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Chemical oceanography in the Cretan Sea: Changes associated to the transient

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Abstract

The intensive research since 1985 in the framework of national and international programmes revealed important modifications in oxygen and nutrients distribution in the Cretan Sea. The significant increase of density and of formation rates of the Cretan Dense Water (CDW) during the last decade is basically responsible for the drastic change of the thermohaline circulation and the installation of a new hydrological regime in the Eastern Mediterranean. In the Cretan Sea, the most important effect of the new regime, is the installation of a well-defined "minimum salinity, temperature, oxygen and maximum nutrient" intermediate layer formed by the intrusion of the Transitional Mediterranean Water (TMW) compensating the massive CDW outflow.

The nutrient enrichment of the intermediate layers of the Cretan Sea, due to the intrusion of the "nutrient rich-oxygen poor" TMW, was observed firstly in 1991 and became very important during 1994-95. During 1994-95 the TMW occupies the intermediate layers of the entire Cretan Sea and the concentrations of nutrients in this layer are often two times higher than in the past. Recently, in 1997-98 the chemical characteristics of TMW are less pronounced probably related to the weaker CDW outflow.

Keywords: Dissolved oxygen; Nutrients; South Aegean Sea; Cretan Dense Water; Transitional Mediterranean Water.

Introduction

The south Aegean (Cretan) Sea occupies the southern and larger basin of the Aegean Sea. The Cretan Sea communicates with the adjacent deep basins of the SE Ionian and NW Levantine Seas through six topographically controlled passages which constitute the so-called Straits of the Cretan Arc (Fig. 1). More specifically, the Cretan sea exchanges waters with the SE Ionian Sea through the Straits of Elafonissos (sill depth: 200m, width: 11 km), Kythira (sill depth: 160m, width: 33 km) and Antikythira (sill depth: 700m, width: 31 km) and with the NW Levantine through the Straits of Rhodes (sill depth: 350m, width: 17 km), Karpathos (sill depth: 850m, width: 43 km) and Kassos (sill depth: 1000m, width: 67 km).

The influence of the straits of the Cretan Arc on the exchanges of water and mass (diluted, suspended or near-bed) between the Aegean Sea and the adjacent open sea regions of the Eastern Mediterranean Basin

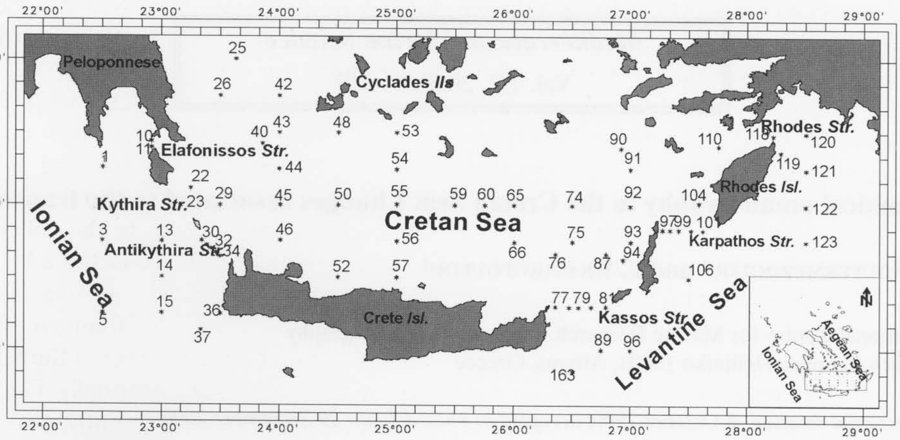

Fig. 1: Grid of the chemical stations in the southern Aegean Sea and the adjacent SE Ionian and NW Levantine regions.

(Levantine and Ionian seas) on the one hand and the intensive convective mixing of the water column on the other hand, make the Cretan Sea the poorer in nutrients and the richer in oxygen among the principal basins of the Mediterranean Sea. The concentrations of nutrients in the Aegean Sea are twelve times lower than in Atlantic Ocean, eight times lower than in the Alboran Sea and three times lower than in the Ionian Sea (Mc GILL, 1965). The recent observations confirm the general depletion of nutrients compared with other parts of the world ocean (SOUVERMEZOGLOU, 1989; SALIHOGLOU *et al.,* 1990; KROM *et al.*, 1991).

The Cretan Sea plays an important role in the dynamics of the Eastern Mediterranean circulation and is considered as heat, salt, and dissolved oxygen reservoir, as high temperature (>14 °C), salinity (>38.9 psu) and dissolved oxygen concentrations (>4.9 ml/l) are detected in its intermediate and deep layers (THEOCHARIS *et al.,* 1993; SOUVERMEZOGLOU, 1989). The deep layers of the Cretan Sea are occupied by the Cretan Dense Water (CDW); with maximum $\sigma\theta$=29.2 near the bottom, during the period 1986-1987. The significant increase of density and of formation rates of the CDW during the last decade are basically responsible for the drastic change of the thermohaline circulation and the installation of a new hydrological regime in the Eastern Mediterranean.

The first period of anomaly (1987-1992) is salinity driven (increase by 0.1 psu) and as a consequence the 29.2 isopycnal is raised up to 400m in 1991 and 30m in 1992. Then, the whole Cretan basin is filled with young and well oxygenated water (DO~5.0 ml/l) with σ_θ that reach 29.26 (THEOCHARIS *et al.,* 1996, 1999; SOUVERMEZOGLOU *et al.,* 1996). A massive outflow of this water towards the Levantine and Ionian Seas, mainly through the three deeper straits of the Cretan Arc (Antikythira, Kassos and Karpathos), affects the structure and the characteristics of the water column in large areas outside the Cretan Sea (THEOCHARIS *et al.,* 1999; SOUVERMEZOGLOU & KRASAKOPOULOU, 1998).

During 1992, large quantities of the outflowing CDW lie beside the Eastern Mediterranean Deep Water of Adriatic origin creating important gradients in the deep layer of the Eastern Mediterranean Sea. Patches of "oxygen rich-nutrient poor" CDW with lateral scale of 100 to 250 kilometres are detected to the south of Crete and eastward of the eastern straits of the Cretan Arc (SOUVERMEZOGLOU & KRASAKOPOULOU, 1999a; Fig. 9).

The second period (1992-1995) is driven by the decrease of temperature (0.3-0.4 °C cooling), while the salinity remains almost in the same high values of the previous period. This results to an increase of the density of the Cretan waters that reaches the extreme value of 29.4 (THEOCHARIS *et al.*, 1999). By the year of 1995, the Cretan Sea dense waters have filled the deepest parts of the Ionian and Levantine Seas changing dramatically the properties of the Eastern Mediterranean deep waters (ROETHER *et al.*, 1996). Furthermore the oxygen rich-nutrient poor patches disappear and the water column below 300 m is homogenised and the oxygen concentration varied between 4.3-4.5 ml/l, whereas the nitrate values are in the range of 3.5-5.0 μmol/l (SOUVERMEZOGLOU & KRASAKOPOULOU, 1999a; Fig. 11). The mean value of oxygen concentration increases from 1987 to 1995 by 0.3 ml/l (13 μmol/l) and that of nitrate concentration decreases by about 1 μmol/l. The old EMDW of Adriatic origin is lifted up several hundreds of meters enriching with nutrients the intermediate depths of the basin (SOUVERMEZOGLOU & KRASAKOPOULOU, 1999a ; Fig. 5 and Fig. 11).

In the Cretan Sea, the most important effect of the new regime, is the installation of a well-defined "minimum salinity, temperature, oxygen and maximum nutrient" intermediate layer formed by the intrusion of the Transitional Mediterranean Water (TMW) compensating the massive CDW outflow (SOUVERMEZOGLOU & KRASAKOPOULOU, 1999b). In the present paper, the different phases of the intermediate layer installation and the modification of the chemical conditions of the South Aegean Sea, during the decade 1987-1997, will be followed.

Methodology

Area of study-Field observations on board of the R/V Aegaio in the Cretan Sea and the straits of the Cretan Arc were performed several times since March 1986 in the framework of the multinational research programme for the exploration of the Eastern Mediterranean, POEM-I (1985-1990), POEM-II-EPICS (1991-continued). During 1994-1995, in the frame of MTP-PELAGOS project, seasonal multidisciplinary oceanographic data were also collected in the South Aegean Sea and the adjacent NW Levantine and SE Ionian Seas. Recently in 1997-1998 in the frame of MTP-MATER project seven stations in the South Aegean Sea were visited seasonally. For this work the data of representative cruises (September-October 1987, November 1991, April 1992, March 1994, March 1997) were evaluated and are discussed below. The location of the stations is shown in Figure 1.

Sampling and analysis-Sea water samples were collected down to 2500 m depth with a General Oceanics rosette equipped with 12 Niskin bottles of 8 l mounted on a CTD probe. For stations deeper than 1500 m, two rosette casts were performed, in order to obtain a denser sampling.

For the dissolved oxygen determination, samples were first taken from the Niskin bottles with the recommended precautions to prevent any biological activity and gas exchanges with the atmosphere (STRICKLAND & PARSONS, 1977). The samples were analysed immediately after collection with the Winkler method as modified by CARPENTER (1965a; 1965b); the precision of the method is estimated at 0.05 ml O_2/l.

Samples for the determination of nutrients were collected in 100 mL polyethylene bottles and kept deep-frozen (-20 °C) until their analysis in the laboratory on a Technicon CSM6 autoanalyser. Phosphate was measured on board of R/V Aegaio by a Perkin Elmer Lambda 2S UV/VIS Spectrometer, in order to improve reliability. The methods described by MURPHY & RILEY (1962) for phosphate, MULLIN & RILEY (1955) for silicate, BENDSCHNEIDER & ROBINSON (1952) and STRICKLAND &

PARSONS (1977) for nitrite and nitrate were employed. The precision is estimated at ±0.02 μmol/l for phosphate and ±0.1 μmol/l for nitrate and silicate.

Results and Discussion

The general remarks for the distribution of oxygen and nutrients in the Cretan Sea, can be summarised to the relative decrease of nutrients and to the corresponding rise of oxygen concentrations in the intermediate and deep waters of this sea with regard to the Eastern Mediterranean Sea for all the periods (summer-winter) of observation (SOUVERMEZOGLOU, 1989). One of the principal reasons is the limited exchange of water masses with the adjacent Ionian and Levantine seas, due to the existence of the straits and the intensive mixing of the water column (SOUVERMEZOGLOU, 1988a). The exchanges through the straits are highly variable and strongly affected by the topography and the variability of the main circulation features occuring in the viscinity of the straits.

Favourable weather and hydrographic conditions, for the development of the winter convective mixing, appear very often and lead to a very important oxygenation of the intermediate and the deep layers of the Cretan Sea. Recent data collected in the Cretan Sea revealed intermediate (down to 250 m) water formation in March 1986 (GEORGOPOULOS *et al.,* 1989) and deep convective mixing that caused homogenisation of the water column down to 700 m in March 1987 (ZODIATIS, 1991). The intensive production of very dense CDW after 1987, generated drastic changes both in the Cretan Sea and in large areas in the neighbouring Ionian and Levantine seas.

1987

During the cruises performed in spring and fall 1987, nutrient rich-oxygen poor water from the Ionian Sea, supplies the intermediate layers of the Cretan Sea through the western straits of the Cretan Arc (SOUVERMEZOGLOU *et al.,* 1988b). The supply mainly occurs through the Antikythira Strait and in a lesser degree through the Kythira Strait. The inflowing water originates from depths 500-1000 metres in the Ionian Sea. In September-October 1987, the maximum nitrate, phosphate, silicate and the minimum oxygen concentrations of the waters that reach the Antikythira sill and occasionally intrude in the Cretan Sea at about 500m are 3.5 μmol/l, 0.17 μmol/l, 4.6 μmol/l and 4.8 ml/l respectively (Fig. 2). The deeper than 500m layer of the Cretan Sea is occupied by the oxygen rich-nutrient poor CDW, which seems to outflow towards the Ionian Sea through the Antikythira Strait (Fig. 2).

During the fall 1987 cruise important inflow from the NW Levantine Sea, in the surface layer (until about 500 m) of the Cretan Sea, has been observed through Karpathos and Rhodes straits (SOUVERMEZOGLOU *et al.*, 1993). The inflow in the deeper layers of the basin is practically nonexistent and that of the surface layer can not supply important quantities of nutrients in the intermediate layer of the Cretan Sea.

The distribution of oxygen and nitrate along a transect through the Kassos strait in fall 1987 (Fig. 3) shows that between the Cretan and the NW Levantine Seas considerable differences exist on the concentration levels of the chemical parameters specially below 1000m. In the deep layer of the Cretan Sea the oxygen concentration is higher than 5.2 ml/l and the corresponding nitrate concentration lower than 1.6 μmol/l; considerably lower oxygen concentrations (O_2~4.1 ml/l) and higher nitrate concentration (NO_3~5.2 μmol/l) are found in the NW Levantine Sea.

During this period, the intermittent supply of nutrients from the Ionian and Levantine Seas influences only the area in the vicinity of the straits while the interme-

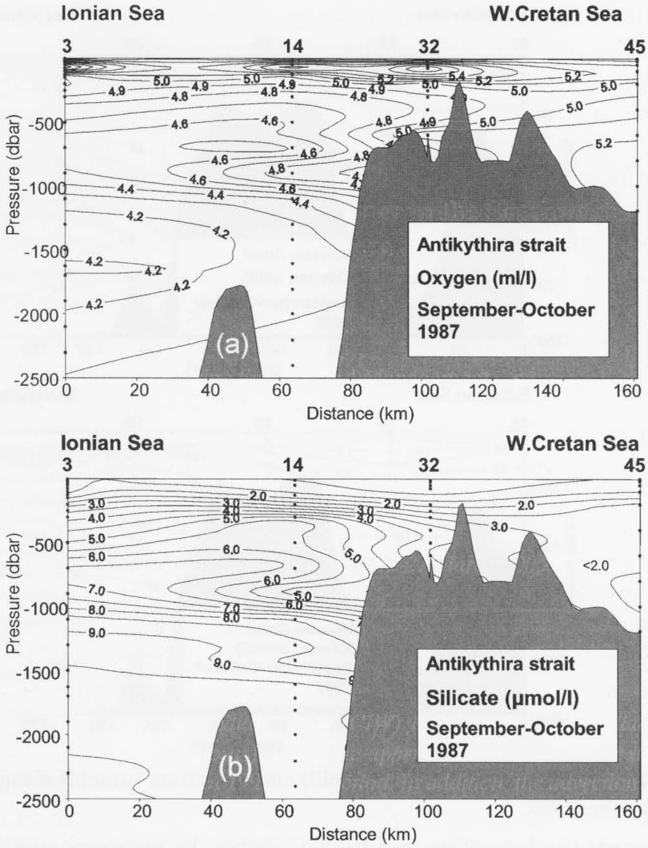

Fig. 2: Vertical distribution of (a) oxygen (ml/l) and (b) silicate (μmol/l) along the Antikythira Strait in September-October 1987.

diate layer in the Cretan Sea remains poor in nutrients (Figs 2 & 3). The concentration of nutrients in the intermediate layer of the Cretan Sea during fall 1987 does not exceed 2.5, 0.10 and 3.0 μmol/l for the nitrate, phosphate and silicate respectively, while the oxygen concentration is higher than 5.0 ml/l.

In the same period the Adriatic Sea continues to be the main contributor to the Eastern Mediterranean Deep Water (EMDW). The contribution of the Aegean Sea in the intermediate and deep waters of the Eastern Mediterranean is secondary, rather sporadic and is restricted in the vicinity of the Cretan Arc regions losing rather quickly its characteristics due to the mixing. It is obvious that this intermittent outflow towards the Ionian Sea of the CDW can not affect the concentrations in the deep layers of the Eastern Mediterranean. The deep layer below 1000 metres, is rather homogeneous during 1987, with oxygen about 4.2 ml/l and nitrate higher than 5.0 μmol/l (SOUVERMEZOGLOU & KRASAKOPOULOU, 1999a; Fig. 5). We must mention that during the fall cruise only a weak CDW outflow was observed through the eastern straits of the Cretan Arc.

1991

In the years following 1987, the massive formation in the Cretan Sea of very dense Cretan Dense Water (CDW), resulted to a drastic change in the circulation through the straits of the Cretan Arc. This very dense and well oxygenated water of Aegean origin

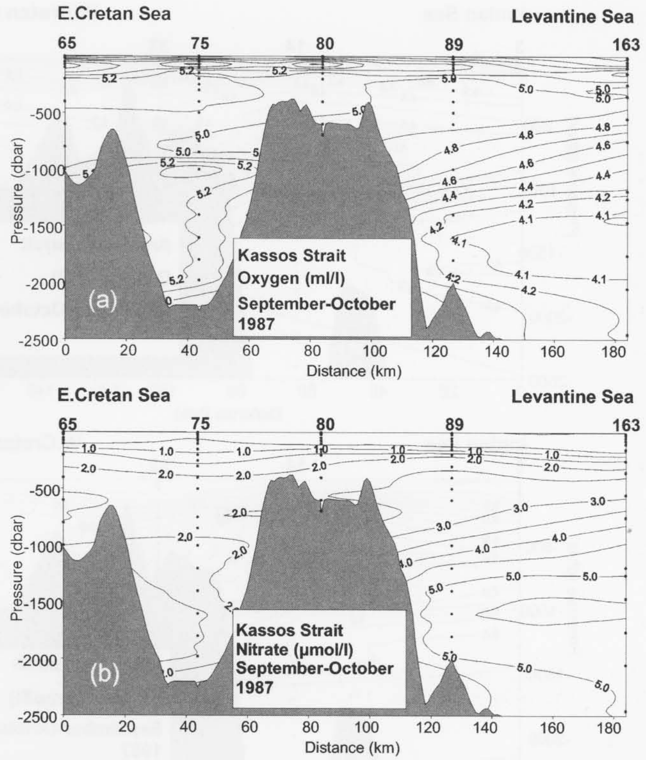

Fig. 3: Vertical distribution of (a) oxygen (ml/l) and (b) nitrate (μmol/l) along the Kassos Strait in September-October 1987.

outflows towards the Levantine and Ionian seas mainly through the three deeper straits of the Cretan Arc, namely; Antikythira, Kassos and Karpathos. It is added to the deep and bottom sections of the Eastern Mediterranean and displaces upwards the waters of Adriatic origin with two important consequences on the distribution of oxygen and nutrients :

a) the important increase of oxygen and decrease of nutrient content in the deep and bottom layers of the Eastern Mediterranean, and

b) the intrusion of the "nutrient rich-oxygen poor" Transitional Mediterranean Water mass (TMW) in the intermediate layers of the Cretan Sea.

Important inflow of TMW from the Eastern Straits of the Cretan Arc is observed in late autumn 1991 compensating the CDW outflow. The inflowing water is richer in nutrients and poorer in oxygen than the inflowing water in 1987 because it originates from greater depths (700-1800 m) in the Ionian and the Levantine seas. During this cruise the new "nutrient rich-oxygen poor" layer between the saline intermediate and the CDW is detected in the Cretan Sea. The characteristics of this layer is more pronounced in the Eastern Cretan Sea and the concentration of silicate and of oxygen in the core of this layer is higher than 3.0 μmol/l and lower than 4.8 ml/l respectively (Fig. 4). The deep layers are well oxygenated and the concentrations are similar to those of 1987 (Figs 2, 3 and 4).

1992

The majority of the stations visited during the March-April 1992 cruise are situated at the eastern part of the Cretan Sea. The

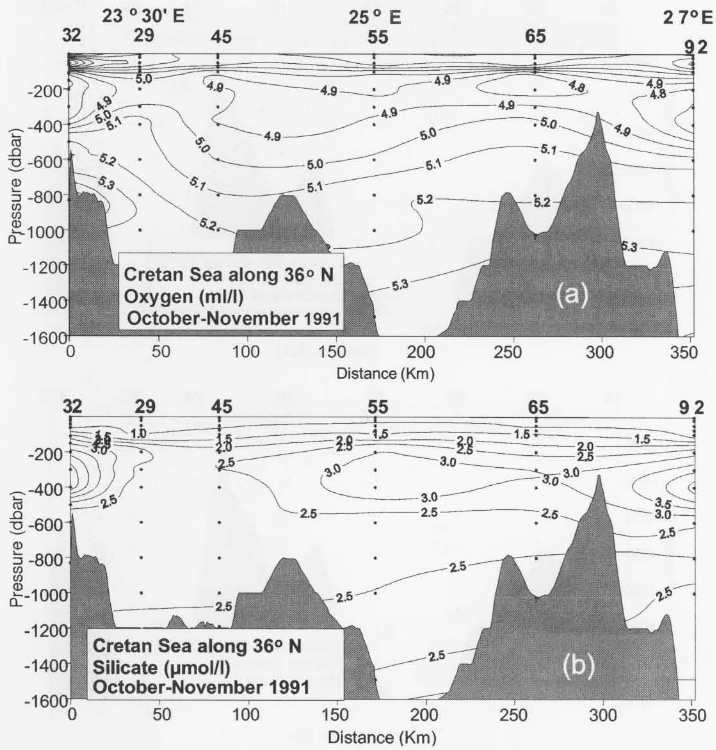

Fig. 4: Vertical distribution of (a) oxygen (ml/l) and (b) silicate (μmol/l) along the 36° N latitude in the Cretan Sea in October-November 1991.

"nutrient rich-oxygen poor" intermediate layer disappears in the central Cretan Sea and the mid-depth layers are very well oxygenated and poor in nitrate. During this period, the concentration of nitrate in the layer between 200 and 600 metres, is lower than 2.5 μmol/l and that of oxygen higher than 5.1 ml/l (Fig. 5). The break down of the TMW layer in the Cretan Sea give evidence of the intense convective mixing occurred during winter 1992 as reported by THEOCHARIS *et al.,* (1996). Contrary important signal of TMW is found shallower (at about 100 m) at the western part of the section presented in Figure 5 (station 50). The presence of TMW in the western Cretan Sea proves the absence of vertical convective mixing in the surface layer and lead us to suppose that the newly formed deep water in the Mirtoan Sea comes from elsewhere (e.g. sinking of dense water formed by shelf process in the Cyclades Plateau).

Near the eastern straits of the Cretan Arc only traces of TMW are found in the Cretan Sea due to the convective mixing between the intermediate and deep layer. The mean concentrations of oxygen (5.2 ml/l) and of nitrates (2.0 μmol/l) in the deep layer are very similar to those of 1991 (Figs 4 & 5).

The distribution of oxygen and nutrients along the Kassos strait during this cruise, give evidence of the intrusion of TMW in the intermediate layer of the Cretan Sea and of the outflow of CDW towards the Levantine Sea, propagating to the south of Crete, in the deep layer (SOUVERMEZOGLOU & KRASAKOPOULOU, 1998; Fig. 6). The important increase of oxygen and decrease of nitrate below 600 meters in the Eastern Mediterranean, due to the CDW outflow, can be seen in the comparative distribution

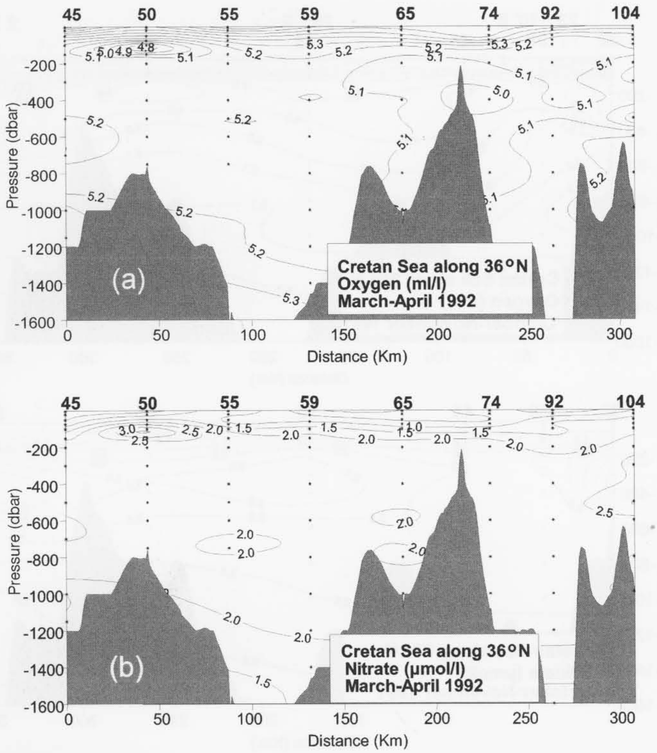

Fig. 5: Vertical distribution of (a) oxygen (ml/l) and (b) nitrate (μmol/l) along the 36° N latitude in the Cretan Sea in March-April 1992.

of these parameters at a station situated at the south of Crete during September-October 1987 and March-April 1992 (SOUVERMEZOGLOU *et al.,* 1996; Fig. 3).

1994-95

During the four cruises of the PELAGOS project in 1994-1995, the "nutrient rich-oxygen poor" water mass is installed in the intermediate depths of the Cretan Sea and has more pronounced characteristics than in 1991 (Fig. 6). It is situated at the density level $\sigma\theta \sim 29.16$, and its presence is very important south of 36°30' N latitude; the sigma-theta of the deep layer is higher than 29.30 in all the stations of the Cretan Sea.

During this period, the two water masses namely the Cretan Dense Water (CDW) and the Transitional Mediterranean Water (TMW) play the leading role on the circulation through the Cretan Arc straits. The massive and continuous outflow of the newly formed CDW towards the Ionian and the Levantine seas, occurs mainly through the deeper parts of the Antikythira and Kassos Straits. The "nutrient rich-oxygen poor" TMW intrudes in the intermediate layer of the Cretan Sea mostly through the Eastern Straits of the Cretan Arc compensating the CDW outflow (KRASAKOPOULOU *et al.,* 1999). These hydrochemicaly very different water masses, exchange through the straits of the Cretan Arc, influence different layers in the Eastern Mediterranean and the Cretan Sea, than in the past and contribute to a vertical redistribution of nutrients in the Eastern Mediterranean. The outflowing CDW ventilates the abyssal depths of the Eastern Mediterranean and reduces their nutrient content and the inflowing TMW enriches with nutrients the intermediate

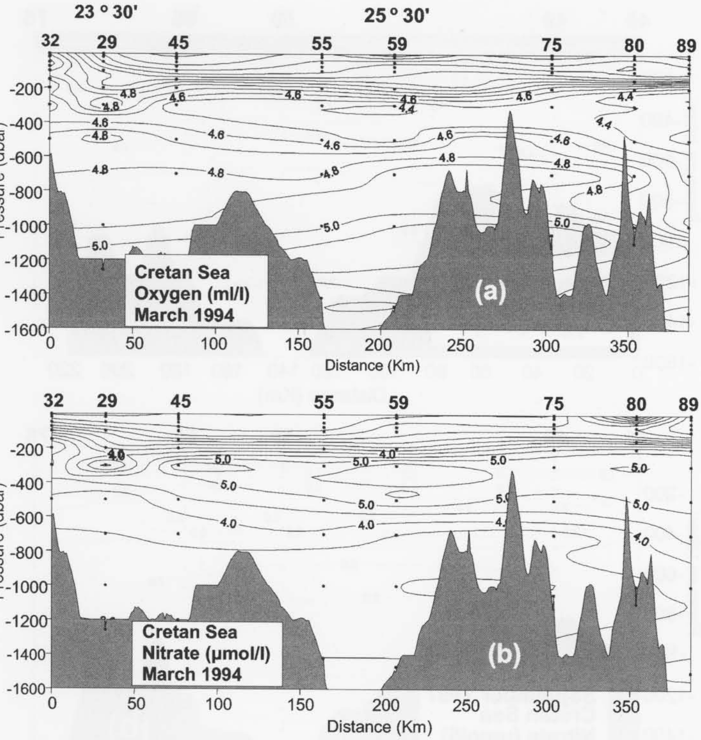

Fig. 6: Vertical distribution of (a) oxygen (ml/l) and (b) nitrate (μmol/l) along the 36° N latitude in the Cretan Sea in March 1994.

depths of the Cretan Sea and tends to influence the extremely oligotrophic character of the South Aegean Sea.

The nutrient concentrations measured in the intermediate layer of the Cretan Sea (5.0, 0.15 and 5.5 μmol/l for nitrate, phosphate and silicate respectively) are the highest measured in the same region over the last ten years, reaching values two times higher than in the past. The mean increase is in the order of ~2.5 μmol/l for nitrate, ~0.05 μmol/l for phosphate and ~2.5μmol/l for silicate. Conversely the dissolved oxygen concentration in these layers range from 4.2 to 4.6 ml/l and exhibit a remarkable decrease (~0.8 ml/l or ~35 μmol/l). The deep layers of the Cretan Sea are affected in a lesser degree by the new hydrological regime. The decrease of oxygen in this layer is about 0.3 ml/l while the corresponding increase of nitrate is about 1.5 μmol/l.

1997-98

During the cruises of the MATER project in 1997-1998 the "nutrient rich-oxygen poor" water mass of TMW still exists and forms a distinct intermediate layer in the Cretan Sea. Its characteristics are less pronounced than those observed in 1994 probably related to the weaker CDW outflow. The core of this layer lies between 200 and 400 meters and the concentrations ranged between 4.6-4.8 ml/l for oxygen, 2.8-3.2, 0.10-0.12 and 3.0-4.0 mmol/l for nitrate, phosphate and silicate, respectively (Fig. 7). The mean concentrations of the chemical parameters in the deep layer are: for oxygen ~5.0 ml/l, for nitrate ~2.8 μmol/l, for phosphate ~0.13 μmol/l and for silicate 3.8 μmol/l.

Figure 8 summarises the installation of the new hydrological regime in the Cretan

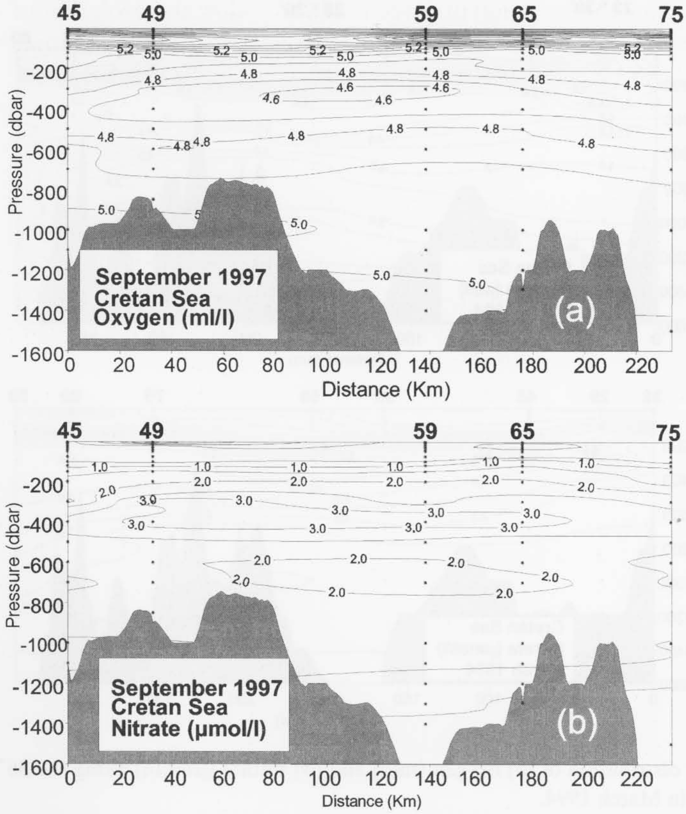

Fig. 7: Vertical distribution of (a) oxygen (ml/l) and (b) nitrate (μmol/l) along the 36° N latitude in the Cretan Sea in September 1997.

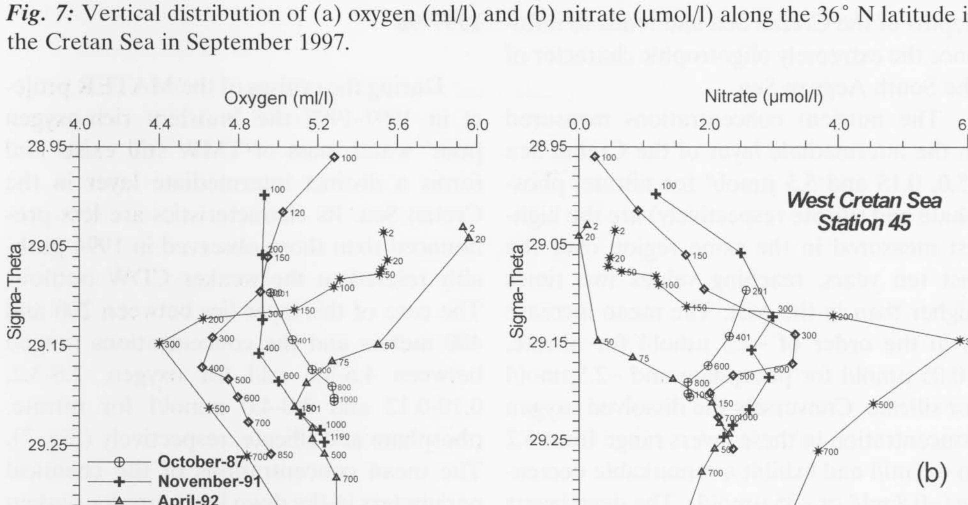

Fig. 8: Distribution of (a) oxygen (ml/l) and (b) nitrate (μmol/l) versus sigma-theta at the station 45 in the western Cretan Sea during October 1987, November 1991, April 1992, March 1994 and September 1997. Numbers in the profiles indicate the sampling depths in meters.

Sea by representing the evolution of oxygen and nitrate versus sigma-theta during the period of 1987-1997 at a station situated in the western Cretan Sea.

From 1987 to 1991 the increase of the deep waters density is followed by the increase of nitrate and the corresponding decrease of oxygen concentrations. After a further increase of density in 1992 the deep waters of the Cretan Sea reach sigma-theta 29.4 although their oxygen and nitrate content remains at the level of 1991. The increase of oxygen and the decrease of nitrate in the intermediate layers is the result of very intense convective mixing occurring this year. A totally different situation in the Cretan Sea is observed in March 1994. The vertical distribution of oxygen and nutrients in the Cretan Sea shows the existence of a large water mass with low oxygen and high nutrient content between 200 and 500 metres. This "nutrient rich-oxygen poor" water mass is installed in the Cretan Sea, between the saline intermediate and the deep CDW (Cretan Dense Water) by the intrusion of TMW (Transitional Mediterranean Water) compensating the deep outflow of CDW. The density of the deep waters remains at the same high levels while an increase of nitrate and a decrease of oxygen by about 1.5 μmol/l and 0.2 ml/l respectively is observed. The same station is visited during the second cruise of the MATER project, during September 1997. The deep water density is lower than 1992 and 1994 at about the same level of 1991. The TMW layer is situated somewhat deeper and is less pronounced than 1994. The intermediate and deep layers are more oxygenated and poorer in nutrients than in 1994.

Conclusions

Nutrient and oxygen data collected in the Cretan Sea, the adjacent eastern Ionian, nothwestern Levantine regions and the straits of the Cretan Arc since 1986, permitted to follow the evolution of the chemical characteristics of the intermediate and deep layers of the Cretan Sea.

In summary, the important increase of Cretan Dense Water outflow, since 1991, resulted in an intrusion of the Transitional Mediterranean Water (TMW) in the intermediate layers of the Cretan Sea. However, very intense convective mixing in winter 1992, prevented from the installation of a distinct "nutrient-rich oxygen-poor" layer in the Cretan Sea.

During 1994-95 an important change in the nutrient and oxygen concentrations of the intermediate layer of the Cretan Sea was detected, due to the intrusion of the "nutrient rich-oxygen poor" TMW compensating the Cretan Dense Water (CDW) outflow. The concentrations of nutrients in this layer are found sometimes double than those observed during the previous years until 1992 (increase ~2.5 μmol/l of nitrate, ~0.05 μmol/l of phosphate and ~2.5 μmol/l of silicate). The decrease of oxygen in this layer is about 0.8 ml/l (35 μmol/l).

In the deep layer, an important outflow of the CDW mainly through Antikythira and Kassos straits towards the open sea regions, results to an important increase of oxygen and decrease of nutrients, in the deep and bottom layers, of the Eastern Mediterranean.

Recently, in 1997-98 the chemical characteristics of TMW are less pronounced probably associated to the weaker CDW outflow, indicating the possible decay of the transient behaviour of the Eastern Mediterranean.

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