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Abstract

Severe winter meteorological conditions promote dense water formation over the shelves of the North Aegean Sea. The newly formed dense water fills the deep basins of the North Aegean Sea, contributing to their ventilation and the downward transport of organic and inorganic material. The great bathymetric variability imposes limitations on the deep circulation and the communication between the various basins and makes the North Aegean Sea an appropriate area for the monitoring of oxygen consumption in the deep layers. Historical hydrographic data suggest that there was extensive production of dense water in the North Aegean Sea on two occasions during the last decade, the winters of 1987 and 1992-1993. Our data series from August 1986 to September 1989 and from March 1997 to February 1999, permitted us to follow, step by step, the oxygen consumption and the nutrient regeneration in the deep basins of the northern Aegean Sea during these periods of isolation. The organic matter reaching the bottom layer just after the deep water formation event is rich in labile and easily oxidizable material and its decomposition leads to a significant oxygen uptake during the first year of stagnation. The further decomposition of the remaining semi-labile and refractory material turns over on greater time scales, by consuming lesser amounts of oxygen. A more significant oxygen decrease is recorded in the eastern basin (Lemnos Basin) of the North Aegean Trough, than in the central (Athos Basin) and the western (North Sporades Basin) ones and is attributed to the irregular contribution of the Black Sea Water (BSW) to the water masses formed on the different shelves of the North Aegean Sea. Our results and the existing data on the Turkish straits showed that dissolved organic matter is the major constituent responsible for this high oxygen consumption. The slightly different particulate organic carbon fluxes to these depressions play a secondary role.

Keywords: Oxygen consumption, Carbon remineralisation, Stagnation, Deep waters, North Aegean Sea, Eastern Mediterranean

Introduction

Dissolved oxygen content in the ocean is governed by the biological activity in the water column as well as by physical processes. The surface water of the ocean usually reaches its saturation oxygen content, except in some areas for example strong upwelling regions.

The downward transport of oxygen-rich surface water by the dense water formation processes enriches the deeper layers. The consumption of oxygen in the deep layers of the ocean by bacterial remineralization of particulate and dissolved organic matter represents an essential process in ocean biogeochemistry. Apparent oxygen utilization (AOU) provides an estimate of the amount of oxygen used since a water parcel was at the surface and hypothetically fully saturated in oxygen.

The North Aegean Sea is characterized by an alternation of deep trenches and troughs, shallow shelves and sills. It receives fresh waters from the rivers of the Greek and Turkish mainland (POULOS *et al.,* 1997) and brackish waters of Black Sea origin (100-1000 km^3yr^{-1}) outflowing through the Dardanelles Strait (UNLUATA *et al.,* 1990). The modified Black Sea Waters (BSW) form a thin (about 20 m) surface layer that covers the majority of the North Aegean (ZERVAKIS & GEORGOPOULOS, 2002). The great bathymetric variability imposes limitations on deep circulation and on communication among the various basins, and makes the North Aegean Sea an appropriate area for the monitoring of the oxygen consumption in the deep layers. The North Sporades and Athos Basins, reaching depths of 1468 and 1149 m, respectively, are separated by a 500m deep sill from the 1550 m deep Lemnos Basin (Fig. 1). All of them form the North Aegean Trough and are separated by a shallow sill of 350 m from the 800 m deep North Skyros Basin, lying to their south. The severe winter meteorological conditions promote dense water formation over the plateaux, which receive warm waters of Levantine origin, considerable amounts of relatively cold and less saline Black Sea water and fresh waters from the rivers of the northern coastline. The newly formed dense water tends to follow the isobaths and finally fills the deep basins of the North Aegean Sea, contributing to their ventilation and the transport of organic and inorganic material. Important information on oxygen consumption, carbon and nutrient recycling in the deep

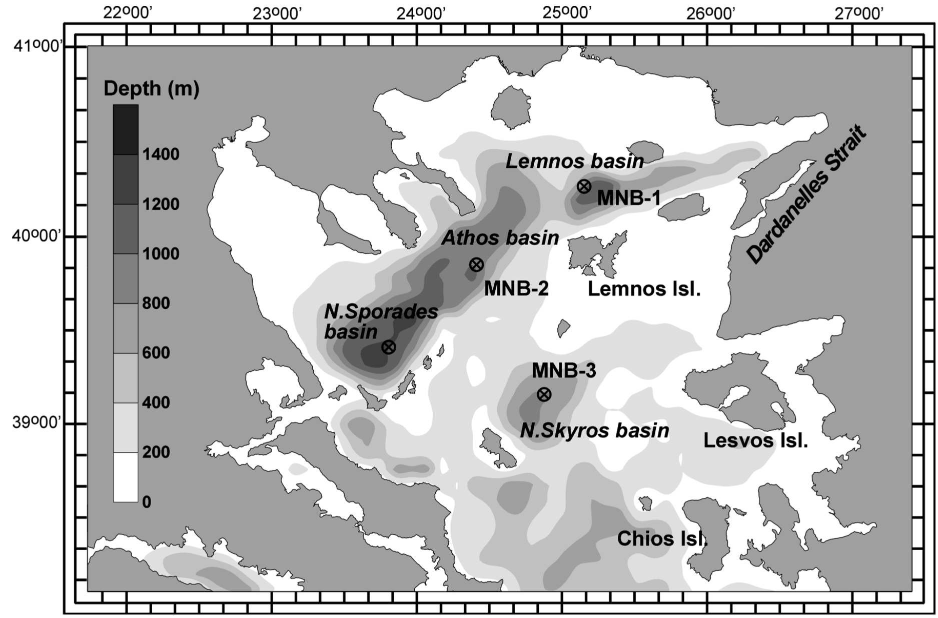

Fig. 1: Bathymetric chart of the North Aegean Sea with the location of the stations discussed in the manuscript.

waters, can be extracted by monitoring the change in the chemical properties in the deep basins and depressions of the North Aegean Sea during the periods of isolation.

Historical hydrographic data suggest that there was extensive production of dense water in the North Aegean Sea on two occasions during the last decade: the winters of 1987 and 1992-1993 (THEOCHARIS & GEORGOPOULOS, 1993; ZERVAKIS *et al.,* 2000). The existing data series from 1986 to 1989 and from March 1997 to February 1999 permitted us to follow, step by step, oxygen consumption and nutrient regeneration in the deep basins of the North Aegean Sea during these periods of isolation.

Materials and Methods

Within the framework of the national Open Sea Oceanography research program, eight oceanographic cruises took place from August 1986 to September 1989 in the North Aegean Sea. The observations are more limited between 1989 and 1997, when interest was focused on the south Aegean and Levantine seas. During the second period of intensive monitoring of the North Aegean, from March 1997 to February 1999, two research projects funded by the European Union, MTP-II MATER Mass Transfer and Ecosystem Response and INTERREG-1 Interregional Pollution in the North Aegean allowed the National Center for Marine Research (NCMR) to conduct several extensive surveys in the region. During these cruises oxygen samples were collected down to 1500 m with a rosette sampler (12 Niskin bottles of 8 L) fixed on a CTD probe. The location of the stations is shown in Figure 1. For the determination of oxygen, samples were first taken from the sampling bottle and analyzed immediately after collection on board by the Winkler method according to CARPENTER (1965a and 1965b); the precision in the method is estimated at 2.2 μmol O_2/L. The apparent oxygen utilization (AOU) was calculated according to the difference of the measured oxygen values from the oxygen saturation given by the algorithm of MILLERO (1986).

Nutrient data presented in the manuscript are related to the first period of intensive monitoring (1986-1989). During this period, samples for the determination of nutrients were collected in 100 mL polyethylene bottles and kept deep-frozen (-20° C) until analysis in the laboratory by a Technicon CSM6 autoanalyser. Phosphate was measured on board R/V Aegaio by a HITACHI Model 100-60 UV/VIS Spectrophotometer, in order to improve reliability. The methods described by MURPHY & RILEY (1962) for phosphate, MULLIN & RILEY (1955) for silicate, SHINN (1941) 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

Deep water formation

The high resolution of data obtained during the period from August 1986 to September 1989, with the eight cruises performed within the framework of the Open Sea Oceanography program, allowed one to make a detailed examination of the evolution of the pycnocline (ZERVAKIS *et al.,* 2000). The two extensive surveys carried out in the North Aegean during February and August 1987 indicated a major formation event during late winter 1987. The dense water formation process over the Samothraki and Lemnos plateaux in the beginning of March 1987 has been presented in detail in THEOCHARIS & GEORGOPOULOS (1993). This dense water formed in the shelf areas slides towards the deeper layers following the isobaths and finally fills the deep basins of the North Aegean Sea. The dramatic increase in the oxygen content below 200 m that was recorded between February and August in both the North Sporades (western) and the Lemnos (eastern) Basins, is an additional proof of the severity of this formation event (Fig. 2). Furthermore, the observed increase of oxygen is followed by a corresponding decrease of the nutrients content (Fig. 2). In the Lemnos Basin, the density (σ_θ) of the newly formed deep waters exceeds 29.40 (ZERVAKIS *et al.,* 2000) and the oxygen concentration reaches 250 μmol/L, while the corresponding values for the North Sporades Basin are 29.35 and 245 μmol/L, indicating a more severe formation in the Lemnos Basin. However, the variation in oxygen and nutrient concentrations between the two periods is more important for the deep layers of the North Sporades Basin (western). The increase of oxygen in the deep layers of the western and eastern basins reaches 28 and 20 μmol/L of O_2 respectively, while the accompanying decrease of nitrate is 1.39 and 0.95 μmol/L; of silicate 4.06 and 2.25 μmol/L and of phosphate 0.045 and 0.040 μmol/L.

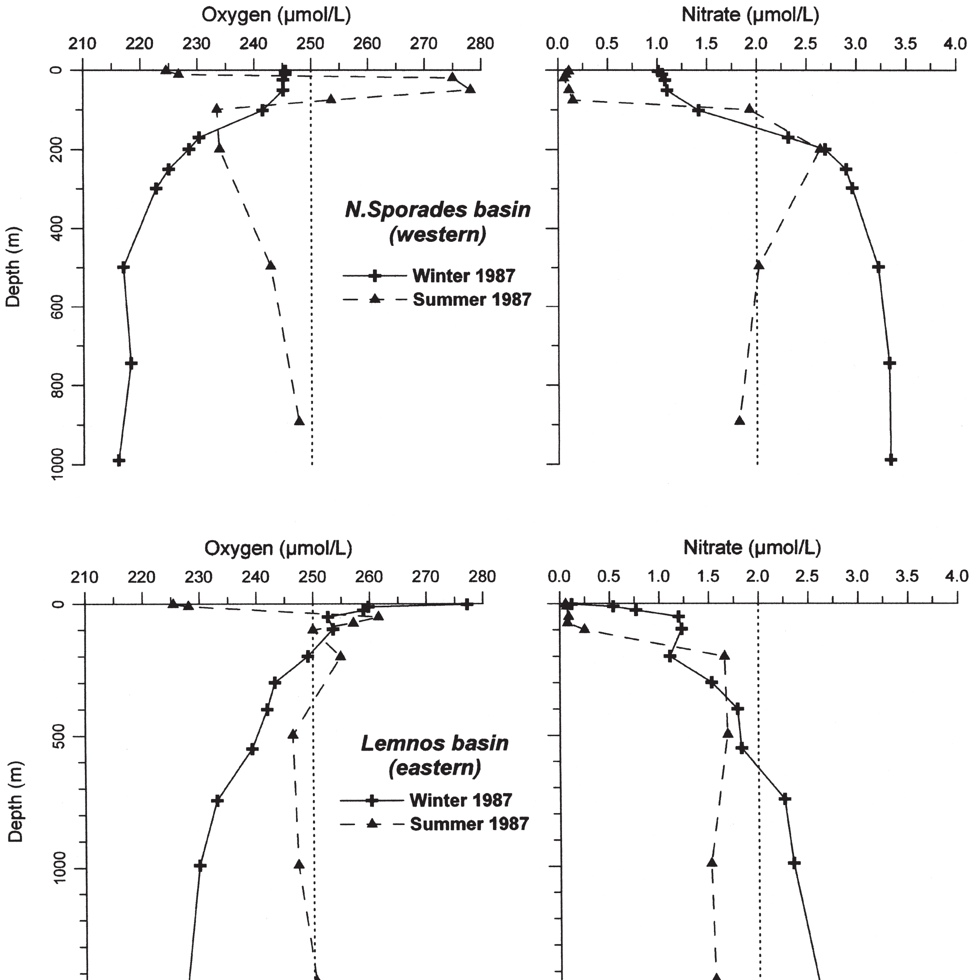

Fig. 2: Vertical distribution of oxygen and nitrate at the same station of the North Sporades basin (upper part) and of the Lemnos basin (lower part) during winter and summer 1987.

Assuming the preformed characteristics of the water masses were the same, then these differences imply that possibly the North Sporades Basin was occupied by 'older' waters (lower oxygen - higher nutrient content) prior to the formation event.

Our observations carried out over an extended period, showed that the degree of oxygenation and the nutrient content in the deep basins of the North Aegean Sea, differ considerably, indicating limited communication between the basins, the possible existence of several source water masses of different composition, and probably the different intensity and timing of deep water formation.

The extensive production of dense water ventilates the deep water and creates a direct pathway for the transport of inorganic and newly formed organic matter into the deep layers. The organic matter reaches the bottom layer very fast and has no time to degrade during sinking. The oxygen consumption for the remineralisation of organic material during the isolation periods provides information about the amount and the composition of the decomposing organic material.

We consider the timing of the Open Sea Oceanography data fortunate, in that within more than a three-year sequence (till September 1989), the deep waters remained practically isolated. This facilitated our strategy of monitoring the temporal evolution of the properties of the trapped water. The lack of data between 1990 and 1997 did not permit us to define the exact timing of the next deep water formation event, but we had the opportunity to monitor a second stagnation period, from March 1997 to February 1999.

Deep water evolution

The oxygen is consumed in the deep layers of the ocean, either by the decomposition of particulate and dissolved organic matter transported from the surface through the formation process, or by the slow degradation of the organic matter produced and settling from the euphotic zone. The relative importance of the two different sources of organic matter depends on either the contribution of shelf waters to the ventilation of the deep layers of the basins and/or on the biological productivity of the area.

Figure 3 represents the apparent oxygen utilization (AOU) in the two basins of the North Aegean Trough from February 1987 to September 1989. The intense deep water formation in late winter 1987 is manifested by an important decrease of AOU at depths below 200 m in both basins. The progressive increase of AOU from August 1987 to September 1989 is due to the oxygen consumption by bacterial remineralization of particulate and dissolved organic matter. It is evident that the increase of AOU in the deep layers is more important during the first year after the formation until August 1988; and then continues to increase with lower intensity. The organic matter reaching the bottom layer during or just after the deep water formation event, is rich in labile and easily oxidizable material and its decomposition leads to a significant oxygen uptake. The subsequent decomposition of the remaining semi-labile and refractory material occurs over a greater time scale and the rate of oxygen consumption is much reduced. Additionally, the recorded oxygen utilization in the deep layer is also influenced by the oxidation of the organic material falling from the upper parts of the water column. Of interest is the fact that during September 1989 the AOU concentrations in the North Sporades Basin stop following an increasing trend (Fig. 3). The possible reasons for the ventilation of the water column in the western basin still remain unclear.

A more schematic presentation of the oxygen evolution in the deep layer of the North Sporades (eastern) and Lemnos (western) Basins, from September 1986 to September 1989, is presented in Figure 4. The mean depth-integrated oxygen values for the depths below 1000 m were used for this presentation. The

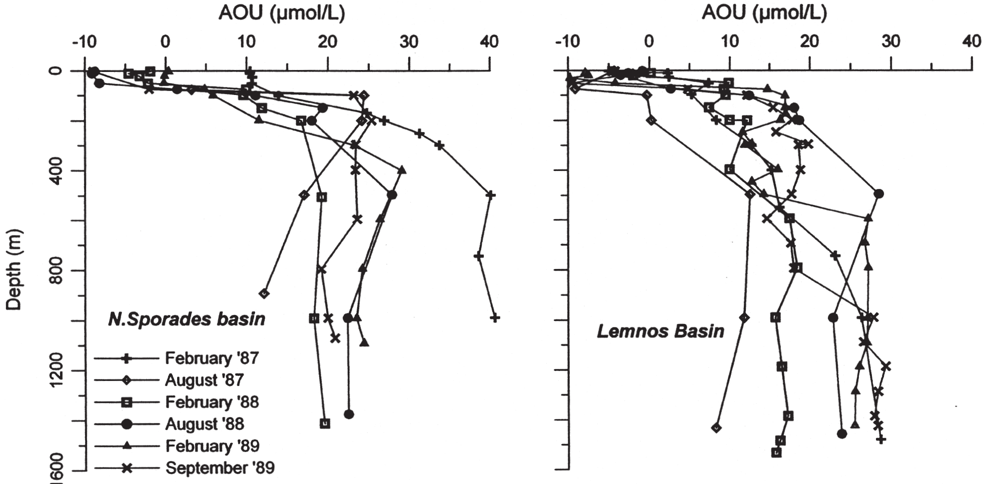

Fig. 3: Vertical evolution of the Apparent Oxygen Utilization (AOU) in the western and eastern basins of the North Aegean Trough (North Sporades and Lemnos basins) from February 1987 to September 1989.

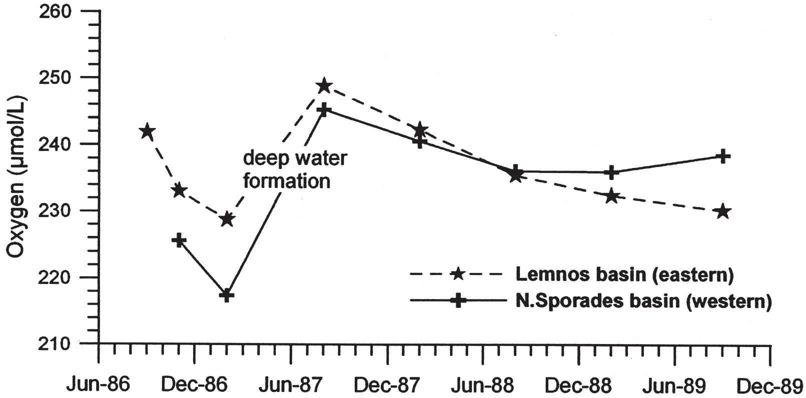

Fig. 4: Temporal variation of mean integrated dissolved oxygen concentrations, for depths below 1000m, in the eastern and western sub-basins of the North Aegean Trough, from November 1986 to September 1989.

oxygen consumption rates for the time intervals between the cruises are presented in Table 1. A well defined decrease of the oxygen concentrations and a high oxygen consumption rate is observed for the period from August 1987 to February 1988 (Fig. 4, Table 1). Another important observation from these data is that the oxygen decrease in the eastern basin seems to be greater than the correspon-ding decrease in the western basin of the North Aegean Trough.

Although the precise period of the next deep water formation event is not exactly defined due to the lack of data between 1990 and 1997, we were able to monitor a second period of isolation from March 1997 to February 1999. Figure 5 represents the evolution of the vertical distribution of AOU during this period in the Athos (central MNB-2) and the Lemnos (eastern MNB-1) Basins (Fig. 1). The gradual increase of AOU is more important in the Lemnos basin, indicating the relative importance of the quantity and probably the different composition of organic matter that is regenerated in this depression. The differences in oxygen consumption-nutrient regeneration rates in the different basins of the North Aegean Sea are confirmed by the representation of the evolution of the depth-weighted oxygen concentrations in the deep layers (depth>500m) of the three basins (Lemnos, Athos, Skyros) for this second period of isolation (Fig. 6). The decrease in oxygen is more important in the easternmost Lemnos Basin. The mean oxygen consumption rates calculated for the same period are 7.8, 5.0 and 6.6 μmol O_2 $L^{-1}yr^{-1}$ for Lemnos, Athos and Skyros Basins respectively. In addition, the integrated rates of oxygen consumption expressed as μmolO_2 $m^{-2}day^{-1}$ for the three depressions are estimated as 15.9 (Lemnos), 6.2 (Athos) and 5.5 (Skyros). The quantity of regenerated carbon can be determined after converting oxygen to carbon equivalents using the Redfield stoichiometry (-O_2:C=1.3). Accordingly, from the Redfield model the organic carbon that has been fully oxidized in the deep layer amounts to 12.2, 4.7 and 4.2 μmolC $m^{-2}day^{-1}$ respectively for the three depressions.

Table 1
Oxygen consumption rates for the time intervals between the cruises taking place from November 1986 to September 1989, in the western (North Sporades) and eastern (Lemnos) basins of the North Aegean Trough.

Period	Oxygen consumption rate (μmol O_2 L^{-1} yr^{-1})	
	Lemnos Basin	N.Sporades Basin
11/86 - 3/87	14.6	28.0
late winter 1987	*deep water formation event*	
8/87 – 3/88	13.2	9.4
3/88 – 8/88	13.8	9.0
8/88 – 2/89	6.2	0.2
2/89 – 9/89	4.3	

The differences in these rates give evidence that there is a differing amount and a diversification in the chemical composition of the decomposing organic material (transported and settling), in these depressions. However, the measured concentrations of particulate organic carbon (POC) are similar in the two depressions of the North Aegean Trough (LYKOYSIS *et al.,* 2002) and the concentration of POC in the water column usually constitutes less than 10% of the total organic carbon (DOVAL *et al.,* 1999). It becomes clear that the differences in the oxygen consumption rates cannot be explained by the POC con-

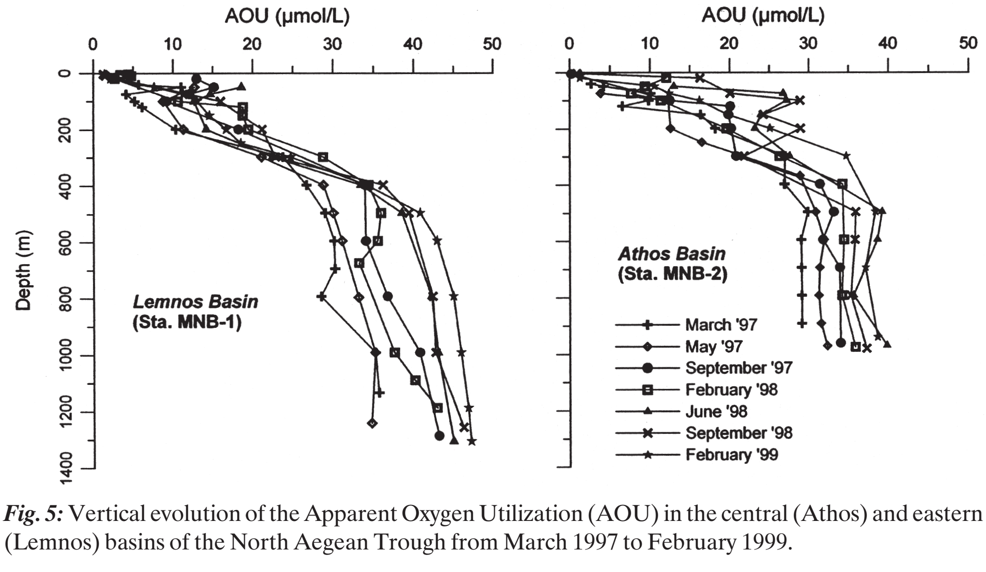

Fig. 5: Vertical evolution of the Apparent Oxygen Utilization (AOU) in the central (Athos) and eastern (Lemnos) basins of the North Aegean Trough from March 1997 to February 1999.

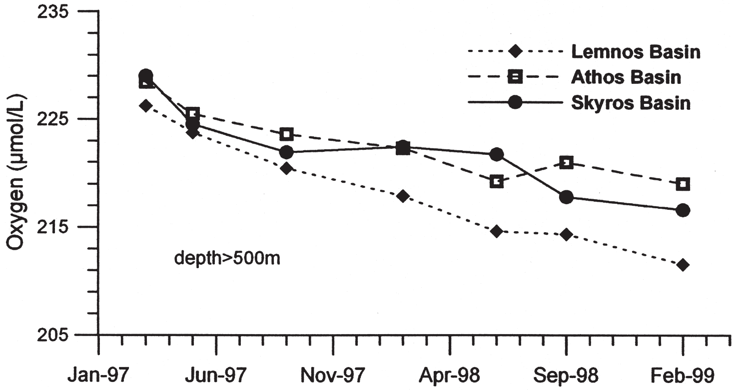

Fig. 6: Temporal variation of mean integrated dissolved oxygen concentrations, for depths below 500m, in three sub-basins of the North Aegean Sea, from March 1997 to February 1999.

centrations. It must be noticed that the material retained on GF/F filters is representative for particles in the 0.7-200 μm size range and, although they are more frequent than the larger particles, they have an insignificant role in vertical mass flux. It has been demonstrated that the dominant mechanism of vertical transport is by the rapid settling of rare large particles (fecal pellets or marine snow >200 μm) collected with particle trap systems (SUESS, 1980). Actually the oxygen consumption rates observed in the three North Aegean depressions are consistent with the organic carbon fluxes obtained from sediment traps deployed 35m above the bottom in the same sites during a 1-year period of sampling (from April 97 to April 98). In particular, in the Lemnos Basin the highest mean annual flux of organic carbon was recorded (2.93 μmol C $m^{-2}day^{-1}$) and in Skyros the lowest (1.13 μmol C $m^{-2}day^{-1}$); the Athos Basin exhibits slightly higher organic carbon flux (1.25 μmol C $m^{-2}day^{-1}$) than Skyros (STAVRAKAKIS *et al.,* 1999). This means that the full oxidation of the organic carbon that is exported vertically to the deep layer is responsible for about 24%, 26.5% and 26.7% of the observed oxygen consumption rates in Lemnos, Athos and Skyros Basins respectively. This finding is in agreement with the recent consideration that in the aphotic layer the particulate organic carbon can support only 20% of the overall organic matter remineralization (LEFEVRE *et al.,* 1996).

Recently, the role of dissolved organic carbon (DOC) in the oceanic carbon cycle has been reassessed and it has been recognized as the main source of organic matter remineralisation in the ocean water column. The significantly higher TOC (POC+DOC) values reported for the North Aegean Sea relative to the South Aegean Sea reveal an important input of organic matter by the (BSW) Black Sea Water (SEMPERE *et al.,* 2002). The irregular contribution of the BSW in the water masses formed on the different shelves of the North Aegean Sea must be responsible for the amount and the chemical composition of the organic matter transported to the deep layers. In addition, it must be mentioned that the bacterial consumption of DOM at depth requires the existence of a form of organic matter that is 'fresh' and sufficiently labile to be available as substrate for bacteria, thereby contributing to oxygen consumption in the deep layer. From the bulk DOC that is transported downwards during the formation event or released from sinking particles, the labile fraction, which turns over on timescales of hours to days and the semi-labile portion that has a lifetime of months to years, are both responsible for the increasing oxygen deficit in the deep layer of the depressions.

Given that the concentrations of particulate organic carbon are of similar magnitude in the depressions of the North Aegean Sea (LYKOYSIS *et al.,* 2002) and that dissolved organic carbon represents the major fraction of the total organic carbon in the water column (DOVAL *et al.,* 1999), it seems that the increased oxygen consumption in the eastern depression could be related to a higher supply of dissolved organic matter. In fact, the surface waters of the eastern depression are under the direct influence of the Black Sea waters entering the Aegean and characterized by high concentrations of dissolved organic matter. A previous study based on long term chemical data showed that the Black Sea surface outflow reaches the Aegean Basin with large DON and DOC values due to their low decay rates, but there is a net decrease of the mean nitrate concentration due to their consumption in the Marmara Basin (POLAT & TUGRUL, 1996). Moreover, high TOC concentrations (>100 μmol C/L) as well as high bacterial production were recorded in the surface layer of the North Aegean Sea and particularly in the waters where the signs of BSW are more pronounced (SEMPERE *et al.,* 2002). However, it is stated in the previous study that although the Black Sea inputs seem to stimulate bacterial activity, the bacterial cycling of TOC is not substantially effective and gives rise to an accumulation of TOC in the surface layer. This accumulated TOC could be exported to depth and mineralized through bacterial respiration in the deep layer in the case of a deep water formation event.

ROETHER and WELL (2001) determined rates of oxygen consumption, prior to the Eastern Mediterranean Transient, by fitting simulated oxygen concentrations obtained by a box model to observations from a medium resolution survey of the eastern Mediterranean in 1987. The consumption rate obtained for water below 700 m, is considerably higher than the rates found in previous works for the deep ocean. The estimated rate for waters below about 1000 m is 0.53 $\mu molO_2 kg^{-1} yr^{-1}$ and it is an order of magnitude less than the rates observed in the deep waters of the depressions of the North Aegean.

The very high oxygen consumption rates observed in these depressions are related to the organic matter transported to the bottom by the two major deep formation events. Our results, coupled with the particulate organic carbon fluxes (STAVRAKAKIS *et al.,* 1999) and the total organic carbon dynamics in the area (SEMPERE *et al.,* 2002) suggest that oxygen consumption in the deep layers of the North Aegean is mainly controlled by the TOC (mostly the dissolved fraction) that was accumulated in the surface layer and transported downwards by the formation process. In addition, during the stagnation periods the only process that can change the oxygen content of the bottom waters in these depressions is diapycnal mixing with overlying waters. The modification of the oxygen content of the deep layers by this process is considered to be negligible.

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