overflow characteristics difficult. However, the simultaneous decrease of salinity and temperature since 1991 is in agreement with the idea of a reduced salt import into the Adriatic, in which case lower temperatures are needed to reach the appropriate density to start convection. It is noteworthy that the average potential density of the overflow waters has remained nearly constant over the period in question, but the data could be biased by the applied averaging procedure, which included only water with densities in excess of 29.18, and additionally one would expect a time lag between changes in the deep water properties in the South Adriatic Pit and the bottom layer in the Strait of Otranto. This holds because it is not the densest water that flows out through the Strait but rather water at sill depth level (~800 m). In fact, the few available measurements in the South Adriatic Pit below the Otranto Strait sill depth show that the density of the bottom layer has been decreasing since 1992 (Fig. 19b).

The compensation of the outflow of CSOW from the Aegean through enhanced inflow further up in the water column once again involves the "old" mid-depth waters. The inflow of these waters into the Aegean at depth around 300 m produces a salinity minimum layer (Fig. 20a). It is associated with a region of stronger vertical density gradients. Both low CFC-12 and high silicate content (Fig. 20b and c) show that these waters are "old". In the deeper layers CFC-12 concentrations are higher in 1995 than in 1987 (Fig. 20b), but the saturation level (Fig. 20d) remains similar (88%), indicating a convective activity of comparable strength. It has been argued that a stronger density gradient near 300 m in the Aegean might impede the CSOW production because it could hinder deep convection (Theocharis et al., 1996), but the high CFC-12 saturation levels observed in 1995 contradict this, at least for the period up to 1995.

While the near-bottom salinity in the Aegean increased to 39.076 in 1995 (Fig. 20a), one notes that convective mixing of the 1987 profile over the entire water column would yield a salinity of only 38.941. An examination of winter profiles in the Aegean dating before 1987 from the MED2 data set give similar, or even slightly lower, depth-averaged salinities. This proves a net salt addition to the Aegean Sea prior to 1995, either through local changes in the evaporation/precipitation budget or by

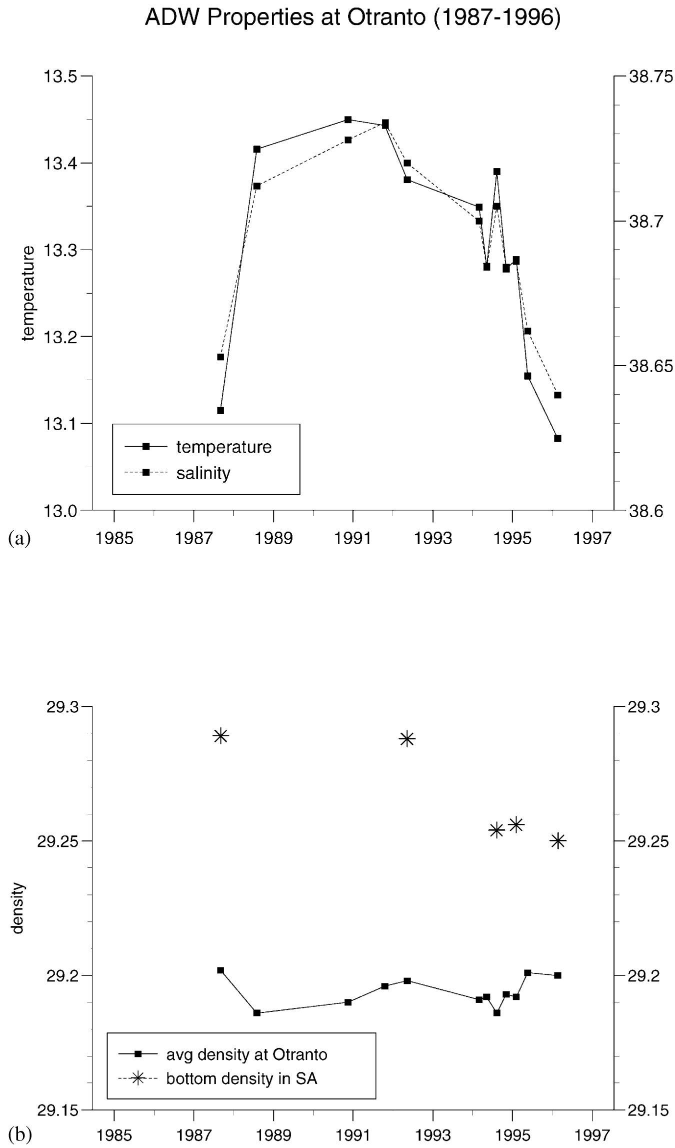


Fig. 19. Time series of ADW properties in the Strait of Otranto. Average temperature values (solid line) and salinities (dashed line) have been calculated for the part of the water column with densities in excess of 29.18 (a). The mean density of the ADW (b) has been calculated for the part of the water column with densities in excess of 29.18. Averages of bottom density in the South Adriatic Pit have been calculated for $\sigma_\theta > 29.20$.

advection of more saline waters. Theocharis et al. (1996) report an increase of the mean salinity of the deep Aegean of about 0.2 between 1987 and 1993 and a yearly average decrease of precipitation over the southern Aegean of about 20 cm/year for

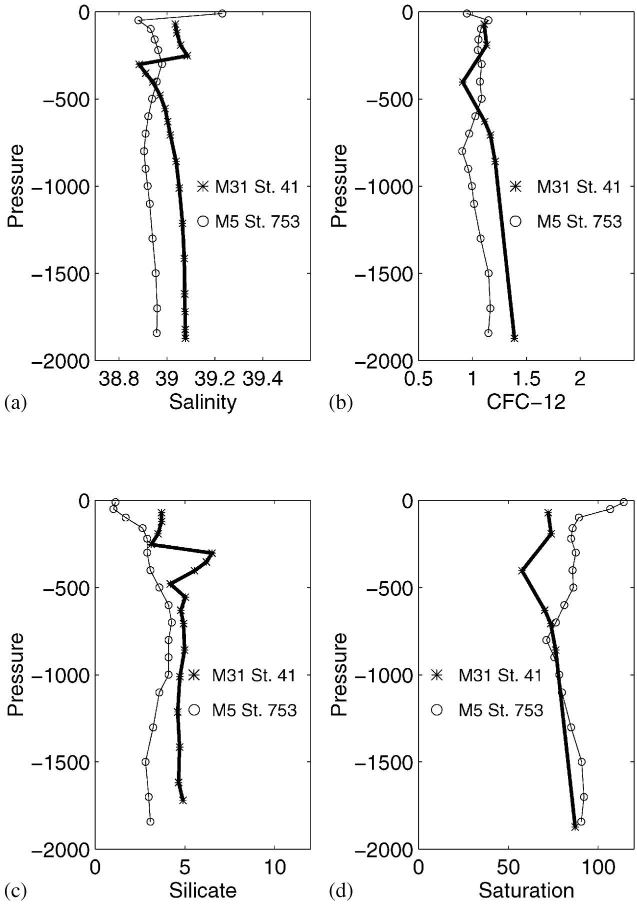


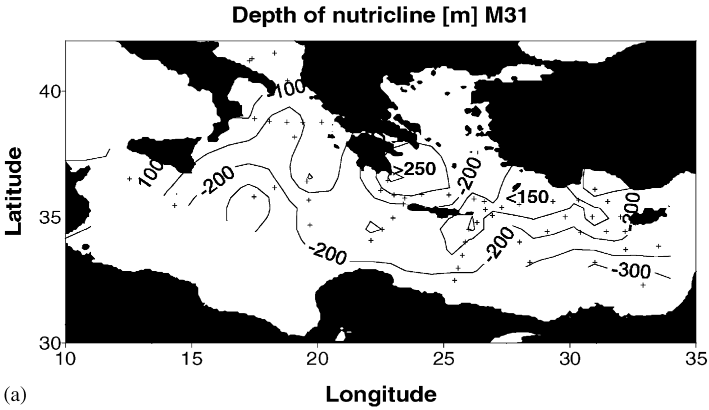
Fig. 20. Vertical profiles of salinity (a), CFC-12 in pmol/kg (b), silicate in μmol/kg (c) and CFC-12 saturation in % (d) in the Aegean in 1987 (thin line) and 1995 (heavy line). For station location cf. Fig. 1.

the period from 1988 to 1993. This change corresponds to as much as a 33% decrease of precipitation and a 25% increase of the long-term E-P budget (Bethoux and Gentili, 1994). Assuming that the salinity increase associated with a decrease of precipitation of this order of magnitude is directly transferred to the deep layer of the Aegean, a mean salinity increase of not more than 0.14 would occur over the period 1988 to 1995 for the volume of water below 600 m. It appears at least possible that the reduction in precipitation triggered the event, but additional sources of salt are required.

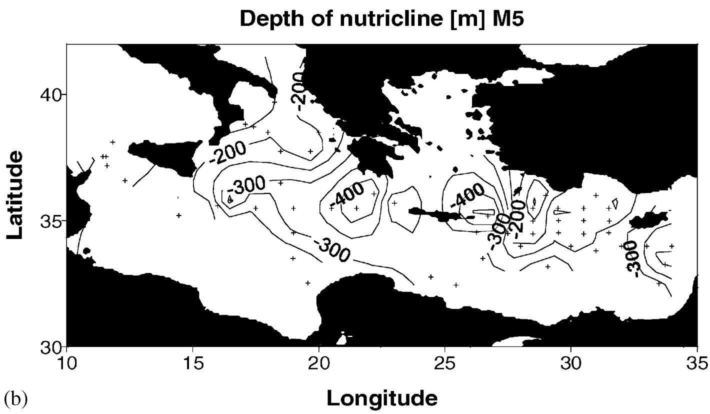
Another important question involves the salt balance of the entire Eastern Mediterranean. Again the source for the extra salt that has been introduced into the deep layers by CSOW could be external, through changes in the fresh-water budget, or internal, by way of vertical redistribution of salt. As mentioned above, part of the observed salt increase in local areas like the Aegean could be accounted for by changes in the fresh water budget. But the net amount of salt added to the Aegean by a yearly average increase of E-P of 20 cm/year for 7 years is equivalent to only 9% of the total salt increase below 1500 m. Roether et al. (1996) have calculated that the increase in evaporation necessary to explain the salt increase below 1500 m amounts to 140 cm total over the entire surface of the Eastern Mediterranean (20 cm/yr times 7 years). A change in evaporation of a magnitude of 20 cm/yr over the entire Eastern Mediterranean is difficult to envisage, and a preliminary assessment of meteorological data sets has shown little evidence of this, although localised enhancement of evaporation was noted in the Levantine Basin and Aegean (Nadia Pinardi, personal communication). As has been discussed in the previous paragraphs, a vertical redistribution of salt could be noted in most parts of the Eastern Mediterranean. The redistribution couples the salt increase in the bottom layer to a salt decrease above 1400 m (cf. Figs. 4, 11 and 12). We believe that the salt decrease in the upper water column results from a reduced presence of CIW, since the Aegean instead of feeding into the CIW, is now discharging salty waters directly to the bottom. Highest salt deficits are therefore found along the main spreading pathways of CIW (Roether et al., 1997a) south of Crete and in the eastern Ionian. A preliminary analysis shows however that the amount of salt transferred from the 300–1400 m layer amounts only to about a third of that added to the deeper waters. A decaying export of salt into the Western Mediterranean might also be significant. In the Strait of Sicily a decrease in the salinity of the water leaving the Eastern Mediterranean below the LIW can be observed (not shown), but the magnitude is no more than secondary. To close the salt balance more information about the large-scale trend of E-P and a detailed analysis of the global salt budget in the seasonally varying upper 300 m, including estimates of the transport through the Strait of Sicily, is necessary.

Besides the dynamic aspects, the modifications of the upper layers are also of interest because of possible implications for the ecosystem. The uplifting of “older” mid-depth waters led to elevated nutrient concentrations in the upper water column, and the signature of this uplifting was still detectable at the lower base of the LIW (cf. Figs. 11a–f and 12a–f). Higher up, possible changes can be masked by seasonal variations (Hecht et al., 1988) and enhanced variability. But coherent changes in the T/S properties could be found as shallow as 200 m and thus would include shallower LIW layers.

The elevation of nutrient levels in the near-surface waters by the upwelling of mid-depth waters might induce enhanced biological activity in the Eastern Mediterranean provided that they reach into the euphotic zone. Fig. 21 shows the depth of the nutricline in 1987 and 1995, i.e. the centre of the gradient region between the nutrient-deprived surface waters and nutrient enriched deeper waters below, being defined by a nitrate concentration of 3 μmol/kg. The western and southernmost parts of the Ionian show only small changes in the nutricline depth between the two surveys, and the nutricline in 1995 is still found below 200 dbar, i.e. it hardly reaches into the photic layer. In the northern and eastern part of the Ionian, however, nutricline depths of only 100–150 m, possibly penetrating into the euphotic layer, are found (Fig. 21a), and these are distinctly shallower than in 1987 (Fig. 21b). In 1987 the nutricline



(a)



(b)

Fig. 21. Nutricline depth in 1995 (a) and 1987 (b). For definition of the nutricline see text.

attained depths as great as ~400 m in the eastern Ionian close to the Peleponnesus due to a very strong Pelops anticyclone (Theocharis et al., 1993, Malanotte-Rizzoli et al., 1996b). In the 1987 survey the nutricline had also tended to be shallower in the Levantine basin than in the Ionian basin (Fig. 21b), so that by the marked rising in the eastern Ionian the difference has been levelled out to a certain degree. Very shallow nutricline depths are found in 1995 (Fig. 21a) in the eastern part of the Levantine, i.e. shallower than 200 m, compared to 250–350 dbar in 1987. On the basin scale, in summary, the nutricline has been elevated from about 300 m depth to 200 m or less. Although the nutricline in 1995 is found in the depth range that is affected by seasonal changes, the observed rising is in contradiction to the tendency for the nutricline to be deeper in winter than in summer, and is therefore probably associated with the upwelling.

5. Summary and conclusions

Although the changes since 1987 are most impressive in the deep layers of the Eastern Mediterranean, effects of deep water production in the Aegean are felt through the entire water column. One of the most prominent features of the Eastern Mediterranean, i.e. the homogeneity of its deep water body, has been nearly obliterated in only a few years, and a far more baroclinic deep water has emerged. EMDW, as it was known in the past, does not exist any longer, and the two competing deep water sources have altered considerable portions of the water body. It has to be expected that the transient behaviour of the Eastern Mediterranean will continue, and further changes in T/S distributions will develop.

Deep water production in the Aegean has occurred at the expense of CIW, which in the past ventilated the water column below the LIW and supplied additional salt for the ADW formation in the Southern Adriatic. The reduction of CIW has raised the vertical density gradient at the lower base of LIW and brought mid-depth waters in direct contact with LIW. This has effected a dilution of LIW through upwelling or mixing up to 30% (Roether et al., 1997b), causing lower salinities, lower CFC concentrations and higher nutrient levels. A reduced advection of salt into the Adriatic can be observed (cf. Figs. 11 and 18) in the LIW layer, and below the LIW "old" mid-depth water which is even less saline is now advected into the Adriatic. Entrainment of these waters into convection events in the southern Adriatic is apparent through reduced CFC-12 saturation levels and can be linked to lower salinities and densities in the South Adriatic Pit (Figs. 17 and 19). The outflowing water in the Strait of Otranto does not yet show significant changes in density, but its salinity and temperature have been declining since 1992 (Fig. 19).

The outflow of CSOW from the Aegean at a rate of 1.0 Sv calls for compensatory inflow into the Aegean. Due to the changed vertical structure outside of the Aegean, the inflow includes "old" mid-depth waters of low salinity which produces a stronger halocline, and thus a stronger vertical density gradient than previously near 300 m depth (cf. Fig. 20). The stronger density gradient might inhibit local convection and could thus provide a negative-feedback mechanism for the production of CSOW. However, the 1995 CFC data in the deepest layers of the Aegean suggest that the deep waters up to 1995 were rather recently ventilated.

A local enhancement of salinity in the Aegean caused by a pronounced decrease in precipitation could have initiated the production of CSOW. But even for the restricted region of the Aegean, the magnitude of the salt increase is too large to be accounted for solely by changes in the evaporation/precipitation budget. For the Eastern Mediterranean as a whole it appears all the more unlikely that the net addition of salt since 1987 to the layers below 1500 m depth could have been supplied totally at the surface, because the required change in the precipitation/evaporation budget (Roether et al., 1996a) is far too large. A vertical redistribution of salt, coupling the salt increase in the bottom layer to a salt decrease above, indicates that internal changes play a role also (Fig. 4). To close the salt budget for the Eastern Mediterranean, a careful analysis of the forcing fields and the salt content of the seasonally changing surface layers is required.

The changes in the vertical distribution of water masses are associated with a significant upward nutrient transport. The data show that on the basin-scale the nutricline rose by about 100 m and is now found within the euphotic zone for large parts of the Eastern Mediterranean. The rise in the nutricline depths (cf. Fig. 21) is most pronounced in the Eastern Ionian Sea. It will be interesting to learn from future work whether or not the enhancement in nutrient levels will result in larger biological productivity.

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